

# **THE INTERACTION OF PICOSECOND AND SUBPICOSECOND LASER PULSES WITH GASES AND PLASMAS.**

By

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## Abstract

The interaction of picosecond and sub picosecond laser pulses with neutral and pre-ionised gaseous targets has been studied. Plasmas were produced by the optical ionisation of gaseous targets by laser pulses, with durations between 0.35 and 12ps, powers from 0.01-10TW at wavelengths of 0.248 and 1.054 $\mu$ m, and with gas densities covering the range  $5 \times 10^{18}$  -  $3 \times 10^{20}$  cm<sup>-3</sup>. The temporal and spatial evolution of the electron density gradients were measured with a time resolved deflectometer. This enabled the electron temperature to be inferred. It was found that as the gas density increased above  $1 \times 10^{18}$  cm<sup>-3</sup> the radius of the plasma increased and it broke up into many small scale density channels. By varying the laser and target parameters it was found that refraction from ionisation induced density gradients were responsible for both these effects. These measurements were compared to theoretical absorption and laser propagation models. Agreement between the absorption models and the data could only be obtained if the laser intensity were reduced far below the value obtained in vacuum. The intensity required for agreement with the absorption models agreed within a factor of two to the limiting intensity predicted by an analytic defocusing model and within 25% of the result predicted by the numerical simulations. The defocusing was overcome by the use of a preformed density channel to guide the laser pulse in density regimes applicable to XUV recombination lasers and laser accelerators. It was discovered that severe channel non-uniformity prematurely closed the wave guide and reduced the channel length. When this was overcome by increasing the energy of the preforming pulse and reducing the target gas density, a 5TW pulse was guided over 1mm. This was equivalent to guiding over 70 times the characteristic defocusing length of the plasma.

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# 1 Introduction.

Laser produced plasmas have been studied extensively since the invention of the first laser devices. During experiments with high power laser pulses focused into gases [1] it was observed that if the laser electric field was above a threshold value the normally transparent gas became ionised and absorbed energy from the laser. An understanding of the ionisation and heating mechanisms that governed the interaction of the laser pulse with gaseous targets is very important for many applications.

In the early experiments the laser pulse duration was long (of the order 10 - 100ns ) and there was time for significant plasma motion during the laser pulse. Under these circumstances it was difficult to model the absorption and ionisation mechanisms accurately, because the laser interacted with an evolving plasma. The theoretical modelling can be greatly simplified by eliminating plasma motion during the laser pulse. When a laser pulse with a duration of less than 10ps ( the definition of a short pulse in this thesis) is focused into the plasma there is not enough time for significant expansion to occur. Time resolved measurements of the initial electron density and temperature gradients can then be compared to the laser absorption and propagation models without the need for modelling of the hydrodynamic expansion.

The propagation of laser pulses through neutral gases and plasmas is in itself a complex subject with many important physical mechanisms, including, absorption, scattering, self focusing and refraction. It is necessary to use space and time resolved diagnostics to investigate the individual contributions of these mechanisms to the energy deposited within the plasma.

For a plasma produced by a short laser pulse, the laser ionisation and heating stage is followed by hydrodynamic expansion. The initial stages are determined by the rate of energy conduction from the hot central region to the colder surrounding gas. The electron energy is then transferred via collisions to the ions on a time scale that depends on the plasma density and temperature [2]. On the same time scale the expansion front develops into an ion shock wave which compresses and heats the unionised gas as it propagates [3]. A representation of the temporal evolution of the plasma density can be seen in Figure 1.1.

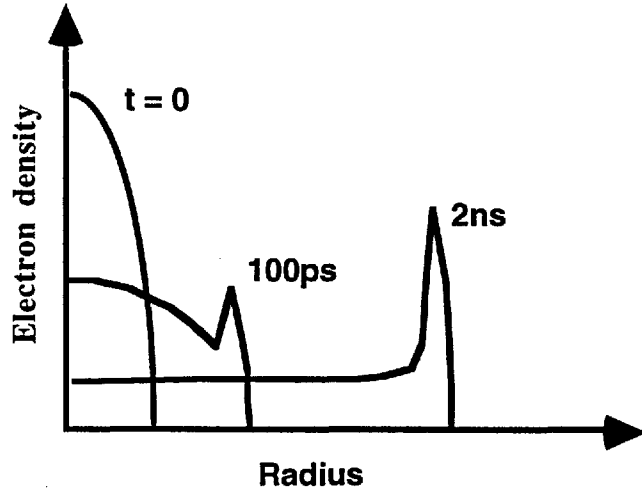


Figure 1.1 Evolution of the radial plasma density profile with time.

In this thesis the temporal and spatial evolution of plasmas produced by short pulses was studied. In a well diagnosed plasma the rate of expansion of the shock front can be related to the amount of energy initially deposited in the gas, thus allowing a measure of the initial plasma temperature to be obtained[3]. This temperature measurement technique is described theoretically in section 2.4 and experimentally in chapter 4 and 5. The density profile of the channel after expanding for a few nanoseconds, as portrayed in figure 1.1, can also be used as a wave guide to confine high intensity laser pulses. Experiments that investigated this are described in chapter 5. The remainder of this introduction will outline some of the fundamental plasma parameters, followed by a summary of the important laser plasma applications that are relevant to the work in this thesis.

## 1.1 The plasma refractive index and plasma frequency

In vacuum the wave number,  $k$ , and frequency of the laser,  $\omega$ , are related to the wave velocity,  $c$ , by  $k = \omega / c$ . In a plasma the collective oscillations of the plasma modify the wave propagation and the phase velocity of the laser through the plasma is determined by the dispersion relation :

$$\omega^2 - \omega_p^2 = k^2 c^2 \quad (1)$$

where the plasma frequency,  $\omega_p$ , is defined by  $\omega_p = (n_e e^2 / 4\pi\epsilon_0 m_e)^{1/2}$ . The refractive index of the plasma is defined by the ratio of the phase velocity in vacuum to the phase velocity in the plasma,  $\mu = c k / \omega$ . Using the dispersion relation from (1) gives  $\mu$  in terms of the laser and plasma frequency

$$\mu = \left[ 1 - \frac{\omega_p^2}{\omega^2} \right]^{1/2} \quad (2)$$

When  $\omega_p > \omega$ ,  $k$  is imaginary, the plasma oscillations are fast enough to shield the electron oscillations driven by the laser and the wave cannot propagate. The laser can only propagate at densities below the critical density, which is defined by  $\omega_p = \omega$ . The critical density is often expressed as a function of laser wavelength, with  $\lambda$  in  $\mu\text{m}$  :

$$n_c = 1.1 \times 10^{21} \lambda^{-2} \quad [\text{cm}^{-3}] \quad (3)$$

For example,  $\lambda = 1.054 \mu\text{m}$ ,  $n_c = 1.1 \times 10^{21} \text{ cm}^{-3}$  and for  $\lambda = 0.248 \mu\text{m}$ ,  $n_c = 1.78 \times 10^{22} \text{ cm}^{-3}$ .

## 1.2 Plasma scale lengths.

In a plasma the maximum distance the electrons can move without causing the ions to move is limited to the Debye length,  $L_d$ , by the space charge (Coulomb) force created between the ions and the electron, where,

$$L_d = \left( \frac{\epsilon_0 k T_e}{q^2 n_e} \right)^{1/2} \quad (4)$$

Where  $T_e$ ,  $n_e$  and  $q$  are the electron temperature, density and charge respectively, and  $k$  is the Boltzmann constant. As the electrons are heated to  $T_e$ , they expand, and after moving a distance  $L_d$ , the ions are pulled along with them. The expansion velocity of the plasma into vacuum is often approximated by the ion sound speed  $c_s$  :

$$c_s = (Z T_e / m_i)^{1/2} \quad (5)$$

Where  $Z$  and  $m_i$  are the ionic charge and mass respectively. This equation is often used for an order of magnitude estimate of the expansion velocity of the critical density surface. For a 10ps pulse that heats a hydrogen plasma to 100eV the plasma will expand at  $c_s = 1 \times 10^7 \text{ cms}^{-1}$  and its radius will increase by less than  $1\mu\text{m}$  within the pulse duration. This is very small compared to a typical plasma radius of  $20\text{-}30\mu\text{m}$ . This simple estimate suggests that for plasmas less than 100eV hydrodynamic expansion will not be significant for laser pulses shorter than 10ps. For smaller plasmas at higher temperatures there will be some plasma motion and modelling of the development of density and temperature gradients requires modelling with simulations. The subject of hydrodynamic simulations will be treated in section 2.4 on the propagation of shock waves.

### 1.3 Applications of laser produced plasmas

As a result of the extremely wide parameter range of laser produced plasmas this thesis will only describe applications of those produced by short, powerful laser pulses. A review of applications of plasmas produced by lasers with a wide range of powers is contained in the book edited by Radziemski and Cremers [4]. Shock tubes and theta pinches produce plasmas that have been used to measure ionisation rates and test atomic physics theories [5]. Plasmas produced by laser pulses are useful sources for the development of atomic physics models at densities and / or temperatures that cannot be obtained with other devices [6]. A model of ionic level populations has been produced by Lee [7] and used for comparisons with experiments. However there are additional experimental difficulties with laser plasmas compared to studies with shock tubes and theta pinches due to the large gradients and short time scales present in most laser plasmas.

The thermal X-rays produced by these plasmas are also of interest for the production of high resolution semiconductor devices and the imaging of living cells [4]. In some materials a population inversion can occur between energy levels in the plasma ions and lasing can occur if the geometry of the targets is favourable. X-ray lasers have been produced in a number of laser plasmas and over a wide range of laser wavelengths [8]. Apart from the fundamental interest of X-ray lasers in the field of atomic physics one of their most important applications is as a source for holographic images with sub micron spatial resolution.

## **1.4 Applications of plasmas produced by short laser pulses.**

The work in this thesis has been confined to laser plasma interactions with laser pulses between 350fs and 12ps. There are a number of potential applications of plasmas produced by pulses with these durations. Picosecond pulses can be used to accelerate particles to velocities close to the velocity of light in the Wakefield accelerator [9]. Pulses with durations less than 100fs have also been proposed as a pumping source for the recombination X-ray laser [10]. Such a laser has the advantage of requiring modest pumping energies compared to collisional pumping schemes [11]. One of the most important potential applications of laser produced plasmas is their potential use in the generation of power through the thermonuclear fusion of deuterium and tritium [12]. Recently a novel scheme [13] that uses extremely intense pulses to ignite the compressed fuel has been published. The first pulse with, a duration of 100ps, creates a channel through the underdense plasma and up to densities 100x critical density for 1 $\mu$ m light, through a combination of its extremely high light pressure and a relativistic lowering of the plasma refractive index. The second pulse is guided through this channel and absorbed at the super critical density surface. The plasma waves produced in the absorption mechanism accelerates electrons to energies exceeding 1MeV and these electrons efficiently heat the compressed fuel ions causing ignition. The laser requirements for this so called "fast igniter" scheme have not yet been achieved but Chirped Pulse Amplification (CPA) systems exist which allow some of the relevant laser absorption and propagation mechanisms to be studied in a similar regime. The laser and target requirements for both recombination X-ray laser and the short pulse fusion ignition scheme will be described in the next section.

### **1.4.1 Recombination X-ray lasers.**

The formation of a population inversion between highly excited states and the ground state in a recombining ion following rapid ionisation and subsequent cooling of a plasma was first studied by Peyraud and Peyraud[14]. In essence the population inversion arises because at high electron densities three body recombination predominantly fills the upper excited states that are strongly coupled to the continuum. This results in a de-excitation cascade amongst the highest levels. The lower level just above the ground state is depopulated through radiative transitions. If the recombination rate is high enough a population inversion builds up between the excited states and lasing can occur. The general requirement for an appreciable population inversion is a rapid recombination rate,

requiring a high electron density and low electron temperature. The initial method for the formation of a rapidly recombining plasma was to use an intense laser pulse to create a plasma that expands and cools extremely rapidly [11]. In a more recent method the required ionisation stage is produced optically, without heating the electrons, with a short pulse laser. The optical field induced ionisation leads to an almost complete emptying of the ground state of the lasing ion and so the population inversion occurs over the highest possible energy gap between the ground state and the first excited state. A number of possible schemes using rapid optical ionisation to achieve a population inversion have been published [14], [15]. The Li-like Neon model published by Eder [10] studied the limiting electron temperature and density regimes that were required for usable gain and energy efficiency.

#### 1.4.2 The Li-like Neon recombination X-ray Laser.

This section will describe the model of the Li-like Neon x-ray laser [10] as an example of the general requirements for the success of this scheme. The model starts with Neon ionised to He-like ions following irradiation with a sub picosecond laser pulse at an intensity greater than  $2 \times 10^{17} \text{ Wcm}^{-2}$ . The threshold intensity for ionisation to the He-like stage is given approximately by the Coulomb barrier model [16] (this will be described in more detail in chapter 2),

$$I_{th} = \frac{2.2 \times 10^{15}}{Z^2} \left[ \frac{U_q}{27.21} \right]^4 \text{ Wcm}^{-2} \quad (6)$$

where  $U_q$  is the ionisation potential in eV and  $Z$  the residual charge of the atom or ion. This model will be discussed in more detail in the section on ionisation in chapter 2. In Neon the threshold intensity for He-like ions is  $2 \times 10^{17} \text{ Wcm}^{-2}$ , and approximately  $3 \times 10^{17} \text{ Wcm}^{-2}$  is required to completely empty the ground state of the Li-like ion [10]. The  $n = 3$  to  $n = 2$  are the levels involved in lasing transitions with the highest gain being  $3d_{5/2} - 2p_{3/2}$  at  $\lambda = 98\text{\AA}$ .

In this model the energy efficiency  $\Sigma$ , defined as the ratio of output energy to input energy, scaled as  $I_{sat} L_{sat}^{-1} \Delta t$ , where  $I_{sat}$  and  $L_{sat}$  are the saturation intensity and length respectively and  $\Delta t$  gain duration. The saturation intensity is defined as the intensity at which the gain is reduced to 1/2 the small signal gain  $G_{ss}$  given by,

$$G_{ss} = \frac{\pi q^2}{m_e c^2} f_{osc} \Psi(\nu) N_u \left[ 1 - \frac{N_l g_u}{N_u g_l} \right] \quad (7)$$

Where  $f_{osc}$  is the emission oscillator strength and  $\Psi(\nu)$  is the line profile,  $N_u$  ( $N_l$ ) and  $g_u$  ( $g_l$ ) are the upper (lower) level population and statistical weight respectively. The term  $[1 - N_l g_u / N_u g_l]$  is the population inversion factor. The saturation length is defined as the length of plasma required for the x-ray laser intensity to reach  $I_{sat}$ . For distances less than  $L_{sat}$  the laser intensity grows exponentially with plasma length and linearly for distances greater than  $L_{sat}$ . The gain and energy efficiencies of the transitions were calculated using a kinetic shell averaged model to determine the level populations. The gain was found to depend strongly on the residual electron temperature because of the slower recombination rate from He-like to Li-like for higher electron temperatures.

The model predicted gain coefficients greater than  $100\text{cm}^{-1}$  for  $T_e$  less than 40eV, reducing to  $13\text{cm}^{-1}$  for  $T_e \sim 100\text{eV}$ . The rate of decrease of gain with temperature scaled as  $G_{max} \sim T_e^{-2.6}$ . The gain also depended strongly on the electron density because of the faster collisional rates at higher densities. The rate of increase of gain with density scaled as  $G_{max} \sim N_e^{1.5}$ . The energy efficiency,  $\Sigma$ , depended very strongly on both the electron temperature and density  $\Sigma \sim T_e^{-2.6}$  and  $\Sigma \sim N_e^{+2.7}$ . As an example of the typical conditions required to observe gain, with a gain length product  $GL > 10$ ,  $T_e = 40\text{eV}$ ,  $N_e = 5 \times 10^{20} \text{ cm}^{-3}$ , the calculated maximum gain was  $G_{max} = 100$  and the energy efficiency was  $\Sigma = 8 \times 10^{-6}$  for a plasma radius of  $10\mu\text{m}$ . The length of the He-like plasma is determined in the model by the diffraction limited depth of focus a Gaussian pulse. This is given by the confocal parameter,  $L_{cf}$ , (defined as the distance between the half intensity points before and after focus [17]) where,

$$L_{cf} = \frac{2\pi w_0^2}{\lambda} \quad (8)$$

where  $w_0$  is the Gaussian spot radius and  $\lambda$  is the wavelength of the pump laser (this parameter will be described in more detail in the chapter 2). For a laser with  $\lambda = 0.248\mu\text{m}$  and  $w_0 = 17\mu\text{m}$ ,  $L_{cf} = 7\text{mm}$ . As the electron temperature is increased the gain is reduced and  $L_{sat}$  is increased. For a plasma with  $w_0 = 17\mu\text{m}$ , an electron density of  $5 \times 10^{20} \text{ cm}^{-3}$ ,  $L_{sat}$  becomes greater than  $L_{cf}$  the energy efficiency drops extremely

rapidly below the  $10^{-6}$  level that is required for most applications, when  $T_e = 40$  eV. The success of this scheme strongly depends on being able to form a highly ionised plasma, with a low electron temperature over a distance of the order of several mm. One of the major problems affecting the success of this scheme is the very high heating rates of inverse Bremsstrahlung and Raman mechanisms at these densities and laser intensities. The contribution of the Raman heating mechanism can be reduced by using laser pulses shorter than 100fs [10]. However, another problem that cannot be overcome by the use of shorter pulses is the reduction in the length of the He-like plasma due to ionisation defocusing.

It will be shown in chapter 4 that for a  $0.248\mu\text{m}$  laser focused into Neon at an atomic density of  $6 \times 10^{19} \text{ cm}^{-3}$  the defocusing effect is extremely strong, preventing the plasma from even reaching a He-like ionisation stage. The refractive effects can be overcome with the use of plasma wave guides to confine the pulse. Experimental measurements of the electron temperature in plasmas in this regime, together with evidence of strong refractive effects and the formation of plasma wave guides are extremely important requirements for understanding of the feasibility of schemes such as the Li-like Neon recombination X-ray laser. This thesis describes, in detail, experiments that quantitatively measured the refraction effects caused by ionisation defocusing and showed that it was overcome with the use of plasma wave guides. Another very important potential application of intense short pulses is as a source of ignition of thermonuclear fusion, the next section will briefly describe this application.

### 1.4.3 The ignition of thermonuclear fusion.

The achievement of fusion depends on the kinetic energy of the nuclei being sufficient to overcome their Coulomb repulsion. At a plasma temperature of 10keV [18] the reaction of deuterium and tritium has the highest cross section,



The rate of thermonuclear burn is proportional to the fuel density  $\rho$  and the Maxwell averaged cross section  $\overline{\sigma v}$  [19],

$$\dot{\phi} = \rho \overline{\sigma v} \quad (10)$$

The Lawson criterion determines the product of ion density,  $n_i$ , and time,  $\tau$ , required for sufficient ion heating to overcome the Coulomb repulsion [ 20].

$$n_i \tau > 10^{14} \text{ cm}^{-3} \text{ s}^{-1} \quad (11)$$

In stellar interiors the density of hydrogen is believed to exist at densities greater than one thousand times liquid density and temperatures around 1-2keV. These conditions are maintained by gravitational attraction. In magnetic fusion the plasma is confined at relatively low densities by a toroidal magnetic field over a sufficiently long time scale (a few tens of seconds). In Inertial Confinement Fusion (ICF) densities of  $1000\text{gcm}^{-3}$  are required to be achieved using ablative compression of spherical shells filled with fuel. The confinement time is determined by the inertia of the compressed fuel, characterised by the expansion of the fuel due to its thermal pressure. This section will describe two methods of achieving ignition of thermonuclear fusion using conventional shock wave heating [21] and a recent novel method using a PetaWatt laser pulse[13].

#### 1.4.4 Conventional ignition

The physics of ICF have been reviewed in a number of articles including J. Nuckolls et al, Brueckner and Jorna [22] and R.G. Evans [18]. The extremely high densities that are required for thermonuclear fusion are obtained in ICF by using laser ablation to compress a fuel filled sphere through the rocket effect [18]. Once the target has been compressed to a density around  $1000\text{gcm}^{-3}$  a series of shock waves converge at the centre of the target, heating the ions to temperatures in excess of 10keV. Thermonuclear ignition occurs from the hot region in the centre of the mass of fuel and the 3.6MeV alpha particles produced in the fusion reaction deposit their energy in the surrounding fuel. If the ion heating time is shorter than the time taken for the plasma to disassemble,  $\tau_{dis}$ , then fusion can occur, where ,

$$\tau_{dis} = \frac{r}{c_s} \quad (12)$$

where  $r$  is the radius and  $c_s$  is the sound speed of the compressed fuel. For  $r = 300\mu\text{m}$  and  $T_e = 10\text{keV}$ ,  $t_{dis} \sim 10\text{ns}$ . This method of igniting the compressed fuel has been compared to ignition using an intense laser pulse in the paper by Tabak [13]. In the first method, as outlined above, pulse shaping is used to achieve a series of converging

shocks that intersect near the middle of the pellet, compressing and heating a small fraction of the pellet mass to ignition temperatures. The temperature equilibration between this high temperature, low density core hot spot and the surrounding high density, low temperature fuel is described by the isobaric model [13, 21]. In the second method, energy is supplied to the compressed core quickly enough to heat it before the density changes. This method can be described by the uniform density or isochroic model [13, 12]. In the isochroic model a greater mass of fuel is compressed to a lower peak density and a higher gain is achieved because more fuel is burnt [13]. This has considerable savings on the amount of energy required to compress the fuel.

#### 1.4.5 Ignition with an ultra powerful laser pulse.

The achievement of thermonuclear fusion in the fast igniter scheme can be split into three stages. The fuel is first compressed to a density of 400-600gcm<sup>-3</sup> with a conventional implosion. An intense, 1μm, 100ps pulse is then used to create a channel leading from vacuum to densities up to 100x critical density ( $n_e \sim 1 \times 10^{23} \text{ cm}^{-3}$ ). A laser pulse with a duration of 10ps is then guided through the channel, at an intensity of  $1 \times 10^{18} \text{ Wcm}^{-2}$ , to the compressed core where the pulse is absorbed, producing electrons with a characteristic temperature of 1MeV. The mean free path of these electrons in the compressed fuel is such that they deposit their energy within a small distance of the laser absorption region. The heated Deuterium and Tritium ions in this region then fuse to produce alpha particles. These propagate into the cold fuel ions producing a self sustaining burn wave that propagates throughout the target causing fusion to occur.

#### 1.4.6 Channel formation and hole boring.

One of the most crucial aspects of this scheme is the formation of the density channel. The laser pulse that forms this channel is focused at an intensity greater than  $1 \times 10^{19} \text{ Wcm}^{-2}$  onto the outer corona of the pellet. At these intensities the quiver velocity of the electrons in the laser field approaches the velocity of light and their mass increases due to their relativistic motion. This causes a reduction in the plasma refractive index by,

$$\omega_p^2 = \frac{q^2 n_e}{\epsilon_o (\gamma m_e)} \text{ where } \gamma \text{ is the relativistic factor } \gamma = \left[ 1 - \left( \frac{v_{osc}}{c} \right)^2 \right]^{-1/2} \quad (13)$$

Where  $v_{osc}$  is the quiver velocity of the electron in the electric field of the laser given by

$$v_{osc} = \frac{eE}{m\omega} \quad (14)$$

This formula can be used to express the effective critical density,  $n_{effc}$ , in terms of the laser intensity,  $I$  [ $\text{Wcm}^{-2}$ ] and the laser wavelength,  $\lambda$  [ $\mu\text{m}$ ],[13];

$$n_{effc} = n_c \left( 1 + \frac{I\lambda^2}{10^{18}} \right)^{1/2} \quad (15)$$

The second channelling mechanism is due to the extreme light pressure that, at these intensities, can push back the critical density surface and effectively bore a hole into the overdense plasma. This hole boring effect has been observed in simulations of laser pulses with  $I\lambda^2 = 1 \times 10^{19} \text{ Wcm}^{-2}$  [23]. Further simulations have shown that laser pulses at this intensity, with durations of 100ps can bore holes up to 100x critical density [18]. A possible problem with this proposed scheme is the break up of the beam due to ponderomotive filamentation of the hole boring pulse. This effect has been experimentally observed in laser plasma interactions of 100ps pulses at an intensity of  $1 \times 10^{17} \text{ Wcm}^{-2}$  with plasmas less than critical density [24]. The channel forming pulse will also be depleted due to inverse bremsstrahlung at super critical densities. Finally transverse density gradients may also cause the beam to refract, reducing the intensity, limiting the effectiveness of both the hole boring and relativistic overdense propagation.

In conclusion the formation of density channels in underdense and overdense plasmas is a subject that requires extensive experimental study before the limitations of filamentation absorption and refraction can be determined. Some of the important issues that affect both the fast igniter and the X-ray recombination laser have been studied experimentally and theoretically. A summary of the most recent and important work in this area will be discussed in the next section.

### 1.5.1 Temperature measurements.

The temperatures generated in short pulse interactions with gas targets has been investigated in a number of experiments covering a range of laser wavelengths and irradiation conditions. Most of the direct measurements have come from Thompson

scattering from either a probe beam [25] or from the interaction beam itself [26]. A more indirect measurement using the shock wave evolution measurement technique described in this thesis was obtained by Dunne et al [27]. In this work the measured expansion of the ionised channel produced by the interaction of 3.5ps KrF pulses with nitrogen at densities below  $1 \times 10^{18}$  a /cc. By comparing this measurement with 1D hydrocode simulations the initial temperature was found to agree with theoretical absorption models within 20%.

There have been a number of theoretical treatments of the effect of the laser field on the electron distribution. Pert [28] determined the contribution of the oscillation velocity in an impact parameter approximation. This theory found a  $E_0^{-3}$  dependence on the laser electric field. More recently Schlessinger and Wright [29] and Rae and Burnett [30] have used a correction factor to the collision frequency that interpolated between the two regimes of electron velocity where  $v_t > v_{osc}$  and  $v_{osc} > v_t$ . Pert has also investigated the role of the quiver velocity on the value taken for the maximum impact parameter in the Coulomb log. For high intensities this factor was found to increase the absorption rate [31]. Polschuck and Meyer-Ter-Vehn [32] have also produced a model that used the Born approximation, resulting in an equivalent modification to the Coulomb logarithm.

### 1.5.2 Self focusing

The problem of the propagation of intense laser pulses in ionising media has been studied extensively in recent years. The interaction of 1TW pulses with dense gases has been studied by Borisov et al [33]. Their experiment observed scattered light that propagated at large angles to the axis with a CCD camera. The angle of the time integrated scattering was used as a diagnostic of the diffracted scale length and thus gave information on the size of the features that generated it. It was found that the angle of refraction was very large and correspondingly the feature size was of the order of a few microns. It was assumed that all of the light was concentrated into a feature of this size and that relativistic self focusing was responsible for this effect. Refraction was not mentioned as a possible source of light at these angles. More recent work measured the spatial distribution of Thompson scattered light to infer self focusing of a 6TW,  $1\mu\text{m}$  wavelength, laser pulse as it propagated through a hydrogen gas jet at a density of  $1 \times 10^{19} \text{ cm}^{-3}$  [34] When the measured profiles were compared to simulations the signal was found to be reduced by ponderomotive expulsion of plasma from the focal spot. The onset of plasma expulsion was found to be consistent with the threshold for

relativistic self focusing. Sprangle et al [35] have theoretically studied the conditions required for relativistic self optical guiding. Sun and Gudzar [36] also predicted that relativistic self focusing would be accompanied by an almost complete expulsion of electrons from the laser spot. This mechanism, caused by ponderomotive self focusing, was termed electron cavitation.

### 1.5.3 Refraction and defocusing

Refractive defocusing of short laser pulses in dense gas targets is an important problem in areas of research that require the simultaneous achievement of high intensities and high densities. One of the most important of these are X-ray laser schemes such as Li-like Neon that require an intensity of greater than  $2 \times 10^{17} \text{ Wcm}^{-2}$  and an electron density in excess of  $1 \times 10^{20} \text{ cm}^{-3}$  to achieve high energy efficiency and gain [10]. Refraction produced by density gradients has been studied theoretically by Rae [37]. They produced a 2D numerical propagation model that predicted the maximum intensity achieved within a gas cell as a function of gas density pulse length and focusing cone angle. A recent analytic treatment of defocusing using Gaussian beam propagation has been published by Fill [38]. This model assumed the laser beam was governed by Gaussian optics and the ionisation stages of the gas were approximated by a fourth order power fit, consistent with the Coulomb barrier model [16]. Fill's model calculates the maximum intensity that can be reached in gas experiments as a function of gas density. The mechanism of defocusing was experimentally studied in gas cell experiments by Monot and Auguste [39]. In this experiment the transmission of a 1TW laser with a wavelength of  $1 \mu\text{m}$  was measured and correlated with the shift of the focus towards the focusing lens as the gas density was increased. The motion of the focal region towards the lens and the reduction in transmission in gas cell were attributed to refraction.

An experiment by the same group [40] with a  $1 \mu\text{m}$  1ps pulse interacting with a hydrogen gas jet showed that higher intensities could be achieved if the laser was focused on the gas vacuum boundary. The length of the ionised plasma was inferred from an image of second harmonic ( $\lambda = 0.527 \mu\text{m}$ ) radiation emitted perpendicular to laser propagation direction. The second harmonic image stretched over a Rayleigh length implying that the intensity remained above the threshold for this distance. There was no quantitative estimate of the threshold required for the production of light at  $0.527 \mu\text{m}$  and so the intensity profile of the laser could not be quantitatively evaluated from this data. In addition no direct measurements of the electron density achieved during or immediately after the pulse have been made when refraction is important.

#### 1.5.4 Guiding.

The subject of guiding of laser pulses through channels with a radially varying refractive index has been studied extensively in connection with optical fibre communications [17,41]. Theoretical studies of channel formation in plasmas include a study of the properties of a channel with a parabolic density profile [42]. This work used a Gaussian optics treatment of the propagation of the normal modes to analyse the confinement of radiation within the channel. The beam was found to be periodically focused and defocused by the channel with an oscillation period that depended on the radial curvature of the guide and the plasma density. Heat conduction was predicted to overcome the non-uniform heating resulting from the oscillation in beam intensity. The use of plasma wave guides to overcome refractive defocusing was studied theoretically by Rankin et al [48].

A more recent theoretical study of channel formation in high density plasmas [43] found that a similar oscillation in mode size occurred but in this case it was due to refractive defocusing of the initial channel forming pulse. The defocusing caused the non uniformity in the channel radius along the laser propagation direction. This theory was applied to the results of the experimental guiding experiments undertaken by Durfee and Milchberg [44]. In these experiments a laser pulse with a duration of 100ps and wavelength of  $1.064\mu\text{m}$  was split into two pulses. The first formed the channel which then guided the second pulse. The energy ratio for the channel forming to the probe pulse of approximately 7:1 and the two pulses were initially focused with the same lens into argon at a gas density of  $1 \times 10^{18} \text{ cm}^{-3}$ . The first pulse was used to create a density channel, after allowing time for the channel to expand, the second pulse was focused into it with an intensity of  $1 \times 10^{14} \text{ Wcm}^{-2}$ . The experiment was diagnosed by imaging of the fluorescence emitted from the plasma perpendicular to the propagation direction and by imaging laser light transmitted along the propagation axis through the channel. The delay duration was varied until lengthening of the fluorescence signal was observed. After a delay of 6ns a slight lengthening of  $600\mu\text{m}$  was observed over the initial channel length of 2mm. At longer delays the fluorescence was found to split into two sparks at either end of the channel. This was attributed to focusing of the beam by the channel after the end of the channel. An alternative explanation by Liu [43] for this feature was that it was due to non uniformity in the width of the channel along the laser propagation axis.

In order to increase the length of the channel the experiment was repeated with an axicon to focus the channel forming pulse. This created a channel approximately 10mm long into which the probe pulse was focused with a conventional lens. Light scattered from the probe was observed to extend over 7mm, equivalent to guiding over twenty times the original depth of focus of the probe pulse. In this experiment the formation of the channel was modelled with a hydrodynamic simulation and no attempt was made to measure experimentally any of the characteristics of the channel. The density regime was also lower than that required for many applications and thus avoided the problem of refraction from density gradients. The laser pulse length was at least two orders of magnitude longer than the optimum required for laser accelerator and relativistic self focusing studies. Finally the intensity was also four orders of magnitude lower than those required for relativistic focusing[33], fast igniter and [18] laser accelerator schemes [9].

## 2 Theory.

This section will outline the theory required in the analysis and interpretation of the experimental results obtained and displayed in this thesis. These areas included laser propagation, optical and collisional ionisation, absorption, heat conduction, shock wave formation and plasma instabilities.

### 2.1 Laser Propagation.

In this thesis the details of the propagation of laser light through the target is fundamentally important to the understanding of the laser plasma interaction. The first section in this chapter will describe a ray treatment of the laser propagation to obtain an estimate of the effect of the plasma density gradients. This will be followed by a description of the refraction of Gaussian beams, after which a number of self focusing mechanisms will be described. Lastly, two refractive defocusing models that are used to compare with the experimental data in chapter 4 will be outlined.

The angular deviation of a laser beam in a density gradient can be derived from the retardation of a wave front in the density gradient as shown in Figure 2.1 [46].

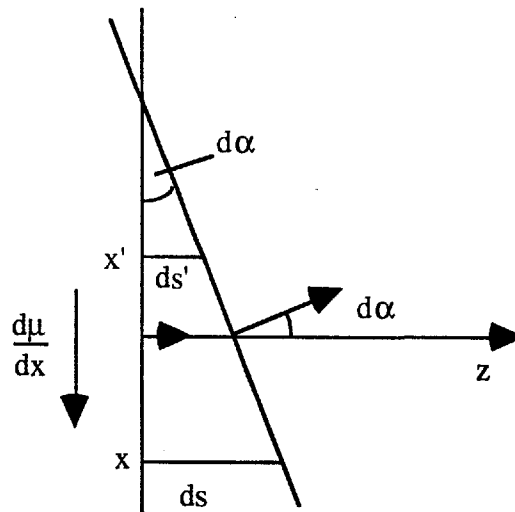


Figure 2.1 Angular deviation of wave front in a density gradient. The wave front initially propagates along the  $z$  axis and is deviated by the transverse gradient  $d\mu/dx$ , by an angle  $d\alpha$ .

It can be seen from figure 2.1 that the refractive index gradient extended over the region  $x'-x$  along the  $x$  axis and the wave front travelled along the  $z$  axis arriving simultaneously at points  $x'$  and  $x$ . After a time delay  $\Delta t$  the wave front moved along the  $z$  axis a distance  $\Delta s = c\Delta t / \mu$  from  $x$  and  $\Delta s' = c\Delta t / \mu'$  from  $x'$ . The refractive index  $\mu'$  at  $x'$  is related to  $\mu$  at  $x$  by  $\mu' = \mu + (\partial\mu/\partial x)\Delta x$ , where  $\Delta x = x - x'$ . The difference between the distance  $\Delta s' = \Delta s(\mu/\mu')$  and  $\Delta s$  can be expressed in terms of the refractive index gradient

$$\Delta s - \Delta s' = (\Delta s / \mu')(\partial\mu / \partial x)\Delta x \quad (16)$$

The distance can also be expressed in terms of the refraction angle  $\Delta\alpha$

$$\Delta s - \Delta s' = \Delta\alpha(x - x') = \Delta\alpha\Delta x \quad (17)$$

The refraction angle can now be expressed in terms of the gradient

$$\Delta\alpha = (1 / \mu')(\partial\mu / \partial x)\Delta s \quad (18)$$

For a plasma with  $n_e \ll n_c$ ,  $\mu' \sim 1$  and  $\partial\mu / \partial x \sim (\partial n_e / \partial x)$  and for small angles the path length can be integrated to give  $\alpha$  in terms of the laser wavelength and the density gradient (in cgs units),

$$\alpha = -\left(\frac{\lambda^2}{2\pi}\right)\left(\frac{q^2}{m_e c^2}\right) \int \frac{dn_e}{dx} \cdot dz \quad [\text{radians}] \quad (19)$$

and inserting the constants gives, for  $n_e$  in  $\text{cm}^{-3}$ , and  $x, z$  and  $\lambda$  in  $\text{cm}$  ;

$$\alpha = -4.36 \times 10^{-14} \lambda^2 \int \frac{dn_e}{dx} \cdot dz \quad (20)$$

This equation can be used to estimate the refraction angle from a density gradient acting over a path  $L$ . For example, if a  $1\mu\text{m}$  laser is focused to a spot of radius  $30\mu\text{m}$  into a plasma with an electron density of  $5 \times 10^{19} \text{ cm}^{-3}$  existing over a plasma length of  $700\mu\text{m}$ , then  $\alpha = 33$  degrees.

### 2.1.1 Refraction of laser hot spots from density gradients.

The ray propagation theory can also be used to estimate the smoothing effect of refraction from density gradients on the hot spots present on a laser beam [47] .

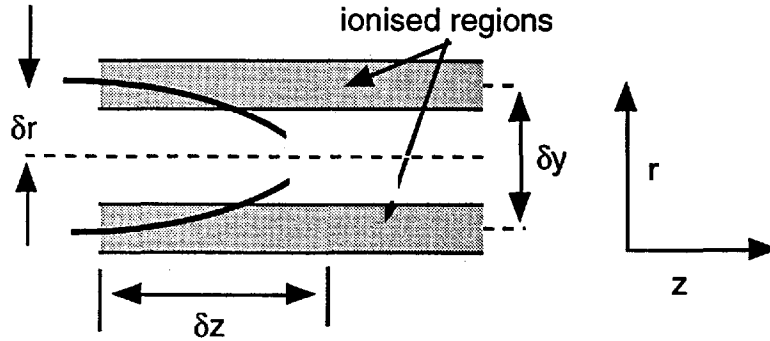


Figure 2.2 Refraction from laser hot spots (taken from reference [47] ), the density gradients act over the distance  $\delta r$  and the radial distance between hot spots is  $\delta y$ . Smoothing occurs over the distance  $\delta z$  where the ray has been refracted radially out of the ionised region and midway between the adjacent hot spots.

The laser hot spots are represented in figure 2.2 by the two shaded ionised regions. The length  $dz$  over which the rays travels before they reach the centre of the neutral region is given by  $\delta r$ . An estimate of  $\delta r$  valid for densities much less than critical is given by [47],

$$\delta r = \frac{1}{2n_c} \frac{dn_e}{dr} z^2 \quad (21)$$

Rearranging this equation in terms of  $z$  allows an estimate of the distance over which the ray refracts out of the hot spot. If the radial density gradient was estimated extend over the spot radius,  $w_0$ , then  $dn_e/dr \sim n_e/w_0$ . The distance  $z$  for rays to be refracted out of the spot is then given by,

$$z = (2n_c/n_e)^{1/2} w_0 \quad (22)$$

For  $n_e = 1 \times 10^{19} \text{ cm}^{-3}$  and  $\lambda = 1.054 \mu\text{m}$ ,  $n_e / n_c = 0.01$ ,  $dr = \delta r = 30 \mu\text{m}$ ,  $z = 212 \mu\text{m}$ . This indicates that a hot spot will split into two after propagating  $200 \mu\text{m}$ . For a real pulse diffraction also needs to taken into account. For a Gaussian beam the characteristic length for diffraction is the Rayleigh length,  $L_R (= \pi w_0^2 / \lambda)$ , where  $w_0$  is the Gaussian

spot radius and  $\lambda$  the laser wavelength [17] ( $L_{cf} = 2L_R$ ). For the conditions above (with  $\lambda = 1\mu\text{m}$ ),  $L_R = 300\mu\text{m}$  and refraction would make the beam expand more quickly than diffraction. A more stringent estimate of the effect of refraction is that if the phase change incurred by the wave as it traverses the plasma with a refractive index  $\mu \sim (n_e/2n_c)$  exceeds  $\pi/2$ , then the beam profile will increase by a one diffraction limited divergence [48]. This gives a characteristic refraction length,  $L_r$ , of

$$L_r = \frac{1}{2} \frac{\lambda n_c}{n_e} \quad (23)$$

For a wavelength of  $1\mu\text{m}$  and  $n_c/n_e = 100$ ,  $L_r = 50\mu\text{m}$ . These estimates are extremely useful for a semi quantitative understanding of the strength of refraction in a plasma but for a more accurate picture the wave nature of the laser must be taken into account. These results were indeed confirmed with a wave optics treatment in [47]. In that work a 3D simulation code that solved the wave equation while calculating the contribution to the refractive index of the free electrons produced during optical ionisation. It was found that the simple estimate of  $dz$  in equation (21) accurately predicted the distance the laser hot spot propagated before it split. A fuller treatment of refraction and diffraction in this thesis will be postponed to section 2.1.5. Before that the next section will briefly describe the self focusing mechanisms that could potentially compete with refraction to increase the focused laser intensity in this short pulse regime.

### 2.1.2 Filamentation and self focusing.

There are a number of mechanisms that can produce self focusing of lasers in plasmas. The applicability of these theories is limited in interactions with short pulses to those that can modify the refractive index of the plasma without the motion of the plasma ions.

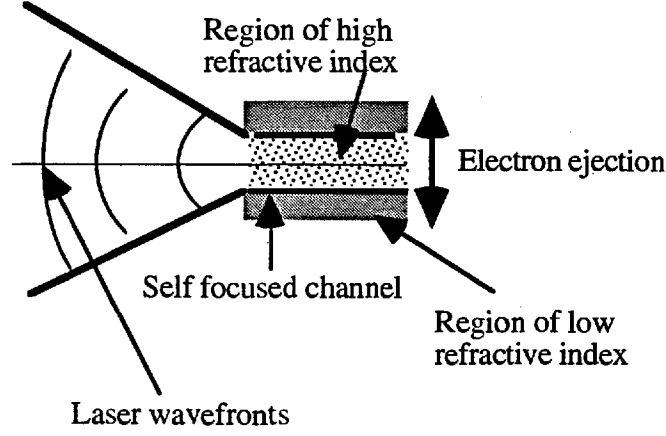


Figure 2.3 The mechanism of self focusing in a plasma. The most intense part of the laser pulse cause an increase in the refractive index, through electron ejection or relativistic effects. This results in a local increase in the plasma refractive index which tends to focus the pulse.

The general self focusing mechanism is depicted in figure 2.3. The plasma refractive index is increased in the regions of the highest laser intensity by electron ejection, plasma motion or relativistic effects. The refractive index gradient across the laser beam acts as a positive lens which focuses the beam, causing a further increase in the intensity. An instability develops as the intensity increases and the beam radius consequently continues to decrease. The actual mechanism that causes modification of the plasma refractive index determines which self focusing model is applicable. In long pulse experiments there is time for the plasma to move out of the laser spot within the duration of the laser pulse. Two mechanisms that are important in this regime are (i) ponderomotive and (ii) thermal self focusing [49]. The ponderomotive force arises from the gradient of the laser electric field within the plasma. If the gradient of the laser field is along the x axis then ponderomotive force on an electron with charge , q, along this axis is given by,[49],

$$F_{NL}(x) = -\frac{q^2}{4m_e\omega^2} \nabla E^2(x) \quad (24)$$

The ejected electrons pull the ions out of the most intense regions of the laser spot on the time scale of the ion sound speed and reduce the plasma refractive index causing self focusing. For thermal self focusing the laser is absorbed strongly at the centre of the spot and the plasma expands hydrodynamically. The threshold for both these mechanisms depend on the laser intensity and plasma density [49]. In experiments

where the laser pulse length is less than 10ps there is no time for significant plasma motion, the ions remain static and these theories do not apply. At these pulse lengths self focusing can still occur through the ponderomotive force but the space charge force that builds up between the ions and the ejected electrons has to be taken into account. This significantly increases the intensity threshold over the mobile ion case. At very high intensities the quiver motion of the electrons becomes relativistic causing an increase in the electron mass and leading a reduction in the refractive index. The thresholds for these effects will be considered in the next section.

### 2.1.3 Self focusing mechanisms in short pulse experiments.

In an electrically neutral plasma a restoring, space charge, force between the electrons and ions acts as soon as the electrons are displaced further than a Debye length,  $L_D$ , from the ion. The space charge force,  $F_{sc}$ , can be estimated from the Coulomb attraction between a cylinder of charge per unit length  $\rho = \pi r^2 q Z n_i$  acting on an electron at a radius  $r$  from the centre of the cylinder,  $F_{sc} = -\frac{2q\rho}{4\pi\epsilon_0 r}$ . The Coulomb space charge force can be overcome by the ponderomotive force in (24) until the radius reaches a critical value,  $r = r_0$ , where the forces are balanced. As the ion density increases, for constant laser intensity,  $r_0$  decreases and the expulsion only occurs for small plasma radii. The ejection distance depends strongly on the electron density and laser intensity profiles. For a laser intensity of  $I = 1 \times 10^{17} \text{ Wcm}^{-2}$ , a wavelength  $\lambda = 0.248 \mu\text{m}$  and an ion density greater than  $1 \times 10^{19} \text{ cm}^{-3}$ ,  $r_0 < 1 \mu\text{m}$ .

At the densities and intensities reached in the experiments described in chapter 4 of this thesis it is highly unlikely that the refractive index could be altered enough to cause self focusing. The threshold for ponderomotive expulsion of electrons from a plasma created by a laser pulse with a Gaussian spatial profiles from published static ion models support this view [51]. Another mechanism that does not depend on ion motion is relativistic self focusing. In this mechanism the refractive index of the plasma is modified by the relativistic motion of the electrons as they quiver in the electric field of the laser. The modification to the refractive index is given by [34],

$$\mu = \left(1 - \frac{\omega_p^2}{\gamma \omega_0^2}\right)^{1/2} \quad \text{and} \quad \gamma = \left[ \frac{1}{1 - \frac{v_{osc}^2}{c^2}} \right]^{1/2} \quad (25)$$

where  $\gamma$  is the relativistic factor and  $v_{osc}$  is the quiver velocity of the electron in the laser field, given by  $v_{osc} = \frac{eE}{m\omega}$ . As the electric field increases,  $v_{osc}$  approaches  $c$  and the relativistic increase in the electron mass causes an increase in the refractive index, leading to self focusing of the most intense part of the laser beam where the refractive index is highest. The threshold of self focusing was determined in [33] by matching the change in angle due to the relativistic refractive index change to the angle of diffraction for a Gaussian beam. This gave a simple expression for the threshold

$$P_c = 17GW * \left( \frac{n_c}{n_e} \right) \quad (26)$$

Evidence for relativistic self focusing has been reported in interactions of 1TW KrF laser pulses [33]. More recently, [34] relativistic self focusing was observed when a  $1\mu\text{m}$  laser with a power of 10TW was focused into a hydrogen gas jet at a gas density of  $1 \times 10^{19} \text{ cm}^{-3}$  and a vacuum intensity of  $3 \times 10^{18} \text{ Wcm}^{-2}$ . The laser intensity during the plasma experiments reported in this thesis are generally limited by refraction from density gradients and relativistic self focusing is unlikely to be important. Defocusing from ionisation induced refraction is therefore the most important limitation preventing the achievement of ultra high intensity interactions with neutral gas targets at high densities. The important features of refraction from density gradients were outlined in sections 2.1.1 - 2.1.2, however to simulate real laser plasma interactions more sophisticated defocusing models are required.

#### 2.1.4 Modelling of defocusing in plasmas

This section will describe the models that have been used to interpret the results obtained in the experiments in terms of the energy absorption and laser propagation. Previously it was shown that the question of laser propagation can be understood by using simple ray tracing techniques. To obtain a more realistic model that accounts for the finite rise time

of the pulse and diffractive effects it is necessary to solve the wave equation numerically. An intermediate step is to use a Gaussian optics treatment for the beam propagation and use a power law representation of the intensity dependence of the ionisation threshold of the gas. A model [38] that used this approach will be used to interpret the results of experimental measurements.

### 2.1.5 The analytic model.

An analytic treatment of refraction of the laser was used to obtain a quantitative picture of the limiting intensity caused by the defocusing. The laser propagation is approximated by a ray optics description of the height of the ray  $r$  above the axis in a parabolic refractive index profile given by

$$\mu(r, z) = \mu_0 - \frac{\mu_2}{2} r^2 \quad (27)$$

Where  $\mu_0$  is the refractive index on axis and  $\mu_2$  is the quadratic parameter describing the radial variation of the refractive index. A differential equation that describes the variation of  $r$  about the  $z$  axis has been derived by [52], [53] and is given by,

$$\frac{d^2 r}{dz^2} = -\frac{\mu_2}{\mu_0} r + \frac{\lambda^2}{4\pi^2} \frac{r}{r_o^4} \quad (28)$$

Where  $r_o$  is the Gaussian spot radius, and the radial intensity profile is given by,  $I = I_o \exp(-r^2 / r_o^2)$ . It should be noted that the beam radius defined in this way differs from the conventional description of a Gaussian spot size  $w_0$  by a factor of  $(1 / \sqrt{2})$ . The peak intensity is then related to the beam power by  $I_o = P / (\pi r_o^2)$ . The last term on the RHS of (28) accounts for diffraction of this Gaussian beam. The refractive index is related to the incident laser intensity through a power law relationship for the ionisation threshold as a function of laser intensity. This was achieved through the use of the Coulomb barrier model [16] to relate the laser intensity to the gas ionisation potential,  $U_q$ , of an ion in state  $q$

$$I_{th} = 4 \times 10^9 \frac{1}{q^2} U_q^4 \quad (29)$$

With  $I$  in  $\text{Wcm}^{-2}$  and  $U_q$  the gas ionisation potential of stage  $q$  in eV. The ionisation potential of charge state  $q$  is approximated by a power law of the form,

$$U(q) = U_0 q^\alpha \quad (30)$$

This is a good approximation for ionisation from a single shell. Some examples of power law fit for Neon, Nitrogen, Argon and Helium are shown in figure 2.4. This fit allowed the determination of  $U_0$  and  $\alpha$ . The charge distribution across the beam is obtained from (29) and (30) to be

$$q = q_0 I^{1/(4\alpha - 2)} \quad (31)$$

where

$$q_0 = (4 \times 10^9 U_0^4)^{1/(2 - 4\alpha)}$$

If  $I$  is now cast in terms of the Gaussian and the exponential phase term expanded (for  $r \leq r_0$ ) the refractive index can be expressed in a form that is quadratic in  $r$  and the terms  $\mu_0$  and  $\mu_2$  are obtained. The differential equation (28) is then solved for  $r = r_0$ , to give an equation relating the propagation of the  $1/e$  radius of the beam

$$\frac{dr_0}{dz} = \pm \left[ -\mu_2 r_0^{1/(1-2\alpha)} - \frac{\lambda^2}{4\pi^2} r_0^{-2} + C^2 \right]^{1/2} \quad (32)$$

where  $C$  is a constant of integration, physically equivalent to the half angle divergence of the beam due to the focusing optic. The quadratic refractive index contribution  $\mu_2$  is then

$$\mu_2 = q_0 \left( n_a / n_c \right) (P / \pi)^{1/(4\alpha - 2)} \quad (33)$$

where  $n_a$  is the atomic density. The minimum spot size  $r_{\min}$  is obtained by setting the LHS of (32),  $dr_0/dz = 0$  and neglecting diffraction compared to refraction, with the result

$$I_m = \left[ \left( \frac{C^2}{q_0} \right) \left( \frac{n_c}{n_a} \right) \right]^{4\alpha - 2} \quad (34)$$

Where  $n_c$  and  $n_a$  are the critical and atomic density in  $\text{cm}^{-3}$ , respectively. This expression can be seen to be independent of laser power, with a strong dependence on the gas density and the cone angle of the focusing optics  $C$ . This model was found to agree well with the experimental results obtained from focusing 1TW pulses in 1Atm of Argon gas [39].

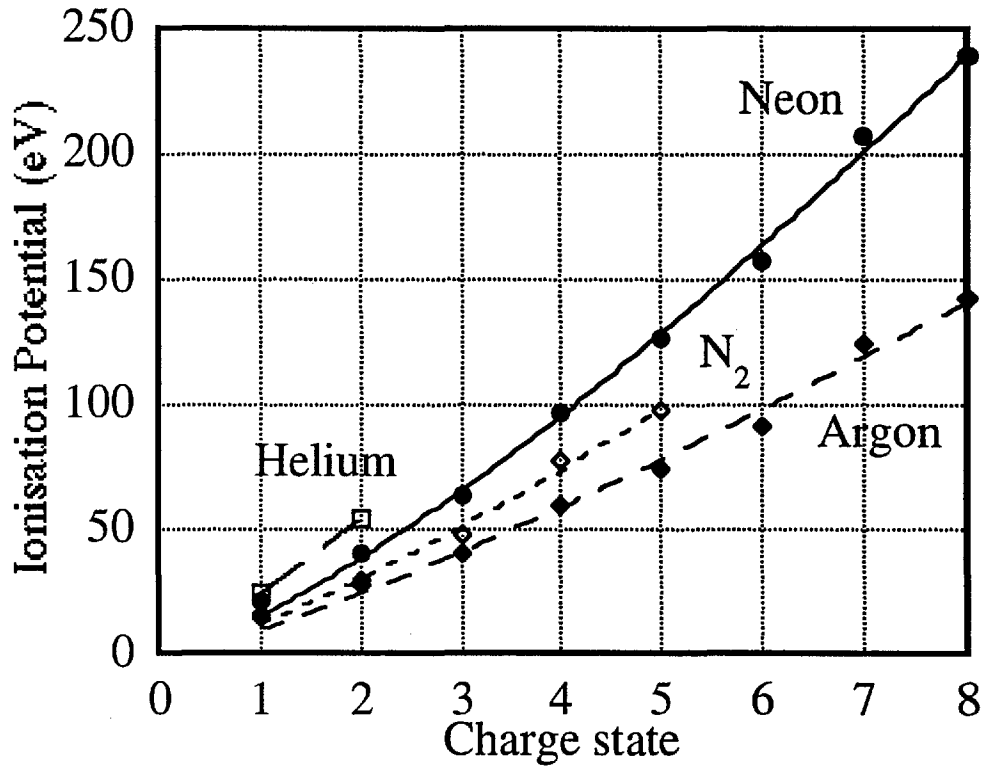


Figure 2.4 Power law fit to the ionisation potentials of Argon, Neon, Helium and Nitrogen.

As an example of the method, this model was used to calculate the maximum focused intensity for a KrF laser with  $\lambda = 0.248\mu\text{m}$ ,  $n_c = 1.78 \times 10^{22} \text{ cm}^{-3}$ , focused with F/5 optics ( $C = 0.1$ ), into Neon at a density of  $5 \times 10^{19} \text{ cm}^{-3}$  ( $n_c/n_a = 356$ ). These conditions are ideal for the creation of a Li-like Neon X-ray laser. Using  $U_0 = 15.398$  and  $\alpha = 1.32$  from figure 2.4, gives  $q_0 = 4.2 \times 10^{-5}$ , and from (34) the maximum intensity is,  $I_m = 1.5 \times 10^{16} \text{ Wcm}^{-2}$ . This intensity was approximately an order of magnitude less than the minimum intensity required for the production of He-like Neon,

and the conditions required for the Li-like Neon X-ray laser scheme [10] would not be fulfilled. This model had the advantage that it was very simple and gave a reasonably accurate measure of the degree of defocusing. For a more detailed understanding of how refraction affected the laser propagation a numerical solution of the wave equation was used. This model solved the wave equation self consistently with the solution of the tunnel ionisation rate equations.

