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PLASMA DYNAMICS OF TWO-WIRE Z-PINCHES

by

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ABSTRACT

This thesis is concerned with a series of experiments on wire z-pinches to study the merging of the plasma from two parallel wires and its dynamics as a function of wire separation and material. The pulsed power generator (IMP) is capable of providing a maximum peak current of 160kA with a rise time of 65ns. Two parallel 15 μ m aluminium and 7.5 μ m tungsten wires were used as load. The separation between electrodes was 20mm. Three different separations between wires were used (0.3, 0.6 and 1.5mm) to study mainly: (i) the plasma expansion, (ii) dynamic of instabilities, (iii) formation of the central plasma column and (iv) x-ray emission.

The plasma was optically probed by schlieren photography in two orthogonal directions: face-on and side-on (perpendicular and parallel to two-wire plane respectively). A 7 ns (FWHD) pulse of Ruby laser (694.3 μ m) was used with a 520 μ m circular stop, the angle detection limits for this probing were from 1.3 to 45.0 mrad. It allowed detecting electron densities in the range of $(3.0 \times 10^{18} - 1.8 \times 10^{20})$ [cm⁻³]. In the optical emission regime, a four-frame optical camera, with an exposure time of 1 ns (inter-frame time of 15 ns and 5 ns), and an optical streak camera in radial mode (perpendicular to z-pinch axis) were used. The x-ray emission was detected using a time-integrated pinhole camera and a couple of filtered PIN diodes.

It was observed that two separated plasmas were formed, localised at: (1) surrounding each of the two wires and (2) a central plasma column at midway between the wires, which is wire separation dependent. Magnetohydrodynamic (MHD) instabilities appear in both plasmas. For aluminium wires, the localised coronal plasma around wires is $m = 0$ unstable. The expansion of the coronal plasma is asymmetric, being faster in the interwire region compared with the expansion in the external region. Spatial correlation along the wire axis of coronal plasma instabilities was observed for both wires, which is associated with the existence of a global magnetic field surrounding the wires. The central plasma column, confined in the plane between wires, shows a $m = 1$ -MHD instability. For tungsten wires, the coronal

instabilities were spatially correlated later compared with aluminium. An important feature of 1.5mm separation tungsten discharges was a series of jets along Z-axis direction streaming towards the centre. These jets were observed at 70ns after current start.

In addition, experiments on single-wire z-pinches are reported. Tungsten wires of various diameters (5, 7.5, 10, 13 and $18\mu\text{m}$) were used and results are compared with $15\mu\text{m}$ aluminium wire. The expansion of the pinch is studied as a function of wire diameter and material. Schlieren observations show that the coronal plasma of tungsten pinches is independent of wire size, it expanding with a mean velocity of $(9.4 \pm 1.0) \times 10^3 \text{ m/s}$.

The aluminium pinch expands with a velocity of $(2.4 \pm 0.2) \times 10^4 \text{ m/s}$, which is in a factor of 2.5 faster than tungsten one. The $m = 0$ - MHD instability appear at about 8 ns for aluminium compared with 20 ns for the tungsten pinch. The instability wavelength and pinch diameter increases with time for both types of wires, and relatively faster for the aluminium pinch.

A 2D(r,z) resistive MHD code was used with the addition of a modified Thomas-Fermi equation of state and dense plasma transport model to allow the phase transitions from solid to plasma. The coronal and core expansions from the code can be compared directly to experimental results obtained by schlieren photography. The simulation and experimental results are compared showing a rapid expansion of the coronal plasma during the first 17ns. The initial coronal expansion and then contraction is evident in the simulation. The delay with reference to current start, of the core expansion and instability development often referred as the “dwell time”, is reproduced in simulation and is associated with the self-pinching time of the corona.

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Symbols and Abbreviations

Chapter 1

B_θ	Magnetic field in θ -direction.
J_z	Current density in Z - direction.
$\mathbf{B}$	Magnetic field
∇p	Pressure gradient
J	Current density
p	Pressure
μ_0	Permeability of free space
$B^2/2\mu_0$	Magnetic energy density
β	Ratio of sound speed to Alfvén speed
C_s	Sound speed
V_A	Alfvén speed
n_i	Ion number density
n_e	Electron number density
n	Number density
K_B	Boltzmann constant
T_i	Ion temperature
T_e	Electron temperature
τ	Energy confinement time
P_c	Power loss per unit volume through heat conduction
P_b	Power loss per unit volume through bremsstrahlung
P_τ	Output power per unit volume due to fusion reactions
σ	Fusion reaction cross section
Z	Charge state
v	Particle velocity
Q_τ	Energy released per fusion reaction
η	Efficiency of plasma heating
δr	Perturbation in radial direction
ξ_0	Perturbation amplitude
k	Axial wave number
m	Mode number
$S(r)$	Stability criterion of Kadomtsev
Γ	Ratio of specific heats
p_0	Equilibrium pressure
B_0	Equilibrium magnetic field
γ	Maximum growth rate
g	Inward acceleration
a	Pinch radius
N	Particle line density
$\langle T \rangle$	Mean temperature
$\langle Z \rangle$	Average ionic charge
I	Electric current
I_{PB}	Pease-Braginskii current
$\ln \Lambda$	Coulomb logarithm

ρ :	Resistivity across a magnetic field
T_m :	Steady state temperature
r_o :	Initial radius of wire arrays
d_w :	Gap between wires
N_w :	Total wire number
t_m :	Time of merger of wire plasma
a_m :	Final radius of wire plasma

Chapter 2

Z_{TL} :	Impedance of water filled transmission line
ϵ_r :	Relative dielectric constant
τ_u :	Single transit time
c_w :	Light speed in water
C_{PFL} :	Capacitance of pulse forming line
C_{MB} :	Capacitance of Marx Bank
V_{PFL} :	Peak voltage value into the pulse forming line
V_{MB} :	Peak voltage value into the Marx Bank
C_p :	Probe capacitance
A_{PFL} :	Pulse forming line area
A_p :	Probe area
t_{RC} :	Time constant
R :	Electric resistance
Φ_M :	Magnetic flux
L :	Inductance
S_{loop} :	Loop sensitivity
Z_M :	Monitor impedance
Z_L :	Load impedance
θ_g :	Angular uncertainty due to geometrical effect
θ_d :	Angular uncertainty due to diffraction
$S(E)$:	PIN diodes sensitivity
$\mu(E)$:	Absorption coefficient
$d\Omega$:	Solid angle
y :	X - ray yield
d_o :	Optimum resolution
ϵ_o :	Permittivity of free space
σ_{cond} :	Plasma conductivity
ϵ :	Dielectric tensor
c :	Light speed in vacuum
μ :	Refractive index
ω_p :	Plasma frequency
ω :	Laser frequency
n_c :	Critical electron density
e :	Elementary charge
m_e :	Electron mass
α :	Laser light deflection

λ : Laser wavelength
 $\Delta\ell$: Optical path
 Φ_S : Diameter of Schlieren stop
 f : Focal lens

Chapter 3

θ : Acceptance angle
 $Q_{1,2}$: Electric charge measured with PIN diodes
 $h\nu$: Cut-off energy

Chapter 4

L_i : Inductance of two parallel wires
 l : Wire length
 R : Returning current radius
 D : Wire diameter
 x_i : Separation between wires
 Face-on: Direction along x - axis
 Side-on: Direction along y - axis
 v_{y+} : Face on expansion velocity in $y+$ direction
 v_{y-} : Face on expansion velocity in $y-$ direction
 v_{x+} : Face on expansion velocity in $x+$ direction
 v_{x-} : Face on expansion velocity in $x-$ direction
 v_{corona} : Radial expansion velocity of coronal plasma
 v_{core} : Radial expansion velocity of core plasma

Abbreviations

FWHM: Full Width at Half Maximum
 PIN: Positive - Intrinsic Negative
 PFL: Pulse Forming Line
 TL: Transmission Line
 MCP: Micro Channel Plate
 DEF: Direct Exposure Film
 GOI: Gated Optical Intensifier
 ND Filter: Neutral Density Filter
 ns: nanosecond

Chapter 1

INTRODUCTION

1.1.- Introduction

Z-pinches were one of the earliest devices proposed for the production of thermonuclear fusion on a laboratory scale. Research and interest on z-pinches began around the time that the hydrogen bomb was successfully tested. The early operation of a z-pinch involved filling an insulating chamber between two electrodes with a low-pressure gas. When a high voltage is applied across the electrodes, the gas breaks down and becomes a conducting plasma. The current flowing between the electrodes produces a self-generated magnetic field. The plasma ions and electrons are subject to the Lorenz force. The macroscopic manifestation is a radial pressure from the magnetic field, which compresses the plasma on axis. Resistance to the compression is provided by the kinetic energy of the particles. Since the particles are compressed by a current flowing along the z-axis, the process is called a z-pinch. The pinch effect was discovered experimentally in a lightning conductor and analysed by Pollock and Barraclough in 1905 [1.1].

A variety of z-pinch configurations have been studied. There have been results recently of experiments with fibre [1.2, 1.3, 1.4], with compressional [1.5, 1.6] and gas-embedded z-pinches [1.7, 1.8, 1.9]. Imploding gas-puff z-pinches [1.10, 1.11, 1.12, 1.13, 1.14] and wire arrays [1.15, 1.16, 1.17, 1.18] indicate that modern, fast z-pinch systems are capable of greater stability and can provide higher compression, much greater energy density, and longer plasma confinement times than predicted by the conventional estimates from the 1950s and 1960s. A comprehensive review of the subject was given by Dangor [1.19].

In this chapter the basic physics of z-pinch will be discussed. Also, it shows recent results on imploding wire-arrays used as x-ray sources.

1.2.- The Z-Pinch

The z-pinch is a one-dimensional model of the toroidal configuration with purely poloidal field and is in many ways orthogonal to the θ pinch (see the Fig. 1.1). In a z-pinch, only B_θ is nonzero and consists entirely of the field self-induced by the longitudinal current J_z flowing in the plasma (hence the name z-pinch). Unlike the θ pinch, when the plasma current vanishes there is no background B_z field remaining.

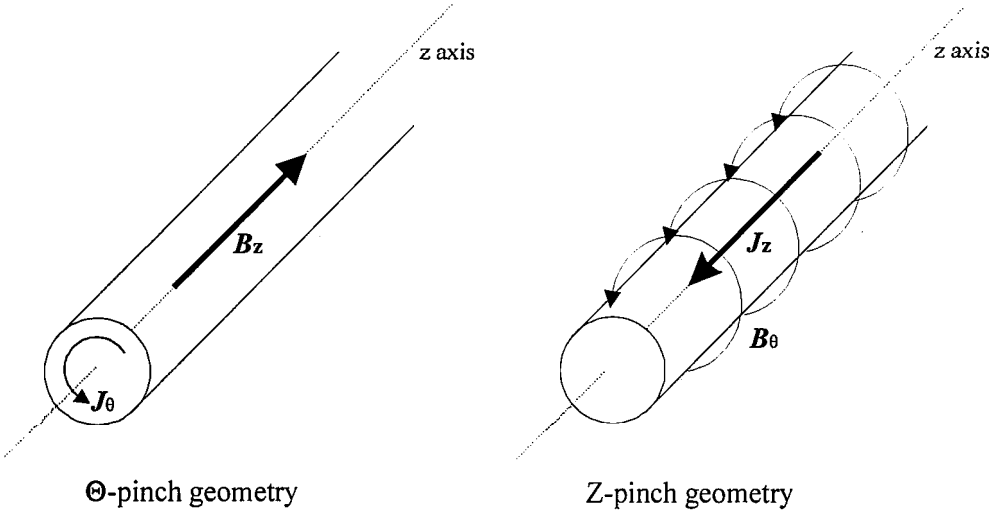


Figure 1.1. The Θ -pinch and Z-pinch geometry

The confinement of the plasma by an external magnetic field is approached by establishing the so-called equilibrium configuration of the magnetic field that confines a plasma within a restricted volume (keeping it away from the walls of a device) and by studying the stability of these configurations.

To formulate the equations that establish the equilibrium configurations we use the stationary magnetohydrodynamics equations. Setting the time derivative equal to zero we obtain

$$\begin{aligned}\nabla p &= \mathbf{J}_z \times \mathbf{B} \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J}_z \\ \nabla \cdot \mathbf{B} &= 0\end{aligned}\tag{1.1}$$

The second equation of (1.1) gives

$$\nabla \cdot \mathbf{J}_z = 0 \quad 1.2$$

This means that there is no source of the current. Interesting conclusions follow from the first equation of the system (1.1), which is usually called the magnetic hydrostatic equation. Multiplying it by the vector $\mathbf{B}$ and $\mathbf{J}_z$ we get

$$\mathbf{B} \cdot \nabla p = 0 \quad 1.3$$

$$\mathbf{J}_z \cdot \nabla p = 0 \quad 1.4$$

These equations show that the magnetic field $\mathbf{B}$ and current density $\mathbf{J}_z$ are perpendicular to the gradient of the plasma pressure. In other words the magnetic field lines and current lines are located on surfaces of constant pressure ($p = \text{const}$).

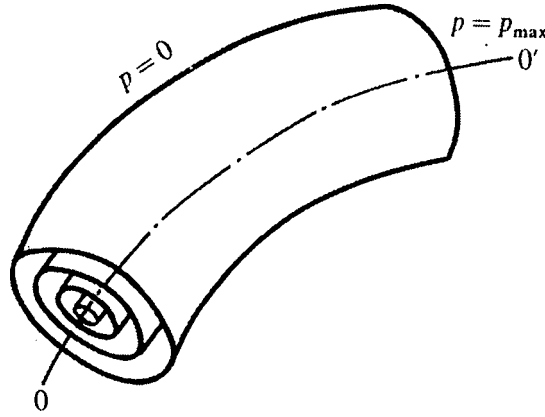


Figure 1.2. Pressure surfaces

The Lorentz force $\mathbf{J} \times \mathbf{B}$ is directed to the axis, so the plasma pressure also increases in that direction. Getting the current density from the second equation (1.1) and substituting it into the first equation of this system we obtain

$$\nabla p + \frac{1}{\mu_o} (\nabla \times \mathbf{B}) \times \mathbf{B} = 0 \quad 1.5$$

or

$$-\nabla \left(p + \frac{B^2}{2\mu_o} \right) + \frac{1}{\mu_o} (\mathbf{B} \cdot \nabla) \mathbf{B} = 0$$

For the simplest equilibrium configuration, when the magnetic field lines are sets of parallel lines, we have

$$(\mathbf{B} \cdot \nabla)\mathbf{B} = 0 \quad 1.6$$

and therefore the following quantity is conserved:

$$p + \frac{B^2}{2\mu_o} = \text{const} \quad 1.7$$

The quantity $B^2/2\mu_o$ by definition is the magnetic energy density, which is called the magnetic pressure. The ratio $2\mu_o p/B^2$ is known as β . Physically β is the ratio of sound speed to Alfvén speed, $\beta = V_s^2/V_A^2$.

If we consider an infinite plasma column with the current density $j_z(r)$ (the current is directed along the pinch axis z). The magnetic field created by the current has only one nonzero component $B_\theta(r) \equiv B_\theta$, which is determined by the second equation of the system (1.1):

$$j_z(r) = \frac{1}{\mu_o r} \left(\frac{\partial}{\partial r} (r B_\theta) \right) = \frac{1}{\mu_o} \frac{\partial}{\partial r} B_\theta \quad 1.8$$

Here we use the cylindrical coordinates. Usually such a plasma column is called a *pinch*. The equilibrium condition (1.5) takes the form

$$\frac{\partial}{\partial r} \left(p + \frac{B_\theta^2}{2\mu_o} \right) + \frac{B_\theta^2}{\mu_o r} = 0 \quad 1.9$$

From Eq. (1.9) it follows that the equilibrium of a cylindrical plasma configuration may be maintained by its proper magnetic field *even in the absence of an external magnetic field*. In this case the equilibrium condition (1.9) reduces to

$$\frac{\partial p}{\partial r} = -\frac{B_\theta}{\mu_o r} \frac{d}{dr} (r B_\theta) \quad 1.10$$

The self-compression of a plasma column by the proper magnetic field is called the pinching. Sometimes such a type of discharge is called the longitudinal pinch.

1.3.- The Lawson Condition

One essential condition must be satisfied by all prospective fusion devices: namely, the energy released by the nuclear fusion reactions must be more than compensate for the energy expended from other sources in generating and maintaining a high temperature plasma. This problem was first examined by J.D. Lawson [1.20]. In his paper, Lawson considered a general model not dependent on any particular method of confinement. The results are summarised below.

Assuming equal electron and ion number densities ($n_i = n_e = n$) and temperatures then the internal energy of the plasma per unit volume is $3nk_B T$. The energy confinement time, τ , is defined by the equation $P_\ell = 3nk_B T / \tau$. Where P_ℓ is the power loss per unit volume (through heat conduction, particle loss etc.), and n is the electron density.

The other energy loss mechanism is taken to be bremsstrahlung and the power loss per unit volume is: $P_b = 1.69 \times 10^{-26} Z^3 n^2 (T_e)^{1/2}$.

The output power due to fusion reactions per unit volume of plasma depends on the components of the reaction. For a deuterium/tritium mixture this power is: $P_t = (n^2/4) \langle \sigma v \rangle Q_t$, where σ is the reaction cross-section; v is the particle velocity and Q_t is the energy released per reaction.

Lawson took into account either the efficiency of converting the thermal energy into electrical energy and the efficiency of heating the plasma; then he denoted this by η which he took to be 1/3. The Lawson condition then states that *the energy necessary to maintain the plasma at thermonuclear conditions must be less than η times the energy released from the plasma and from thermonuclear burn* i.e.: $P_b + P_\ell < \eta(P_b + P_\ell + P_t)$.

Substituting for the various energy losses and gains, one finds that this imposes a condition on the product $n\tau$:

$$n\tau > \frac{3kT}{\frac{\eta}{1-\eta} \frac{Q_t}{4} < \sigma v >} \quad 1.11$$

Where it is assumed that the power generated is much greater than the bremsstrahlung loss. So $n\tau$ is a function of temperature only. For Deuterium-Tritium

(DT) reaction, at about a temperature of 25 keV , $\langle \sigma v \rangle$ is approximately $4.7 \times 10^{-22} \text{ m}^3 \text{ s}^{-1}$. Therefore the Lawson condition becomes (with $Q_t \approx 3.5 \text{ MeV}$):
 $n\tau > 1.5 \times 10^{20} \text{ m}^{-3} \text{ s}$.

1.4.- Stability of Z-pinchs

In order to utilise the Z-pinch as a fusion device then the equilibrium state must be stable for at least as long as the energy confinement time, τ . Figures 1.3a and 1.3b show the form of two of the simplest perturbations that can occur in a linear pinch. The first one consists of the local contractions of the plasma along its length. As a result the magnetic pressure in the contracted region is greater than in the neighbouring regions. Since the plasma is free to flow in the axial direction then this rise in magnetic pressure is not offset by an increase in the internal pressure. Hence the deformation carries on growing and disrupts the pinch. From its appearance this instability is frequently referred to as 'sausage' instability. The second deformation is known as 'kink' instability, since the plasma axis is displaced in a sinusoidal fashion. In this case the field strength on the outside of the bend is less than that on the inside and so the amplitude of this perturbation also increases in time.

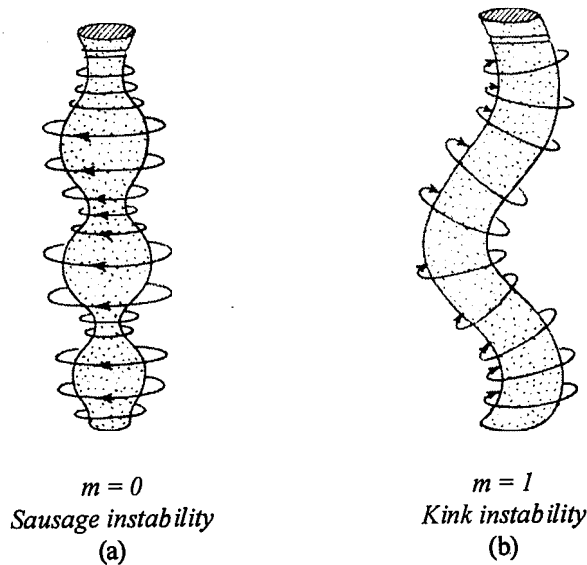


Figure 1.3. MHD instabilities

The stability analysis of the z-pinch has been treated and reviewed in some detail [1.21,1.22]. The salient features are summarised below.

If we consider a cylindrical z-pinch, then a perturbation changes the distance from the surface of the pinch, and it ceases to be cylindrical. The perturbation changes the distance from the surface to the axis by an amount δr . This displacement can be represented as a superposition of Fourier components of the form: $\delta r = \xi_o e^{i(m\theta + kz - \omega t)}$. Where ξ_o is the amplitude of the component, k is the axial wave-number, the coefficient m is called the mode-number and it determines the azimuthal periodicity of δr . When $m = 0$ the displacement is independent of the azimuth. This is just the *sausage instability*. The $m = 1$ mode is the *kink instability* where the axis of the pinch column is disturbed helically. The $m = 0$ and $m = 1$ modes are found to be the most unstable both theoretically and experimentally.

For a z-pinch plasma to be stable to the $m = 0$ MHD mode, the pressure profile must satisfy the Kadomtsev criterion [1.23]:

$$S(r) = -\frac{r}{P_o} \frac{dP_o}{dr} - \frac{2\Gamma}{(1 + \Gamma\beta(r)/2)} < 0 \quad 1.12$$

where $P_o(r)$ is the equilibrium pressure profile; $B_o(r)$ is the equilibrium magnetic field; $\beta(r) = 2\mu_o P_o / B_o^2$; and Γ is the ratio of specific heats.

A profile in which P_o falls off more steeply with r at any point is unstable. Also note that since P_o is finite for all r , then any equilibrium where P_o falls to zero at the edge is unstable to $m = 0$ modes. It can be also shown that a profile is Kadomtsev stable only if the current density is slightly peaked on axis.

For modes with $m \neq 0$, the z-pinch is stable to internal modes if

$$-\frac{r}{P_o} \frac{dP_o}{dr} - \frac{m^2}{\beta(r)} < 0 \quad 1.13$$

is satisfied everywhere. A z-pinch with a finite current density on axis is always unstable to $m = 1$ mode.

A thorough discussion of the stability of z-pinchs with respect to experimental observations at Imperial College can be found in Coppins [1.24]. The conditions under which ideal MHD is valid are discussed in detail by various authors [1.22,1.25].

Another instability that must be considered is the Rayleigh-Taylor instability, it occurs at the interface of two fluids, when a light fluid is supporting a heavy fluid in the presence of a gravitational field. In z-pinch, see Fig. 1.4, this instability occurs when the plasma is accelerated inwards by a rapidly rising pinch current and has a growth rate given by $\gamma = \sqrt{gk}$ [1.26]. Where γ is the maximum growth rate, g the inward acceleration, and k is the wave-number of the instability.

The other two types of MHD instabilities ($m = 0$ and $m = 1$) occur in steady state, without any inward acceleration, and growth rate of order a/V_A , where a is the pinch radius and V_A is the Alfvén velocity. Both these growth rates are too rapid to allow the practical realisation of Lawson's criterion in a simple pinch.

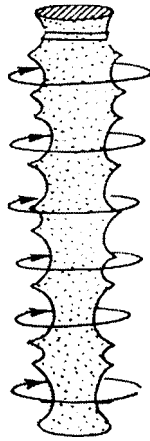


Figure 1.4. Rayleigh-Taylor instability

1.5.- *The Bennett Relation*

The fundamental relation between the current, the line density and the mean temperature was derived by Bennett [1.27] in relation to electron beams. The original paper did not mention its applicability to magnetically confined plasmas.

From the radial pressure balance (1.10), we have:

$$dp/dr = -jB_\theta \quad 1.14$$

where

$$j = \frac{1}{2\pi r} \frac{dI}{dr}, \quad B_\theta = \frac{\mu_0 I}{2\pi r} \quad 1.15$$

I is the current enclosed by r over the line integral (Gauss' Law). Thus, Eq. 1.14 can be written as:

$$\mu_0 d(I^2) = -8\pi^2 r^2 dp \quad 1.16$$

Now, integrating by parts and noting that at the pinch radius, a , the pressure is zero ($p = 0$) and the current is I_p ($I = I_p$):

$$\frac{\mu_0}{8\pi^2} I_p^2 = \left[-r^2 p \right]_{p=0}^{r=0} + \int_0^a 2r p dr \quad 1.17$$

Putting $p = (1 + \langle Z \rangle) n_i k_B T$, where n_i is the ion density and $\langle Z \rangle$ is the average ionic charge, then:

$$\mu_0 I_p^2 = 8\pi(1 + \langle Z \rangle) \int_0^a n_i k_B T 2\pi r dr = 8\pi(1 + \langle Z \rangle) N k_B \frac{\int_0^a T dN}{\int_0^a dN} \quad 1.18$$

$$\mu_0 I_p^2 = 8\pi(1 + \langle Z \rangle) N k_B \langle T \rangle \quad 1.19$$

where N is the particle line density $N = \int_0^a n_i 2\pi r dr$ and $\langle T \rangle$ is the mean temperature.

The Bennett relation (1.19) determines the temperature of a pinch in pressure equilibrium. If for any reason the temperature of the pinch departs from the Bennett value while the current remains constant, the pinch will adjust its radius so that the Bennett temperature is restored.

1.6.- *The Pease-Braginskii Current*

R. S. Pease (1957) and S. I. Braginskii (1958) carried out the analysis of the equilibrium pinch. They found that in absence of losses other than bremsstrahlung there is a unique current at which the energy radiated is balanced by ohmic heating,

and the pinch is in a steady state. This current was derived independently by Pease [1.28] and Braginskii [1.29].

Assume that the temperature T is uniform across the radius of the pinch a . The ohmic heating power per unit length is:

$$P_{\Omega} = \frac{I^2 \eta}{\pi a^2} \quad [Wm^{-1}] \quad 1.20$$

where η is the Spitzer resistivity ($\eta = 1.03 \times 10^{-4} \langle Z \rangle \ln \Lambda T_e^{-3/2}$) across a magnetic field. The power radiated per unit length as bremsstrahlung is:

$$P_b = 1.69 \times 10^{-26} Z^3 n^2 (T_e)^{1/2} \cdot (\pi a^2) \quad [Wm^{-1}] \quad 1.21$$

From the expressions for P_{Ω} , P_b and the Bennett relation, we found that:

$$\frac{P_{\Omega}}{P_b} = \frac{I_{PB}^2}{I^2} \quad 1.22$$

where I_{PB} is the current, independent of N or T , at which the radiation loss is exactly balanced by ohmic heating. This current is given by:

$$I_{PB} = 0.499 (\ln \Lambda)^{1/2} \frac{I + Z}{2Z} \quad [MA] \quad 1.23$$

Putting $\ln \Lambda = 10$, $Z = 1$ (for hydrogen) we obtain the characteristic current I_{PB} derived by Pease: $I_p = 1.58 MA$.

1.7.- *The Haines-Hammel current waveform*

Haines [1.30] considered the Joule heating of a stable hydrogen pinched plasma and derived a current wave-form which is necessary to maintain radial pressure balance. This was done by casting the energy balance equation in the form:

$$\frac{d}{dt} \left[\frac{3}{2} (n_i k T_i + n_e k T_e) \right] + P_c + P_{rad} = \eta J^2 \quad [Wm^{-3}] \quad 1.24$$

Where P_c is the power per unit volume conducted away from the pinch, P_{rad} is the radiated power per unit volume, $n_e k T_e$ is the electron pressure and $n_i k T_i$ is the ion pressure. For the case of quasi-neutral hydrogen with equal electron and ion temperatures, T , neglecting radial losses and writing the axial losses, P_c as:

$$P_c = \frac{5}{2} n_e k_B T_e \frac{v_e}{l} \quad 1.25$$

where v_e is the electron drift velocity, l is the length of the pinch.

The bremsstrahlung power per unit volume radiated away from the pinch can be rewritten as:

$$P_{rad} = 1.56 \times 10^{-28} n_e^2 \left(\frac{k_B T_e}{\xi_H} \right)^{1/2}$$

where ξ_H is the ionisation potential for hydrogen [1.31]. Using the pressure balance equation:

$$\mathbf{J} \times \mathbf{B} = \nabla(p_e + p_i) \quad 1.26$$

Haines [1.32] gave a steady state solution to the energy equation:

$$T_m^{5/2} = 2.04 \times 10^7 \frac{l}{\pi \alpha^2} I \left(1 - \left[\frac{I}{I_{PBM}} \right]^2 \right) \quad 1.27$$

Where I_{PBM} is the modified Pease-Braginskii limiting current. The equation for T_m defines a steady state current at which the Joule heating is balanced by axial and bremsstrahlung losses. Thus a steady state can exist for any current below the Pease-Braginskii limit with a temperature T_m .

The current required can then be evaluated from the Bennett relation. Such a curve with a waveform $I \sim t^{1/3}$ is known as Haines-Hammel curve [1.33].

1.8.- Exploding Wires as x-ray Sources

Exploding wires have been used as intense soft x-ray sources as early as 1961 [1.34]. When enough energy is deposited into an exploding wire, a thermal x-ray source is obtained. An exploding wire will produce x-rays at somewhat random spots along its length, generally places where the MHD instabilities cause pinching and localised heating.

When a small diameter wire is heated, it begins to radiate. At sufficiently high temperatures, the resulting wire plasma will radiate efficiently in the soft x-ray regime ($100 \text{ eV} < h\nu < 5 \text{ keV}$). The x-ray can be generated through line radiation or by thermal bremsstrahlung. The term line radiation is given when a bound electron undergoes a transition to a lower energy state, emitting a photon whose energy is characteristic of the particular atomic transition. Thermal bremsstrahlung occurs when the electrostatic field of the ions continuously deflects the trajectory of energetic electrons.

A thermal x-ray source such as an exploding wire or an exploding Z-pinch is an efficient source for production of soft x-rays. The photon intensities in the soft x-ray regime can be greater than ten times that of a conventional electron bremsstrahlung source [1.35]. When an annular wire array is imploded on axis, the kinetic energy gained during the implosion is thermalized on axis in the pinch region. This method of x-ray production (intense and pulsed) has been used for simulating nuclear weapons effects.

1.9.- *Pulsed Power technology*

A goal of modern pulsed-power technology is the development of an intense, high energy density x-ray source by converting the energy of the magnetically imploded plasma into radiation and material internal energy. An intermediate-term goal is to obtain a source with which experiments on radiation transport, opacity, equation of state, and implosion physics may be performed. Ultimately, with a multimega-joule source it is envisioned that fusion experiments will be possible.

The past decades have been characterised by an increase in the total energy radiated, E_{rad} , by z-pinches, as well as an increase in peak radiated power, P_{rad} . In 1980-81, the black jack machine [1.36] at Maxwell Laboratories and the Python machine [1.37] at Physics International produced approximately 0.16 MJ of radiated energy with a power of 4 TW. By 1988, the Shiva Star machine [1.38] at the Phillips Laboratory produced 0.95 MJ and 5 TW of power. In 1991 the Los Alamos inductive store machine Pegasus II [1.39] generated 0.28 MJ with a power of 0.9 TW. In 1993, Russia, the Angara V machine [1.40] produced 0.075 MJ at 25 TW and 0.12 MJ at 3 TW [1.41]. In 1994, The Los Alamos high-explosive driven system Procyon [1.42] produced 1.5 MJ with a power of 3 TW. In 1996, at Sandia National Laboratories,

Saturn machine [1.43] generated 0.4 MJ with a power of 85 TW. And finally, in 1998, at Sandia National Laboratories, Z-Machine [1.44] generated 1.8 MJ at 210 TW.

1.10.- *Imploding Wire Arrays*

In 1976, Stallings, Nielsen, and Schneider [1.45] reported that a wire array, c.f. Fig. 1.5, was better coupled to a 1Ω waterline pulsed-power generator than a single on-axis wire. These experiments found that due to the high initial inductance ($40\text{-}60\text{ nH}$) of single wires, only 40% of the generator current flowed in them at the time of peak current. On the other hand, all the current was found to flow through wire arrays that had lower inductance. Kilovolt x-ray measurements of wire arrays [1.46,1.47] have shown these z pinches to be very efficient radiators and this was and still is the main motivation for their study. In recent years, fast z pinches driven by the Z accelerator at Sandia National Laboratories [1.48,1.49] a multi-mega-ampere pulsed power accelerator, have fulfilled the earlier promise with peak radiation energies of 2.5MJ for Marx generator to x-ray efficiencies of $\sim 25\%$. These rapid advances have been possible through the use of high wire number cylindrical arrays to provide a very uniform and symmetric initial current path and resulting plasma [1.50].

The z current flowing through the array generates a very large magnetic field pressure $B_\theta^2/2\mu_0$ that accelerates the wires radially inward. As a consequence of this radial acceleration, the Rayleigh-Taylor instability can exhibit several e-foldings over the course of the implosion, broadening the extent of the plasma shell as it approaches the axis. The radial width of the plasma shell and the velocity of the outer extent of the shell give a characteristic time-scale t for the radiation output. The primary limitation on the broad-spectrum x-ray power, proportional to $1/t$, is believed to be the Rayleigh-Taylor instability [1.51].

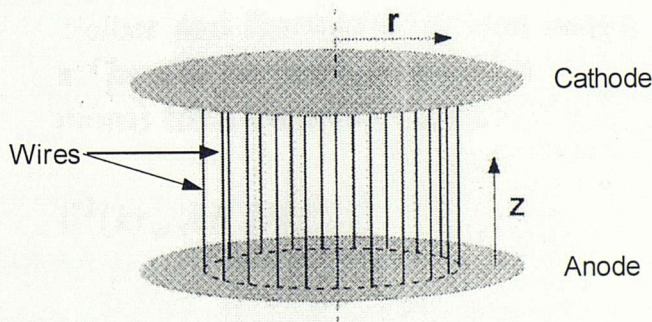


Figure 1.5. A schematic of a fast z-pinch wire array load

One of the more intriguing phenomena relating to multiple wire z pinches is the strong dependence of the radiation pulse width on the number of the wires. Experimental results from Saturn with aluminium wires [1.52], Saturn with tungsten wires [1.53] and Z accelerator with tungsten wires [1.54] are plotted in Fig. 1.6, with the full-width-half-maximum (FWHM) of the radiation pulse as a function of the interwire gap $g = 2\pi r_o / N_w$. Where r_o is the initial array radius and N_w is the number of wires. The optimised x-ray pulse (*width* < 10 ns) is for a wire separation in the range of (0.3 – 1.0) mm.

These previous experimental observations represent the main motivation of this research project: study of dynamic behaviour of two parallel wires for different wire separation using aluminium and tungsten wires.

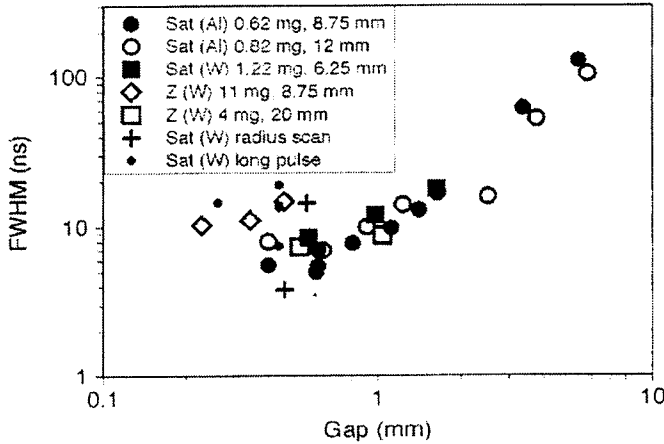


Figure 1.6. The FWHM pulse width plotted as a function of interwire gap for several experiments on Saturn and Z accelerators with both aluminium and tungsten wires of various mass and radius as indicated in the legend.

1.11.- *A Heuristic Model of the Wire Array Z-Pinch by M. G. Haines*

Haines in his heuristic model [1.55] presents an analysis of the behaviour and dynamics of wire array, which is summarised in four different phases. First, **Formation of coronal plasma**, in this phase each wire carries a rising current and behaves independently in the way similar to that found for single-wire z-pinch experiment [1.55]. Each wire will form a cloud that then expands with an

approximately constant radial velocity. Merger of the wire plasma will occur after a time t_m when the wire array as a whole has accelerated inward from its initial position r_o to a radius a_m . The time of merger of the wire plasma depends on number of wires, expansion velocities of each wire, and initial wire array diameter. Thus, it is important to determine the critical wire number to ensure merger before significant pinching. On the other hand to optimise the load for a given pulsed generator, the mass loading of the wire array would have to be adjusted so that the pinch time occurs close to peak current. At phase 2, **Merger of the wires**, the shell width will be determined by the diameter of the wire plasmas. Each wire behaves independently up to this phase, and the dominant axial mode $m = 0$ instabilities will be random. In short, in this phase, the private magnetic flux around each wire will start to decay in favour of a larger global magnetic field. At phase 3, **Inward acceleration and Rayleigh-Taylor instability**, the shell of plasma is accelerated inwards under the influence of the $\mathbf{J} \times \mathbf{B}$ pinch force. In this phase, the more important instability is the Rayleigh-Taylor instability rather than the MHD instability. And finally **stagnation on the axis**, in this phase the plasma energy is mainly in the directed inward motion of the ions. The shell thickness and the amplitude of the Rayleigh-Taylor modes will determine the pinch radius. Both the viscosity heating of the ions and the equipartition of energy from the ions to electrons help to obtain a high efficiency of conversion to x-rays.