### 2.1.6 The Numerical model

The coupling of a 2D wave equation solved in the paraxial limit together with the ionisation allows the effect of ionisation induced density gradients on the laser beam to be studied. A time dependent code [37] that used this model was compared to the data obtained in this thesis. In this model the wave equation is then solved with the ionisation as a source term in the plasma current,

$$\frac{\partial^2 E}{\partial r^2} - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} - \frac{1}{\mu_0} \frac{\partial J}{\partial t} = 0 \quad (35)$$

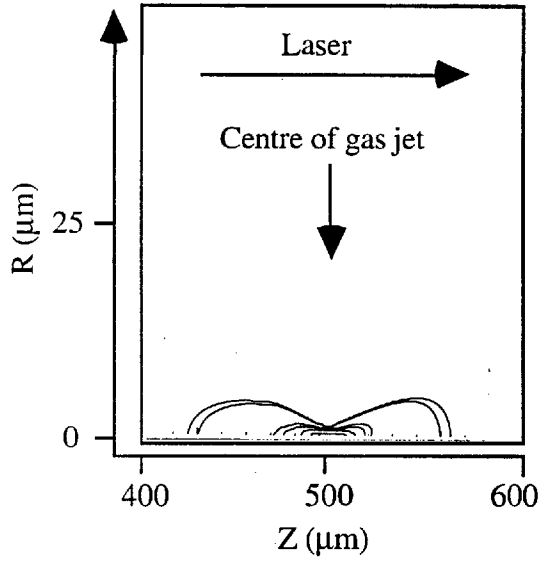
The plasma current is related to the electron density and electron velocity through,

$$J(r, t) = -qn_e(r, t)v(r, t) \quad (36)$$

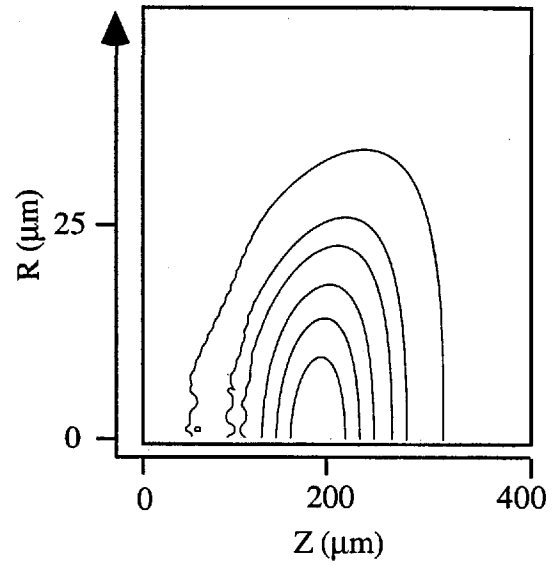
The electron velocity is described in terms of the equation of motion

$$\frac{\partial v}{\partial t} + v_{ei}v = \frac{-qE}{m_e} \quad (37)$$

The code also accounts for self focusing in the gas through the intensity dependent refractive index term [54] but the space charge limited ponderomotive and relativistic mechanisms were not treated. The electron density is calculated at each grid point using the ionisation rates of Ammosov, Delone and Krainov [55], with the number of ionisation stages included in the model limited to three. This ionisation model will be discussed in the section on optical ionisation (section 2.2 ). The laser pulse was represented by a 2 dimensional grid in the radial and longitudinal directions. The initial width of the pulse in the radial direction was set by the diffraction limited radius, defined by the focusing optics. The length of the pulse in the z direction was defined by the

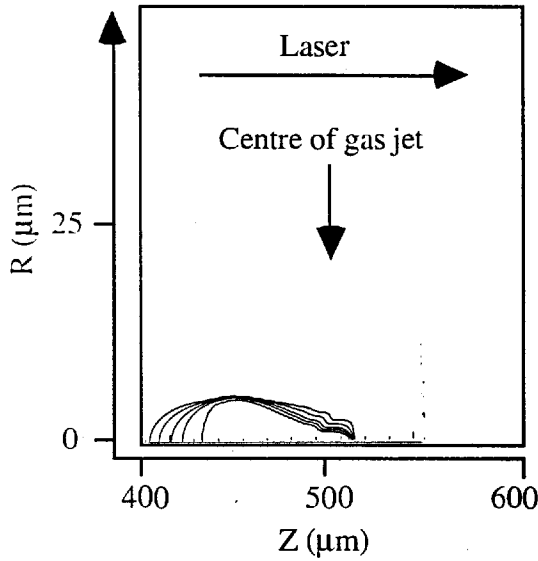


(a) Density contours

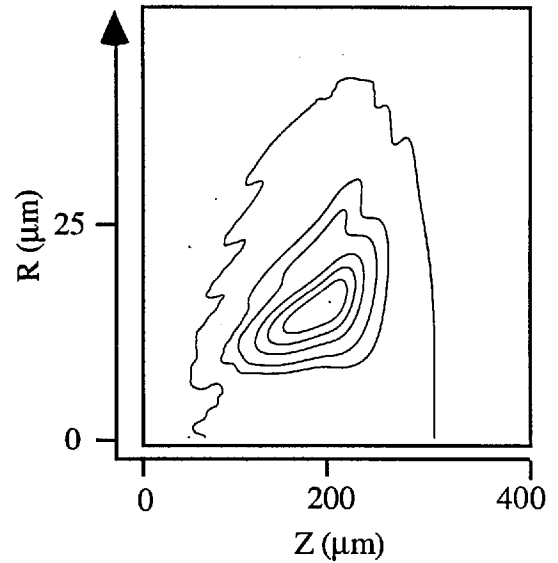


(b) Intensity contours

Figure 2.5 Intensity and density contours for  $I = 8 \times 10^{16} \text{ Wcm}^{-2}$  and  $n_a = 1 \times 10^{16} \text{ cm}^{-3}$  (essentially vacuum). In all these contour plots the levels decrease from the maximum in 20% intervals.



(a) Density contours



(b) Intensity contours

Figure 2.6 Intensity and density contours for  $I = 8 \times 10^{16} \text{ Wcm}^{-2}$  and  $n_a = 1.5 \times 10^{20} \text{ cm}^{-3}$

pulse duration. The number of grid points was adjusted to avoid numerical instabilities up to a maximum of 400x400. The grid was transported through the gas cell with an adjustable time step also to avoid numerical instabilities. The length of the cell was set to 1mm, equal to the length of the gas jet, by varying the total number and the duration of the time steps.

The model output was in the form of intensity and density contours at the end of the simulation. The intensity contours represent the spatial distribution of the laser pulse at the last time step, while the density contours represented the spatial distribution of the electron density through the whole gas at last time step. Figure 2.5(a) and (b) show these for the laser pulse that propagated through a very low density gas. It can be seen from figure 2.5(a) that when the gas density was negligible the plasma was symmetric around the position of best focus in the centre of the jet. As the gas density increased the plasma became asymmetric, with very little plasma formed past the position of best focus. When the gas density was increased to  $1.5 \times 10^{20} \text{ cm}^{-3}$  the plasma formed by the rising edge of the pulse refracted the laser, as can be seen in figure 2.6(a). The plasma radius also increased, implying a reduction in the focused intensity and a consequent suppression of the peak ionisation stage that was achieved. The intensity contours confirmed this interpretation, as can be seen by comparing figure 2.5 (b) with 2.6 (b). The peak of the intensity is on the z axis when there was negligible gas present in figure 2.5 (b). When the gas density was increased it can be seen from figure 2.6 (b) that the peak shifted radially away from the laser axis. All these features are characteristic of strong ionisation defocusing. This code has also been successfully used to model interactions of lower intensity pulses at a wavelength of  $1 \mu\text{m}$  with hydrogen gas [37] at densities up to  $3 \times 10^{19} \text{ cm}^{-3}$ . More recently it has been used to model experimental studies of interactions with noble gases at gas densities in excess of  $1 \times 10^{20} \text{ cm}^{-3}$  [56]. The most promising method of overcoming refraction and achieving long interaction lengths with high intensity beams and dense plasmas is the use of density channels to confine and guide the laser. An elementary outline of the theory of wave guides is the last subject of this section on laser propagation.

### 2.1.7. Guiding of intense laser pulses

The propagation of laser pulses at high intensities for large distances is extremely important for the success of recombination X-ray lasers and the ignition of inertial confinement fusion. The refraction of the pulse due to ionisation gradients makes the

formation of a highly ionised plasma over the centimetre lengths of plasma impossible at the densities required for the X-ray laser. Using a parabolic density profile to guide the pulse has been suggested in order to obtain long interaction lengths at high laser intensities [48]. Guiding of a 100ps duration,  $1\mu\text{m}$  laser pulses over a distances in excess of 20 Rayleigh lengths and at an intensity of  $1 \times 10^{14} \text{ Wcm}^{-2}$  has been observed experimentally in argon at a gas density of  $1 \times 10^{18} \text{ cm}^{-3}$  [44]. Guiding has not, however, been studied at the higher laser intensities short pulses and at gas density where refraction significantly affects the channel formation.

The propagation of a laser pulse within a plasma wave guide can be treated most simply within the geometric optics approximation. This is valid for channel widths much larger than the laser wavelength and can be used to determine the transmission of the channel. It cannot, however, be used to determine the intensity of the laser pulse within the guide, because this requires knowledge of the minimum beam radius that the guide will allow. This requires a solution of the wave equation to account for diffraction effects. The simplest derivation of the refractive index change required to confine a ray is a fibre with a discontinuous increase in refractive index from the core  $\mu_c$  to the cladding  $\mu_{cl}$ . Figure 2.7 shows the confinement criterion of the ray following geometrical optical principles.

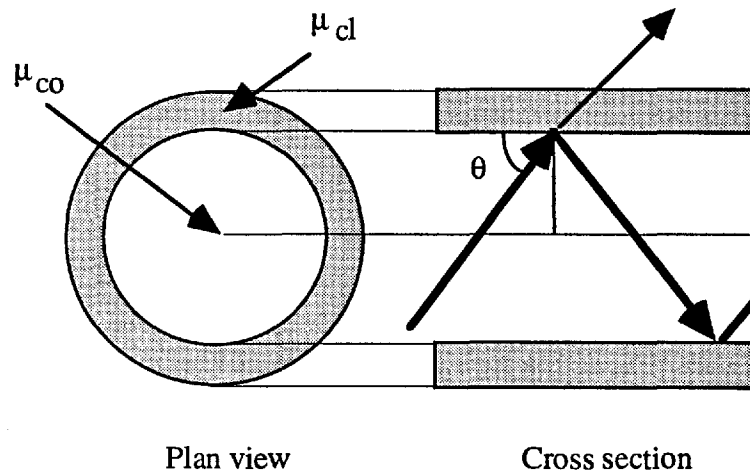


Figure 2.7 Geometric picture of guiding in an optical fibre with a step function in the refractive index profile at the channel walls.

From the geometry outline in figure 2.7 the maximum ray angle that can be contained by a refractive index change can be simply calculated from Snell's law,

$$\theta = \cos^{-1} \left( \frac{\mu_{cl}}{\mu_{co}} \right) \quad (38)$$

This expression will be used as a first order approximate estimate of the maximum ray angles that remained bound with the plasma wave guides formed in the experiments. This is useful because it can be directly compared to the measured refractive index at the channel walls obtained from the experimental diagnostics. This gave an accurate measure of the refractive index at the channel walls but it did not give any information regarding the profile of the guided beam. To obtain this information required a wave optics treatment.

### 2.1.8 Guiding of optical beams in plasma wave guides.

The infinite channel walls of the optical fibre model provided the simplest representation of the guiding properties of a plasma wave guide. Generally if a radial refractive index profile exists with an on axis maximum then it can act as a wave guide. The outer parts of a beam will travel faster than the inner parts and so an initially flat wave front develops a radius of curvature as the wave propagates. The ray equation can be used to obtain a simple estimate of the characteristic focusing length of a cylindrical element of length  $\partial z$  with a refractive index of  $\mu_0$  at the centre and  $\mu_0 + d\mu$  at a radius  $w_0$

$$L_F \approx \frac{w_0^2}{2\Delta\mu\partial z} \quad (39)$$

A more realistic treatment is provided by depiction of the channel as a parabolic density profile [17] given by,

$$n_e = n_o \left( a + br^2 \right) \quad (40)$$

Where  $n_o$  is the density on axis,  $a$  and  $b$  are the curvature parameters. The propagation of EM radiation within the guide is limited to a discrete number of modes. The lowest order mode  $w_0$  defines the smallest spot size that can propagate in the guide, and is given by [42],

$$w_o = \left( \frac{\lambda}{\pi} \right)^{1/2} \left( \frac{n_c}{n_o b} \right)^{1/4} \quad (41)$$

In a plasma wave guide that can be approximately described in terms of the quadratic profile can be formed by heating a plasma and then allowing the channel to expand due to the pressure of the electron gas . After an initial transient period where the expansion depends on the speed of the thermal wave [57] the expansion front develops into an ion shock wave. This depletes the density at the core and forms a refractive index maximum at the channel centre and a minimum at the channel shock front. The formation and propagation of shock waves in gases will be described in the section 2.4. The next section will outline the theory of the initial plasma formation and heating mechanisms that determine the ionisation stage reached within the plasma and the electron temperature existing at the end of the laser pulse.

## 2.2 Optical Ionisation.

Ionisation of a gas by a high power laser pulse will occur when the magnitude of the laser electric field approaches the atomic field felt by the outermost electron. The electric field of the laser is given by equation (42) ;

$$E = \left( 2 \frac{I}{\epsilon c} \right)^{1/2} \quad (42)$$

For  $I$  in  $\text{Wcm}^{-2}$ ,  $E = 27.5 * (I)^{1/2} [\text{Vcm}^{-1}]$ . For example with an intensity of  $3.5 \times 10^{16} \text{Wcm}^{-2}$ ,  $E = 5.142 \times 10^9 \text{Vcm}^{-1}$  and the laser field is equal to the atomic field seen by the electron. The probability of ionisation is obtained by considering the motion of the electron in the combined potential of the laser and atomic electric field. As the laser field increases the potential barrier seen by the electron is reduced and there is a finite probability of the electron tunnelling through the barrier, as shown schematically in figure 2.8.

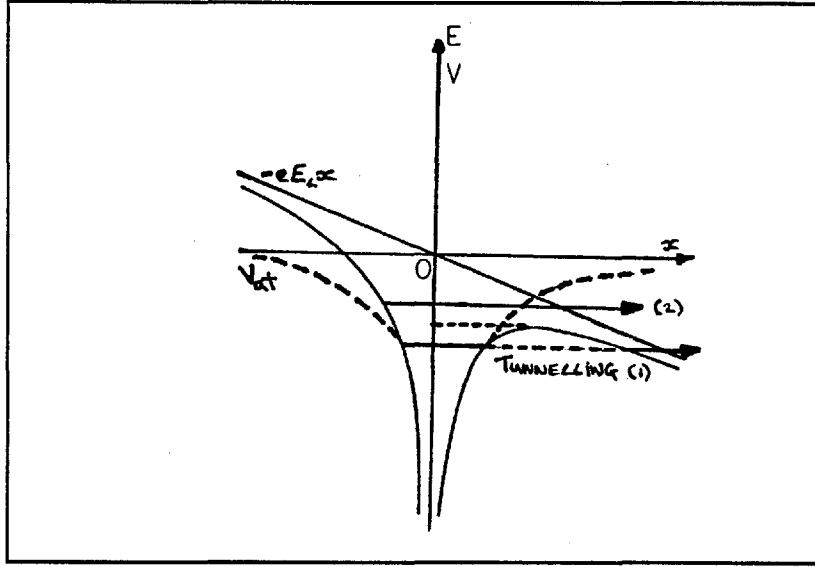


Figure 2.8 Lowering of the Coulomb barrier by a static field along the x axis,  $-eE_L x$ . As the laser field increases, the potential barrier is lowered and the rate of tunnel ionisation through the barrier increases (situation (1)). This continues until the barrier is suppressed below the binding energy of the electron. The laser field at which this occurs is given by equation (43). Above this value the electron is effectively unbound (situation (2)).

The Coulomb barrier model [16] gives a quantitative estimate of the field required for ionisation through barrier suppression, by equating the ionic field to the laser field while neglecting the Stark shift ;

$$E_{th} = \frac{Z^3}{16n_{eff}^4} E_{a.u.} \quad (43)$$

Where  $Z$  is the ionic charge,  $E_{a.u.} = 5.142 \times 10^9 \text{ Vcm}^{-1}$ , is the atomic unit of the electric field and  $n_{eff}$  is the effective quantum number of the ionising electron. The variable  $n_{eff}$  is obtained by equating the ionisation potential of the critical orbit to a hydrogenic ion. Allowing for the Stark red shift of the level in the laser field gives an ionisation threshold of [16]:

$$I_{th} = \frac{2.2 \times 10^{15}}{Z^2} \left[ \frac{U_q (eV)}{27.21} \right]^4 \text{ Wcm}^{-2} \quad (6)$$

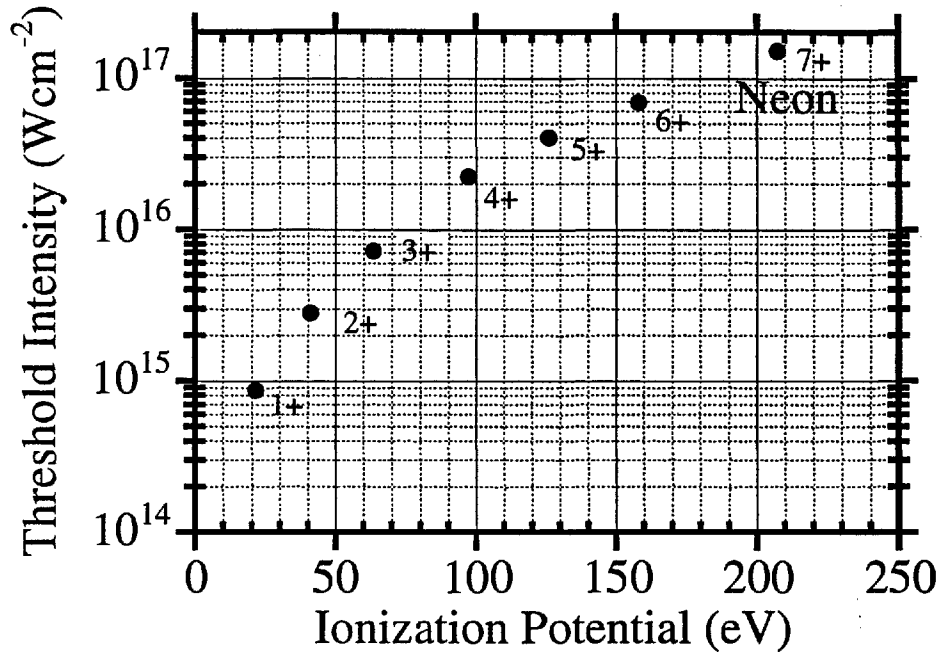


Figure 2.9 Threshold intensity as a function of ionisation potential for Neon from Coulomb barrier model,[16].

The Coulomb barrier model provides an estimate of the threshold laser intensity required to cause ionisation, as shown for Neon in figure 2.9. To calculate the actual ionisation rate, it is necessary to account for the finite probability of an electron tunnelling through the barrier at laser fields below the classical threshold. This is obtained from the quantum mechanical calculation. In practice the ionisation rate is calculated from the Schrodinger equation with the combined potential well in the presence of the laser field in parabolic co-ordinates. The ionisation rate of non hydrogenic atom in an arbitrary state of energy  $\epsilon_i$ , with angular momentum  $l$ , and has been calculated by Perelmov et al and Ammosov, Delone and Krainov [55] to be;

$$w = \frac{\omega_{at}}{2} C_{n^*}^2 \frac{\epsilon_i}{\epsilon_h} \left( \frac{3}{\pi} \left( \frac{\epsilon_h}{\epsilon_i} \right)^{3/2} \right)^{1/2} \frac{(2l+1)(l+|m|)!}{2^{|m|} (|m|)! (l-|m|)!} \left( 2 \left( \frac{\epsilon_i}{\epsilon_h} \right)^{3/2} \right)^{2n^* - |m| - 1} \\ \times \exp \left( \frac{-2}{3} \left( \frac{\epsilon_i}{\epsilon_h} \right)^{3/2} \frac{E_{at}}{E_L} \right) \times \left( \frac{E_{at}}{E_L} \right)^{2n^* - |m| - 3/2}$$

$$n^* = Z \left( \frac{\epsilon_h}{\epsilon_i} \right)^{1/2} \quad \text{and} \quad (44)$$

$$C_{n^*}^2 = \left( \frac{2e}{n^*} \right)^{n^*} (2\pi n^*)^{-1/2} \text{ where } e = 2.7182818...$$

where  $\omega_{at}$  and  $E_{at}$  are the atomic units of frequency and electric field respectively,  $\epsilon_h$  is the ionisation potential of hydrogen,  $\epsilon_i$  is the ionisation potential of the atom or ion,  $l$  is the orbital angular momentum and  $m$  is the projection of  $l$  onto  $E_L$ .  $C_{n^*}$  is of order 2.

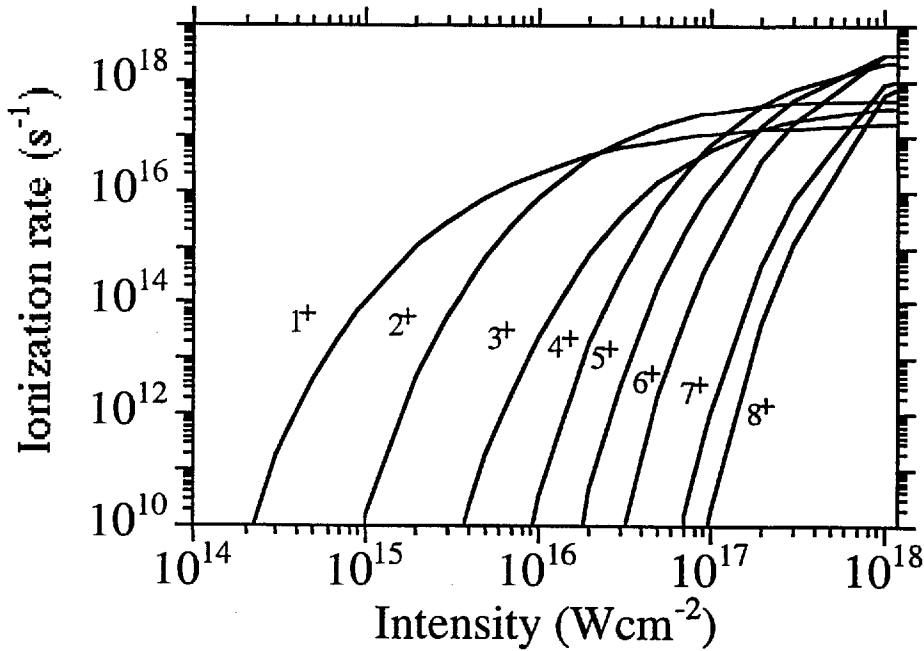


Figure 2.10 Tunnel ionisation rate from the Ammosov formula [55] as given in Penetrante and Bardsley [16], for stages 1 to 8, as a function of laser intensity for Neon.

Figure 2.10 shows the ionisation rate for Neon as a function of laser intensity. The rates shown in this figure have been calculated from the Ammosov formula [55] as given by Penetrante and Bardsley [16]. The ionisation threshold from the Coulomb barrier model corresponds to an ionisation rate of  $1 \times 10^{12} \text{s}^{-1}$ . The time taken for ionisation determines if the depiction of the laser field as a static field is justified. If the electron tunnels in a time scale less than the period of the laser then the field can be taken as constant. However, if the tunnelling time is longer than the laser period then allowances must be made for the oscillation of the beam. In this case the electron appears to simultaneously absorb more than one photon to achieve ionisation and the theory of multiphoton ionisation is more appropriate [59].

The Keldysh parameter,  $\gamma$ , defines the demarcation between the two regimes, and is given by [55, 59]:

$$\gamma = \tau_i / \tau_p \quad (45)$$

where  $\tau_i$  is the ionisation time and  $\tau_p$  is the laser period. If  $\gamma \ll 1$  the electron tunnels through the barrier before the laser field changes significantly and then the ionisation is described by DC tunnelling theory. If  $\gamma \gg 1$  then the electron is ionised over many optical cycles and the multiphoton treatment is more appropriate. A test of the accuracy of these models was made by comparing them with experimentally measured appearance intensities of noble gas ions when ionised with a  $1 \mu\text{m}$  laser [16]. It was found that the data agreed closely with the Coulomb barrier model [16] and the Ammosov tunnelling rates [55]. In order to determine the most appropriate theory for this thesis the Keldysh parameter was evaluated for the typical laser and target parameters. For a laser intensity of  $1 \times 10^{17} \text{Wcm}^{-2}$  and an ionisation potential of  $200 \text{eV}$   $\gamma = 0.01$ , the DC tunnelling rates and the Coulomb barrier model are valid and consequently they are used rather than the multiphoton treatment. For a realistic laser pulse with a finite rise time, the initial turn on phase of the pulse will cause ionisation to occur in the multiphoton regime. However this transient time period and the contribution of multiphoton ionisation are very small, and the tunnelling theory will give an overall description of the ionisation rate that is accurate. At the other extreme if the laser field is so high that the Coulomb barrier is completely suppressed below the binding energy of the electron then it becomes free and tunnelling theory is no longer applicable.

In a rarefied plasma the peak ionisation stage reached in the regions of peak intensity is determined entirely by the optical field. However as the electron density increases,

elastic collisional processes such as inverse Bremsstrahlung absorption and inelastic collisions such as ionisation and excitation become more important. The elastic processes are an important source of heating of the plasma electrons during the pulse while the inelastic ones provide important ionisation routes long after the laser pulse turns off.

For the pulse lengths used during the experiments described in this thesis (350fs -12ps) the ionisation stage populations are determined by the optical field and not the electron temperature and density at the end of the laser pulse. However the heated electrons can continue to ionise the plasma long after the end of the laser pulse. In this case the evolution of the plasma electron density is governed by the rates of collisional ionisation, excitation and three body and radiative recombination. In order to gain an insight into the importance of collisional effects it is necessary to understand how the rates vary with plasma temperature and density. The next section will outline the simple classical theory followed by the results of more complete quantum mechanical theory.

### 2.2.1 Collisions in plasmas.

After the production and heating of free electrons by the laser they will have a velocity distribution function determined by the mechanism of energy absorption from the laser. If the plasma number density is low then the initial distribution function will be determined by the ATI heating rate [15], if the density is high enough then the function will quickly relax to a Maxwellian. The rate at which this occurs depends on how efficiently the collisions transfer the energy between the electrons. The classical cross section for collisions between plasma particles is given in terms of the impact parameter  $R$  defined from figure 2.11 and where  $r_c$  is the classical distance of closest approach [60].

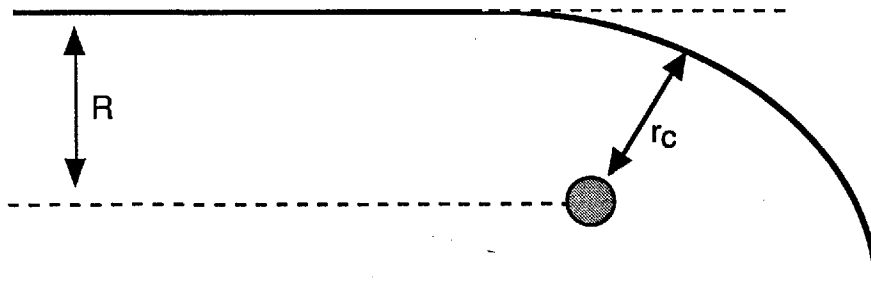


Figure 2.11 Electron colliding with ion with an impact parameter  $R$ .

An estimate of the cross section for a collision can be obtained by equating the kinetic energy of the particle to the atomic potential at an impact parameter of  $r_0$ . This gives a cross section of,

$$\sigma \approx \pi r_0^2 \approx \frac{1}{9} \frac{Z^2 q^4}{\pi \epsilon_0^2 (kT_e)^2} \quad (46)$$

This cross section only accounts for collisions where the particles are deflected over angles of the order of  $90^\circ$ , however as a result of the long range of the Coulomb force distant weak collisions are also very important [2]. These long range collisions are taken into account by equating the change in velocity of the colliding particle with the Coulomb force for large impact parameters over the time taken for a collision. In a plasma the upper limit on the impact parameter is given by the shielding distance of the plasma, the Debye length,  $L_d$ . In this simple theory the lower limit is given by the distance of closest approach  $r_0$ . The inclusion of the distant collisions modifies the cross section with the inclusion of the Coulomb Logarithm -  $\ln \Lambda$ , where  $\Lambda = L_d/r_0$  [2].

$$\sigma \approx \pi r_0^2 \approx \frac{1}{9} \frac{Z^2 q^4}{\pi \epsilon_0^2 (kT_e)^2} \ln \Lambda \quad , \quad \Lambda = \frac{L_d}{r_0} = \frac{3(kT_e)^{3/2}}{2(4\pi)^{1/2} Z^3 q^3 n_e^{1/2}} \quad (47)$$

At very large electron velocities  $r_0$  becomes extremely small, the absolute lower limit of  $r_0$ , in  $\ln \Lambda$ , then becomes the de Broglie wavelength of the electron,  $r_0 = \lambda_d = h / m_e v$  [61].

The relaxation time taken for the plasma to evolve into a Maxwellian distribution is obtained from the collision cross section  $t_{ee} = 1/Nv\sigma$  [3],

$$\frac{1}{t_{ee}} = v_{ee} = \frac{3.8 n_e}{T_e} \ln \Lambda \quad [s^{-1}] \quad (48)$$

Where  $T_e$  is in degrees K and  $n_e$  is in  $\text{cm}^{-3}$ . For  $T_e = 50\text{eV}$  ( $= 5 \times 10^5$  K) and an electron density of  $1 \times 10^{20} \text{cm}^{-3}$ ,  $t_{ee} \sim 186\text{fs}$ . The time taken for energy equilibration between electrons and protons is greater than that of electrons to electrons because of the inefficiency of energy transfer between two particles of different masses. For ions of

atomic weight  $A$ , number density  $n$  in  $\text{cm}^{-3}$  and with electrons at a temperature  $T_e$  in K [3],

$$\frac{1}{t_{ei}} = \nu_{ei} = \frac{2.9 \times 10^{-3} n Z^2}{A T_e^{3/2}} \ln \Lambda \quad s^{-1} \quad (49)$$

The time taken for equi-partition between electrons and ions at  $T_e = 50\text{eV}$ , ( $=5 \times 10^5$  K), He-like Neon ions,  $Z = 8$ ,  $A = 20$ , and at a density of  $5 \times 10^{19} \text{ cm}^{-3}$ ,  $\ln \Lambda \sim 5$ , is  $t_{ei} \sim 150\text{ps}$ . For the typical plasma conditions studied in this thesis the electrons will be described by a Maxwellian before the end of the laser pulse and the equi-partition between the ions and electrons will occur over the times scale of hundreds of picoseconds. The collisions between plasma particles also determines the rate at which the ionisation and excitation approaches the equilibrium populations.

### 2.2.2 Ionisation balance.

In general it is not possible to describe the entire state of a plasma with a single temperature and density. Often the temperature that applies to the electron distribution function does not necessarily correspond to the temperature that defines the radiation field. This is because if the radiation field is described by a Planck function the plasma must be optically thick for all wavelengths, which is not achieved in practice. It is however possible to describe a local temperature and density that defines the electron distribution function and the ionisation and excitation balance of the plasma. This is local thermodynamic equilibrium (LTE), where a Maxwellian defines the local temperature, which determines the ionisation balance through the Saha - Boltzmann equation given by [62]

$$\frac{n_e}{n_a} = 2 \left( \frac{2\pi m k T_e}{h^2} \right)^{3/2} \left( \frac{g_+}{g} \right) \exp\left(-\frac{U_q}{k T_e}\right) \quad (50)$$

For typical conditions in this thesis  $n_e = 2 \times 10^{20} / \text{cc}$ ,  $T_e = 100\text{eV}$ , and for Neon the majority of the plasma ions would be in a Helium - like ionisation stage (with  $U_q =$

240eV). However the time taken for ionisation to this stage is determined by the collisional ionisation, excitation and recombination rates, and is of the order of 50-100ps for these conditions. At times less than this the plasma is far from equilibrium and the ionisation stage will not be determined by the Saha-Boltzmann equation.

### 2.2.3 Transient ionisation.

If the density is too low, the temperature very high or the time scales shorter than the relaxation times then the ionisation excitation distribution will not be determined by collisions and the Saha-Boltzmann equation does not describe the ionisation balance. The populations of the states in the plasma atoms are determined by a coupled set of rate equations describing the excited level populations in a particular ion together with another coupled set of rate equations describing the ionisation balance between ions with charges of  $Z-1$ ,  $Z$  and  $Z+1$ . The evolution of the electron population of the ionisation stage  $Z$  is then given by

$$\frac{dn_e^Z}{dt} = n^{Z-1} S^{Z-1} - n^Z (S^Z + \alpha^Z) + n^{Z+1} \alpha^{Z+1} \quad (51)$$

Where  $S^Z$  is the ionisation rate from the  $z$ th ion and  $\alpha$  is the recombination coefficient to the  $z-1$  stage. To obtain the correct population distribution all possible excitation, ionisation and recombination routes between all levels, both collisional and radiative, must be taken into account. The state of the plasma as a function of time can be approximately determined by evaluating the simple collisional excitation and ionisation rates. For a more accurate estimate that can be compared in detail with the experimental measurements a code that calculates the contribution of all the rates can be used to post process the results of hydrodynamic simulations

### 2.2.4 Collisional rates.

Seaton [60] has calculated the collisional ionisation cross for H-like ions by treating the ionisation as a photo-ionisation process,

$$S = 2.15 \times 10^{-6} T_e^{-3/2} \exp(-V) / V^2 \quad \text{cm}^3 \text{s}^{-1} \quad (52)$$

where  $V = U_q/T_e$ , with  $U_q$  and  $T_e$  in eV. For ions with more than one electron in the outer shell, screening of the nuclear charge alters the ionisation rate and use of the hydrogenic rate in equation (52) would underestimate the ionisation rate. Kunze measured the ionisation rates of Li - Like and Be - like ions produced in a theta pinch plasma [5] and compared the results to ionisation rates that used an effective gaunt factor treatment. The ionisation rate for Li-like and Be-like in the state  $q$  determined from the experiment was found to be:

$$S = 7.7 \times 10^{-8} \left( \frac{g_q}{U_q} \right) \left( \ln \left( \frac{40T_e}{U_q} \right) + 40 \right) \left( \frac{T_e^{1/2}}{U_q + 3T_e} \right) \exp \left( -\frac{U_q}{T_e} \right) \text{cm}^3 \text{s}^{-1} \quad (53)$$

where  $g_q$  is the number of electrons in the  $q$ th shell,  $U_q$  and  $T_e$  are in eV. If it is assumed that the electron temperature does not change during the ionisation time, the characteristic ionisation time can be estimated by,

$$\tau_i = \frac{1}{SN_e} \quad (54)$$

For high ionisation stages and low temperatures in a cooling plasma this is not a good assumption, and the rate obtained from (53) is only useful as an order of magnitude estimate. As an illustration of typical time scales involved in the experiments described in this thesis the ionisation times for Neon have been calculated using (52) and (53) for states up to He-like, at an electron temperature,  $T_e = 80\text{eV}$  and a gas density of  $1.5 \times 10^{20} \text{cm}^{-3}$ .

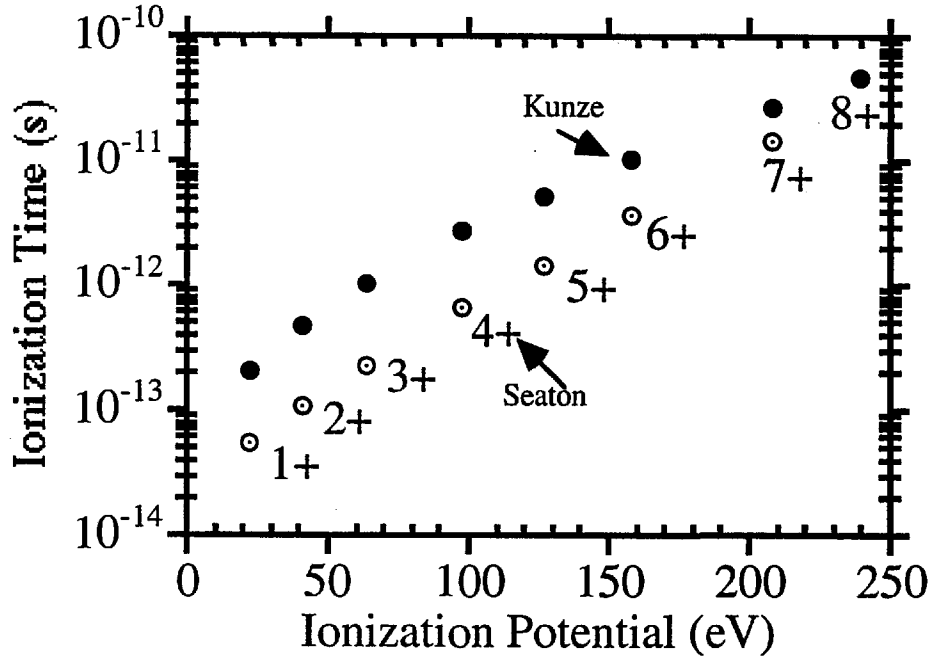


Figure 2.12 Ionisation times for Neon at  $T_e = 80\text{eV}$  and  $n_i = 1.5 \times 10^{20} \text{ cm}^{-3}$  calculated using equations (52) (filled circles) and (53) (open circles).

It can be seen from figure 2.12 that, as expected, the rates for the H-like ion from Seaton's formula predict longer ionisation times than the Li-like rates from Kunze. The rates also correctly converge to the same value as the ion approached the H-like state. These rates are a good estimate of the ionisation time scale for the initial transient stage of plasma formation. It should also be noted that the rates are very much slower than the corresponding optical ionisation rates and are not important during the laser pulse. After the initial optical and collisional ionisation stages the plasma cools and recombination begins. It is also important to have a general understanding of the typical recombination time scales for the plasmas described in this thesis.

### 2.2.5 Three body Recombination.

The rate of three body recombination can be calculated by assuming LTE holds for the upper excited states [63] and use the principal of detailed balance to relate the recombination rate to the collisional ionisation rate,  $S$ . This gives [30],

$$\alpha = 1.66 \times 10^{-22} g_p T_e^{-3/2} \exp(V) S \quad \text{cm}^6 \text{s}^{-1} \quad (55)$$

Where  $T_e$  is in eV,  $g_p$  is the statistical weight of the level  $p$ , and  $V$  is the ratio of ionisation potential  $U_p$  to  $T_e$  (both in eV). For conditions typical of the experiments described in this thesis,  $T_e \sim 100\text{eV}$ , and an electron density of  $1 \times 10^{20} \text{cm}^{-3}$ , the time scale for an ion recombining from a He-like to a Li-like state is around 100ps-1ns.

### 2.2.6 Radiative recombination.

The electron can also recombine with the emission of a photon. For a system in equilibrium the rate of radiative recombination can be obtained from its inverse process through the principal of detailed balancing to the photo-ionisation rate given by Kramers formula [3]. The radiative recombination coefficient for hydrogen like-ions is [3],

$$\alpha_v = 2.7 \times 10^{-13} Z^2 T_e^{-3/4} \quad \text{cm}^3 \text{s}^{-1} \quad (56)$$

With  $T_e$  in eV and  $Z$  the nuclear charge. For  $T_e = 100\text{eV}$  and  $Z = 8$  for He-like Neon, the recombination rate to Li-like Neon is  $5.5 \times 10^{-13} \text{cm}^3 \text{s}^{-1}$ , which, at an electron density of  $4 \times 10^{20} \text{cm}^{-3}$ , leads to a recombination time of 4.5ns. In this density and temperature regime three body and radiative recombination are comparable but are much longer than the ionisation times for ions up to He-like. For time scales less than 100ps it can be assumed that recombination is negligible compared to ionisation. To study the ionisation mechanisms in more detail an average atom model was used to describe the plasma energy level populations.

### 2.2.7 Time dependent models.

Estimates obtained from the ionisation and recombination rates are a useful first step to the interpretation of experimentally measured electron densities. However they assume that the electron density and temperature remain constant during the ionisation and do not take into account of ionisation routes through excited states. In order to obtain a more accurate interpretation it is necessary to construct a model of the plasma atom that includes all the possible excited states of the atoms and ions and use this to post process the hydrodynamic simulations. The spatial evolution of the free and bound electron

populations can then be followed, allowing a comparison with the measured free electron density to be made. In practice calculating the populations of many possible states together with the hydrodynamic variables in each time step is a formidable undertaking for complex atoms. The most complete model uses an atomic structure model to calculate the energy levels and oscillator strengths of the levels within the atom. The relative populations of the levels can then be calculated using collisional ionisation, excitation, de-excitation, three body, Di-electronic and radiative recombination and spontaneous emission. Although this method is the most accurate it is very expensive in terms of calculation time. A simpler method is to treat the ions as a hydrogenic system with an average number of electrons per level, this is the average atom model [67]. The remainder of this section will describe how an average atom model was used to post process the output of the MEDUSA simulations to give an indication of the electron density that could be measured after the laser pulse turns off.

### 2.2.8 The average atom model.

The average atom model is an approximation of the more detailed configuration accounting. The atom is split into  $m$  levels and the intensity of a spectral line from an electron undergoing a transition from  $p$  to  $q$  in the atom is

$$I(p,q) = n(p)A(p,q)h\nu(p,q) \text{ erg cm}^{-3}\text{s}^{-1} \quad (57)$$

$n(p)$  is the population of level  $p$ ,  $A(p,q)$  is the spontaneous emission coefficient, and  $h\nu$  the photon energy.  $A(p,q)$  is determined by the atomic structure and depends on the screening effect of the plasma electrons on the local charge seen by the electron undergoing the transition. A simplified picture of the energy levels can be seen in figure 2.13.

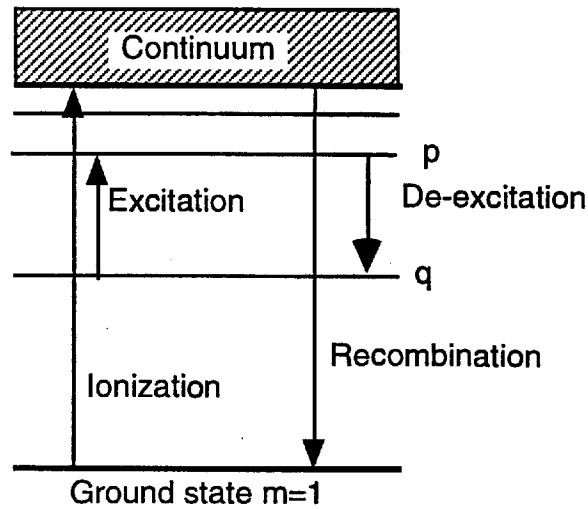


Figure 2.13 Ionisation, excitation and their inverse processes.

In the average atom approximation only the average number of electrons per level is calculated and  $A(p,q)$  is assumed to be a function of the populations of  $p$  and  $q$  only. This avoids the necessity of calculating the populations of the many possible configurations thus greatly reducing the calculation time required. The level populations are calculated with hydrogenic collisional ionisation, excitation, de-excitation, three body and radiative recombination rates. In order to account for the screening effect of the plasma electrons the energy of the levels and the collisional and radiative coefficients are calculated using an effective screened charge  $Z^*$  in place of the nuclear charge  $Z$  [67]. The average number of electrons per level is then calculated using the rate equations.

An average atom model based on a routine called XSN [67] (which is described in detail by Edwards and Rose[68]) was used to post process the output from the hydrodynamic simulation code MEDUSA. This section will summarise the important points and present the results of some simulations for comparison with the estimates calculated directly from the rates. The atoms are split into a number of levels  $m$  ( $m_{\max} = 5$ ). The probability of occupancy of level  $m$  is  $P_m$  and the number of electrons in level  $m$  is then,

$$n(m) = nP_m \quad (58)$$

The degeneracy  $g_m = 2m^2$  of the final level must be taken into account when calculating the populations. The availability  $Q_m$  of the  $m$ th level is then

$$Q_m = 1 - P_m/g_m \quad (59)$$

Initially the electrons are distributed amongst these levels according to the statistical weight of the level,  $g_m = 2m^2$ . The energy levels of the atom are calculated using the Dirac Formulation and the screening constant are obtained from Mayer [67]. The code calculates the probability of occupancy of the levels as a function of cell temperature and density in accordance with the rate equations. It then recalculates the energy levels accounting for screening of the remaining bound electrons. The temporal evolution of the bound level and the free electrons can then be followed as the plasma expands and cools. In order to test the code the rate of ionisation was obtained with the same as the simple ionisation rates in figure 2.14.

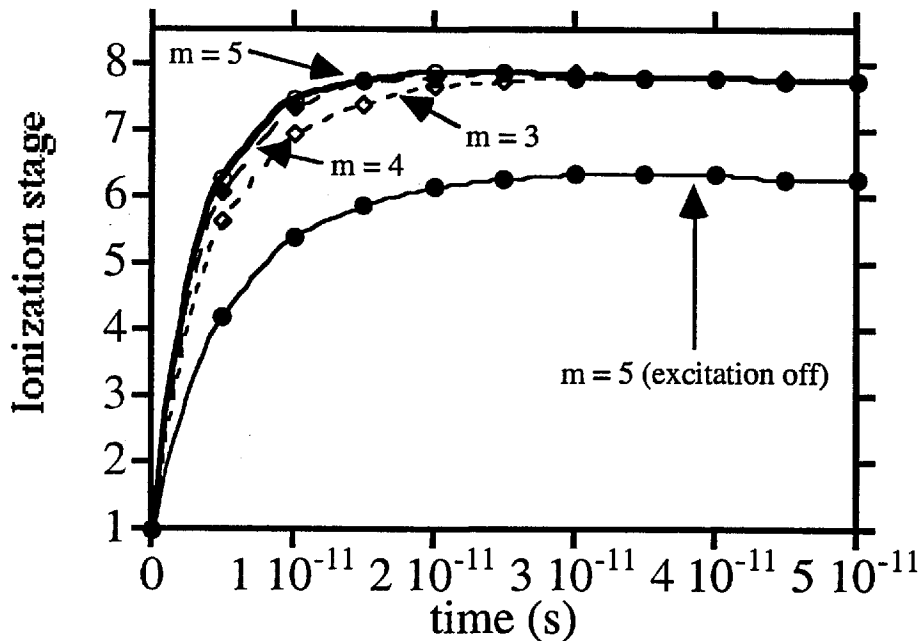


Figure 2.14 Ionisation of Neon at  $1.5 \times 10^{20}$  atoms  $\text{cm}^{-3}$  and  $T_e = 83\text{eV}$ , calculated using the average atom model to post process the output of the MEDUSA simulations, for the first 50 picoseconds of the simulation. It can be seen that as the number of levels,  $m$ , was varied from 3 to 5 the rate of ionisation increased, with the time taken for the stage to reach Li-like  $\sim 8\text{ps}$  for  $m = 5$ , increasing to  $12\text{ps}$  for  $m = 3$ . In addition the rate of ionisation was found to be drastically reduced by turning off the ionisation routes through stepwise excitation with  $m = 5$ .

The predictions obtained from the average atom model for the rate of ionisation of Neon at a density of  $1.5 \times 10^{20}$  atoms  $\text{cm}^{-3}$  and a maximum electron temperature of  $83\text{eV}$  can be seen in figure 2.14. The input to the code was obtained from a 1D simulation that simulated the deposition of energy from a laser in the centre of a gas jet target. The

hydrocode supplied the average atom code with the gas density, electron and ion temperature for each cell and time step. This hydrodynamic simulation will be described in more detail in section 2.4. In order to assess the importance of the number of bound levels  $m$  was increased from 3 to 5. It can be seen in all cases the plasma ionises extremely rapidly in the first 10ps. However there is a noticeable difference in the ionisation rate as  $m$  increased from 3 to 4 but not from  $m = 4$  to 5. The reason for this difference was that the ions were initially collisionally excited into the low lying excited states and then immediately ionised from those levels. As the number of levels increased the number of possible ionisation routes available also increased and the ionisation proceeded more quickly. To test this hypothesis the code was run with the collisional excitation routes switched off. It can be seen that, as expected, the ionisation rate was subsequently reduced. Comparing the simple ionisation rates from figure 2.12 with the model predictions in figure 2.14 showed that the simple rates agreed within a factor of 2-3 with the model. For example in the model the Li-like (7+) ionisation stage was achieved within 10ps, whereas Seaton's rate required 30ps and Kunze, 15ps. The initial rate of ionisation was faster in the average atom model as a result of the additional ionisation routes through the step wise excitation route.

The theory presented in this section has outlined how the laser interacted with a dense gas. For densities low enough for refraction of the laser to be neglected the dominant ionisation process was due to optical ionisation. At higher densities collisional ionisation was found to continue up to 20ps after the end of the laser pulse, for typical plasma temperature and density parameters. This had important implications for any density diagnostic with an effective integration time in excess of a few picoseconds. In the  $0.248\mu\text{m}$  experiments described in this thesis the density diagnostic had an integration time of around 10ps and was used to measure the plasma electron density gradients at least 6ps after the end of the laser pulse. In these circumstances the interferometer will measure electron densities that include contributions from collisional ionisation giving a higher density than that achieved by laser ionisation alone. If these ionisation stages are attributed to optical ionisation then the implied laser intensity will be overestimated. From this section it can be seen that the rate of collisional ionisation depends strongly on the electron temperature produced by laser heating. The mechanisms of laser heating will be discussed in the next section.

## 2.3 Absorption models.

The previous sections dealt with the propagation of the laser through the gas and the subsequent production of free electrons through optical and collisional ionisation. This section will describe the electron heating mechanism by the laser and how the heating rates varied with parameters such as the laser intensity and plasma density.

### 2.3.1 Above threshold ionisation.

If there is a phase mismatch between the time an electron is ionised and the peak of the laser field they can be left with a residual energy, this is termed Above Threshold Ionisation (ATI) [15]. In the classical treatment for a sinusoidal pulse the average kinetic energy gain,  $E_k$  for a phase mismatch,  $\phi$  is given by,

$$E_k = 2U_p \cos^2 \phi \quad (60)$$

Where  $U_p = \frac{e^2 E^2}{4m\omega^2}$  is the ponderomotive potential for a laser with an amplitude  $E$  and angular frequency  $\omega$ . The average ATI energy is obtained by multiplying by the ionisation rate  $W(\phi)$  and integrating over a laser cycle.

$$E_{ATI} = \frac{\int W(\phi) E_k(\phi) d\phi}{\int W(\phi) d\phi} \quad (61)$$

To calculate the total ATI heating rate the contribution from each ionisation stage is taken and the average taken. The ATI energy depends strongly on laser intensity giving approximate energies of  $0.1U_p$  for linear and  $2U_p$  circular polarisation. The  $\lambda^2$  dependence of the ponderomotive potential also means that ATI is reduced significantly at  $0.25\mu\text{m}$  compared to  $1\mu\text{m}$ . At low electron densities and high laser intensities the electron temperature is determined by ATI rather than collisional heating. However at the electron densities and laser intensities typical of the experiments in this thesis collisional absorption is more important than ATI and will be discussed in greater detail.

### 2.3.2 Inverse Bremsstrahlung.

As the electron density increases so does the influence of heating through inverse Bremsstrahlung. Energy is absorbed from the laser as the quivering electrons undergo elastic collisions. The rate of energy absorbed  $W$  is given by  $W = 2U_p v_{ei}$  where  $v_{ei}$  is given by [2].

$$v_{ei} = \frac{4\sqrt{\pi}}{3} \frac{Zq^4 n_e}{(4\pi\epsilon_0)^2 (kT_e)^{3/2}} \ln \Lambda \quad (62)$$

This expression holds for low laser intensities where the quiver velocity of the electron given by  $v_{osc} = \frac{qE}{m\omega}$  can be neglected compared to the thermal velocity

$$v_{th} = \left( \frac{kT_e}{m_e} \right)^{1/2}. \text{ However at high laser intensities the collision frequency is altered to}$$

include the oscillation velocity of the electrons,  $T_e$  is replaced with a term containing  $v_{th}$  and  $v_{osc}$  [30]  $v_{eff} = [v_{th}^2 + v_{osc}^2]^{1/2}$ . As the laser intensity increases  $v_{eff}$  becomes dominated by  $v_{osc}$  and the heating rate becomes independent of electron temperature and proportional to  $I^{-1/2}$  [30]. For intermediate laser intensities where  $v_{osc} \sim v_{th}$ , the heating rate is decreased by roughly a factor of two [71] (for  $Z \gg 1$ ) due to the non Maxwellian nature of the electron distribution function.

Recently the role of  $v_{osc}$  in the value of the Coulomb logarithm,  $\ln \Lambda$ , has been investigated [31] in detail. The maximum impact parameter,  $b_{max}$  in  $\Lambda$  is determined by the shielding of the plasma and is equal to the Debye length,  $L_D$ . There is however a stricter restriction [31], that the collision time be less than the period of the laser, giving  $b_{max} = v_t / \omega$ . This factor does not hold at high laser fields when  $v_{osc} \gg v_t$ , in this regime the plasma electrons cannot react more quickly than  $\omega_p$  and oscillation of the electrons in the field can overcome the Debye shielding, and  $b_{max}$  is given by the maximum excursion distance of the electron from its equilibrium position as it oscillates in the laser field. This factor can greatly increase the contribution of the Coulomb logarithm to the heating rate. A model based on this improved treatment was used in this thesis to predict the temperatures achieved by laser heating of initially gaseous targets. Other authors [32] have also recently published similar work that accounted for the

contribution to  $\ln A$ . The model based on this work gave a modified heating rate in cgs units of [32],

$$\frac{dT_e}{dt} = \frac{8n_i e^4 Z^2 v_E^2}{3m(v_E^2 + v_e^2)^{3/2}} \left[ \frac{1}{4} \ln^2 \left[ 1 + \frac{mv_E^2}{kT_e} \right] + \ln \left[ \frac{mv_E^2}{kT_e} + \exp \left( \frac{1}{3} \sqrt{\frac{\pi}{2}} \right) \right] \times \ln \left[ \frac{kT_e}{\hbar \omega} \right] \right] \quad (63)$$

The heating rate (63) was also used to estimate the temperature at the end of a 350fs KrF laser pulse with a wavelength of 0.248 $\mu$ m and a laser intensity of 8x10<sup>16</sup> Wcm<sup>-2</sup> with a laser pulse length of 350fs. Figure 2.15 shows how the electron temperature, reached after 350fs, predicted by equation (63) varied with gas density.

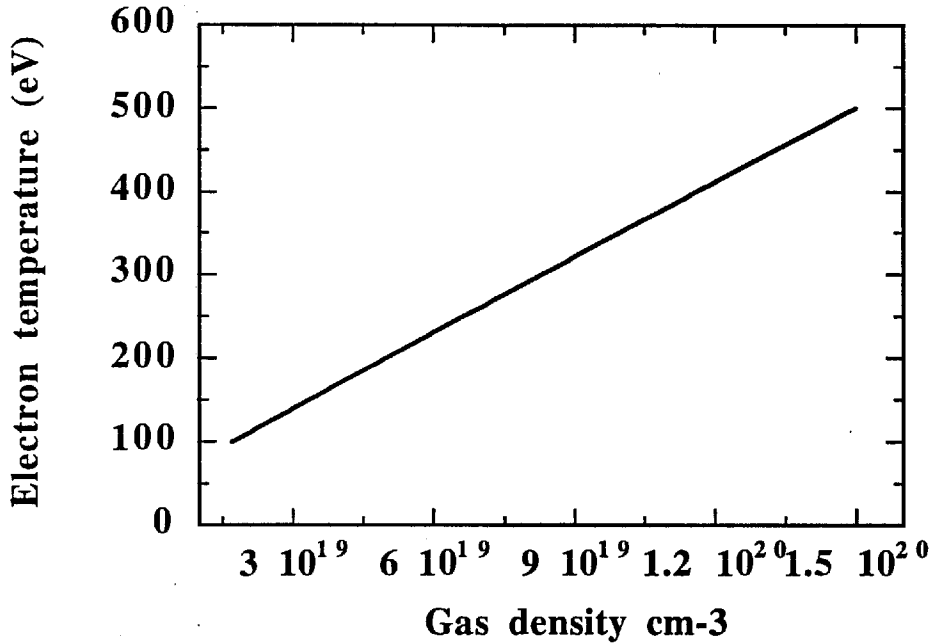


Figure 2.15 Electron temperature as a function of Neon gas density obtained from equation (63) at the end of a (temporal) square laser pulse with a duration of 350fs (zero to zero).

In order to use equation (63) it was necessary to know the ionisation stage,  $Z^*$ . This was obtained from the peak laser intensity via the Coulomb barrier model. It should be noted that the heating rate was not calculated self consistently with the increase in electron temperature. The heating rate was simply calculated for a particular laser intensity,  $Z^*$ , and gas density with a finite electron temperature. It can be seen from figure 2.15 that the electron temperature increased linearly with gas density in accord

with equation (63). In reality the increase with density will not be linear because the heating rate will depend on the details of the laser pulse such as the pulse rise time and electron distribution function which will change throughout the pulse. The results in figure 2.15 are however a good order of magnitude approximation to the electron temperatures that should be achieved in practice.

For a more accurate treatment it is necessary to perform a time dependent calculation of the ionisation rates, ATI and collisional heating directly as the laser intensity rises in time. Pert [31] has written a code that solved the tunnelling rates for an arbitrary pulse duration and calculated the ATI and the collisional heating rates, taking the high field corrections to the collision frequency into account. This code was used to check the heating rate from equation (63) and gave results a factor of 1.5 higher. This difference is not unreasonable considering that the temperature was obtained from (63) with crude assumptions about the laser pulse. For the plasmas considered in this thesis the main contribution to the electron temperature arose from this heating mechanism. The electrons can also be heated by Raman instabilities, this will be briefly described in the next section.