Moreover, experiments performed on the MAGPIE generator [1.57] show the existence of Rayleigh-Taylor instabilities and radial streamers of plasma toward the axis. However, in those experiments, there was no experimental evidence of shell formation during the time of observation. This poses an interesting question: when shell formation in the early stage of a wire array discharge occurs. In fact, to diagnose experiments with such a large numbers of wires and power is a very difficult task, due to geometrical limitations in the load chamber.

It is important to mention that this heuristic model for wire arrays was derived using cylindrical coordinates, therefore it is not reliable for two-wire configuration. If we consider the two-wire configuration there is an attractive force that accelerates the wire material towards the axis. Furthermore the current per wire is a half of the total current. Checking out the expression of merging time, eq. 5 in ref [1.55], we observe that it was obtained considering a cylindrical geometry and a critical number of wires.

For example, the gap between wires is $g = 2\pi r_o / N_w$, if $N_w = 2$ then $g = \pi r_o$ and this result is false in our case. However, we present a treatment for the attraction force of two-wire in chapter 5. Current redistribution is the only effect valid in both cases. Related to global magnetic field configuration, we have that in the case of two-wire there is a field null point located on the axis, but for wire arrays there is a field null in the inner region of the array.

1.12.- *Previous Two-Wire Experiments*

Various experiments on two-wire z-pinchs have been performed [1.58,1.59,1.60], where a variety of wire materials and separations were used. A common characteristic observed in these was the formation of a plasma column in the interwire region by accumulation of wire material.

Perat and Koest [1.58] performed experiments with 30mm-long stainless steel wires spaced 6mm apart. The diameters of the wires were 10 μ m and 15 μ m. The maximum diode voltage was approximately 1MV and the peak current through the wires was 700kA with a rise time of 100ns. The most interesting result shown in this experiment is a plasma column with a helix-like structure, which was recorded by a time-integrated x-ray pinhole camera. This camera consisted of a stainless-steel lead shielded box through which the plasma image was collected through five 75 μ m pinholes covered with various thin filter materials and recorded onto x-ray film. There is no specification about filter materials and their cut-off energies.

Zakharov *et al* [1.59], used 10 μ m Nichrome wire as load on the DON accelerator (260kV, 140kA at 50ns). Discharges on two and four wire configuration were performed in these experiments. The wires were stretched between electrodes along the axis of a cylinder of 2-4mm diameter. The formation of central plasma was studied by optical interferometry. Interferograms show how the coronal plasma formed in each wire starts to be affect by the attraction force between wires. By 80ns of the discharge, a plasma column with a density grater than $10^{19} cm^{-3}$ was observed. The cores of the wire were observed at the initial wire position up to 150ns. The brake up of the pinch was at 270ns. A filtered time-integrated pinhole camera recorded the x-ray emission, showing a plasma column ($h\nu > 1.5keV$) of about 100 μ m diameter formed at the axis, which is $m = 0$ and $m = 1$ MHD unstable. No x-ray emission

($h\nu > 1.5\text{keV}$) from wire cores was recorded. This may be due to the wire mass being excessively large compared with the low energy delivered by the Don accelerator ($\sim 1\text{kJ}$).

Other experiments related with two-wire z-pinch were performed by Yadlowsky *et al* [1.60]. These were specifically to study the current channel formation between wires and how the inhomogeneous nature of this channel can produce a significant impact on the dynamics of the pinch. A variety of current generators with single and double wire as loads were used to study different initial conditions in the generation of x-rays. These ranged from current per wire of the prepulse used in Saturn, which ramps up to 300kA in 200ns , to fast current pulses with rise time close to the values per wire encountered on Double Eagle [1.61]. Two $25\mu\text{m}$ aluminium wires separated by 2.5mm and 20mm long were used as load. They observed the effect of an attractive magnetic force, which permits the formation of a current channel between wires.

1.13.- *Structure of this thesis*

This thesis is structured as follows:

Chapter 2

APPARATUS AND DIAGNOSTICS: Physical description of the pulsed power generator; voltage and current monitors; timing trigger sequences of the experiments. Description of the different diagnostics: schlieren photography; gated optical intensifier; optical streak camera; time-integrated x-ray pinhole camera, and x-ray PIN diodes.

Chapter 3

EXPERIMENTAL OBSERVATIONS ON SINGLE WIRE Z-PINCHES: Presentation and comparison of dynamic behaviour of tungsten wires of various diameters ($5\mu\text{m}$, $7.5\mu\text{m}$, $10.16\mu\text{m}$, $13\mu\text{m}$, and $18\mu\text{m}$) and $15\mu\text{m}$ aluminium wire z-pinch.

Chapter 4

EXPERIMENTAL OBSERVATIONS ON TWO-WIRE Z-PINCHES: Presentation of the main results of two-wire z-pinch experiments for $7.5\mu\text{m}$ tungsten and $15\mu\text{m}$ aluminium wires using three different wire separations (0.3mm , 0.6mm , and 1.5mm). The first section contains results of aluminium z pinches, and the second one results of tungsten wires.

Chapter 5

DISCUSSION AND CONCLUSIONS: This chapter shows a summary of observations for both wire configurations. Comparisons with simulations of the dynamic behaviour of the pinch. Discussion about MHD instabilities. Interpretation of the different behaviours observed between aluminium and tungsten wire z-pinches. Also, it gives a brief description of future work on two-wire z-pinches to study mainly the central-plasma formation.

Chapter 2

APPARATUS AND DIAGNOSTICS

2.1.- Apparatus: IMP Generator

The main requirement on a pulsed power generator is given by the confinement parameters of the plasma. Such conditions demand a rate of rise of current, dI/dt , greater than 10^{12} A/s , which is compatible with ohmic heating of a high-density pinch in pressure balance [2.1]. The large internal impedance is much greater than the characteristic pinch impedance, thus ensuring that the driving current is not affected by the pinch dynamics. IMP is a high voltage pulsed power generator, which consists of a Marx bank, a pulse forming line (PFL), a self-break switch, a transfer line section (TLS), and a load chamber, as is shown in Fig. 2.1. IMP can deliver a maximum current pulse of 200 kA with a rise time ($10\% - 90\%$) of 70 ns .

This generator was designed and constructed in order to perform experiments in small scale, as well as to develop new diagnostics and alternative load configurations that would be later used on MAGPIE generator [2.2]. Its design shows a very clear structure, where a series of sensors have been installed to monitor each part individually. This feature permits easy localisation of failures. Moreover, due to its low energy output, IMP can perform several shots a day (five per day).

The Marx bank, which is housed in an oil filled tank, consists of eight capacitors of 700 nF at 100 kV distributed in four vertical columns of two units. These are connected in a bipolar configuration using four SF_6 filled spark gaps (Physic International T508A), and charged by two separated 100 kV power supplies of opposite polarity. Different charging voltages are catered by varying gas pressure at a fixed electrode separation. The Marx trigger pulse is provided by an Aldermaston air cored pulsed transformer, which produces a pulse with a peak voltage of 150 kV .

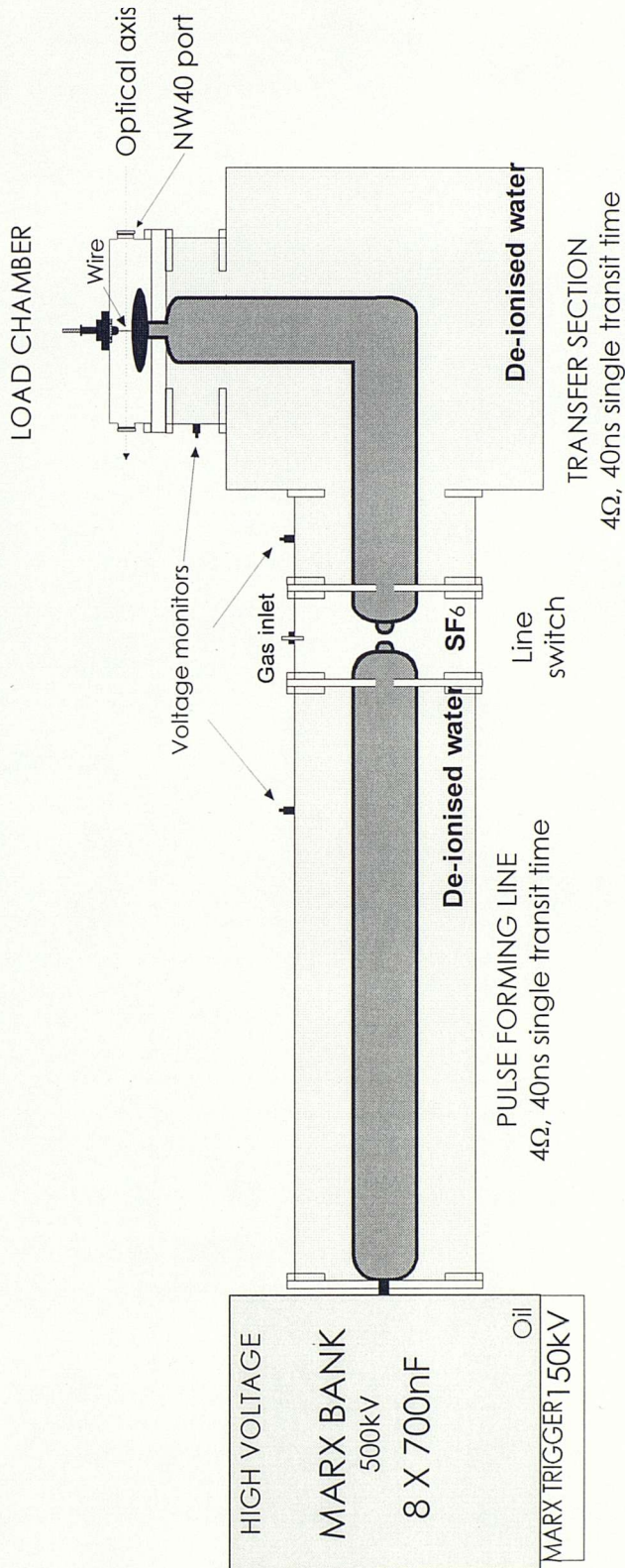


Figure 2.1. Schematic of IMP generator

Only the first two gaps of the Marx are triggered. The third and fourth gaps each have their trigger electrodes connected to earth via a resistor of approximately $2k\Omega$. They therefore break down in sequence once the first two gaps have closed [2.3]. The circuit is shown in Fig. 2.2.

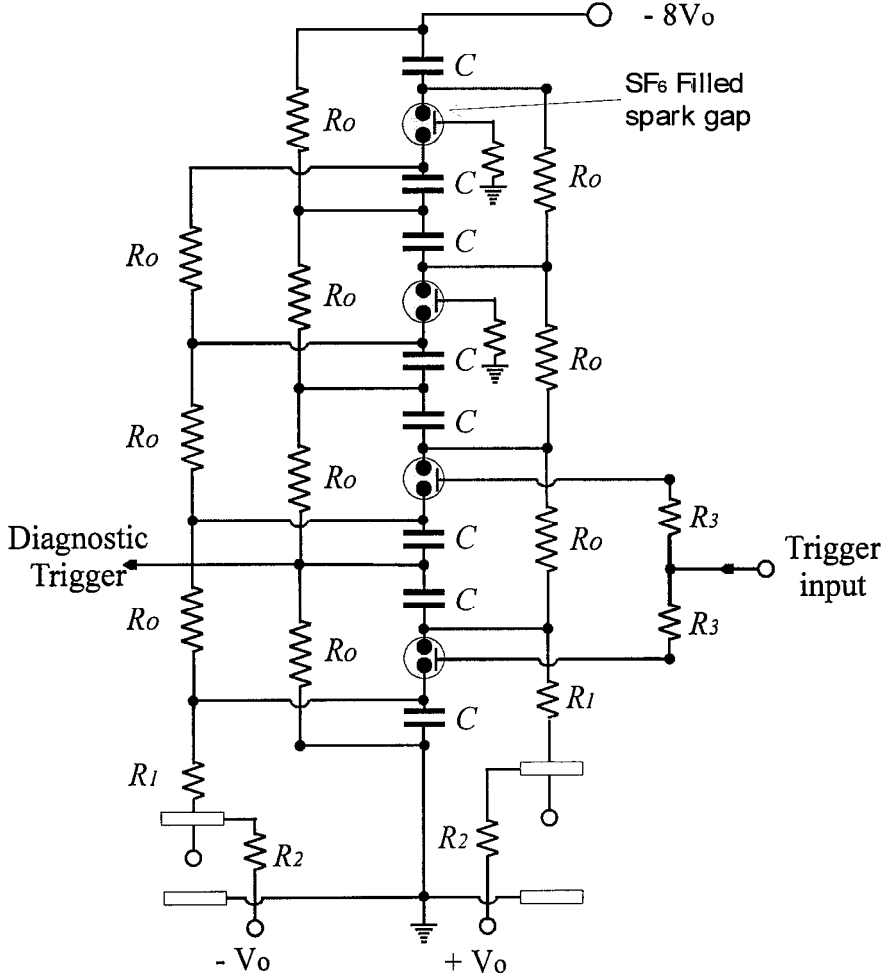


Figure 2.2. Circuit of IMP generator. Series capacity is $87.5nF$. $C = 700nF$, R_0 and R_3 are about $2k\Omega$, and R_1 and R_2 are about $50k\Omega$

The output of the Marx bank, V_{MB} , is taken out through a polythene diaphragm to the water filled cylindrical Pulse Forming Line (PFL), with an impedance of 4Ω and $40ns$ single transit time. The impedance Z of a water filled transmission line, with a inner radius a and outer radius b is given by

$$Z = \frac{377}{2\pi\epsilon_r^{1/2}} \ln\left(\frac{b}{a}\right) \quad \text{Ohms}$$

where ϵ_r is the relative dielectric constant, for water $\epsilon_r = 78.38$. For this PFL, the inner and outer radii are: $a = 13.4\text{cm}$ and $b = 24.1\text{cm}$ respectively, giving an impedance of $Z = 4.0\Omega$. The single transit time τ is defined by $\tau = d/c_w$, where $d = 125.0\text{cm}$ is the line length, and $c_w = c/\sqrt{\epsilon_r} \cong c/9$ is the light speed in water, giving $\tau = 39.0\text{ns}$ (measured: $\tau = 40\text{ns}$). The water is de-ionised to a resistivity better than $10^4\Omega\text{m}$. The inner line is supported at both ends by polythene diaphragms. The capacitance of the pulse forming line, C_{PFL} , is given by $C_{PFL} = \tau/Z$, thus $C_{PFL} = 40\text{ns}/4\Omega = 10\text{nF}$.

In order to get an effective voltage transfer, the capacitance of the pulse forming line, C_{PFL} , must be smaller than the capacitance of the Marx bank, C_{MB} . This condition is satisfied, because $C_{MB} = 87.5\text{nF}$.

The peak value voltage into the PFL, V_{PFL} is given by: $V_{PFL} = 2C_{MB} \cdot V_{MB} / (C_{PFL} + C_{MB})$, where $V_{MB} = 480\text{kV}$ (for a charging voltage of 60kV) and $C_{PFL} = 10\text{nF}$. For these values $V_{PFL} = 861\text{kV}$, exceeding V_{MB} by 80%. This is referred to as the *ring-up effect*.

Once the Marx generator is discharged into the PFL, the stored energy is then transferred to the transfer line section (TLS) through a self-break SF_6 filled line switch, which is mainly used for shaping the current pulse (c.f. Fig. 2.1). This switch was calibrated to break down at 70% of the PFL peak voltage ($V_b = 600\text{kV}$), yielding a jitter of about 5ns .

One possible improvement for this pulsed power generator would be to use a triggered switch rather than a self-break one, enabling a much higher voltage with lower jitter. In a self-break switch, jitter is a trade off against output voltage.

The transfer line section (TLS), whose characteristics are similar to the PFL (4Ω , 40ns) is used to isolate the pinch from the switch inductance, improving the current rise time [2.4]. Due to its right-angle design, it introduces an additional inductance of about 20nH [2.5].

The capacitor bank was charged up to 60kV , to deliver a current pulse to the load of about $(150 - 160)\text{kA}$ with a $(10\% - 90\%)$ rise time of 70ns . The complete sequence (Marx discharge $\rightarrow$ PFL $\rightarrow$ self-break switch $\rightarrow$ TLS) takes approximately 600ns .

The load chamber is located in the top of the transfer line section. A Perspex plate of 40mm of thickness is used as an interface, between water and vacuum. The working base pressure of the vacuum chamber is about 10^{-4} mbar .

The cylindrical load chamber has a diameter and height of 47cm and 12.5cm respectively, c.f. Fig. 2.3. It has eleven NW40 ports for diagnostics and a NW50 port to connect the vacuum pumping system.

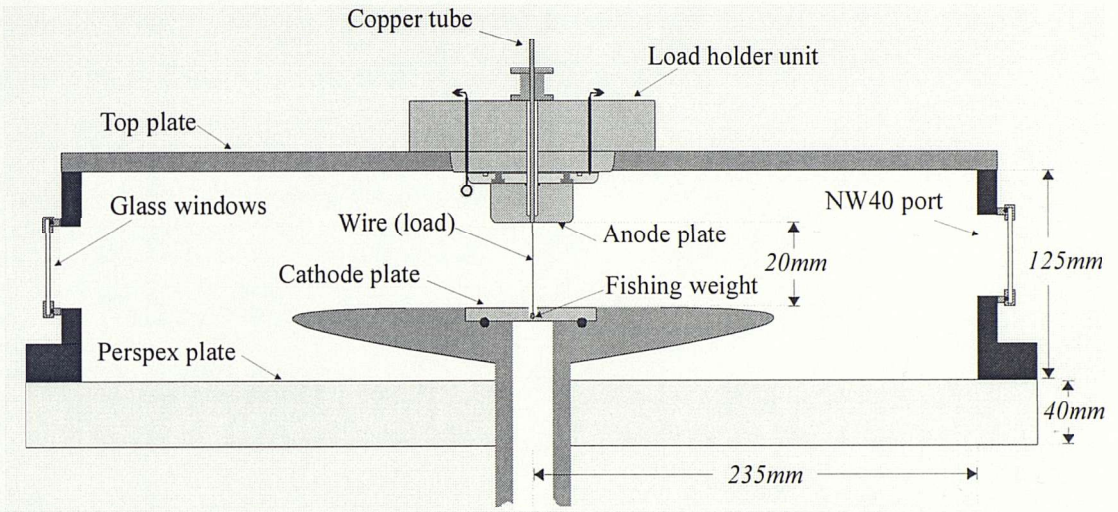


Figure 2.3. Schematic cross-section of the load chamber.

The top of the chamber is a plate that can be removed easily. In the centre of this plate, there is a NW100 port where the load holder unit is fitted. In the bottom end of this unit is located the anode. The load (one or two wires) is fed in through the anode using a 1.5mm external diameter copper tube. In order to keep the wire straight (perpendicular to anode and cathode surfaces), we use a small fishing weight ($m = 170\text{mg}$) attached to the bottom end of the load. This weight is placed inside a hole ($\phi = 3\text{mm}$) on the cathode plate by pushing down the copper tube. It is important to be sure that the fishing weight is in contact with the cathode. The anode-cathode separation, which is 20mm , enables both cathode and anode to be viewed through all ports.

2.2.- Voltage and Current Monitors

In the IMP generator, there are two types of voltage monitors, simple resistive dividers, and D-dot probes. The current monitors are a Rogowski coil and a B_θ -loop located at the chamber load, c.f. Fig. 2.4

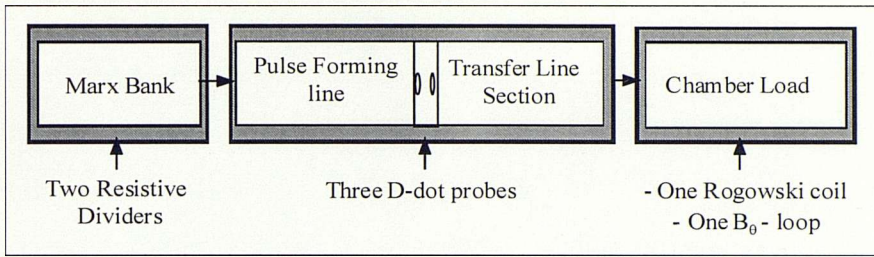


Figure 2.4. Voltage and current monitors in the IMP generator

The signals monitored with resistive dividers are the Marx Trigger and the diagnostic trigger (see Fig. 2.2). The D-dot probes are used in the water filled sections and are located as follows: one in the pulse forming line and two in the transfer line section. Finally the current pulse is monitored with a Rogowski coil and a B_θ - loop. These current monitors are installed in the load chamber.

2.2.1.- Voltage Monitors

2.2.1.1.-Resistive Dividers

A resistive divider is simply an arrangement of resistors in series that attenuates an input signal, c.f. Fig. 2.5. The monitor impedance, Z_M , must be much greater than load impedance Z_L , ($Z_M \gg Z_L$). Two of these dividers, with an attenuation factor of 800:1, were used to monitor voltage signals from the Marx trigger and from the diagnostic trigger output. The resistive dividers are designed to give an output voltage of greater than 100V so that the signal is much greater than any stray voltage that may be picked up. Further attenuators are used at the oscilloscope.

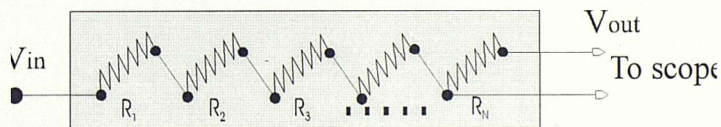


Figure 2.5. Schematic of a resistive divider

2.2.1.2.-D-Dot Probes

D-dot probes are suitable for measurements of high voltage transients in liquid filled transmission lines [2.6]. The advantages of these over resistive dividers are: 1) no distortion of the field in the region of measurement. 2) Immunity to surface tracking and

breakdown. 3) do not shunt the load with a lower impedance. And 4) do not require balancing of resistive and capacitive elements [2.7].

Figure 2.6 shows a schematic of a D-dot probe. It acts as a small capacitance from the inner conductor of the line to the 50Ω monitoring cable.

The capacitance of the probe can be estimated using the following relation: $C_{PFL}/C_p = A_{PFL}/A_p$. The ratio of C_{PFL} (Pulse Forming Line capacitance) to C_p (probe capacitance) is equal to the ratio of their respective areas. Where $A_p = \pi r^2$ ($r = 10.0 \times 10^{-3} m$) and $A_{PFL} = 2\pi r l$ ($r = 24. \times 10^{-2} m$ and $l = 1.25 m$). Therefore, the capacitance of the divider is equal to $C_p = 1.66 pF$.

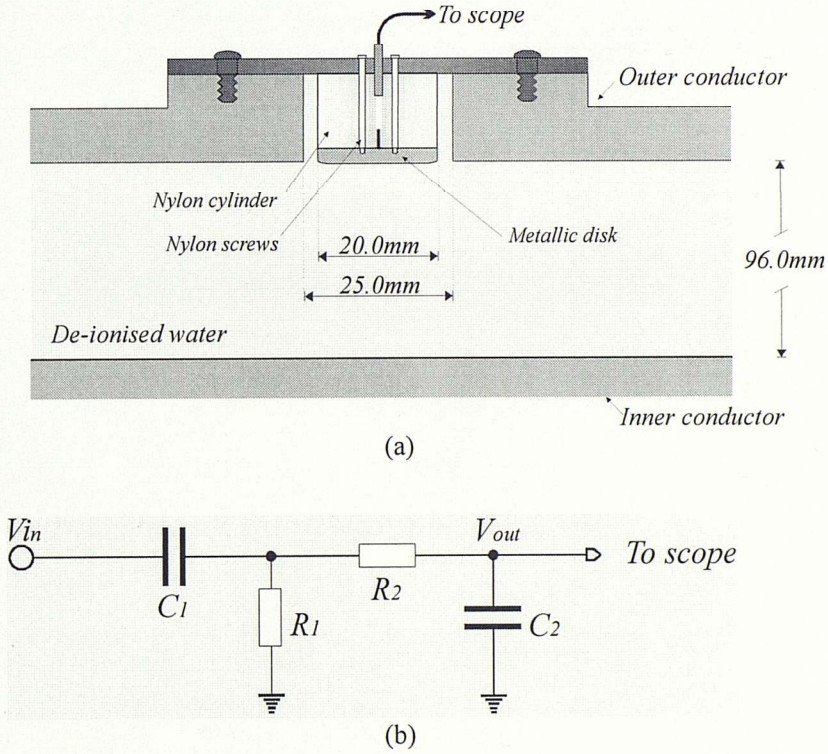


Figure 2.6. (a) Schematic of a D-dot monitor and (b) Equivalent electric circuit.

A 50Ω coaxial cable transfers the voltage pulse to the integrator ($\tau_2 = R_2 C_2$) on the scope. If $\tau_2 \gg \tau_1$, where $\tau_1 = R_1 C_1$ and $\tau_2 = R_2 C_2$ are time constants of the monitor and integrator respectively, then the output voltage of the divider is $V_{out} = (R_1 C_1 / R_2 C_2) \cdot V_m$. For $R_1 C_1 = 83 ps$ and $R_2 C_2 = 1.24 \mu s$, we have a monitor sensitivity of $14.9 kV$ per Volt ($1 : 14900$).

2.2.2.- Current Monitors

2.2.2.1.-Rogowski Coil

The inductive-shunt current monitor [2.8], see Fig. 2.7, consisted of an annular channel machined in a metallic plate. It is located on the load holder unit over the anode plate. An annular insulator sheet (Mylar) covers the channel, so that the axial current through the plasma is forced to flow around the inside surface of this. Temporal variations of the magnetic flux will induce a voltage in a pick up point P .

The voltage at P is

$$V_P = -\frac{d}{dt}\Phi_M \quad 2.1$$

where Φ_M is the magnetic flux,

$$\Phi_M = \oint_s \mathbf{B} \cdot d\mathbf{S} = \frac{\mu_o I}{2\pi} \oint_s \frac{dzdr}{r} \quad 2.2$$

In our case (see Fig. 2.7), the area over which the integral is evaluated is bounded by the return-current path at the point r_p . Thus,

$$\begin{aligned} \oint_s \frac{dzdr}{r} &= \int_0^{D+\Delta} dz \int_{r_i}^{r_o} \frac{dr}{r} + \int_0^{\Delta} dz \int_{r_o}^{r_p} \frac{dr}{r} \\ &= (D + \Delta) \ln \frac{r_o}{r_i} + \Delta \ln \frac{r_p}{r_o} \end{aligned} \quad 2.3$$

So that

$$V_P = \left(\frac{\mu_o}{2\pi} \left((D + \Delta) \ln \frac{r_o}{r_i} + \Delta \ln \frac{r_p}{r_o} \right) \right) \frac{dI}{dt} = L \frac{dI}{dt} \quad 2.4$$

where D is the depth of the groove, Δ is the thickness of the Mylar insulator, r_i and r_o are the internal and external radius of the groove and dI/dt is the time rate of change of the current. The values of r_i , r_o , r_p , D , Δ are shown in Fig. 2.7, and we obtain $L = 40.83 \times 10^{-12} \text{ H}$.

To measure the current waveform through the plasma it is necessary to integrate the output V_p . Normally a passive integrator is used to do this operation. If the time constant of the integrating circuit, RC , is much larger than the period of the input signal, τ (the rise time of current pulse), then Eq. 2.4 can be written as:

$$V_p = \frac{L}{RC} I_{plasma} = S \cdot I_{plasma} \quad 2.5$$

Where V_p is the integrated signal measured in the scope, with $RC \gg \tau$. Knowing L , and the time constant of the integrating circuit RC , we can determine the sensitivity of the probe. An integrator circuit with a $RC = 1.21 \mu s$ was used.

Then, a sensitivity of $S = 34.03 \times 10^{-6} (V/A)$ was obtained. So, for an output voltage of $1V$, the measured load current is $29.39 kA$.

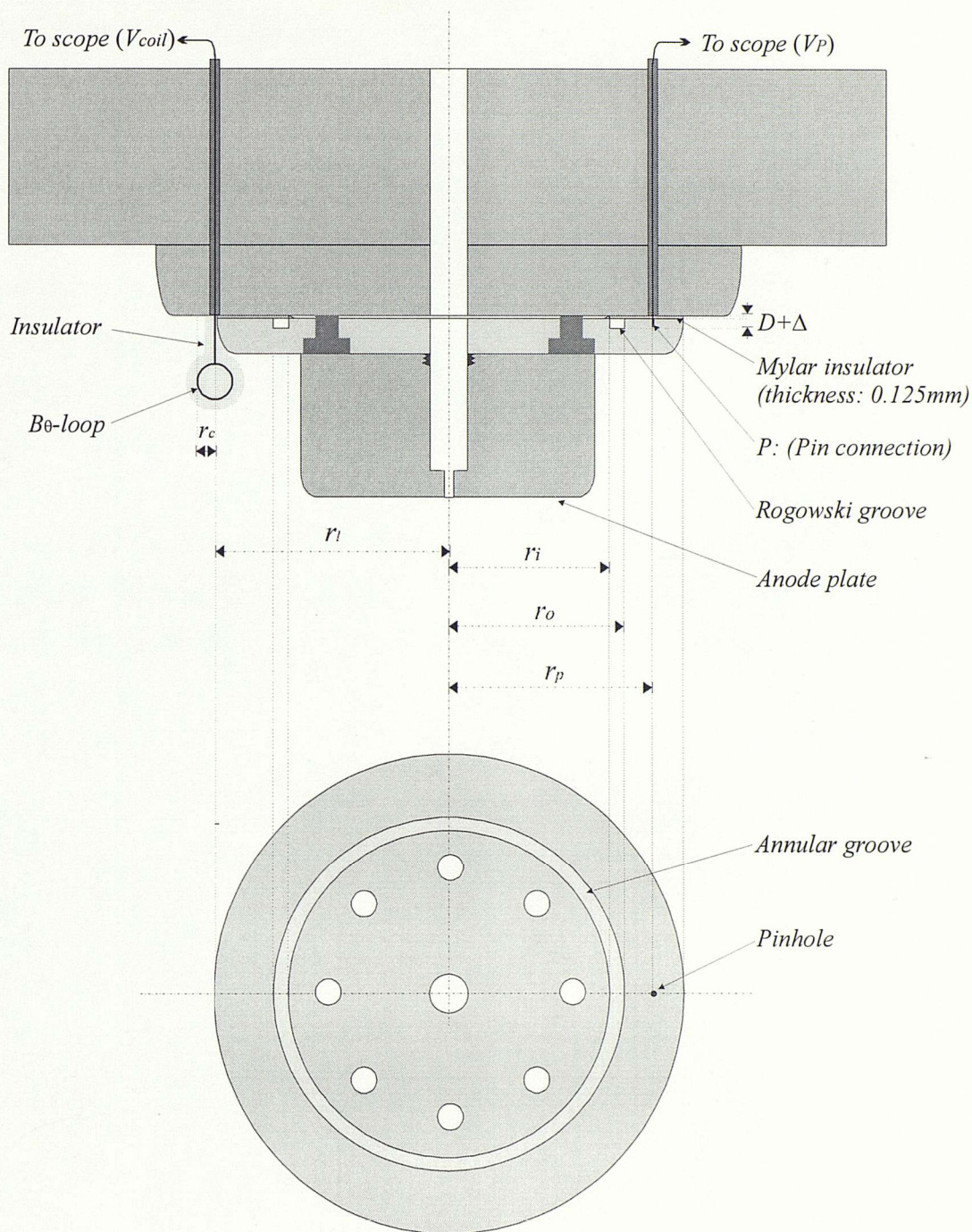
2.2.2.2.- B_θ - LOOP

This current monitor (see Fig. 2.7) is based on the same principle as the previous monitor, that is: *rate of change of magnetic flux induces a voltage*. In this case, the coil has only a single loop ($N = 1$), with a radius, $r_c = 3.0 mm$. Thus, the magnetic flux is given by $\Phi_M = \mathbf{B} \cdot \mathbf{A} = \mu_o I A$ (provided the monitor area is perpendicular to $\mathbf{B}$), and the induced voltage by $V_{coil} = -d\Phi_M/dt = d(\mu_o I A)/dt$. Then

$$V_{coil} = (\mu_o A) \frac{dI}{dt} = S \frac{dI}{dt} \quad 2.6$$

Where $\mu_o A$ is the sensitivity of the monitor, S . To determine the current we must integrate Eq. 2.6, This is performed via an RC integrator. Thus $I = (RC/S)V_{coil}$, this depends on the time constant, RC , and the loop sensitivity, S .

In our case, these values are: $RC = 1.1 \mu s$ and $S = 35.5 \times 10^{-12} Hm$. Therefore, if we measure a voltage signal of $1V$, this corresponds to a plasma current of about $31.0 kA$.



Dimensions: $r_i = 27.5\text{mm}$, $r_o = 30.0\text{mm}$, $r_p = 35.0\text{mm}$, $D = 2.0\text{mm}$,
 $\Delta = 0.125\text{mm}$, $r_l = 40.0\text{mm}$, $r_c = 3.0\text{mm}$

Figure 2.7. Schematic of the load holder unit, showing in detail the current monitors: Rogowski groove and B θ -loop.

2.3.- *Timing Trigger Sequence*

In order to correlate a large number of diagnostics simultaneously with a jitter less than 10 ns , it was necessary to study the behaviour of different signals from IMP, i.e., Marx Voltage, PFL voltage, TLS voltage, see Fig. 2.8. Due to the continuous sampling mode of the digital scope, which was used during these experiments, it is possible to record events that happen before the trigger signal.

At the junction of Marx capacitor 2 and 3 (see Fig. 2.2) a positive pulse at the time of Marx discharge, with a jitter of only 5 ns was found (J. Worley, private communication). A resistive divider at this junction was used. The trigger-timing sequence diagram is shown in Fig. 2.8. A fiducial time of 22 ns was added to the laser signal monitored by the photodiode in order to have the same reference time as the Rogowski coil signal. The time delay of signals, associated with cables to the scope, was measured using a pulse generator. All signals are referenced to the load-current signal.

2.4.- Generator Performance

Voltage waveforms from the pulse forming line (PFL) and transfer line section (TLS) are shown in Fig. 2.9 and 2.10. These voltage waveforms were monitored at the positions shown in Fig. 2.1.

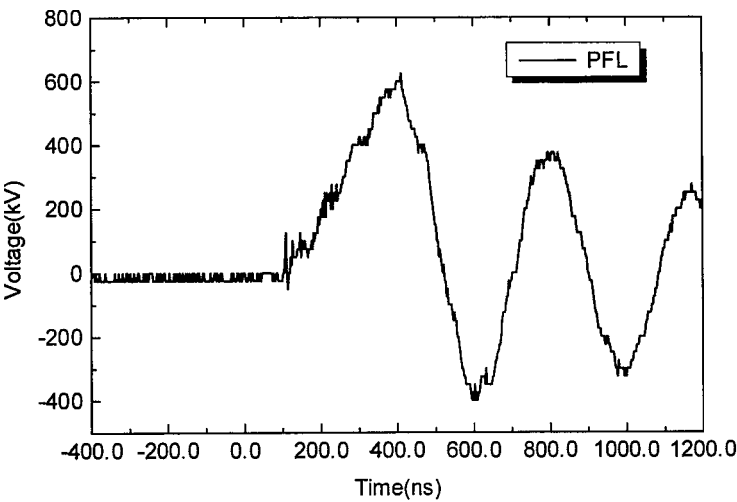


Figure 2.9. The measured voltage waveform at PFL using a D-dot probe.

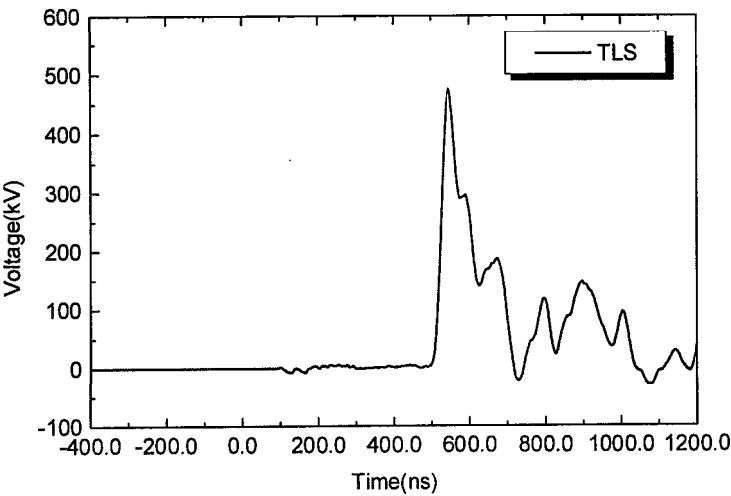


Figure 2.10. The measured voltage waveform at TLS using a D-dot probe.

These represent typical voltage signals for a capacitor bank discharge of 480kV. The line switch located between the PFL and the TLS enables shaping of the current pulse. Reliable operation and low temporal jitter was obtained by operating the switch at the 70% self-break condition. For the present transmission line, the time at which the switch break down was ~ 500 ns after the Marx had discharged. The measured signal at the TLS shows a compressed pulse with a rise time 10 times faster compared to the pulse forming line signal.

The performance of IMP has been modelled using the SCREAMER code [2.9] by A. Lorenz [2.5], it is fully described in his PhD thesis.

2.5. - *Diagnostics*

In general to describe a plasma is necessary to know parameters such as electron density, ion density, state of ionisation, electron temperature, and ion temperature. In addition, one wants to know the evolution of the plasma column, expansion, and instability growth rates.

In this work, some of these parameters were studied through detailed measurements of the optical self-emission, x-ray self-emission, and by pulsed laser probing. According to the diagnostic employed, the information obtained was spatial resolved or time resolved.

Description of the diagnostics employed is presented in detail in this section.

2.5.1.-*Optical-Diagnostic Instruments*

2.5.1.1.- *Optical Streak Camera*

A Kentech optical streak camera was used to study the plasma self-emission. With it, time-resolved information in one spatial direction is obtained.

This camera has an internal micro channel plate intensifier (MCP) giving a gain of up to about 10^3 . The MCP is coupled with a 40mm diameter fibre optic. The camera has an internal magnification of 1.2 and a spatial resolution of 7 lines/mm . Sweep speeds of 2.5 ns/mm and 7.5 ns/mm with a 0.5mm wide slit were used, giving a time resolution of 1.25 and 3.75 ns respectively. The images were recorded on Ilford HP5™ film. A schematic of the arrangement is shown in Fig. 2.12. Variation of object and image distance, with reference to the image lens, enabled us to obtain different magnifications (4, 8, and 12). Neutral density filters, ranging from 0.9 to 2.5 were used in order to obtain the correct light exposure into the camera.

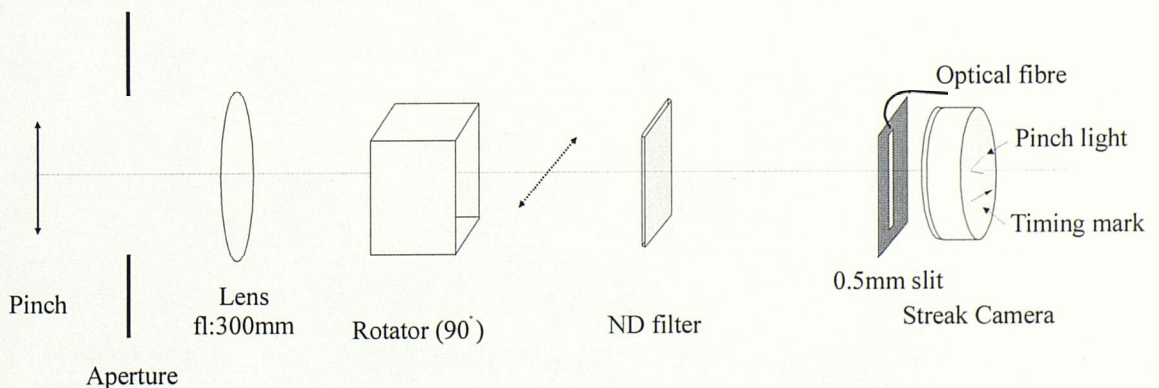


Figure 2.12. Schematic of radial streak set up.

Normally two streak directions are used: along to the z-pinch axis, called axial mode, and perpendicular to this axis, called radial mode. The axial mode was used to study the axial structure and its time history. The radial mode enabled to determine the diameter of the pinch at a particular axial position. The image rotator facilitated to change between both modes (see Fig. 2.12). The camera was triggered as shown Fig. 2.8. In order to time the streak image with the current waveform, a monitor signal from a trigger unit located at screened room was simultaneously recorded on the film using a fast LED monitor (timing mark) and in a oscilloscope (See Fig. 2.8).

2.5.1.2.- *Four-Frame Gated Optical Imager*

The Kentech Gated Optical Imager, GOI18/4™ [2.10], is a set of four micro channel plates of 18mm diameter each, which can be triggered individually. This camera has a shortest gate time of 120ps . This feature permits events to be recorded over a very short time. The spatial resolution is about 10lp/mm . The camera records the images onto $5''\times 4''$ format film. The inter-frame delay can be set via cables. The input trigger signal is buffered and taken to four pulse driver boards, via external loop connections. The length of the cable making these loops sets the timing of each frame. Thus, any inter-frame delay combination can be set up. Also, each frame has an output signal, which enables monitoring of the framing time. This camera was also triggered from a delay unit that was synchronised with the diagnostic trigger signal as is shown in Fig. 2.8.

For these experiments, the GOI18/4™ was gated for 1ns with inter-frame delays of either 5 or 15ns . A pulse monitor signal from each intensifier was recorded on the scope.

A schematic of the arrangement is shown in figure 2.13. The image of the pinch is collected by two lenses, in a Kepler scope configuration, with a magnification of four. Then, this image arrives to a splitter beams arrangement, which splits the beam into four. At the image plane, four images with approximately the same intensity, magnification and optical path are created.

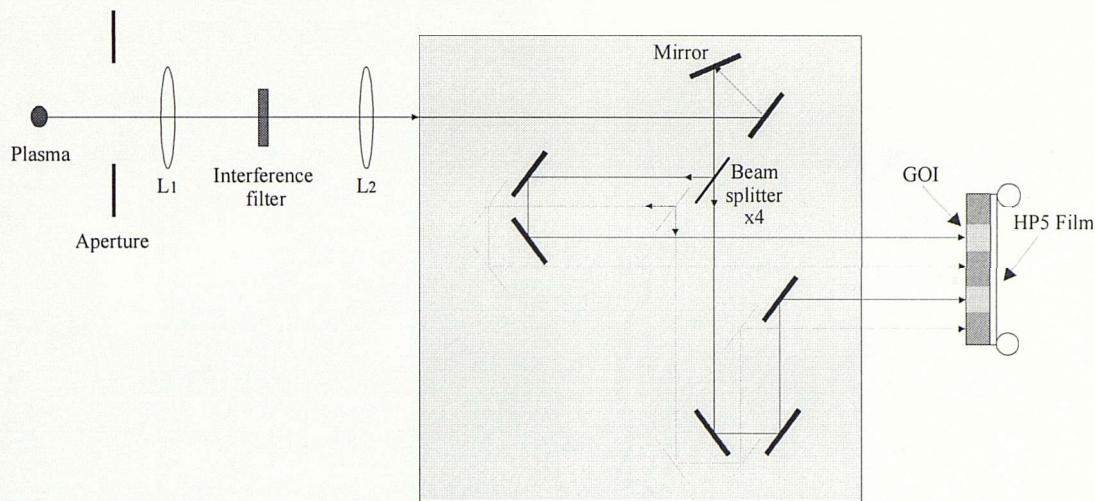


Figure 2.13. Schematic arrangement of the four frame GOI camera.

Considering that a magnification of 4x was used in this arrangement, only 4mm of the plasma was framed. Images were recorded on Ilford HP5™ film. An interference filter, $\lambda = 486\text{nm}$, with a bandwidth FWHM of 10nm permitted to get images with a high quality and a better definition of the pinch structure. At this wavelength, the photo-cathode has a spectral response of 50mA/W, c.f. Fig. 2.14 [2.10]. Spectroscopic observations of this filtered plasma light were performed in order to be sure that there is not any line emission inside of this wavelength range. This was done both for aluminium and for tungsten wire plasmas, showing that only continuum radiation from the plasma was collected.

In short, images from the optical emission of the wire plasma with 10nm bandwidth at $\lambda = 486\text{nm}$ and 1ns gating time resolution were obtained.

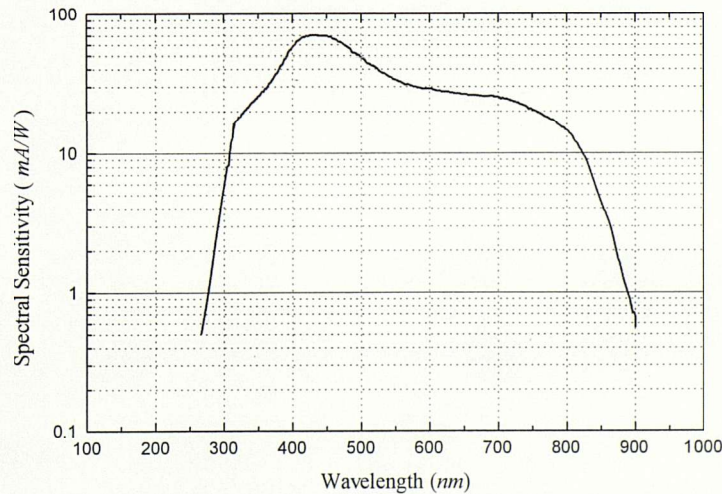


Figure 2.14. Photocathode spectral response

2.5.2.- X-Ray Diagnostics

The x-ray emission from the plasma was measured using passive (x-ray film) and active (x-ray *PIN* diodes) detectors. A time-integrated pinhole camera and two filtered *PIN* diodes were used.

2.5.2.1.- Time-Integrated X-Ray Pinhole Camera

Pinhole cameras are capable of record a two-dimensional views of the plasma pinch. This provides spatially resolved information of the x-ray emission from the pinch. Also, by using filters, an estimate of the energy emitted by the plasma for a given spectral energy range can be obtained [2.11].

Figure 2.15 shows the principle of the camera. A point source at the object distance p (from a pinhole) will produce a uniform penumbra disc of light in the recording material located at a distance q . The diameter of this disc is $d = D(1 + m)$, where D is the pinhole size and m is the camera magnification ($m = q/p$). Thus, the illuminated disc or circle of penumbra is proportional to the pinhole size D , and increases with increasing magnification. The image size D_i is related to the object size D_o through: $D_i = mD_o + d$. Moreover, the resolvable object size D_o became $D_o = D(1 + 1/m)$.

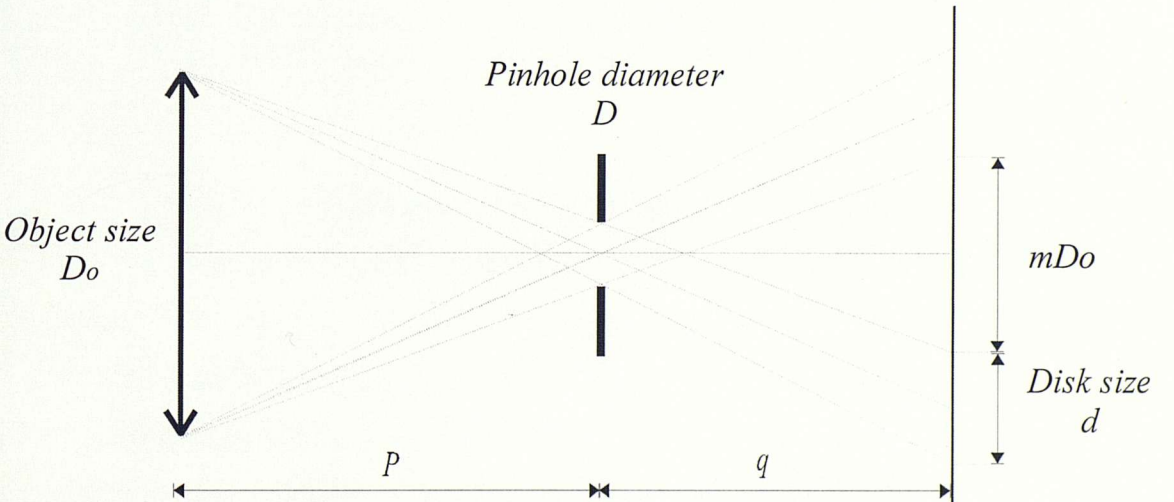


Figure 2.15. Physical principle of pinhole camera

For a given pinhole size and x-ray energy; film, geometry and diffraction effects determine the resolution of this camera [2.12].

The angular uncertainty θ_g due to geometrical effects is defined by $\theta_g = D(1/p + 1/q)$. The uncertainty introduced by diffraction is given by $\theta_d = \kappa(\lambda/D)$, where κ is of order unity and λ is the wavelength of the radiation. Minimising the total angular uncertainty, $\theta = \sqrt{\theta_g^2 + \theta_d^2}$, the minimum is when $\theta_g = \theta_d = \theta_o$, which gives the pinhole diameter at optimum resolution $d_o = \sqrt{k\lambda pq/(p+q)}$ [2.13].

A six-pinhole camera with individual x-ray foil filters was used to record soft x-ray images of the pinch. Pinhole diameters ranging from 20 to 300 μm were used. The camera was placed at about 32cm from the z-pinch plasma, producing images with a magnification of 0.6 times the object size.

Table 2.I shows some parameters of the camera used in these experiments, details related with transmission and energy windows of x-ray filters are presented in chapter 3 and 4.

Table 2.I. Geometrical properties of the Pinhole Camera.

Pinhole diameter (μm)	Penumbra (μm) (disk diameter)	Resolvable Object Size (μm)
20	32	52
50	80	130
100	160	260
200	320	520
300	480	780

The pinhole images were recorded on Kodak-DEF™ x-ray film. It has a lower ground fog level in comparison with others films. A calibration for this film has been performed by Rockett *et al* [2.14] in the energy range of 0.93 to 6.93 keV. There also exists experimental calibration in the energy range of 1 to 10 keV [2.15].

On the other hand, Niffikeer [2.16] calculated the film sensitivity based on Henke's model [2.17] for a wider energy range (100eV to 20keV).

Figure 2.16, shows the DEF film sensitivity for an energy range between 100eV to 10keV.

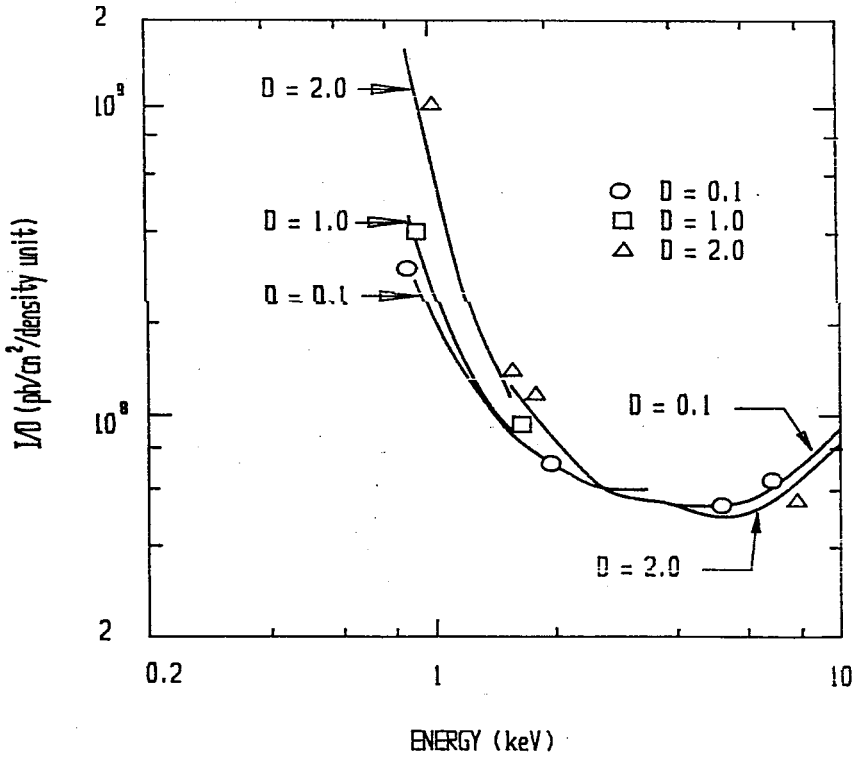


Figure 2.16. Sensitivity of Kodak DEF film as a function of incident photon energy.

2.5.2.2.- X-Ray PIN Diodes

Silicon positive-intrinsic-negative (PIN) diodes are very convenient devices to obtain time-resolved information on x-ray emission from transient plasmas. These x-ray detectors are used mainly to determine an estimate of plasma temperature according to the filters that are used, and the energy of electron beam. Their simple construction, fast response, and high sensitivity make them suitable for measurements of pulse radiation between 1 to 20 keV [2.18]. The spectral response of bulk intrinsic silicon is basically a flat function giving out about 0.282 *Coulombs* of charge for each *Joule* of absorbed x-rays. The sensitivity $S(E)$, can be described by a two-thickness model [2.19],

$$S(E) = 0.282 \times e^{-\mu(E)x_d} [1 - e^{-\mu(E)x_i}] \quad 2.10$$

where $\mu(E)$ is the absorption coefficient of silicon, x_d and x_i are the thickness of the dead and intrinsic layer respectively. The first exponential term represents transition through the n-type dead layer and the term in bracket represents absorption in the intrinsic layer. The PIN diode sensitivity is determined by the thickness of the intrinsic layer. Hohlfelder [2.19] presents a detailed PIN diode calibration between 1.8 and 5.0 keV, and Corallo *et al* [2.20] between 1.5 and 17.4 keV.

Figure 2.17 shows the sensitivity curve of these *PIN* diodes, which was obtained from a code written by R. Spielman [2.21] in the energy range of 0.2 to 10 keV .

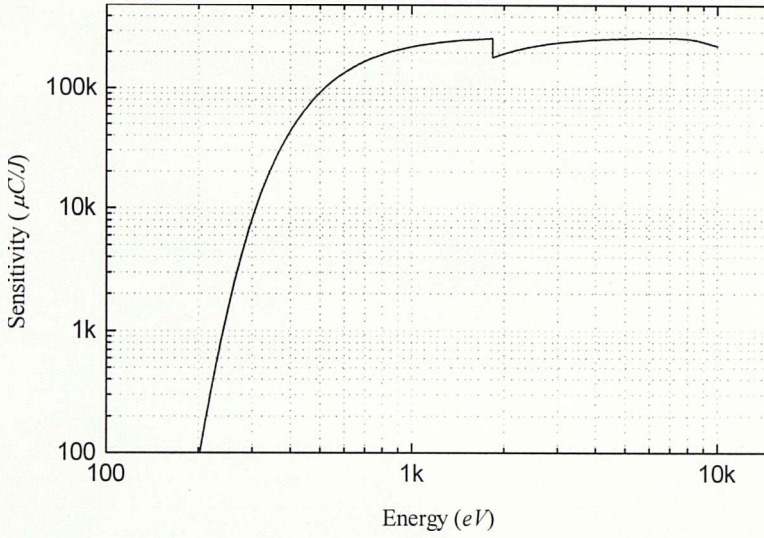


Figure 2.17. Sensitivity curve of a *PIN* diode with intrinsic and dead layer thickness of $250\text{ }\mu\text{m}$ and $0.5\text{ }\mu\text{m}$ respectively.

Two Quantrad™ *PIN* diodes with an intrinsic and dead layer thickness of $250\text{ }\mu\text{m}$ and $0.5\text{ }\mu\text{m}$ respectively were used, see Fig. 2.18.

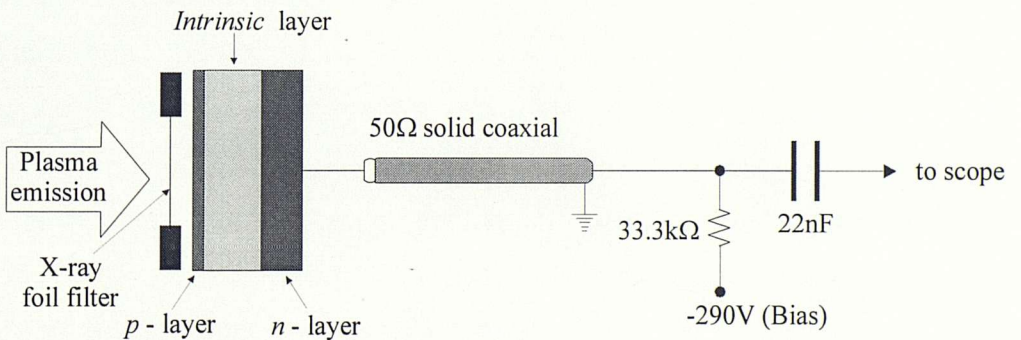


Figure 2.18. Schematic of *PIN* diode set up.

The filtered *PIN* diodes were used either collimated or non-collimated. In the first case, c.f. Fig. 2.19(a), an aperture of 4 mm in a steel disk was located to block the radiation that comes directly from the electrodes. With this configuration only the soft x-ray emission ($h\nu \sim 0.1 - 5\text{ keV}$) from the plasma column is detected. In the non-collimated

configuration the aperture was removed, allowing detection of the hard x-ray emission ($h\nu > 5\text{keV}$) from the electrodes, c.f. Fig. 2.19(b).

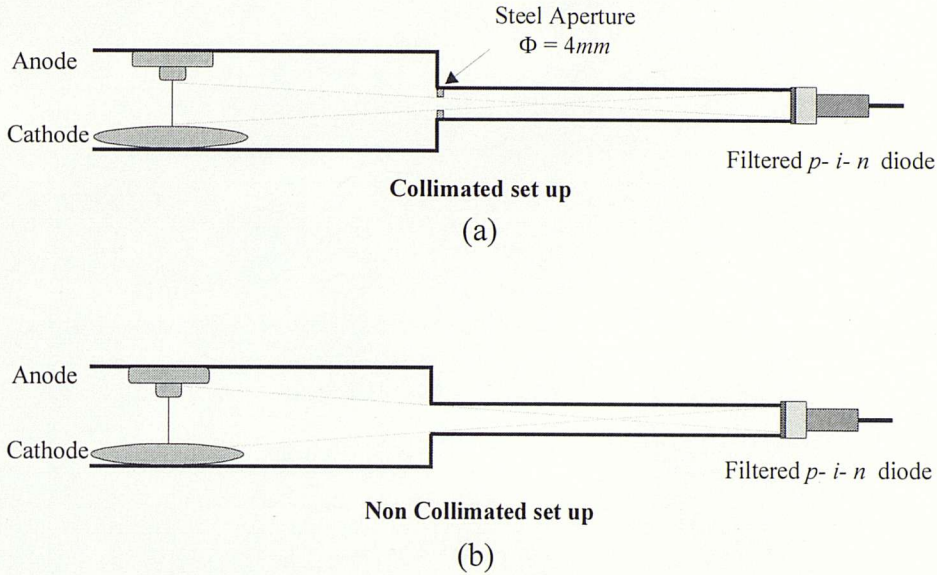


Figure 2.19. Schematic of *PIN* diode configurations

The use of PIN diodes in combination with Ross filters provided a time-resolved spectrum. The Ross filters [2.22] or balanced filter consists of two foils made from adjacent or nearly adjacent elements in the periodic system. The amount of transmitted radiation is nearly the same for all x-ray energies except in the energy range between the absorption K-edges of the two elements. The difference in transmitted x-ray energy then measures the radiation in the energy interval between the two K-edges.

For each configuration, Fig. 2.19(a) and 2.19(b), two x-ray foil filters were used with two PIN diodes. Filters were placed directly in front of each detector to minimise secondary fluorescent radiation. The characteristics required for the x-ray filter combination are: 1) different transmission bands in the wavelength range of interest; 2) opacity to ultraviolet and visible radiation (light tight); and 3) low transmission of radiation with $\lambda \geq 100\text{\AA}$, to avoid line emission from low Z impurity ions.

Any radiation in the interval measured using Ross filter pair produces a difference in the output signal from each of the two detectors. The difference between signals can be obtained by subtraction of the two traces recorded on an oscilloscope. To calculate the x-ray yield in the energy band, the sensitivity of PIN diodes, filter transmission and solid angle are taken into account. The yield is given by

$$Y = \frac{(Q_1 - Q_2)}{d\Omega} \frac{4\pi}{S \cdot T} \quad 2.11$$

where Q_1 and Q_2 are the charge measured with the PIN diodes in Coulomb ($Q = \int (V/R) dt$ [C], $V =$ Voltage signal and $R = 50\Omega$), $d\Omega$ is the solid angle, S is the diode sensitivity in [$\mu C/J$] and T is the filter transmission.

2.5.3.- LASER PROBING

2.5.3.1.- OPTICAL REFRACTIVITY OF PLASMAS

In order to find a specific expression that allows us to correlate the deflection of the beam with parameters of the plasma, it is necessary to know the dispersion relation of the plasma

Firstly, it is necessary to consider the nature and properties of electromagnetic waves in plasma. The plasma will be considered as a continuous medium in which current can flow, but that is otherwise governed by Maxwell's equations in a vacuum. The important equations are then

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} \quad 2.12$$

where all the electromagnetic properties of the plasma appear explicitly in the current $\mathbf{j}$. There may be equilibrium values of fields $\mathbf{B}_0, \mathbf{j}_0, \mathbf{E}_0$ that are present in the absence of the considered waves. If so, then Eq. 2.12 applies to the equilibrium and wave parts separately and we shall consider now that non-subscripted variables refer to the wave quantities only.

By taking $\nabla \times$ (to the first Eq. in 2.12) and $\partial/\partial t$ (to the second one), it is possible to eliminate $\mathbf{B}$. Thus,

$$\nabla \times (\nabla \times \mathbf{E}) + \frac{\partial}{\partial t} \left(\mu_0 \mathbf{j} + \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} \right) = 0 \quad 2.13$$

This equation may be written for a single Fourier mode as

$$\mathbf{k} \times (\mathbf{k} \times \mathbf{E}) + i\omega (\mu_0 \sigma \cdot \mathbf{E} - \varepsilon_0 \mu_0 i\omega \mathbf{E}) = 0 \quad 2.14$$

which may be rewritten (noting $\epsilon_0 \mu_0 = 1/c^2$) as

$$\left(\mathbf{k}\mathbf{k} - k^2 \mathbf{I} + \frac{\omega^2}{c^2} \boldsymbol{\epsilon} \right) \cdot \mathbf{E} = 0 \quad 2.15$$

where σ is the plasma conductivity, $\mathbf{I}$ is the unit dyadic and $\boldsymbol{\epsilon}$ is the dielectric tensor

$$\boldsymbol{\epsilon} = \left(\mathbf{I} + \frac{1}{\omega \epsilon_0} \boldsymbol{\sigma} \right) \quad 2.16$$

The properties of the plasma may be equally well specified through the permittivity $\boldsymbol{\epsilon}$ as through the conductivity $\boldsymbol{\sigma}$. These contain equivalent information since they are related by Eq. 2.16; it is often more convenient to think of the plasma as a dielectric medium whose permittivity is specified, rather than its conductivity.

Now, Eq. 2.15 represents three homogeneous simultaneous equations for the three components of $\mathbf{E}$. In order for these to have a nonzero solution, the determinant of the matrix of coefficients must be zero:

$$\det \left(\mathbf{k}\mathbf{k} - k^2 \mathbf{I} + \frac{\omega^2}{c^2} \boldsymbol{\epsilon} \right) = 0 \quad 2.17$$

The Eq. 2.17 relates the $\mathbf{k}$'s and ω 's for different waves and is the “*dispersion relation*” for these waves. For any given wave vector $\mathbf{k}$ it determines the corresponding frequency ω or vice versa. The dispersion relation of transverse waves is just the familiar expression of simple optics $\mu \equiv kc/\omega = \epsilon^{1/2}$ where μ is the refractive index.

In order to calculate the properties of propagation of transverse waves in plasmas, it is necessary to have knowledge of the permittivity $\epsilon(k, \omega)$. Assuming the electrons are taken to be at rest (cold plasma approximation), except for motions induced by the wave fields. The dielectric constant is given by $\epsilon = 1 - \omega_p^2 / \omega^2$, where $\omega_p = (n_e e^2 / \epsilon_0 m_e)^{1/2}$ denotes the electron plasma frequency. Therefore, the refractive index is

$$\mu^2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c} \quad 2.18$$

where n_c is the critical electron density ($n_c = \omega^2 m_e \epsilon_0 / e^2$).

The refractive index depends both on the wave frequency and on the electron density n_e . It should be no surprise that the values of the refractive index obtained depends only on density, since our cold plasma treatment has explicitly excluded other plasma effects, such as finite temperature. However, the fact that this treatment represents a typical plasma very well, allows one to use the refractive index to measure these two parameters with excellent confidence and accuracy. This relation is valid for all modes (provided no magnetic fields), independently of the direction of propagation, because the plasma is isotropic.

2.5.3.2- SCHLIEREN PHOTOGRAPHY

The deflection of light rays by transverse density gradients, is a limitation on the utility of interferometry. However, it is the basis of a considerable number of diagnostic procedures to detect spatial variations of the refractive index in hot dense plasmas. It is now customary to designate all such methods as *schlieren*, although the older literature reserves the term *schlieren* for techniques that detect the uniform deflection of a constant refractive index gradient and uses the term *shadowgraph* for techniques used to observe non-uniform deflections due to varying gradients [2.23].

The practical distinction between *schlieren* and *shadowgraph* methods is generally the *schlieren* techniques are sensitive to the first derivative of the refractive index while *shadowgraphy* depends on the second derivative [2.24]. The basic principle of the *schlieren* is shown in Fig. 2.20, it introduces subsidiary elements into the optical systems that cause intensity variations in the location of the focused image. A *shadowgraph* system, Fig. 2.21, on the other hand, examines the redistribution of the laser light, permitting study of brighter regions in the film. These variations of light intensity are associated with the second derivative of the refractive index. With the *shadowgraph* system and constant density gradients, one can obtain only an outline of the boundary within which the constant gradient exists. Whereas if the gradients vary within these regions there may also be a richness of detail in intensity fluctuation, due to variable amount of overlap of initially parallel rays. Both *schlieren* and *shadowgraphy* methods can be very effective in delineating discontinuities and, overall visualising of plasma configurations; but quantitative evaluation is difficult and generally requires further specialised arrangements.

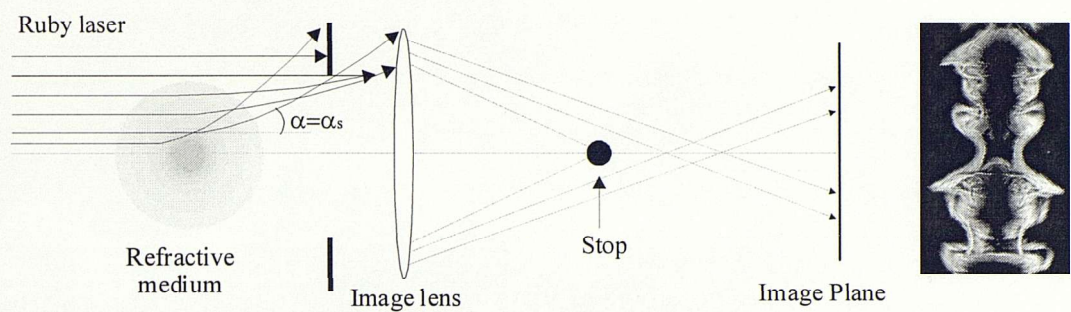


Figure 2.20. Schlieren photography set-up. Schlieren photograph of a $13\mu\text{m}$ diameter tungsten wire z-pinch

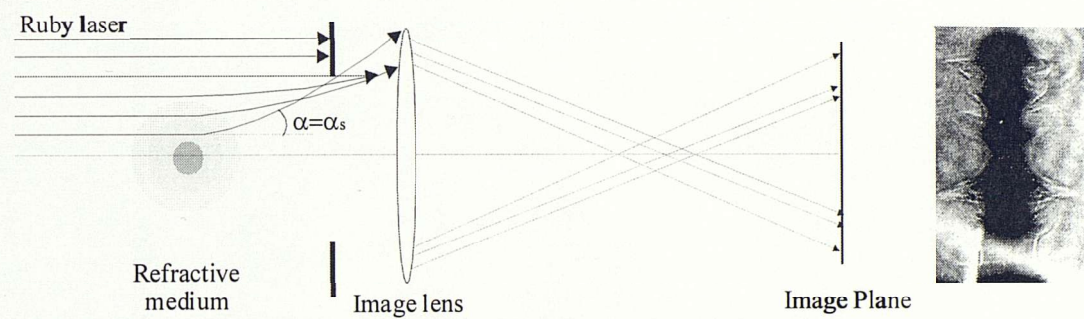


Figure 2.21. Shadowgraphy photography set-up. Simultaneous shadowgraph image of the $13\mu\text{m}$ diameter tungsten wire z-pinch of Fig. 2.20.

2.5.3.3.- DERIVATION OF ANGULAR DEFLECTION

For the case of a constant density gradient perpendicular to the direction of propagation, the amount of angular deflection is easily derived with the aid of Fig. 2.22.

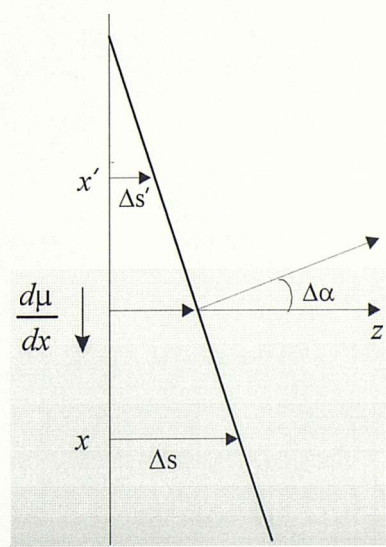


Figure 2.22. Angular deviation of wavefront due to a density gradient.

A phase front propagating along z arrives simultaneously at x and x' , which demarcates the incident boundary of the region containing the gradient. In a subsequent time interval Δt , the portions incident at x and x' travel distances proportional to their velocities, $\Delta s = c \Delta t / \mu$ and $\Delta s' = c \Delta t / \mu'$, respectively, where the refractive index μ' at x' is related to the refractive index μ at x by $\mu' = \mu + (\partial\mu/\partial x)\Delta x$ and $\Delta x = x - x'$. Thus $\Delta s' = \Delta s(\mu/\mu')$ and

$$\Delta s - \Delta s' = \Delta s(1 - \mu/\mu') = \left(\frac{\Delta x}{\mu'}\right)\left(\frac{\partial\mu}{\partial x}\right)\Delta s \quad 2.19$$

However, $\Delta s = x\Delta\alpha$ and $\Delta s' = x'\Delta\alpha$, so that $\Delta s - \Delta s' = \Delta x\Delta\alpha$ and, combining with Eq. 2.19

$$\Delta\alpha = \left(\frac{1}{\mu'}\right)\left(\frac{\partial\mu}{\partial x}\right)\Delta s \quad 2.20$$

For a non-constant density gradient the derivation can be generalised by a limiting process to $d\alpha = (1/\mu')(\partial\mu/\partial x)ds$, and as long as the total deflection from the z -axis remains small, we obtain

$$d\alpha_x = \int_0^{\ell} (1/\mu')(\partial\mu/\partial x)dz \quad 2.21$$

Substituting Eq. 2.18, this relates the refractive index with the electron density. Therefore, integrating Eq. 2.21, we obtain

$$\alpha = -(\lambda^2/2\pi)\left(e^2/m_e c^2\right)\int_0^{\ell}(dn_e/dx)dz \quad (\text{cgs units}) \quad 2.22$$

The significance of the minus sign is that the deflection is in the direction of decreasing electron density. Using the average value of the density gradient over the integration length $\Delta\ell$, the deflection α becomes for the ruby laser:

$$\alpha = -2.2 \times 10^{-22} (\Delta n_e / \Delta x) \Delta\ell \quad (\text{radians}) \quad 2.23$$

Schmidt and Ruckle [2.25] give the relationship between the maximum angular deflection $\alpha_{\max}$ and the electron density n_e , where $\alpha_{\max} = C_1 n_e / n_c$, where C_1 is a constant and n_c is the critical electron density. (For a ruby laser ($\lambda = 694.3 \text{ nm}$) $n_c = 2.31 \times 10^{21} \text{ cm}^{-3}$). For cylindrical plasmas having a parabolic density profile $n_e = n_o(1 - (r/R)^2)$, the value of C_1 is 1.