### 2.3.3 Heating by Raman scattering.

As the laser propagates through the underdense plasma it can be scattered by electron plasma oscillations. This process is called Raman scattering. The frequency,  $\nu$ , and wavelength,  $\lambda$ , of the incident and scattered waves are related through energy ( $h\nu$ ) and momentum conservation ( $h/\lambda$ ):

$$\begin{aligned}\nu_0 &= \nu_s + \nu_{ep} \\ 1/\lambda_0 &= 1/\lambda_s + 1/\lambda_{ep}\end{aligned}\tag{64}$$

Raman scattered light is caused by plasma density fluctuations from an electron plasma wave that interact with the electric field of the propagating laser to generate a transverse current which in turn creates a small amplitude scattered light wave. An instability is created when the scattered wave interferes with the incident light wave leading to a variation in plasma pressure through the ponderomotive force. The variation in plasma pressure creates a plasma fluctuation which in turn generates more scattered light. In this way the Raman instability grows until damping mechanisms cause it to saturate. In this

thesis Raman scattered light was not measured directly but the Raman instability provided an important additional heating mechanism to collisional or ATI processes and it is important to be able to estimate its contribution to the plasma heating rate since this may be appreciable.

### 2.3.4 Steady state growth rates.

In order to calculate the growth rate it is necessary to determine how the transverse current is generated from the interaction of the laser field with the plasma density fluctuations. The generation of the density fluctuation from the scattered wave and the incident wave is then determined using the continuity and force equations for the plasma. [49]. The dispersion relation is generated from these equations by assuming a laser amplitude,  $A_I = A_0 \cos(k_0 x - \omega t)$ . The transverse current and plasma fluctuation equations are then Fourier analysed. The frequency of plasma oscillations in a warm plasma are given by the Bohm-Gross relation [72].

$$\omega_{ek} = \omega_p^2 + 3k^2 v_e^2 \quad (65)$$

The maximum growth rate is determined from the dispersion relation [49] and the growth rate for back scatter is given by,

$$\gamma = \frac{k v_{osc}}{4} \left[ \frac{\omega_p^2}{\omega_{ek}(\omega_o - \omega_{ek})} \right]^{1/2} \quad (66)$$

And the wave number of the plasmon is given by,

$$k = k_0 + \omega_0 / c (1 - 2 \omega_{pe} / \omega_0) \quad (67)$$

for densities substantially less than  $n_c / 4$  the wave number for backscatter is,  $k = 2k_0$  while at  $n = n_c/4$ , it is  $k = k_0$ , and for side scatter  $k = \sqrt{k}$  [49]. These equations are valid for steady state pump pulses, for laser pulses that change within the growth time of the plasma waves a transient theory must be used.

### 2.3.5 Transient growth rate.

The growth rate in equation (66) above was obtained for a steady state case. The transient case where the pump length is finite has been treated by Eder [10] and results in a growth rate that is reduced by a factor of  $\sqrt{2}$  from the steady state case. The product of pulse length and growth rate that determined the heating was calculated using energy balance. It was found that for heating to be neglected  $\tau_p \gamma_p < 12-14$  for plasma waves that grow from thermal fluctuations. Eder also carried out detailed simulations of heating rates carried out with a 1D particle in cell (PIC) code. The growth rate pulse length product threshold for heating was confirmed with these simulations. In this thesis the pulse length growth rate product,  $\tau_p \gamma_p$ , was calculated in order to determine if Raman heating was important. However, no attempt was made to estimate the quantitative contribution to the actual heating rate.

## 2.4 Shock Formation

When a hot plasma expands into a cool gas the expansion front rapidly evolves into a shock front on the time scale of the ion electron energy equi-partition time, given by equation (49). A great deal of work has been published on many aspects of shock waves, their formation and propagation. A good review can be found in the book by Zel'dovich and Raizer [3]. More recently the propagation of a shock wave following laser heating has been studied by Greissman [57], Dunne et al [27]. In these studies the physics of the expansion after the laser irradiation were shown to be similar to the case of the propagation of a blast wave following a strong explosion. In the work of Dunne et al [27] the measurements of the expansion history of the blast wave were obtained with an optical probe and simulated with a hydrocode simulation. This enabled the initial plasma electron temperature to be quantitatively inferred. The temperature measured in this way was found to agree to within 20% of the prediction from a 2D particle in cell (PIC) absorption model [27].

The following section will outline the important fluid variables that characterise shock propagation, followed by a description of the theory of a strong blast wave [3]. Finally the simulation method developed by J Edwards and M Dunne [27] to infer the electron temperature will be described.

### 2.4.1 Simple theory of shock formation.

A shock is a discontinuity in the density profile of a compression wave. This results from the dependence of the wave propagation speed on the wave amplitude. In first order theory the speed of sound is constant and equal to,

$$c_s = \left( \frac{P}{\rho} \right)^{1/2} \quad (68)$$

where  $p$  and  $\rho$  are the gas pressure and density respectively. From (68) it can be seen that the speed of propagation of a disturbance does not depend on the sound wave amplitude and the possibility of shock does not exist. The process of sound wave propagation is isentropic and therefore reversible and no heating of the gas takes place. However if the sound wave is not infinitely small then its propagation irreversibly changes the state of the gas and all the fluid variables, density, pressure and gas velocity are found to depend on the wave velocity. Physically this results from a greater wave velocity at the compression compared to the rarefaction point. This leads to the compression catching up on the rarefaction, causing the wave front to overshoot and steepen into a shock.

### 2.4.2 Fluid variable representation of shock propagation.

The fluid variables on either side of the shock wave are determined by treating the wave as a mathematical discontinuity and using the conservation laws of mass, momentum and energy, together with an equation of state to relate them before and after the passage of the shock. For an ideal gas equation of state and in the limit of a strong shock, where the final pressure,  $P_1$ , is much greater than the initial pressure,  $P_0$ , the relations are, for the density [3],

$$\frac{\rho_1}{\rho_0} = \frac{\gamma + 1}{\gamma - 1} \quad (69)$$

Where  $\gamma$  is the ratio of the gas specific heats. The temperature following the shock is proportional to the pressure, for a strong shock,

$$\frac{T_1}{T_o} = \frac{\gamma-1}{\gamma+1} \frac{P_1}{P_o} \quad (70)$$

The shocked pressure can be expressed in terms of the shock wave velocity,  $D$ , as,

$$P_1 = \frac{2}{\gamma+1} \rho_o D^2 \quad (71)$$

The gas velocity behind the shock can also be related to the shock velocity,

$$u_1 = \frac{2}{\gamma+1} D \quad (72)$$

For an ideal monatomic gas with  $\gamma = 5/3$ , the limiting density increase for a strong shock is  $\rho_1/\rho_o = 4$ . The shock propagates with a supersonic velocity with respect to the undisturbed gas and a subsonic velocity with respect to the compressed gas behind it.

### 2.4.3 Propagation of the blast wave.

The formation and propagation of a blast wave was solved originally by Taylor and also by Sedov [75] using the assumption that the expansion is self similar, that is, the flow variable characterising the explosion retains a similar distribution with respect to the spatial co-ordinates with time. The energy driving the blast wave is assumed to be liberated over a short time interval and the solution is only valid for times much greater than this. The shock wave was also assumed to have moved a great distance compared to the original radius of the explosion. In this case the energy released by the explosion is considered instantaneous and coming from a single point, (or from a line if the explosion is cylindrically symmetric). The self similar variable is obtained by combining the energy and density. For a strong explosion with an initial energy deposition,  $E$ , driving a blast wave in a gas of density  $\rho_o$  the similarity variable, in cylindrical symmetry is [3],

$$\xi = r \left( \frac{\rho_o}{Et^2} \right)^{1/4} \quad (73)$$

Some time after the blast front has developed most of the mass of the gas is concentrated in a thin layer around the shock front surface, as shown in figure 2.16.

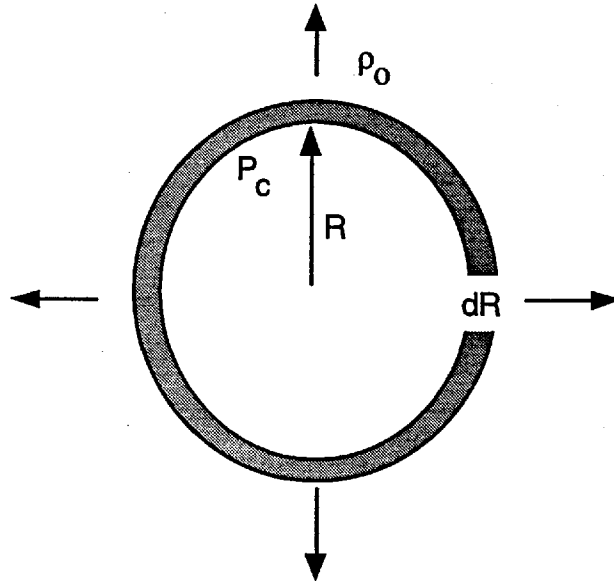


Figure 2.16 Cross section of an exploding cylinder at a radius  $R$  expanding into a perfect gas with an ambient density of  $\rho_0$ .

For a strong shock the density within the layer,  $dR$  is  $\rho_1 = (\gamma+1)/(\gamma-1)\rho_0$ . The thickness  $dR$  of the gas layer is determined from the conservation of mass

$$4\pi R^2 dR \rho_1 = \frac{4}{3} \pi R^3 \rho_0 \quad \Rightarrow \quad dR = \frac{R}{3} \frac{\gamma-1}{\gamma+1} \quad (74)$$

For  $\gamma = 1.3$ ,  $dR / R = 0.04$  and the layer can be considered in practical terms as being infinitely small with a mass  $M$  and of infinite density. The pressure,  $P_c$ , on the inside of the shell is a fraction  $\alpha$  of the wave front pressure  $P_1$  ;  $P_c = \alpha P_1$ . By using Newton's second law and the conservation of energy, the relationship between energy and radius can be found. In cylindrical symmetry Newton's second law gives,

$$\frac{d}{dt} M u_1 = \frac{d}{dt} \pi R^2 L \rho_0 u_1 = 2\pi R L P_c \quad (75)$$

using (71) and (72) to obtain  $u_1$  and  $P_c = \alpha P_1$  in terms of the shock velocity  $D$ , with  $d/dt = (dR/dt)(d/dR)$  and integrating gives  $D$  in terms of  $R$ .

$$D = a_k R^{2(\alpha-1)} \quad (76)$$

Where  $a_k$  is a constant of the integration. The law of conservation of energy now gives  $E$  in terms of the distance  $R$ . The total energy of the gas is the kinetic energy of the shock front plus the internal energy of the gas at the pressure  $P_c$ .

$$E = \frac{1}{\gamma-1} \pi R^2 L P_c + \frac{1}{2} M u_1^2 \quad (77)$$

By expressing  $P_c$  and  $u_1$  in terms of  $D$  the relationship between  $R$  and  $E$  is obtained,

$$E = 2\pi L \rho_0 a_k^2 R^{4\alpha-2} \left[ \frac{\alpha}{\gamma^2-1} + \frac{1}{(\gamma+1)^2} \right] \quad (78)$$

The energy is constant and so the exponent of  $R$  must vanish, giving  $\alpha = 1/2$ . The constant of integration is now obtained from equation (78),

$$a_k = \left( \frac{E}{2\pi L \rho_0} \right)^{1/2} \left[ \frac{1}{2(\gamma^2-1)} + \frac{1}{(\gamma+1)^2} \right]^{-1/2} \quad (79)$$

The radius of the shock front can be expressed as a function of time from (76),

$$R = (2a_k)^{1/2} t^{1/2} \quad (80)$$

$$R = \sqrt{2} \left( \frac{E}{2\pi L \rho_0} \right)^{1/4} \left[ \frac{1}{2(\gamma^2-1)} + \frac{1}{(\gamma+1)^2} \right]^{-1/4} t^{1/2}$$

The initial energy of the plasma can be determined if the radius of the shock front is measured as a function of time and the plasma density is known. The expansion radius of the shock front and the initial plasma density can both be measured with an interferometer allowing the initial energy content of the plasma to be determined. However, the theory of blast wave expansion is valid only for the asymptotic radius. The initial rate of expansion occurs before the development of the blast wave and is governed by the conduction by the electrons. Modelling of all stages of the expansion is required in order to obtain a quantitative measurement of the initial electron temperature.

#### 2.4.4 Simulations of the plasma expansion with MEDUSA.

One dimensional simulations of the expansion of the density channel were performed with MEDUSA code [76]. This model was originally developed to simulate laser plasma interactions in connection with ICF. The target is represented by Lagrangian mesh with the number of cells set to the maximum of 80. The original mesh size was set to be around  $1.5\mu\text{m}$ . The plasma size was modelled by dumping a variable fraction of the laser energy within a Gaussian profile with a spot size equal to the initial plasma size measured with the density diagnostic. No realistic attempt was made to model the energy absorption mechanism.

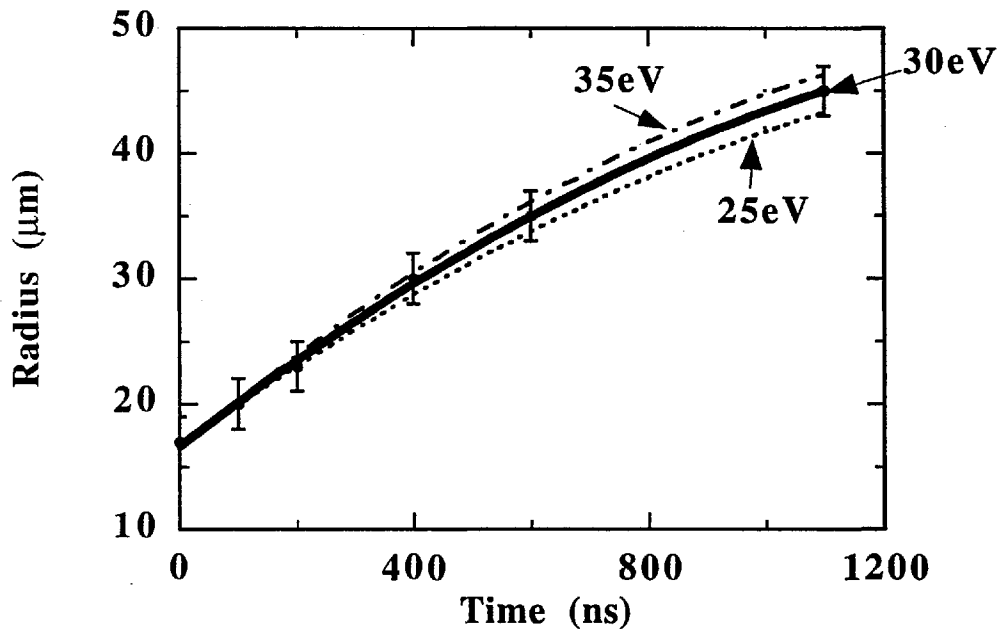


Figure 2.17 This graph shows the measured radius of expansion as a function of time of the blast wave produced by focusing a 3.5ps KrF pulse at an intensity of  $6 \times 10^{16} \text{ Wcm}^{-2}$  into Nitrogen gas at an ion density of  $1 \times 10^{17} \text{ cm}^{-3}$ . This was obtained from optical probe measurements of the radius of the blast wave taken at discrete times up to 1.2ns. Also shown are the results of two MEDUSA simulations with initial electron temperatures of 25 and 35 eV. The fit to the data indicates that the initial electron temperature was  $30\text{eV} \pm 5\text{eV}$ [27].

The fraction of energy deposited in the original plasma energy dump was varied until the simulated expansion front matched that measured by the interferometer. Figure 2.17 shows the simulation fit to the expansion radius as a function of time for a plasma produced by focusing a 3.5ps KrF pulse at an intensity of  $6 \times 10^{16} \text{ Wcm}^{-2}$  into nitrogen gas at an atomic density of  $1.25 \times 10^{17} \text{ cm}^{-3}$ . It can be seen that the simulations gave an electron temperature of  $T_e = 30 \pm 5 \text{ eV}$ . This agreed well with the predicted value of  $T_e = 27 \text{ eV}$ , from the 2D PIC simulation [27].

In all cases the expansion characteristics were found to be agree well with the observed density profiles when the thermal conduction in the plasma was modelled with the use of flux limited diffusion [27], with  $f = 0.1$ . The initial cooling of the plasma depends on the thermal conduction from the hot plasma to the cool gas. The presence of a temperature gradient  $\nabla T_e$  produces a flux of electrons  $Q$  that flow down the temperature gradient, where the flux is given by,

$$Q = -\kappa \nabla T_e \quad (81)$$

This expression is valid for small temperature gradients where the electron mean free path  $\lambda_{mfp}$  is small compared to the temperature gradient scale length  $L_T$ . The mean free path,  $\lambda_{mfp}$ , is related to the collision time for 90 degree collisions by  $\lambda_{mfp} = \tau_e v_{te}$ , numerically [77],

$$\lambda_{mfp} = 1.1 \times 10^7 \frac{T_e^2}{Z n_e \ln \Lambda} \quad \text{cm} \quad (82)$$

For  $T_e$  in K and  $n_e$  in  $\text{cm}^{-3}$ . The thermal conductivity coefficient has been calculated by Spitzer to be [2],

$$\kappa = 2 \times 10^{-4} \frac{T_e^{5/2}}{Z \ln \Lambda} \text{ ergs K}^{-1} \text{ cm}^{-1} \quad (83)$$

The heat flow is driven by the distortion of the Maxwellian velocity distribution with an excess of energetic electrons that carry the heat to the cold region of the plasma. It has been shown [78] that the heat flow is dominated by electrons with velocities of  $\sim 2.5 v_{th}$ , corresponding to mean free paths 40 times that of the thermal electrons. From (81) it can be seen that if the temperature gradient increases towards infinity then the heat flow also

increases without limit. This is clearly unphysical, a maximum heat flow can be defined by the heat flow carried by a flux of electrons free streaming into vacuum. The maximum heat flow is then,

$$Q_f = N_e kT_e (kT_e / m)^{1/2} \quad (84)$$

The condition for the validity of the Spitzer-Härm model has been investigated [79] and the limit was shown to be  $L_t > 100\lambda_{\text{mfp}}$ . If the gradient is greater then electrons carrying the heat flux affect the heat flow at any point in the gradient and the heat flow is then non local in nature [80]. In hydrodynamic codes where the non local nature of the heat flow is not accounted for explicitly, the reduction in heat flux from the Spitzer value is introduced by the use of a flux limiter,  $f$ , defined as  $f = Q/Q_f$ . This ensures that the heat flux remains physically realistic when the  $L_t < 100\lambda_{\text{mfp}}$ . In the hydrodynamic simulations of the expansion of the blast wave in the gas targets the simulated density profiles were found to match the measured profiles when  $f = 0.1$  [27]. However, in solid target experiments strong inhibition of the electron conductivity has been observed. In this case a reduction in the flux limiter to  $f = 0.03$  was required in order to match experimental heat flows with the thermal conductivity models [79].

Another method of accounting for the reduced heat flux is the use of a convolution integral formula [81]. This method has been used to model heat transport in thin filaments [82] and was used to predict new self focusing thresholds for thermal self focusing. This method has also been used to model the heat transport in cylindrical plasmas produced by focusing 12ps KrF laser pulses into Neon gas at 100 Torr [83]. The electron temperature at the centre of the plasma was found to be extremely sensitive to the value of flux limiter used when the radius of the plasma was small. The convolution method predicted thermal conduction with  $f$  between 0.1 and 0.5. For strong gradients in underdense plasmas, with little or no inhibition, the convolution method thus gave higher rates of heat conduction than the simple treatment with a flux limiter  $f = 0.1$ .

As a result of the reasonable agreement between the simulation and the electron density profiles in the 3.5ps experiment with a flux limiter of  $f = 0.1$ , this was used in the simulations of the plasma expansion in the experiments described in this thesis. As the thermal conductivity increases the density channel expands more rapidly and the energy required to match the simulation to the data reduces. This means that if the 1D

hydrocode simulations to the channel expansion were underestimating the heat conduction then the simulations would have consequently overestimated the electron temperature. If the measured temperature is compared to an absorption model then it will give an upper limit on the focused laser intensity in the gas target. The use of the measured temperature to infer the laser intensity from a comparison with the absorption models will be discussed in more detail in chapter 4.

### **3 Target design, diagnostics and laser systems.**

This chapter will describe the diagnostics, targets and laser systems used in a series of experiments that investigated the interaction of high intensity laser pulses with underdense gas targets.

#### **3.1 Gas targets.**

In order to study the mechanisms affecting laser propagation through gases it is necessary for the laser pulse to interact with a well diagnosed target volume and an easily varied gas density. In many experiments the laser pulse is focused into a gas cell or vacuum chamber backfilled with the gas to be studied. The use of backfills or gas cells has the advantage that the gas density can be easily controlled and the initial gas density is well known. However their most serious disadvantage is that the laser pulse propagates at high intensity through long regions of gas. This can lead to self focusing and beam break up due to filamentation, arising from the intensity dependent refractive index of the gas [84]. The laser also begins to ionise the gas as soon as its intensity exceeds the ionisation threshold. For high intensity pulses this can occur far before the vacuum focusing position. The plasma produced during the early stages in the pulse rise time refracts the most intense portion of the pulse leading to defocusing, a reduction in the maximum intensity achieved and ultimately a larger plasma with a lower peak ionisation stage.

Some of these disadvantages can be overcome with the use of a gas jet target where a pulsed valve allows gas to flow through a nozzle into the vacuum chamber. The nozzle shape can be adjusted to provide a well defined gas density that extends only over the focal depth of the lens. The details of gas flow through shaped nozzles into vacuum is complicated and would require detailed modelling to accurately predict the spatial distribution of gas density above the nozzle. However, a simple estimate of the density drop expected can be obtained by assuming isentropic flow.

### 3.1.1 Gas expansion into vacuum.

An estimate of the density conditions at the output of the nozzle can be obtained by assuming that the flow is isentropic. This allows the nozzle density  $\rho$  to be expressed in terms of the gas reservoir density  $\rho_0$  [85],

$$\frac{\rho_0}{\rho} = \left[ 1 + \frac{\gamma-1}{2} M^2 \right]^{1/(\gamma-1)} \quad (85)$$

where  $M$ , the Mach number, is the ratio of the gas flow velocity to the local sound speed and  $\gamma$  is the ration of the specific heats (for Neon  $\gamma = 1.67$ ).

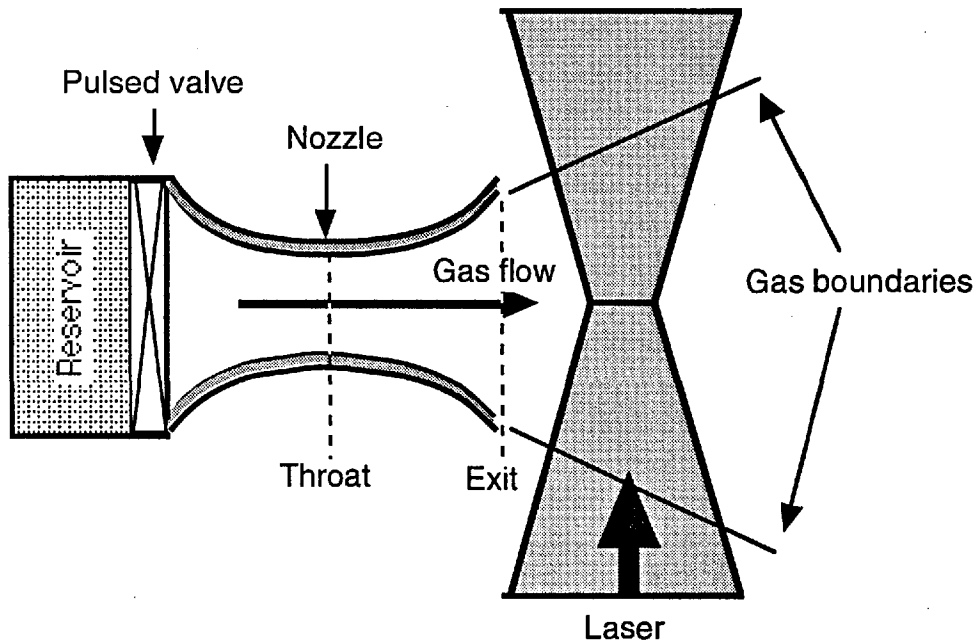


Figure 3.1 Laser pulse focused into the gas flow from a simple Laval nozzle.

It can be seen from equation (85) that the density at the nozzle exit depends strongly on the Mach number of the flow, which in turn depends on the shape of the nozzle. For  $M > 1$  a converging / diverging ("Laval") nozzle with a vacuum pressure less than the critical pressure [85] is required. A Laval nozzle is shown in Figure 3.1. An estimate of the required reservoir pressure can be obtained by first fixing the required target density. A relevant electron density to aim for is that set by the condition of high energy efficiency in the Li-like Neon recombination laser, where  $n_e \sim 4 \times 10^{20} \text{ cm}^{-3}$  [10], this requires an atomic density of  $\sim 5 \times 10^{19} \text{ cm}^{-3}$ , or a gas pressure of 1.87 atmospheres

(by definition, at STP, gas at a pressure of 1 atmosphere is equal to a number density of  $2.68 \times 10^{19} \text{ cm}^{-3}$ ). If supersonic flow with  $M = 2$  is assumed then the reservoir density  $\rho_0$  required for a gas density at the nozzle exit of  $\rho = 5 \times 10^{19} \text{ cm}^{-3}$  is,  $\rho_0 = 3.5\rho$  [86]. This corresponds to a reservoir pressure of  $P_B = 7$  atmospheres for a gas at room temperature. This simple description does not account for the fact that in the experiments the gas expanded into vacuum. If the vacuum pressure is below the critical pressure the flow becomes choked [85] and the isentropic relations are only valid up to the exit plane of the nozzle. After the exit plane the gas expands in three dimensions and cannot be treated with 1D theory. For the above example the critical pressure was [85]  $(P_0 / 10) = 0.7 \text{ bar}$ . In the experiments the chamber pressure was less than  $1 \times 10^{-3} \text{ mBar}$ , so the flow was choked.

In practice the laser is focused at distances up to 1mm from the nozzle exit and so an independent measure of the density conditions must be obtained. This can be achieved by characterising the gas jet directly with (a) an interferometer and / or (b) measuring the electron density after fully ionising the gas. This can be achieved by focusing a high intensity laser pulse into a gas, such as Hydrogen or Helium. In this thesis the gas jet density was calibrated by measuring the plasma density of Helium with high intensity pulses and this was also compared to results obtained from neutral gas characterisations when they were available.

### 3.1.2 Density of high pressure gas jet

To obtain high densities, the nozzle used in these experiments was not of the Laval type, but was a simple aperture 1mm in diameter with  $M \sim 1$  at the nozzle exit for choked flow. As a result of the sonic flow the gas density was high at the nozzle exit but it dropped extremely rapidly with distance above the nozzle as the gas flow expanded in three dimensions. This nozzle was characterised by workers at the University of Alberta [88], the characterisation has also been confirmed recently with a repeated measurement at the Rutherford Appleton Laboratory [87]. Figure 3.2 shows how the gas density reduces as a function of height above the centre of the nozzle [88].

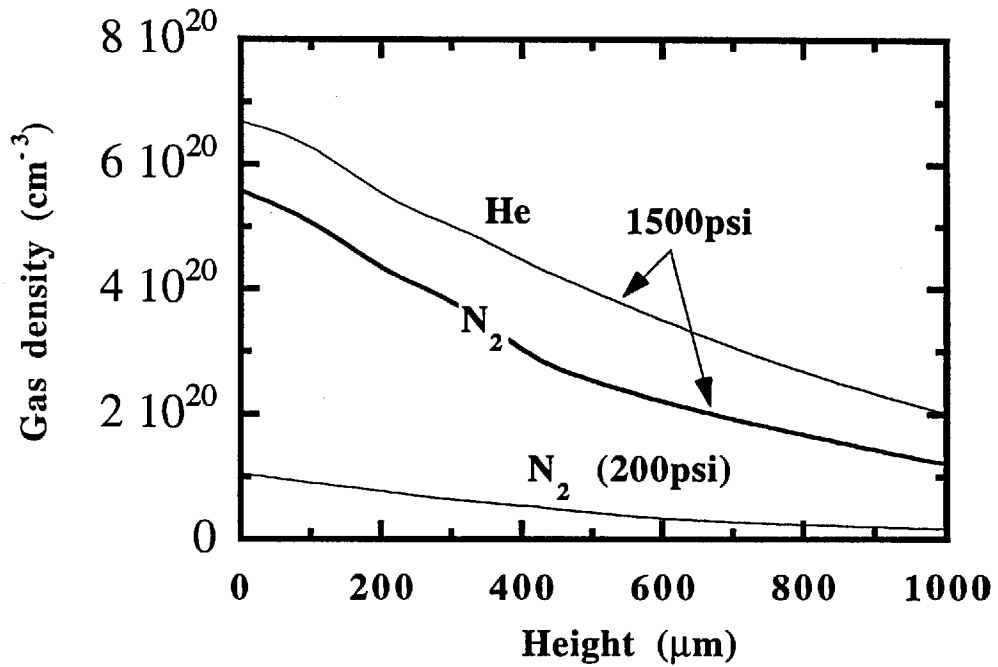


Figure 3.2 Characterisation of the density gas jet for different reservoir pressures of Helium and Nitrogen [88] (1 atmosphere = 14.7 psi).

It can be seen from figure 3.2 that the gas pressure decreased rapidly as the distance from the nozzle exit increased. For a reservoir pressure of Helium at 1500psi (102 atmospheres) the gas density at the nozzle exit was  $6.8 \times 10^{20} \text{ cm}^{-3}$ , this reduced to  $2 \times 10^{20} \text{ cm}^{-3}$ , 1mm above the nozzle exit. This gas jet was used for all the experiments in this chapter with the neutral gas density covering the range  $1.7 \times 10^{19} - 1.7 \times 10^{20} \text{ cm}^{-3} \pm 10\%$ . This characterisation was calibrated by focusing a 500GW KrF laser pulse a known height above the centre of the nozzle and measuring the electron density with a Moiré deflectometer. Helium gas was used and the gas density was varied over the range of  $3 \times 10^{19} - 1.5 \times 10^{20} \text{ cm}^{-3}$ . The intensity of the laser was always greater than the threshold for doubly ionised Helium, so the measured density was simply divided by 2 to obtained the gas density.

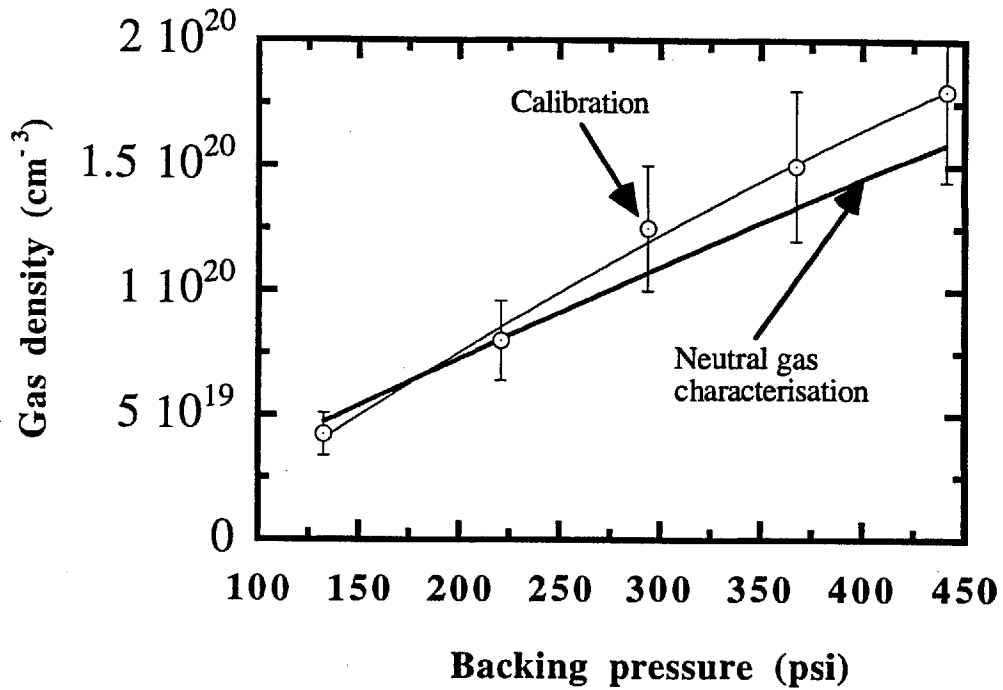


Figure 3.3 Calibration of the neutral gas characterisation of the gas flow. The open circles correspond to the experimentally determined neutral density of Helium, (obtained by dividing the electron densities measured by the Moiré deflectograms by 2). The thick line is the density measured by the neutral gas characterisation [88] ( 1 atmosphere = 14.7 psi).

In figure 3.3 the gas density inferred from the electron density agreed within 20% to the gas characterisation shown in figure 3.2. This knowledge of the neutral gas density allowed the determination of the peak ionisation stage reached in the laser gas interaction. The laser intensity was then inferred from the Coulomb Barrier Model [16]. The next section will describe the diagnostics used to measure the plasma electron density and the imaging system that was used to measure the distribution of light refracted from density gradients in the focal region.

### 3.2 Diagnostics

The majority of the experimental observations in this thesis used short pulse probes to measure the plasma refractive index. This section will briefly describe the methods that were used, including their relative advantages and limitations.

### 3.2.1 Spatial measurement of the plasma refractive index.

When a laser beam propagates through a plasma its phase is shifted by the plasma refractive index,

$$\mu = \left( 1 - \left( \frac{n_e}{n_c} \right) \right)^{1/2} \quad (86)$$

The change in refractive index after propagating through the plasma can be measured through interference or refractive effects and the electron density extracted from equation (86). In this thesis two methods were used to observe the spatial distribution of the electron density and density gradients. Shadowgrams were used to obtain a qualitative indication of the location of the strongest density gradients and Moiré deflectometry was used to quantitatively measure the plasma density gradients.

### 3.2.2 Shadowgraphy.

When a collimated laser beam with a uniform intensity cross section travels through a region with a traverse electron index gradient, refraction of the beam can occur. If the plasma is imaged onto a screen, the intensity of the light transmitted through the plasma will no longer be uniform. The refraction of the light causes bright and dark regions to appear around the density gradients. The intensity of light on the screen is quantitatively related to the density gradients by [46],

$$\frac{\Delta I}{I} = L \int_0^z \left( \frac{1}{\mu} \left( \frac{\partial^2 \mu}{\partial x^2} + \frac{\partial^2 \mu}{\partial y^2} \right) \right) dz \quad (87)$$

Where the refractive index gradients are  $\partial\mu/\partial x$  and  $\partial\mu/\partial y$  and  $L$  is the distance from the plasma to the recording screen. As a result of the dependency of the intensity fluctuations on the second derivative of the refractive index gradient, the method is not as sensitive as methods that depend only on the first derivative. In addition this equation is only valid for situations where the gradients are small enough that the rays do not cross each other in the recording plane. In practice it is not possible to obtain quantitative information from this technique, but it is extremely useful for visualising the regions with the strongest density gradients [89]. To obtain quantitative measurements of the

density gradients it is necessary to measure the refraction angle of the probe beam directly. This can be done using the Schlieren or Moiré techniques, the latter was used in the measurements in this thesis.

### 3.2.3 Moiré deflectometry.

Consider a collimated beam of light incident on two identical Ronchi gratings which have an angular mismatch between them as shown in figure 3.4. The light transmitted onto a detecting screen placed behind the second grating will consist of a set of fringes perpendicular to the direction of the rulings on the grating. These fringes are a result of the Moiré effect and were first analysed by Rayleigh [90]. The source of the fringes is the projection of the first grating onto the second by the laser beam.

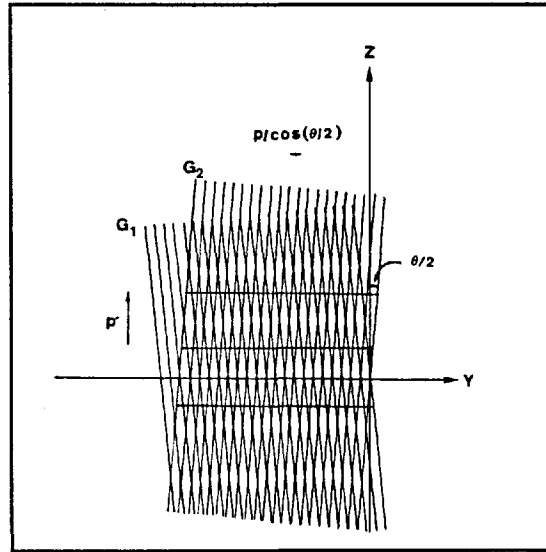


Figure 3.4 The Moiré effect when two gratings  $G_1$  and  $G_2$  are tilted with angle  $\theta$  to each other. It can be seen that the Moiré fringes are formed parallel to the  $y$  axis.

The pitch of the Moiré fringes is related to the pitch of the original gratings  $p$  and the mismatch angle  $\theta$  by [91],

$$p' = \frac{p}{2 \sin(\theta / 2)} \quad (88)$$

From figure 3.4 it can be seen that if the first grating moves along the y direction by a distance equal to  $p / (\cos\theta/2)$  then the fringe pattern will move a distance  $p'$  in the z direction. Consequently if a ray is shifted in the y direction then the fringe pattern will move in the z direction a distance amplified by the factor ;

$$A = \frac{p'}{p / \cos(\theta/2)} = \frac{1}{2} \cot(\theta/2) \quad (89)$$

When a ray is deflected in the y direction by the transverse refractive index gradient the fringe pattern is shifted in the z direction at the point (j,k) by an amount  $h_{j,k}$  as shown in figure 3.5.

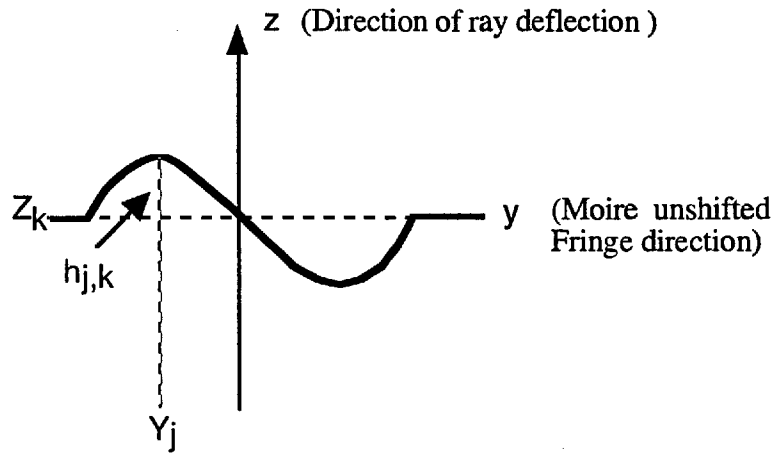


Figure 3.5 This shows one Moire fringe running along the y axis (perpendicular to the grating rulings). When the ray is deflected in the y direction by an angle  $\phi_{j,k}$  the fringe shifts by a distance  $h_{j,k}$  in the z direction [91].

From figure 3.5 a fringe shift in the z direction of  $h_{j,k}$  is equivalent to the incident ray being deflected through an angle of,

$$\phi_{j,k} = \frac{h_{j,k}}{A\Delta} = \frac{2h_{j,k} \tan(\theta/2)}{\Delta} \quad (90)$$

where  $\Delta$  is the grating separation along the x axis, as shown in figure 3.6.

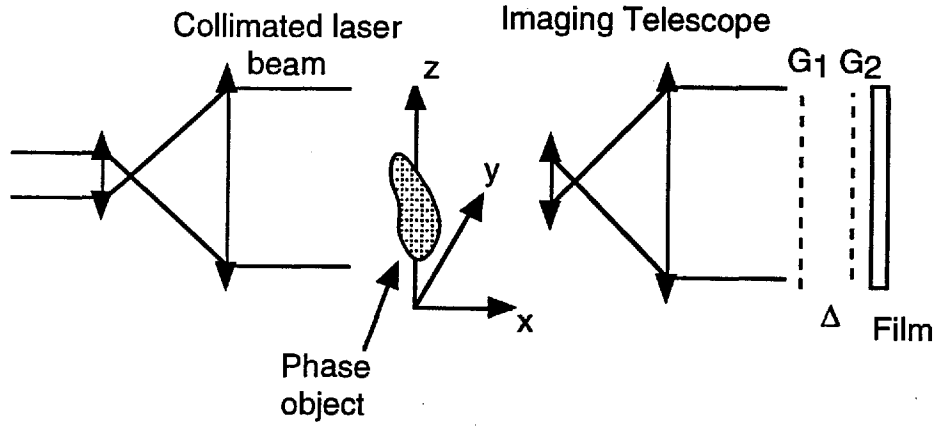


Figure 3.6 Moiré experimental arrangement with the imaging telescope. The gratings are rotated by the small angle  $\theta/2$  about the  $z$  axis and the Moiré fringes run along the  $y$  axis. The telescope collects the probe rays and forms an image of the phase object on  $G2$ . When the phase object deflects the rays in the  $y$  direction the fringes shift in the  $z$  direction, this is recorded on the film plane immediately behind  $G2$ .

The ray deflection angle is related to the refractive index gradient through the eikonal equation [45];

$$\frac{d}{ds} \left[ \mu \frac{dr}{ds} \right] = \nabla \mu \quad (91)$$

For a gradient in refractive index in the  $y$  direction and ray propagation in the  $x$  direction, this reduces to

$$\frac{dr}{ds} = \phi_{j,k} = \frac{1}{\mu} \int \frac{\delta \mu}{\delta y} dx \quad (92)$$

The refractive index gradient can be obtained by assuming cylindrical symmetry and inverting the integral in equation (92) either with an Abel inversion [92] or numerically. In this thesis the refractive index gradient was unfolded using a standard numerical inversion technique following the method of Schlachter [93]. The density gradient can be obtained from the refractive index gradient and then integrated to give the total density.

### **3.2.4 Sensitivity and resolution of the Moiré deflectometer.**

The deflectometer used for the experiments in this thesis was slightly different to the one described by Kafri [91], in that grating pair were placed at the image plane of a telescope that gave a magnified image of the plasma. The diagnostic arrangement can be seen in figure 3.6.

### **3.2.5 System Sensitivity.**

The introduction of a telescope into the system introduced a complication in the analysis of the fringe shifts. The angular magnification of the telescope altered the angle of the deflected rays that were incident on the gratings. The angular magnification of a telescope with an objective and an eyepiece of focal lengths  $f_o$  and  $f_e$  is,  $M_A = f_e/f_o$ , (equivalent to  $1/M_L$ , where  $M_L$  is the lateral magnification). The telescope increases the lateral magnification but decreases the angular magnification by the same factor, making the deflectometer less sensitive to the density gradients. The sensitivity can be increased by using a larger grating separation, but this leads to resolution problems from diffractive effects [94].

### **3.2.6 System resolution.**

The resolution normal to the fringes is set by the minimum measurable fringe shift in the  $z$  direction. The fringe separation in the image plane is adjusted by rotating the gratings to change the angular mismatch and typically corresponded to a resolution of  $5\text{-}10\mu\text{m}$  along the  $z$  axis. In the absence of diffractive effects, the resolution in the  $y$  direction, along the fringes, is determined by the pitch in the Ronchi gratings. For a typical Ronchi grating with 20 lines / mm,  $p = 50\mu\text{m}$ , this is similar to the grain size on the recording film. However, the ultimate resolution in the  $y$  direction is actually set by diffractive effects from the Moiré gratings. As the grating separation is increased, different orders from the first grating begin to spread in the  $y$  direction. If the grating separation is large enough the different orders to become visibly displaced from each other, they lead to a blurring of the image and a consequent reduction in contrast of the fringe pattern.

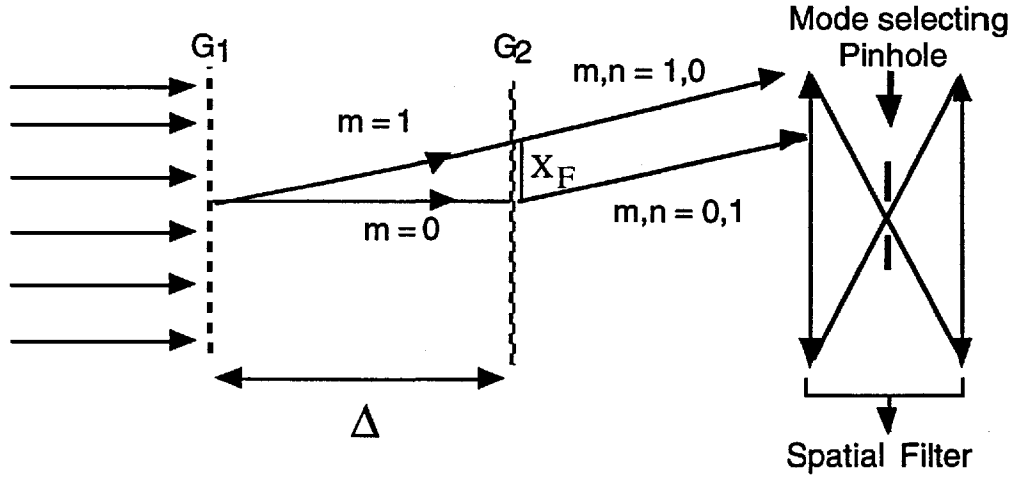


Figure 3.7 Diffraction effects from the gratings. The angles of the two orders (1,0) and (0,1) from the grating set propagate with the same angle and are thus both transmitted through the mode selecting aperture in the spatial filter. They are however spatially separated at the image plane (located at G2) by the distance  $X_F$ . This gives rise to a double image at the film plane that limits the spatial resolution of the diagnostic to  $X_F$ .

The problem is outlined in Figure 3.7, which shows how different orders that are diffracted from both gratings travel with identical angles. The orders (0,1) and (1,0) propagate with the same angle and are thus both transmitted through the mode selecting spatial filter, forming images that are separated by the distance  $X_F$  at the image plane. This problem of diffraction in Moiré deflectometry was studied by Keren and Kafri [94]. They found that to have maximum contrast the second grating G2 must be placed at the Fourier image plane of the first grating G1 given in terms of the laser wavelength and p the pitch of the gratings by,

$$L_F = \frac{p^2 q}{\lambda} \quad \text{where} \quad q = 1, 2, 3, \dots \quad (93)$$

For  $q = 1$  and a 20 lines / mm grating with  $0.248 \mu\text{m}$  light,  $L_F = 1\text{cm}$  and the contrast should be acceptable as long as  $\Delta < L_F$ . The spatial resolution of the system depends on the diffractive effects of the overlapping orders. The limiting case is for diffraction arising from a discontinuity, the resolution limit for this was given in terms of the spatial frequency  $\nu_s = 2\pi / p$  and the grating separation  $\Delta$  as [94],

$$\delta x = \frac{v_s \Delta}{k} = \frac{\Delta \lambda}{p} \quad (94)$$

For a grating with a pitch of 20 lines / mm grating  $p = 50\mu\text{m}$ ,  $\Delta = 40\text{cm}$  and  $\lambda = 0.248\mu\text{m}$ ,  $\partial x_{\text{img}} = 2\text{mm}$  at the image plane. This is equivalent to a resolution in the object plane of  $\partial x_{\text{obj}} = 30\mu\text{m}$  for a typical lateral magnification of  $M = 65$ . The Moiré deflectometer differed to that described by Keren and Kafri in that a spatial filter was used to select one of the many overlapping orders. This gave images with improved contrast and helped to overcome plasma self emission.

The resolution limit was still set by  $\delta x$ , as can be shown by referring to figure 3.7 [95]. When the mode selecting aperture is set to transmit 1st order from  $G_2$ , both orders  $(m,n) = (0,1)$  and  $(1,0)$  propagate at the same angle, and are both transmitted. These orders are displaced on  $G_2$  by the amount  $X_F$  which sets the resolution limit. The displacement is determined from the diffraction angle  $\tan \theta = \frac{\delta x}{\Delta}$  but the angle  $\theta$  is related to the grating pitch for 1st order by  $p \sin \theta = \lambda$ . The resolution limit  $\delta x$  is then,

$$\delta x = \frac{\lambda \Delta}{p} = X_F \quad (95)$$

Which is the same result as equation (94). This resolution limit places a constraint on the maximum grating separation that can be used to achieve the required spatial resolution. For a discontinuity like a shock front, the resolution limit is manifested by a double image displaced by  $\delta x$ . For smoothly varying density gradients  $\delta x$  was the scale length of the smallest gradient that can be measured. In practical terms the main limitation is the measurement of density gradients in the initial stages of plasma formation when the plasma is small. In this case the grating separation must be reduced when plasmas formed by tightly focused laser beams are measured.

### 3.2.7 Imaging of the refracted light.

The distribution of refracted light was used to infer information about the intensity of the laser beam at the focal point. This was used to support the side on emission and Moiré deflectometry measurements. The experimental arrangement can be seen in figure 3.8. (a) shows an overall plan view of the focusing and imaging geometry, and (b) shows a

magnified side elevation of the focal region. It is important that the lens used to re-image the focal region collected all the refracted light otherwise it will not give an accurate indication of the intensity distribution. In the experiments described in this thesis a quartz lens operating with a focusing cone angle of  $F/2.5$  and a resolution of  $25\mu\text{m}$  was used to re-image the middle of the gas jet target onto a CCD camera. This system had an acceptance angle of 11 degrees.

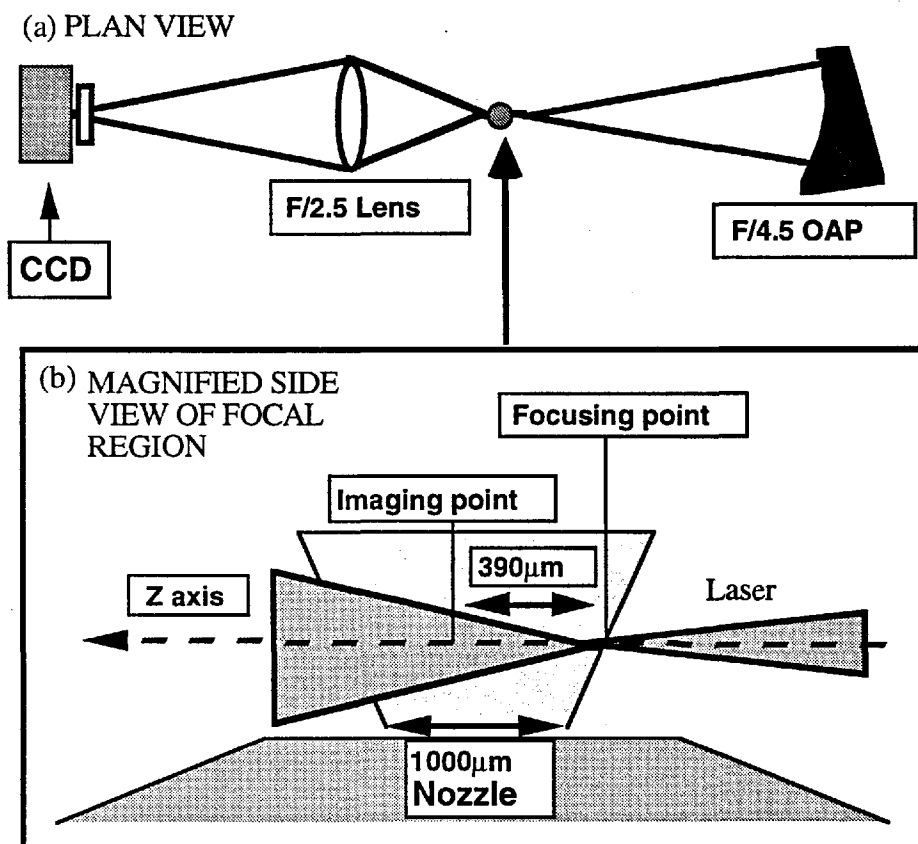


Figure 3.8 Geometry for the imaging of the refracted laser light, (a) shows a plan view of the whole focusing and imaging system while (b) shows a magnified side view of the focal region. The laser pulse was focused by the F/4.5 OAP into the gas flow from the jet. The laser light transmitted through the target is imaged by the F/2.5 lens onto the CCD.

### 3.2.8 Timing of the probe beams.

The probe and heating beams were timed by using a lens to image the focal region on to the slit of an optical streak camera sensitive to ultraviolet or infrared light, depending on the experiment. The optical path of the probe is varied until the signals coincided. This

timing technique was used, with a temporal resolution limited by the streak rate of the camera, generally around 20ps for the streak cameras used in the experiments. Another, more accurate method, was to use the Moiré deflectometer or a shadowgram to find the time of formation of the initial plasma. This method was used with a low intensity interacting pulse and a gas with a high ionisation threshold, such as Helium or Neon. This had the advantage that it was very sensitive to the start of the interacting pulse but not to any plasma created by a prepulse, and could time the pulses to within a few picoseconds. The probe pulses used in all the experiments described in this thesis had pulse durations less than 12ps. For the plasma temperatures typical of the experiments, this pulse length was short enough to freeze the plasma ion motion, as was described in section 1.2.

### **3.3. Laser systems.**

The laser used for the 0.248 $\mu$ m experiments has been described in Rutherford annual report 1994 [96]. It consisted of a tripled Ti:Sapphire oscillator, producing 100fs laser pulses at a wavelength of 0.248 $\mu$ m. The oscillator pulses were stretched using a grating pair to produce 10ps pulses. The 10ps pulses were then amplified from 1 $\mu$ J up to 600mJ in a series of KrF amplifiers. The duration of the amplified pulse was measured before and after the experiment with a single shot autocorrelator to be 350fs  $\pm$  10% [97]. The target and laser arrangement is shown in figure 3.9.

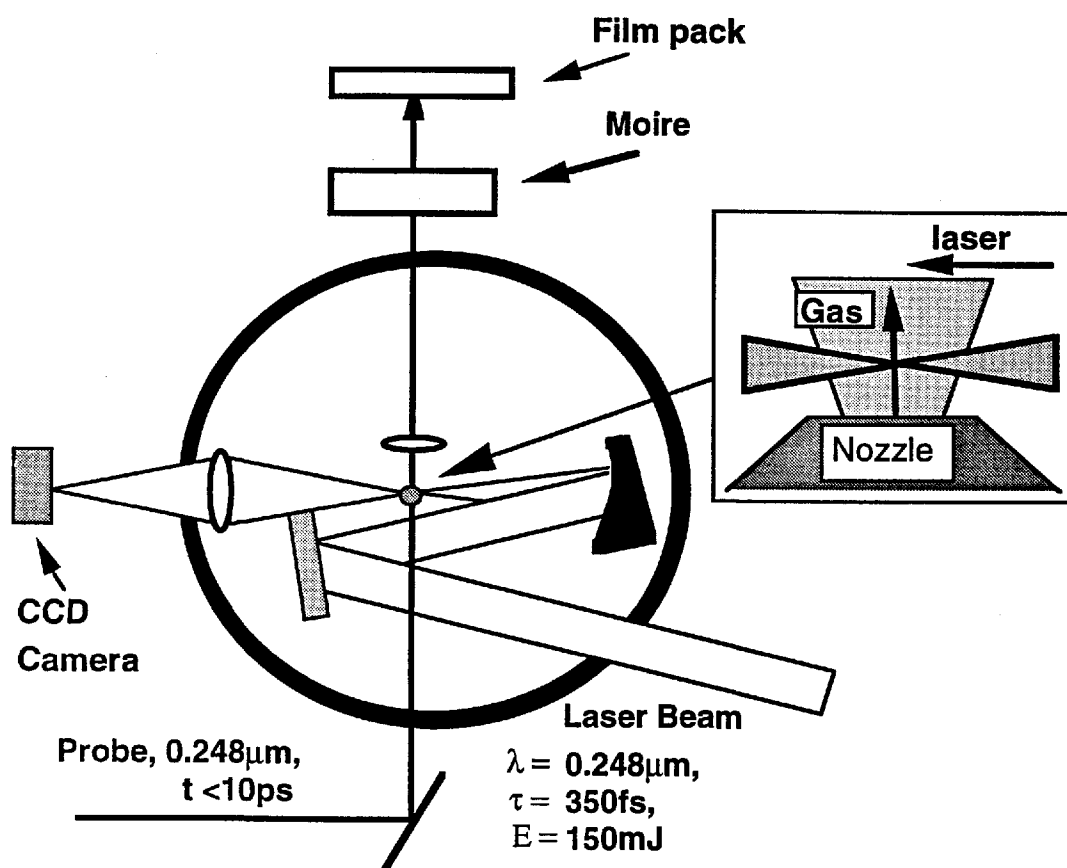


Figure 3.9 Experimental arrangement for the KrF laser interactions. The inset box shows a magnified side elevation of the laser pulse focused into the middle of the gas flow from the jet.