The maximum electron density that can be measured by schlieren photography is limited by the acceptance angle of the chamber port (See Fig. 2.20). In our case $\alpha_{\max} = 78 \text{ mrad}$, corresponding to a maximum detected electron density of $1.8 \times 10^{20} \text{ cm}^{-3}$.

On the other hand, the minimum density that can be measured is defined by the diameter of the schlieren stop, Φ_s . This defines the minimum schlieren angle, $\alpha_{\min} = \Phi_s / 2f$, where f is the focal length of the imaging lens. For $\Phi_s = 550 \mu\text{m}$ and $f = 350 \text{ mm}$, the minimum deviation is $\alpha_{\min} = 0.8 \text{ mrad}$. Then, the minimum detectable electron density is $n_{\min} = 1.8 \times 10^{18} \text{ cm}^{-3}$. It means that no laser light will be refracted out of the schlieren aperture if the electron density is lower than $1.8 \times 10^{18} [\text{cm}^{-3}]$.

The optical probing consisted of a 70 mJ Q-switched ruby laser with a pulse duration (FWHM) of 7 ns. Two lenses forming a Galilean expander magnified the beam by twenty ($m = 20\times$). A beam splitter (50/50) could be used to obtain two mutually perpendicular schlieren photographs, see Fig. 2.23. This set-up was only used for two-wire z-pinch experiments, where each frame was looking in a specific direction, parallel and perpendicular to the plane formed by the two parallel wires.

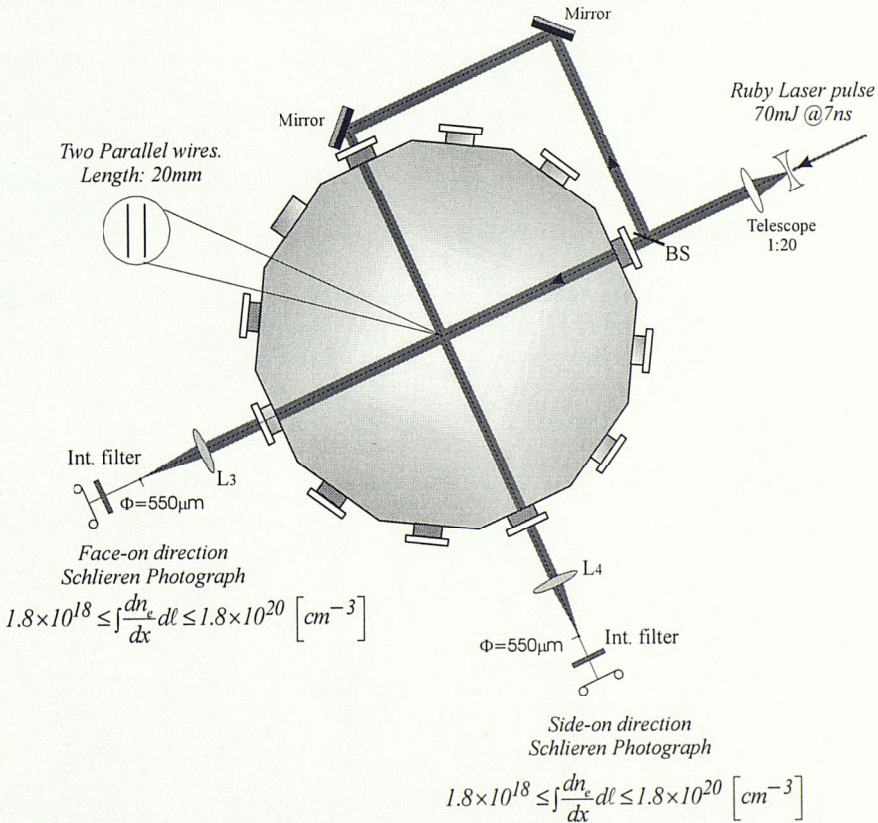


Figure 2.23. Schematic of two-frame schlieren photographs.

The background is completely black (black field schlieren photograph) since it has no density gradients. The field of view of the system is about 9mm in the central region of the pinch. The magnification (ratio of image to object size) was six for both frames.

Now, if one wants to find the maximum gradient of electron density that can be detected when the laser-beam passes through the plasma. We can substitute in Eq. 2.23 $\alpha_{\max} = 78\text{mrad}$ and $\Delta\ell \approx 300\mu\text{m}$, which are: the maximum accepted refraction angle and laser path respectively. From that, we obtain: $dn_e/dx|_{\max} = 1.2 \times 10^{22} [\text{cm}^{-4}]$. This represents ones of the most important parameters of schlieren systems, any gradient greater than this value will be beyond the detection limit. On the other hand, the minimum detectable value of gradient is associated with the stop diameter, Φ_s , and the focal length, f , of the image lens (see Fig. 2.20), where $dn_e/dx|_{\min} = 7.15 \times 10^{19} [\text{cm}^{-4}]$. Any gradients less than this value will be blocked by the stop.

The laser pulse was monitored using a fast (1 ns rise time) photodiode, which allowed us to know both the timing of the pulse and its full width at half maximum (FWHM). The time reading of the photodiode signal was taken at the maximum.

The spatial resolution of the images depends both of the expansion velocity of the plasma and the laser pulse duration. Expansion velocities greater than 10^4 m/s will produce a blur of $70\mu\text{m}$.

Finally, a complete layout of how all the diagnostics were distributed around the chamber load during these experiments is shown in Fig. 2.24. It was impossible to modify the optical probing layout so that three ports were unusable.

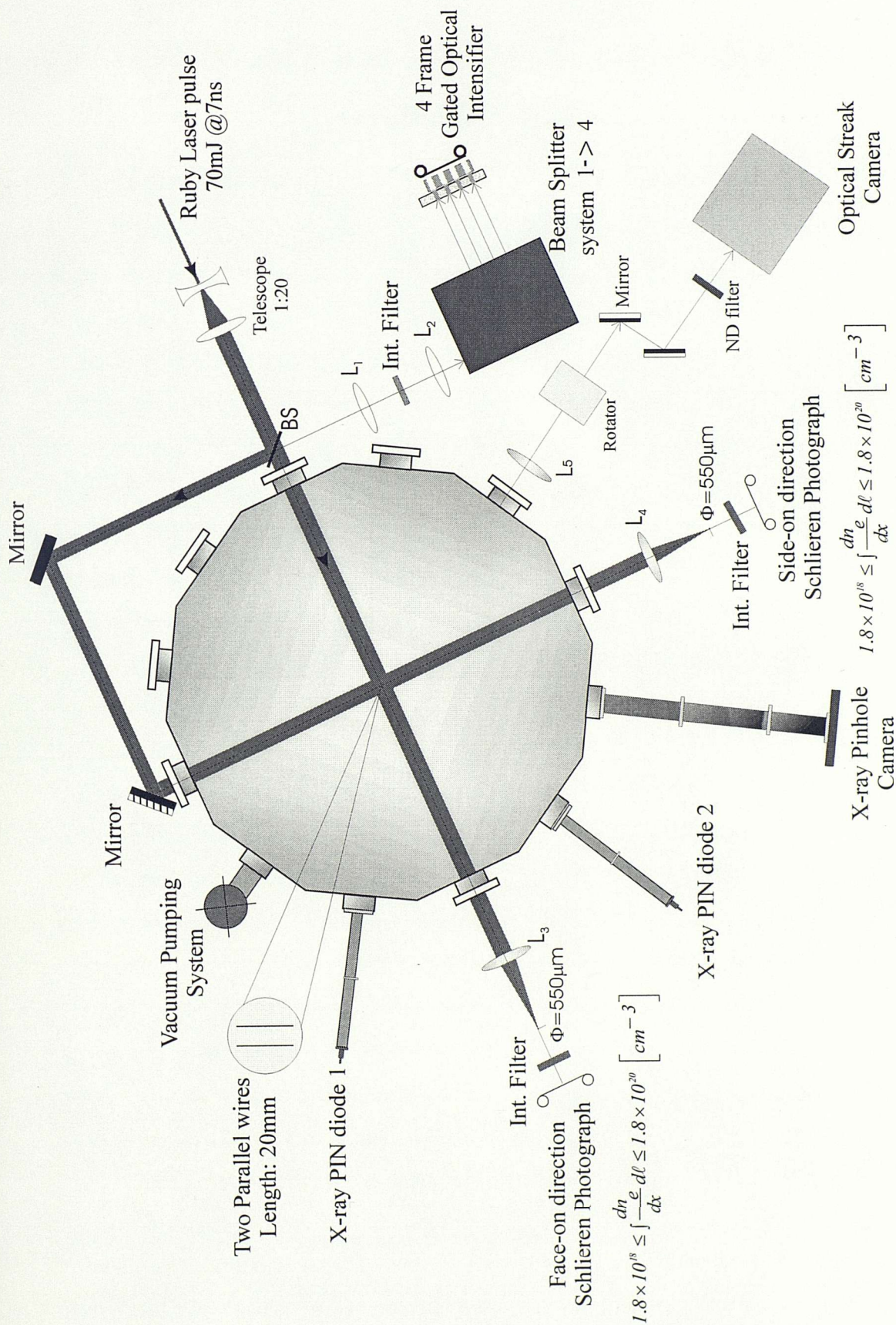


Figure 2.24. Schematic of different diagnostics around the load chamber.

Chapter 3

EXPERIMENTAL OBSERVATIONS ON: SINGLE ALUMINIUM AND TUNGSTEN WIRE Z-PINCHES

3.1.- Introduction

Recently, there has been a great interest in z-pinch plasmas produced by wire arrays [3.1,3.2]. Deeney *et al.* [3.3] reported results with titanium and stainless steel wire arrays producing 100 kJ of x-rays above 4 keV and above 100 TW, 1.3 MJ of total radiation. Spielman *et al.* [3.4] reported a series of experiments on “Z” driven by a current generator up to 20MA in 80ns. X-ray powers greater than 200 TW with x-ray energies of 2 MJ in a single 7.5-ns FWHM (full width high maximum) pulse were recorded. The detailed investigation of pinch dynamics in these experiments is a difficult task. However, the study of dynamics of single wires under similar conditions, on a smaller facility, is possible and will give the picture of early behaviour of these wire arrays when each wire behaves as a single entity.

Previously, it has been shown that the fibre z-pinch becomes unstable very early in the discharge [3.5 - 3.8]. The main feature of these experiments was localised regions emitting intense x-rays called ‘bright spots’. The physics of bright spots in carbon fibres has been discussed by Chittenden *et al.* [3.9]. The temporal and spectral characteristics of these bright spots changed with the wire material. Contrary to earlier observations [3.10], experiments performed with cryogenic deuterium fibres showed instabilities very early in the discharge [3.11]. However, experiments with a controlled prepulse showed a remarkable change in the pinch behaviour when the prepulse was launched between 100-300 ns before the main current for a carbon fibre z-pinch [3.12]. The optical and x-ray emission was delayed by 30-40 ns into the main current. The instabilities were seen to appear later with a larger growth rate due to higher temperature and current at that time. X-ray yield was also at least an order of magnitude higher.

Here, we report on experiments performed using tungsten wires of various diameters ranging from 5 to 18 μm and 15 μm aluminium wire. The expansion and dynamics of the pinch were studied as a function of wire diameter and material. This information is relevant to understanding the behaviour of wire-array z-pinches, e.g., in the heuristic model proposed by Haines [3.13].

3.2.- *Experimental Set-Up and Diagnostics*

Experiments were performed with single aluminium and tungsten wires 2cm long. The physical properties of these wires are shown in Table 3.I.

Table 3.I. Physical Properties of aluminium and tungsten wires.

Wire	<i>Z</i>	Density (g/cm ³)	Line Density (1/cm)	Mass (μg/cm)
Aluminium	13	2.7	15 μm : 1.1×10^{17}	4.8
Tungsten	74	19.3	5 μm : 1.2×10^{16}	3.8
			7.5 μm : 2.7×10^{16}	8.5
			10 μm : 4.9×10^{16}	15.0
			13 μm : 8.2×10^{16}	25.0
			18 μm : 1.6×10^{17}	180.0

The optical probing during single wire z-pinch experiment consisted of a single schlieren photograph, where a $\Phi_s = 520 \mu\text{m}$ stop (disk) and a $f = 200 \text{ mm}$ focal length lens were used.

The maximum density that can be detected is limited by the acceptance angle $\theta = \int \nabla_{\perp} \mu \cdot d\ell$, corresponding to the line integral along the optical path $d\ell$ of the perpendicular gradient of refractive index μ . The electron density n_e and μ are related as $\mu = \sqrt{1 - n_e/n_c}$, where $n_c = 2.31 \times 10^{21} \text{ cm}^{-3}$ is the critical electron density for a ruby laser (c.f. Sec. 2.5.3). Because of the laser beam can only propagate in the plasma where $n_e < n_c$, we can define two plasma regions: 1) the overdense region ($n_e > n_c$) and 2) the coronal region ($n_e < n_c$).

Assuming a parabolic density profile, the acceptance angle can be written as $\theta = n_e/n_c$. There exist two limits, the maximum one, defined by the *f-number* of the imaging lens (see Fig. 2.20) and the minimum detection limit, which depends on the stop diameter and the focal length of the imaging lens ($\theta_{\text{min}} = \Phi_s / 2f$). In our case $\theta_{\text{max}} < f - 4$ corresponding to a maximum detected electron density of $1.8 \times 10^{20} \text{ cm}^{-3}$. On the other hand, the minimum detection limit was 1.3 mrad , which corresponds to a density of $3 \times 10^{18} \text{ cm}^{-3}$. Image magnifications from two to seven times were used. Schlieren photographs were recorded on Ilford HP5™ film.

An optical streak camera was used in radial mode to obtain information about the expansion of the pinch. Streak speeds of 2.5 ns/mm or 7.5 ns/mm with a $300\text{ }\mu\text{m}$ wide slit were used for the radial streak photographs giving time resolution of less than 1 ns and 2.25 ns respectively. A section of the plasma column, 8 mm away from the cathode, was imaged on the slit and magnified five times.

A six-channel time integrated pinhole camera was used to collect the spatial and spectral information about the x-ray emission from the pinch. Pinhole diameters ranging from $50\text{ }\mu\text{m}$ to $300\text{ }\mu\text{m}$ and x-ray filters for energies from $100\text{ eV} - 10\text{ keV}$ were used. Images were recorded on Kodak Direct Exposure Film (DEF) -59™ x-ray film. For most of the shots, two layers of the film were used. Where the first layer acting as a $210\text{ }\mu\text{m}$ Mylar filter, indicating hard x-ray emission from the pinch. On the second film, the bright spots were less prominent compared with the first layer, indicating that the spots mainly emit in $1.5 - 3\text{ keV}$ energy range.

A x-ray streak camera fitted with a Cesium Iodide (CsI) photocathode was used to obtain time resolved information about the x-ray emitting regions. $12\text{ }\mu\text{m}$ beryllium and $1.5\text{ }\mu\text{m}$ aluminised Mylar filters were used with a $300\text{ }\mu\text{m}$ diameter pinhole to detect x-rays at $h\nu > 1\text{ keV}$ and $h\nu > 200\text{ eV}$ respectively. In order to obtain the lifetime of the bright spots and duration of x-ray emission, two different sweep speeds, 2.5 ns/mm and 7.5 ns/mm , were used respectively.

A pair of collimated positive-intrinsic-negative (PIN) diodes were also used for time-resolved information of the pinch. The PIN diodes were placed at 70 cm away from the pinch with a 5 mm steel collimators to block hard x rays generated by electron beams hitting the anode. Most of the diagnostics were employed simultaneously.

3.3.- *Experimental Results*

3.3.1.- *Current Waveform*

Typical current and voltage waveforms for a pinch and a 5 mm diameter steel rod short, recorded with a Rogowski coil and D-dot probe, are shown in Figure 3.1 and 3.2 respectively. The peak current for the short circuit is at least 5 ns earlier than for the

pinch, due to its relatively lower inductance. The current through the wire crowbars after 380 ns , due to the breakdown across a dielectric interface composed of Perspex™ (PMMA) which separates the deionised water in the transfer line from the vacuum chamber. A maximum current of $(160 \pm 4)\text{ kA}$ with a rise time (10% - 90%) of 70 ns was obtained for a 60 kV charging voltage.

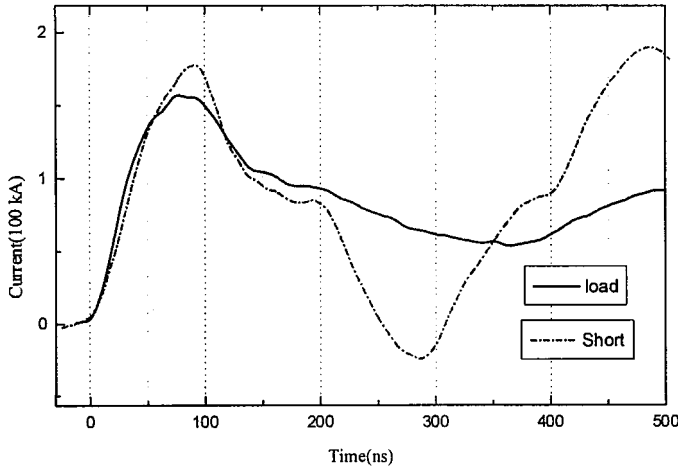


Figure 3.1. The typical measured current through pinch and a short circuit.

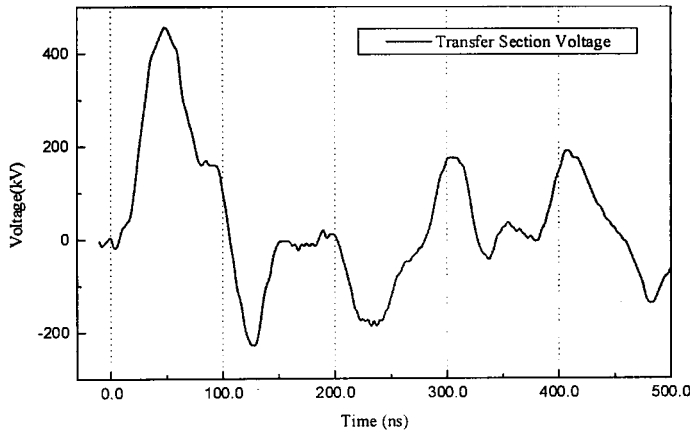


Figure 3.2. The typical measured voltage at transfer section for wire pinch using a D-dot probe.

3.3.2.- Optical Probing

Single schlieren images for $5\text{ }\mu\text{m}$ tungsten wires, are shown in Figure 3.3. The coronal plasma expansion was observed after 20 ns of the start of the current discharge. There was no appreciable expansion detected at early time. This was probably due to low-density coronal plasma being below the detection limit of the diagnostic. This

coronal plasma expanded to a diameter of $130\ \mu\text{m}$ in $22\ \text{ns}$. Short wavelength perturbations in the coronal plasma may also be seen, appearing relatively later for larger diameter wires.

At $40\ \text{ns}$, the diameter of the inaccessible dense region ($n_e > n_c$) was about $120\ \mu\text{m}$. The wavelength and the amplitude of the instabilities increase with time, the pinch evolving into density islands at about $130\ \text{ns}$, with a diameter of $2.25\ \text{mm}$. The expansion velocity obtained from the schlieren photographs was $(9.8 \pm 1.0) \times 10^3\ \text{m/s}$.

For $7.5\ \mu\text{m}$ tungsten wires (see Fig. 3.4), the instabilities are well developed at $38\ \text{ns}$, and similar observations were made for 10.16 , 13 and $18\ \mu\text{m}$ tungsten wire pinches. However, density islands were not seen for larger diameter (see Fig. 3.5, 3.6, and 3.7 respectively). The inaccessible dense region and short wavelength instabilities persisted for a longer time for larger diameter wires.

Figure 3.8 shows schlieren photographs for $15\ \mu\text{m}$ aluminium wire. The coronal plasma is observed at $8\ \text{ns}$, expanding with a velocity of approximately $(2.4 \pm 0.2) \times 10^4\ \text{m/s}$. Moreover, the inaccessible region starts to be observed at $24\ \text{ns}$, expanding with a velocity of approximately $(7.2 \pm 0.2) \times 10^3\ \text{m/s}$ (see Fig. 3.9). There is also, a change from short to long wavelength instabilities for aluminium wire during the current discharge. Figure 3.10 shows the wave-number k of $m = 0$ -like instability for aluminium pinch.

Experimental observations show that expansion velocities are very similar for different diameters of tungsten wires, as is shown in Fig. 3.11, giving a mean value of $(9.4 \pm 1.0) \times 10^3\ \text{m/s}$. Simulation results [3.14] show that expansion velocity does not depend on initial wire diameter. This is because it is determined by MHD instability and hence the Alfvén velocity in the coronal plasma.

In contrast to tungsten pinch, the coronal expansion of aluminium pinch increases much faster. It is due to that heats of vaporization and ionization energies are very different for tungsten and aluminum wires. For example, to triply ionize aluminum one needs three times ($1.73\ \text{J}$) the energy compared to that required to triply ionize tungsten $0.17\ \text{J}$. To ionize it four times the total energy needed for aluminum is $5.73\ \text{J}$

compared to the energy needed for tungsten $0.278 J$. This indicates that after the third ionization, the temperature of aluminum pinch will rise significantly before further ionization and hence it will expand faster than tungsten wire. In the early expansion phase, radiation loss does not play a significant role due to the low density of the coronal plasma.

On the other hand, it is interesting to note that tungsten pinches have an instability structure completely different to aluminium ones, with a much slower time evolution.

The aluminium pinch starts to break up at about $50 ns$, and density islands start to appear at about $70-80 ns$, in contrast to $5 \mu m$ tungsten wire where density islands appear at about $130 ns$. The diameter of density islands for aluminium wire is about $4 mm$ at $100 ns$ compared to $2.2 mm$ at $130 ns$ for $5 \mu m$ tungsten.

ERROR ANALYSIS

Systematic errors of the measurements included:

- 1.- Refraction of the laser beam: 5%
- 2.- Time resolution of the scope, affecting synchronism of LED signal with current waveform: 5%
- 3.- LED - scope cable length for correlation of signal with current waveform: 3%
- 4.- Error in scaling of schlieren photographs to the evaluation of the pinch diameter: 10%.
- 5.- Error in the evaluation of wavelengths of $m = 0 - MHD$ instability: 10%

An overall systematic error of 10% was estimated in the determination of expansion velocity of the pinch.