The compressed laser pulse was superimposed on a long duration low intensity pedestal which arose from Amplified Spontaneous Emission (ASE) from the KrF amplifiers. The pedestal had a peak intensity  $1 \times 10^{-8}$  of the compressed pulse with a temporal width of 20ns. In addition to this long duration prepulse there was also a 10ps prepulse that arose from portions of the expanded laser pulse that were not compressed by the final set of gratings. The peak intensity of the 10ps prepulse was not measured but typically for these systems was  $1 \times 10^{-4}$  -  $1 \times 10^{-6}$  of the compressed pulse [97].

In this experiment the laser was focused with an off axis parabola at F/4.7 into the middle of the gas jet 250 $\mu\text{m}$  above the nozzle exit plane. The focal spot quality was quite poor with the minimum waist around 25-30 $\mu\text{m}$ . This gave peak vacuum intensities of  $6 \times 10^{16}$  -  $1 \times 10^{17} \text{Wcm}^{-2}$  depending on the laser energy. A profile through a typical equivalent plane image of the focal spot is shown in figure 3.10.

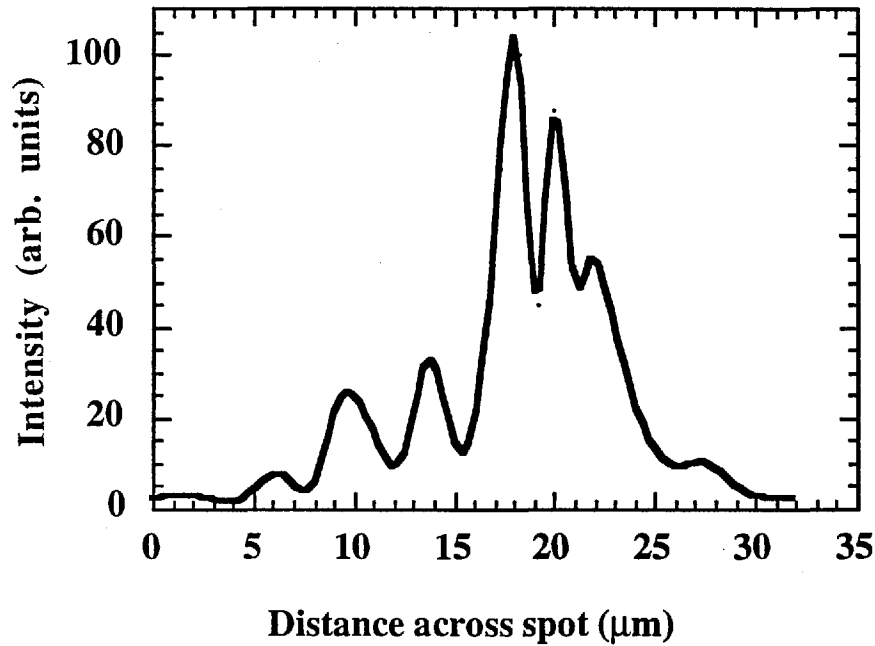


Figure 3.10 Profile through the centre of an equivalent plane image of the focal spot in arbitrary intensity units.

From this figure the focal spot can be seen to be very non uniform, with typically 2-3 hot spots with intensities greater than double the average intensity. The number and energy distribution of the hot spots also changed from shot to shot. These hot spots were possible sources from small scale self focusing or refraction effects that were described in section 2. 1.

### 3.3.1 The 1 $\mu$ m laser and the experimental arrangement.

The laser pulses used in this experiment were derived from the 1.054 $\mu$ m, VULCAN glass laser system operated in CPA mode, with a stretched pulselength of 200ps, a compressed pulselength of 1.5 - 3.5ps [98] and an energy up to 20J on target. At this energy the maximum power delivered to the target ranged from 5-35 TW depending on the laser pulse length. A prepulse with a width of 200ps with an intensity  $1 \times 10^{-4}$  of the peak pulse intensity [98] was present but it was not intense enough to cause ionisation. The laser was focused with an Off Axis Parabola (OAP) at F/5 on the gas vacuum boundary of the high density gas jet target described in section 3.1. The arrangement can be seen in figure 3.11.

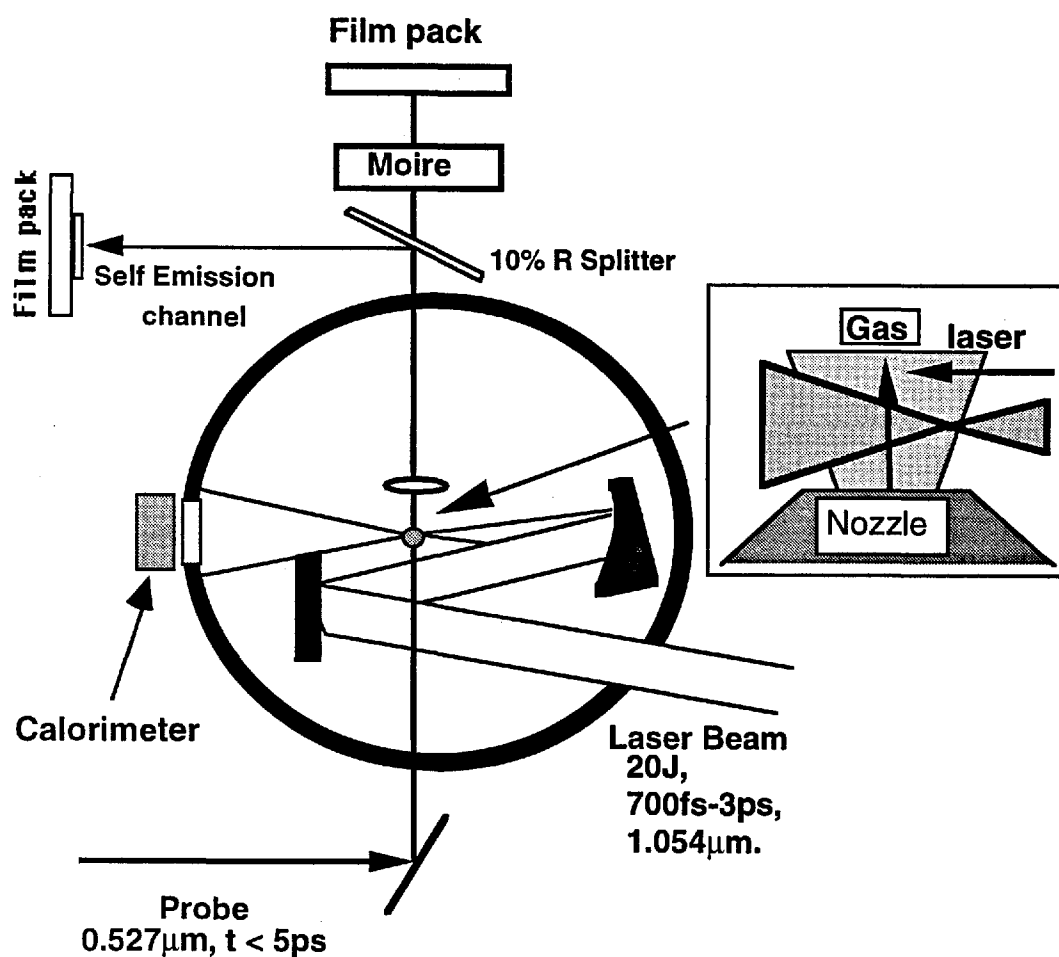


Figure 3.11 Diagram of the 1  $\mu$ m experiments. The inset box shows a magnified side elevation of the laser pulse focused onto the edge of the gas flow from the jet.

The width of the focal spot in vacuum was obtained by pinhole transmission measurements. Transmission fractions of 100% through a 100  $\mu$ m pinhole and 50% through a 50  $\mu$ m pinhole corresponded to a Gaussian with a width of 30  $\mu$ m. This would correspond to a Rayleigh length of  $z_R = 470 \mu$ m if the pulse were indeed Gaussian. However, the spatial profile of the pulse was closer to a flat topped profile than a Gaussian in the near field.

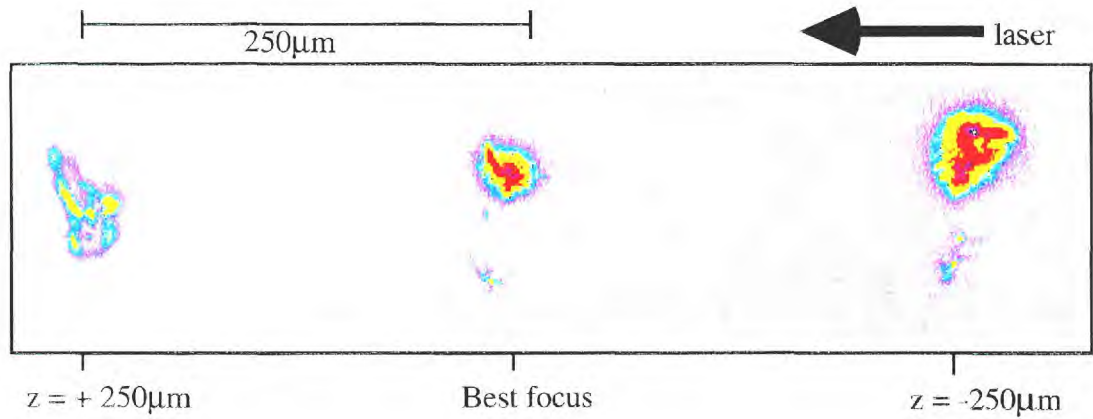


Figure 3.12(a) Laser spot size at 250μm intervals through focus.

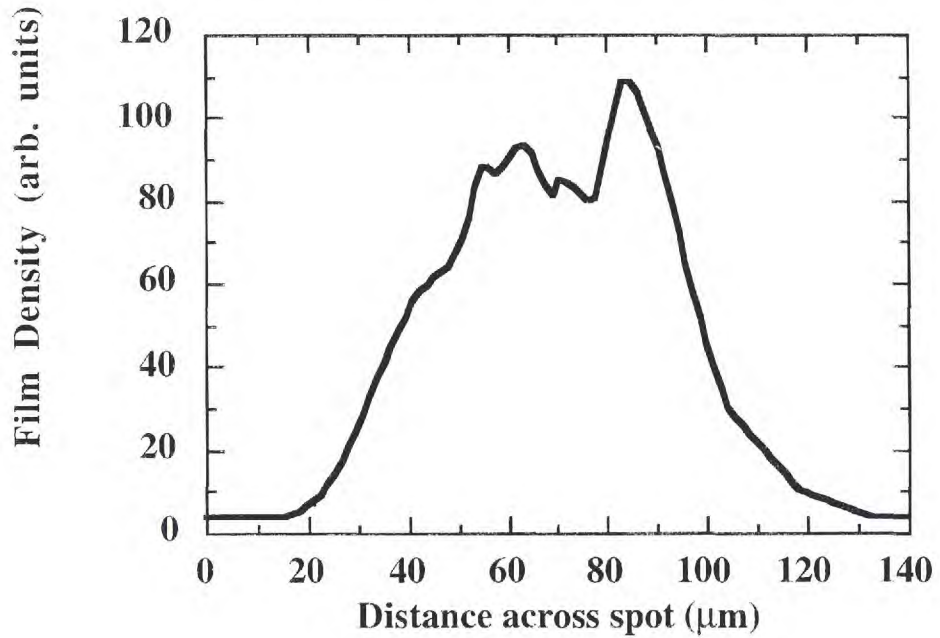


Figure 3.12(b) Profile through the equivalent plane image 250μm before focus. The double peak structure was thought to seed refractive splitting of the laser beam in the plasma density gradients.

For a flat topped profile the diffraction limited depth of focus was determined from [99] to be  $z_d = 1 / 2 (2F/\#)^2 \lambda$ , and was approximately 50μm for  $\lambda = 1.054\mu\text{m}$ , and F/5 optics. At distances greater than  $z_d$  from focus the spot width was determined by the cone angle of the focusing optic, in accordance with geometric optics. This was

confirmed with the equivalent plane images of the laser spot at different points through focus shown in figure 3.12(a). From this figure it was observed that the width of the laser spot at the focal point was  $30\mu\text{m} \pm 5\mu\text{m}$  at the half intensity points, increasing to  $60\mu\text{m} \pm 5\mu\text{m}$  at  $z = -250\mu\text{m}$  ( $250\mu\text{m}$  before focus), in agreement with the geometrical optical beam description of the beam focusing. For a laser spot with a width of  $30\mu\text{m}$  the peak vacuum intensity was in the range  $5 \times 10^{17} - 3.5 \times 10^{18} \text{ Wcm}^{-2}$  depending on the pulse length.

A cross section through the middle of the spot at  $250\mu\text{m}$  before best focus can be seen in figure 3.12(b). The double peaked structure that was visible on the beam profile before it reached focus in figure 3.12(b) was important because it could either seed filamentation or cause the beam to break up into beamlets, through refraction from the small scale density gradients as described in section 2.1.2.

### **3.3.2 The diagnostics.**

The main diagnostics of the experiments were (a) a time and space resolved Moiré deflectometer, (b) a space resolving, time integrated, self emission channel and (c) a calorimeter in the  $1\mu\text{m}$  experiment or (d) an imaging lens in the  $0.248\mu\text{m}$  experiment.

#### **(a) The Moiré deflectometer**

The main diagnostic of the interaction was the Moiré deflectometer [91], described in section 3.2.3, utilising a CPA probe pulse that was completely independent from the main heating beam. Following compression of the stretched pulse the probe was frequency doubled using a KDP crystal to a wavelength of  $\lambda = 0.527\mu\text{m}$ . The duration of the probe beam was measured [100] to be 3ps before being frequency doubled. The deflectometer enabled two dimensional snapshots of the plasma electron density to be obtained with a temporal resolution of 3-6ps and a spatial resolution of  $5\mu\text{m}$ , from 3ns before the main pulse interaction to 3ns after it.

#### **(b) Imaging of the plasma self emission around $0.6\mu\text{m}$ .**

In the  $1\mu\text{m}$  experiment light emitted perpendicular to the laser propagation direction at a wavelength of  $0.622\mu\text{m} \pm 0.025\mu\text{m}$  was imaged with a spatial resolution of  $10\mu\text{m}$  onto

time integrated Polaroid 612 high speed or Ilford HP5 film. This diagnostic provided data complimentary to the Moiré deflectograms regarding the length of the plasma and the distance over which guiding or refraction took place. The light that was emitted around  $0.622\mu\text{m}$  perpendicular to the laser propagation direction was not thought to arise from recombination. This was because it was observed to come from small scale structures of the order of  $50\mu\text{m}$  or less. For the density and temperature conditions of these plasmas recombination emission occurred over time scales of  $100\text{ps} - 10\text{ns}$ . The plasma column would expand to diameters  $> 200\mu\text{m}$  in this time and the emission would give diffuse images with typical radial scalelengths in excess of  $200\mu\text{m}$ .

The light was thought to arise from Raman scattered light shifted from the second harmonic wavelength of  $0.527\mu\text{m}$  to  $0.600\mu\text{m}$ . The approximate wavelength shift can be used to estimate the electron density of the plasma oscillations from the Bohm Gross relation [49,72];

$$\omega_s^2 = \omega_p^2 + 3k^2v_t^2 \quad (65)$$

Where  $\omega_s$  and  $\omega_p$  are the frequencies of the scattered light and the plasmon respectively. If the thermal contribution  $3k^2v_t^2$  is neglected, an upper limit on the electron density can be obtained. For  $v_t = 0$  a wavelength shift from  $0.527$  to  $0.600\mu\text{m}$  corresponds to an electron density of  $\sim 6 \times 10^{19} \text{ cm}^{-3}$ , which is close to the densities measured by the Moiré deflectometer. If the self emission did arise from Raman scattered light it would occur within the duration of the interacting pulse and would correspond to the spatial extent of the heating pulse, which was of the order of  $5 - 20\mu\text{m}$ . Structures of this size were observed in self emission images obtained during the  $1\mu\text{m}$  experiments, confirming this interpretation. In the  $0.248\mu\text{m}$  experiment the laser intensity was low and the self emission was diffuse and extended over many hundreds of microns in the radial direction, indicating that, in this experiment, recombination was responsible for the emission.

### (c) Calorimetry of the transmitted laser energy.

In the  $1\mu\text{m}$  experiment an absorbing glass calorimeter [101] with a diameter of  $122\text{mm}$  was placed immediately outside the exit window of the interaction chamber,  $650\text{mm}$  from the target plane. There was no collimating lens between the target and the chamber window and the laser beam expanded freely on to the face of the calorimeter. The acceptance angle of the system was  $5.5$  degrees, this was smaller than the  $5.7$  degree

cone angle of the F/5 focusing optic and led to a transmission of  $T = (5.5 / 5.7)^2 = 89\%$ , of the energy reaching the target.

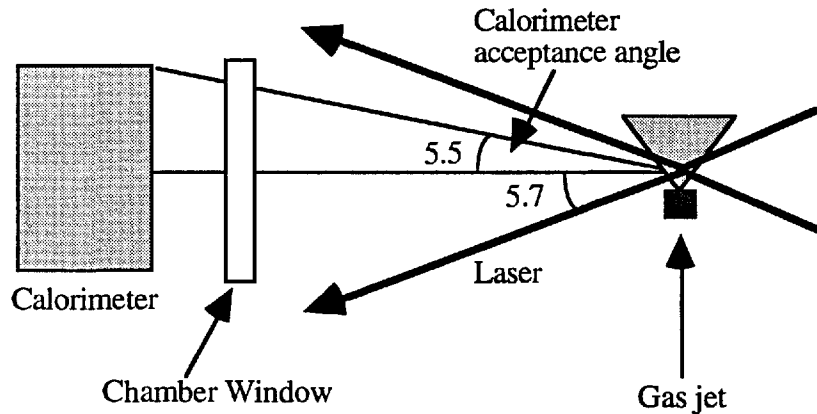


Figure 3.13 Geometry of laser beam expansion and the calorimeter acceptance angle.

The arrangement can be seen in figure 3.13. The transmission of the system was calibrated by measuring the energy reaching the calorimeter when there was no gas in the vacuum chamber. The geometric considerations described above, resulted in a transmission ratio of the target plane laser energy on to the calorimeter of  $T = 89\%$ . However, the total system transmission also included the 50% absorption and scattering losses from the compression gratings, leading to a final transmission fraction of 45%. This agreed well with the measured transmission fraction of 43%.

#### (d) Imaging of the refracted laser light

In the  $0.248\mu\text{m}$  experiment the laser light transmitted through the target was imaged with a quartz lens at F/2.5, with spatial resolution of  $25\mu\text{m}$ , as described in section 3.2.6 This diagnostic enabled the distribution of refracted light to be related accurately to the density gradients measured by the Moiré deflectometer.

### 3.3.3 The formation of pre-pulses.

In the guiding experiments the guiding channel was formed by focusing a pre-pulse co-linear with the main heating beam into the gas jet in advance of the main heating beam. The prepulse beam was derived from a split of either 1 or 10% from the main pulse depending on the reflectivity of the splitting mirror. The preforming pulse was thus

temporally and spatially identical to the main interaction pulse but with an energy level reduced to either 1 or 10% of the main beam energy . The delay between the formation of the preformed plasma and the start of the heating pulse could be adjusted from a minimum of 500ps to a maximum of 2.3ns by varying the separation between the mirrors of the prepulse and heating beams. The next chapter will describe observations of refractive effects when 0.248 $\mu$ m and 1 $\mu$ m laser pulses were focused into the centre and edge of the gas jet respectively.

## 4. Interaction of short pulse lasers with neutral gases.

In the introduction to this thesis the interaction of short laser pulses with gas targets was described in connection with a number of laser plasma applications. Schemes such as the recombination X-ray laser generally require a long region of plasma at a high electron density to achieve a reasonable gain and energy efficiency. The Li-like Neon X-ray laser [10] operating at 80Å that was described in some detail in the introduction, is a good example of the desired laser and target parameters. It was shown from this model that to obtain a reasonable energy efficiency of around  $10^{-5}$ , requires an electron density of  $4 \times 10^{20} \text{ cm}^{-3}$  and an electron temperature of 50eV. In this model the formation of a plasma with  $n_e > 4 \times 10^{20} \text{ cm}^{-3}$  at  $T_e = 50\text{eV}$  is achieved by focusing a  $0.248\mu\text{m}$  laser, at an intensity of  $2 \times 10^{17} \text{ Wcm}^{-2}$  and a pulse length less than 100fs into Neon gas at a neutral density around  $5 \times 10^{19} \text{ cm}^{-3}$ . A study of the formation of density channels using 3.5ps KrF laser pulses at gas densities around  $1 \times 10^{17} \text{ cm}^{-3}$  and laser intensities in vacuum of  $6 \times 10^{16} \text{ Wcm}^{-2}$  [27] showed that, in this low density regime refraction and filamentation were not important. However the theory outlined in section 2.1 indicated that the ionisation defocusing and self focusing mechanisms are much stronger as the gas density increased to around  $5 \times 10^{19} \text{ cm}^{-3}$ . A study of the propagation of sub-picosecond KrF laser pulses in gas jet targets is crucial for the understanding of the feasibility of the recombination X-ray laser application. The propagation of picosecond laser pulses with the longer wavelength of  $1\mu\text{m}$  and at powers in excess of 10 TW is also very important for the study of applications such as laser accelerators [9] and fundamental physics issues such as relativistic self focusing and other beam instabilities [23,39].

This chapter will present the results of a series of three experiments that were carried out in order to study the propagation of intense laser pulses over a range of gas densities, laser wavelengths and pulse duration, they were : (i) 0.35ps ,  $\lambda = 0.248\mu\text{m}$ , KrF laser pulses at powers up to 800GW, intensities up to  $5 \times 10^{16} \text{ Wcm}^{-2}$  (ii) 12ps Raman shifted KrF pulses,  $\lambda = 0.268\mu\text{m}$ , at powers of 10-300GW and intensities up to  $5 \times 10^{17} \text{ Wcm}^{-2}$ . (iii) 0.7 - 2.8ps pulses,  $\lambda = 1.054\mu\text{m}$  laser at powers up to 10TW and intensities up to  $3 \times 10^{18} \text{ Wcm}^{-2}$ .

## 4.1 Interaction of 0.350ps KrF pulses with dense gases.

Laser pulses from the SPRITE CPA system, with  $\lambda = 0.248\mu\text{m}$ , and  $\tau_p = 0.350\text{ps}$ , (as described in section 3.3) were focused into the centre of the high density gas jet with vacuum intensities up to  $1 \times 10^{17} \text{ Wcm}^{-2}$ . The formation of plasmas in Helium gas was initially studied as part of the gas jet density calibration described in section 3.1. A Moiré deflectogram of the plasma formed in Helium at a reservoir pressure of 10 atmospheres (147psi), taken 6ps after the end of the heating pulse can be seen in figure 4.1.

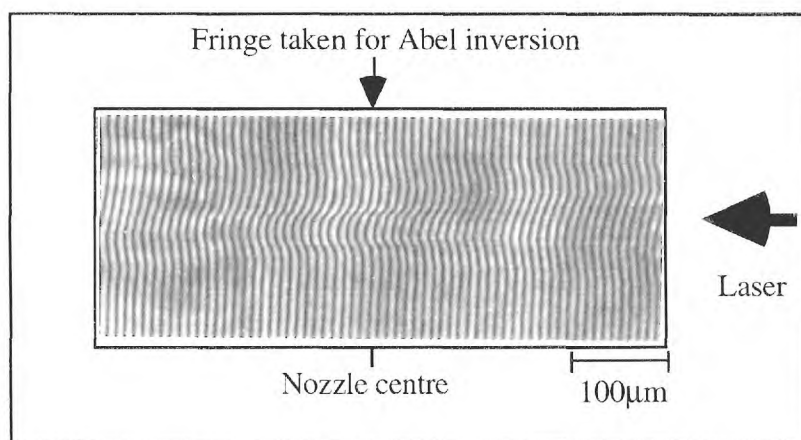


Figure 4.1 Moiré deflectogram of plasma formed in Helium by the 0.350ps KrF pulse.

At probe delays less than 6ps after the main pulse the fringe contrast was very poor. This effect was thought to be due to transient collisional ionisation occurring after the termination of the laser pulse. This feature will be considered in more detail in the section on collisional ionisation. From figure 4.1 it can be seen that the maximum fringe shift occurred near the centre of the field of view and at the location of the minimum plasma radius. This corresponded approximately to the centre of the gas jet. The maximum electron density for this shot was obtained by Abel inversion of the fringe with the maximum shift, at the position marked in figure 4.1. This measurement was also repeated for increasing reservoir pressure of Helium gas,  $P_B$ . The resulting electron density profiles can be seen in Figure 4.2. From the figure it can be seen that the peak electron density increased from  $8 \times 10^{19}$  to  $3.5 \times 10^{20} \text{ cm}^{-3}$  as the reservoir pressure increased from 10 to 30 Bar. The atomic density was obtained from the electron density by assuming that the laser intensity was high enough to doubly ionise the gas, and then dividing by a factor of 2. The gas density that was obtained from this method was found

to agree to within 20% to the gas density predicted by the characterisation over the range of electron densities measured, as was shown in figure 3.3 of chapter 3.

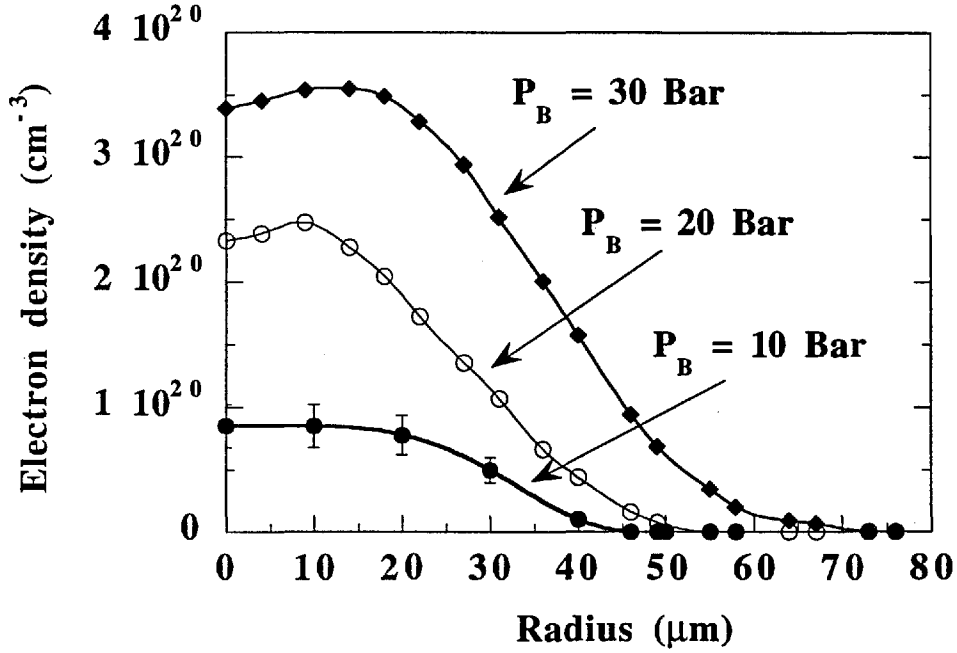


Figure 4.2 Radial electron density profiles for increasing Helium gas density.

The assumption of doubly ionised Helium depended on the focused intensity being greater than the threshold value of  $9 \times 10^{15} \text{ Wcm}^{-2}$  predicted by the Coulomb barrier model [16]. This assumption may not be valid if refractive effects reduced the focused intensity below this threshold value. The increase in the plasma size as the gas density increased that can be seen in figure 4.2 was thought to be the result of ionisation defocusing. The radius of the plasma did show a small increase of 30% from  $31 \mu\text{m}$  to  $41 \mu\text{m}$  as the gas density increased from  $4.25 \times 10^{19}$  to  $1.75 \times 10^{20} \text{ cm}^{-3} \pm 20\%$ , but it was unlikely that the refractive effects were severe enough to reduce the intensity below the threshold for  $2^+$ . This was confirmed with the observed linear increase in electron density with increasing reservoir pressure that showed that the ionisation stage remained at  $2^+$ . A simple estimate of the importance of refraction can be obtained from equation (23), the defocusing length,  $L_r$  [48],

$$L_r = \frac{1}{2} \frac{\lambda n_c}{n_e} \quad (23)$$

For a singly ionised gas at an atomic density of  $8 \times 10^{19} \text{ cm}^{-3}$ ,  $l_d = 30 \mu\text{m}$ . Although the increase in plasma size with gas density indicated that defocusing was important it could not be directly related to the beam intensity. Comparisons with the analytic theory [38] confirmed that though defocusing was occurring at these densities it lowered the intensity below  $9 \times 10^{15} \text{ W cm}^{-2}$  for densities greater than  $1 \times 10^{20} \text{ cm}^{-3}$ . In order to establish if refractive defocusing was occurring at Helium gas densities below  $1 \times 10^{20} \text{ cm}^{-3}$  the electron temperature was inferred through the plasma expansion measurement as described in section 2.4.3 and compared to the predictions of absorption models described in section 2.3 to estimate the focused laser intensity.

## 4.2 Measurement of density channel expansion in Helium.

The increase in the plasma radius measured by the deflectometer as a function of time for an atomic density of  $4.25 \times 10^{19} \text{ cm}^{-3}$  can be seen in figure 4.3. The scatter in the expansion radius resulted from variations in the incident laser power.

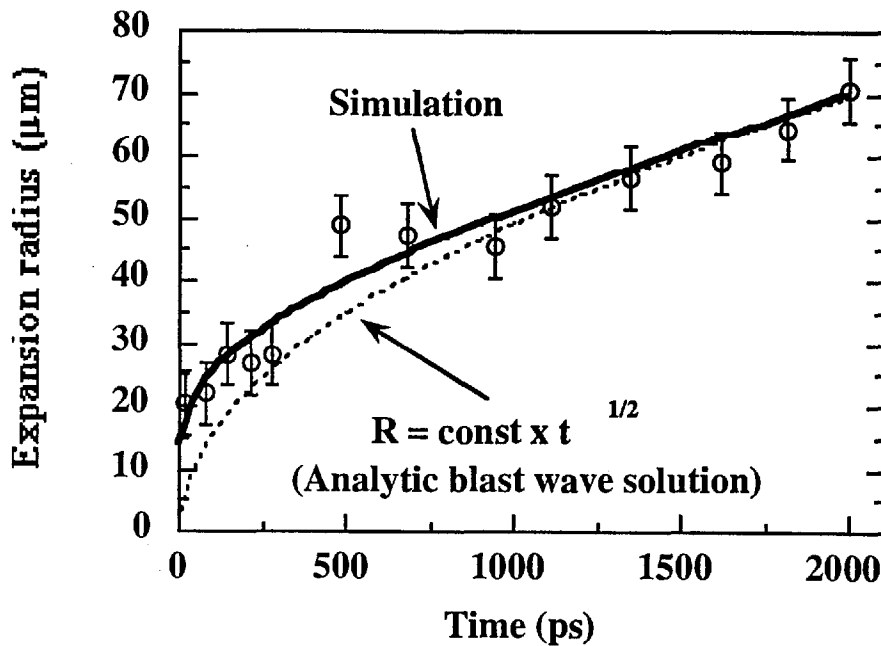


Figure 4.3 Experimental points (open circles) show the measured expansion of the density channel in Helium at  $n_a = 4.25 \times 10^{19} \text{ cm}^{-3}$ . The dashed line shows the analytic fit (blast wave theory), while the full line shows the fit from the MEDUSA simulation.

The analytic blast wave solution of equation (80) that was described in section 2.4 can be seen as the adiabatic ( $R \propto t^{1/2}$ ) fit to the expansion radius. The fit to the experimental data is good for times greater than 1ns, confirming that the blast wave model gives a reasonable description of the later stages of the expansion. However the disagreement was greater at earlier times where the electron thermal conduction determined the rate of expansion. In order to accurately infer the electron temperature from the expansion data shown in figure 4.3 it was necessary to model the complete expansion with the hydrocode simulations as described in section 2.4.

The full curve on figure 4.3 shows the results of MEDUSA simulations of the plasma expansion for  $T_e = 145\text{eV} \pm 20\text{eV}$  and  $n_a = 4.25 \times 10^{19} \text{ cm}^{-3} \pm 20\%$ . At this pulse length thermal conduction did not alter the electron temperature during the pulse, but was important during the early stages in the expansion. The simulations showed good agreement with the experimental data at all times during the expansion. The relative error of this temperature measurement was estimated by running simulations with different initial energy contents and bracketing the experimental data. This resulted in a relative error of  $\pm 20\text{eV}$ .

The experimentally inferred temperatures did not agree well with the theoretical model of Polischuck [32], which predicted an electron temperature of 40eV for Helium at  $n_a = 4.5 \times 10^{19} \text{ cm}^{-3}$  and a laser intensity of  $6 \times 10^{16} \text{ Wcm}^{-2}$ . This large discrepancy may be the result of Raman heating, an estimate of the transient growth rate from the model of Eder was described by equation (66) of section 2.3.4,

$$\gamma = \frac{1}{2\sqrt{2}} \frac{v_{osc}}{c} \left[ \frac{\omega_p / \omega_0}{(1 - \omega_p / \omega_0)} \right]^{1/2} \omega_0 \quad (66)$$

Where the factor of  $1 / \sqrt{2}$  arises from the finite pump duration. Significant plasma heating will occur if the energy density of the plasma waves approaches the total energy of the plasma,  $E_{th} = \frac{3}{2} n_e T_e$ . This occurs when the product of the laser pulse length,  $\tau$  and the instability growth rate,  $\gamma$ , is  $\gamma\tau > 12-14$  [10]. For the conditions existing in the Helium plasma, with,  $\lambda = 0.248\mu\text{m}$ ,  $I = 8.5 \times 10^{16} \text{ Wcm}^{-2}$ ,  $n_e = 8.5 \times 10^{19} \text{ cm}^{-3}$  and a laser pulse length  $\tau = 350\text{fs}$ ,  $\gamma = 4.39 \times 10^{13} \text{ s}^{-1}$  and  $\gamma\tau = 15$ . There should be an appreciable contribution from Raman heating to the electron temperature at the end of the laser pulse. It was not possible to accurately predict the contribution without the use of

detailed 1D PIC simulations but the increase in the measured electron temperature above the theoretical predictions was consistent with Raman heating. These measurements were repeated for Neon gas in order to investigate the propagation of the laser pulse in conditions applicable to the Li-like Neon X-ray recombination laser.

### **4.3 Interactions with Neon.**

The Li-like Neon recombination X-ray laser requires a plasma with an electron density greater than  $4 \times 10^{20} \text{ cm}^{-3}$  and a temperature less than 50eV to achieve high gain and energy efficiency [10]. It was been suggested that such a plasma can be formed by focusing a  $0.248 \mu\text{m}$  laser at an intensity of  $2 \times 10^{17} \text{ Wcm}^{-2}$  into Neon gas at a density around  $5 \times 10^{19} \text{ cm}^{-3}$ . A study of the propagation of high intensity KrF pulses at these densities was carried out to understand the feasibility of this scheme. In order to investigate the effect of refraction the initial radius of the plasma was measured with the deflectometer as the gas density was increased while maintaining the laser intensity at a constant level. The results showed that the defocusing was more severe for Neon than it was for Helium. This was due to the lower ionisation potential of the first two stages in Neon compared to Helium and also to the additional stages that were available in Neon, resulting in larger electron density gradients in Neon compared to Helium.

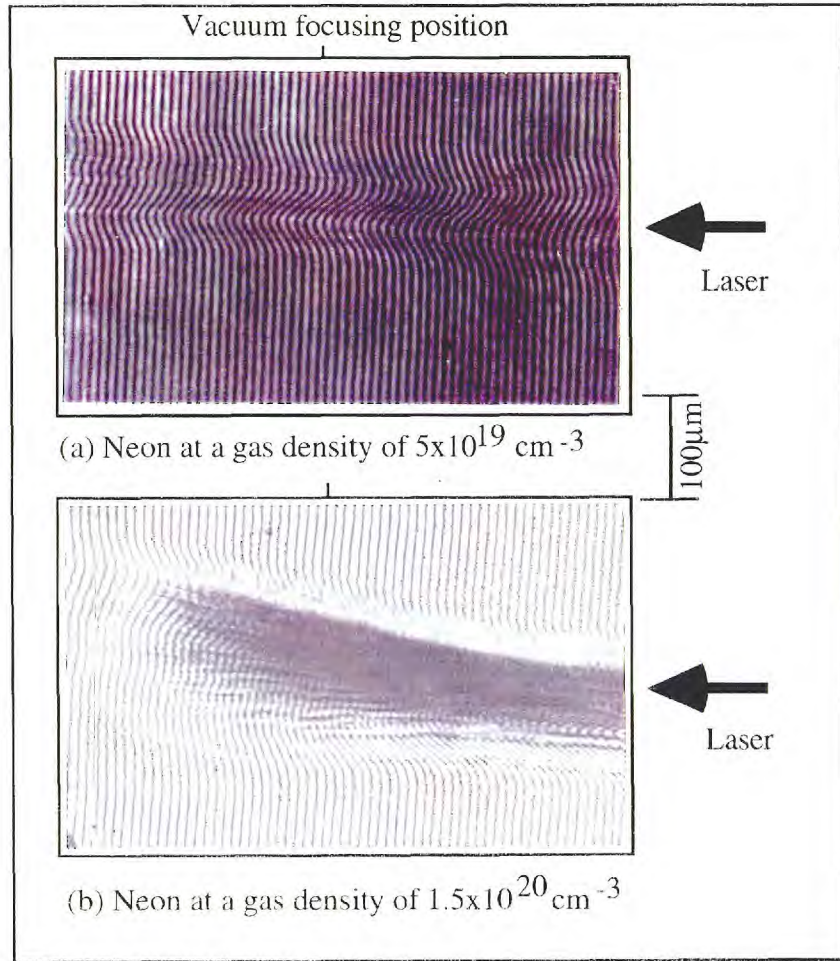


Figure 4.4 Deflectograms of Neon at a probe delay of  $t_d = +6\text{ps}$  for increasing gas density .

The results showed strong evidence of refractive defocusing, with an increase in plasma radius and the onset of plasma non uniformity as the gas density increased. Figure 4.4(a) and (b) show the deflectograms at a gas densities of  $5 \times 10^{19}$  and  $1.5 \times 10^{20} \text{ cm}^{-3}$  respectively. The deflectograms were taken at a relative probe delay of,  $t_d = +6\text{ps}$ . A comparison of the general features of these figures showed that as the gas density increased the point of peak density moved towards the laser, the radius of the plasma increased and the plasma expanded in the radial direction. At the highest density the plasma was observed to break up into numerous small scale density channels. These effects were all consistent with refraction of the incident laser pulse from ionisation induced density gradients.

### 4.3.1 The spatial resolution of the deflectograms.

An important feature of these images was the lack of fringe contrast that was observed in the upper portion of the plasma of figure 4.4(b). This was due to the diffractive effects of the gratings described by equation (95) in chapter 3 that limited the spatial resolution. The diffractive smearing effect that limited the spatial resolution in the radial direction, was determined by the grating separation,  $\Delta$ , the grating pitch,  $p$ , and the probe wavelength,

$$\delta x = \frac{q\Delta}{k} = \frac{\Delta\lambda}{p} \quad (95)$$

In these deflectograms,  $\lambda = 0.248\mu\text{m}$ ,  $p = 50\mu\text{m}$  and  $\Delta = 40\text{cm}$ , giving a spatial resolution of  $\delta x = 30\mu\text{m}$ . The diagnostic may have overestimated the initial plasma radius when there was little or no defocusing because the minimum laser beam waist of  $30\mu\text{m} \pm 5\mu\text{m}$  that was achieved in vacuum was on the edge of the resolution. This was investigated by repeating the measurement with the grating separation reduced from 40 to 10cm, thus increasing the resolution from 30 to 8 $\mu\text{m}$ . The radial profile of the plasma and the peak electron density were found to agree with the results obtained with 30 $\mu\text{m}$  resolution within the experimental uncertainty of  $\pm 20\%$ .

### 4.3.2 Plasma radius as a function of atomic density.

In order to quantify the refractive effects the initial plasma radius was measured using the deflectometer for a series of shots as the gas density was increased. The density profiles were obtained from the deflectograms by Abel inversion of the fringes at the point of peak density. Figure 4.5 shows the density profiles as the gas density increased from  $3.5 \times 10^{19}$  to  $1.5 \times 10^{20} \text{ cm}^{-3}$ .

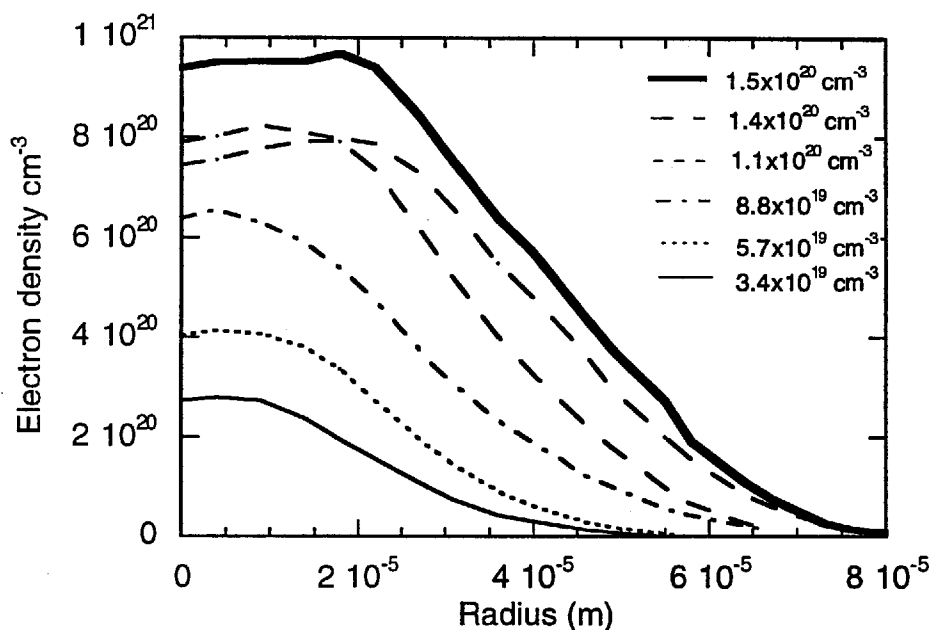


Figure 4.5 Density profiles for increasing gas density at constant laser intensity obtained from Abel inversion of the deflectograms.

It can be seen from this figure that as the gas density increased so did the radius of the plasma. The radius (at half the peak density) of the plasma increased from  $25\mu\text{m}$  to  $44\mu\text{m}$  as the gas density rose from  $3.4 \times 10^{19} \text{ cm}^{-3}$  to  $1.5 \times 10^{20} \text{ cm}^{-3}$ . This data was used to infer the increase in the laser focal spot with increasing density. In order to achieve this it was assumed that the laser profile was initially Gaussian and remained Gaussian as the laser expanded due to refraction (the validity of this assumption will be discussed at the end of section 4.3.3). The radial dependence of the ionisation balance was then used in conjunction with the Coulomb barrier model to infer the reduction in laser intensity as the gas density was increased.

#### 4.3.3 Inferred increase in laser spot size.

Information about the ionisation balance was obtained by comparing the density profiles with the neutral gas density obtained in section 3.1. A graph of the radial ionisation balance for increasing Neon density is shown in figure 4.6 .

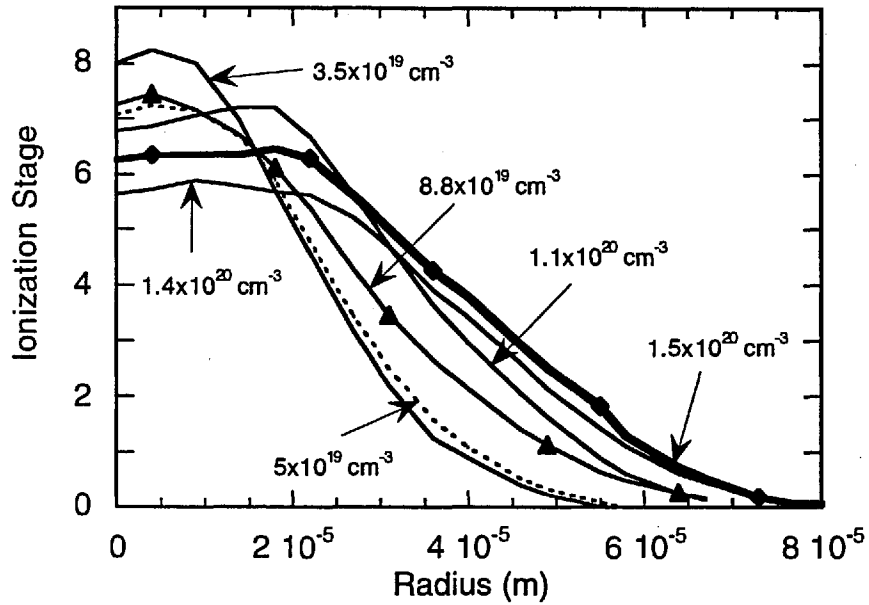


Figure 4.6 The radial ionisation distribution for increasing gas density obtained from the density profiles and the neutral gas density profiles (from the gas jet characterisation).

As the gas density was increased from  $3.4 \times 10^{19} \text{ cm}^{-3}$  to  $1.5 \times 10^{20} \text{ cm}^{-3}$  the peak ionisation stage was not significantly reduced, however the radius at which the plasma became singly ionised increased from  $39 \mu\text{m}$  to  $61 \mu\text{m}$ . To obtain a measure of the increase in the laser focal spot it was assumed that the spatial profile of the laser was described by a Gaussian profile, this was obtained from the density profile by equating the radial ionisation profile to the threshold intensity from the Coulomb Barrier Model [16]. The resulting relation between plasma width and gas density is shown in figure 4.7.

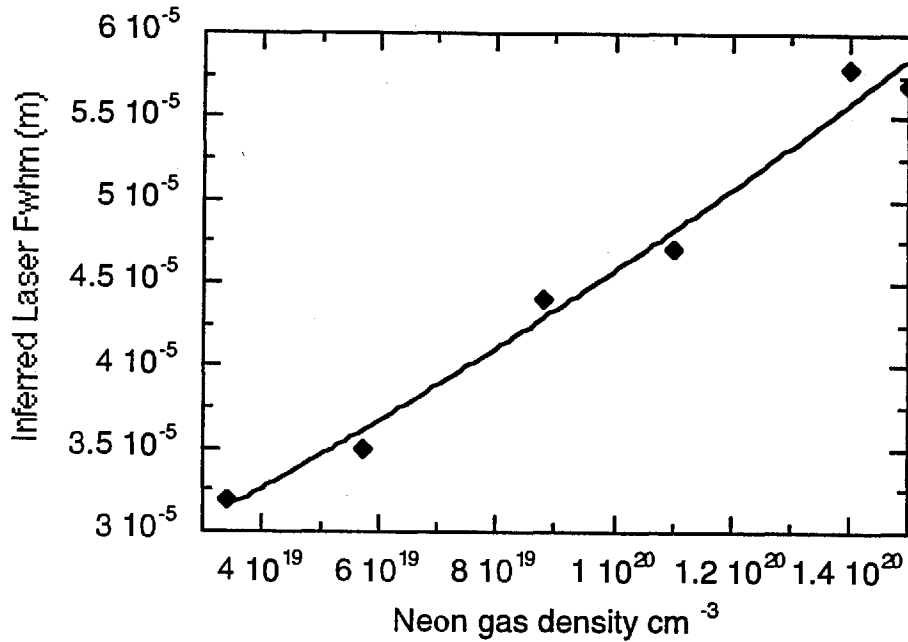


Figure 4.7 Inferred laser spot width from the Gaussian fit to the ionisation stage profiles in figure 4.6 using the Coulomb barrier model [16] to estimate the appearance intensities of the various ionisation stages.

The spot size can be seen to increase by approximately a factor of two as the gas density increased from  $3.4 \times 10^{19}$  to  $1.5 \times 10^{20} \text{ cm}^{-3}$ . This corresponded to a reduction in focused intensity from  $6 \times 10^{16} \text{ Wcm}^{-2}$  to  $1.5 \times 10^{16} \text{ Wcm}^{-2}$ . This fitting procedure showed that the laser spot was increasing but it only gave an upper estimate on the laser intensity because the diagnostic was not sensitive to the refracted laser light that did not cause ionisation of the plasma. The assumption that the refracted light remained Gaussian was also probably not accurate, this was investigated by imaging the refracted laser light.

The peak level of ionisation of  $8^+$  for  $n_a = 3.5 \times 10^{19} \text{ cm}^{-3}$  in figure 4.6 implied a peak intensity greater than  $2 \times 10^{17} \text{ Wcm}^{-2}$ . This intensity level was inconsistent with the value inferred from the plasma radii and also the measured laser spot width in vacuum of  $30 \mu\text{m}$ , which implied an absolute maximum intensity of  $8 \times 10^{16} \text{ Wcm}^{-2}$ . It was thought that this inconsistency was the result of collisional ionisation occurring after the laser pulse.

#### 4.3.4 Ionisation mechanisms.

There were two possible reasons for the discrepancy between the measured ionisation stage and laser intensity, either additional ionisation was occurring after the laser pulse through collisions or there were hot spots on the laser spot with intensities greater than  $2 \times 10^{17} \text{ Wcm}^{-2}$ . Intensity spikes on the laser profile did exist and can be seen in figure 3.10. The contribution from the hot spots to the ionisation balance is hard to quantify. From figure 4.4 the small scale structures split as the laser propagated through the gas. This is the refractive splitting that was described in section 2.1.2. The strong refractive effects indicated that the laser intensity was reducing rather than increasing and it seems likely the intensity in the hot spots was reduced, rather than increased, as the laser propagated through the gas.

The contribution from the collisional ionisation to the electron density was investigated by inspection of the collisional rates. Using the hydrogenic collisional ionisation rate of Seaton [60] for  $n_a = 1.5 \times 10^{20} \text{ cm}^{-3}$  and assuming a constant electron temperature of 80 eV gave ionisation times of 30 ps and 50 ps for Li-like (7+) and He-like Neon (8+) respectively. The rate of Kunze [5] gave times of 15 ps and 50 ps to reach the same stages. The ionisation times for both rates can be seen in figure 4.8.

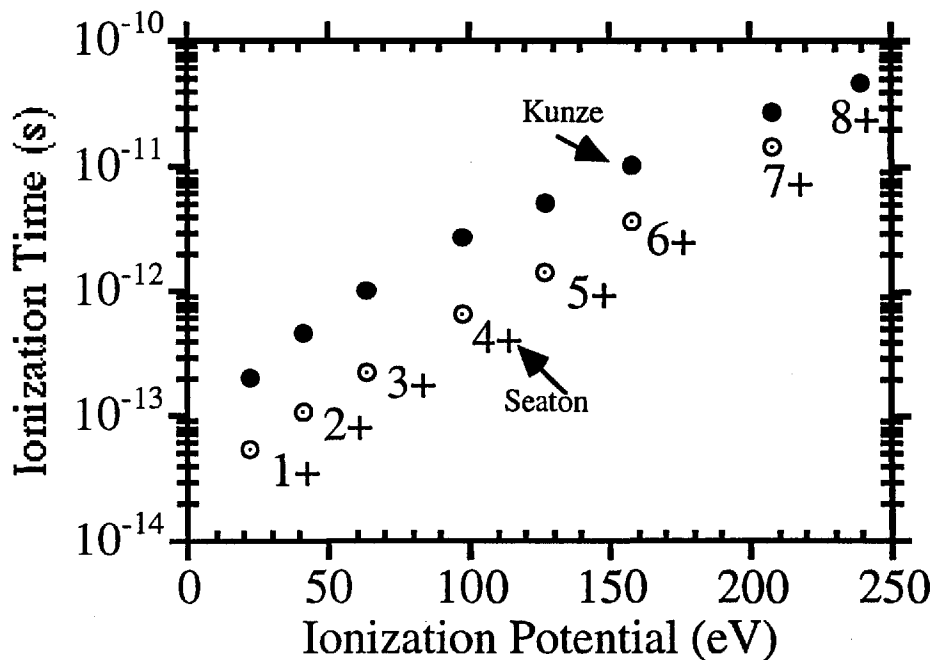


Figure 4.8 Ionisation times for Neon at an ion density of  $1.5 \times 10^{20} \text{ cm}^{-3}$  and an electron temperature of 80 eV from the simple ionisation rates of Seaton [60] and Kunze [5].

These rates showed that collisional effects were important after the pulse, but they were too slow to achieve He-like Neon within the total integration time of the probe (16ps). In order to model these effects more accurately the average atom model that included collisional excitation as well as ionisation and recombination was used

#### 4.3.5 The average atom model

The model, described in some detail in section 2.2.8, was used to post process the density and temperature information output of MEDUSA. The number of bound levels was set to 5 and the model was run for the first 50ps of the plasma expansion. The ionisation time for a gas density of  $1.5 \times 10^{20} \text{ cm}^{-3}$  and an electron temperature of 80eV is shown in figure 4.9. It can be seen that the ionisation grew rapidly in the first 10ps and then stabilised for times up to 50ps. After 50ps the electron density reduced as the plasma cooled due to the expansion and thermal conduction and recombination began to occur. During the first 10ps the plasma was in a transient state, this was consistent with the observed smearing of the fringes at probe times less than  $t_0 + 6\text{ps}$ .

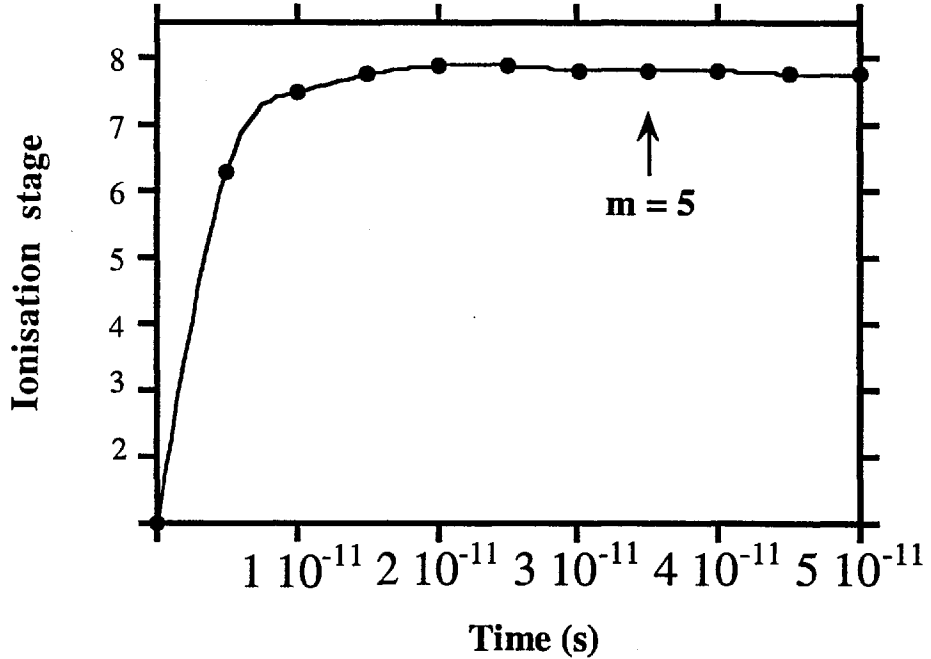


Figure 4.9 Collisional ionisation times in Neon at an ion density of  $1.5 \times 10^{20} \text{ cm}^{-3}$  and an electron temperature of 80eV predicted by the average atom model for  $m=5$  levels.

The collisional rate depended strongly on the Boltzmann factor  $\exp(-U_q / kT_e)$  and occurred predominately in the hot regions near the centre of the spot. It was unlikely that collisional ionisation occurred at the edge of the spot, around the threshold intensity for Neon, because the temperature was very low (a few eV) and the collisional rates negligible. The temperatures used to calculate the collisional ionisation rates were inferred from hydrocode simulations of the expansion. The method for undertaking these measurements was identical to that described in section 2.4 and for the expansion of the channel in Helium in this chapter.

#### 4.3.6 The Expansion characteristics for Neon.

To confirm whether ionisation defocusing was occurring in Neon the temperature was inferred by measuring the expansion characteristics of the density channel and comparing it to 1D hydrocode simulations using the method described in section 2.4. This temperature was then compared with the results of the two absorption models described in section 2.3.

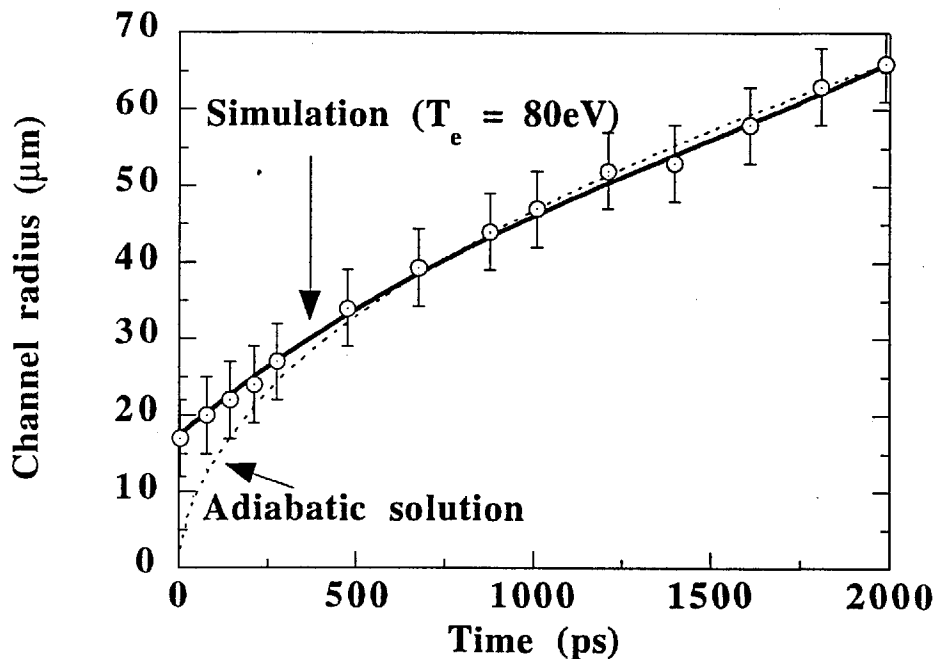


Figure 4.10 Channel expansion for a Neon gas density  $5 \times 10^{19} \text{ cm}^{-3}$ . The open circles are the experimental measurements of the radial expansion of the shock front, obtained from the deflectograms. The dashed line is the fit from the analytic blast wave model

(labelled as the Adiabatic solution because  $R \propto t^{1/2}$ ) from equation (80). The full MEDUSA simulation is shown as the full line fit, which gave an initial electron temperature of 80 eV.

The adiabatic expansion (blast wave) solution described by equation (80) in section 2.4, gave a good fit to the data at times greater than 800ps. This again confirmed that the blast wave propagation description was a good one for the asymptotic limit of the expansion, the dis-agreement at earlier times again confirmed that the model did not apply early in the expansion. It can be seen from figure 4.10 that, as in the Helium data, the MEDUSA simulation gave a very good fit throughout the temporal evolution of the channel. A temperature of  $80\text{eV} \pm 20\text{eV}$  gave a good fit throughout the expansion. The electron temperature measured from the channel expansion for a higher gas density of  $1.5 \times 10^{20} \text{ cm}^{-3}$  was found to be  $85\text{eV} \pm 40\text{eV}$ . The error was larger for the higher density case because there was a greater uncertainty due to the low number of points in the expansion time series.

If there was no refractive defocusing, then from the models described in section 2.3.2, the electron temperature would be expected to increase approximately linearly with increasing gas density. This was not the case, as the temperature inferred from the simulations was clamped around  $80 \text{ to } 85\text{eV} \pm 40 \text{ eV}$  as the gas density increased by a factor of three at constant laser power. The theoretical predictions from the models of Pert [31] and Polischuck et al [32], together with the experimental temperatures are plotted in figure 4.11.

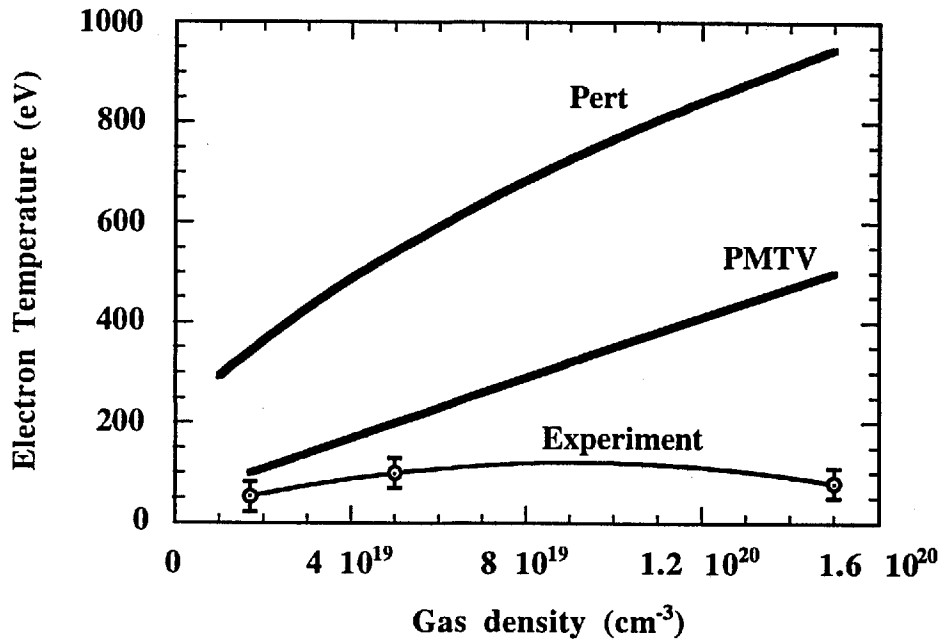


Figure 4.11 Experimentally inferred temperatures, obtained from measurements of the expansion characteristics of the channel (open circles) compared to the model predictions of the electron temperature. Both theoretical models are significantly higher than the data supporting the supposition that refraction has limited the laser intensity and thus lowered total absorbed energy. On the solid lines "PMTV" refers to the approximate treatment of Polischuck's model [31] and "Pert" to the code results from Pert's model [32]. The difference between the two models is due to the crude application of equation (63) without a realistic treatment of the laser pulse.

In the models the intensity was set to  $6 \times 10^{16} \text{ Wcm}^{-2}$ . It can be seen that the experimental temperatures were significantly lower than the model predictions. If the intensity were equal to its vacuum value, the models predicted that the electron temperatures would be in the range of 218-400eV and 633-900eV respectively. It was clear from this clamping of the electron temperature with increasing gas density that the electron temperatures inferred from the experiment were severely limited by refractive defocusing. In order to quantify the reduction in intensity, these temperatures were compared directly with the absorption models. At these densities and vacuum laser intensities the ATI contribution was very small and the absorption was dominated by inverse Bremsstrahlung. The input intensity to the absorption models was varied in order to match the measured temperature. The two models gave the intensity within a

factor of two for each density. That is, for  $n_a = 5 \times 10^{19} \text{ cm}^{-3}$  and  $T_e = 80 \text{ eV}$ ,  $I = 1.4 \times 10^{16} \pm 4.5 \times 10^{15} \text{ Wcm}^{-2}$ . While for  $n_a = 1.5 \times 10^{20} \text{ cm}^{-3}$  and  $T_e = 85 \text{ eV}$ ,  $I = 5 \times 10^{15} \pm 2 \times 10^{15} \text{ Wcm}^{-2}$ . The contribution of Raman heating to the total electron temperature will be discussed in the next section.

#### 4.3.7 Raman heating.

No account was taken of Raman heating in the modelling of the electron temperatures achieved in Neon. In order to investigate the effect the inferred intensity obtained above was used in equation (66) from section 2.3 to calculate the transient growth rate,  $\gamma$ , of the instability. If the plasma was assumed to be singly ionised then for the densities measured  $n_a = 5 \times 10^{19}$  and  $1.5 \times 10^{20} \text{ cm}^{-3}$  and  $I = 1.4 \times 10^{16}, 5 \times 10^{15} \text{ Wcm}^{-2}$   $\gamma\tau_p = 3$  and  $6$ . These values were significantly less than the threshold value of  $\gamma\tau_p > 12-14$  that was required in the 1D simulations [10] to affect the thermal electron temperature. Consequently there will be little or no contribution from Raman heating to the thermal electron temperature if the intensities were reduced to the values inferred from the measured electron temperatures.

#### 4.3.8 Imaging of the refracted laser light.

The previous sections have shown that the laser intensity that was consistent with the measured electron temperature was much lower than the intensity that was inferred from Gaussian fit to the initial radius of the plasma. This can be understood if the refracted laser light did not follow a Gaussian spatial profile, but instead consisted of a profile with a large amount of energy in low intensity wings that did not cause ionisation of the gas.

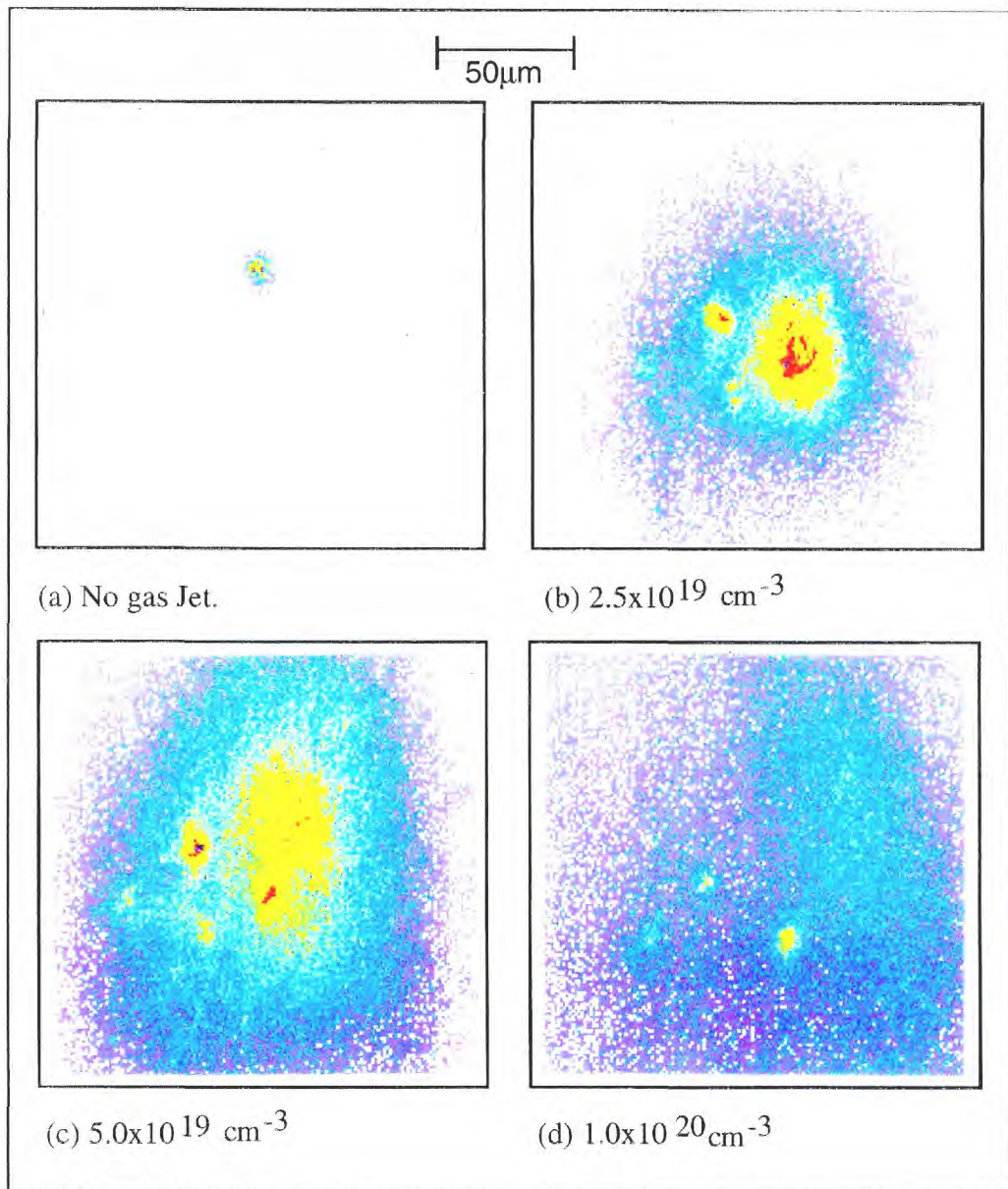


Figure 4.12 Images of the light distribution at the focal plane for increasing gas density, measured using an F/2.5 lens to image the focal region onto a CCD camera.

In order to investigate this further, an imaging lens was used to measure the light distribution in the focal plane of the laser as a function of gas density. A quartz lens, operating at F/2.5 was used to image focal region, near the centre of the gas jet, onto a CCD camera. The camera was filtered with an absorbing filter that transmitted  $0.248\mu\text{m}$  light but cut out the plasma emission. This measurement was made during a separate experiment that was carried out under identical density conditions with an identical gas jet but with slightly higher vacuum intensities. The increase in the diameter of the images obtained with increasing gas density shown in figure 4.12 were consistent with refraction. Cross sections through the peak intensity of each spot are shown in figure 4.13, this gave a quantitative measurement of the increase in laser spot size as a function of gas density. It can be seen from figure 4.13 that as the density increased the profile of the refracted laser light did contain considerable energy within the wings of the spot.

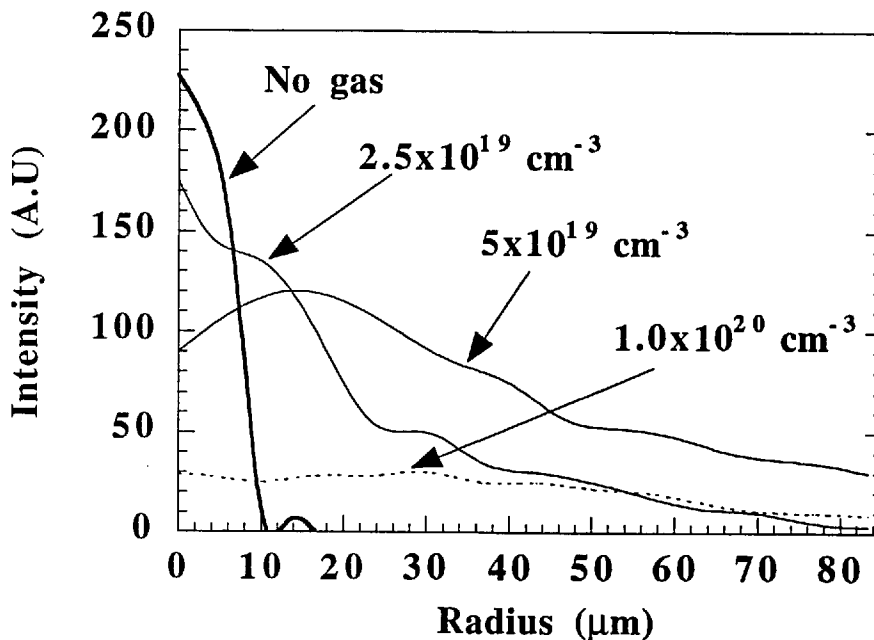


Figure 4.13 Radial cross sections through the centres of the images shown in figure 4.12. As the gas density increased the laser spot size increased due to refraction from ionisation induced density gradients.

The filtering was changed between the vacuum case of figure 4.12(a) and the other high density shots. This meant that the peak intensity could not be compared directly, however, it was clear from the respective areas under the profiles that refraction had

increased the width of the spot. The laser spot grew from a width ( at half the peak intensity points) of  $w_0 = 17\mu\text{m}$  in vacuum,  $w_0 = 78\mu\text{m}$  at  $n_a = 5 \times 10^{19} \text{cm}^{-3}$  and  $w_0 > 100\mu\text{m}$  for  $n_a = 1.0 \times 10^{20} \text{cm}^{-3}$ . This corresponded to a reduction in laser intensity ,for a typical beam power of 500GW, from  $I = 1.5 \times 10^{17}$  in vacuum, to  $I = 7 \times 10^{15} \text{Wcm}^{-2}$  at  $n_a = 5 \times 10^{19} \text{cm}^{-3}$  and  $I = 3 \times 10^{15} \text{Wcm}^{-2}$  at  $n_a = 1 \times 10^{20} \text{atoms cm}^{-3}$ . These results agreed well with the intensities obtained from the temperature measurements,  $I = 8 \times 10^{15} \text{Wcm}^{-2}$  at  $5 \times 10^{19} \text{atoms cm}^{-3}$  and  $I = 3 \times 10^{15} \text{Wcm}^{-2}$  at  $1.5 \times 10^{20} \text{atoms cm}^{-3}$ . A summary of these experimental results can be found in figure 4.18. These results were also compared to predictions from the two theoretical models that were described in section 2.1.

#### 4.3.9 The analytical defocusing model.

The analytical model described in section 2.1.5 was used to determine the maximum focused intensity that could be expected when the KrF pulse was focused into neon gas.

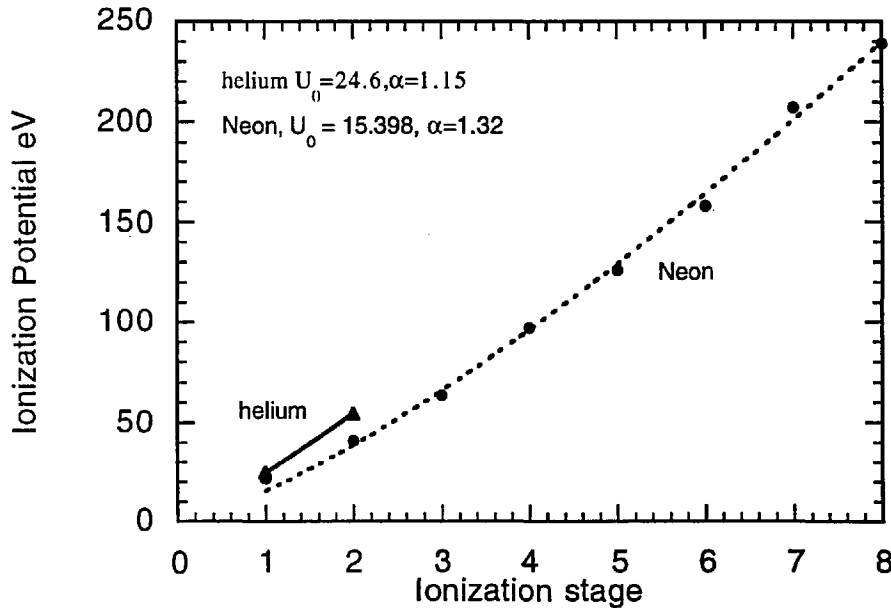


Figure 4.14 Power law fit to the Ionisation potential for Helium and Neon. This gave the parameters  $\alpha$  and  $U_0$  that were required by the analytic model [38].

The model [38] required that a power law fit was made to the ionisation potentials of the ion, this can be seen for Helium and Neon in figure 4.14. This enabled the parameters  $\alpha$  and  $U_0$  to be determined. The charge distribution across the beam is related to these parameters through equation (31)

$$q_0 = (4 \times 10^9 U_0^4)^{1/(2-4\alpha)} \quad (31)$$

This expression allowed the refractive index to be related to the laser intensity, which was assumed to be Gaussian. The maximum beam intensity,  $I_m$ , in a strongly refracting plasma was found to be independent of beam power and was given by equation (34),

$$I_m = \left[ \left( \frac{C^2}{q_0} \right) \left( \frac{n_c}{n_a} \right) \right]^{4\alpha-2} \quad (34)$$

Where  $C$  was the divergence half angle of the beam, defined as ( $C = 1/2F\#$ ) and  $n_c$ ,  $n_a$  were the critical and gas density respectively. Once the parameters  $\alpha$  and  $U_0$  were found the next stage was to determine the divergence angle of the focusing optic. For this experiment  $F\#$  was measured directly by imaging the beam profile at points before and after focus. Figure 4.15 shows images of the beam profiles for 450 $\mu$ m and 225 $\mu$ m before focus and 182 $\mu$ m and 390 $\mu$ m after focus. The average  $F$  number was measured from this figure to be  $F/4.7$ , giving  $C = 0.11$ . Inserting  $C$ ,  $\alpha$  and  $U_0$  into equation (34) allowed  $I_m$  to be evaluated. For Neon at  $n_a = 5.7 \times 10^{19} \text{ cm}^{-3}$ ,  $I_m = 1.7 \times 10^{16} \text{ Wcm}^{-2}$ . When the gas density was increased to  $n_a = 1.2 \times 10^{20} \text{ Wcm}^{-2}$ , then,  $I_m = 1.5 \times 10^{15} \text{ Wcm}^{-2}$ . These values agreed well, within the factor of two estimated experimental error, to the intensities inferred from the temperature measurements. This showed conclusively that ionisation defocusing was limiting the focused laser intensity to values much lower than the value obtained in vacuum. However in order to investigate the refraction in more detail a numerical model was used to simulate the ionisation defocusing.

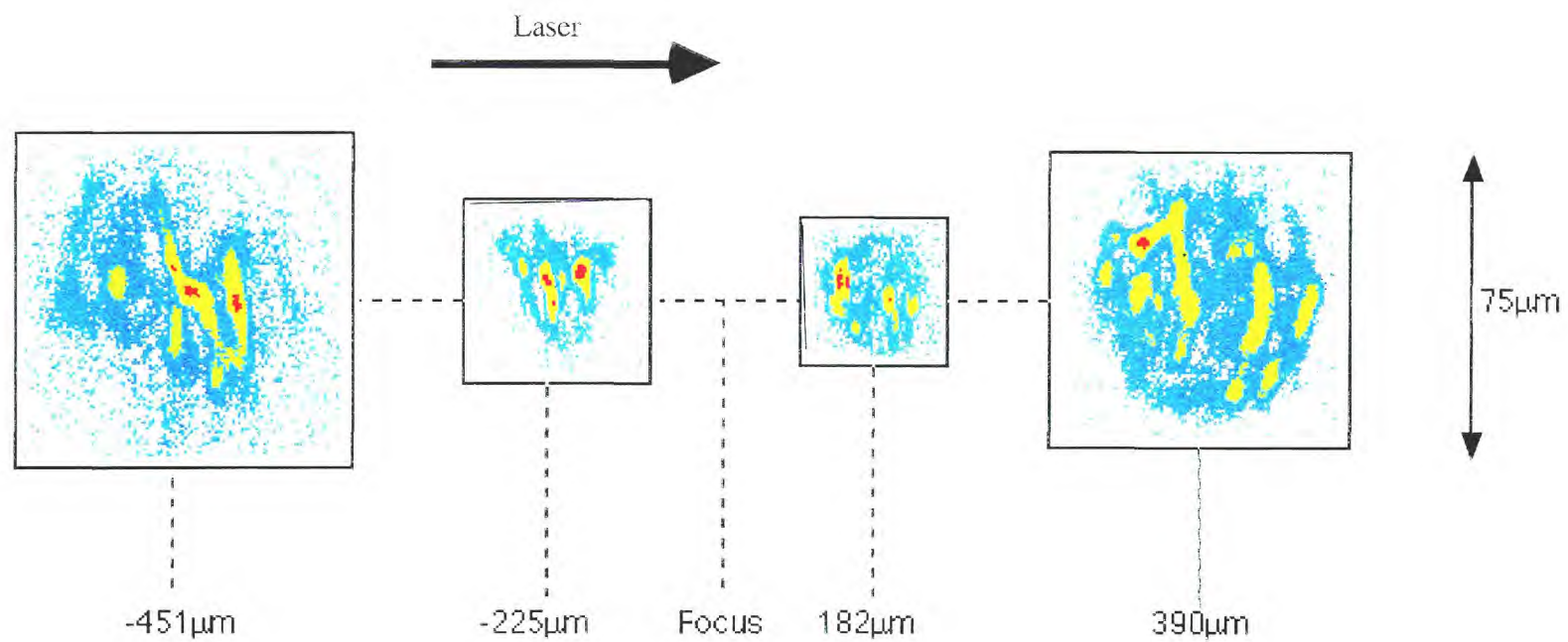


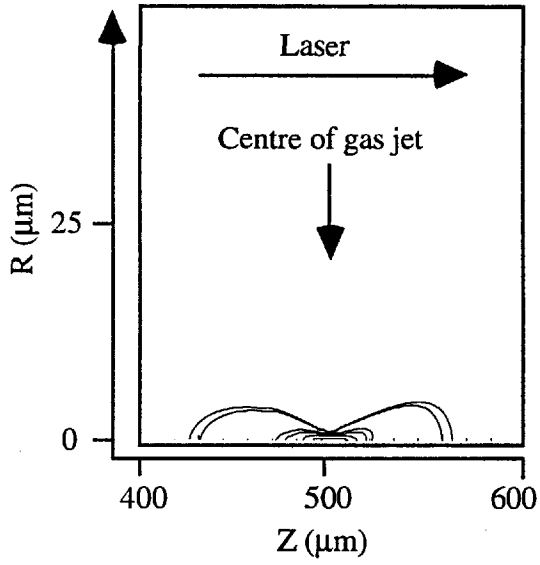
Figure 4.15 Images of the laser spot at points through focus.

### 4.3.10 The numerical model.

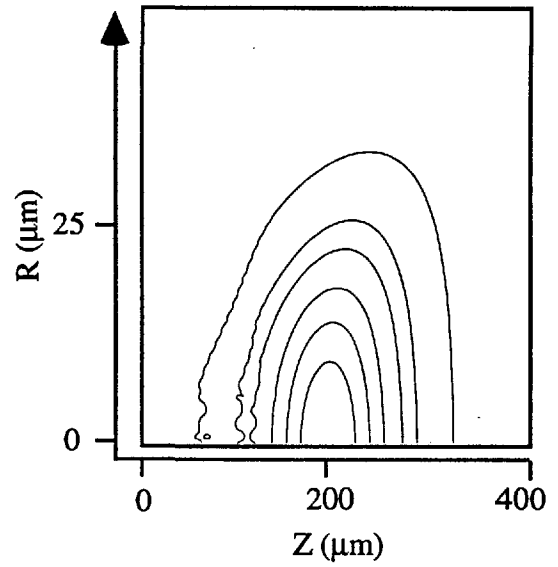
In order to accurately model the refraction it was necessary to solve the wave equation numerically while self consistently calculating contribution of optical ionisation to the plasma refractive index. The 2D wave propagation code described in chapter 2 [37] was used to solve the wave equation in cylindrical geometry using the paraxial approximation, while calculating the ionisation through the tunnel ionisation rates of Ammosov et al [55]. The model was limited to non relativistic intensities and the ionisation was calculated for the first three ionisation stages only. The model has previously been used to study defocusing and refraction in hydrogen gas at intensities up to  $5 \times 10^{15} \text{ Wcm}^{-2}$  and at atomic densities from  $3 \times 10^{16}$  to  $2.7 \times 10^{19} \text{ cm}^{-3}$  [37]. It was found to model accurately the important features of defocusing, such as the plasma moving towards the laser from the vacuum focusing position and the reduction in focused intensity as the gas density increased.

The code was run for both Neon and Helium with a pulse length of 350fs, with  $F / 5$  optics,  $\lambda = 0.248 \mu\text{m}$  and a vacuum intensity of  $8 \times 10^{16} \text{ Wcm}^{-2}$ . The calculation started with the pulse below the ionisation threshold of the gas. The initial spatial profile of the laser was defined by a diffraction limited Gaussian with a minimum waist of  $w_0 = 2\lambda F/(\pi D)$  in the radial direction. The code transports the laser pulse through the gas with a user defined time step, keeping a track of the peak ionisation stage and laser intensity reached throughout the gas. The output of the model was in the form of 2D electron density and laser intensity contours. The density contours represented the final density of the plasma along the gas jet and the intensity contours the light distribution across the 2D grid at the last time step at the end of the gas jet. Figure 4.16 and 4.17 showed the model predictions of how the plasma density contours changed as the Neon gas density increased from vacuum to  $5.6 \times 10^{19} \text{ cm}^{-3}$ . The contours for both the intensity and electron density were symmetric about the  $z$  axis and thus only half the plasma is shown. The contour levels decreased from the maximum density in 20% intervals.

In vacuum the plasma density contours are symmetric about the position of best focus. As the density was increased to  $n_a = 5.6 \times 10^{19} \text{ cm}^{-3}$  there was a slight increase in the radius of the plasma but it still appeared to be symmetric about the vacuum focusing position. However, the peak intensity was considerably reduced to  $1.1 \times 10^{16} \text{ Wcm}^{-2}$  from the vacuum value of  $8 \times 10^{16} \text{ Wcm}^{-2}$ . This confirmed the experimental evidence that suggested that the increase in plasma size was not a reliable guide to the degree of defocusing that was occurring.

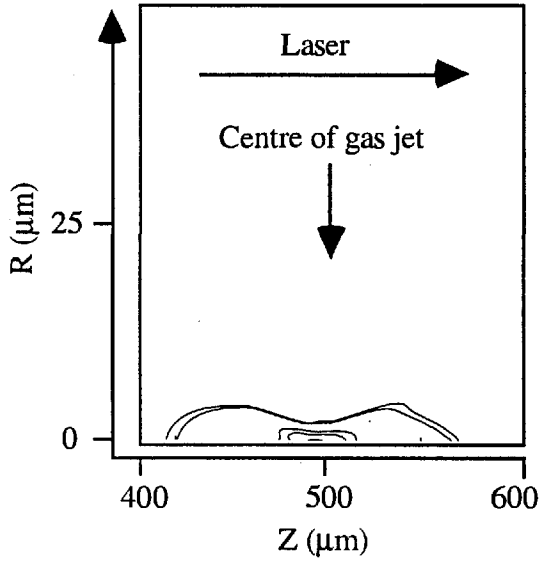


(a) Density contours

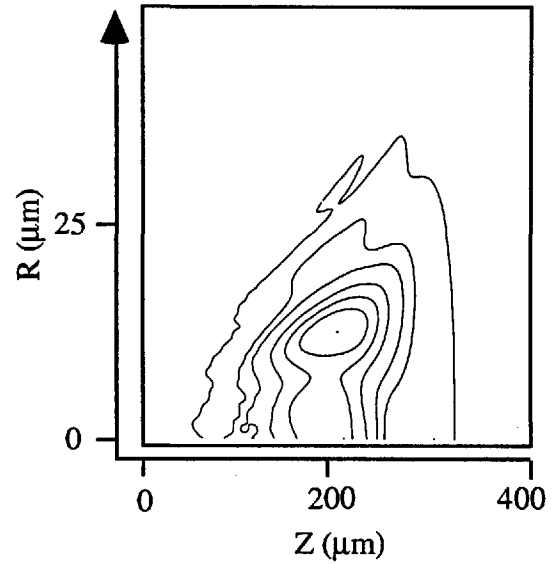


(b) Intensity contours

Figure 4.16 Model predictions for a 350fs, 0.248μm pulse at  $I = 8 \times 10^{16} \text{ Wcm}^{-2}$   $n_a = 1 \times 10^{16} \text{ cm}^{-3}$  (this is effectively vacuum for a laser pulse of this wavelength).



(a) Density contours



(b) Intensity contours

Figure 4.17 Simulation results for  $I = 8 \times 10^{16} \text{ Wcm}^{-2}$  and  $n_a = 5.6 \times 10^{19} \text{ cm}^{-3}$  (All the intensity and density cotnour levels in figures 4.16 and 4.17 decreases from the maximum in 20% intervals).

The laser intensity contours showed that the intensity maximum moved off axis as the gas density increased from Figure 4.16(b)  $n_a = 1 \times 10^{16} \text{ cm}^{-3}$  (effectively vacuum for a laser pulse with this wavelength) to 4.17(b)  $5.6 \times 10^{19} \text{ cm}^{-3}$ . This confirmed that the density gradients were refracting the laser light away from the axis and reducing the peak intensity. At higher gas densities the plasma did increase appreciably in radius and became asymmetric around the vacuum focusing position. For example when the gas density was increased to  $1.75 \times 10^{20} \text{ cm}^{-3}$  the code predicted that the peak intensity in the interaction was reduced to  $3.3 \times 10^{15} \text{ Wcm}^{-2}$  and there was no plasma formed after the vacuum focusing position. The density and contour plots for this case can be seen in figures 2.6(a) and (b) of section 2.1.

These predictions agreed well, within 25%, to the inferred intensities from the temperature and refracted light measurements, but were a factor of 1.5 less than the analytical model for densities below  $5 \times 10^{19} \text{ cm}^{-3}$ . The source of this discrepancy may be traced to a numerical instability that was discussed in the section 2.1.6. In practical terms this limited the accuracy of the peak intensities predicted by the simulations to a factor of 1.5 - 2. The agreement with data and the analytical model is within this factor for the data simulated.

The simulation was also limited to an initially diffraction limited laser pulse whereas in the experiment the pulse was 10x the diffraction limit. This factor may cause the code to overestimate the amount of refraction, as the experimental profile ionised later in the pulse, or at larger radii, as a result of its lower intensity. This could lead to smaller gradients and less refraction. The limitation of the code to only the first three ionisation stages acted in the opposite sense for interactions with intensities greater than  $1 \times 10^{16} \text{ Wcm}^{-2}$  where ionisation continued above the third stage for Neon. For the conditions of the experiment the model predicted a maximum laser intensity of  $1.2 \times 10^{16} \text{ Wcm}^{-2}$  and an ionisation stage of  $Z^* = 2.76^+$ , for  $6 \times 10^{19} \text{ cm}^{-3}$  Neon and  $3 \times 10^{15} \text{ Wcm}^{-2}$ ,  $Z^* = 1.2^+$ , for  $1.8 \times 10^{20} \text{ cm}^{-3}$  and this problem did not apply.

A summary of the experimental measurements and the theoretical predictions can be seen in Figure 4.18.

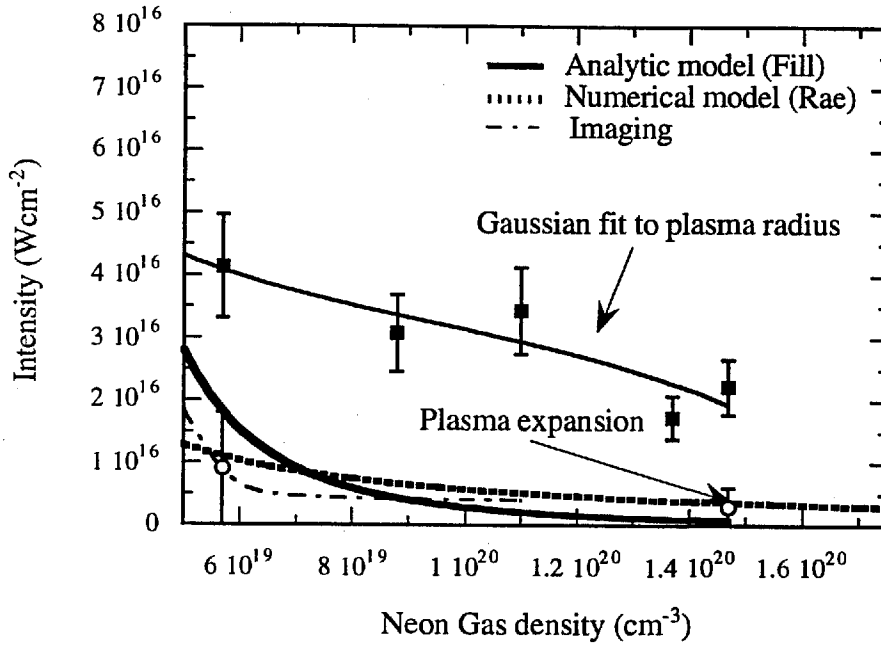


Figure 4.18 Experimental measurements and theoretical predictions of the maximum focused intensity as a function of gas density in Neon. The Gaussian fit to the plasma size (filled squares) can be seen to underestimate the severity of the defocusing as measured by the refracted light images (open circles), the value inferred from the measured plasma temperature and the theoretical models.

The data in figure 4.18 showed that the increase in plasma radius measured by the deflectometer was caused by plasma defocusing but this could not be related quantitatively with the reduction in focused intensity. This was thought to be because the density profile did not accurately match the Gaussian fit. This interpretation was confirmed with the images of refracted laser light and with the results of the numerical modelling. The focused intensity inferred from the measurements of the electron temperature agreed with the laser intensity inferred from the measured spatial distribution of refracted light and the theoretical and numerical models. The inferred intensities agreed within a factor of two with the predictions of the theoretical models. This was within both the estimated experimental error and limiting error that resulted from the numerical instability in the simulations.

#### 4.4 Plasma non uniformity and refractive splitting of the laser hot spots.

The ionisation channels observed in fig 4.4 (b) were thought to be formed either from a filamentation mechanism or through refraction from small scale ionisation gradients arising from laser non uniformities. A simplified picture of the refraction from ionisation hot spots was described in section 2.1 using a ray tracing model, figure 4.19 shows how the beam refracts from the hot spots.

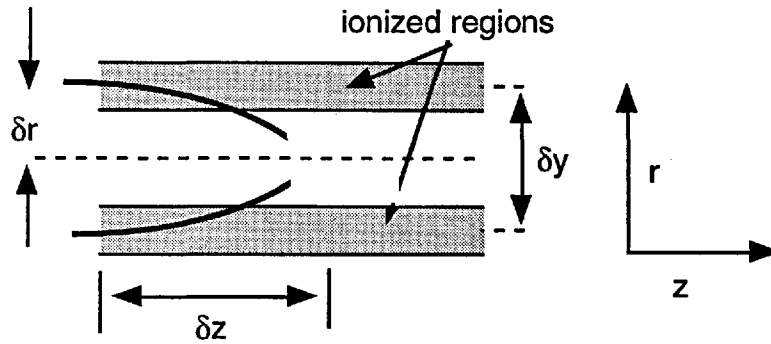


Figure 4.19 Refraction from laser hot spot ( from reference [47]).

In this figure the hot spots are depicted by the shaded regions,  $\delta y$  is the distance between hot spots on the beam,  $\delta r$  the density scale length, and  $\delta z$  the characteristic refraction distance;

$$\delta r = (1/2n_c)(\partial n_e / \partial y) z^2 \quad (21)$$

The distance required for the hot spots to spread due to refraction is then

$$\delta z = (2n_c/n_e)^{1/2} \cdot \delta y \quad (22)$$

For the plasma conditions existing in the 0.248 $\mu$ m experiments,  $n_e = 4.5 \times 10^{20}$ ,  $n_c = 1.78 \times 10^{22} \text{ cm}^{-3}$ , and a hot spot separation of 5 $\mu$ m gave  $\delta z = 50 - 100 \mu\text{m}$ . This distance agreed very well with the lengths the channels were observed to propagate before splitting in figure 4.4(b), at a gas density of  $1.5 \times 10^{20} \text{ cm}^{-3}$ . This estimate of the characteristic refraction distance has also been shown to agree well with the results from a three dimensional laser propagation model that solved the wave equation and the ionisation defocusing self consistently [47]. This code showed that an incident hot spot

of half width  $\partial y$  split after propagating a distance approximately equal to  $\partial z$  in (22). If the two hot spots were themselves still above the ionisation threshold then they too will split after propagating through their own density gradient. In this way the hot spots will produce ionisation channels that increase in number as they propagate. This important feature of this plasma break up was observed experimentally. In figure 4.4(b) the number of filaments and their angle of refraction increased as the laser propagated through the gas jet. The existence of hot spots on the laser beam was also shown from the equivalent plane image of the laser focal spot in figure 3.10 and the images of the planes through focus shown in figure 4.15. These images showed very clearly that the beam was non uniform with most of the energy contained in a few hot spots with peak intensities 2-5x the mean.

#### 4.4.1 Self focusing thresholds.

An alternative interpretation of the origin of the ionisation channels was that they were produced by self focusing of the beam hot spots. This possibility was investigated by examining the power and intensity thresholds of relativistic and space charge limited ponderomotive the self focusing[33,34]. The threshold for space charge limited and relativistic self focusing was first derived by Max, and has since been confirmed by many theoretical studies [33, 34]. The threshold laser power required for relativistic guiding of a diffraction limited beam is given numerically by

$$P_{cr} = 17x \left( \frac{\omega_0^2}{\omega_p^2} \right) GW \quad (26)$$

For a laser with  $\lambda = 0.248\mu m$  and a plasma with an electron density of  $2x10^{20}$ , equation (26) gave  $P_{cr} = 1.5TW$ . This was actually a very optimistic threshold because it applied to a diffraction limited Gaussian beam. However, in this experiment the spot size was at least 10x the diffraction limit. The maximum laser power attained in the experiment with the 350fs KrF pulses was 800GW, a factor of 2 below  $P_{cr}$ . The ponderomotive and thermal self focusing theories that assumed ion motion are not relevant for these conditions because the ions cannot move over the time scale of the laser pulse. The origin of the small scale ionisation channels was investigated further at power levels around 100GW with 12ps Raman shifted KrF pulses [103] interacting with the high density gas jet.

#### 4.4.2 Refraction of 12ps, 0.268 $\mu$ m, laser pulses.

The refraction experiments were extended to higher densities and longer laser pulses using a 12ps laser and densities up to  $3 \times 10^{20} \text{ cm}^{-3}$ . In this case the laser beam quality was good with generally only one hot spot with a width of  $10 \mu\text{m}$ , equivalent to 2-3x diffraction limit. The observations confirmed that refraction also dominated the interaction at this pulse length and in this gas density regime. The diagnostic and experimental parameters were similar to the 350fs experiment except that the deflectometer was replaced with a shadowgram system. This gave qualitative information on the location of the strongest density gradients.

The onset of the small scale ionisation channels was studied as a function of gas density, laser power and delay time between the probe and the ionising pulse. Figure 4.20 shows a sequence of shadowgrams taken 16ps after the end of the ionising pulse for increasing gas density with constant laser power. It should be noted that in all the rest of the shadowgrams and deflectograms in this thesis the laser is always incident from the right. Another feature that is common to all these shadowgrams is the black bar near the centre of the picture that runs vertically from the top to the bottom of the image. This is an imperfection in the imaging system, where two filters have been joined together in front of the film pack. It served a useful purpose as a spatial fiducial, allowing the position of the vacuum focus to be referenced on each picture. In this figure the position of the focus was  $300 \mu\text{m}$  after the filter join, as marked on 4.20 (a).

It can be seen from figure 4.20 (a) to (d) that the contrast of the shadowgrams improved as the gas density was increased. At the lowest gas density of  $2.5 \times 10^{19} \text{ cm}^{-3}$  in (a) and in (b)  $5 \times 10^{19} \text{ cm}^{-3}$  the plasma was approximately symmetric around the vacuum focusing point. As the gas density increased to (c)  $1.5 \times 10^{20} \text{ cm}^{-3}$  the radius of the plasma increased, small scale ionisation channels emerged, and the minimum plasma radius moved back towards the laser. As the density increased further to (d)  $2.5 \times 10^{20} \text{ cm}^{-3}$  the angle between the small scale structures and the laser propagation axis increased, together with the overall plasma radius. At this point the plasma was very asymmetric about the vacuum focusing position, as the peak density region moved further back towards the laser. The ionisation channels continued to become more distinct and their refraction angle increased as the gas density increased, until at a density of  $2.75 \times 10^{20} \text{ cm}^{-3}$  a strong density feature at the centre of the plasma appeared to converge towards the vacuum focusing position, where it terminated, while the edges of the plasma refracted at large angles away from the axis.

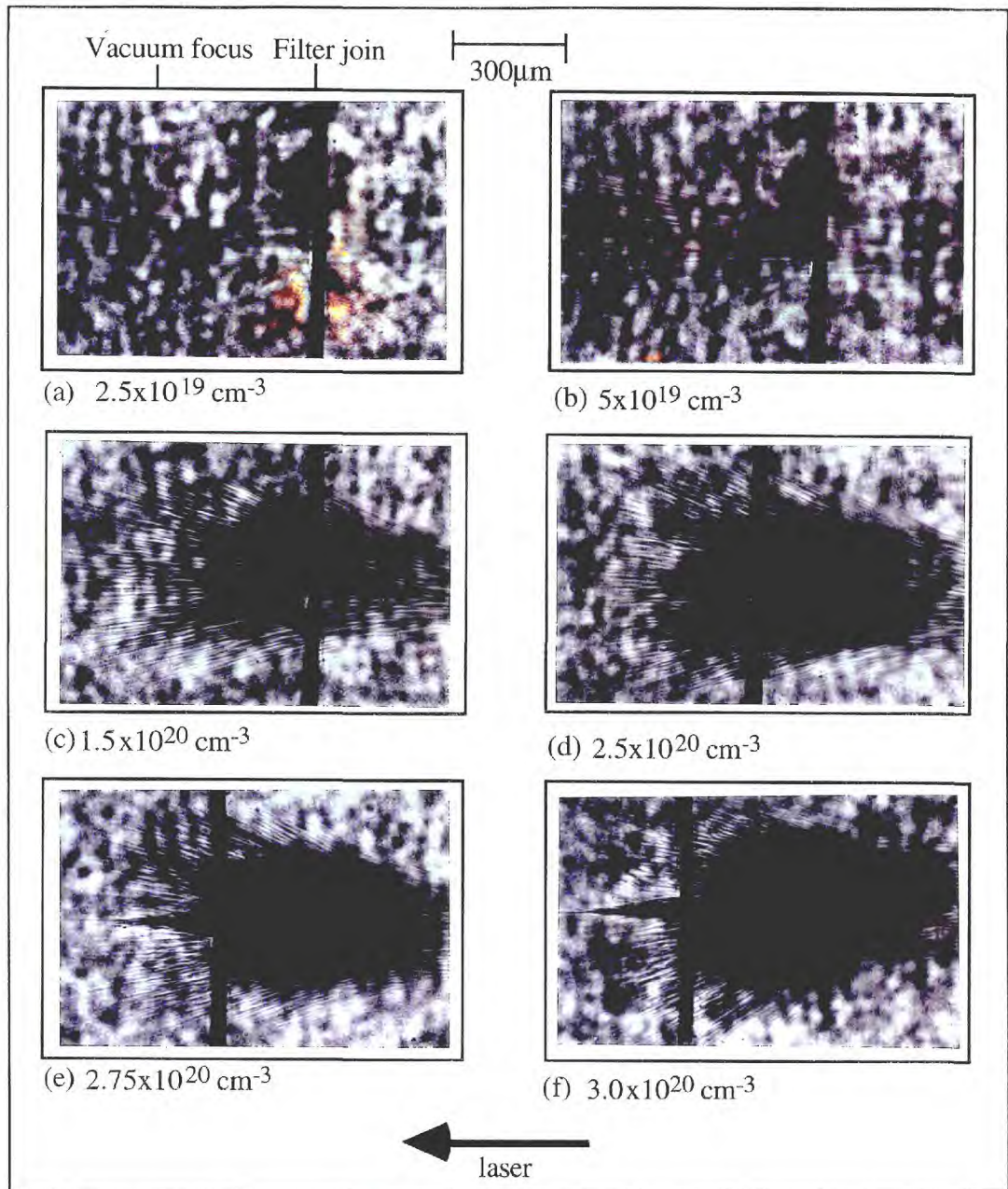


Figure 4.20 Shadowgrams of plasmas formed as a function of increasing gas density. As the gas density increased the plasma breaks into small scale channels and at the highest density a central high density region appeared. The angle of the channels with respect to the laser propagation direction increased as the gas density increased.

The origin of this feature was investigated by reducing the laser power at constant gas density to determine if there was a intensity threshold. Figures 4.21 shows shadowgrams taken at the same delay as figure 4.20 but as a function of reducing beam power,  $P$ , and at a gas density of  $1.5 \times 10^{20} \text{ cm}^{-3}$ . In figure 4.21 (a)  $P = 160 \text{ GW}$  and

the plasma is almost identical to figure 4.20 (c) with strongly refracting ionisation channels. However as the power was decreased to (b) 70GW the central density feature began to emerge. At a beam power of (c) 30GW there was still some evidence of the outer ionisation channels but the central feature was beginning to become quite distinct. At a beam power of (d) 10GW all that was left was the central density feature, with no outer ionisation channels. It also did not extend past the vacuum focusing position.

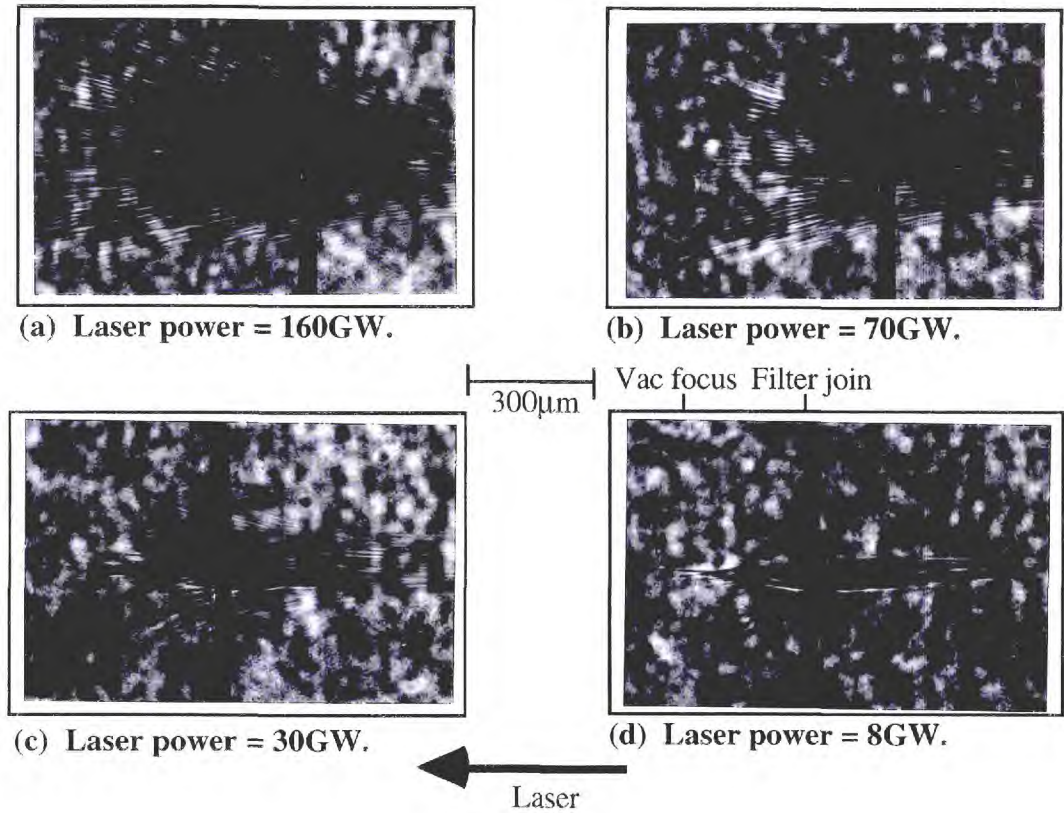


Figure 4.21 Shadowgrams with decreasing laser power at constant gas density of  $1.5 \times 10^{20} \text{ cm}^{-3}$ . As the laser power decreased a central plasma region again appeared, similar to those observed in figure 4.20 (e) and (f). This region is the plasma that is formed in the initial rise time of the pulse. This plasma refracts the rest of the laser pulse.

The central feature in 4.21 (d) was identical to that observed in figure 4.20 (e) and (f). This power scaling series of shots proved that it was formed from a low intensity part of the pulse. The fact that it did not extend past the vacuum focusing position also suggested that it was limited by refraction. Otherwise it would be symmetrical about the vacuum focus as in figure 4.20 (a). This also indicated that the central density feature

was formed during the low intensity rising edge of the pulse. The radial density gradients in this plasma then caused the later, higher energy parts of the beam to refract away and break up into small scale ionisation channels. This supposition was positively confirmed with a sequence of shadowgrams at different times. The delay time between the probe and the ionising pulse was decreased 16 to 6ps with the gas density and laser power maintained at constant levels of 300GW and  $3 \times 10^{20} \text{ cm}^{-3}$  respectively. The resulting shadowgrams of the plasma can be seen in figure 4.22 (a) 6ps and (b) 16ps.

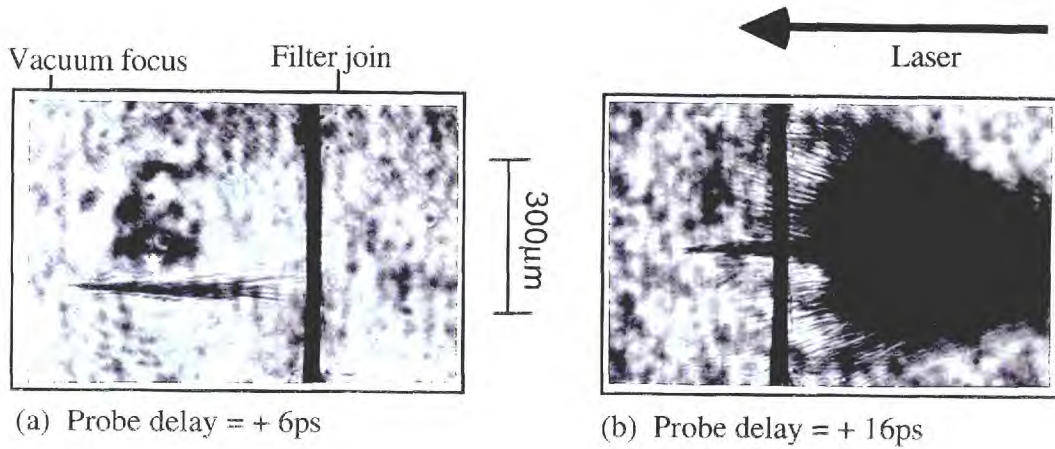


Figure 4.22 Shadowgrams at a probe delay of  $\tau_d = 6\text{ps}$  and  $\tau_d = 16\text{ps}$  for a gas density of  $n_d = 1.5 \times 10^{20} \text{ cm}^{-3}$ . At early times the plasma, as shown in (a), is small and extends back from the vacuum focusing position, later in time this plasma refracts the remainder of the laser pulse. These two figures confirmed the conclusions drawn from figures 4.20 and 4.21 that the plasma formed in the initial rise of the pulse refracted the laser pulse thus reducing the focused intensity.

The central density feature in figure 4.22 (a) is almost identical to the features observed in figs 4.20 (e) and (f) and Figure 4.21 (d). This confirmed that the central plasma was formed by the rising edge of the pulse. As the delay of the probe was increased the plasma evolved so that the strongly refracted light at the edges of the beam masked the underlying plasma that initially caused the refraction. It was evident from these measurements that the central focusing region was formed in the early part of the pulse and was the result of refraction not self focusing. The central feature appeared as the density increased because the outer plasma was strongly refracted before it reached the vacuum focusing position. The multiple small scale channels that dominated the high density pictures disappeared as the laser power was reduced and their angle increased as the gas density was increased.

The results of this experiment were consistent with evidence from the 350fs experiment. The small scale ionisation channels appeared at intensity density products far below the thresholds predicted by relativistic or ponderomotive space charge limited self focusing. The length of the filaments was inversely proportional to the gas density and the angle of refraction of the channels increased as the gas density increased. For the highest densities the channels disappeared after 100 $\mu\text{m}$ , this agreed well with the simple scaling of 50-100 $\mu\text{m}$  predicted by equation (37). This experiment confirmed the origin of the multiple small scale density channels observed in the 350fs and 12ps pulses was refractive splitting from laser hot spots. This is the first experimental observation of small scale plasma break up due to refraction induced splitting of laser hot spots. The refraction from ionisation defocusing was investigated further with the 1 $\mu\text{m}$  laser, in a plasma density regime suitable for laser accelerators and fast igniter studies.

#### **4.5 Refraction of 1 $\mu\text{m}$ , 0.7 - 3.0ps laser pulses.**

The experiments with the 0.248 and 0.268 $\mu\text{m}$  lasers showed the importance of refraction in the interaction of intense short pulses with gas jet targets. In these experiment the laser was focused into the middle of the gas jet and as a result, propagated more than 500 $\mu\text{m}$  through the gas before it reached the vacuum focusing position. The defocusing length for the lowest gas density used,  $5 \times 10^{19} \text{cm}^{-3}$ , was around  $l_d = 60 \mu\text{m}$  and so the beam suffered a great deal of refraction before it reached the centre of the gas jet. The resulting plasmas showed an increase in plasma radius with gas density but not all the refracted light caused ionisation. In order to observe the ionisation caused by the refracted light the experiment was repeated with a 1 $\mu\text{m}$  laser at vacuum intensities up to  $3 \times 10^{18} \text{Wcm}^{-2}$ . The increased intensity allowed more of the refracted light to ionise as it propagated out of the plasma. A time resolved deflectometer was used to give an image of the refracting plasma.