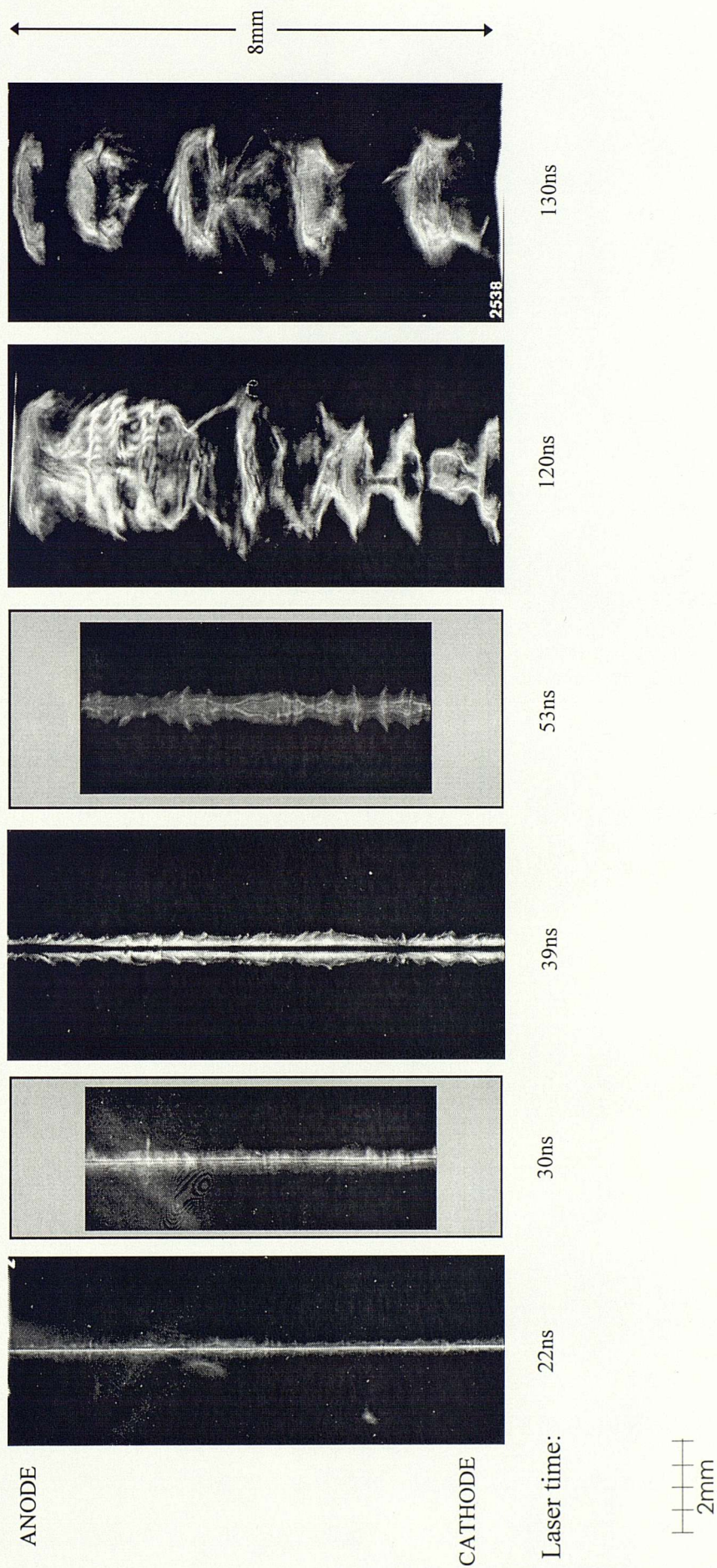


Figure 3.3. Schlieren photographs of 5 μ m tungsten wires

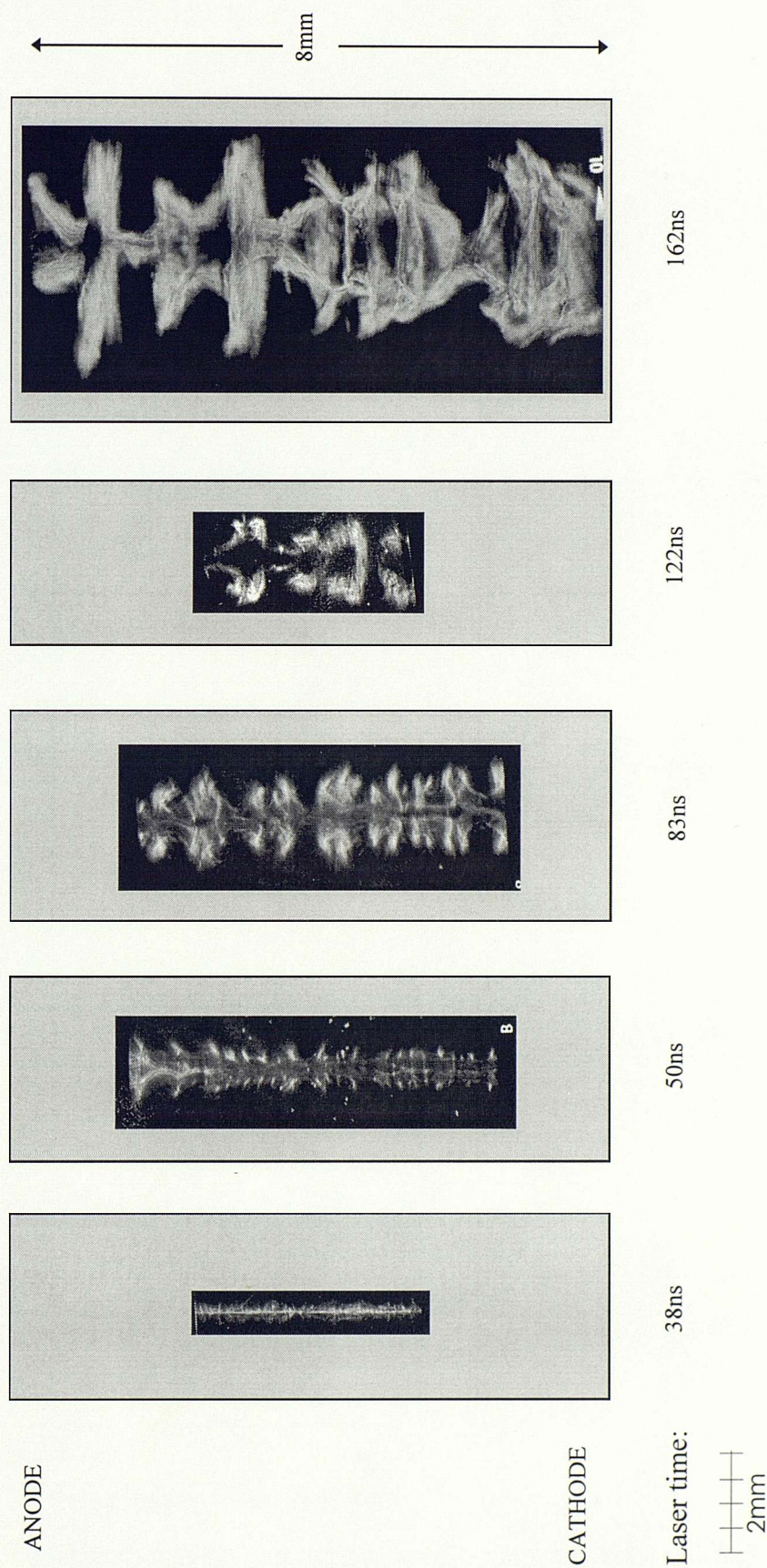


Figure 3.4. Schlieren photographs of 7.5μm tungsten wire

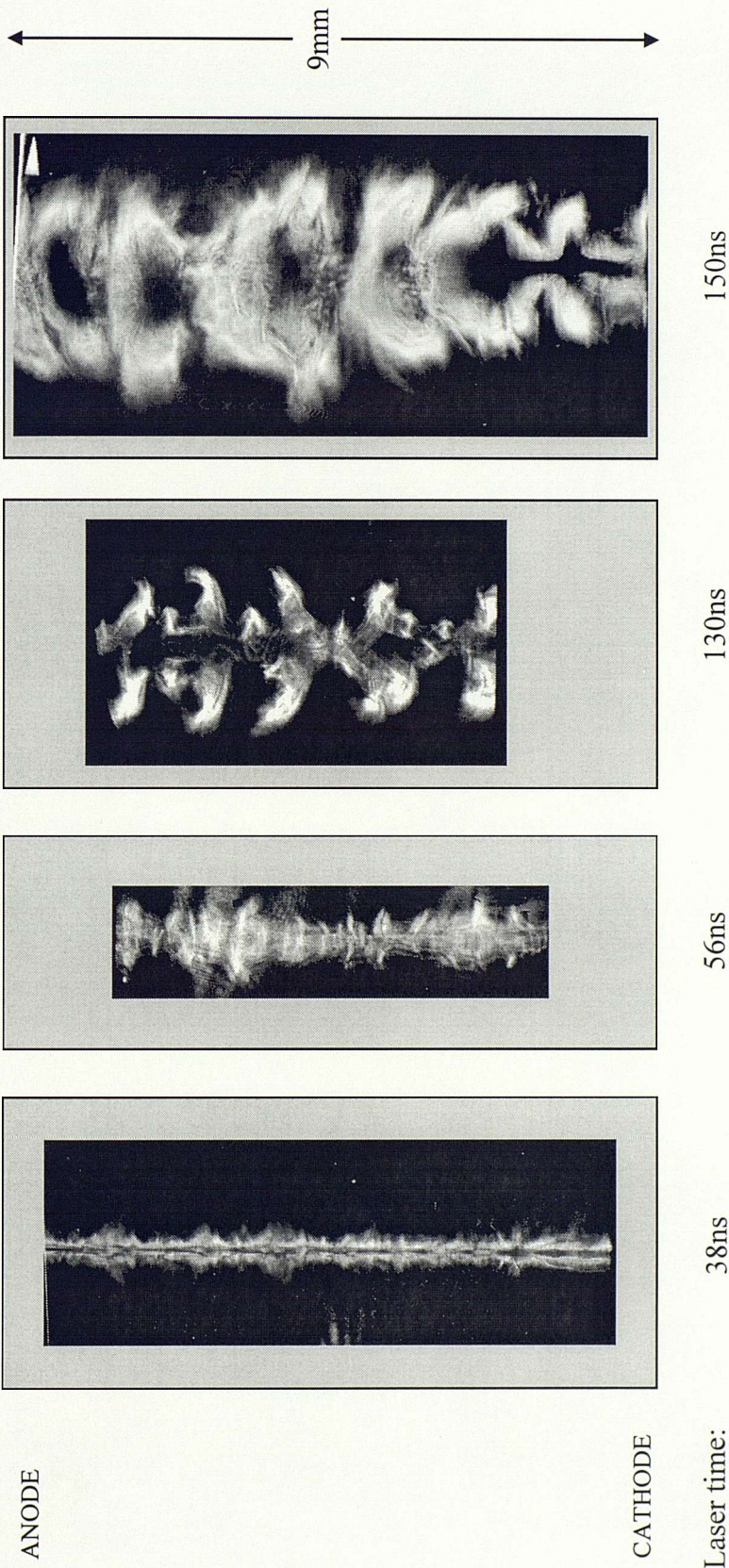


Figure 3.5. Schlieren photograph of 10.16μm tungsten wire

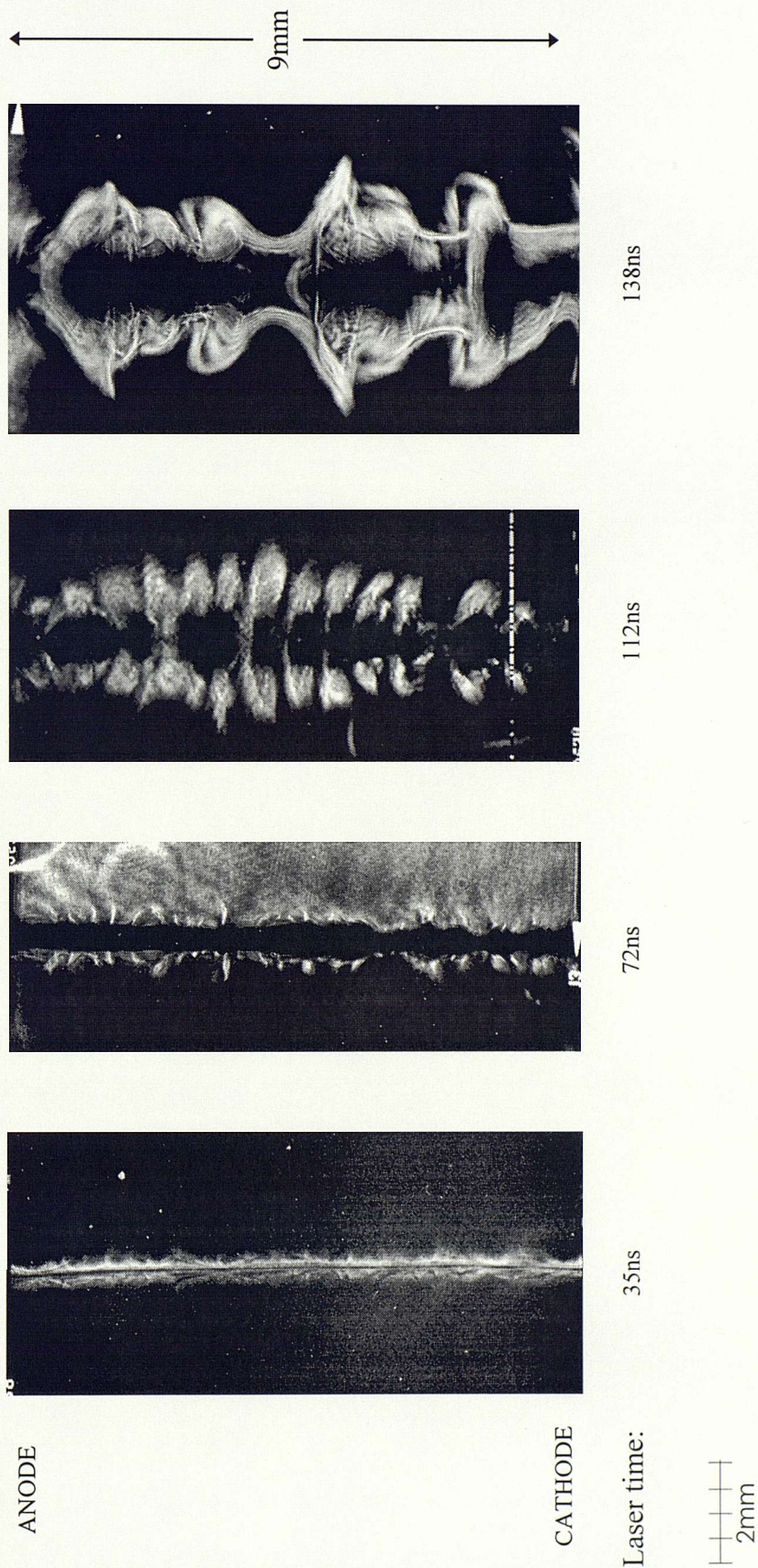


Figure 3.6. Schlieren photograph of 13 μm tungsten wire

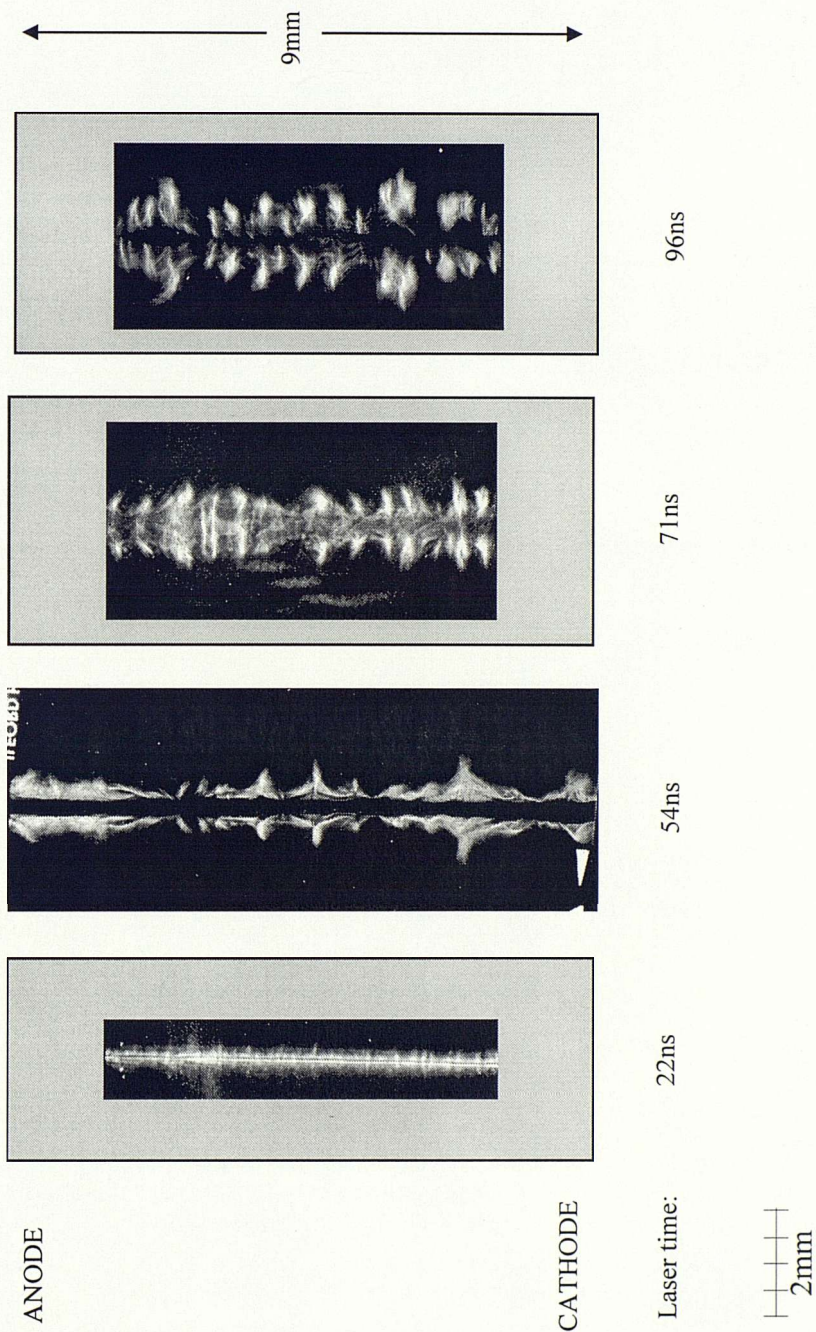


Figure 3.7. Schlieren photographs of 18µm tungsten wire

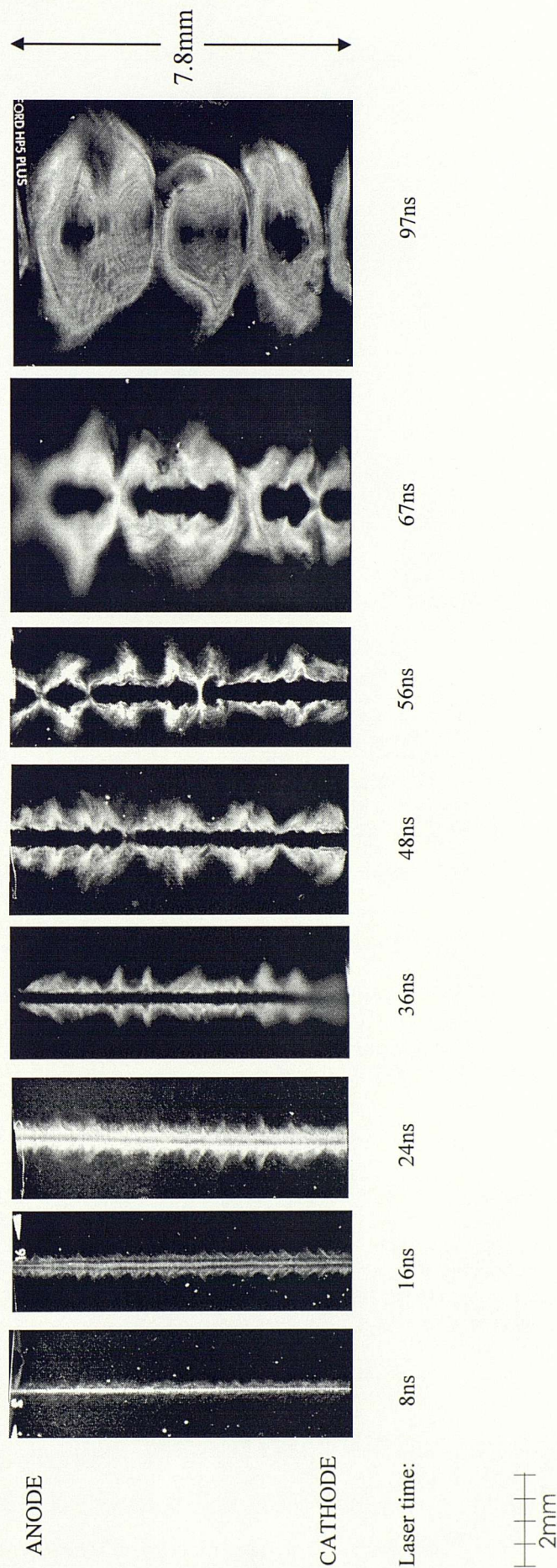


Figure 3.8. Schlieren photographs of 15µm aluminium wire

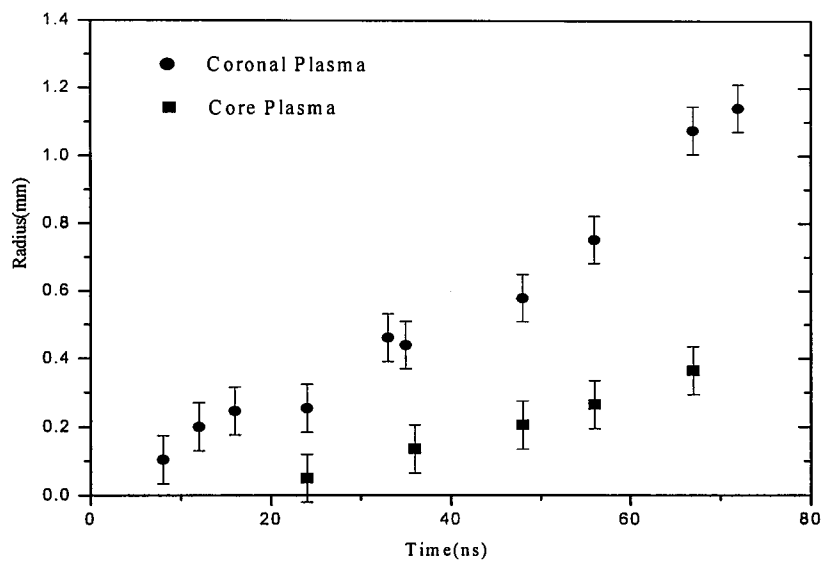


Figure 3.9: Radius vs. time for 15 μm aluminium wire.

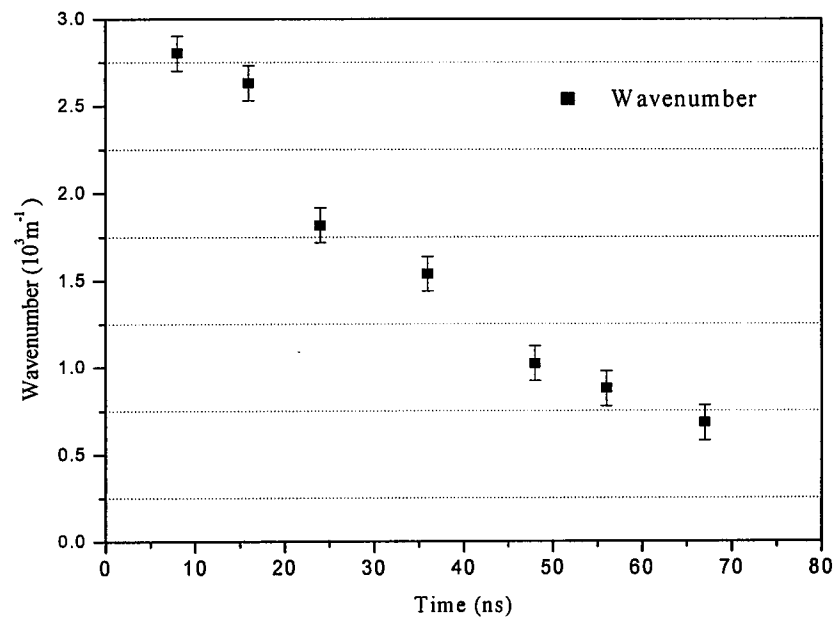


Figure 3.10. Wave number k ($m = 0$ -MHD) vs. time for 15 μm aluminium wire.

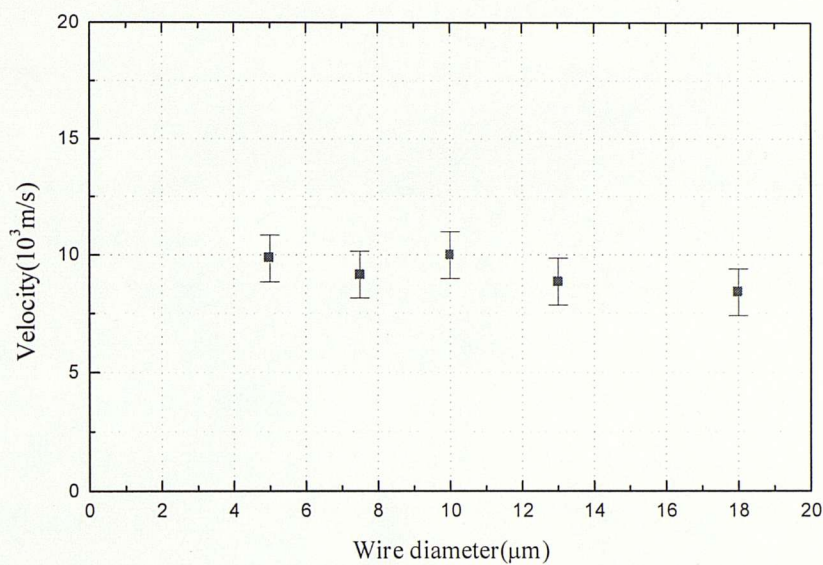


Figure 3.11. Average of coronal expansion velocities for different diameters of tungsten wire.

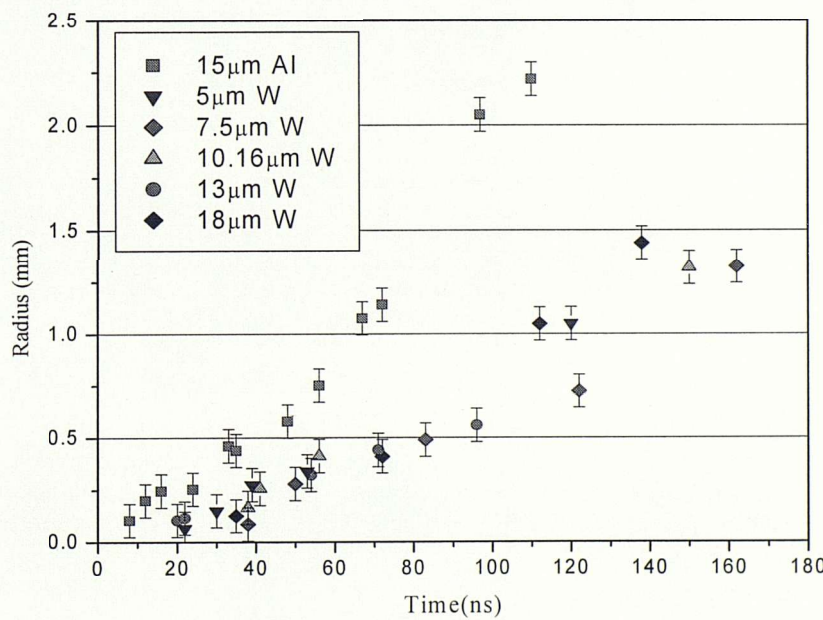


Figure 3.12. Radius vs. time for 15 μm aluminium and various diameter tungsten wires.

The expansion velocities obtained from Fig. 3.12 clearly shows that the aluminium pinch expands at least two times faster than for tungsten one.

3.3.3.- Optical Emission

Figure 3.13, shows two optical radial streak photographs for $5\ \mu\text{m}$ and $13\ \mu\text{m}$ tungsten wires. Variation shot-to-shot was the dominant feature for all tungsten discharges. Streak photographs for $5\ \mu\text{m}$ tungsten wire show very faint optical emission from the pinch for the first $10\ \text{ns}$. The optical emission after $15\text{--}20\ \text{ns}$ is from a larger diameter and is more intense. Within $45\ \text{ns}$, the emission is from a diameter of $2.8\ \text{mm}$.

For $13\ \mu\text{m}$ tungsten wire, the streak photograph shows faint optical emission at $10\ \text{ns}$. However, after $20\ \text{ns}$, the emission becomes intense and from a relatively large diameter. The diameter of optical emission is about $1.8\ \text{mm}$ after $60\ \text{ns}$.

In summary, radial streak photographs show that there are three phases of optical emission. In the first phase, the emission is faint; in the second phase, emission is relatively intense and from a smaller diameter; in the third phase, the pinch expands rapidly yielding an intense optical emission. The optical emission from all diameters lasts for more than $100\ \text{ns}$. The expansion velocities for 5 and $13\ \mu\text{m}$ tungsten wires are $(10.0 \pm 2.0) \times 10^3\ \text{m/s}$ and $(8.0 \pm 2.0) \times 10^3\ \text{m/s}$ respectively.

An overall systematic error of 20% was estimated in the determination of expansion velocity of the pinch.

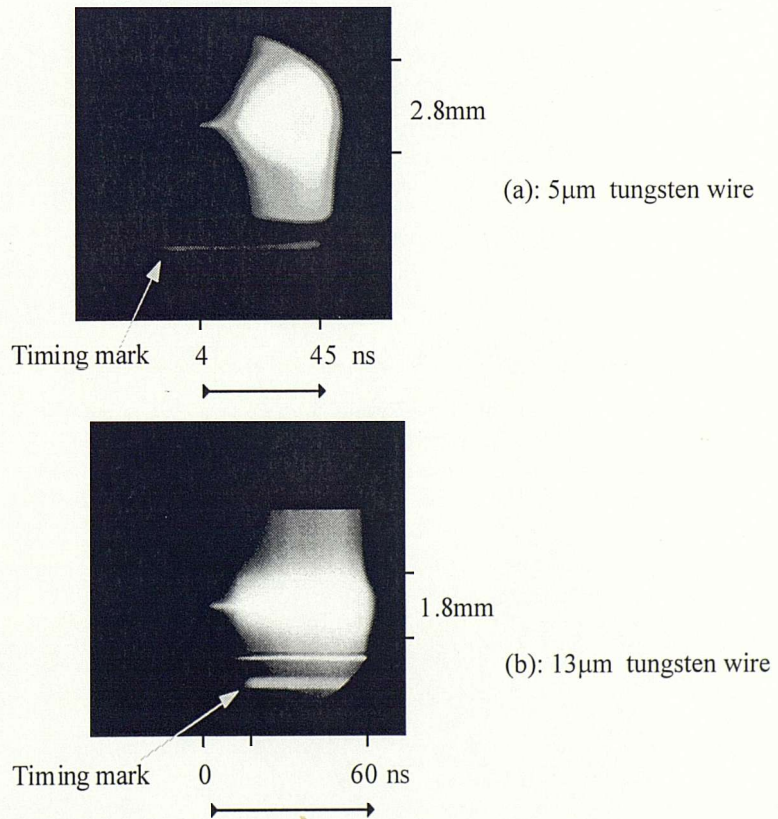


Figure 3.13. Optical radial streak photographs for a) $5\ \mu\text{m}$ and b) $13\ \mu\text{m}$ tungsten wires at $160\ \text{kA}$ (Charging voltage $\sim 60\ \text{kV}$).

A comparison of tungsten and aluminium wires is shown in Figure 3.14. In contrast to tungsten discharges, the aluminium pinch was reproducible from shot-to-shot. Streak photographs were taken at a lower peak current of $(120 \pm 4) \text{ kA}$. The aluminium pinch expands faster with a velocity of $(2.2 \pm 0.4) \times 10^4 \text{ m/s}$ compared with $(8.0 \pm 2.0) \times 10^3 \text{ m/s}$ for a $13 \text{ } \mu\text{m}$ tungsten pinch. After 40 ns , the diameter of the emitting region is 1.5 mm for aluminium and $900 \text{ } \mu\text{m}$ for $13 \text{ } \mu\text{m}$ tungsten wire.

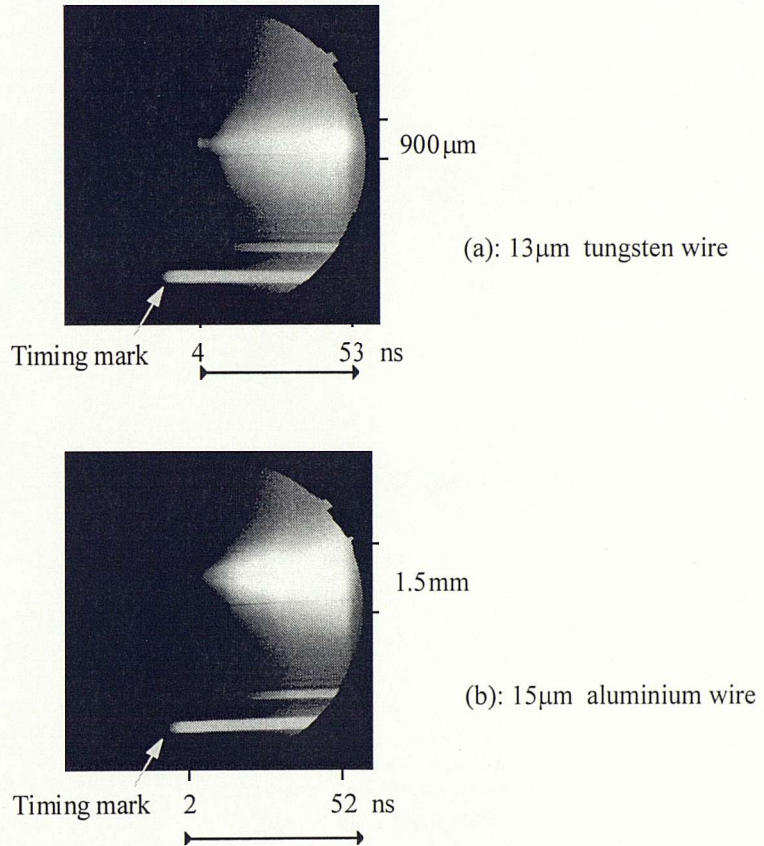


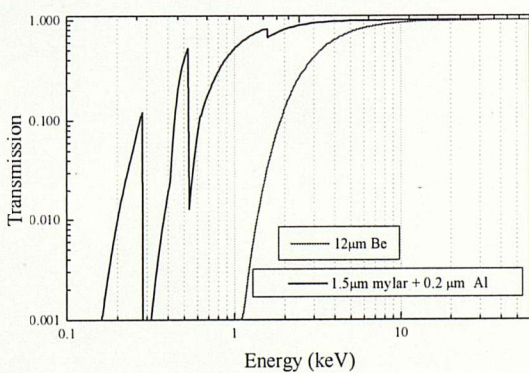
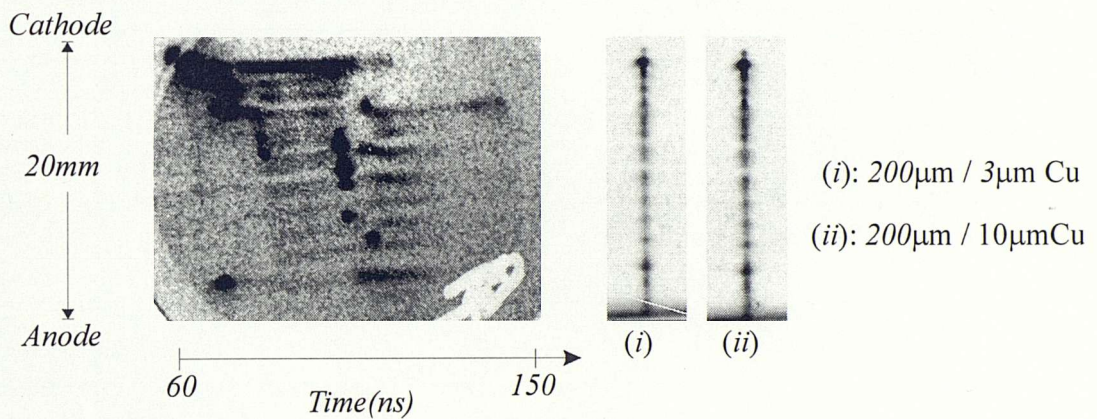
Figure 3.14. Optical streak photographs for a) $13 \text{ } \mu\text{m}$ tungsten and b) $15 \text{ } \mu\text{m}$ aluminium wires at lower current of 120 kA (charging voltage $\sim 50 \text{ kV}$).

3.3.4.- X-Ray Emission

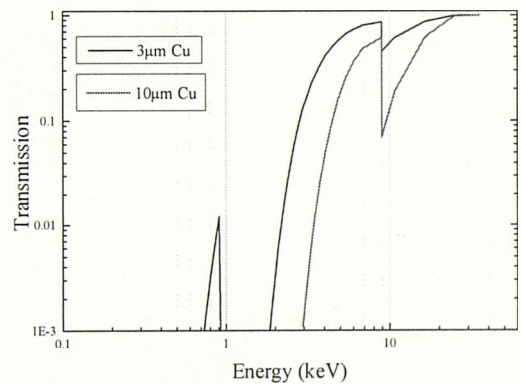
Figure 3.15 shows three x-ray streak photographs taken for different diameter tungsten wires, along with time integrated pinhole photographs. For the streak photographs, a $300 \text{ } \mu\text{m}$ pinhole and a $12 \text{ } \mu\text{m}$ beryllium filter were used. For the time integrated pinhole camera, several pinhole diameters, and filters were used, as is also shown in Figure 3.15. Two layers of DEF-59 film were used on top of each other. To

make a comparison of emission for different diameter wires, the same pinhole diameters and filters were used in each case.

Figure 3.15a shows that for $5\mu\text{m}$ tungsten wire, the bright spots appear at 60 ns after the current start at different axial positions. The lifetime of brightest emission is less than 1 ns , but the decay time of some of the bright spots is about 40 ns . Simultaneous time integrated pinhole and axial streak photographs show that the bright spots are correlated in space. Some of the intense regions in time integrated pinhole photographs are due to the long duration of x-ray emission from the pinch. The x-ray emission from the pinch column is hard ($h\nu > 6\text{ keV}$).



X-ray filters for
Streak Camera



X-ray filters for
Pinhole Camera

Figure 3.15.a. Simultaneous x-ray streak and time integrated x-ray pinhole photographs for $5\mu\text{m}$ tungsten wires. A $12\mu\text{m}$ beryllium filter and $300\mu\text{m}$ pinhole were used to record the x-ray streak images. X-ray filters and pinhole diameters are shown on the right hand side of the images.

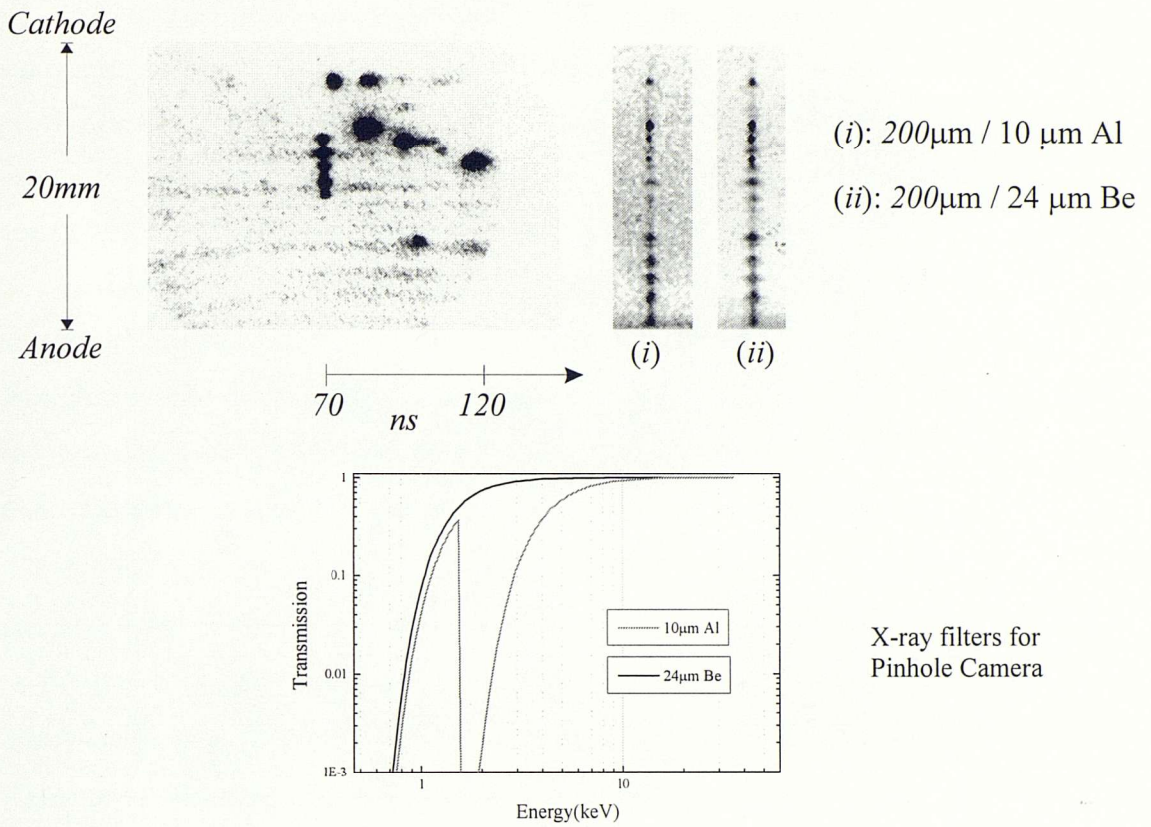


Figure 3.15.b. Simultaneous x-ray streak and time integrated x-ray pinhole photographs for 10.16 μm tungsten wires.

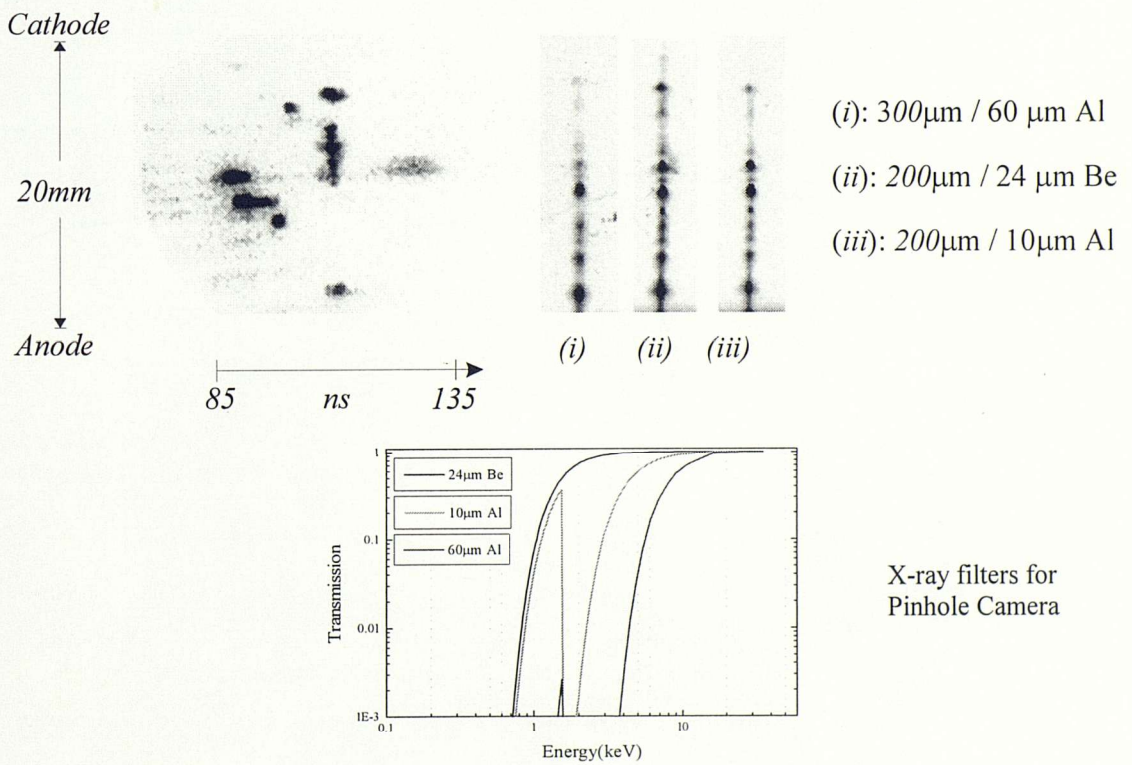


Figure 3.15.c. Simultaneous x-ray streak and time integrated x-ray pinhole photographs for 13 μm tungsten wires.

Pinhole images of Fig. 3.15 were obtained on the second layer of the film, the first layer acting as a $210\text{ }\mu\text{m}$ Mylar filter, indicating hard x-ray emission from the pinch. On the second layer of film, the bright spots were less prominent than on the first layer, indicating that the bright spots mainly emit in the $1.5\text{--}3\text{ keV}$ energy range. X-ray streak photographs for other diameter wires show that there is a delay in the start of x-ray emission from bright spots as the diameter of the tungsten wires increases. The number of bright spots also decreases for larger diameter wires (c.f. Fig. 3.15.c), whilst their decay time is shorter and x-ray emission becomes fainter. The x-ray streak for $18\text{ }\mu\text{m}$ tungsten wire shows that there is a faint x-ray emission but, in contrast to other diameter wires, bright spots are not seen in either x-ray streak or time integrated pinhole photographs.

Comparison of Fig. 3.15.b and 3.15.c images with $10\text{ }\mu\text{m}$ Al and $24\text{ }\mu\text{m}$ Be filters shows that the x-ray emission is in the range of $1.5\text{--}3\text{ keV}$. The bright spots above $h\nu > 3\text{ keV}$ are pinhole limited (with $200\text{ }\mu\text{m}$ diameter pinholes). The size of bright spots and diameter of the column at $h\nu \sim 1\text{ keV}$ is $250\text{--}400\text{ }\mu\text{m}$ and $500\text{--}600\text{ }\mu\text{m}$ respectively.

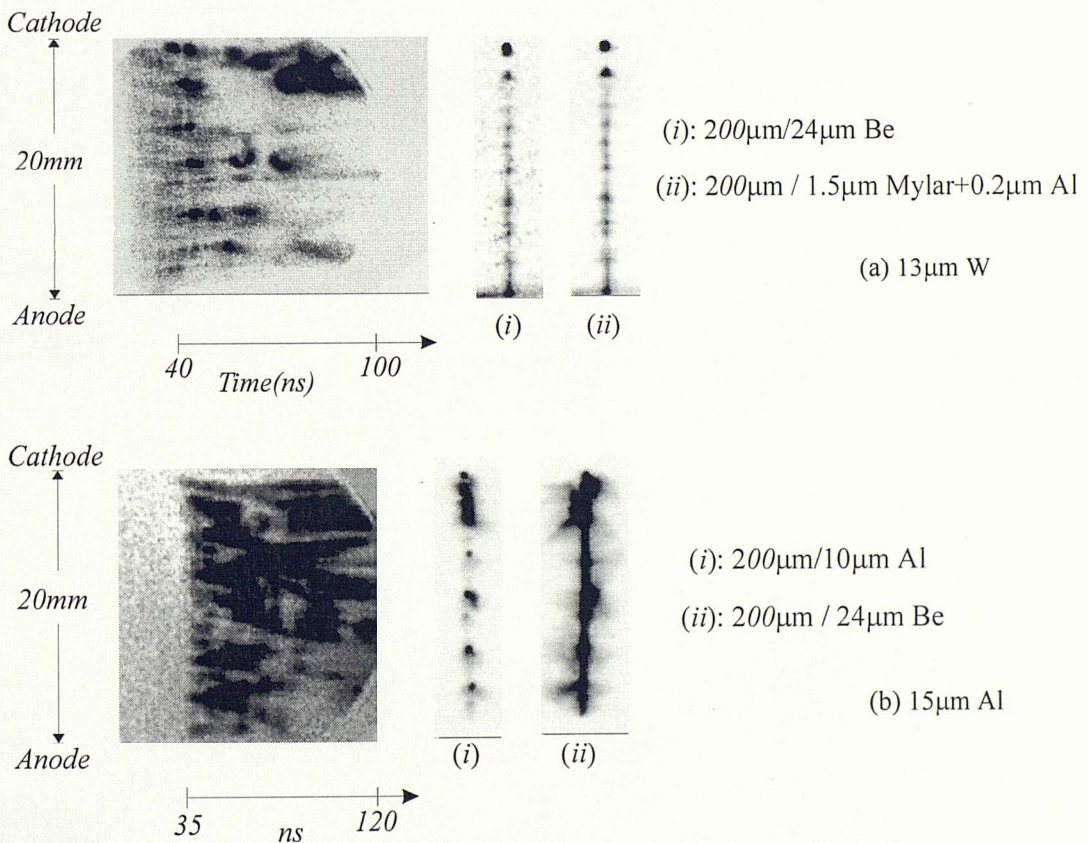


Figure 3.16. A comparison of simultaneous x-ray streak photographs and time integrated pinhole images for a) $13\text{ }\mu\text{m}$ diameter tungsten and b) $15\text{ }\mu\text{m}$ aluminium wires.

Figure 3.16 shows x-ray streak photographs for $13\ \mu\text{m}$ tungsten and $15\ \mu\text{m}$ aluminium wires. X-ray streak photographs taken with a $12\ \mu\text{m}$ Be filter ($h\nu > 1\text{keV}$) at lower current ($120\ \text{kA}$) for $13\ \mu\text{m}$ tungsten wires (c.f. Fig. 3.16(a)), show very faint images and only three or four bright spots. Therefore, a softer x-ray filter ($1.5\ \mu\text{m}$ aluminised Mylar ($h\nu > 500\text{eV}$)) was used.

The x-ray streak photographs for $15\ \mu\text{m}$ aluminium wire (c.f. 3.16(b)), shows that faint emission starts at $35\ \text{ns}$. It was recorded with a $12\ \mu\text{m}$ Be filter, only bright spots are visible after $40\ \text{ns}$, having a diameter of $300\text{-}400\ \mu\text{m}$ and an irregular structure compared to tungsten wires. Pinhole images from a aluminium pinch with a x-ray filter with cut-off energy of $200\ \text{eV}$, show a saturated emission from the whole pinch. In contrast to the tungsten pinch, the x-ray emission is weak for $h\nu > 2\ \text{keV}$.