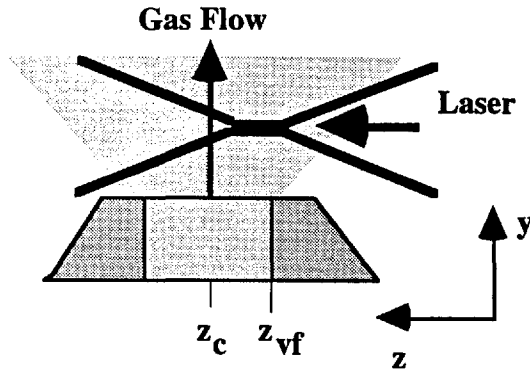


Figure 4.23 Diagram of target geometry for  $1\mu\text{m}$  experiments. The laser is focused near the edge of the gas flow, at  $z_{vf}$ , rather than the centre, at  $z_c$ , to reduce the length over which refraction could occur.

The laser was focused at a point  $400\mu\text{m}$  above the nozzle exit plane (along the  $y$  axis) and  $500\mu\text{m}$  (at  $z = z_{vf}$  along the  $z$  axis) before the nozzle centre ( $z = z_c$ ), as shown in Figure 4.23. This target geometry was also used in the guiding experiments described in chapter 5. It was important to know how the gas density varied along the  $z$  axis, this was estimated from the gas jet characterisation described in chapter 3.

#### 4.5.1 Spatial gradients in the gas density.

The gas density decreased with height above the nozzle and with radial distance from the centre. The gas density at the centre of the gas jet ( $z = z_c$ ) for a reservoir pressure of 15 atmospheres was  $5 \times 10^{19} \text{ cm}^{-3}$ , reducing to  $1.8 \times 10^{19} \text{ cm}^{-3}$ , at  $z = z_{vf}$  and to  $3.5 \times 10^{18} \text{ cm}^{-3} \pm 15\%$ , at  $z = z_{vf} - 500\mu\text{m}$ . The gas density gradient along the  $z$  axis can be seen in figure 4.24 [88].

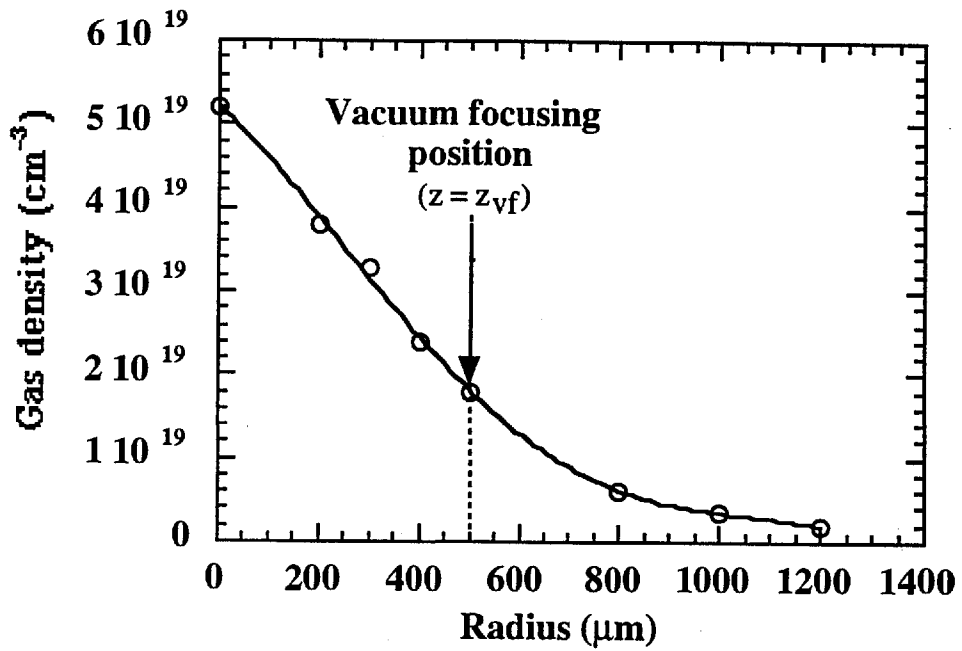


Figure 4.24 Gradient of gas density along the  $z$  axis for Neon at a reservoir pressure,  $P_R$ , of 15 atmospheres. The laser was focused near the edge of the flow at  $z = z_{vf}$ .

The relatively shallow gradient in gas density that can be seen in figure 4.24 meant that appreciable plasma formation occurred before the laser reached its minimum vacuum radius at  $z_{vf}$ . This led to refractive effects which reduced the focused intensity in the gas before the laser reached the  $z_{vf}$ .

#### 4.5.2 Plasma formation with the 5TW, 3ps laser pulse

A Moiré deflectogram obtained 6ps after the interaction of the laser pulse with the neutral gas target of neon gas at reservoir pressure of 15 atmospheres can be seen in figure 4.25(a).

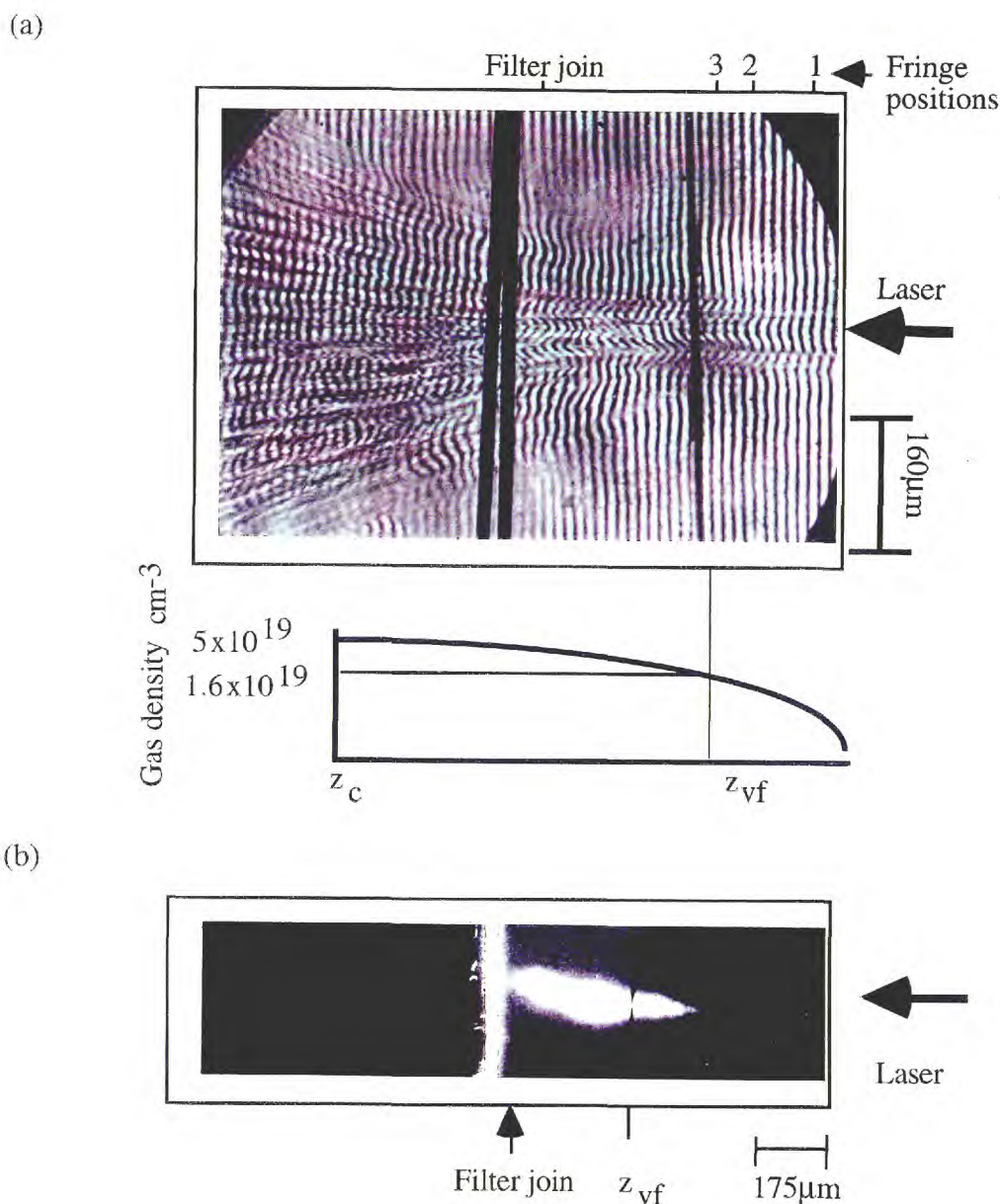


Figure 4.25 (a) Deflectogram and (b) image of the plasma self emission, after the interaction of a 7 TW pulse with Neon at gas density of  $5 \times 10^{19} \text{ cm}^{-3}$ , at the centre of the nozzle ( $z = z_c$ ). Strong whole beam refraction can be seen in (a), the plasma also broke up into many small scale channels. The length of plasma measured by the extent of the self emission shown in (b) was also much less than a Rayleigh length.

In both the figures the laser enters from the right hand side, the vertical bar near the centre of both images is the join between the filters on the film pack and the vertical line near the right hand edge of both images marks  $z = z_{vf}$ . In figure 4.25 (a) the plasma can be seen to expand with a very large angle radially as the laser propagated through the

gas. There is evidence of fringe shifting before  $z = z_{vf}$  showing that there was plasma present before the focal point,  $z_{vf}$ . The numbers above the deflectogram refer to position of the fringes that were inverted to obtain the density profiles.

#### 4.5.3 Observation of strong ionisation defocusing before and after the vacuum focus.

From figure 4.25(a) the plasma was observed to break up into discrete density channels which propagated at angles up to 30 degrees with respect to the  $z$  axis. The radius of the plasma increased from  $22 \pm 5\mu\text{m}$  as it entered the field of view from the right (at  $z = z_{vf} - 160\mu\text{m}$ ) to  $> 220\mu\text{m}$  as it left the field of view to the left (at  $z = z_{vf} + 570\mu\text{m}$ ). This was the result of refraction from transverse electron density gradients arising from optical ionisation. From figure 4.24 the gas density at  $z_{vf}$  was  $1.6 \times 10^{19} \text{ cm}^{-3}$ , resulting in a defocusing length,  $l_d = 36\mu\text{m}$  for singly ionised Neon. However the density gradients caused refraction induced defocusing before the laser reached  $z_{vf}$ . In figure 4.25(a) the onset of plasma formation was observable up to the right hand edge of the field of view (at  $z = z_{vf} - 160\mu\text{m}$ ). The field of view of the self emission system was greater and it detected plasma before even this point. The self emission imaging system detected light at a wavelength of  $\lambda = 0.625\mu\text{m} \pm 0.025\mu\text{m}$ , as described in section 3.3, it was mainly used to give information on the length of the ionised plasma and as a complement to the deflectometer. From figure 4.25 (b) the onset of self emission was observed to be at  $z = z_{vf} - 280\mu\text{m}$  and terminated abruptly at  $z = z_{vf} + 300\mu\text{m}$ . The centre of the gas jet was situated at  $z = z_{vf} + 500\mu\text{m}$  and so the laser intensity was dissipated  $200\mu\text{m}$  before the centre of the gas jet. The size of the self emitting region was also observed to increase radially from  $w_0 = 40 \pm 5\mu\text{m}$  at the onset ( $z = z_{vf} - 280\mu\text{m}$ ), to  $w_0 = 95 \pm 5\mu\text{m}$  at  $z = z_{vf} + 288\mu\text{m}$ , where it abruptly terminated.

The length of plasma before  $z_{vf}$  depended on the gradient in gas density and the intensity of the laser as it approached the focus, which in turn depended on the beam power and the convergence cone angle of the F/5 optic. By combining a geometric optics description of the beam radius with the gas density gradient from figure 4.24 an estimate of the distance before  $z_{vf}$  of the onset of plasma formation was obtained.

For a 5 TW shot the vacuum intensity  $500\mu\text{m}$  before  $z_{vf}$  was  $3.5 \times 10^{16} \text{ Wcm}^{-2}$  for a cone angle of 5.7 degrees. The Coulomb barrier model [16] predicted an ionisation stage of  $4^+$  for this intensity, giving an electron density of  $1.4 \times 10^{19} \text{ cm}^{-3}$  at this point along

the axis. The detection threshold of the deflectometer was set by the minimum resolvable shift of  $1/2\pi$  of a fringe [94] to be  $1.2 \times 10^{19} \text{ cm}^{-3} \pm 20\%$ , and so with this simple treatment the plasma should have been detectable at  $z = z_{vf} - 500\mu\text{m}$ . This was in reasonable agreement with the observed onset of plasma formation at  $z = z_{vf} - 280\mu\text{m}$  from the self emission data in figure 4.25(b). The formation of plasma up to  $280\mu\text{m}$  before  $z_{vf}$  caused appreciable refraction and led to significant defocusing before the beam reached its minimum radius at  $z_{vf}$ . A quantitative measure of the degree of defocusing was obtained from inversion of the fringes in figure 4.25(a).

#### 4.5.4 Electron density profiles.

An analysis of plasma electron density was obtained by inversion of fringes at the points (1), (2), (3) marked on figure 4.25(a). These corresponded to distances before  $z_{vf}$  of  $44, 114$  and  $158\mu\text{m}$  respectively.

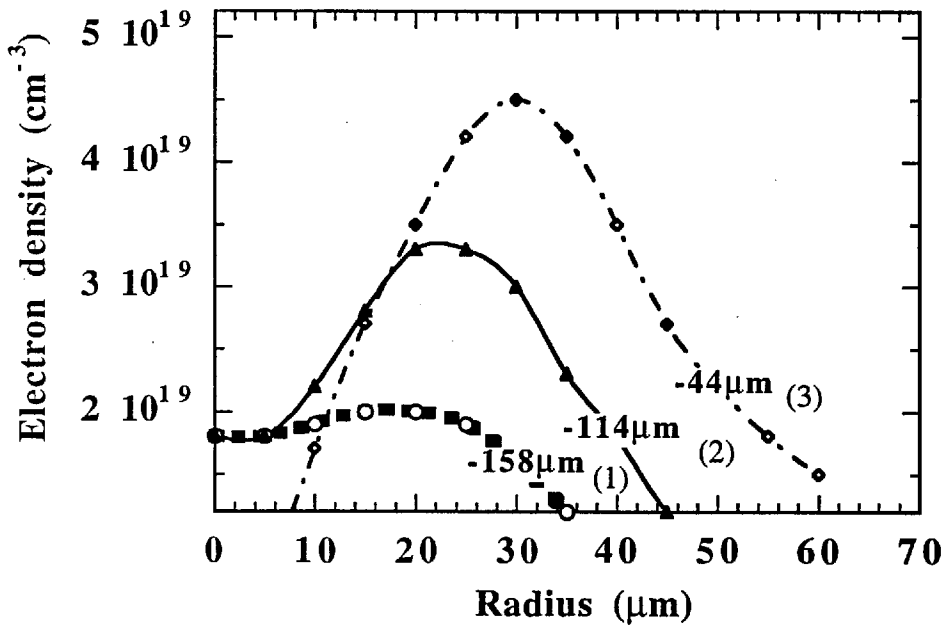


Figure 4.26 Electron density profiles at points corresponding to (1), (2) and (3) along the  $z$  axis in figure 4.25 (a). The double peak structure that can be seen to develop along the  $z$  axis was thought to be caused by whole beam refraction seeded by a double peaked laser focal spot structure (as seen in figure 3.12(b)).

The clearest feature of figure 4.26 was the off axis maximum in the electron density profiles. This was consistent with refractive splitting of the laser from the double peaked intensity structure, observed on the equivalent plane image of the focal spot  $250\mu\text{m}$  before the vacuum focus, as shown in figure 3.12(b). The peak electron density can be seen to increase as the laser propagated up the gas density gradient but the peak ionisation stage was only  $2.8^+$  at  $z = z_{vf} - 44\mu\text{m}$  and was never greater than  $3.3^+$  within the field of view of figure 4.25(a). Comparing this with the Coulomb barrier model gave a focused intensity less than  $2 \times 10^{16} \text{Wcm}^{-2}$  along the length of the nozzle. This confirmed that strong ionisation defocusing was occurring before the laser reached  $z_{vf}$ .

#### 4.5.5 Whole beam refraction from the density gradients.

The divergence angle of the plasma of 30 degrees observed in figure 4.25(a) was very much greater than the divergence angle of 5.7 degrees of the focusing optics. Figure 4.27 shows how the radius of the plasma increased in figure 4.25(a) compared to that expected from the normal defocusing angle of the F/5 optics.

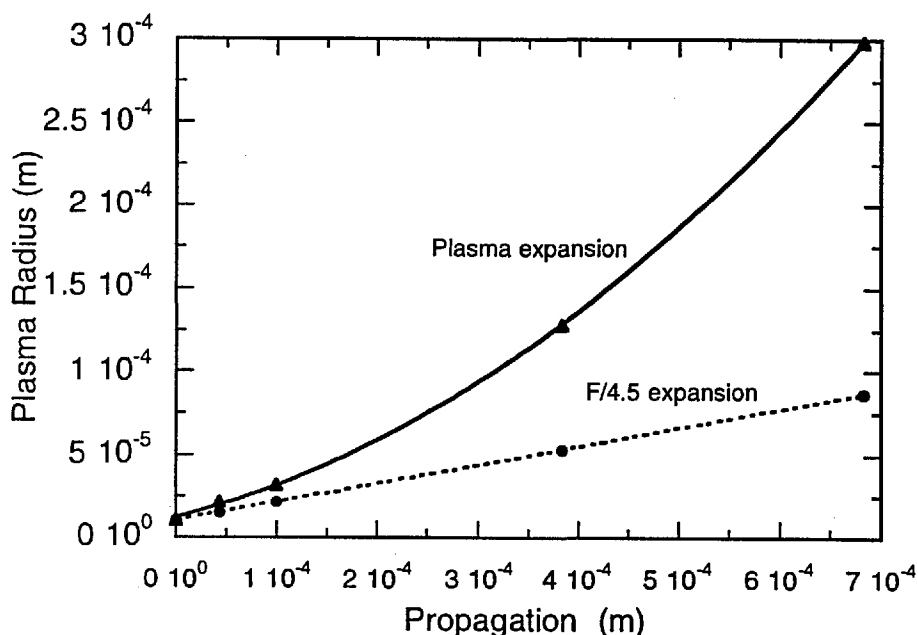


Figure 4.27 Plasma radius as a function of propagation distance (filled triangles) compared to a F/5 optic (filled circles). The rate of plasma expansion is far greater than the diffraction limited beam divergence due to refraction.

It can be seen from this figure, that the rate at which the plasma radius increased as a function of  $z$  was significantly greater than predicted by the divergence angle of the focusing optic. If this increase in angle was due to refraction then it could be related to the density gradient through equation (20) of section 2.1,

$$\alpha = -4.36 \times 10^{-22} \int_0^L \frac{dn_e}{dx} dz \quad (\text{radians}) \quad (20)$$

where all units are in cm and  $n_e$  is the electron density in  $\text{cm}^{-3}$ . To refract laser light at a wavelength of  $1\mu\text{m}$  through an angle of 27 degrees over a plasma length,  $L$ , of  $790\mu\text{m}$  would require an electron density gradient of  $1.37 \times 10^{22} \text{ cm}^{-4}$ . If the gradient was averaged over the radius of the focal spot, that existed over the length  $L$ , then for a radius of  $15 \mu\text{m}$  the average electron density required was  $2 \times 10^{19} \text{ cm}^{-3}$ . The use of (20) can only be a rough estimate because the density and radial scale length did not remain constant over the length of the plasma in the field of view of figure 4.25(a), but the reasonable agreement with the measured parameters did indicate that refraction was entirely consistent with the observed increase in plasma radius as the laser propagated along the  $z$  axis. The observed refraction angle of 30 degrees was also confirmed by the transmission data for this shot which gave a transmission fraction (within the calorimeter acceptance angle of 5.4 degrees) of 3%. For a beam expanding at 30 degrees the fraction captured by the calorimeter with an acceptance angle of 5.7 degrees would  $T = (5.7/30)^2 = 3.2\%$ , so this confirms the refraction angle measured from figure 4.25(a).

The intensity limitation before the vacuum focus was estimated with equation (20) and a geometric optics consideration of the beam focusing. The geometry can be seen in Figure 4.28, which showed that as the laser rays propagated through the gas, their angles increased as a result of the increase in plasma density gradients along the ray path length. If the rays began to refract at  $z = z_{vf} - 350\mu\text{m}$ , where the focal spot radius was approximately  $50\mu\text{m}$ , then for a vacuum intensity at this position of  $6 \times 10^{16} \text{ Wcm}^{-2}$ ,  $Z^* = 5^+$  from the Coulomb barrier model [16]. For an atomic density of  $n_a = 5 \times 10^{18} \text{ cm}^{-3}$ , the electron density,  $n_e = 2.5 \times 10^{19} \text{ cm}^{-3}$  giving  $\alpha = 5$  degrees from equation (20).

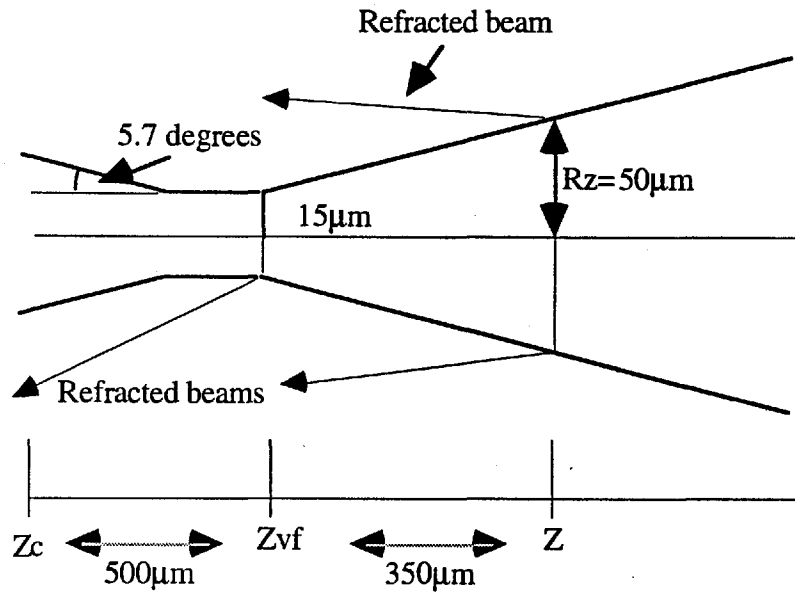


Figure 4.28 Ray diagram of the limitation of the laser intensity as a result of refraction.

If the laser continued to propagate while expanding at 5 degrees from a spot radius of  $50\mu\text{m}$  then the intensity at  $z_{vf}$  would be  $2.5 \times 10^{16} \text{ Wcm}^{-2}$ . This implied  $Z^* = 4^+$  from [16]. This agreed to within an ionisation stage to the maximum  $Z^*$  of  $3.3^+$  determined from the electron density profiles measured from figure 4.25(a). These simple geometric refraction models in conjunction with the quantitative measurements obtained from the deflectograms proved that the laser intensity was limited by ionisation defocusing even when the laser was focused onto the edge of the gas jet.

#### 4.5.6 Refraction as a function of gas density and atomic number.

The refraction effects described above were investigated further, by varying the density and atomic number of the target gas. When the Neon gas density was increased to  $1 \times 10^{20} \text{ cm}^{-3}$  the fraction of transmitted laser energy measured by the calorimeter was found to fall to less than 1%. Conversely this increased to 12% when the gas was changed to Helium with a density of  $5 \times 10^{19} \text{ cm}^{-3}$ . These results are summarised in figure 4.29

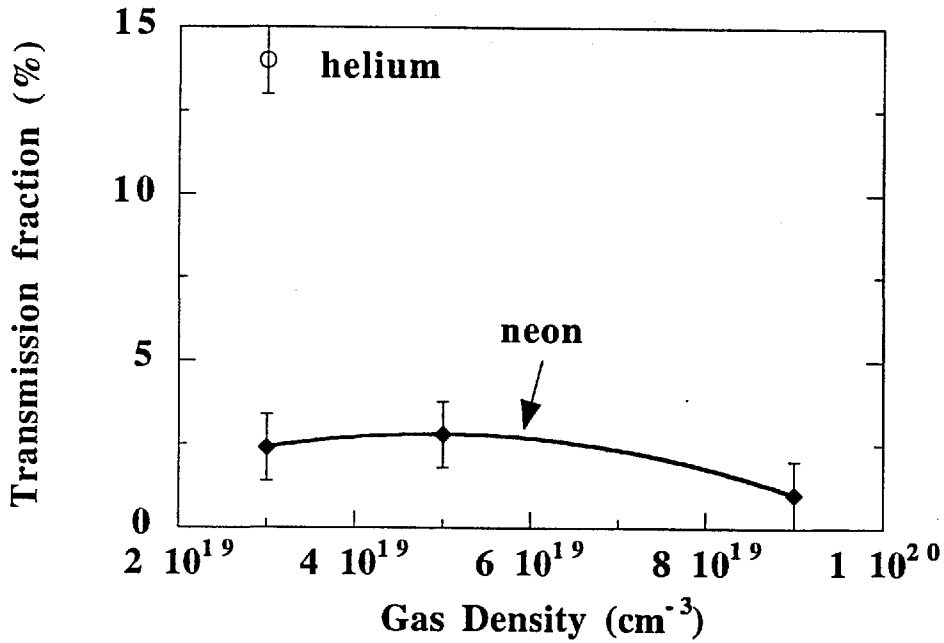


Figure 4.29 Calorimetry of the transmitted laser light, for Helium and Neon. The open circle shows the measured laser transmission fraction for Helium while the filled diamonds show the same for Neon. The full curve indicates the trend in the data. The laser energy transmitted through the Helium target was a factor of 7 larger than the Neon data because of the lower electron density in the Helium.

The role of absorption in the reduction in transmission can be estimated conservatively by treating the plasma as a cylinder, with an average radius  $r = 200\mu\text{m}$ , a mean electron density  $n_e = 5 \times 10^{19} \text{ cm}^{-3}$ , a length  $L = 1\text{mm}$  and an energy  $E$  per electron of  $1000\text{eV}$ . The absorbed energy is then given by,  $E_{\text{abs}} = \pi r^2 L n_e E$ . For the estimates above  $E_{\text{abs}} \sim 1 \text{ J}$ , which accounts for a loss of 6% of the beam energy, compared to a measured reduction of 98% of the beam energy. In reality the loss through absorption will be less than this due to the reduced length of plasma and a lower average density. It is clear from this simple estimate and the agreement between the measurements of the expansion angle from the deflectograms and the transmission fraction, that the major contribution to the loss in laser energy was due to refraction from ionisation gradients, not absorption.

Using geometric considerations the measured transmission fractions were converted into beam refraction angles. This gave 60 and 14 degrees for Neon at  $1 \times 10^{20} \text{ cm}^{-3}$  and

Helium at  $3 \times 10^{19} \text{ cm}^{-3}$  respectively. These inferred angles also agreed well with the observed refraction angles of the ionisation channels obtained from deflectograms of  $> 50$  and  $17$  degrees respectively.

## 4.6 Conclusions.

The reduction of the focused laser intensity in gas jet targets has been observed. In the experiments with the KrF  $0.248 \mu\text{m}$  laser, the radius of the plasma at the position of best focus was found to increase as the density increased. An estimate of the laser intensity was obtained by fitting a Gaussian to the plasma radius, assuming that each ionisation stage was produced at an intensity derived from the Coulomb barrier model [16]. This method showed that refraction was taking place, but it was not sensitive to all of the refracted light. The electron temperature was measured by fitting a simulation to the temporal evolution of the plasma. The intensity was inferred from this measurement by comparing the electron temperature with theoretical predictions. This intensity was found to agree well with the laser spot size measured from images of the transmitted laser light. Agreement within a factor of two was obtained between the experiment and the analytical and numerical defocusing models.

It was also clear from the  $1 \mu\text{m}$  experiments that strong ionisation induced refraction limited the focused intensity of  $5 - 10 \text{ TW}$  laser pulses in dense gas jet targets. The degree of defocusing was directly and quantitatively measured for the first time with time resolved optical probing. The plasma was observed to break up into small scale density channels, of a similar nature to those observed in  $0.248$  and  $0.268 \mu\text{m}$  experiments. These were consistent with refractive splitting from hot spots observed on the laser intensity profile. The measured refraction angle of these density channels was related to the electron density gradient through equation (20). The density gradient obtained from this method agreed well with those measured by the deflectometer. The observed refraction angle also correlated extremely well with the measured laser energy transmitted through the target. When the measured ionisation stage was compared to the Coulomb barrier model [16], the focused intensity was found to be limited by refraction to less than  $2 \times 10^{16} \text{ Wcm}^{-2} \pm 50\%$  [103].

The results obtained in this work indicate that it will be impossible to achieve a long highly ionised plasma under the conditions required for many applications, including the recombination X-ray laser, without some means of overcoming the refraction. One of the most promising solutions to this problem is the use of preformed density channels to

overcome the refraction. This subject has not been studied in the density, intensity and pulse width regimes that are of interest to many important laser plasma interactions. A study of laser beam guiding in plasma density channels in these regimes is the subject of the next chapter.

## 5 Guiding of laser pulses in plasmas.

In the last chapter strong ionisation defocusing was shown to greatly reduce the intensity of short laser pulses when they were focused into neutral gas targets. One way of overcoming this problem is to use a low intensity laser pulse to ionise the gas before the arrival of the main, high intensity heating pulse [48]. The preformed plasma helps to overcome the refractive effects in two ways. First after the end of the prepulse the free electrons produced during the optical ionisation continue to collisionally ionise the plasma. If their temperature is high enough, the plasma will be in a highly ionised state. If the main pulse then interacts with this plasma any consequent increase in the electron density due to the additional optical ionisation is then a small fraction of the total electron density. This helps to reduce the electron density gradients that cause the ionisation defocusing.

The second effect is a result of the guiding properties of the density channel that develops over time scales much greater than 50-100ps. The density channel, which was described in detail in section 2.1.8 and 2.4, acts as a wave guide to confine the high intensity laser pulse over distances much greater than the characteristic depth of focus of the system. The formation of wave guides capable of confining laser pulses with low intensity pulses over large distances in low density gases has recently been studied [44]. This chapter describes the investigation of channel formation at significantly higher gas densities, laser intensities and shorter laser pulses than the previous work [44]. The gas density was increased from  $1 \times 10^{18}$  to  $1 \times 10^{20} \text{ cm}^{-3}$ , this introduced the major new problem of ionisation induced refraction of the preforming pulse, which limited the length and uniformity of the preformed channel. The laser intensity was increased from  $1 \times 10^{14}$  to  $3 \times 10^{18} \text{ Wcm}^{-2}$  and the laser pulse duration reduced from 100ps to 1-3ps. This allowed the study of channel formation and guiding in plasmas that were relevant to studies of recombination X-ray lasers [10], the fast ignitor [13] and plasma accelerator schemes[9,35].

### 5.1 Plan of the chapter.

A study of optical guiding in preformed density channels was carried out in a series of experiments at the Central Laser Facility. The channels were formed in Helium, Nitrogen and Neon gas at gas densities between  $5 \times 10^{18}$  -  $1.5 \times 10^{20}$  with two different lasers. The first, used the VULCAN CPA [98] laser, with a wavelength of,  $\lambda = 1 \mu\text{m}$ ,

and a pulse duration of,  $\tau_p = 1\text{-}3\text{ps}$ . The second used the SPRITE KrF CPA laser [96] where,  $\lambda = 0.248\mu\text{m}$  and  $\tau_p = 350\text{fs}$ . Both these laser systems and the experimental diagnostics were described in section 3.3.

The first section of this chapter shows the general features of plasma wave guides and how they overcame refraction in neon at a wavelength of  $1\mu\text{m}$ . This is followed by a quantitative study of the factors affecting the formation and uniformity of the channel. The last section investigates the guiding of a  $\lambda = 0.248\mu\text{m}$ ,  $\tau_p = 0.350\text{ps}$  pulse in Neon plasma at densities within the suggested parameter range for the He-like Neon X-ray laser [10]. The chapter concludes with a discussion of the relevance of the results of both experiments to the various applications.

## **5.2 Guiding of 5TW pulses in preformed density channels.**

This section describes how a preformed plasma was used to overcome the ionisation induced refraction and guide a 3ps, 5 TW pulse with a wavelength of  $1\mu\text{m}$  in Neon at a peak gas density of  $5 \times 10^{19} \text{ cm}^{-3}$ . The channel was formed by focusing a pulse containing 1% of the main beam energy into the gas jet, before the arrival of the main pulse. In this experiment the pulse duration and spatial profile of the prepulse were identical to (and collinear with) the main pulse. Both pulses were focused with the F/5 optic to a maximum vacuum intensity of  $7 \times 10^{15} \text{ Wcm}^{-2}$  at the vacuum focusing position (defined by  $z = z_{vf}$  in figure 5.1).

Deflectograms of the interaction of the main pulse without and with the preformed channel can be seen in Figure 5.1(a) and (b) respectively. Figure 5.1(c) shows the preformed channel without the interacting pulse, obtained by advancing the probe by 10ps, so that it measured the density gradients immediately before the arrival of the main pulse.

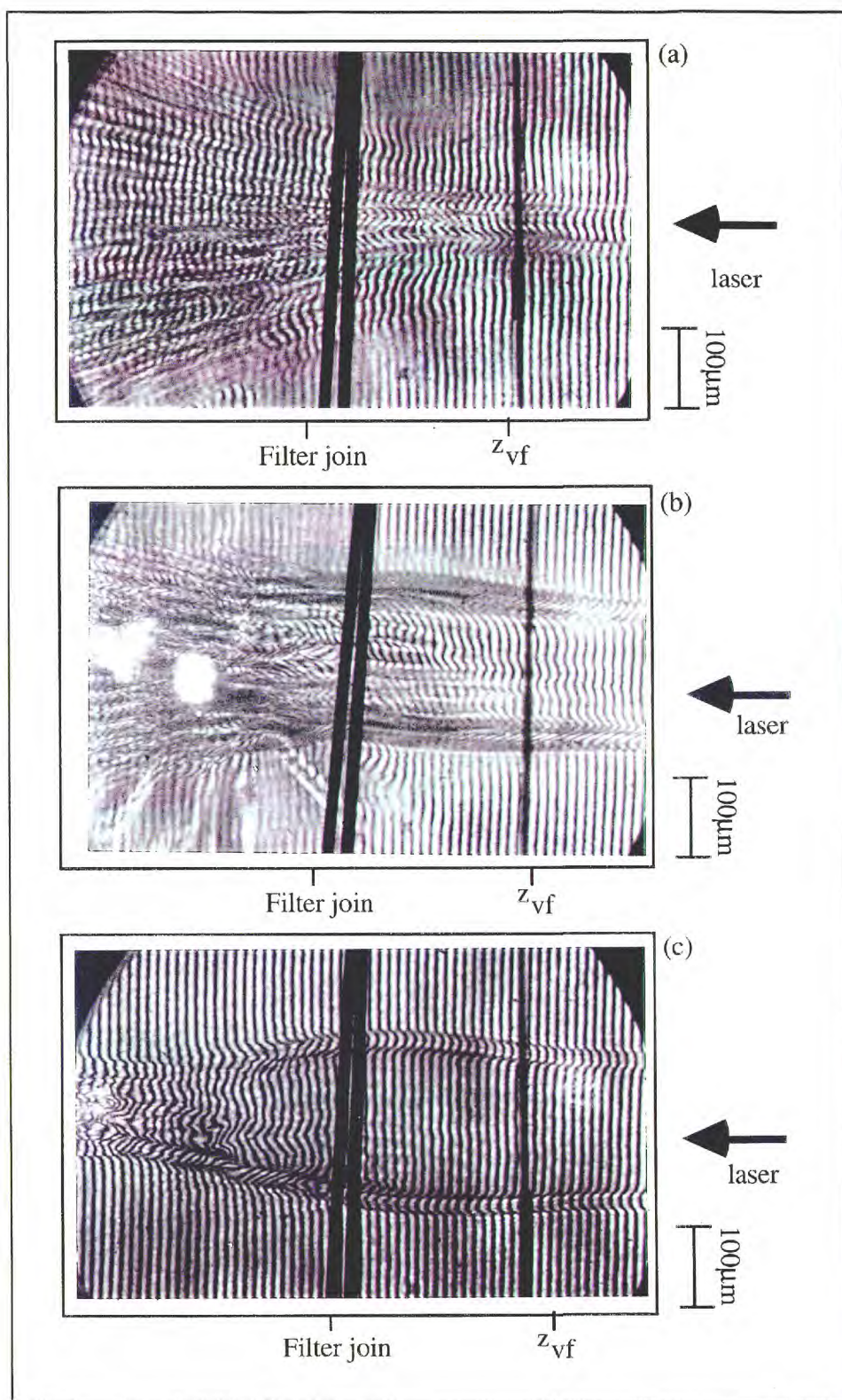


Figure 5.1 Deflectometer images (a) 5 TW pulse, no prepulse, (b) 5TW pulse focused into the wave guide formed with a 1% prepulse and (c) The 1% prepulse just before the arrival of the 5TW pulse.

Many of the important features of the guiding process emerge from a direct comparison between Figures 5.1 (a) and (b). Figure 5.1 (a) shows the characteristics of a plasma that was severely affected by ionisation induced refraction. The plasma broke up into many small scale ionisation channels, which propagated at angles of up to 30 degrees to the  $z$  axis. It was clear from fig 5.1 (b), that when the 5TW pulse was focused into the channel, confinement of the beam and guiding occurred. The strongest indication of guiding was that, although the plasma did break up into small scale ionisation channels at the end of the wave guide, the angle of their refraction reduced from 30 to 10 degrees. The loss of contrast and general fringe smearing outside the channel in figure 5.1 (b) indicated that there was some light leakage through the channel walls. However the refraction was generally controlled very effectively until the laser reached the end of the channel. These pictures showed clearly and directly, for the first time how the walls of the channel confined the light and guided the beam from the vacuum focusing position, (at  $z = z_{vf}$ ), to the centre of the gas jet (at  $z = z_c$ ) ( a distance of approximately  $500\mu\text{m}$ ).

### **5.2.1 Termination of the wave guide due to channel non uniformity.**

It can be seen from figures 5.1(b) that guiding was abruptly terminated at the end of the channel (at  $z = z_c$ ), where the plasma broke up into the small scale ionisation channels that were characteristic of a laser pulse interacting with a plasma with a large electron density gradient. The bright features that can be seen at this position were also consistent with the laser beam interacting with regions of high density. The non uniform nature of the density channel caused these features, as can be seen from figure 5.1 (c). In this figure the radius of the channel began to decrease around  $z = z_{vf} + 300\mu\text{m}$  and the positions of two high electron density regions at the end of the channel ( $z = z_{vf} + 500\mu\text{m}$ ) corresponded exactly to the locations of the bright features observed in figure 5.1 (b). These regions of high density and the reduction in the channel radius were due to defocusing of the prepulse beam, that led to a lowering of intensity, reduced energy absorption and a colder plasma that did not expand significantly. The curvature of the channel at  $z > z_{vf} + 300\mu\text{m}$ , also enabled the small scale ionisation channels to penetrate the refractive index barrier and escape from the channel.

Some of the small scale channels that were refracted off the high density regions propagated at extremely large angles, can be seen in figure 5.1 (b). This was another indication that refraction from the extremely steep density gradients was taking place.

The channel non uniformity, caused by defocusing of the prepulse, described above prevented the laser from being guided over the complete length of the nozzle ( $>1\text{mm}$ ). This has never previously been observed experimentally, but a similar effect has been predicted theoretically [43]. It was crucial to determine the origin of the channel non uniformity and if possible, to overcome it, if this wave guiding scheme were to be used in any applications. The laser and target parameters that were required to overcome the defocusing of the prepulse were studied in order to create long regions of plasma capable of guiding the laser pulse over distances approaching 1mm.

### **5.2.2 Increase in channel wall electron density due to optical ionisation.**

Another novel feature of this interaction was clear from a comparison of the fringe shifts at the channel walls in figure 5.1 (c) before the arrival of the 5TW pulse, and in (b) after the arrival of the 5 TW pulse. In (b) the shifting of the fringes is significantly increased over (a), indicating an increase in the electron density at the channel walls due to the 5 TW pulse. This feature has also not previously been treated experimentally or theoretically. Two possible mechanisms for this were, either an increase in the ionisation stage due to tunnel ionisation at the shock fronts, or ponderomotive expulsion of electrons from the channel. The ponderomotive ejection of electrons over distances of 50-100 $\mu\text{m}$  in the presence of the space charge restoring force would require intensities greater than  $1 \times 10^{18} \text{ Wcm}^{-2}$  which was very unlikely for these laser parameters, and this mechanism was rejected.

In order to determine if optical ionisation could cause this increase, the intensity of the pulse was estimated at the channel walls. If the beam was simply assumed to have a top hat profile, that completely filled the channel, then the intensity at the walls, 100 $\mu\text{m}$  from the centre, would be  $I_w = 1.6 \times 10^{16} \text{ Wcm}^{-2}$ . This would be enough to tunnel ionise Neon up to  $3^+$ . An increase in electron density would be observed, when the 5TW pulse arrived, if the existing ionisation stage at the channel walls were less than  $3^+$ . This possibility was studied quantitatively by observing the interaction of a 5TW pulse with Helium gas. It was also compared to calculations of the ionisation balance at the shock front in Neon obtained from hydrocode simulations coupled with the average atom model. This experiment and the simulations are described in section 5.4 after the investigation of the channel non uniformity.

The features observed in the deflectograms were confirmed with the corresponding images of self emission obtained on the same shots at a wavelength of  $0.625 \pm 0.25\mu\text{m}$ . Figure 5.2 (a) shows the self emission image obtained when the 5 TW pulse interacted with the neutral gas and Figure 5.2 (b) shows the self emission image obtained when the 5 TW pulse was focused into the waveguide formed with the 1% prepulse.

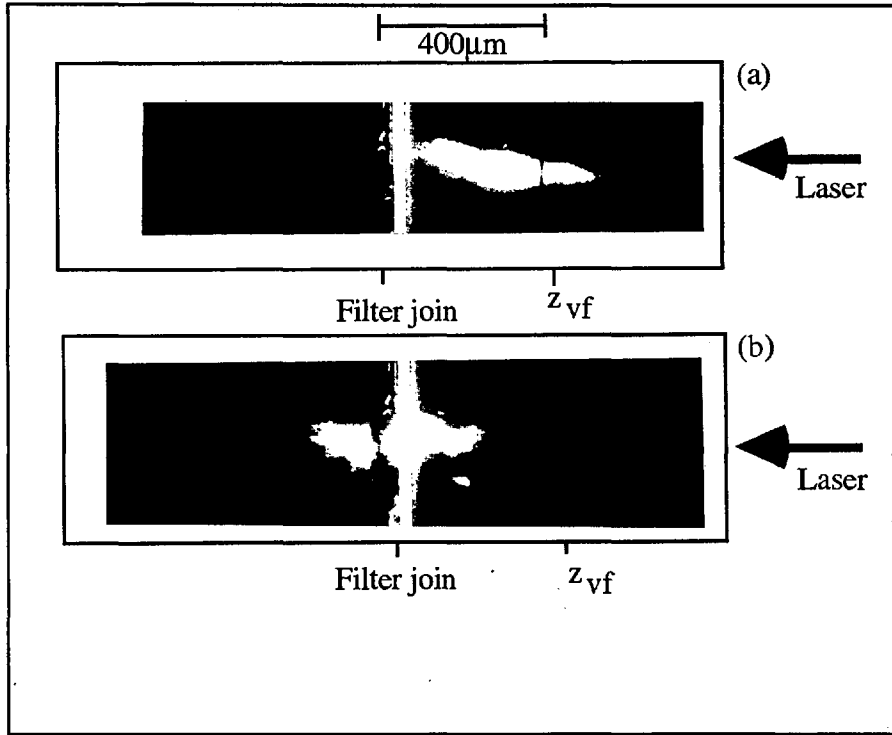


Figure 5.2 Images of plasma self emission obtained for, (a) the 5 TW pulse with no prepulse and (b) the 5TW pulse focused into the waveguide formed after allowing the channel produced by the 1% prepulse to expand for 2.3ns. These images corresponded with the deflectograms in figure 5.1 (a) and (b) for a peak Neon gas density of  $5 \times 10^{19} \text{ cm}^{-3}$ , at the nozzle centre.

The self emission images showed that the onset of plasma emission was shifted along the laser propagation axis by approximately  $500\mu\text{m}$  when the high intensity pulse was focused into the guide. The high intensity beam was therefore guided over a distance equivalent to approximately 20-50 defocusing lengths. This agreed well with the observed channel length in fig 5.1(b).

### 5.3 Study of non uniform channel formation.

The most straightforward analysis of the guide is to use a simple comparison to an optical fibre with a step function in the refractive index between the cladding and the core, as was described in section 2.1. Geometric optics theory based on Snell's laws then gives the critical angle that will be guided by the change in refractive index between walls and channel, as  $\theta_c = \cos^{-1} (\mu_c / \mu_{co})$ , where  $\mu_c$  is the refractive index of the walls and  $\mu_{co}$  is the refractive index of the channel. At electron densities  $\ll n_c$  the refractive index can be approximated by  $\mu = n_e / 2n_c$ . The density at the shock front was measured by inverting a fringe at the vacuum focusing position (at  $z = z_{vf}$ ). The electron density was found to be  $6 \times 10^{19} \text{ cm}^{-3}$  at the shock front and  $2.4 \times 10^{19} \text{ cm}^{-3}$  in centre of the channel. This gave  $\theta_c = 10$  degrees, and agreed well with the measured refraction angle of most of the ionisation channels that were observed to emerge from the end of the channel in figure 5.1(b). However, some of the small scale channels refracted off the high density regions at angles much greater than 10 degrees. This break down in guiding was also confirmed by a fall rather than a rise in the measured percentage of laser energy transmitted through the plasma when the laser was focused into the wave guide. The percentage transmission was 2% in the guided case compared to 3% with no preformed channel. It is clear from these measurements that channel non uniformity sets an important limitation on the distance over which guiding can be achieved.

The most probable reason for the closure of the channel was defocusing of the 1% prepulse, either from the 5.7 degree focusing optic cone angle or from ionisation induced refraction. In the absence of refraction, the depth of focus of the beam in vacuum depended on the near field beam profile, top hat or Gaussian. In vacuum the diffractive spreading of a laser pulse with a Gaussian spatial profile is characterised by the Rayleigh length  $L_R = (\pi \omega_0^2 / \lambda)$ , the distance before or after focus before the intensity is reduced to half of its peak value at best focus. For a Gaussian spot radius of  $25 \mu\text{m}$  (corresponding to the measured width of  $30 \mu\text{m}$ )  $L_R = 1.8 \text{ mm}$ .

If however, the pulse had a top hat spatial profile, the diffraction limited depth of focus of the beam depends on the F/number of the focusing optics ( $F/^\circ$ ) and the laser wavelength  $\lambda$ , [99]  $dz = 0.5(2F/^\circ)^2 \lambda$ . (This definition is slightly different to the Rayleigh length in that it defines the distance required for the intensity to reduce by 20% rather than 50%). For  $F/5$  and  $\lambda = 1.054 \mu\text{m}$ ,  $dz = 50 \mu\text{m}$ . At distances much greater than  $dz$  the radius of the laser spot was determined by the geometric expansion at the 5.7 degree cone angle of the  $F/5$  optics. In this case the length of the plasma formed by the

prepulse would be determined by the radius at which the intensity fell below  $9 \times 10^{14} \text{ Wcm}^{-2}$ .

For a 1% prepulse with a beam power,  $P = 50 \text{ GW}$  the intensity fell to  $9 \times 10^{14} \text{ Wcm}^{-2}$  at a distance  $\sim 300 \mu\text{m}$  on either side of focus. However, in figure 5.2(c) the length of the channel was observed to extend up to  $500 \mu\text{m}$  after  $z_{vf}$ . This can be explained by hydrodynamic expansion of the plasma after end of the prepulse. If the channel expanded at the same rate along the  $z$  axis as it did in the radial direction then the end of the channel would travel around  $100 \mu\text{m}$  in the time period of  $2.3 \text{ ns}$  before the arrival of the main pulse.

A comparison of deflectograms taken  $500 \text{ ps}$  and  $2.3 \text{ ns}$  after the termination of the prepulse in Nitrogen at a centre nozzle density of  $1 \times 10^{20} \text{ cm}^{-3}$  confirmed that hydrodynamic expansion did increase in length of the channel over this time scale (by  $200 \mu\text{m}$  in this case). A quantitative comparison between Nitrogen and Neon at these different densities was difficult because there are too many parameters, such as the laser absorption, plasma temperature and expansion velocity to be taken into account. It did, however qualitatively confirm that there was significant plasma expansion along the  $z$  axis after the termination of the prepulse. Following this it was reasonable, therefore, that the length of the plasma formed by a 1% prepulse in Neon at a density of  $5 \times 10^{19} \text{ cm}^{-3}$  was determined by the intensity of the beam due to the focusing optics and by hydrodynamic expansion along the  $z$  axis. The effect of refraction on the length of the channel was determined by increasing the gas density.

### 5.3.1 Variation of channel length with gas density.

The formation of a wave guide in Neon at a higher gas density of  $1 \times 10^{20} \text{ cm}^{-3}$  showed how refraction reduced the length of the channel. Deflectograms of the interaction of a  $3 \text{ ps}$  pulse with neutral Neon can be seen in figure 5.3(a) and in (b) with a preformed channel (in this case formed by a prepulse formed  $1.5 \text{ ns}$  before the main pulse). The corresponding images of the self emission can be seen in Figure 5.3 (c) the neutral gas and (d) with the  $1.5 \text{ ns}$  prepulse. From figure 5.3(a) the increased gas density was observed to cause stronger refractive effects when the  $7 \text{ TW}$  pulse was focused into the jet, without a density channel. It can be seen from Figure 5.3(a) that plasma again broke into many ionisation channels, which propagated at angles of up to  $50$  degrees. The radius of the plasma at  $z = z_{vf}$  was approximately  $125 \mu\text{m}$ , much larger than the  $15 \mu\text{m}$

radius of the spot in vacuum. It can also be seen from figure 5.3 (c) that the onset of plasma self emission occurred further before the vacuum focus at  $z = z_{vf} - 457\mu\text{m}$ .

Using the same geometric optics approximation as in section 4.5.3, a spot radius of  $60\mu\text{m}$  corresponded to a vacuum intensity of  $4 \times 10^{16} \text{ Wcm}^{-2}$  at this position, for a flat top beam. From the gas jet characterisation the gas density at this point was  $8 \times 10^{18} \text{ cm}^{-3}$ , giving an electron density of  $4 \times 10^{19} \text{ cm}^{-3}$  for  $Z^* = 5^+$ , from the Coulomb barrier model [16]. An order of magnitude estimate of the refraction angle at  $z_{vf}$  from equation (26) was 8 degrees for an average electron density of  $4 \times 10^{19} \text{ cm}^{-3}$ , and a radial scale length of  $60\mu\text{m}$  acting over a length of  $470\mu\text{m}$ . If the refraction angle was constant at 8 degrees until  $z_{vf}$ , the laser would expand from a radius of  $w_0 = 125\mu\text{m}$  at  $z_{vf}$ , in reasonable agreement with the plasma radius of  $140\mu\text{m}$  observed in fig 5.3(a).

When the pulse was focused into a plasma wave guide 1.5ns after the termination of the 10% prepulse there was evidence of some light confinement before the end of the channel, the refraction angle of the filaments was also reduced but only from 50 to 45 as can be seen in figure 5.3(b). A region of self emission was also seen in this figure at  $z = z_{vf} + 350\mu\text{m}$ , this was again the result of the high intensity beam interacting with the high density plasma at the end of the channel.

The self emission image of the beam within the channel in figure 5.3 (d) showed that the beam was guided with an approximately constant radius of  $20\mu\text{m}$  over a distance of  $400\mu\text{m}$  before it encountered the end of the channel. At this point there was an approximately circular region of extremely strong emission,  $180\mu\text{m}$  wide and centred around a point  $280\mu\text{m}$  from  $z_{vf}$ . The location of this region corresponded well with the self emission feature observed in the deflectogram of figure 5.3(c), this was the non uniform plasma that blocked the end of the channel.

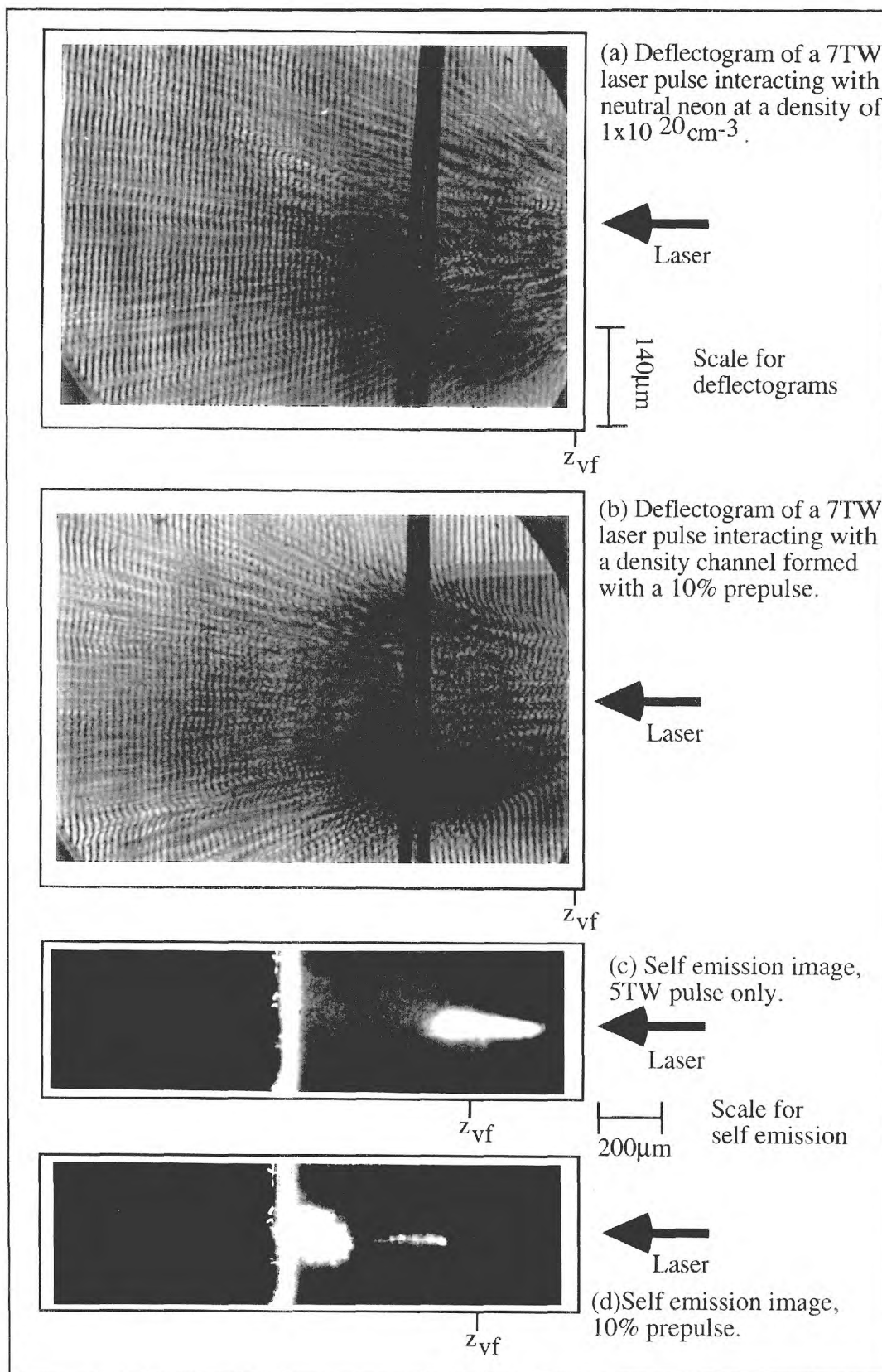


Figure 5.3 Deflectograms and images of the self emission with a wave guide, (b) and (d), and without, (a) and (c).

Using the same geometric optics approximation as above, for the 10% prepulse would predict the onset of plasma formation around 1.2mm before  $z_{vf}$ . However, the gas density at this point was negligible. Detectable plasma, capable of refracting the pulse, would have been formed as soon as the electron density increased above  $1 \times 10^{19} \text{ cm}^{-3}$ . According to the gas jet characterisation this would have occurred 500 $\mu\text{m}$  before the vacuum focusing position (at  $z = z_{vf} - 500\mu\text{m}$ ), where  $n_a = 8 \times 10^{18} \text{ cm}^{-3}$ ,  $I = 3 \times 10^{15} \text{ Wcm}^{-2}$  and  $Z^* = 2^+$  from the Coulomb barrier model [16].