Figure 3.17 shows two x-ray pinhole images for $5\ \mu\text{m}$ tungsten pinch. Image (a) was taken with a $60\ \mu\text{m}$ aluminium filter and a $300\ \mu\text{m}$ pinhole. Image (b) is on the second DEF film, indicating that the hard x-ray emission, $h\nu > 6\ \text{keV}$, is from the whole column. The lineout of both images is shown in Figure 18c, where the second film shows that the emission is from a relatively uniform pinch.

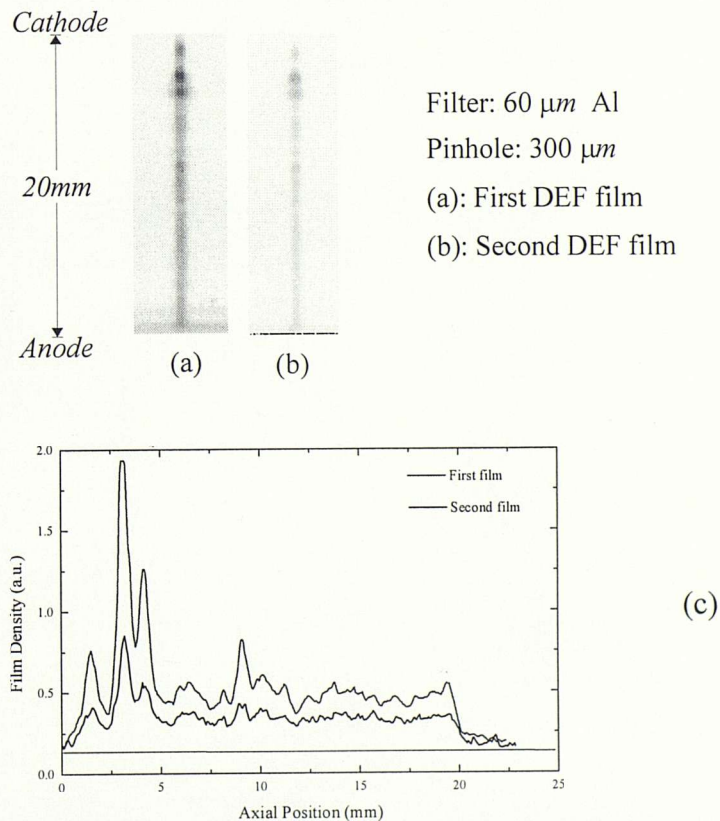
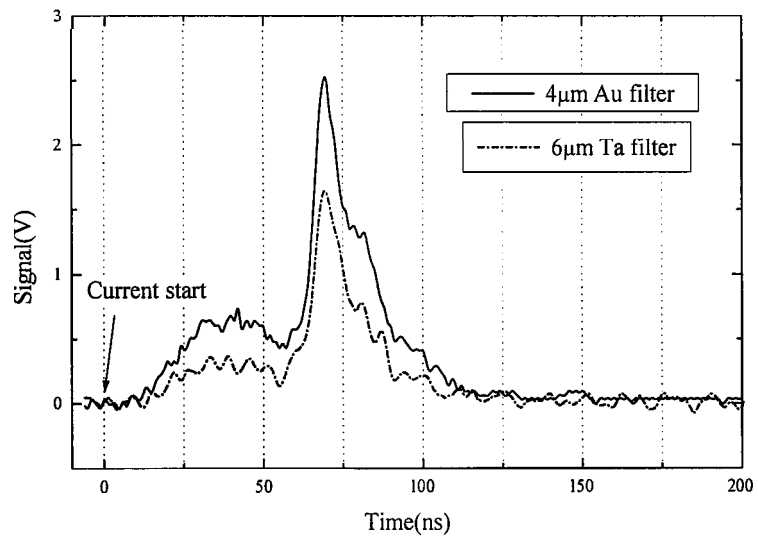


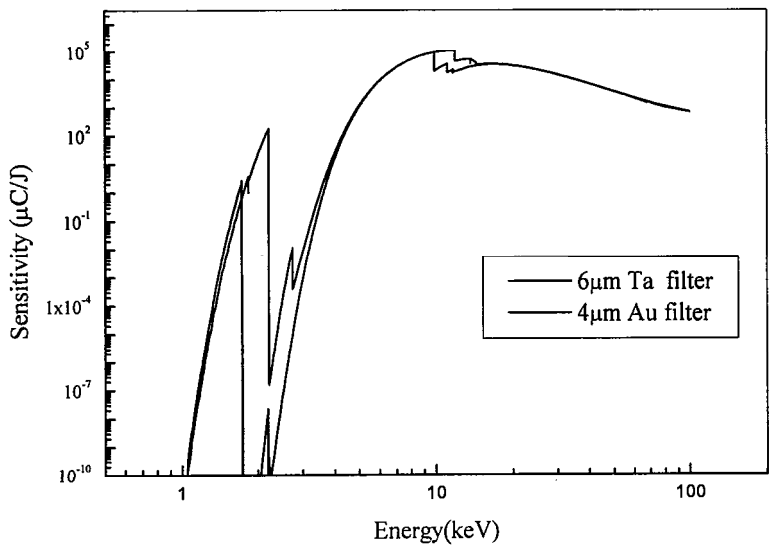
Figure 3.17. Time integrated x ray pinhole images for a $5\ \mu\text{m}$ tungsten wire. Image (a) is with $60\ \mu\text{m}$ aluminium filter. Image (b) is on the second layer of film. The lineout of images (a) and (b) is shown in figure (c).

X-RAY PIN DIODE SIGNALS

Time resolved x-ray emission from the pinch was also observed with filtered PIN diodes. For tungsten pinches, foil filters of $4\ \mu\text{m Au}$ and $6\ \mu\text{m Ta}$ were used, whilst for aluminium ones, $5\ \mu\text{m Fe}$ and $10\ \mu\text{m Al}$ filters were employed. Typical cross calibrated PIN diode signals for tungsten and aluminium pinch are shown in Figure 3.18 and 3.19 respectively.



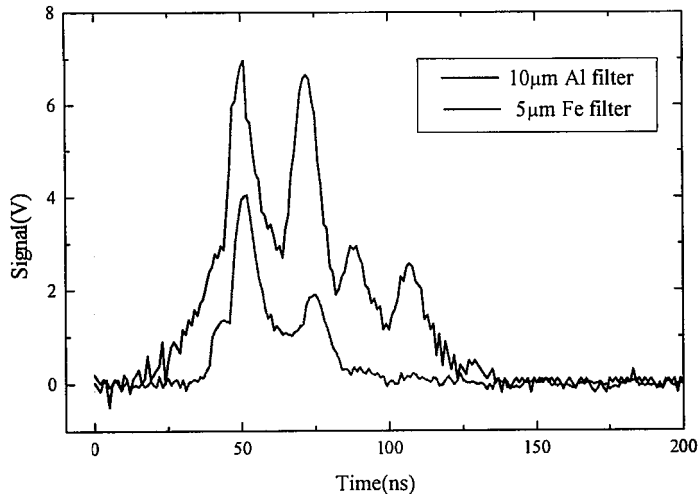
(a)



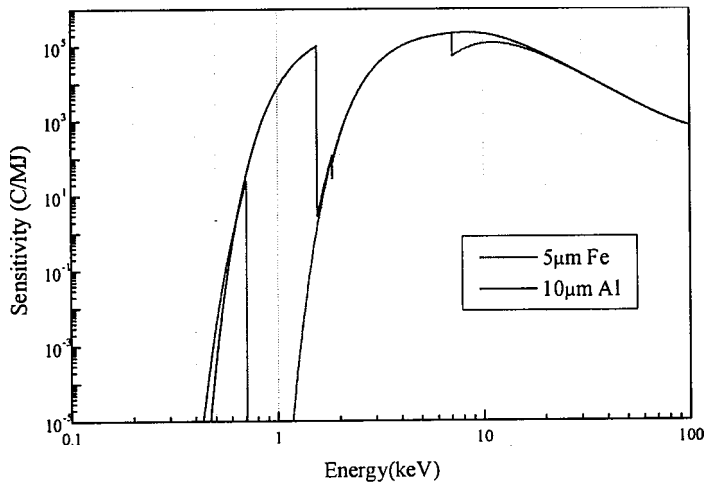
(b)

Figure 3.18. (a): PIN diode signals for $7.5\ \mu\text{m}$ tungsten and (b): PIN diode sensitivity for tantalum and gold filters.

Signals for tungsten (see Fig. 3.18a) show that the x-ray emission starts at 35-40 ns after the current start, and the second larger peak appears at 60-70 ns, depending on the diameter of the wire. The second peak corresponds to the bright spots in x-ray streak photographs. For aluminium wire (c.f. Fig. 3.19(a)), the PIN diode signals show multiple peaks due to the bright spots. Number of peaks is not reproducible and the timing of peaks varies greatly from shot-to-shot. Very small x-ray signals were observed when filters used for tungsten were employed for an aluminium pinch.



(a)



(b)

Figure 3.19. (a): PIN diode signals for 15 μm aluminium and (b): PIN diode sensitivity for aluminium and iron filters

The x-ray yield can be determined from filtered PIN diode signals for an energy window ΔE . It is given by (see Section 2.5.2.2):

$$Y = \frac{(Q_1 - Q_2)}{d\Omega} \frac{4\pi}{S \cdot T}$$

where Q_1 and Q_2 are the charge measured with the PIN diodes in Coulomb ($Q = \int (V/R) dt$ [C], $V =$ Voltage signal and $R = 50\Omega$), $d\Omega$ is the solid angle, S is the diode sensitivity in [$\mu C/J$] and T is the filter transmission. Table 3.II, shows the measured x-ray yield for $7.5\mu m$ tungsten and $15\mu m$ aluminium wires. Narrow energy windows of $490eV$ and $850eV$ were used for tungsten and aluminium wires respectively. This explains the low x-ray yield measured in both wire z-pinch.

Table 3.II. The measured x-ray yield from PIN diode signals

Wire	Energy window	X-ray yield (mJ)
$7.5\mu m$ Tungsten	$1.72keV < hv < 1.56keV$	5.7 ± 0.7
$15\mu m$ Aluminium	$708eV < hv < 1560eV$	23.0 ± 3.0

ERROR ANALYSIS

Systematic errors in the measurements included :

- 1.- Filter thickness: 1%
- 2.- Filter absorption: 10%
- 3.- PIN-diode sensitivity: 5%
- 4.- Time resolution of the scope: 5%
- 5.- Cable length from PIN diode to the scope for correlation of diode signal with current waveform: 3%

An overall systematic error of 12% was estimated in the measurement of x-ray yield.

Chapter 4

EXPERIMENTAL OBSERVATIONS ON TWO-WIRE Z-PINCH

4.1.- Introduction

In this chapter, we present results related with the plasma dynamics of z-pinchs with two parallel wires for different material and separations. Aluminium and tungsten wires of 15 and 7.5 μm diameter were used. Three different separations of 0.3, 0.6, and 1.5 mm were studied.

The second section of this chapter describes the load configuration and the current generator performance. Similar conditions of rise-time and peak current per wire were used, as delivered to each wire in the arrays used in the Z accelerator [4.1,4.2] at Sandia National Laboratories.

Section three, contains observations related to aluminium wires for the three different separations. These observations are classified in three different categories: 1) Optical probing; 2) Optical emission; and 3) X-ray emission.

The plasma z-pinch was diagnosed by pulsed laser schlieren photography; an optical gated four-frame camera, an optical streak camera, an x-ray time-integrated pinhole camera, and filtered x-ray PIN diodes.

Section four, contains the observations of tungsten wires for the same wire separations, which were also performed under the same experimental conditions and with the same diagnostics as for aluminium.

It is important to mention that the two-wire experiments were done under the same experimental condition that for single wire. Therefore, error analysis of two-wire is similar to the presented in the chapter 3.

4.2.- General Considerations

The current and voltage waveform tell us about the dynamical behaviour of the z-pinch through its transient changes in impedance and inductance during the discharge. The IMP generator provided a peak current of 160 kA with a rise-time (10%-90%) of 70 ns, giving a maximum rate of increase of current of $2.45 \times 10^{12} \text{ A/s}$.

Figure 4.1 shows the magnetic field lines of a two-wire z-pinch configuration, which corresponds to a magnetic quadrupole.

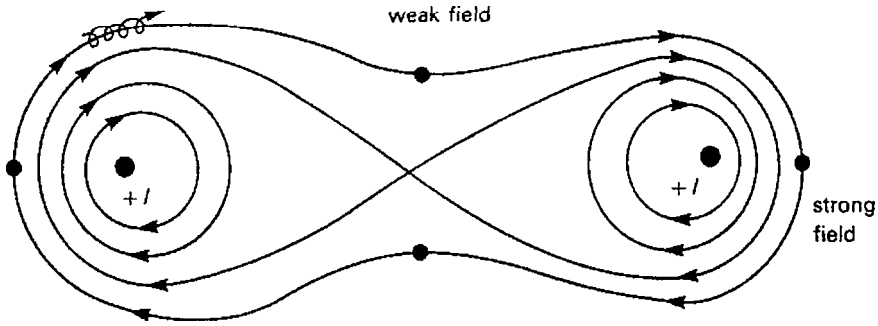


Figure 4.1. Magnetic field lines of two-wire Z-pinch configuration, generated by two parallel wires carrying current I .

The load inductance is a geometrical property of the system. In our case, it depends on the wire diameter, length, and separation between wires. The inductance L_i for two parallel wires, is given by (Eq. 4.1):

$$L_i = \frac{\mu_0 l}{2\pi} \left(\frac{l}{2} \ln \left(\frac{R}{2D} \right) + \frac{l}{2} \ln \left(\frac{R}{x_i} \right) \right) \quad 4.1$$

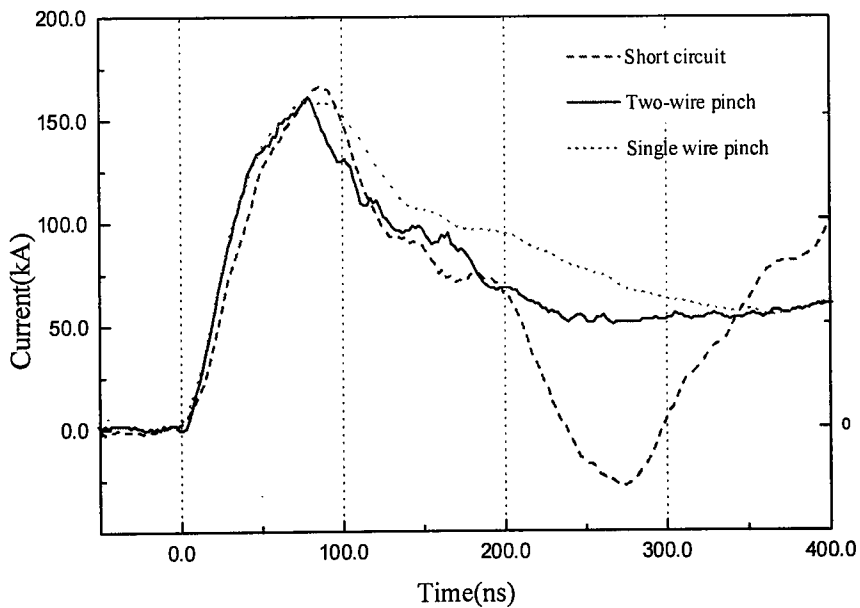
Where l is the wire length, R the returning current radius, D the wire diameter, and x the wire separation. Thus, substituting in Eq. (1) the respective values: $l = 2 \text{ cm}$, $R = 47 \text{ cm}$, $x_1 = 0.3 \text{ mm}$, $x_2 = 0.6 \text{ mm}$, $x_3 = 1.5 \text{ mm}$ (the three respective separations), $D = 15 \mu\text{m}$ for aluminium, and $D = 7.5 \mu\text{m}$ for tungsten. The inductance L associated with each wire separation are shown in Table 4.I. For single $15 \mu\text{m}$ aluminium and $7.5 \mu\text{m}$ tungsten wire the inductance is 41.4 nH and 44.2 nH respectively.

Table 4.I. Inductance determined by Eq. (1) for two wires of different separation.

Material	Wire separation		
	<i>0.3mm</i>	<i>0.6mm</i>	<i>1.5mm</i>
<i>15μm Al</i>	<i>34.0nH</i>	<i>32.6nH</i>	<i>30.8nH</i>
<i>7.5μm W</i>	<i>35.4nH</i>	<i>34.0nH</i>	<i>32.2nH</i>

An inductance difference of approximately 20% between single and double wires, enables a better coupling (load – generator) for a two-wire load than for single one.

Figure 4.2 and 4.3 show the current through and the voltage across the pinch and a 1.5 mm diameter short. The current rise-time was faster for the two-wire pinch within the firsts 50ns of the discharge. There was no change in peak current and rise time when wire separation and material were changed.

**Figure 4.2.** The measured current through the pinch and a 1.5 mm rod short circuit.

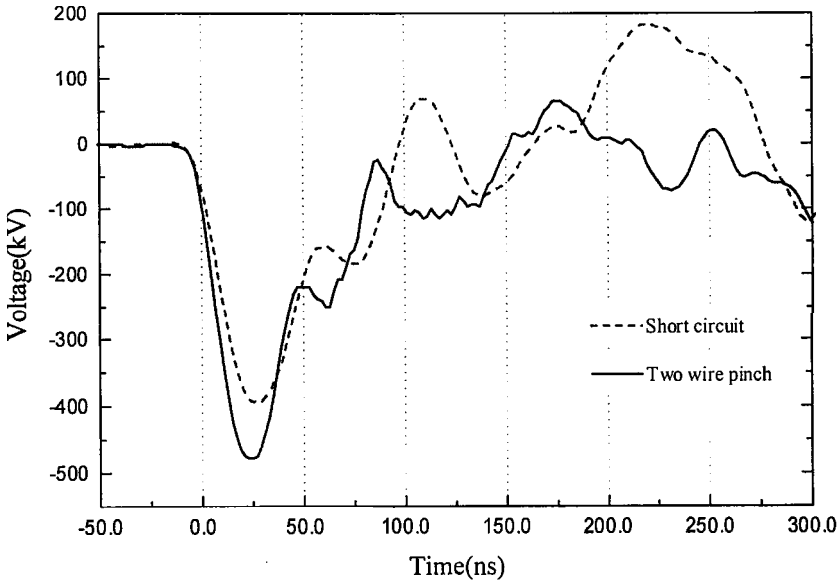


Figure 4.3. The measured transfer section voltage for the pinch and a 1.5 mm rod short circuit.

Experiments at Sandia National Laboratories (SNL) on cylindrical wire-array z-pinchs for different wire materials were driven by the Z accelerator [4.3], delivering a current pulse of 20 MA with a time-to-peak current of 105ns. Wire arrays 20mm long mounted on a 40mm diameter cylinder built with 240 tungsten wires of $7.5\mu\text{m}$ diameter emitted a peak K-shell x-ray of averaged power of 200 TW in a single 7.5 ns FWHM pulse. For this array configuration, the wire separation was about $500\mu\text{m}$ and current per wire was 80kA. These parameters (wire separation and current per wire) are perfectly reproducible by the IMP generator for a two-wire load.

Different number of wires, lengths, and materials have been explored to enhance the emitted x-ray pulse [4.4,4.5,4.6] in wire array experiments, but keeping the mass per unit length and array radius constant, so that the implosion dynamics are roughly the same. They found that the x-ray power per unit length increases when both the wire numbers was increased and the array length was reduced [4.7].

4.3.- Two 15 μm Aluminium Wire Results

In this section experimental observations and results of two parallel 15 μm aluminium wires for 0.3, 0.6, and 1.5 mm separations will be presented.

4.3.1.- Optical Probing Observations

The plasma was probed with a 7 ns full width at half maximum (FWHM), 70mJ ruby laser pulse, in two directions: face-on (perpendicular to the plane defined by the wires) and side-on (parallel to the plane defined by the wires), see Fig. 4.4. This enabled us to study the axial correlation of instabilities, formation of a central plasma column, plasma streamer formation (material injection from wires towards the axis), and the coronal and core expansion in the two directions mentioned above. The schlieren system consisted of a 550 μm stop (disk) and a 350mm focal length lens, which enabled detection of gradients of electron density with a sensitivity of 0.8mrad, corresponding to an electron density of $1.8 \times 10^{18} \text{ cm}^{-3}$. The maximum electron density detected is limited by the acceptance angle of 78mrad, corresponding to a minimum electron density of $1.8 \times 10^{20} \text{ cm}^{-3}$ (assuming a parabolic density profile).

As a consequence of magnetic field configuration for two wire z pinches, two different expansion velocities were defined in the face-on direction: the internal coronal wire-plasma v_{y-} and the external coronal wire-plasma v_{y+} , where $v_{y-} > v_{y+}$ as is shown in Fig. 4.4. On the other hand, in the side-on direction, we found that the expansion in both directions has the same magnitude ($v_{x-} = v_{x+} = v_x$).

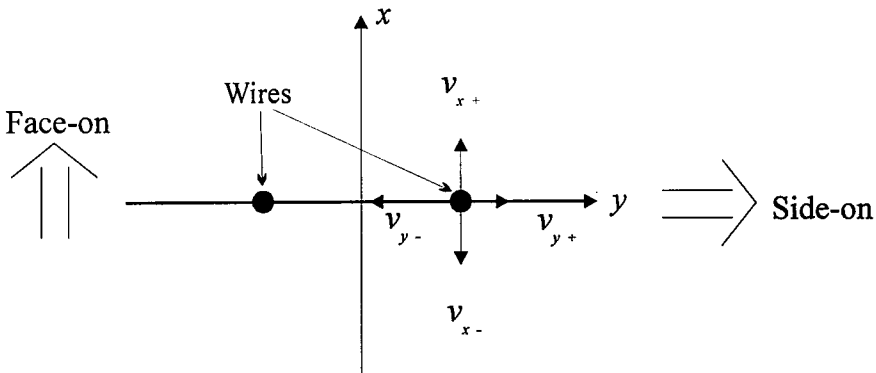


Figure 4.4. Schematic of expansion velocities in two-wire z pinches (end-on view).

4.3.1.1.- *Initial Wire Separation: 0.3 mm*

Figure 4.5 shows a sequence of simultaneous face-on and side-on schlieren photographs taken at different laser times for different current discharges. The central plasma column starts to form around the geometrical axis of the two-wire configuration. Axial correlation of $m = 0$ - MHD instability in the coronal plasma of both wires was observed in face-on direction at 13ns. This indicates the existence of an external global magnetic field surrounding both wires.

The face-on schlieren photograph taken at 35 ns shows that the central plasma column is brighter at the same axial position as coronal plasma instabilities observed are both wires. At 76ns, the central region became completely inaccessible to the laser light. It is $m = 0$ -MHD unstable, showing similar wavelengths to the external coronal plasma.

Expansion velocities of coronal and core plasma in face-on and side-on directions are presented in figure 4.6 and 4.7 respectively. The ratios of side-on to face-on expansion velocity of coronal and core region are 1.5 and 2.1 respectively.

A comparison of evolution of wavelengths λ , for $m = 0$ -MHD mode, in the coronal plasma is shown in Fig. 4.13 both for the three wire separations and for a single wire.

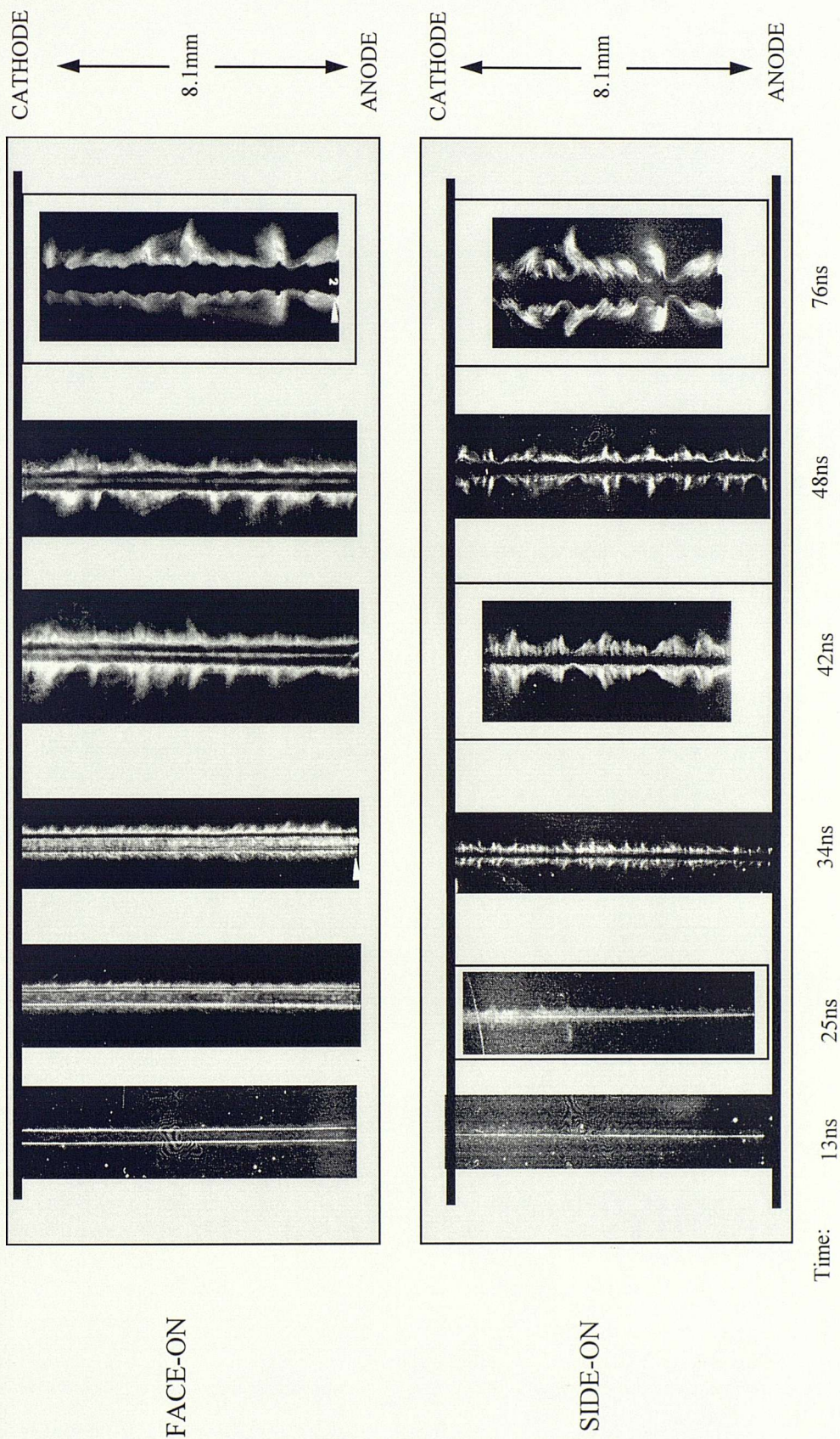


Figure 4.5. Face-on and side-on schlieren photographs of two parallel 15 μm aluminium wires separated by 0.3mm

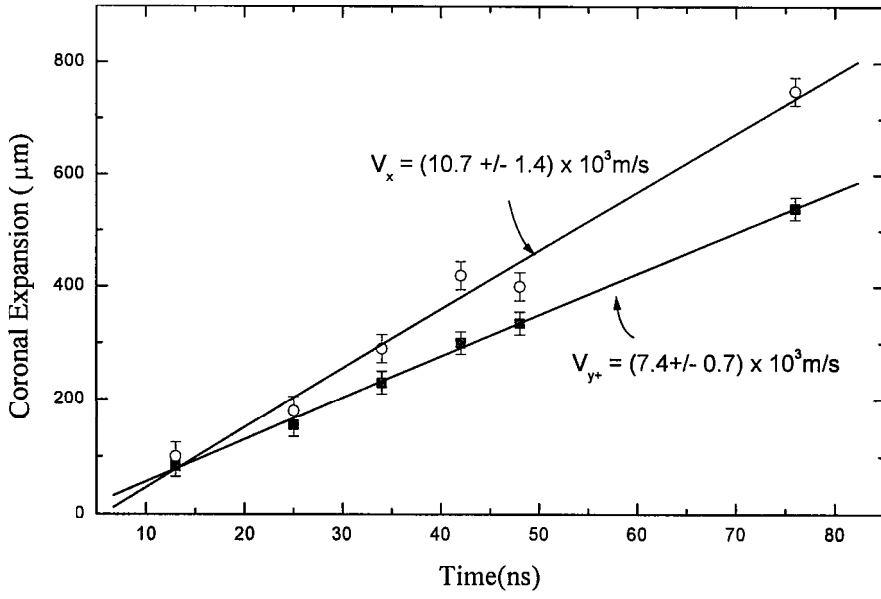


Figure 4.6 Face-on and side-on coronal expansion velocity for 0.3 mm separation.

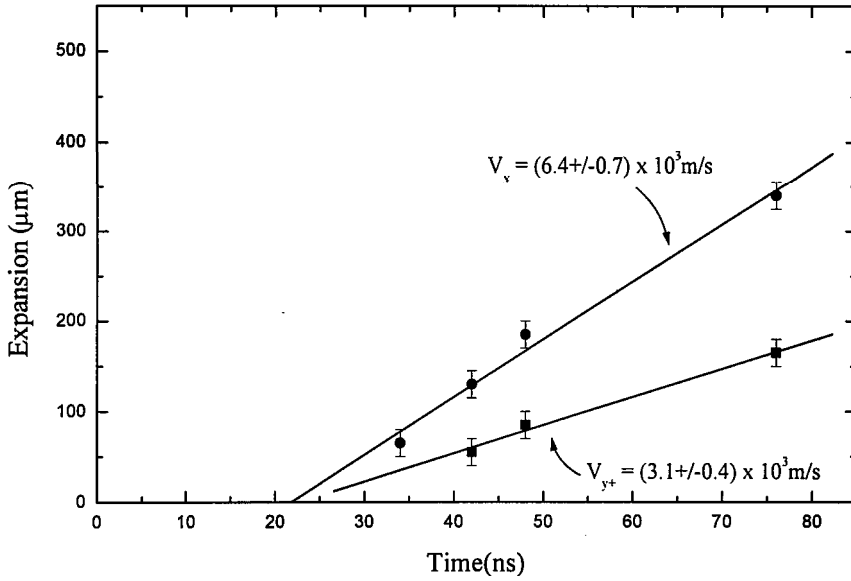


Figure 4.7 Face-on and side-on core expansion velocity for 0.3 mm separation.

4.3.1.2.- *Initial Wire Separation: 0.6 mm*

Figure 4.8 shows a sequence of simultaneous face-on and side-on schlieren photographs taken at different laser times. At 10 ns, it was possible to observe the individual expansion in each wire. The face-on photograph taken at 15 ns shows the plasma column between wires. By contrast to the 0.3mm separation (see Fig. 4.5, frame at 35ns), the face-on photographs for 0.6mm separation does not show any brighter regions along the central column. The central column is more homogeneous compared with the 0.3mm separation.

Correlation of instabilities in the face-on direction occurs at 15ns compared to 10ns for 0.3mm separation. Comparison of external coronal expansion face-on and side-on shows that it is faster in the side-on direction.

At about 60 ns, the laser light can not pass through to the central plasma region. This maybe due to a high refractivity of the laser light by the plasma. The instability wavelengths of MHD $m = 0$ mode are shorter compared with the 0.3mm separation.

Density island formations (break-up of pinch column) [4.8] were seen earlier, at about 75ns, compared with 0.3mm separation. This feature may be because current flow through the central plasma is higher for smaller separation, where the pinch behaves as a thick single wire. This shows that the pinch dynamics changes with the change in wire separation from the 0.3mm to 0.6mm.

Figure 4.9 and 4.10 show the coronal and core expansion velocities in face-on and side-on directions respectively for 0.6mm separation. The ratio of coronal expansion velocity side-on to face-on was 2.1, while that for the core expansion was 2.7.

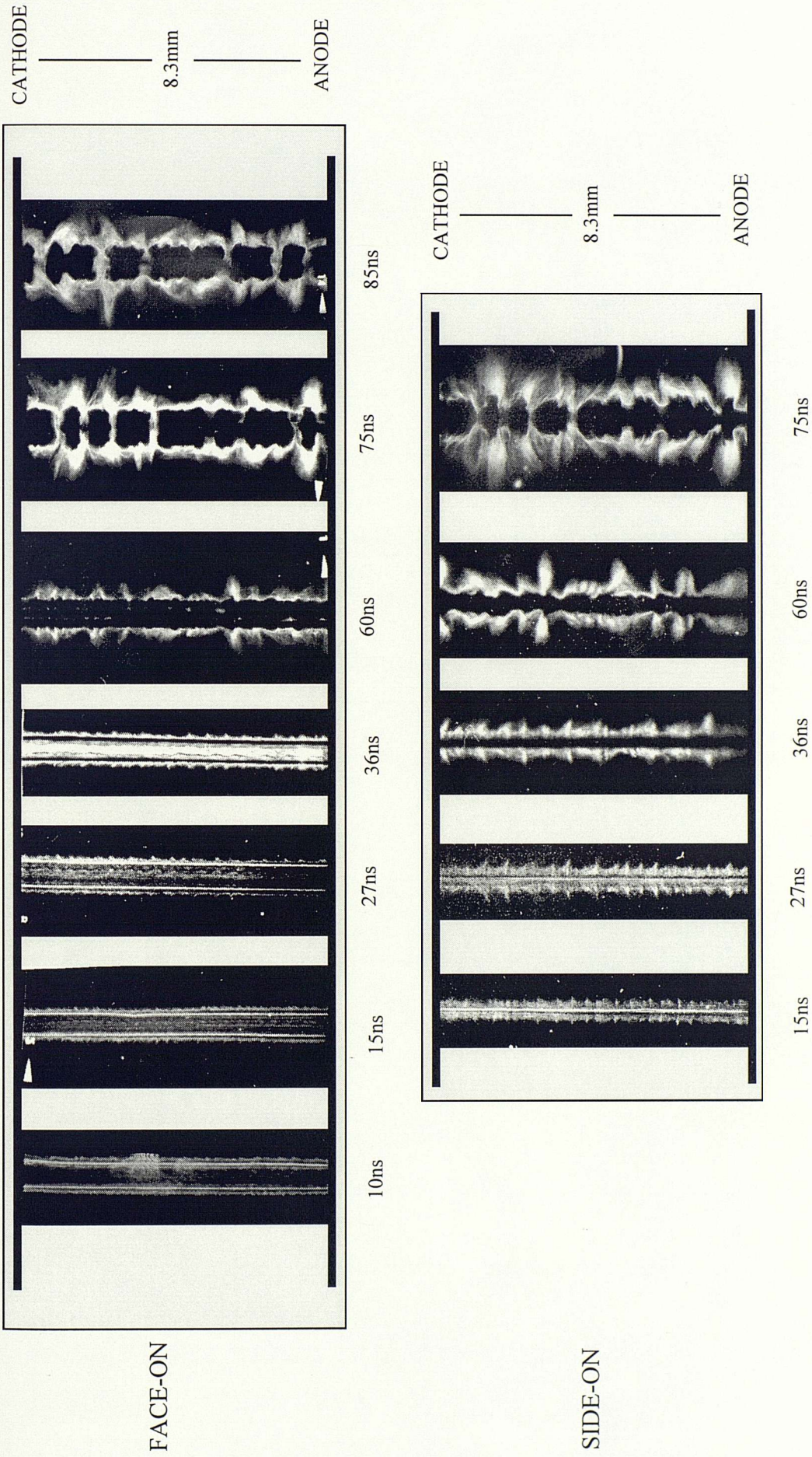


Figure 4.8. Face-on and side-on schlieren photographs of two parallel 15 μm aluminium wires separated by 0.6mm

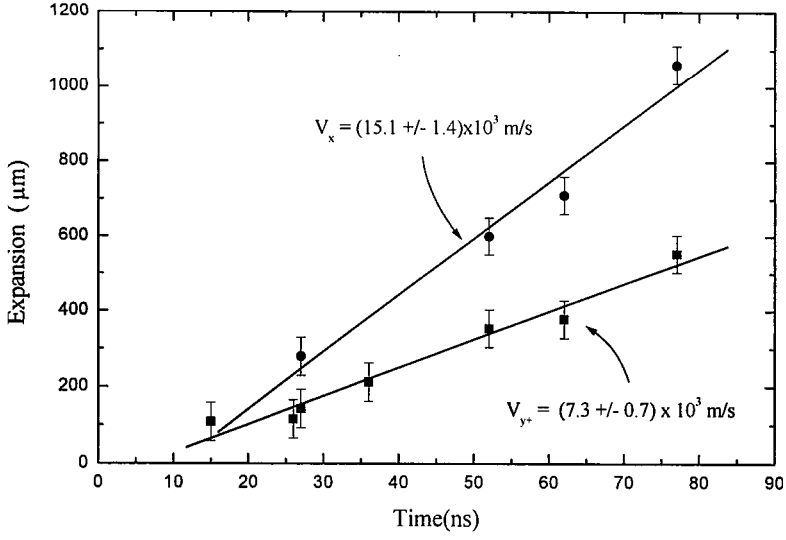


Figure 4.9. Face-on and side-on coronal expansion velocity for 0.6 mm separation.