If the length of the channel was determined by the focusing optics then it would occur at the same position regardless of gas density. Figure 5.3 (c) and (d) showed that this was not the case, as at this higher density the length of the channel was located 400 $\mu\text{m}$  after the vacuum focusing position (at  $z = z_{vf} + 400\mu\text{m}$ ), compared to 550 $\mu\text{m}$  after (at  $z = z_{vf} + 550\mu\text{m}$ ), for lower density case in figures 5.1 (b) and 5.2 (b). A summary of the measurements of the location of the end of the channel for the 1 and 10% pre-pulses over a range of gas densities for a prepulse advance of 2.3ns is shown in Figure 5.4

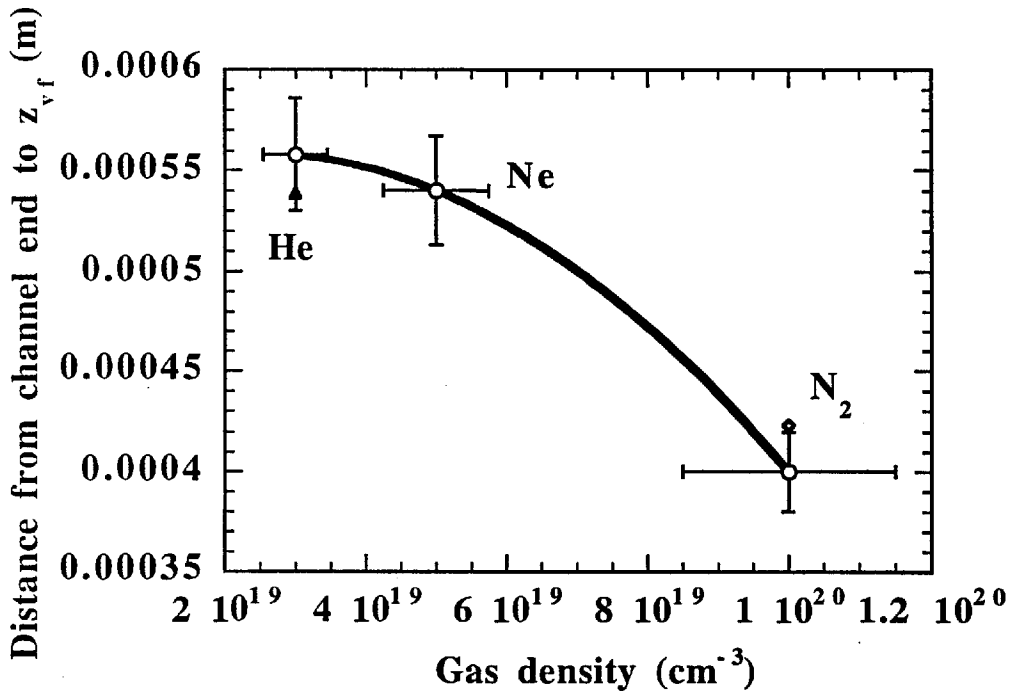


Figure 5.4 Channel length versus gas density for He, Neon and Nitrogen  $t_d = 2.3\text{ns}$

From figure 5.4 the length of the channel measured from  $z_{vf}$ , for the 1% prepulse can be seen to reduce as the gas density increased. This was the result of refraction of the prepulse from the ionisation induced density gradients at densities greater than  $5 \times 10^{19}$

cm<sup>-3</sup>. The fact that the channel length in Helium agreed with Neon to within the experimental uncertainty at gas densities below  $5 \times 10^{19}$  cm<sup>-3</sup> confirmed that refraction was not the limiting factor at this density.

### **5.3.2 Limitation of the guiding length due to the energy content of the prepulse.**

In most of the laser plasma applications relevant to the work in this thesis the object of using a channel to guide the high intensity pulse is to maximise the length of the high density and intensity interaction. To investigate the optimum parameters for maximising the channel length and uniformity the relative delay between the two pulses was varied and measurements of the density gradients, self emission and the energy transmission were made. The series was undertaken with the gas jet density reduced to  $3 \times 10^{19}$  cm<sup>-3</sup> to minimise the effects of refraction on the length of the channel. Figure 5.5(a)-(c) Moiré deflectograms and the corresponding self emission images in figure 5.6 (a) - (c) of the interaction of 5TW pulses with the gas jet at a centre gas density of  $3 \times 10^{19}$  cm<sup>-3</sup> showed how the channel developed as the delay between the 1% prepulse and the heating pulse was increased.

It should be noted that in the deflectograms in figure 5.5 (c) the film pack was moved so that the vacuum focusing position was on the extreme right hand side of the field of view. This explains why the join between the filters does not match figures 5.5 (a) and (b). This was done to enable the end of the channel to be observed as it expanded further along the z axis with increasing prepulse advance.

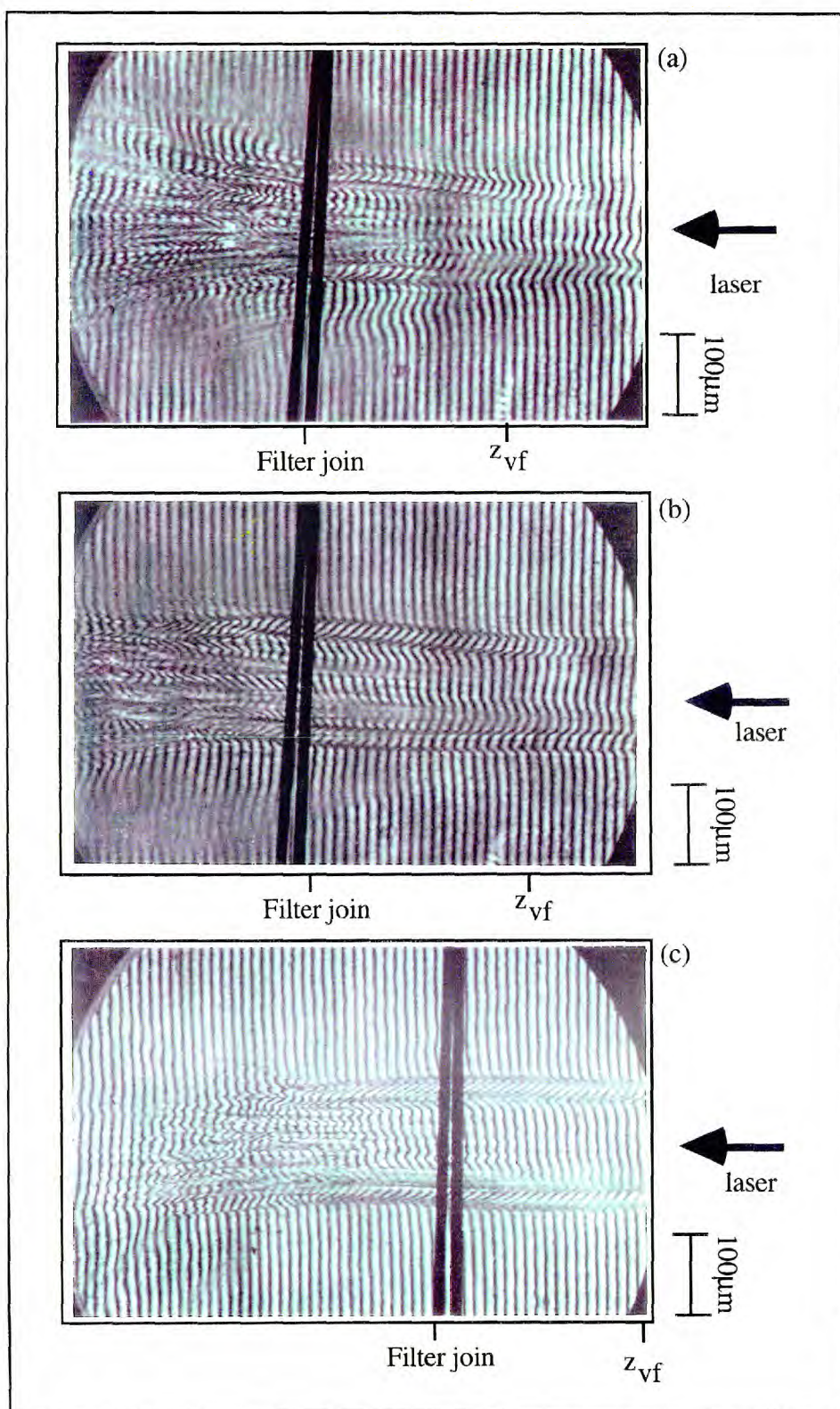


Figure 5.5 Deflectograms of a 5TW pulse focused into a guide formed after allowing the wave guide to expand for increasing time,(a) 500ps, (b) 1ns (c) 2.3ns. Please note the change in the position of  $z_{vf}$  in (c) compared to (a) and (b).

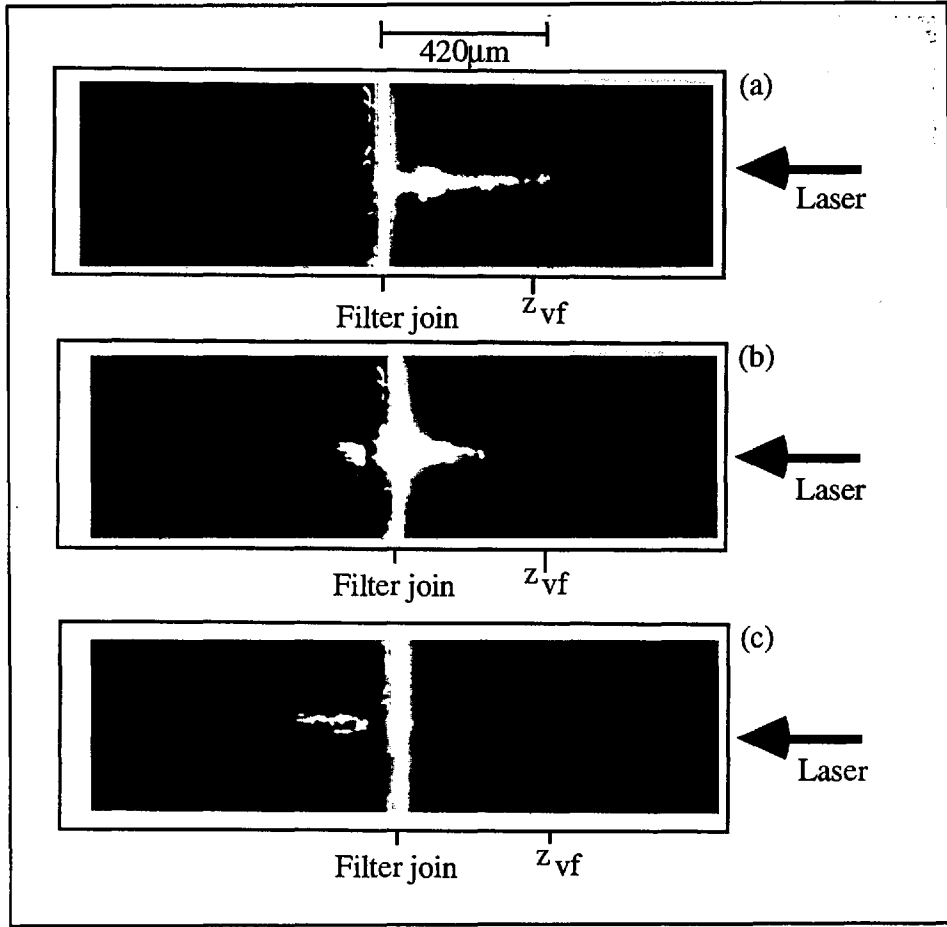


Figure 5.6 Increase in guiding length as a function of prepulse advance, (a) 500ps, (b) 1ns, (c) 2.3ns. All these images corresponded to the deflectograms in figure 5.5 (a), (b) and (c).

It is clear from figure 5.6 that as the prepulse advance increased from 500ps to 2.3ns the self emission region was displaced by 700 $\mu$ m along the z axis, corresponding to a guiding over approximately 20 defocusing lengths. There were a number of features visible in both figures 5.5 and 5.6 which confirmed that increasing the delay between the prepulse and the interaction beam created a longer and more uniform plasma that guided the pulse further into the gas jet. In figure 5.5 the distance between the end of the channel and  $z_{vf}$  increased from 400 $\mu$ m to 600 $\mu$ m as the delay increased from 500ps to 2.3ns. Secondly, there was no smudging of the fringes outside the channel in figure 5.5 (c), indicating that the wave guide became more effective in confining the laser light as the prepulse advance increased. Thirdly, the ionisation channels at the end of the channel refracted at a marginally smaller angle in figure 5.5(c) compared to (a). Fig 5.7

summarises the increase in the channel measured by the deflectometer and the increase in guiding length inferred from the self emission.

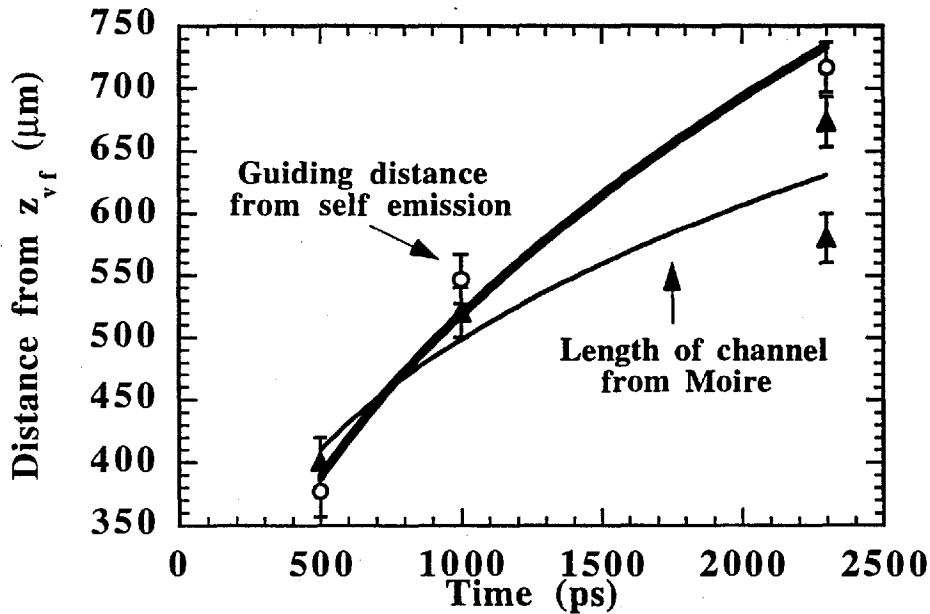


Figure 5.7 The open circles show the measured guiding distance obtained from the self emission images while the triangles show the measured channel length from the Moiré as a function of prepulse advance. The full lines show the increasing trend in the data as the prepulse advance increases.

The large scatter in the Moiré data was the result of differences in the laser energy and in the uncertainty of the location of the measuring the location of the end of the channel due to the non uniform nature of the plasma there. Both the self emission and Moiré data supported the interpretation that the high intensity beam was guided over longer distances as the prepulse advance was increased. This occurred because the channel expanded further along the radial and longitudinal axes and the plasma at the end of the channel became more uniform as the time interval increased. The percentage of laser energy transmitted within the acceptance angle of the calorimeter also confirmed this interpretation and is plotted in figure 5.8.

The fraction of laser energy increased from 3 to 9% and the length of the channel increased from 400 to 580μm as the relative time interval increased from 500ps to

2.3ns. The maximum transmission was found from figure 5.8 to be 9% at the maximum advance of 2.3ns. A transmission fraction of 9% within the acceptance angle of 5.5 degrees of the calorimeter corresponded to a refraction angle of 18 degrees. It was shown in section 5.3 that the maximum angle of propagation of a bound ray for this channel was around 10 degrees. The 18 degree angle was the result of refraction in the non uniform plasma created at the end of the channel.

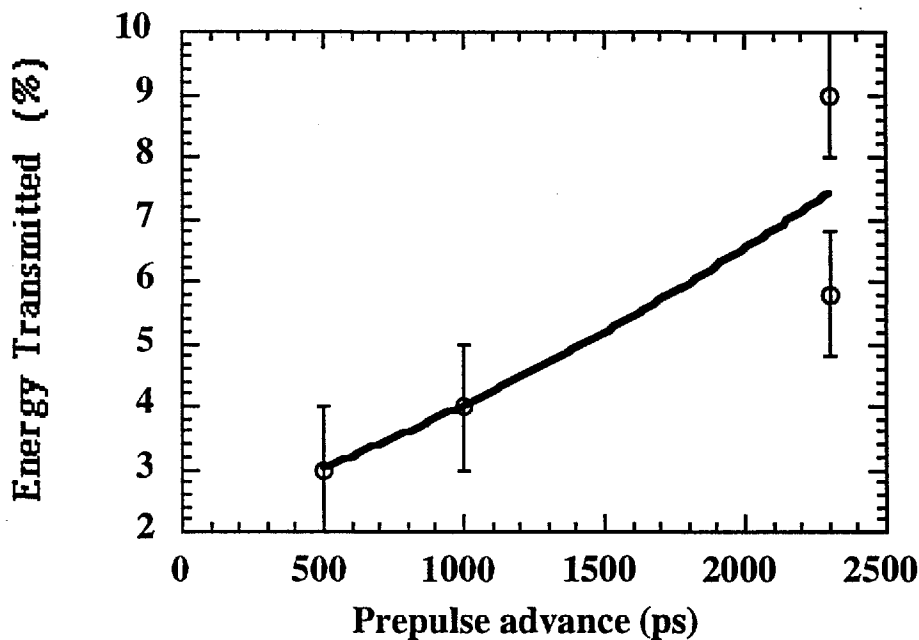


Figure 5.8 The open circles show the measured fraction of laser energy transmitted as a function of prepulse advance. The full line is a polynomial fit to the data showing the increasing trend

To investigate the source of the channel non uniformity a deflectogram of the channel before the arrival of the 5 TW pulse was obtained. This channel was allowed to expand for the maximum advance of 2.3ns. Figure 5.9 shows a Moiré deflectogram of the development of the channel after expanding for 2.3ns after the incidence of the 1% prepulse.

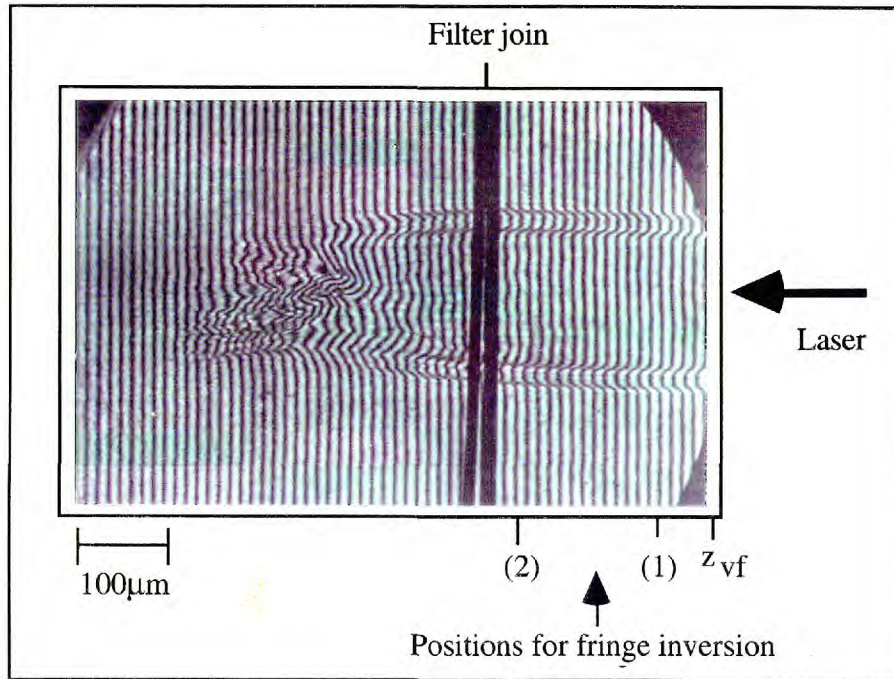


Figure 5.9 Deflectogram of density channel, formed 2.3ns after the end of the 1% prepulse, taken just before the arrival of the main pulse.

In this figure the plasma was observed to have expanded uniformly about the  $z$  axis until  $z = z_{vf} + 300\mu\text{m}$  where radius began to reduce. This continued until the channel was closed by the high density, non uniform plasma at  $z = z_{vf} + 520\mu\text{m}$ . It was this plasma that was responsible for refracting the laser energy at large angles from the  $z$  axis. Density profiles were taken at the points (1) and (2) along the uniform portion of the channel, and are shown in Figure 5.10. The neutral density at these points was (1)  $n_a = 1.3 \times 10^{19}$  at  $z = z_{vf} + 50\mu\text{m}$  and (2)  $n_a = 2.2 \times 10^{19} \text{ cm}^{-3}$  at  $z = z_{vf} + 200\mu\text{m}$ . The increase in peak density that can be seen at the shock front between the two positions  $z = z_{vf} + 50\mu\text{m}$  and  $z = z_{vf} + 200\mu\text{m}$  was a result of this gas density gradient.

It can be seen from figure 5.10 that the electron density at the shock was only twice the neutral gas density for both points. This was surprising, as it was shown in chapter 2 that the limiting ion density was four times the neutral density for a strong shock. The electron density is then determined by the ionisation level  $Z^*$ . If the electron temperature was of the order of 10eV the ionisation level would be  $Z^* = 3$ , resulting in electron densities up to  $10n_a$ . If, for the profiles in figure 5.10, the ion density was indeed set by the limiting value for a strong shock of  $4n_a$  [3] then the ionisation stage was very low, around,  $Z^* \sim 0.5$ .

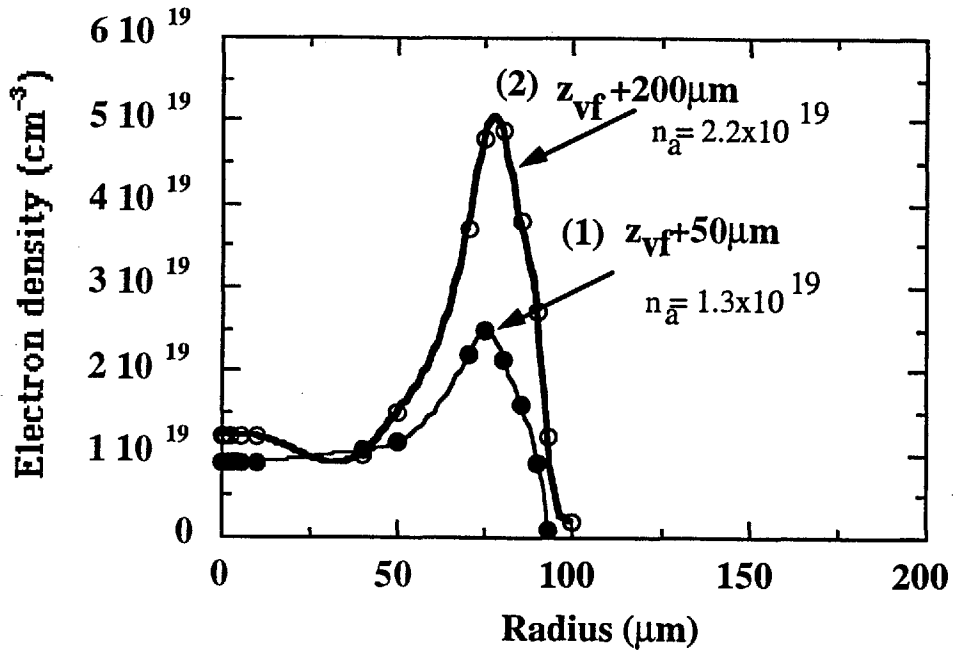


Figure 5.10 Density profiles of the waveguide before the arrival of the main pulse.

This low level of ionisation was supported by the observed increase in electron density when the high intensity pulse was guided through the channel as described in section 5.2.2. This issue was investigated quantitatively by measuring the density conditions that existed in the shock before and after a 5TW pulse was focused into Helium at the same gas density  $n_a = 3 \times 10^{19} \text{ cm}^{-3}$  as for figure 5.9.

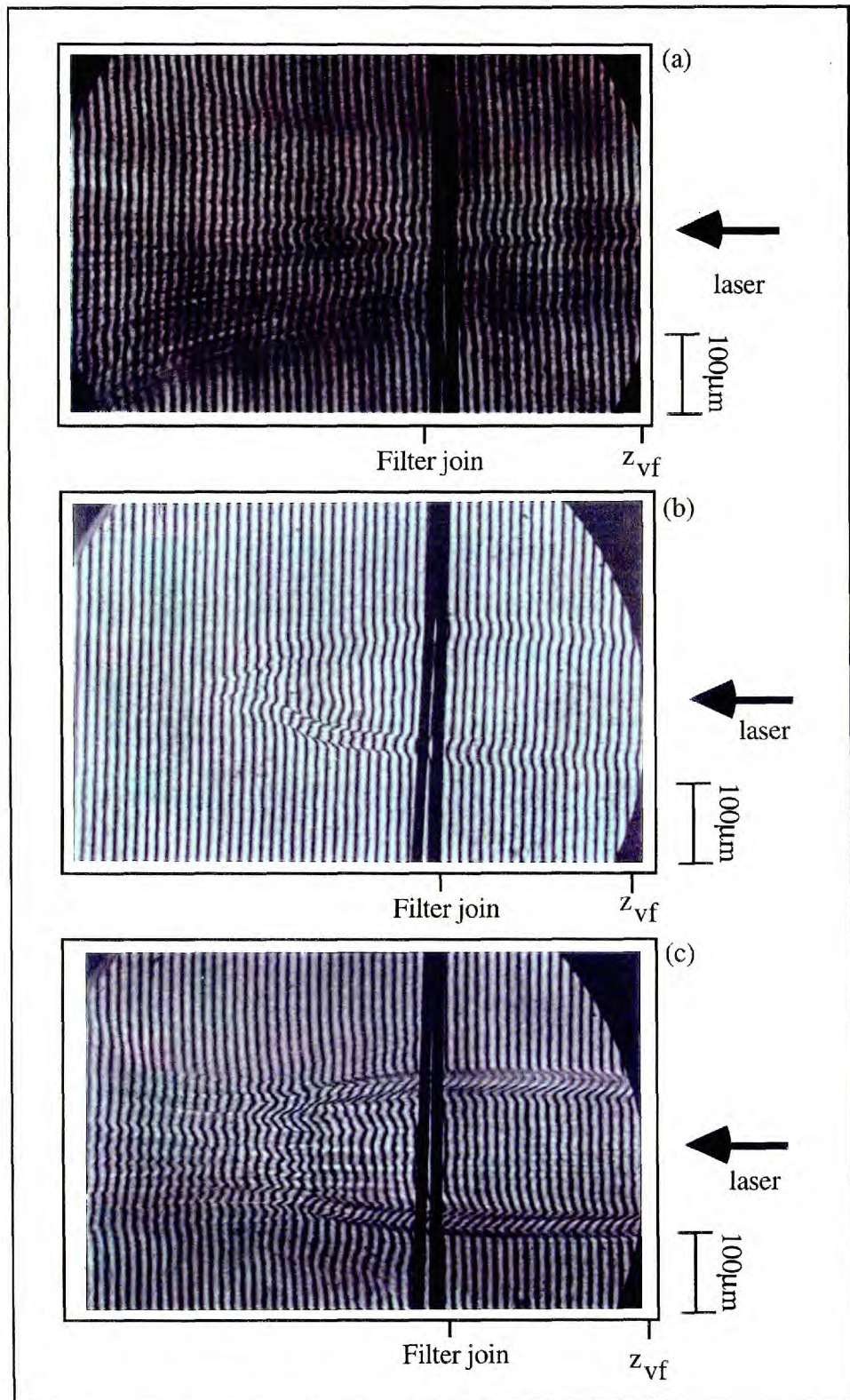


Figure 5.11 Deflectograms of Helium for, (a) 4TW pulse only, (b) prepulse only, prepulse advance = 2.3ns, level = 1%, (c) 4TW pulse focused into the waveguide.

## 5.4 The ionisation balance at the shock fronts in Helium.

The measurements described for Neon at a gas density of  $3 \times 10^{19} \text{ cm}^{-3}$  and with the 1% prepulse were repeated for Helium at the same gas density. Figure 5.11 shows deflectograms of (a) the refraction of the laser without a guide, (c) the main pulse focused into the channel formed after expanding for 2.3ns, (b) the density channel 10ps before the arrival of the main pulse.

The refraction angle of  $\alpha = 17$  degrees that can be observed in figure 5.11(a) agreed well with the refraction angle of 14 degrees inferred from the measured laser transmission fraction of 14%. These results were also consistent with the refractive effects observed when the laser pulse was focused into Neon.

It can be seen by comparing figure 5.11(b) and (c) that when the main pulse was focused into the channel the number of fringe shifts occurring at the channel walls increased. This corresponded to an increase in electron density. Figure 5.12 shows electron density profiles at the same positions on the z axis as (1) and (2) in figure 5.9(b) and (c).

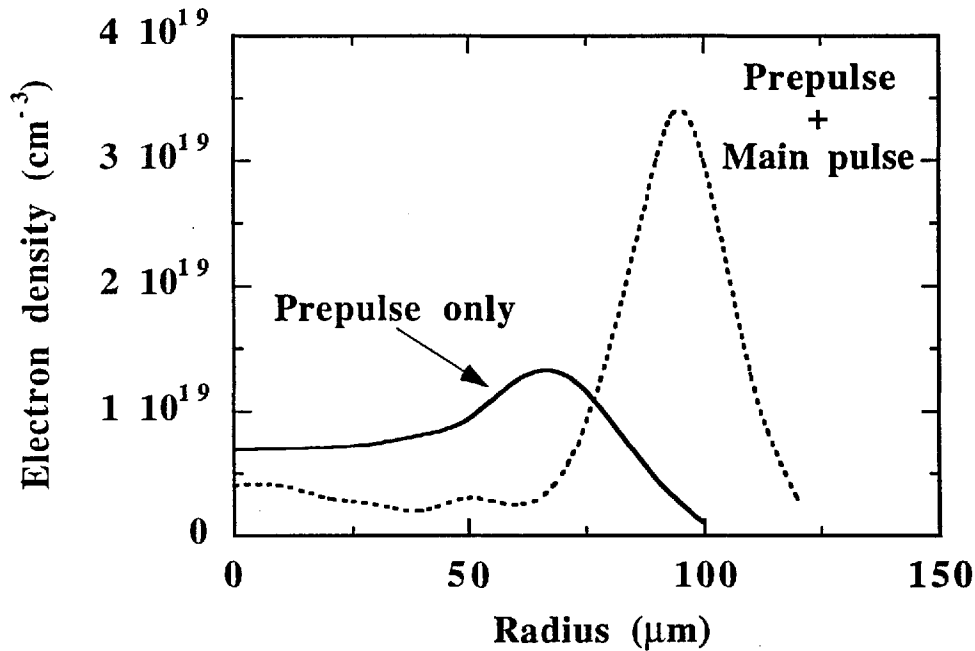


Figure 5.12 Increase in electron density at the shock front, due to optical ionisation.

From the profiles in figure 5.12 the density at the channel walls was a factor of 2.7 higher when the high intensity pulse was focused into the channel compared to the electron density just before the arrival of this pulse. The most probable cause of this increase was through tunnel ionisation by the main pulse. A crude estimate of the intensity at the channel walls was obtained by assuming a top hat spatial profile with radius equal to the channel radius. For this shot the laser power was 4TW, giving an intensity at the channel walls of  $1.7 \times 10^{16} \text{ Wcm}^{-2}$ , for a channel radius of  $100 \mu\text{m}$ . This intensity was significantly above the threshold of  $9 \times 10^{15} \text{ Wcm}^{-2}$  for doubly ionised Helium. If it was assumed that the shock became doubly ionised ( $Z^* = 2$ ) following the arrival of the main pulse, then the ionisation stage before this was indeed less than 1, at  $Z^* = 0.75$ .

This was in fact an upper limit because the assumption of a flat top beam would overestimate the intensity at the shock fronts compared to a profile such as a Gaussian. If the main pulse profile was a Gaussian with a  $1/e$  radius of,  $\omega_0 = 100 \mu\text{m}$  then the intensity at the shock front was  $4 \times 10^{15} \text{ Wcm}^{-2}$  and  $Z^* = 1$ . This indicated that the ionisation stage before the arrival of the main pulse was then  $Z^* = 0.37$ . The real situation is likely to fall somewhere between these two extremes. This confirms that the ionisation stage at the shock front was less than unity. This section showed that the observations with Helium were completely consistent with the observed increase in the electron density at the shock fronts in Neon following optical ionisation by the main pulse. The data in both cases were consistent with low ionisation stages at the shock fronts, this suggested that the plasma had recombined strongly after the 2.3ns expansion time. Hydrodynamic simulations were carried out to investigate the mechanisms affecting the electron density, ion density and ionisation balance throughout the temporal and spatial evolution of the plasma.

## 5.5 Simulations of channel formation.

The simulation of channel formation and expansion has been described in detail in section 2.4. The deposition of energy in the centre of the plasma was treated as a free parameter and varied until the simulated expansion characteristics matched the observed expansion measured by the Moiré deflectometer. In order to match the simulated electron density to that measured by the deflectometer it was also necessary to account for the non equilibrium nature of the plasma. This was achieved by post processing the output of the hydrodynamic simulations with an average atom treatment of the ionisation. This model

has also been described detail in section 2.2 and has been used to successfully model transient ionisation in chlorine plasmas [68] and to model the initial stages of collisional ionisation in chapter 4. Figure 5.13 shows the simulation results for the expansion of the density channel following the irradiation by a 1% prepulse in Neon at an average gas density of  $n_a=2.5 \times 10^{19} \text{ cm}^{-3}$

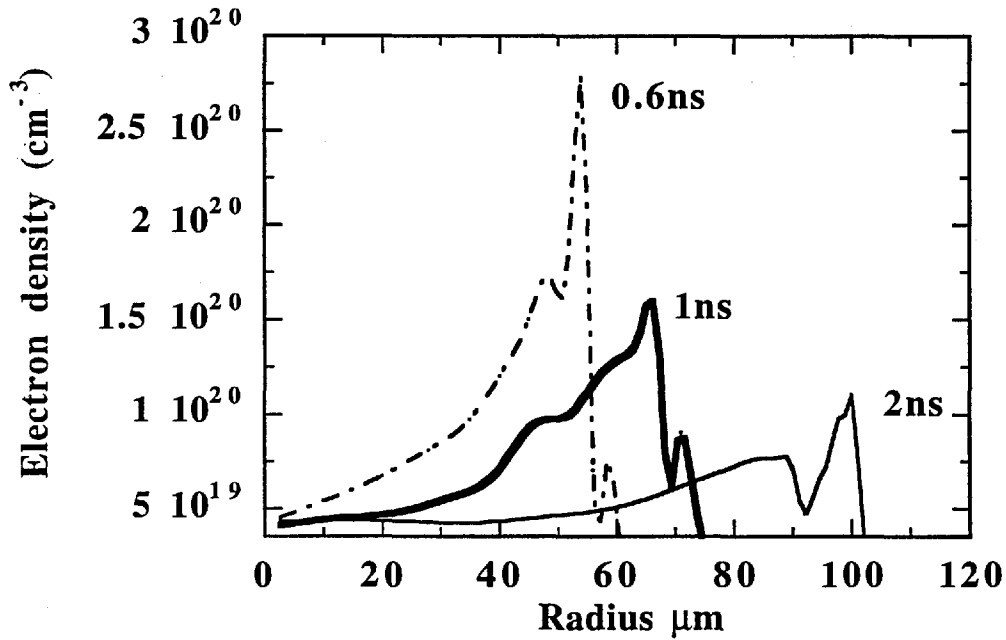


Figure 5.13 Simulations of electron density at  $n_a=2.5 \times 10^{19} \text{ cm}^{-3}$  for the 1% prepulse. The non physical double pulse structure that develops after 0.6ns in the electron density profiles is caused by a limitation of the Average Atom model that sets the minimum ionisation level to  $Z^* = 1$  [68].

It can be seen from this figure that the peak density reduced as the channel expanded. This was due to recombination in the cooling plasma, confirming the interpretation in the previous section. The decrease in shock density with time supported the interpretation of the low ionisation balance observed at the shock fronts in the Helium and Neon data, described in section 5.2.2 and 5.4. A more detailed analysis of the simulation examining the ionisation stage  $Z^*$ , electron and ion density for one time step confirmed this interpretation, and is shown in figure 5.14.

The profiles shown in Figure 5.14 showed a large decrease in the ionisation stage from around  $Z^*=8$  at  $r = 20\mu\text{m}$  to  $Z^* = 1$  at the shock front,  $r = 90\mu\text{m}$ . This strongly supported the interpretation of the Helium and Neon data that the ionisation stage was reduced near the shock front. However, this model could not be compared directly to the data because the minimum ionisation stage was artificially limited in the simulation to  $Z^* = 1$ . This explained why the electron density replicated the ion density at the shock front and predicted a peak electron density of over  $1 \times 10^{20} \text{ cm}^{-3}$  compared to the value of  $4 \times 10^{19} \text{ cm}^{-3}$  measured from figure 5.10 for the same atomic density. If the model could predict levels of ionisation less than 1 then there would have been closer agreement with the data.

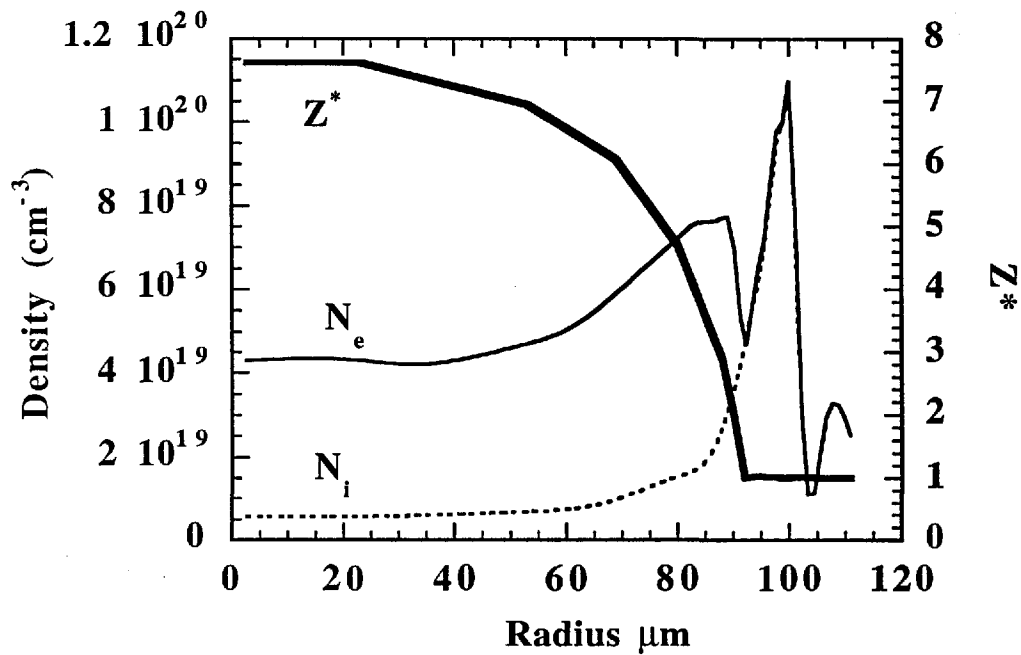


Figure 5.14 Electron and ion density and the ionisation stage,  $Z^*$ , for the simulation at 2ns. The double structure seen in the electron density profile is a result of the artificial limiting of  $Z^* = 1$  in the Average Atom model [68].

These simulations confirmed that the ionisation balance at the channel walls was low prior to the arrival of the 5-7TW pulse and the increase in the electron density was caused by optical ionisation due to the interaction pulse.

## 5.6 Study of guiding with 10% pre-pulses as a function of prepulse advance

The previous section showed that the length over which guiding occurred was limited by defocusing of the prepulse from two distinct limiting mechanisms. The first at gas densities greater than  $5 \times 10^{19} \text{ cm}^{-3}$  was due to refraction of the pre-pulse from the ionisation induced density gradients. The second, at densities below  $5 \times 10^{19} \text{ cm}^{-3}$ , was due to a combination of the energy content of the prepulse and the natural divergence of the beam due to the focusing optics. It was shown in section 5.3 that for the 1% prepulse, the distance over which guiding occurred was ultimately limited by the high density plasma formed at the end of the channel. To maximise the channel length for a given prepulse advance required a prepulse with a higher energy content. There were two reasons for this, (i) the initial length of the plasma that was created extended for a greater distance after  $z_{vf}$ , due to the increased laser power. (ii) The electron temperature was higher for 10% compared to 1% pre-pulses and so the channel expanded more rapidly, thus reducing the density of the plasma at the end of the channel.

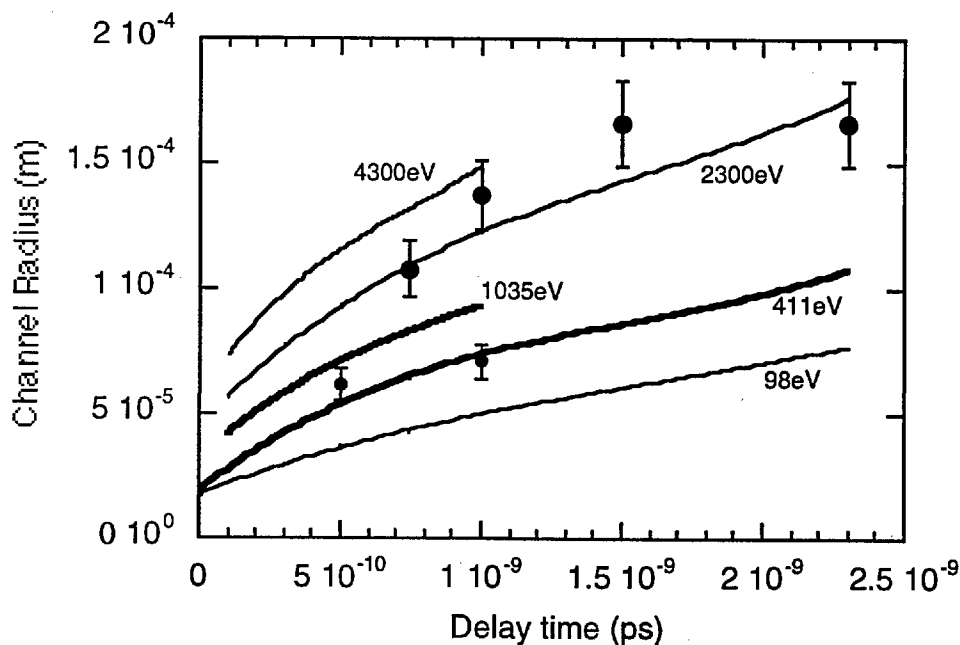


Figure 5.15 Channel expansion characteristics for an initial spot width of  $30 \mu\text{m}$ . The filled circles are the channel radii measured by the Moiré deflectometer for the channels produced by 1 and 10% prepulses. The full lines are the results of simulations with the MEDUSA code over a range of energies.

A study of the optimum channel formation in Neon and Helium at a nozzle centre gas density of  $3 \times 10^{19} \text{ cm}^{-3}$  was carried out as a function of prepulse advance for the 10% prepulse. To gain an insight into the increase in the electron temperature that drove the channel expansion for the 1 and 10% prepulses 1D simulations were fitted to the observed expansion characteristics, as described in section 2.4 and 4.3.6. Figure 5.15 shows the channel expansion measured at the same position in the gas jet for  $2.5 \times 10^{19} \text{ cm}^{-3}$  Neon for the two levels of prepulse.

The accuracy of the temperature measurement from the channel expansion was limited both by limited number of measurements taken and the uncertainty of the initial channel radius at zero time. This was estimated from the spatial radius of the plasma observed for the full energy shots. The best fits to the data were  $T_e = 400 \text{ eV}$  and  $2.3 \text{ keV}$  for the 1% and 10% pre-pulses respectively. If there was no defocusing then the laser intensity was around  $5 \times 10^{15}$  and  $5 \times 10^{16} \text{ Wcm}^{-2}$  for the 1% and 10% prepulses respectively. The absorption model of Pert [31] predicted a temperature of  $T_e = 382 \text{ eV}$  and  $1912 \text{ keV}$  respectively for these laser intensities. This agreed very well with the temperatures obtained from the simulation. However, as a result of the uncertainty in the initial plasma size the error in the temperature inferred from these simulations was not less than a factor of 2.

The density and self emission measurements were repeated with the 10% prepulse to investigate if this improved the capabilities of the channel to guide the pulse over longer distances. Moiré deflectograms of the interaction of 7 TW pulses with Neon at a centre density of  $3 \times 10^{19} \text{ cm}^{-3}$  are shown in Figure 5.16 (a) 500ps (b) 1.5ns and (c) 2.3ns. Evidence of guiding over longer distances was also obtained from the images of the self emission in Figure 5.17 (a) 500ps (b) 750ps (c) 1.0ns (d) 1.5ns and (e) 2.3ns. Generally the observations were of the same nature as for the 1% prepulse but the channel increased more rapidly in the radial and axial directions as the delay time increased. The most important difference was the lack of regions of self emission in any of the deflectograms in figure 5.16 even at the earliest times. This was because the increased energy of the prepulse caused the plasma to expand more quickly, removing the high density regions at the end of the channel.

The loss of contrast in the outer radial regions of the deflectogram of the channel was again observed at a delay of 500ps, as shown in Figure 5.16 (a). This showed that some leakage of the beam had taken place, as a result of the less than fully developed shock fronts at this time. The ion density of the radial shock wave increased as the time delay

increased and strong evidence of guiding over the length of the nozzle was observed when the delay was increased to the maximum of 2.3ns in Figure 5.16(c). A number of features from figure 5.16(c) were consistent with guiding over the whole length of the gas jet. The channel was observed to extend over the whole field of view, at least 790 $\mu$ m past  $z_{vf}$ . Strong fringe shifts were also observed close to the centre of the channel over a width of approximately 30 $\mu$ m. These were the result of additional ionisation arising from the passage of the main beam. The shifts extended along the z axis for 640 $\mu$ m past the vacuum focus at ( $z = z_{vf}$ ) at an approximately constant radius of 18 $\mu$ m. It will be shown that this is consistent with the propagation of the beam at the fundamental mode size of the guide [42]. Finally there was little or no evidence of beam leakage as the density at the shock front was fully developed.

In figure 5.16 (c) two additional symmetric ionisation channels were observed to develop from the main beam as it propagated through the guide. These channels then propagated away from the z axis at 10 degrees. If all the beam energy were contained within this 10 degree cone angle, the fraction of energy measured by the calorimeter would have been 30%. The measured transmission fraction was actually less than this at 22% which corresponded to an average refraction angle of 12.5 degrees. The most likely source of the additional refraction was from regions of neutral gas at the end of the channel.

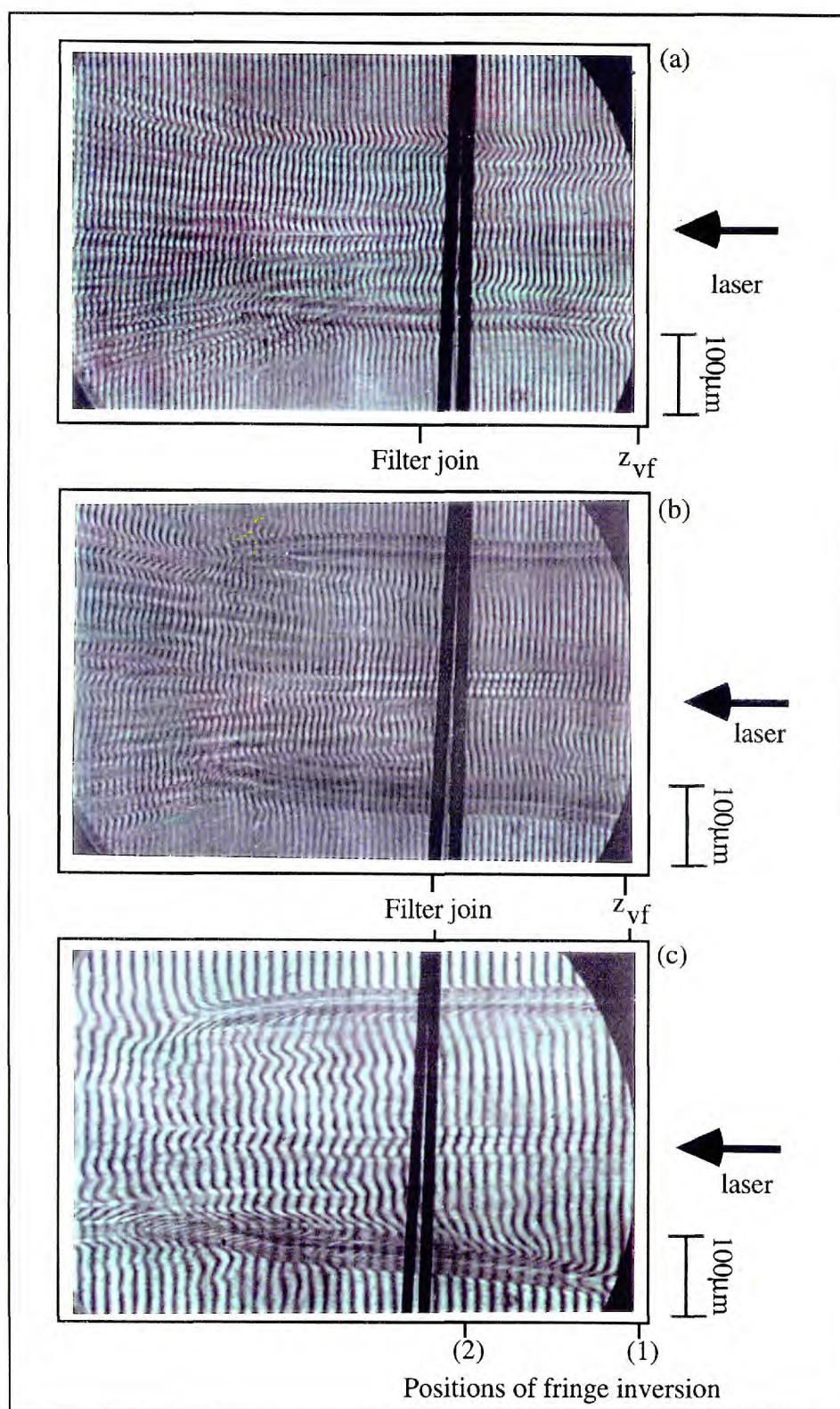


Figure 5.16 Deflectograms of 7 TW pulses focused into wave guides formed using 10% pre-pulses. The prepulse advance was varied from (a) 500ps, (b) 1.5ns and (c) 2.3ns.

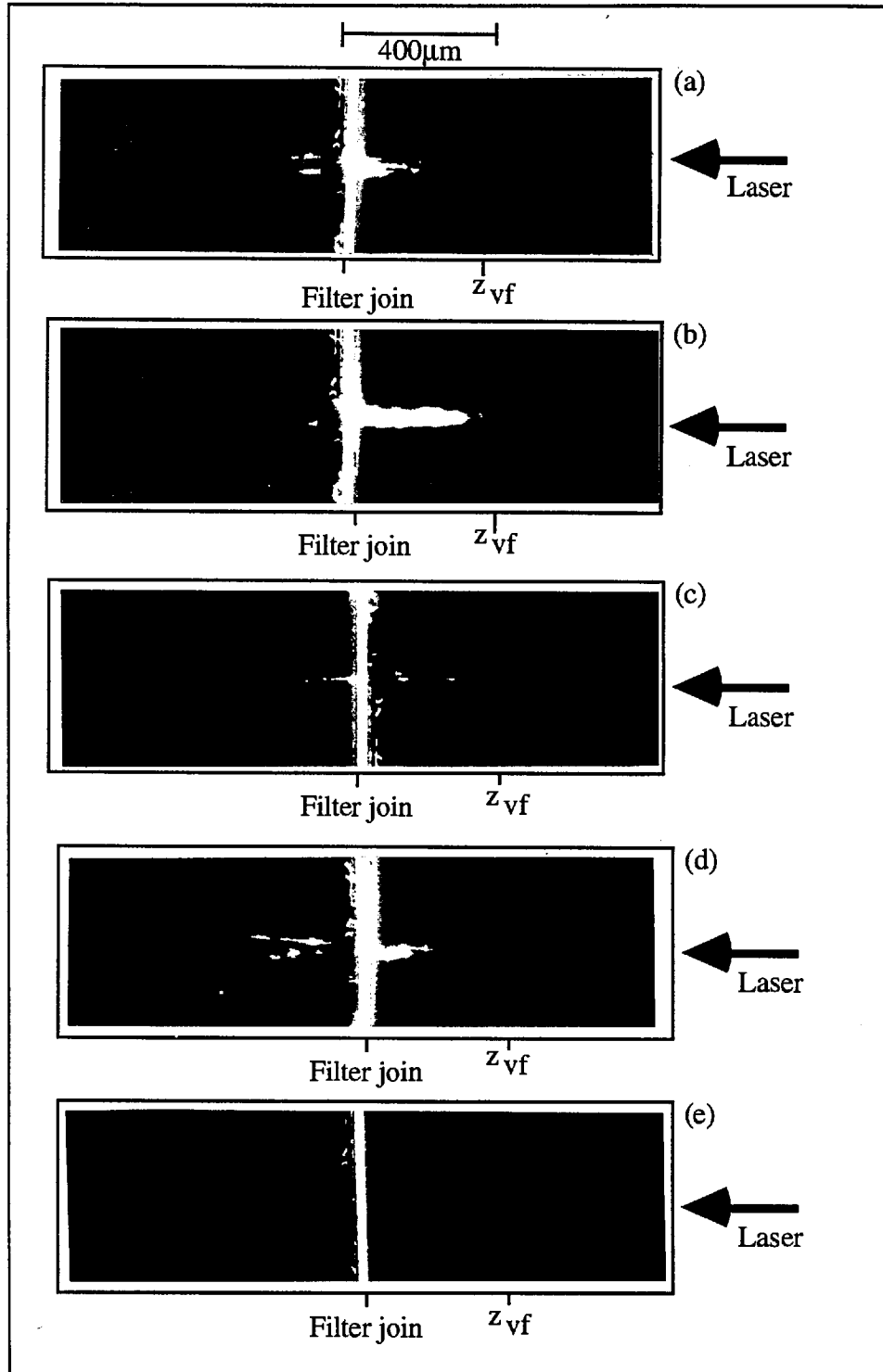


Figure 5.17 Self emission images for increasing prepulse advance , (a) 500ps, (b) 750ps, (c) 1ns, (d) 1.5ns and (e) 2.3ns. The images for delays of 500ps, 1.5ns and 2.3ns corresponded to the deflectograms in figure 5.16 (a) , (b) and (c).

### 5.6.1 Guiding over 70 defocusing lengths

The evolution of the self emission images with increasing prepulse advance supported these observations. The extent of the self emission increased from 600 to 900 $\mu\text{m}$  as the delay increased from 500ps to 2.3ns. The width of the self emission also reduced as the delay increased above 750ps, confirming that guiding at the fundamental mode size of the channel occurred. A graph of the increase in guiding length with prepulse advance from the self emission images is shown in figure 5.18.

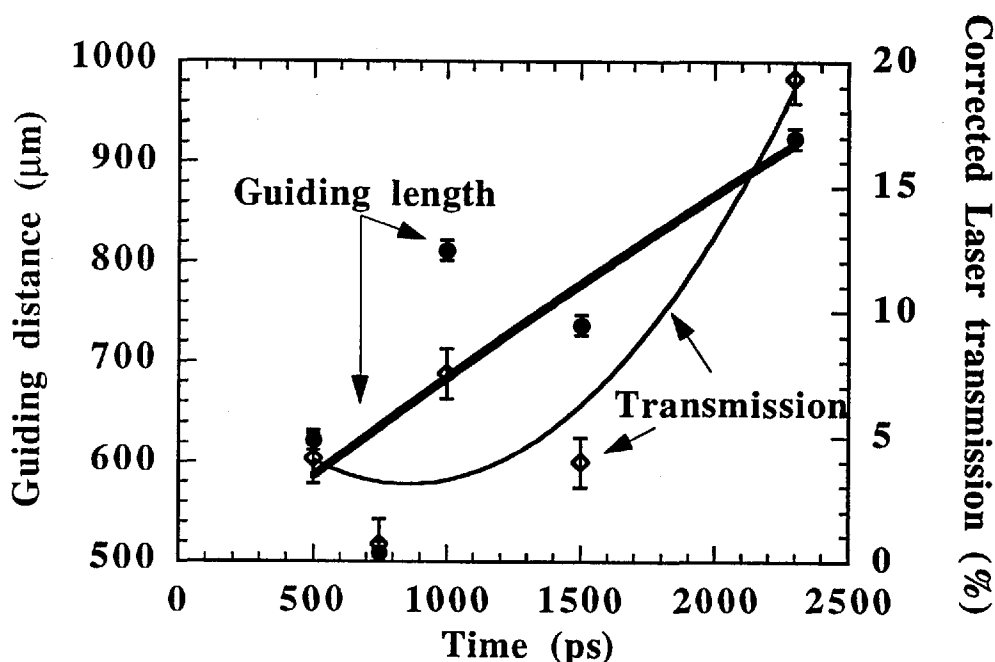


Figure 5.18 The filled circles show the guiding length measured from the extent of the plasma self emission in figure 5.17 (a) -(e). The diamonds show the measured laser energy transmissions for the same shots. The full lines are linear and quadratic fits to the guiding length and transmission respectively. These fits indicate the increasing trend of both the guiding length and energy transmission fraction.