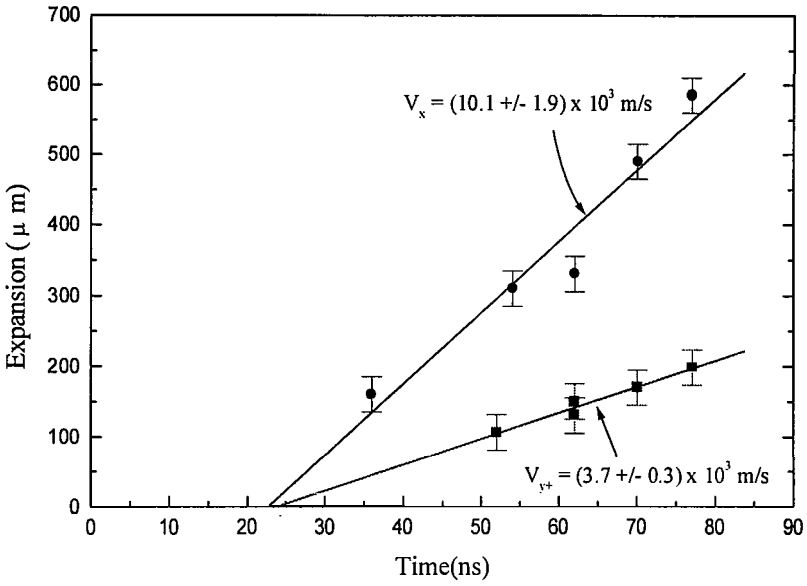


Figure 4.10. Face-on and side-on core expansion velocity for 0.6 mm separation.

The behaviour of instability wavelengths will be discussed together with the others wire separations in Section 4.3.1.3.

4.3.1.3.- Initial Wire Separation: 1.5 mm

Figure 4.11, shows a sequence of simultaneous face-on and side-on schlieren photographs for 1.5 mm separation. At about 30 ns different coronal expansions and instability growth rates for each wire were observed. The central plasma column was seen at 35ns showing a MHD $m = 1$ mode. Compared to 0.3mm and 0.6mm separations, it was more unstable. It is probably due to a combination of an asymmetric mass flow from both wires and a flow of current through this column. Comparison of simultaneous schlieren photographs taken at 65 ns, shows that this central plasma column is in the plane between wires. Density islands were seen at 110ns.

Comparison of face-on and side-on coronal expansion, shows clearly that the coronal plasma expands faster (two or three times) in the side-on direction. Like the other wire separations, the external coronal plasma developed a $m = 0$ -like MHD instability axially correlated in both wires.

Schlieren photographs taken at different times enabled us simultaneously to determine the expansion velocities in the corona and core for both directions. These velocities are summarised in Table 4.II.

Table 4.II. Coronal and core expansion velocities from schlieren photographs for two 1.5µm aluminium wire

	0.3mm separation		0.6mm separation		1.5mm separation	
	Face-on $\times 10^3 \text{ m/s}$	Side-on $\times 10^3 \text{ m/s}$	Face-on $\times 10^3 \text{ m/s}$	Side-on $\times 10^3 \text{ m/s}$	Face-on $\times 10^3 \text{ m/s}$	Side-on $\times 10^3 \text{ m/s}$
Corona	7.4	10.7	7.3	15.1	6.3	13.6
Core	3.1	6.4	3.7	9.9		6.1

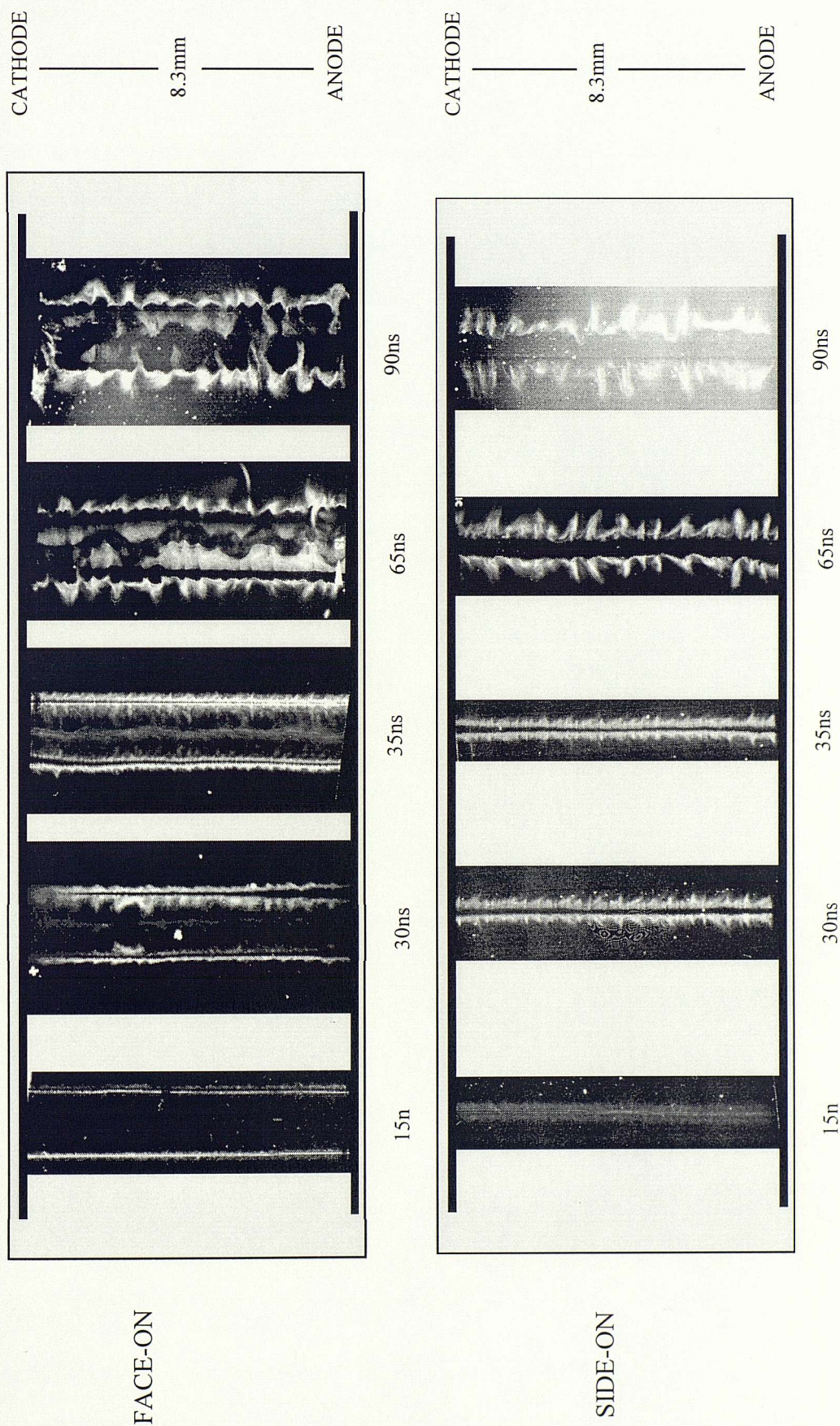


Figure 4.11. Face-on and side-on schlieren photographs of two parallel 15 μ m aluminium wire separated by 1.5mm

Figure 4.13 shows the evolution of instability wavelength for the three different separations and for a single wire. It shows a similar behaviour for 0.3mm and 0.6mm separation. For the 0.3 mm separation, λ increased from 0.3mm up to 1.0mm in 25 ns . Then it was increasing with a lower linear rate up to 1.1mm for the next 28ns . For 0.6 mm , the wavelength increased from 0.3mm up to 0.5mm in 20 ns . After that time, λ increased with a lower linear rate up to 0.7mm in 50ns .

For 1.5mm separation, λ showed the lowest rate of growth. It increased from 0.28mm up to 0.33mm in 20 ns , then reached a value of 0.65mm in 56ns . Comparison with results for single wire shows that both configurations have the same characteristic of growth. These were observed to dominate at late times.

Short wavelengths are dominant in two-wire configuration. These observations show that the instability wavelengths decrease as the separation between wire increases. Results from wire arrays experiments performed in MAGPIE generator [4.9] show that there exists a dominant instability wavelength in the external coronal plasma, ranging from 0.5 to 1.0mm . It was observed during the discharge for long time along the pinch length.

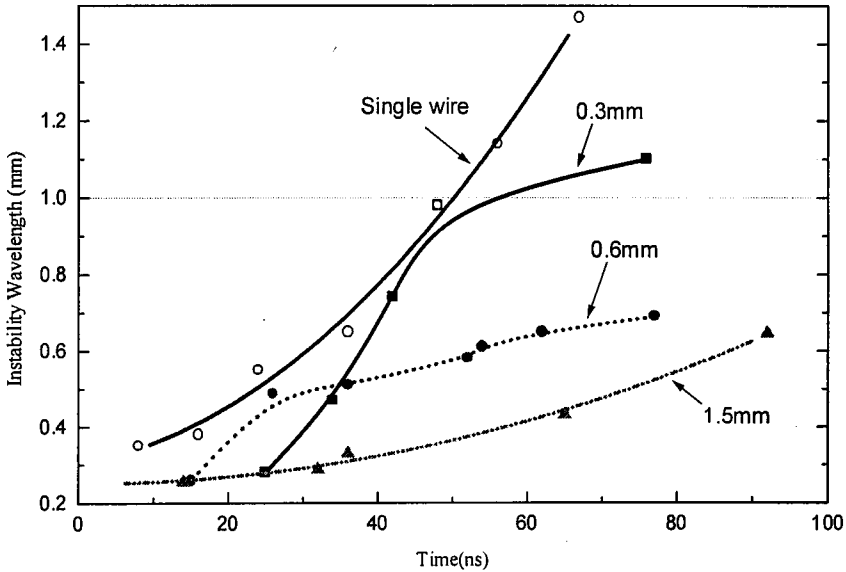


Figure 4.13. Instability wavelength of single and double $15\mu\text{m}$ aluminium wire z-pinchs.

4.3.2.- *Optical Emission Observations*

Time resolved observations of optical emission enables us to study the dynamical behaviour of two-wire z-pinch plasmas. Radial streak and framing photography were performed to observe the evolution of the wire-plasma and the formation of the central plasma column for aluminium and tungsten wires using different wire separation.

4.3.2.1.- *Gated Optical Framing Images*

A gated optical intensifier (GOI) framing camera was used with an exposure time of 1 ns and inter-frame time of 5 or 15 ns . The collected plasma light with the camera was filtered using an interference filter with a bandwidth of 10 nm at $\lambda = 486\text{ nm}$.

Optical spectroscopy measurements (visible region) were performed for both wire materials (aluminium and tungsten) in order to check that there was no strong line emission in this wavelength range.

The framing camera enabled us to observe both the emission from the wires and from the central plasma region with a spatial and time resolution of $20\text{ }\mu\text{m}$ and 1 ns respectively. Optical framing images show emission from each wire initially, then a central plasma column is formed in the interwire region, which becomes brighter than with wire emission.

Figure 4.14 shows framing images for 0.3 mm separation. At 15 ns , it was possible to distinguish the emission from each wire, as well as from the central plasma. At 30 ns , the central column became brighter compared to the wire emission, where the pinch behaves like a thick single wire. At 45 ns this shows a $m = 0$ -like ($\lambda = 550\text{ }\mu\text{m}$) MHD instability. The diameter of the plasma column increased with time, but its instability wavelength does not change much after it was formed. Density islands were seen at 80 ns .

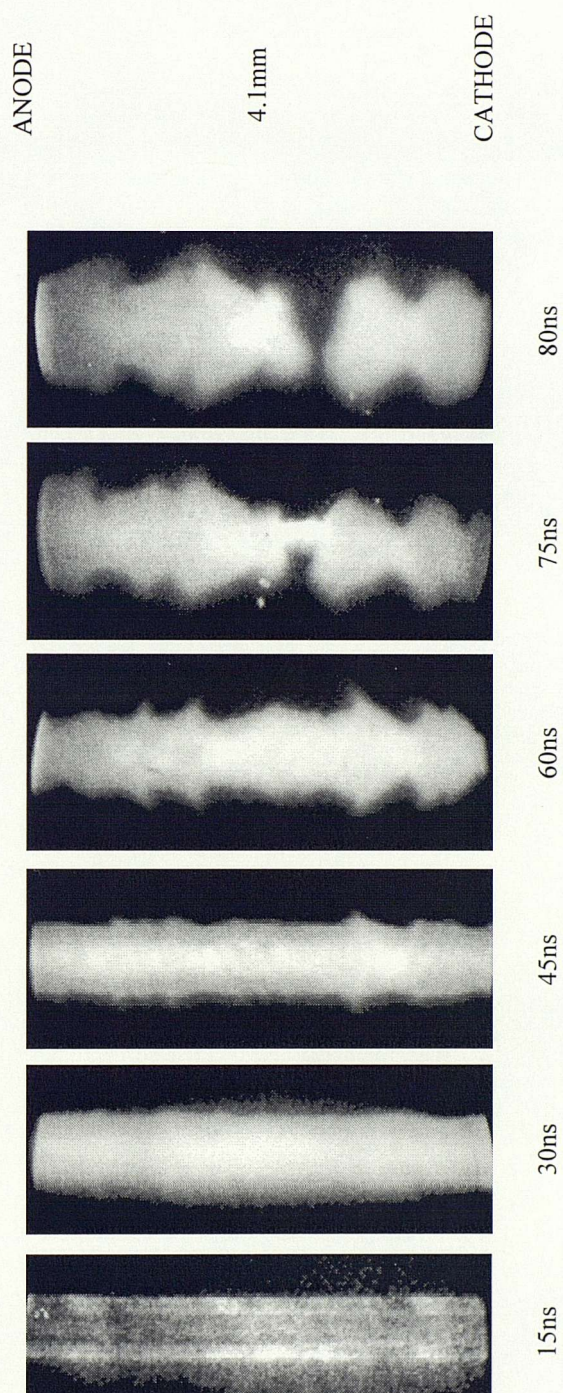


Figure 4.14. Optical framing images for 0.3 mm separation of two 15 μm aluminium wire taken in face-on direction.

For 0.6 mm separation (see Fig. 4.15), at 20 ns it was possible to distinguish the emission from wires and central region. At 35 ns, the central region shows a $m = 1$ ($\lambda = 940\mu\text{m}$) MHD instability. After 40 ns, it was possible to observe simultaneously both $m = 0$ ($\lambda = 680\mu\text{m}$) in the outer region, and $m = 1$ ($\lambda = 940\mu\text{m}$) in the inner region for about 15ns. At 65 ns, the density islands were formed. By contrast to 0.3mm separation, the density islands appears earlier for 0.6mm.

Figure 4.16 and 4.17 show expansion velocities determined from the optical emission images for 0.3 and 0.6mm separations. Comparison of these velocities with the core expansions from schlieren (Table 4.II) shows that these are slower in a 20% and 5% respectively.

For 1.5mm , see Fig. 4.18, it was possible to distinguish the emission from wires and central plasma until about 50ns. The central plasma column was formed at about 30ns, it is possible to observe three different emitting regions completely separated. Two of them correspond to the wires and the central region to the plasma column formed by accumulation of wire material. The central column was $m = 1$ MHD unstable, furthermore it became brighter than the wire plasma. At 65ns was not possible to distinguish the emission from wires and central column. At 75ns the whole pinch column became $m = 0$ unstable. The density islands were observed at 80ns.

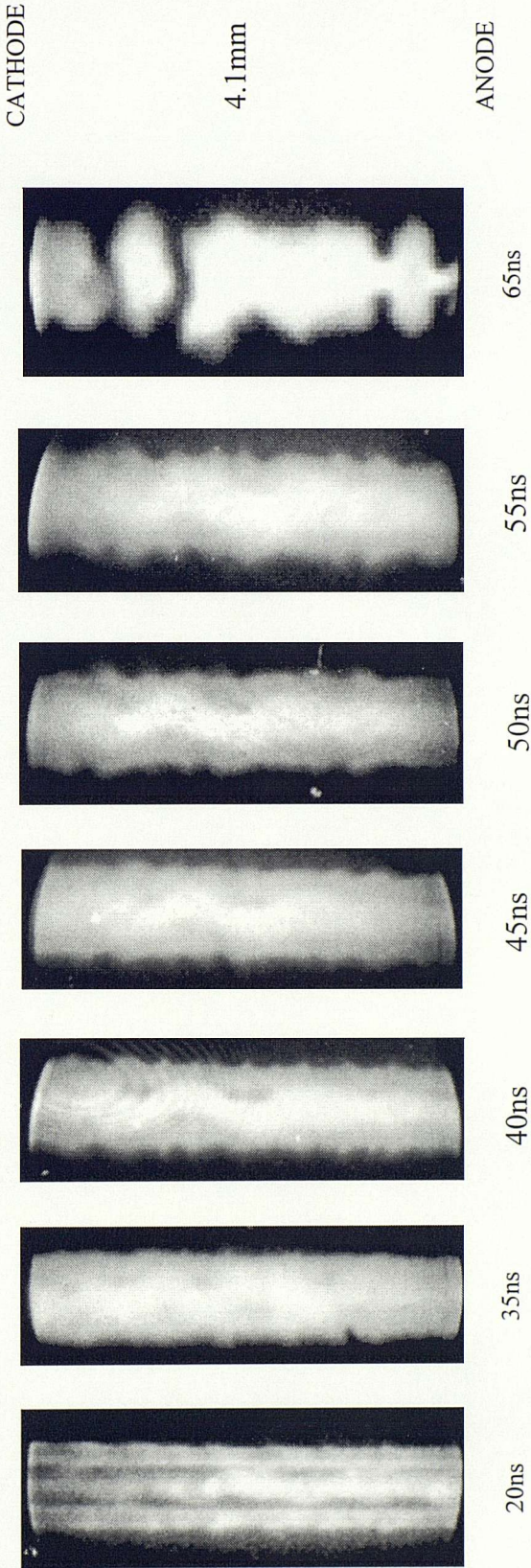


Figure 4.15. Optical framing images for 0.6 mm separation of two 15 μm aluminium wire taken in face-on direction.

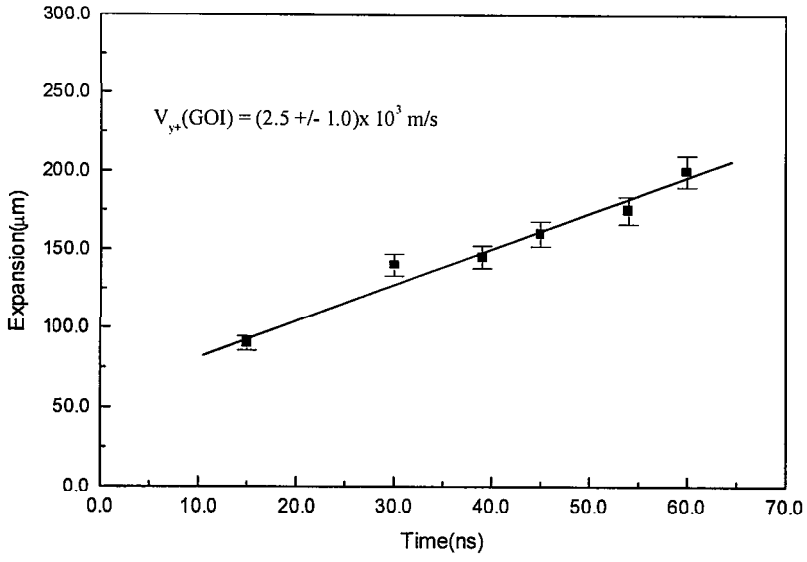


Figure 4.16. Core expansion velocity from optical emission for 0.3 mm separation.

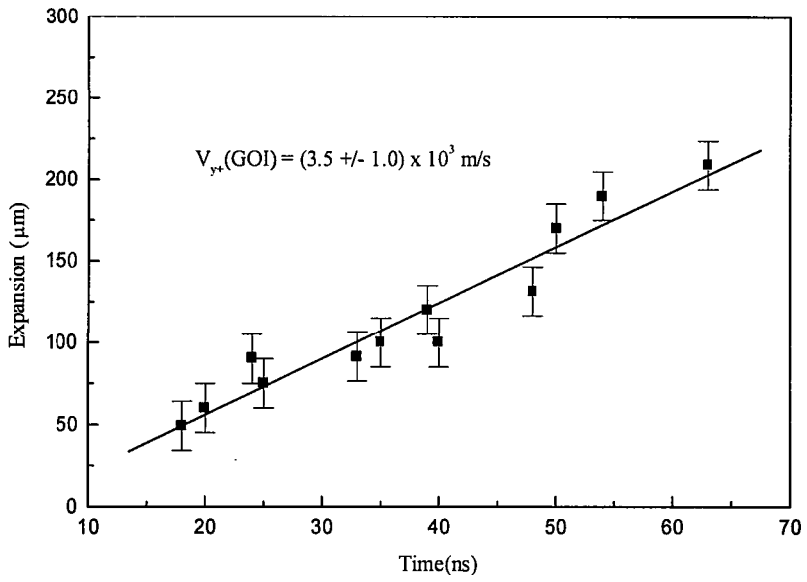


Figure 4.17. Core expansion velocity from optical emission for 0.6 mm separation.

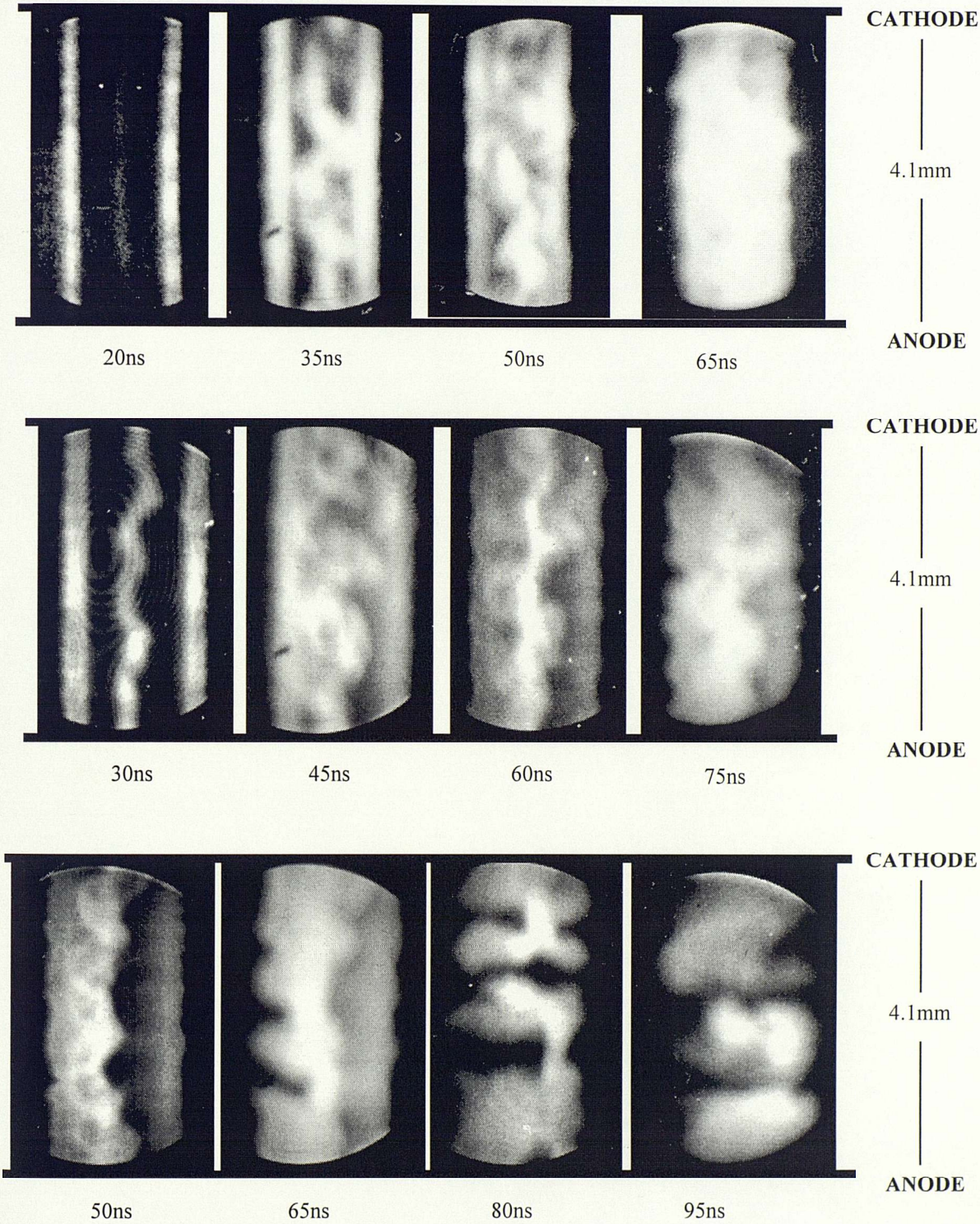


Figure 4.18. Optical framing images of two 15 μm aluminium wire for 0.3 mm separation taken in face-on direction.

4.3.2.2.- *Optical Streak Camera Observations*

An optical streak camera was used to study both the pinch expansion in the y direction (see Fig. 4.4) and the formation of the central plasma column. The plasma image was rotated by 90° and magnified by 12x, to give a spatial resolution of $8\ \mu\text{m}$. A time resolution of $1\ \text{ns}$ was obtained by the combination of a streak speed of $2.5\text{ns}/\text{mm}$ with a $300\ \mu\text{m}$ slit placed in front of the photocathode. HP5 film was used as the recording media. The advantage of this film over commercial film is its dynamics range, which enables us to observe the pinch structure with more detail, as well as to define different phases in the transient pinch. In order to get a non-saturated image of the pinch, the plasma light was filtered only with a neutral density (ND) filter of 0.9.

Figure 4.19, shows a set of optical radial streak photographs of two $15\ \mu\text{m}$ aluminium wires for three different separations. The shot-to-shot reproducibility was good. Fig 4.19.a, shows the radial expansion for 0.3mm separation. At 5ns, it was possible to observe the emission from each wire. The inter-region between wires became brighter after 10ns. Similarly for 0.6 and 1.5mm separation, the central plasma was formed at 15 and 30ns respectively, see Fig. 4.19.b and 4.19.c.

Comparison of these times with those observed by schlieren photography and framing images, shows that the different diagnostics agree very well on the time of formation of the central plasma column for the different wire separations.

Expansion velocities for different separations in the perpendicular direction to the wires are shown in Table 4.III.

Table 4.III. Expansion velocities of the pinch in face-on direction.

Wire Separation	Time of central plasma formation	External Expansion velocity ($10^3\ \text{m/s}$)
0.3mm	10	$9 \times 10^3\ \text{m/s}$
0.6mm	20	$1.1 \times 10^4\ \text{m/s}$
1.5mm	35	$5 \times 10^3\ \text{m/s}$

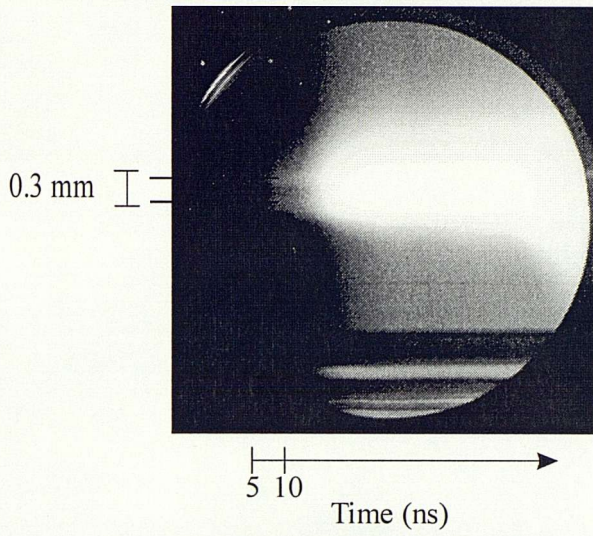


Fig. 4.19.a
Wire separation: 0.3mm

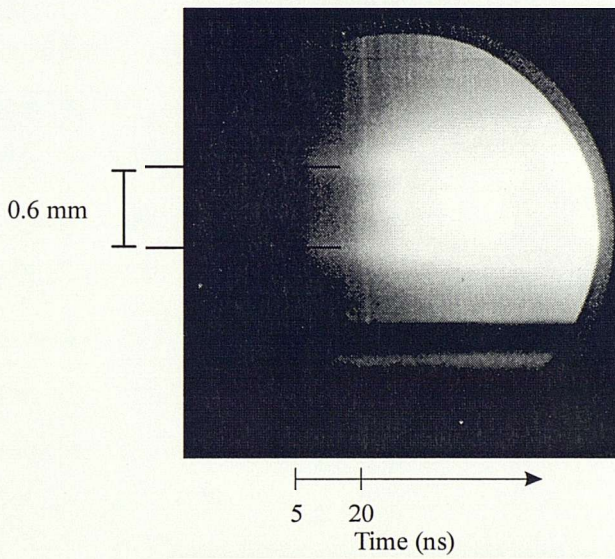


Fig. 4.19.b
Wire separation: 0.6mm

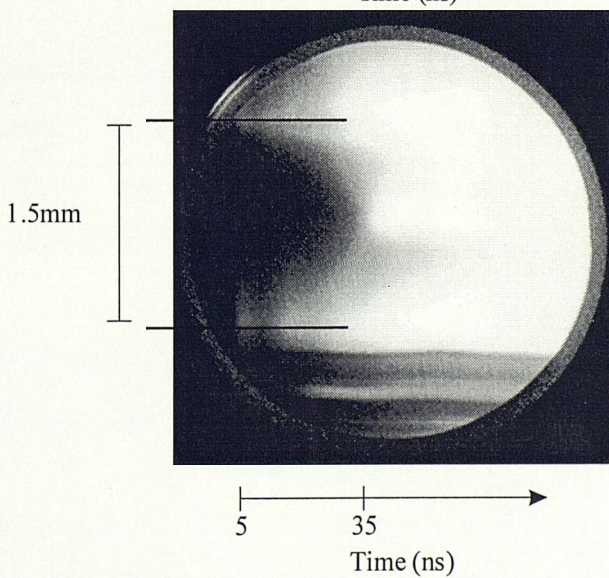


Fig. 4.19.c
Wire separation: 1.5mm

Figure 4.19. Optical streak photograph of two 15μm aluminium wire for different wire separations.
Streak speed: 2.5ns/mm

4.3.3.- X-Ray Emission Observations

A filtered time integrated pinhole camera and PIN diodes monitored the x-ray emission from the pinch. These diagnostics were used to obtain time and space resolved information.

4.3.3.1.- Time-Integrated Pinhole Camera

The time integrated pinhole images of two 15 μm aluminium wire pinch for the three different separations are shown in Fig. 4.20. Several pinhole sizes and filters (see Table 4.V) were used to obtain spatial and spectral information of x-rays from the pinch. Fig. 4.20.a shows a set of images for 0.3mm separation. Image 1 with filters transmitting x-rays above 240 eV shows 12 bright spots irregularly separated along the length of the pinch varying in intensities. Image 2 was recorded with a 25 μm Mg filter ($h\nu > 4.4\text{keV}$), which does not transmit line radiation. The emission from bright spots was faint and pinhole limited. Image 3, a Ross filter pair ($h\nu > 1.9\text{keV}$) was used to isolate the line radiation. A comparison of these images (2 and 3) shows that the emission from line radiation is significant. Image 4 and 5 were recorded with a filter pair that isolated the K_α line (see Table 4.IV). A comparison of these images shows that there is a significant emission due to highly ionised lines.

A set of time integrated pinhole x-ray photographs for 0.6 mm separation is shown in Fig. 4.20.b. Like 0.3 mm wire separation, bright spots are non-uniformly distributed along the pinch axis. Image 1 shows a faint emission from the central plasma. Also, like 0.3 mm separation, x-ray emission is significant from the line radiation but images with filters that do not transmit line radiation are brighter compared to the 0.3 mm wire separation.

When the wire separation was increased to 1.5 mm (Fig. 4.20.c), simultaneous x-ray emission from the central plasma and bright spots was evident. As with the other two separations, the line radiation emission is significant. However, bright spots are off axis unlike with the other two separations. Presumably the bright spots are from the central plasma, which also shows a kink like structure. This is in agreement with the optical emission observations where emission becomes intense from the central plasma later in the discharge.

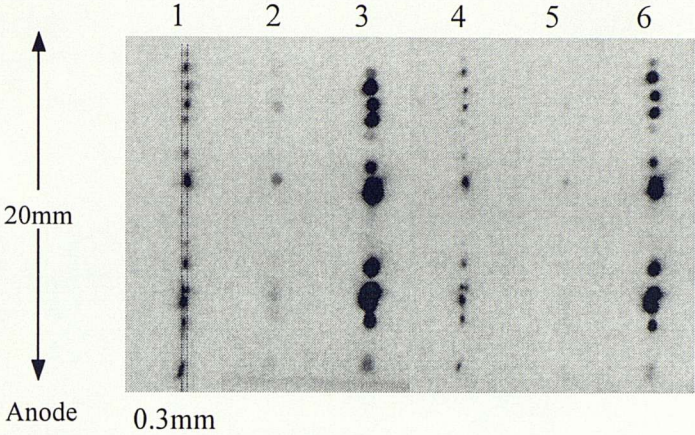


Fig. 4.20.a.
0.3mm separation

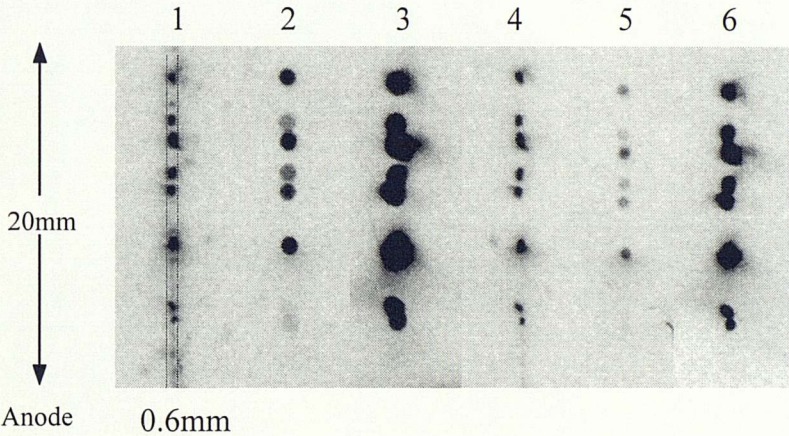


Fig. 20.b.
0.6mm separation

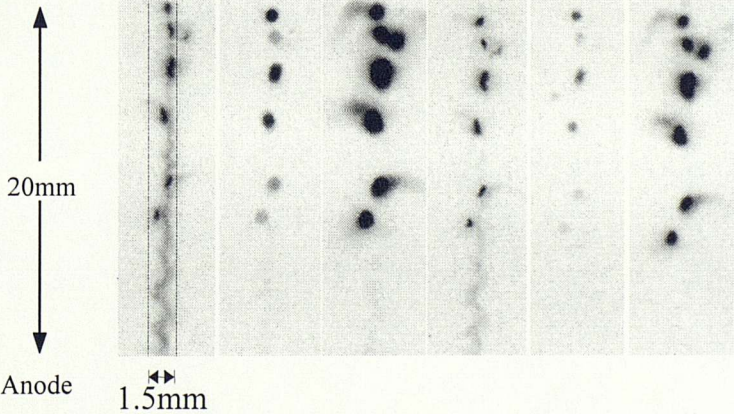


Fig.4.20.c.
1.5mm separation

Figure 4.20. X-ray pinhole photographs for different wire separations.