It can be seen from figure 5.18 that there was a definite correlation between the guiding length observed from the self emission and the measured energy transmission fraction (corrected for the contribution of the fraction of the 10% prepulse that was transmitted). The maximum transmission corresponded to a divergence angle of the beam of 12.5 degrees. This was compared to the critical confinement angle obtained from the density

profile of the shock. The electron density was measured at two points (1)  $z_{vf}$  and (2)  $z_{vf} + 200\mu\text{m}$  along the  $z$  axis as marked in figure 5.16(c). The corresponding electron density profiles can be seen in figure 5.19 at both points. It can be seen that the central plasma formed at (2) (at  $z = z_{vf} + 200\mu\text{m}$ ) had a diameter (at half the maximum density) of  $18\mu\text{m} \pm 8\mu\text{m}$ .

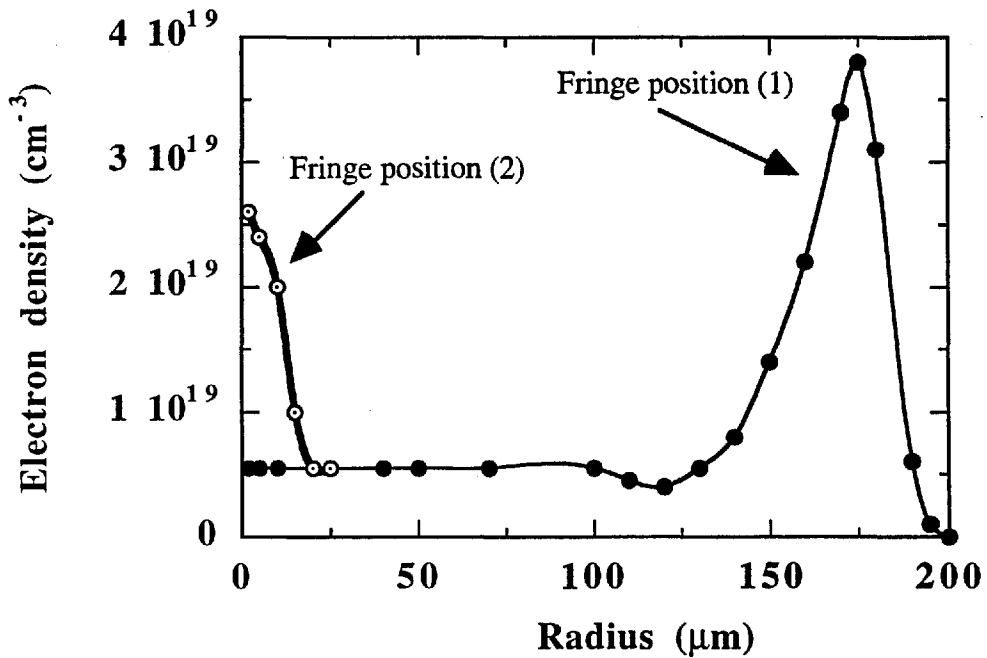


Figure 5.19 Electron density profiles from the deflectogram at a prepulse advance of 2.3ns. If a Gaussian profile is fitted to the plasma at the centre of the channel at fringe position (2) then this corresponded to a spot diameter (full width half maximum) of  $18\mu\text{m}$ . A simple analysis of the refractive index change at fringe position (1) demonstrated that the guide would confine rays with angles up to 10 degrees.

The simple ray optics treatments of the channel resulted in a critical angle,  $\theta_c = 10$  degrees at position (1) ( $z = z_{vf}$ ). If all the energy was confined by the plasma and the channel extended over the whole length of the gas jet the fraction of energy transmitted measured by the calorimeter would be 30%. The measured transmission was 22% implying that the either the channel did not extend over the entire gas jet or that there was some energy leakage through the shock fronts. The most probable interpretation was that the energy transmission was still limited by the channel length and not leakage. This was confirmed from the observation that the density of the shock fronts on one side of

the channel could be seen to reduce towards the end of the field of view in figure 5.16 (c). The intensity at the centre of the channel was estimated from the density profile at point (2)  $z = 200 + z_{vf}$  to a first approximation by assuming a flat top focal profile. The radius was  $18\mu\text{m}$  and the mean intensity for a beam energy of  $12\text{J}$  and a laser pulse length of  $3\text{ps}$  gave an intensity of  $6 \times 10^{17} \text{ Wcm}^{-2}$ .

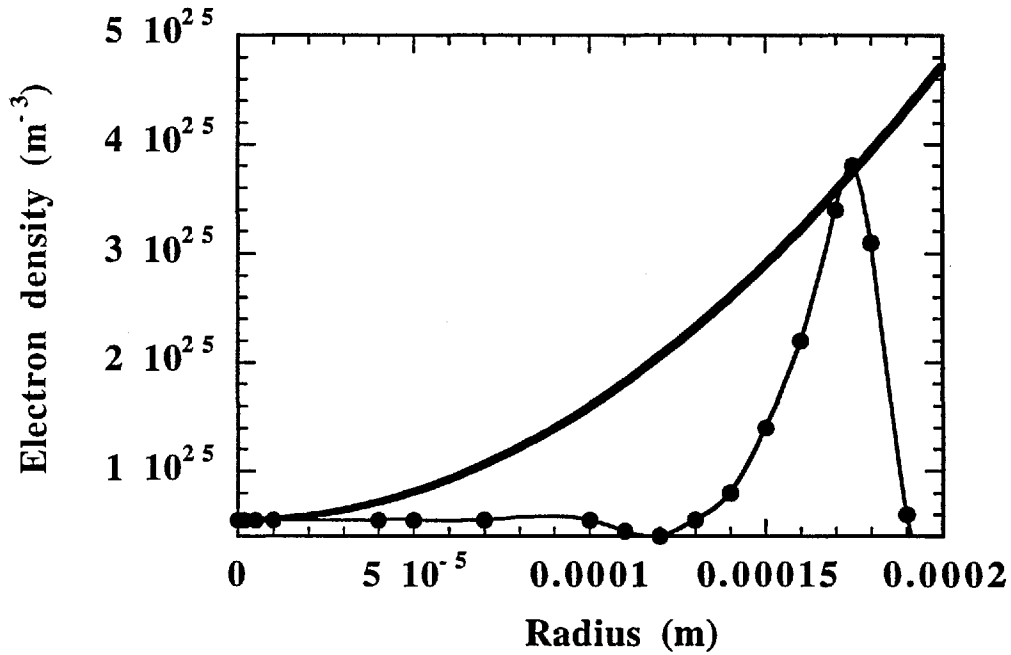


Figure 5.20 The points show the experimental density profile obtained by Abel inversion of figure 5.15 (c) at position (1). The full line shows the quadratic fit to the experimental guide density profile.

A more accurate method is to fit a Gaussian to the profile [42], then use the Coulomb barrier model to estimate the guided pulse intensity. However this method required knowledge of the ion density, which could not be measured at the centre of the channel. However, if it was assumed from the simple top hat assumption that the peak intensity was greater than  $2 \times 10^{17} \text{ Wcm}^{-2}$  then the plasma would have been in a He like ionisation stage (8+), giving an ion density of  $3.3 \times 10^{18} \text{ cm}^{-3}$ . A Gaussian fit assuming this ion density gave a  $1/e$  radius  $w_0 = 10\mu\text{m} \pm 5\mu\text{m}$ , which agreed well with the simple estimate from the flat top profile. This was compared to the radius of the fundamental mode of a Gaussian beam through a waveguide,  $w_0$  as described in section 2.1,

$$w_0 = \left( \frac{\lambda}{\pi} \right)^{1/2} \left( \frac{n_c}{n_0 b} \right)^{1/4} \quad (41)$$

The guide parameters from the quadratic fit to the density profile shown in figure 5.20. In SI units the parameters were,  $n_0 = 5.5 \times 10^{24} \text{ m}^{-3}$ ,  $a = 1$  and  $b = 1.8 \times 10^9 \text{ m}^{-2}$ . The  $1/e$  radius of the fundamental mode was  $w_0 = 19 \mu\text{m}$  from equation (41). Considering the approximate nature of the Gaussian fit to the plasma profile this agreement was very reasonable. This confirmed that the density profile observed at the centre of the channel resulted from optical ionisation from the main laser beam propagating at the fundamental mode width  $w_0$ .

This experiment investigated guiding of terawatt pulses in dense gases where refraction was important. This regime was relevant for applications such as particle accelerators [9] and studies of relativistic self focusing. It showed that the use of plasma wave guides in this regime could overcome the very strong refractive effects. The focused intensity in the plasma was increased by more than an order of magnitude from  $2 \times 10^{16} \text{ Wcm}^{-2} \pm 50\%$  to  $1 \times 10^{18} \text{ Wcm}^{-2} \pm 50\%$  by focusing the 5TW pulse into the waveguide rather than the neutral gas. For applications such as the recombination X-ray laser it was necessary to study guiding in denser plasmas with shorter pulse durations and lower intensities. Guiding in plasmas with these parameters was studied by focusing a KrF laser at a wavelength of  $0.248 \mu\text{m}$ , a pulse duration of 350fs into Neon gas at a density of  $1.5 \times 10^{20} \text{ atoms cm}^{-3}$  and a maximum intensity in vacuum of  $4 \times 10^{17} \text{ Wcm}^{-2}$ .

## 5.7 Channel formation with 500GW, KrF laser pulses.

In these experiments the conditions required to guide a laser pulse in a density channel was studied with KrF laser pulses with  $\lambda = 0.248 \mu\text{m}$  and a temporal pulse width of 0.350ps. The gas density was increased to  $1.5 \times 10^{20} \text{ cm}^{-3}$ , however for  $\lambda = 0.248 \mu\text{m}$ , the critical density was also increased to  $n_c = 1.78 \times 10^{22} \text{ cm}^{-3}$ . For this experiment the ratio of the gas to the critical density was an order of magnitude less than the experiments with the  $1 \mu\text{m}$  laser ( $n_a / n_c \sim 0.001$  compared to  $> 0.01$  for the  $1 \mu\text{m}$  experiment). As a result refraction was not as obvious, but it did affect the formation of the channels to some extent. For measurable gain in the X-ray laser long interaction regions are required and so the limitations of channel formation was an important subject to be studied for the feasibility of this scheme.

The diagnostic set up used in this experiment was similar to the previous experiments except that the calorimeter was replaced with a lens to image the refraction of the incident interaction beam. This enabled the distribution of light refracted with and without the preformed plasma to be compared directly. The Moiré density gradient diagnostic was again used to give a simultaneous picture of the plasma density. The self emission diagnostic did not produce well defined images and was not used. The imaging system used for this diagnostic was a quartz doublet with an aperture of 100mm and a focal length of 250mm. The numerical aperture of the F/2.5 optic allowed the capture of rays within an angle of 11 degrees, rays that were refracted at angles greater than this did not reach the detection system. The laser was again focused 500 $\mu$ m before the nozzle centre (defined as the point  $z_{vf}$ ) and the lens system imaged a point at 390 $\mu$ m after the vacuum focus (at  $z = z_{vf} + 390\mu\text{m}$ ). A description of the laser system and diagnostics was included in the diagnostic section of chapter 3. The pre-pulses were formed with a 50% beam splitter, so that the channel was formed by a pulse with an identical energy to the guided pulse. This was useful because it allowed the formation of the channel to be directly compared to the initial plasma formation.

## 5.8 Channel formation in Neon

Moiré deflectograms of plasmas formed in Neon with gas density at the centre of the nozzle of  $1.5 \times 10^{20} \text{ cm}^{-3}$  are shown in figure 5.21(a) no channel, (b) the channel expansion after 800ps and (c) the channel plus the high intensity pulse. It can be seen from figure 5.21 (a) that the plasma expanded radially as the laser propagated along the z axis. From this figure the angle was measured to be approximately 6 degrees. The cone angle of the focusing optics was also 6 degrees so it was possible that this plasma expansion was the result of normal defocusing of the beam. The numbers on the bottom of each figure mark the positions of the fringes that were inverted to obtain the electron density profile. The maximum plasma radius within the field of view of the figure was 66 $\mu$ m at  $z = z_{vf} + 625\mu\text{m}$ , if the spatial profile of the beam was a top hat then the intensity at this point was  $1.5 \times 10^{15} \text{ Wcm}^{-2}$ . From the Coulomb barrier model a Neon plasma would be singly ionised at this intensity. This is in qualitative agreement with the observation of plasma at this point.

Figure 5.21 (b) showed how the plasma developed after a delay of 800ps. A channel with well defined density jumps at the shock fronts could be observed to exist from  $z =$

$z_{vf}$  to  $z = z_{vf} + 300\mu\text{m}$  but after this point the density jumps were not so pronounced. This was because the plasma did not expand as rapidly here due to a reduction in the beam intensity and plasma temperature. The plasma formed by focusing a second pulse into the channel showed strong evidence of guiding with a large enhancement of the fringe shifts, over (a) and (b), around position (8) at  $z = z_{vf} + 430\mu\text{m}$ . A quantitative evaluation of the deflectograms in figure 5.21(a) to (c) was undertaken by inverting fringes at points (1) - (9) along the  $z$  axis to obtain the density profiles

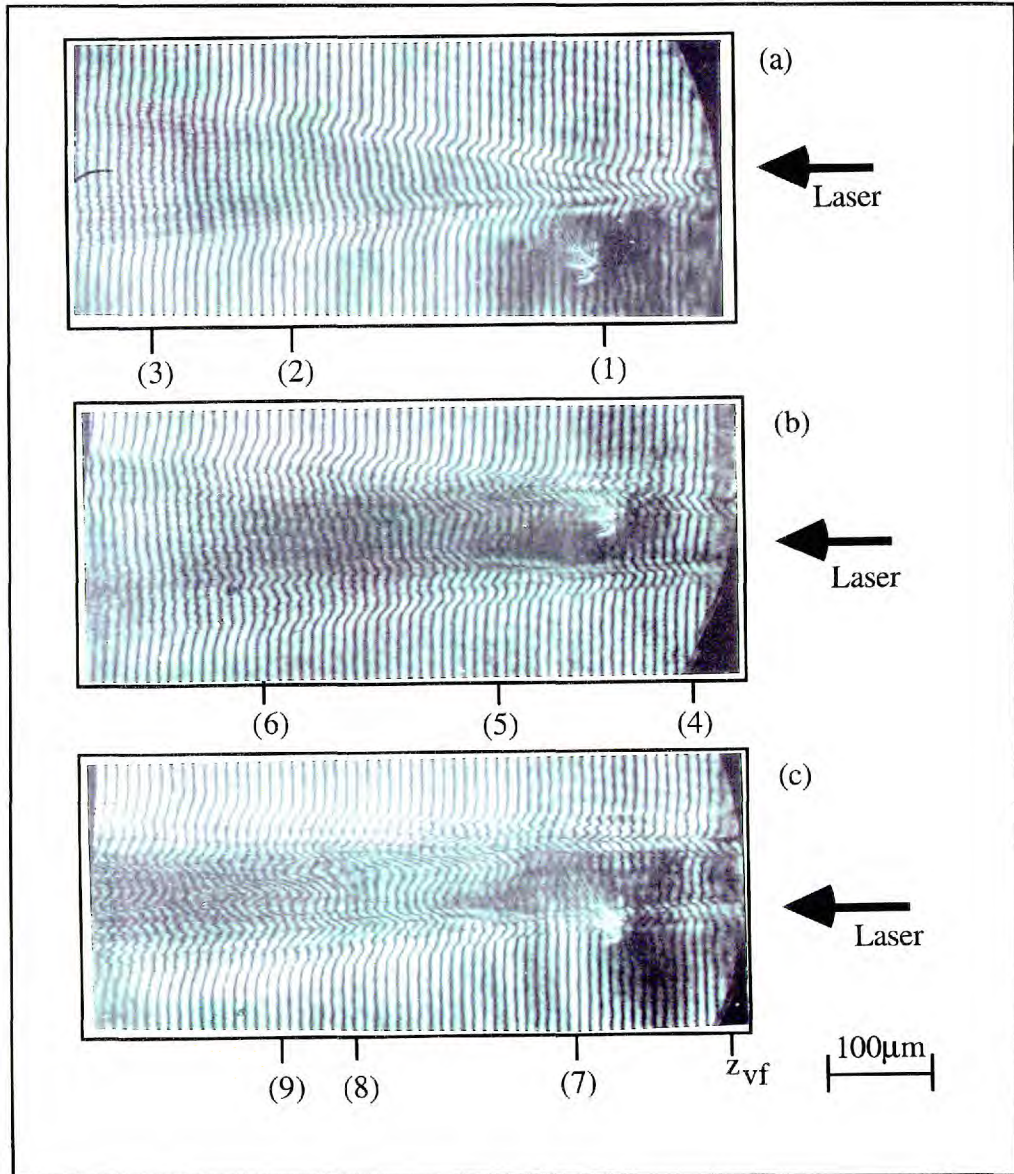


Figure 5.21 Deflectograms (a) without the channel, (b) the channel only, (b) the main pulse focused into the channel. The numbers (1) - (9) show the positions of the fringes that were inverted to obtain the electron density profiles.

### 5.8.1 Plasma density profiles formed by focusing the laser into the neutral gas.

The fringes in figure 5.21 were inverted at intervals along the z axis to give the density profiles along the length of the channel. Figure 5.22 shows electron density profiles at points (1) to (3) along the z axis for figure 5.21(a).

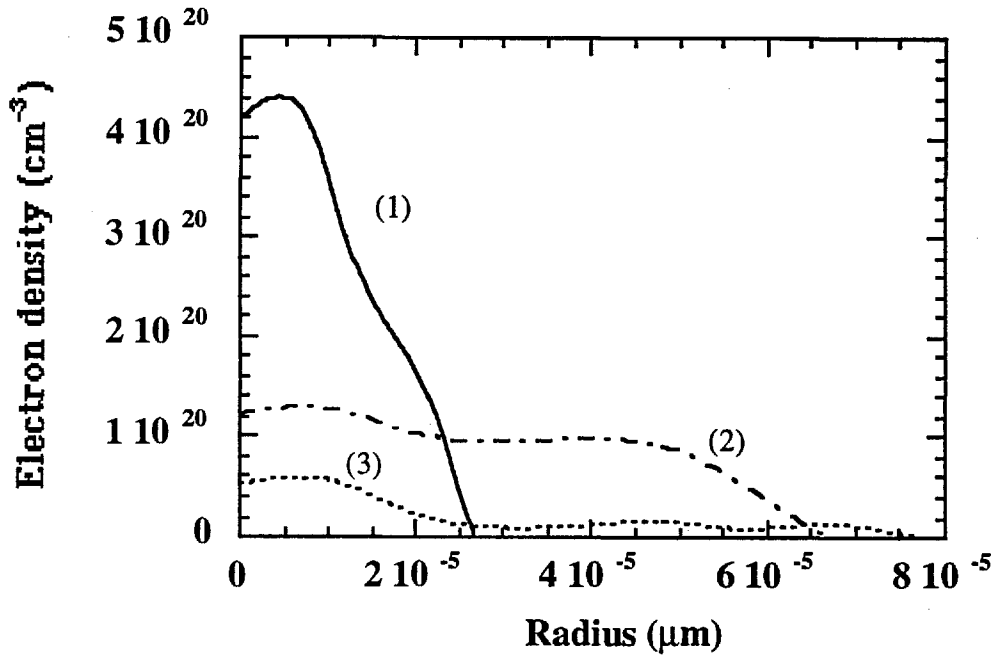


Figure 5.22 Density profiles along the axis of the gas jet for points (1)  $z = z_{vf} + 100\mu\text{m}$ , (2)  $z = z_{vf} + 400\mu\text{m}$  and (3)  $z = z_{vf} + 550\mu\text{m}$ . The plasma density was highest near the focus point, (1), and decreased as refraction lowered the laser intensity as it propagated to points (2) and (3).

From the density profiles shown in figure 5.22 it can be seen that the peak electron density was reducing as the laser propagated towards the centre of the gas jet (at  $z = z_{vf} + 500\mu\text{m}$ ). According to the characterisation the gradient in gas density in section 3.1, the peak electron density at point (1),  $z = z_{vf} + 100\mu\text{m}$ , represented an ionisation stage of  $7 - 8^+$ , this reduced to less than  $1^+$  at point (3),  $z = z + 550\mu\text{m}$ . The intensity was estimated, from the Coulomb barrier model [16] to fall from  $I = 1 - 2 \times 10^{17} \text{ Wcm}^{-2}$  at point (1) to less than  $9 \times 10^{14} \text{ Wcm}^{-2}$  at point (3).

If the beam expanded with the 6 degree divergence angle of the focusing optic the intensity at  $z = z_{vf} + 550\mu\text{m}$  would have been around  $1 \times 10^{15} \text{ Wcm}^{-2}$ , close to the threshold. The refraction angle from equation (20), was 6.8 degrees for  $\lambda = 0.248\mu\text{m}$ , an average scale length  $\partial r = 20\mu\text{m}$ , density,  $n_e = 3 \times 10^{20} \text{ cm}^{-3}$  and plasma length,  $\partial l = 300\mu\text{m}$ . Refraction from the density gradient consequently caused defocusing of the same order as the natural divergence of the focusing optic.

### 5.8.2 Plasma density profiles after the plasma had expanded for 800ps.

The density profiles along the z axis of the channel formed after allowing the plasma to expand for 0.8ns can be seen in figure 2.23.

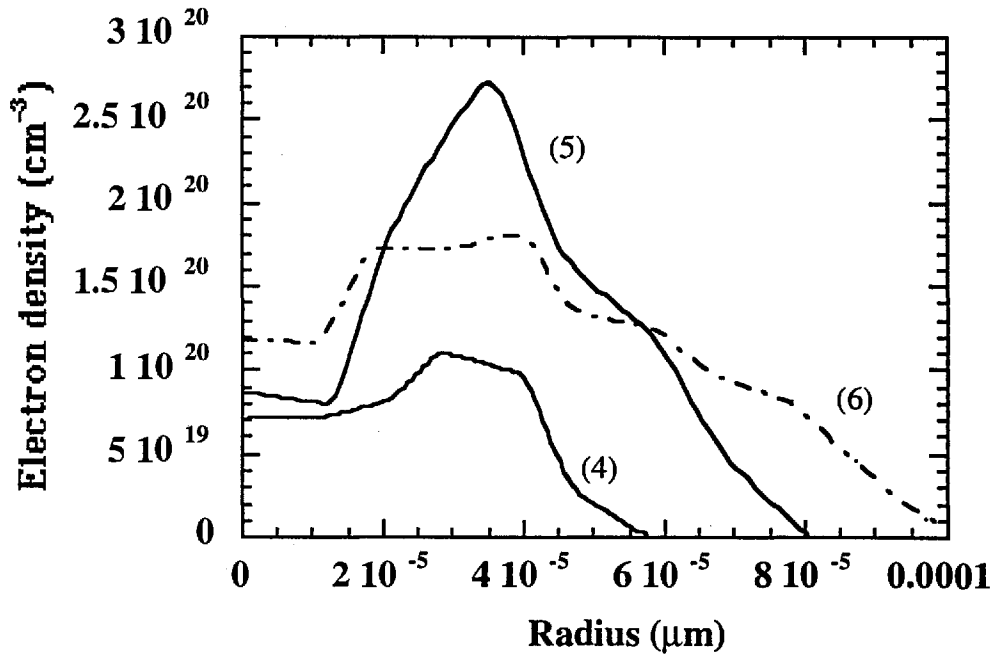


Figure 5.23 Density profiles along the z axis for the channel only at the points (3)  $z = z_{vf} + 50\mu\text{m}$ , (4)  $z = z_{vf} + 250\mu\text{m}$  and (5)  $z = z_{vf} + 500\mu\text{m}$ .

The density difference between the expanding shock front and the centre of the channel was used as a simple estimate of the range of angles that were confined by the plasma. Following the ray optics treatment of section 2.1, the critical angle for the shock near the

middle of the guide at point (5)  $z = z_{vf} + 250\mu\text{m}$  was,  $\theta_{cr} = 6$  degrees, from equation (38). This coincided with the observed refraction angle of the plasma without a guide in figure 5.22 and so the guide should be capable of confining all of the beam within the channel walls. The relative density difference between the channel centre and the walls can be seen to first increase up to point (5) (at  $z = z_{vf} + 250\mu\text{m}$ ) and then decrease for (at  $z > z_{vf} + 300\mu\text{m}$ ). The initial increase was due to the gas density gradient, while the decrease after  $z_{vf} + 300\mu\text{m}$  was due to the beam defocusing that reduced the energy deposited in the plasma. The reduced energy content of the plasma, reduced the rate of expansion, and led to limited channel formation after  $z_{vf} + 300\mu\text{m}$ .

### 5.8.3 Density profiles of the plasma formed within the channel.

When the second pulse was focused into the channel, regions of plasma with greatly enhanced densities were observed. This proved that the channel was confining the pulse and maintaining the laser intensity for distances much greater than the characteristic defocusing length. The electron density profiles at the evaluated at the points (7), (8) and (9) can be seen in figure 5.24.

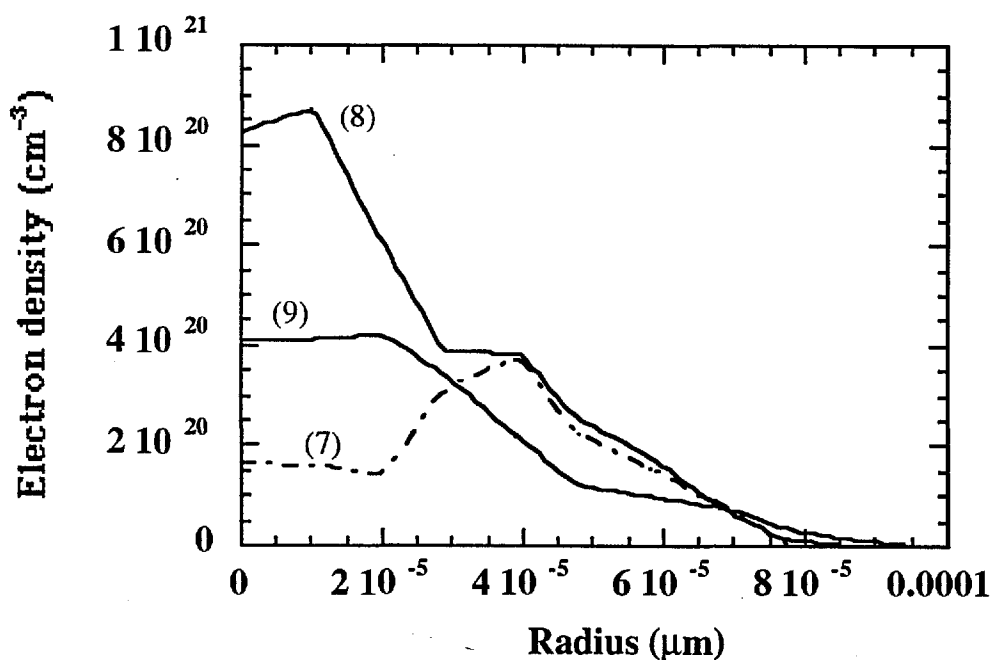


Figure 5.24 Density increase due to channel guiding at points along  $z$  axis for points (7)  $z = z_{vf} + 215\mu\text{m}$ , (8)  $z = z_{vf} + 430\mu\text{m}$  and (9)  $z = z_{vf} + 500\mu\text{m}$ .

The electron density profiles within the channel shown in figure 5.24 were all greater than the corresponding profiles with no wave guide shown in figure 5.22. This was true for all points along the  $z$  axis, from (at  $z = z_{vf}$ ) to the end of the channel (at  $z = z_{vf} + 500\mu\text{m}$ ). It was clear from this that the shock fronts that formed the channel walls did confine the beam within the channel walls. The most striking feature of the density profiles that proved the guiding efficiency of the channels was the increase in plasma density at point (8) (at  $z = z_{vf} + 430\mu\text{m}$ ) by a factor of 7 for the guided case compared to the density at point (2) (at  $z = z_{vf} + 400\mu\text{m}$ ) for the plasma formed without a guide. This density increase must have been due to higher levels of optical ionisation within the guide, again proving that the laser was enhanced by the wave guide at this point. The increase in intensity was explained with a simple geometrical analysis of the divergence of the beam, as shown in fig 5.25.

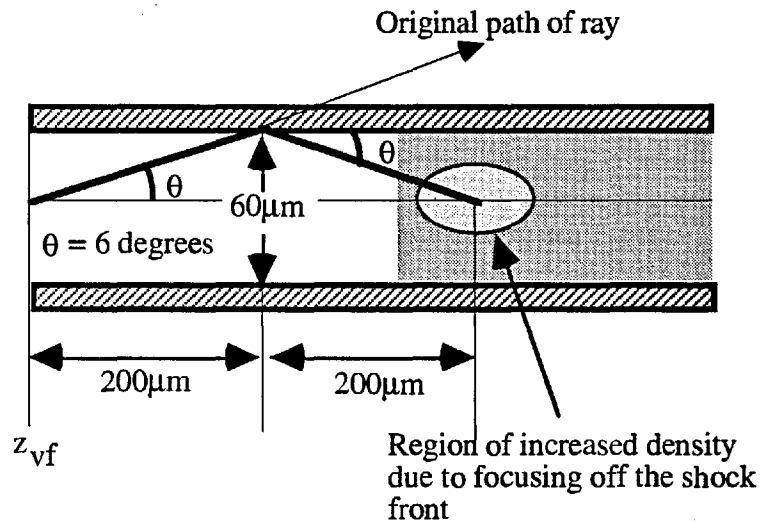


Figure 5.25 Geometric interpretation of the observed increase in plasma density. As the beam expanded due to refraction at an angle of 6 degrees it first encountered the shock front after propagating for  $200\mu\text{m}$ . It was then reflected off the density gradient at the same angle into the guide.

These studies confirmed that the guide was capable of confining rays with angles less than 6 degrees, in agreement with the geometrical optics estimate of the critical angle  $\theta_{cr} = 6$  degrees that was obtained in the previous section. The radius of the guided laser beam was inferred from the width of the region of enhanced density, this was measured to be  $25\mu\text{m}$  from figure 5.24. This plasma size was compared to the radius of the confined laser beam, obtained from the images of the transmitted laser light, shown in figure 5.26.

## 5.9 Further evidence of laser confinement from imaging.

The imaging diagnostic confirmed the interpretation of the last section and showed that the channel did indeed confine the laser, preventing refraction from decreasing the laser beam intensity.

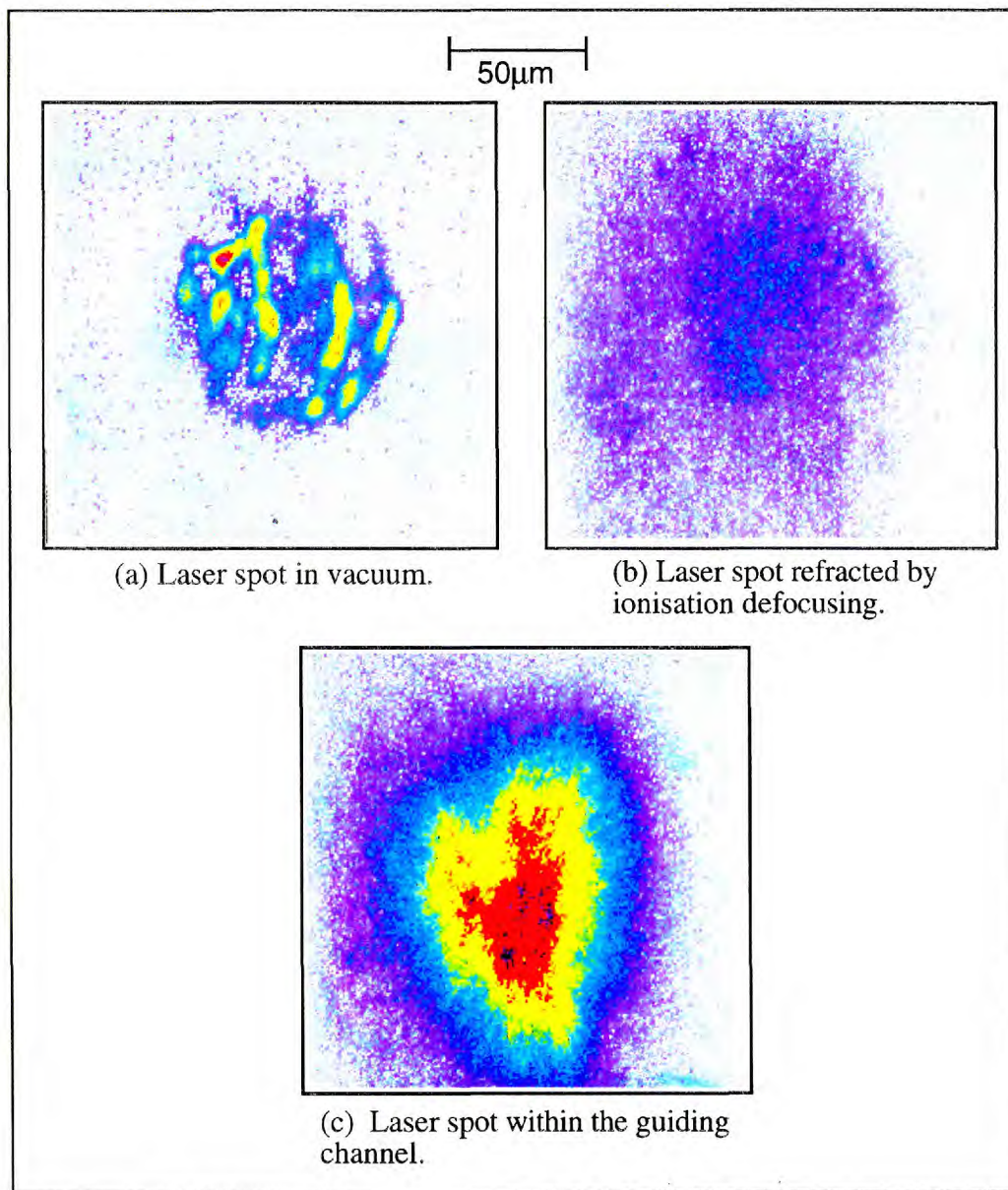


Figure 5.26 Images of the transmitted laser light (a) the beam profile in vacuum (b) with no channel, and (c) with a prepulse with a delay of 800ps.

The features of the beam within the channel were clear from a comparison of figure 5.26 (b) and (c), that showed that the laser intensity within the channel was significantly enhanced when the channel was present. A more quantitative analysis was obtained from 1D cross sections through figs 5.26 (b), (c) . The results can be seen in figure 5.27.

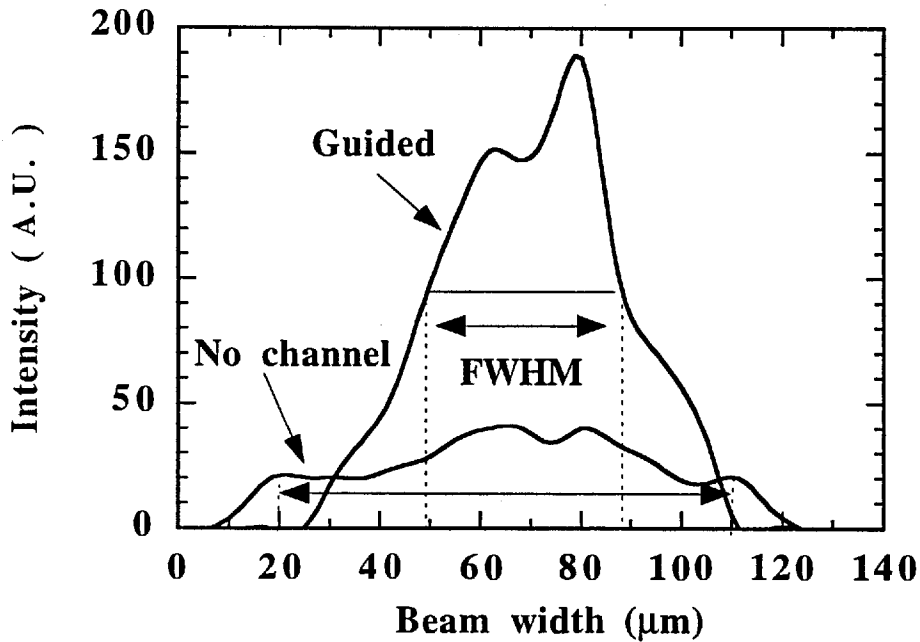


Figure 5.27 Laser intensity with and without the guiding channel. The laser spot size within the waveguide was a factor of 2.25 less than the unguided case.

The radius of the beam without the guide was  $45\mu\text{m}$  ( defined as the radius where the intensity fell to half the maximum). When the beam was focused into the guide the radius reduced to  $20\mu\text{m}$ . The guide thus decreased the laser radius by a factor of 2.25 when the beam was focused into the plasma guide. The reduced beam radius was also completely consistent with the factor of 5 increase in the peak intensity observed in figure 5.27. A comparison between the beam radius within the guide and the radius in vacuum showed that channel also overcame the natural divergence of the beam due to the focusing optic. The beam radius within the guide also corresponded well with the observed radius of  $25\mu\text{m}$  of the high density plasma created at point (8) (at  $z = z_{vf} + 430\mu\text{m}$ ) in figure 5.24. The formation of preformed plasmas capable of guiding intense lasers over a distance much greater than the characteristic length for defocusing from

refraction has been studied in this chapter. The major limitation was found to be the length and width of the preformed channel that were limited by the defocusing of the preforming pulse. It was clear from this experiment that the guiding process allowed the confinement of radiation in a strongly defocusing plasma, in a regime of great interest to the formation of recombination X-ray lasers [10].

## 6 Conclusions and further work

### 6.1 Refractive defocusing

The experiments described in this thesis investigated the effect of refraction on the plasmas formed by focusing intense laser pulses into gas jet targets. These types of targets have been proposed as a suitable medium for experiments, and applications, that required the interaction of high power laser pulses with dense plasmas over extended distances. The major advantage of a gas jet over a back filled chamber or gas cell is the small nozzle length that minimises the distance the laser pulses is required to propagate through the target gas before it reaches focus. For gas cells this distance is of the order of 100-200mm, two orders of magnitude higher than for a typical nozzle length of 1mm. This reduction reduces the effect of refraction due to ionisation induced density gradients and filamentation resulting from the intensity dependent refractive index of the neutral gas.

However, the work in this thesis has shown that refractive effects were still important when high power laser pulses were focused into neutral gas jet targets. In the experiment with 350fs KrF pulses refraction was found to reduce the laser intensity by up to a factor of 10 below the vacuum value, when the pulse was focused into the centre of the jet. The plasma was also observed to break up into numerous small scale ionisation channels. These were shown to be the result of refraction of intensity hot spots by local density gradients. The reduction in focused intensity inferred in this experiment agreed within a factor of two to the predictions of analytic and numerical models. This agreement was acceptable and within the estimated experimental uncertainty of the intensity inferal method.

These measurements were taken in a laser intensity and gas density regime that was directly applicable to the recombination Li-Like Neon XUV laser scheme. The results showed that it would be impossible to achieve the He-like ionisation stage that was required for this application by focusing the laser into the middle of a Neon gas jet. In the experiment with 1 $\mu$ m laser pulses the two dimensional spatial distribution of the electron density of a plasma produced by focusing a 1 $\mu$ m laser on the edge of the jet was obtained. The plasma was again observed to break up into small scale ionisation channels, which propagated at large angles to the laser propagation axis. These angles were found to be extremely well correlated with the measured laser energy transmission fraction and with the measured electron density gradients.

This results of this experiment showed that strong refractive effects caused the beam to diverge much more rapidly than the normal divergence of the focusing optics. The length of the interaction between the high intensity pulse and the high density plasma was shown to be severely limited. These measurements had implications for applications such as plasma accelerators and X-ray lasers that required long interaction lengths with high intensity pulses and dense plasmas. The only reliable method for overcoming the strong refractive effects in this regime was to use a plasma wave guide.

## 6.2 Guiding

The formation of wave guides in dense plasmas was studied with both the  $1\mu\text{m}$  and  $0.248\mu\text{m}$  lasers. The experiments described in this thesis were carried out with a gas density and laser intensity that was up to two orders of magnitude greater and a laser pulse duration up to three orders of magnitude shorter than the only previous plasma wave guide experiment [44]. The experiments in this thesis showed that factor that limited distance over which the high intensity pulse could be guided was the defocusing of the pre-pulse. This caused the width of the channel to be non uniform along the laser propagation axis. At gas densities in Neon below  $5 \times 10^{19} \text{ cm}^{-3}$  and 50GW pre-pulses the defocusing was found to be due to the natural divergence of the pulse due to the focusing optic. Increasing the prepulse to a power of 500GW overcame this limitation, enabling a 5TW pulse to be guided over the complete length of the gas jet, equivalent to many times the characteristic defocusing length. The laser intensity was inferred to increase from  $2 \times 10^{16} \text{ Wcm}^{-2}$  when the 5TW pulse was focused into the neutral gas compared to  $1 \times 10^{18} \text{ Wcm}^{-2}$  within the wave guide.

The experiment with  $0.248\mu\text{m}$  light showed that the waveguide could be used to increase the length of the highly ionised in the density and intensity regime that was directly applicable to the Li-like recombination XUV laser. The contribution of refraction to the divergence angle of the pre-pulse was calculated to be approximately equivalent to that of the focusing optic for these density conditions. The increase in channel length was modest in this experiment because of the limitation set by the finite depth of focus of the focusing optic. The depth of focus could be increased by the use of a Gaussian beam and an axicon to form the preformed plasma, as used in the low density / intensity experiments by Durfee and Milchberg[44].

### 6.3 General conclusions

In conclusion, the work in this thesis showed that refraction from ionisation induced density gradients limited the peak focused intensity and the length of highly ionised plasma when picosecond and sub-picosecond laser pulses were focused into gas jet targets with gas densities greater than  $3 \times 10^{-3}$  of critical density. The refractive effects were also observed to cause the plasma to break up into small scale ionisation channels.

The most promising method of overcoming these effects was the use of plasma density channels to confine and guide the pulse. This method was extensively studied in this thesis and shown to work successfully in a plasma and laser intensity regime that has not previously been studied. Further experiments are required to investigate the optimisation of the length and radial uniformity of the wave guide and their ultimate suitability for applications such as recombination XUV lasers. A detailed model of the propagation of the laser pulse within the channel would also be very useful to compare directly with the experimental observations.

## 6.4 References

1. R. G. Meyerand Jr and A. F. Haught, Phys. Rev. Lett. **13**, 7 (1964).
2. L. Spitzer, *Physics of Fully Ionised Plasmas*, (1st ed. Wiley, Interscience, New York and London, 1962).
3. Ya. B. Zel'dovich and Yu.P. Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena* (Academic, New York, 1966).
4. L. J. Radziemski and D. A. Cremers. (Ed), *Laser Induced Plasmas and Applications* (Dekker, New York and Basel, 1989).
5. H. J. Kunze, Phys. Rev. A . **3**, 937 (1971)
6. A. P. Thorne, *Spectrophysics* (2nd Ed. Chapman and Hall, London, New York, 1988).
7. Y. T. Lee, J. Quant.Spectrosc.Radiat. Transfer **38**, 131 (1987).
8. C. H. Skinner, Phys. Fluids B **3**, 2420 (1991)
9. F. F. Chen, *Laser Accelerators* (in Handbook of Plasma Physics, vol 4. 1987).
10. D. C. Eder, P. Amendt, S. C. Wilks, Phys. Rev. A. **45**, 6761 (1992)
11. D. J. Jacoby, G. J. Pert, S.A.Ramsden, L. D. Shorrok and G. J. Tallents. Opt. Comm. **37**, 193 (1981).
12. E. Teller. Science, **121**, 267 (1955).
13. M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, R. J. Mason, Phys. Plasmas **1**, 1626 (1994).
14. J. Peyraud and N. Peyraud, J. Appl. Phys. **43**, 2993 (1972).
15. N. H. Burnett and P. B. Corkum, J. Opt. Soc. Am. B. **6**, 1195 (1989).
16. S. Augst, D. Strickland, D. D. Meyerhofer, S. L. Chin, J. H. Eberly, Phys. Rev. Lett. **63**, 2212 (1989), B. M. Penetrante and J. N. Bardsley, Phys. Rev. A. **43**, 3100 (1991).
17. A. E. Seigman, *Lasers*, (University Science Books, Mill Valley, CA, 1986).
18. Evans R.G Can journal of physics, **64**, 893 (1986).
19. J. Nuckolls, L. Wood, A. Thiessen, G. Zimmerman, Nature **239**, 139, (1972).
20. J Lawson. Proc. Phys Soc. (Lond) B70, 6, (1957)
21. J. Meyer Ter Vehn, Nucl. Fusion, **16**, 405 (1976).
22. K. A. Brueckner and S. Jorna, Rev. Mod. Phys. **46**, 325 (1974).
23. S. C. Wilks, W. L. Kruer, M. Tabak, A. B. Langdon, Phys. Rev. Lett. **69**, 1383 (1992).
24. S. C. Wilks, P. E. Young, J. Hammer, M. Tabak, and W. L. Kruer, UCRL-JC-117745. (1994).

- 25 T. E. Glover, T. D. Donelly, E. A. Lipman, A. Sullivan, R. W. Falcone, Phys. Rev. Lett. **73**, 78 (1994).
- 26 A. A. Offenberger, W. Blyth, A. E. Dangor, A. Djaoui, M. H. Key, Z. Najmudin and J. S. Wark, Phys. Rev. Lett. **71**, 3983 (1993).
- 27 M. Dunne, T. Afshar-Rad, J. Edwards, A. J. Mackinnon, S. M. Viana, W. Willi and G. J. Pert, **72**, 1024 (1994).
- 28 G. J. Pert, J. Phys. A. **5**, 506 (1972).
- 29 L. Schlessinger and J. Wright, Phys. Rev. A, **20**, 1934 (1979)
- 30 N. H. Burnett and G. D. Enright, IEEE J. Quantum Electron. JQE **26**, 1797 (1990).
- 31 G. J. Pert, To be published, Phys Rev E (1995)
- 32 A. Ya. Polischuck and J. Meyer-Ter-Vehn, Phys. Rev. E, **49**, 663 (1994).
- 33 C. Max, J. Arons, A. B. Langdon, Phys. Rev. Lett. **33**, 209 (1974), A. B. Borisov, A. V. Borovskiy, O. B. Shiryayev, V. V. Korobkin, A. M. Prokhorov, J. C. Solem, T. S. Luk, K. Boyer, C. K. Rhodes, Phys. Rev A. **45**, 5830 (1992).
- 34 P. Monot, T. Auguste, P. Gibbon, F. Jakober, G. Mainfray, A. Delieu, M. Louis-Jacquet, G. Malka, J. L. Miquel, Phys. Rev. Lett. **74**, 2953 (1995).
- 35 P. Sprangle, and E. Esarey, Phys. Fluids. B **4**, 2241 (1992).
- 36 G-Z. Sun, E. Ott, Y. C. Lee and P. Gudzar, Phys. Rev. A. **30**, 526 (1987).
- 37 S. C. Rae, Optics Comm. **97**, 25 (1993).
- 38 E. E. Fill, J. Opt. Soc. Am. B **11**, 2241 (1994).
- 39 P. Monot, T. Auguste, L. A. Lompre, G. Mainfray, C. Manus, J. Opt. Soc. Am. B **9**, 1579 (1992).
- 40 T. Auguste, P. Monot, G. Mainfray, C. Manus, S. Gary and M. Louis-Jacquet, Optics Comm. **105**, 292 (1994).
- 41 N. S. Kapany and J. J. Burke, *Optical Waveguides* ( Academic Press, New York and London, 1972 ).
- 42 S. A. Mani, J. E. Eninger and J. Wallace, Nucl. Fusion **15**, 371 (1975).
- 43 C. S. Liu and V. K. Tripathi, Phys. Plasmas **1**, 3100 (1994).
- 44 C. G. Durfee II and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409, (1993).
- 45 M. Born and E. Wolf, *Principals of optics* (Pergamon Press )
- 46 F. C. Jahoda and G. A. Saywer, in *Methods of Experimental Physics*, vol. 9B, (Academic, New York, 1 1971).
- 47 J. Denavait and D. W. Phillion, Phys. Plasmas **1**, 1971 (1994).
- 48 R. Rankin, C. E. Capjack, N. H. Burnett and P. B. Corkum, Opt. Lett. **16**, 835 (1991).

- 49 W. L. Kruer, *The physics of laser plasma interactions* (Addison-Wesley, Redwood City, CA, 1988).
- 50 R. L. Berger, B. F. Lasinski, T. B. Kaiser, E. A. Williams, A. B. Langdon, B.I.Cohen, *Phys. Fluids. B*, **5**, 2243 (1993).
- 51 J. C. Solem, T. S. Luk, K. Boyer, C. K. Rhodes, *IEEE J.Quantum. Electron*, QE **25**, 2423 (1989).
- 52 P. K. Tien, J. P. Gordon and J. R. Whinnery , *Proc. IEEE*, **53**, 129 (1965).
- 53 H. Kogelnik. *Appl. Opt.* **4**, 1562 (1965).
- 54 H. J. Lehmeyer, W. Leupacher and A. Penzkofer, **56**, 67 (1985).
- 55 A. M. Perelomov, V.S. Popov and M. V. Terent'ev, *JETP* **23**, 924 (1966) and M. V. Ammosov, N. B. Delone and V.P Krainov, *Zh. Eksp. Teor. Fiz.* **91**, 2008 (1986) [*Sov. Phys. JETP* **64**, 1191 (1987)].
- 56 M. S. N. Ciarrocca et al *Optics Communications* **110**, 425 (1994), *J. Opt. Soc Am. B* (to be published) and University of London Thesis (1995) (unpublished).
- 57 J. C. Griesemann and M. Decroisette, *J. Appl. Phys.* **50**, 3915 (1979).
- 58 L. D. Landau and E. M. Lifshitz, *Quantum mechanics* (3rd Ed. Pergamon, 1978).
- 59 L. V. Keldysh, *Sov. Phys. JETP.* **20**, 1307 (1965).
- 60 M. J. Seaton, in *Atomic and molecular processes.*( D. R. Bates Ed. Academic, New York, 1962 p 374 - 420)
- 61 M. G. Haines, in *Laser Plasma Interactions 4* (M. B. Hooper Ed. Scottish Universities Summer School in Physics, IOP Publishing, Bristol, 1989)
- 62 H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).
- 63 R. W. P. McWhirter in *Plasma diagnostic techniques* (R. H. Huddleston and S. L. Leonard Ed. Academic, New York, 1965) .
- 64 H. S. W. Massey and D. R. Bates *Atomic and molecular processes.*( D. R. Bates Ed. Academic, New York, 1962).
- 65 R. Mewe, in *Astrophysical & Laboratory Spectroscopy* ( R. Brown and J. Lang Ed. SUSSP Publications , Edinburgh, 1987).
- 66 S. B. Healy, A. Djauoi, P. B. Holden, G. J. Pert, S. J. Rose, *J. Phys. B: At. Mol. Opt.Phys.* , **28**, 1381 (1995).
- 67 W. A. Lokke and W. H. Grasberger, LLNL Report No. UCRL-52276, (1977)
- 68 J. Edwards and S. J. Rose, *J. Phys B: At. Mol. Opt.Phys.* **26**, L523 (1993).
- 69 A. Djauoi and S. J. Rose, *J Phys B: At . Mol . Opt. Phys.* **25**, 2745 (1992).
- 70 N. H. Burnett and G. D.Enright, *IEEE J.Quantum Electron. JQE* **26**, 1797 (1990).
- 71 A. B. Langdon, *Phys. Rev. Lett.* **44**, 575 (1980).

- 72 T. P. Hughes in *Laser Plasma Interactions 1* (Scottish Universities Summer School in Physics, IOP Publishing, Bristol, 1979).
- 73 For a review of work in area of shock waves see, Ya. B. Zel'dovich and Yu.P. Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena* p 234 (Academic, New York, 1966).
- 74 Li. Y. and E.Fedosojevs, Optics Comm.
- 75 G. I. Taylor. *Proc roy Soc. A* **201**, 155, 175 (1950), L. I. Sedov, *Similarity and Dimensional methods in Mechanics*. (Academic , New York, 1959) .
- 76 J. P Christiansen, D.E.T.F Ashby and K.V. Roberts, *Computer Phys. Comm.* **7** 271 (1974).
- 77 M. H. Key, in *Handbook of Plasma Physics*, (Eds. M. N. Rosenbluth and R. Z. Sagdeev. Vol. **3**, Elsevier Science p575, 1991)
- 78 P. Schwartz, J. Delettrez, R. C. McCrory and C. P. Verdon, *Phys. Rev. Lett.* **47**, 247 (1981).
- 79 D. R. Gray and J. D. Kilkenny, *Plasma Phys.* **22**, 81 (1980).
- 80 A. R. Bell, R. G. Evans and D. J. Nicholas, *Phys. Rev. Lett.* **46**, 243 (1981).
- 81 E.M. Epperlein and R.W. Short, *Phys. Fluids. B*, **3**, 3092 (1991)
- 82 E. M. Epperlein and R.W.Short, *Phys. Fluids. B*, **4**, 2211, (1992)
- 83 A. Djaoui and A. A. Offenberger, *Phys. Rev. E*, **50**, 4969 (1994).
- 84 A. B. Borisov, X. Shi, V. B. Karpov, V.V. Korobkin, J. C. Solem, O. B. Shiryayev, A. McPherson, K. Boyer, C. K. Rhodes, *J.Opt. Soc. Am. B*, **11**, 1941, (1994).
- 85 R. W. Fox and A. T. Macdonald, *Introduction to fluid mechanics* (3rd. Ed, J. Wiley, New York, 1985 p600).
- 86 R. W. Fox and A. T. Macdonald, *Introduction to fluid mechanics* (3rd. Ed, J. Wiley, New York, 1985). Pressure ratios from tables in Appendix D.1 p702.
- 87 Private communication D Neely.
- 88 Private communication W. Blythe.
- 89 The effect of density gradient on intensity fluctuations on film can be seen in, *Methods of Experimental Physics: Fluid dynamics* (Vol. **18**, part A, Academic, New York, 1981)
- 90 Lord Rayleigh, *Phil. Mag.* **47**, 81, 193 (1874).
- 91 O. Kafri, *Optics letters* , **5**, 555 (1980).
- 92 K. Bockasten, *J. Opt. Soc. Am.* **51**, 943 (1961).
- 93 J. Slachter University of California thesis (unpublished).
- 94 E. Keren and O.Kafri, *J. Opt. Soc. Am A*, **2**, 111 (1985).
- 95 Marco Borghesi, Private communication.

- 96 I. A. Ross, A. R. Damerell, E. Divani, J. V. Evans, G. J. Hirst, C. J. Hooker, J. R. Houliston, M. H. Key, Z. Najmudin, P. Norreys, K. Osvay, J. M. D. Lister, Annual Report to the Central Laser Facility, No. RAL - 93-100 (1993).
- 97 J. M. D. Lister, Private communication.
- 98 C.N Danson et al, Annual Report to the Central Laser Facility, No. RAL 94, 117 (1994).
- 99 M. Born and E. Wolf, Fundamentals of Optics p441
- 100 F Walsh, Private communication.
- 101 D. Pepler private communication, the Scientec calorimeter was calibrated by National Physical laboratories.
- 102 C. J. Hooker et al, Annual Report to the Central Laser Facility, No. RAL 94, 136 (1994).
- 103 A. J. Mackinnon, accepted for publication in Phys. Rev. Lett, February 1996.