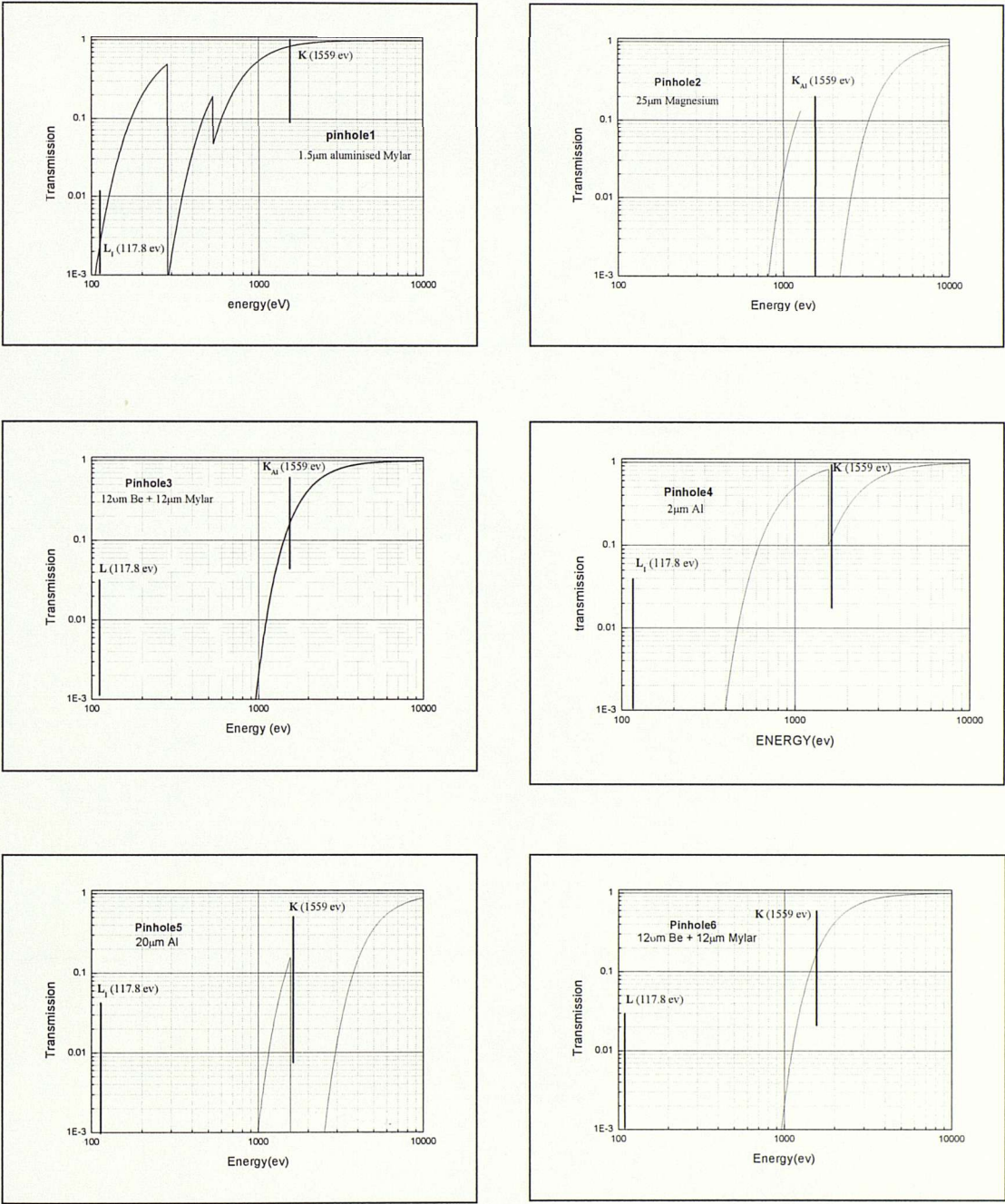


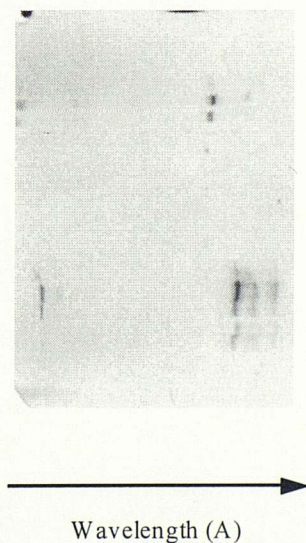
Figure 4.21. Transmission of x-ray filters for six pinhole camera and main line emissions of aluminium

Table 4.IV. Pinhole diameters and filters used in the x-ray pinhole camera.

Pinhole size/ Filter & Thickness	cut-off Energy
1: 50 μm /1.5 μm aluminised Mylar	$h\nu > 240\text{eV}$
2: 300 μm / 25 μm Magnesium	$h\nu > 4.4\text{keV}$
3: 300 μm /12 μm Beryllium+12 μm Mylar	$h\nu > 1.9\text{keV}$
4: 200 μm /2 μm Aluminium	$h\nu > 880\text{eV}$
5: 200 μm /20 μm Aluminium	$h\nu > 5.0\text{keV}$
6: 200 μm /12 μm Beryllium+12 μm Mylar	$h\nu > 1.9\text{keV}$

Figure 4.21 shows the transmission of the filters used on the six pinhole camera, and the line emissions of aluminium. Multiplying the DEF film sensitivity with the transmission of the filter gives the transmitted spectrum of that filter. Pinhole 4, 5 and 6 are 300 μm diameter. Here, we can see that the aluminium K line is going through the filters, in this case it is hard to get information about the temperature from pinhole images.

However, F. N. Beg and I. ROSS [4.10], using a crystal x-ray spectrometer performed estimates of temperature and density of the pinch. Spatially resolved time integrated spectra were recorded in the wavelength range of 5 – 10 Å with a 1200 ℓ/mm grating. It was spatially resolved along the wire length. The spectra consisted of aluminium lines from hot spots, see Fig. 4.22.

**Figure 4.22.** Time integrated x-ray spectrum of two-aluminium wire pinch.

A quantitative analysis of four aluminium lines was performed to determine electron temperature and density estimates using intensity line ratios. Comparing the measured ratios with those calculated in a spectrum data code called FLY [4.11] permitted to do this analysis. The code is capable of generating information on lithium-like, helium-like and hydrogen species from $Z = 2$ to 26 (from helium to iron).

The spectral film sensitivity, the spectral efficiency of the diffraction grating, and the spectral filter transmission were normalised to obtain the measured intensities in terms of relative numbers of photons per unit area.

Figure 4.23. shows the line out of the spectrum for two different hot spots located in the anode – cathode gap. The lines selected for analyses are shown in the Table 4.V.

It is important to mention that this data was recorded simultaneously with the others diagnostics used during the two-wire pinch experiments.

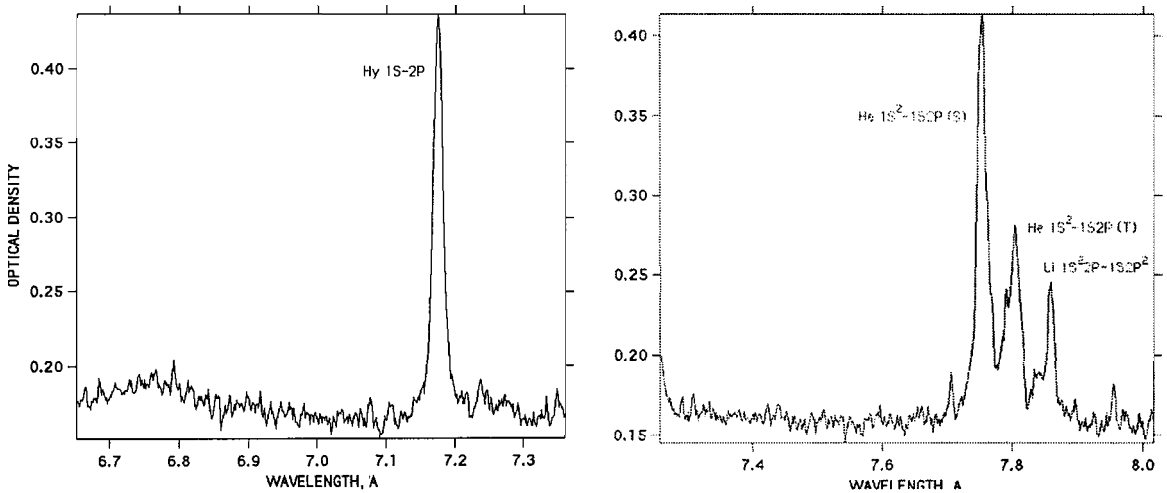


Figure 4.23. Line out of spatially resolved time-integrated spectrum of two-aluminium wire pinch.

Table 4.V. Selected spectral lines from two-aluminium wire pinch

Lines	Ratios	Temperature (eV)	Density (cm^{-3})
H 1S-2P	$(\text{He}2\text{PS}-\text{He}1\text{S})/(\text{Hy}2-\text{Hy}1)$	400	$10^{20} - 10^{21}$
He 1S^2 -1S2P (T)	$(\text{jkl} - \text{Li } 2\text{P})/(\text{He}2\text{PS}-\text{He}1\text{S})$	300 - 450	$10^{20} - 10^{21}$
He 1S^2 - 1S2P (S)			
Li 1S^2 2P-1S2P ²			

4.3.3.2.- PIN Diode Signals

The time resolved information about x-ray emission was obtained with a pair of filtered PIN diodes. A softer filter (25 μm Be+25 μm PVDC) with the cut-off energy of 2 keV was used to detect softer x-rays, and a harder filter of 10 μm copper was used for hard radiation ($h\nu > 6\text{keV}$).

Figure 4.24 shows x-ray signals for three different wire separations recorded with soft and hard foil filters. The current signal is also shown to distinguish when the x-rays were emitted. For 0.3mm separation, see Fig. 4.24.a, the soft x-ray emission start at 62ns (close to peak current). There are two peaks, the first one occurs at 75ns and the second peak at 90ns. The characteristics of x-ray emission are very similar to for thick wire [4.12]. The hard x-ray signal is small.

For 0.6mm separation, see Fig. 4.24.b, only one peak was observed with the soft filter, the x-ray signal starts at 80ns. The signal from the hard filtered PIN diode shows two peaks, the first one coincides with the soft signal. The second peak appears at 130ns, and is probably due to an electron beam interacting with the anode. Note that this peak cannot be seen on the soft filtered x-ray PIN diode due to collimation.

For 1.5mm (see Fig. 4.24.c), there are two peaks in both soft and hard x-ray signals. The first peak of soft x-ray emission appears after current peak at about 130ns. Unlike the 0.3mm separation, the second soft peak is higher than the first one. Interestingly for this separation, the first peak of hard x-ray emission appears at about 70ns. The second hard peak coincides with the second soft peak. This indicates that bright spots appear much later in current for 1.5mm separation.

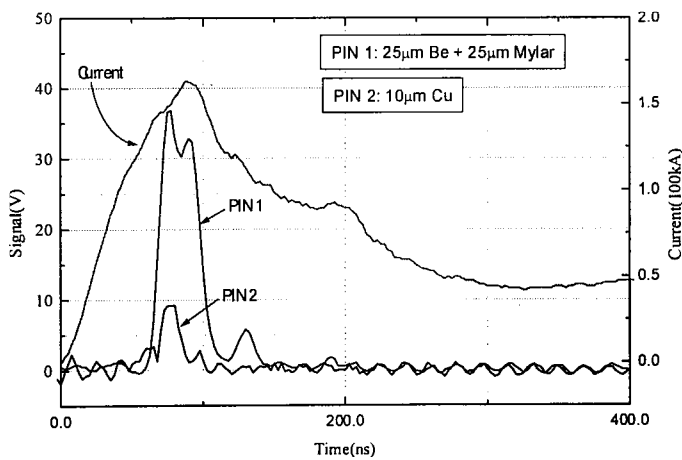


Figure 4.24.a. X-ray PIN diode signal for 0.3mm separation

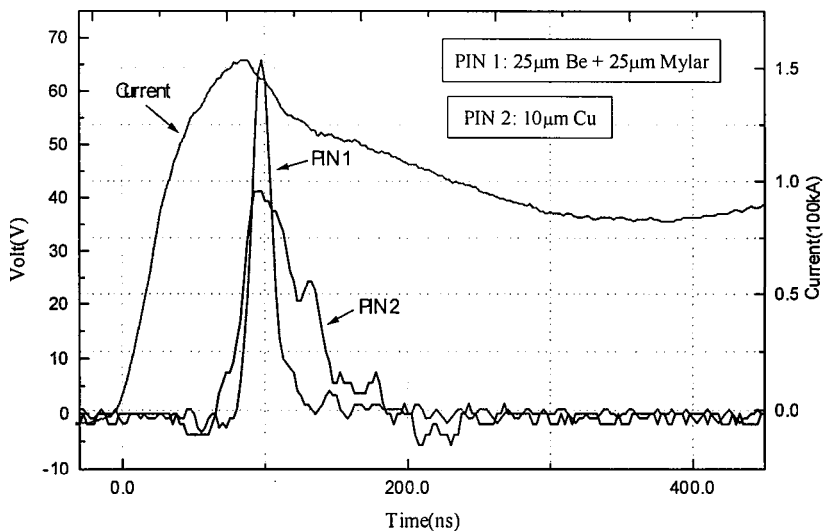


Figure 4.24.b. X-ray PIN diode signal for 0.6mm separation

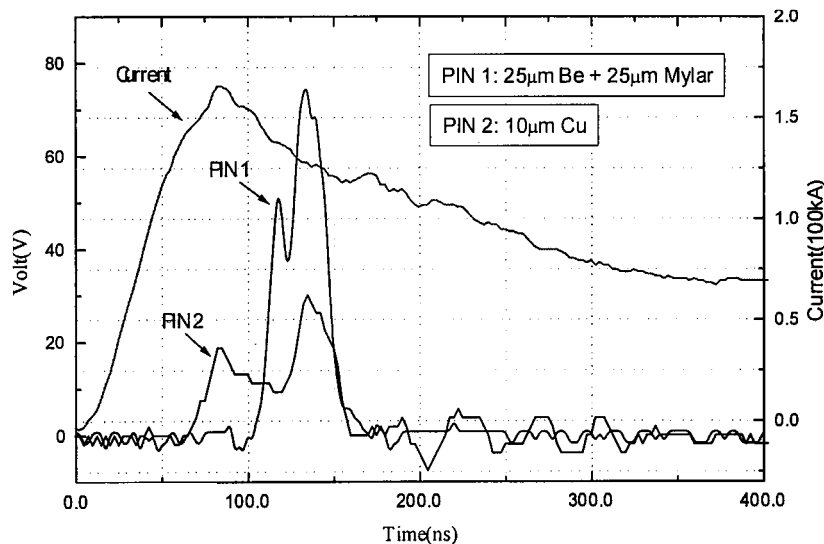


Figure 4.24.c. X-ray PIN diode signal for 1.5mm separation

The x-ray yield for the three wire separations was determined from filtered PIN diode signals for an energy window ΔE . It is given by (see Section 2.5.2.2):

$$Y = \frac{(Q_1 - Q_2)}{d\Omega} \frac{4\pi}{S \cdot T}$$

where Q_1 and Q_2 are the charge measured with the PIN diodes in Coulomb ($Q = \int (V/R) dt$ [C], $V =$ Voltage signal and $R = 50\Omega$), $d\Omega$ is the solid angle, S is the diode sensitivity in [$\mu C/J$] and T is the filter transmission. The signal of a PIN diode was filtered with $10\mu m$ Copper filter and the other one with a $25\mu m$ Beryllium + $25\mu m$ Mylar filter. The solid angle was 1.6×10^{-4} str.

Table 4.VI, shows the measured x-ray yield of two $15\mu m$ aluminium wire for three different wire separations.

Table 4.VI. The measured x-ray yield from PIN diode signals

Wire Separation	Energy window	X-ray yield (mJ)
300 μm	$1.9 keV < h\nu < 6.1 keV$	13.2 ± 0.4
600 μm	$1.9 keV < h\nu < 6.1 keV$	87.3 ± 2.1
1.5mm	$1.9 keV < h\nu < 6.1 keV$	44.0 ± 1.0

4.4.- *Two 7.5 μ m Tungsten Wires Results*

In this section, experimental observations and results of two 7.5 μ m tungsten wires for 0.3, 0.6, and 1.5 mm separations will be presented. Comparisons of dynamical behaviours with the aluminium pinch will enable us to establish differences and similarities between the wire materials.

4.4.1.- *Optical Probing Observations*

Face-on and side-on schlieren photographs for 0.3, 0.6 and 1.5mm, were taken with the same experimental conditions as for aluminium. Experimental observations for the three wire separations are presented below.

4.4.1.1.-*Initial Wire Separation: 0.3 mm*

Figure 4.25 shows a sequence of simultaneous face-on and side-on schlieren photographs taken at different laser times during different current discharges. The coronal wire plasma and the central plasma formation were observed 35ns after current start. Like aluminium wires, the axial correlation of coronal instabilities in both directions (face-on and side-on) was observed at 68ns. This indicates the existence of a global magnetic field that correlates the coronal instabilities of both wires. Comparison of face-on and side-on photographs at this time shows that the central plasma column is in the midway between the wires. The external coronal plasma shows shorter instability wavelengths along the pinch compared with the aluminium case (see Section 4.3.1.1). At 90ns, the face-on photograph shows that the laser cannot pass through the central region. There was shot-to-shot variation in instability wavelengths. The irreproducible behaviour of tungsten pinch was also observed in single wire experiment (see Section 3.3.4). Therefore, it was difficult to obtain a change in instability wavelengths with time as done for aluminium pinches (see Fig. 4.13). Figure 4.26, shows the above-explained behaviour of wavelength vs. time.

It is interesting to note that the correlation of corona instabilities has a time delay of 50ns compared with 0.3mm separation aluminium (see Section 4.3.1.1).

Fig. 4.27 shows the expansion velocities of coronal and core plasma in face-on and side-on directions. The ratio of side-on to face-on coronal expansion shows a

value of 1.4 compared with 1.5 for aluminium wires, (see Table 4.II). This indicates that the ratio of expansion for 0.3mm separation is independent of wire material.

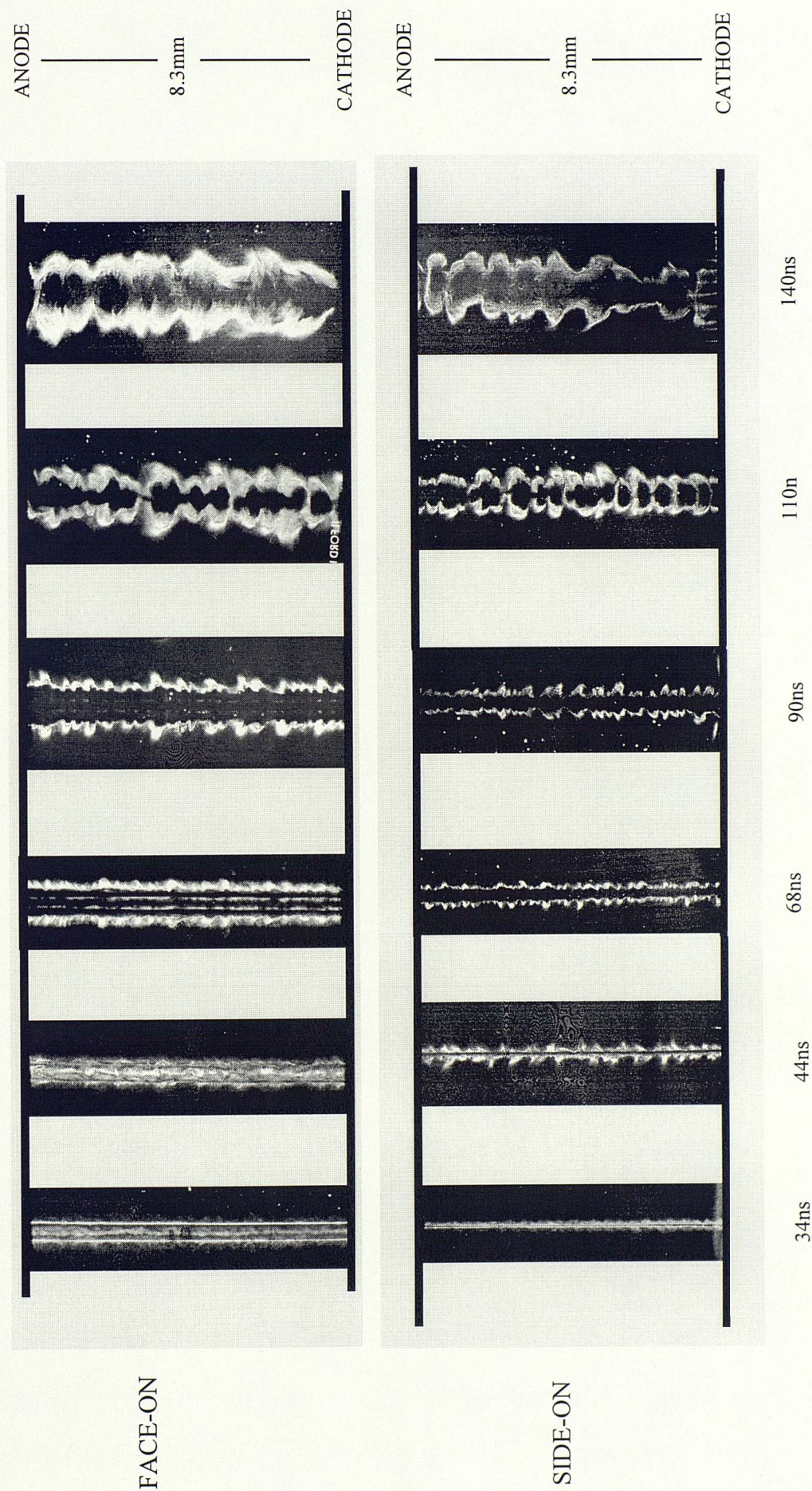


Figure 4.25. Simultaneous face-on and side-on schlieren photographs of two parallel 7.5 μm tungsten wires separated by 0.3mm

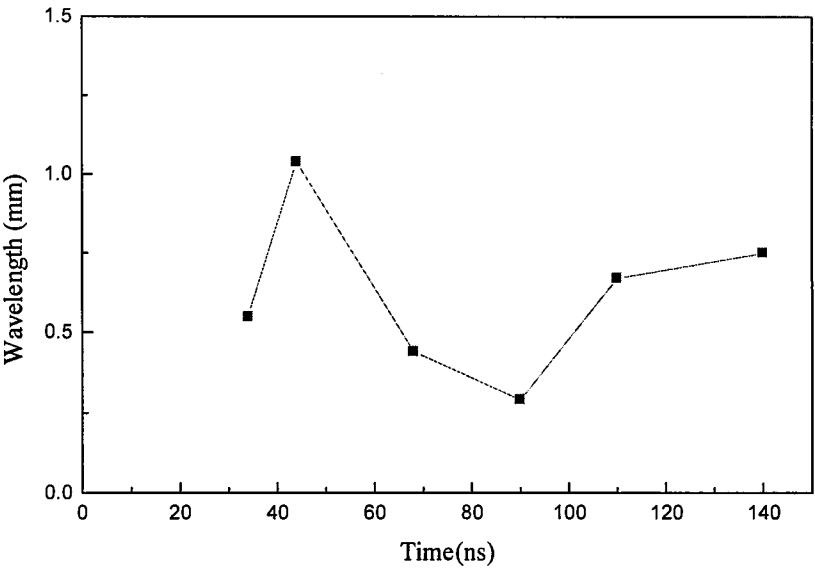


Figure 4.26. Instability Wavelengths vs. time for 0.3 mm separation.

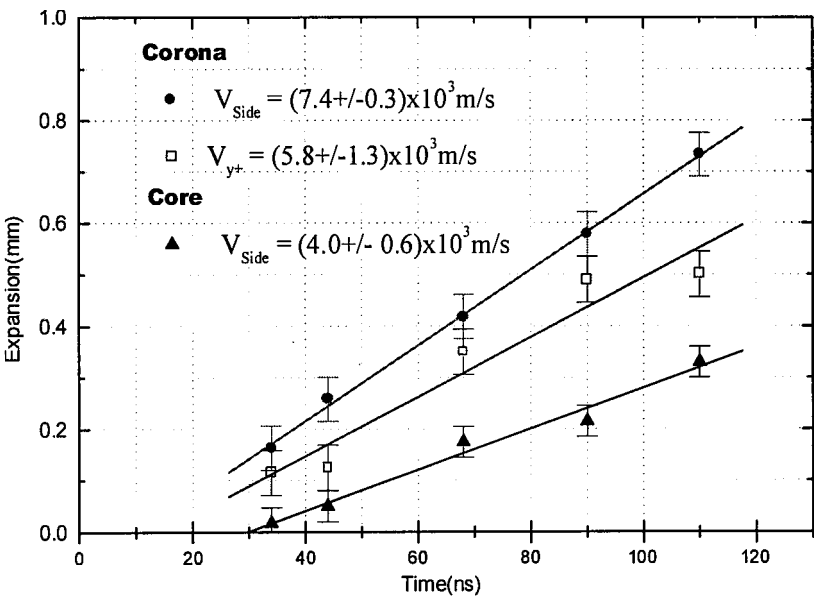


Figure 4.27. Face-on and side-on expansion velocities for 0.3 mm separation.

4.4.1.2.- *Initial Wire Separation: 0.6 mm*

Figure 4.28, shows a sequence of simultaneous face-on and side-on schlieren photographs for 0.6mm separation. The central plasma was seen at 35ns, this becomes very unstable at 56ns. The correlation of corona instabilities was observed at 82ns. In addition, at that time, the laser could not pass through the central column. This characteristic was observed for 0.3mm separation and also in the aluminium pinch.

Like the 0.3mm separation, there was shot-to-shot variation in instability wavelength. The formation of density islands was observed at 138ns. The pinch behaviour was very similar to 0.3mm separation tungsten.

Figure 4.29 shows the expansion velocities of coronal and core plasma. In contrast to the aluminium pinch, the corona expansions in side-on and face-on directions show very similar velocities. For this tungsten wire separation, the ratio of coronal expansion velocity side-on to face-on was 1.1 (see Table 4.I), which indicates a high symmetry in coronal expansion. However, for 0.6mm separation aluminium, we observed a ratio of 2.1.

Comparison of side-on coronal expansion with single tungsten wire expansion shows that the single wire expands at least 2.2 times faster. This shows that the magnetic field configuration of two-wire z-pinch strongly affects the coronal plasma expansion in an asymmetric way. This is because the coronal plasma on one wire is affected both by its self-magnetic field and by the magnetic field of the other wire. This creates stronger and weaker regions in the configuration of magnetic field lines (see Fig. 4.1).

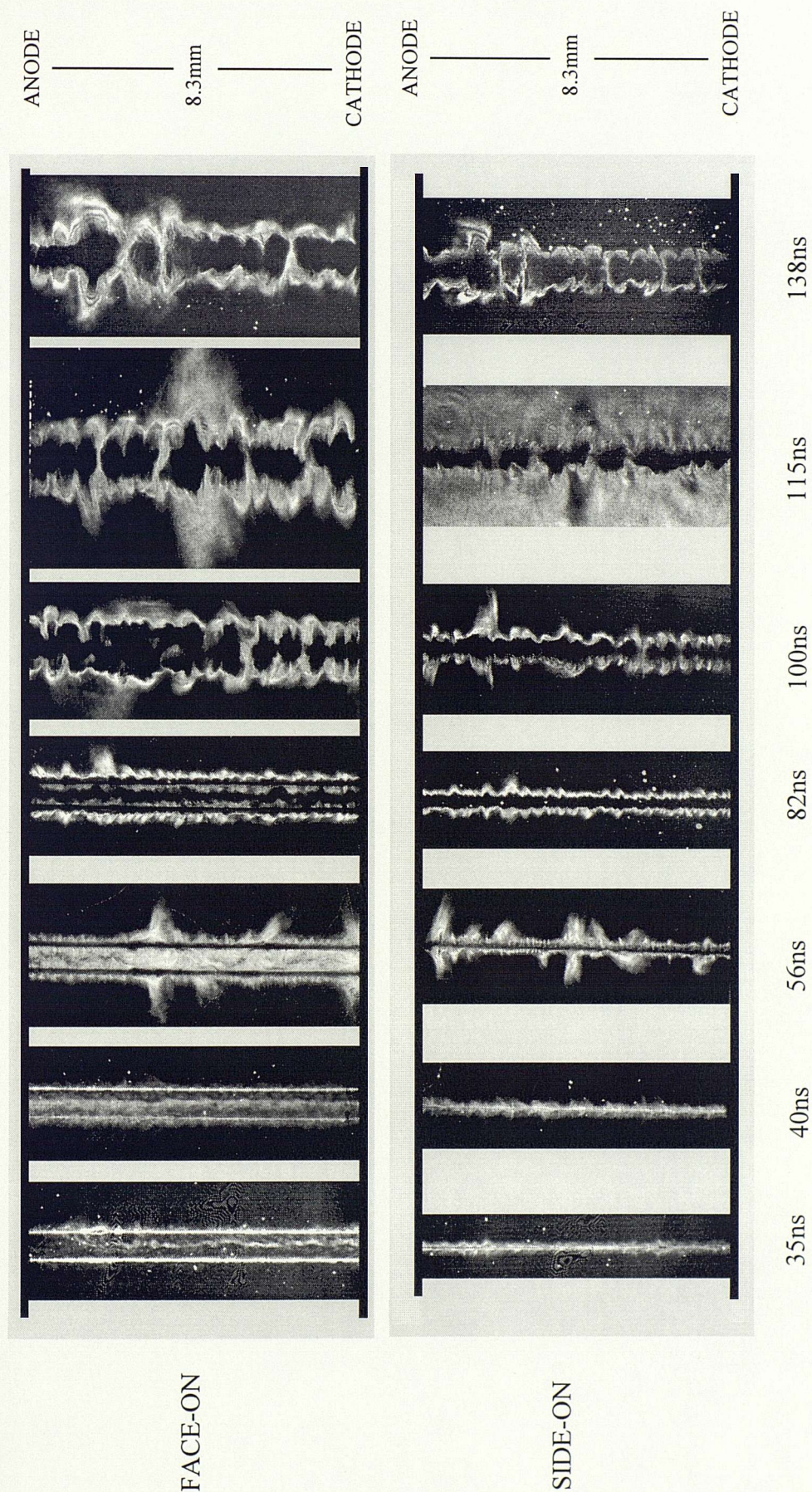


Figure 4.28. Simultaneous face-on and side-on schlieren photographs of two parallel $7.5\text{ }\mu\text{m}$ tungsten wires separated by 0.6mm

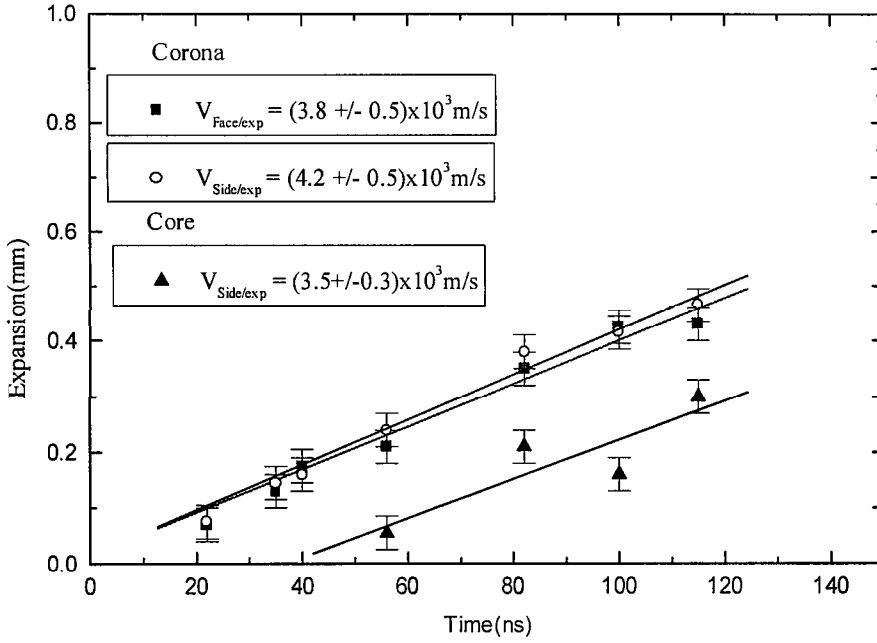


Figure 4.29. Face-on and side-on expansion velocities for 0.6 mm separation.

4.4.1.3.- Initial Wire Separation: 1.5 mm

Figure 4.30 and 4.31 show a sequence of simultaneous face-on and side-on schlieren photographs for 1.5mm separation. The central plasma column was formed at 70ns after current start. By contrast, for 1.5mm-separation aluminium, the central plasma was observed 30ns after current start.

Unlike aluminium wires, there is no correlation of instabilities until 70ns. Due to the large wire separation, it was possible to observe different phases of pinch evolution. Firstly, for $t < 70\text{ns}$, each wire showed a corona expansion without any correlation of instability growth rates. Some bubbles were observed along the core in both wires. These were produced by impurities in the wire surface from the manufacturing process of tungsten wires. Normally the tungsten wires must be heated to relieve these contaminants from its surface. These bubbles were reported from z-pinch experiments at Sandia and Cornell University [4.13]. This coincidence arises because the same wire manufacturer is used in all three different experiments.

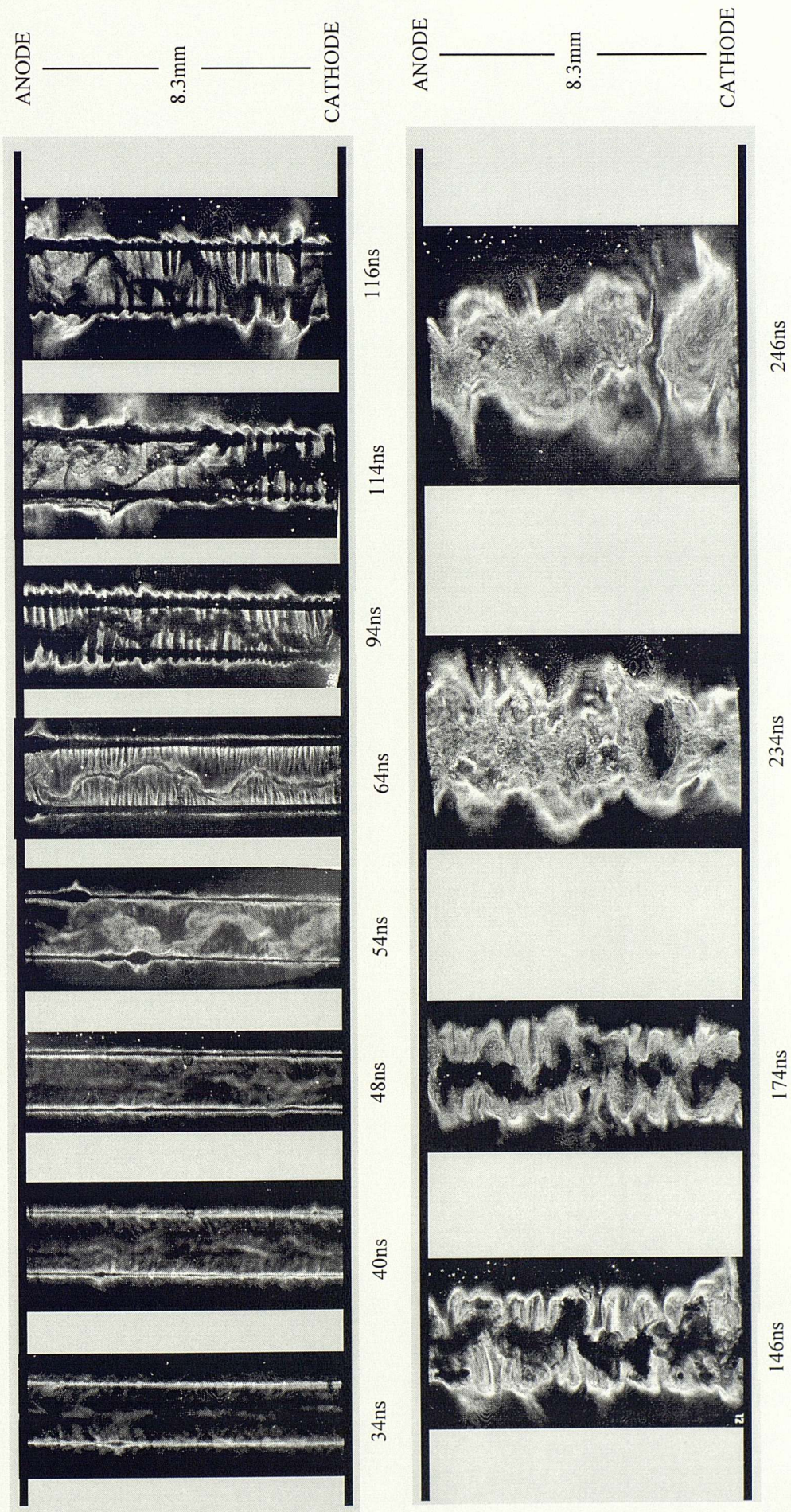


Figure 4.30. Face-on schlieren photographs of two parallel 7.5 μm tungsten wires separated by 1.5mm

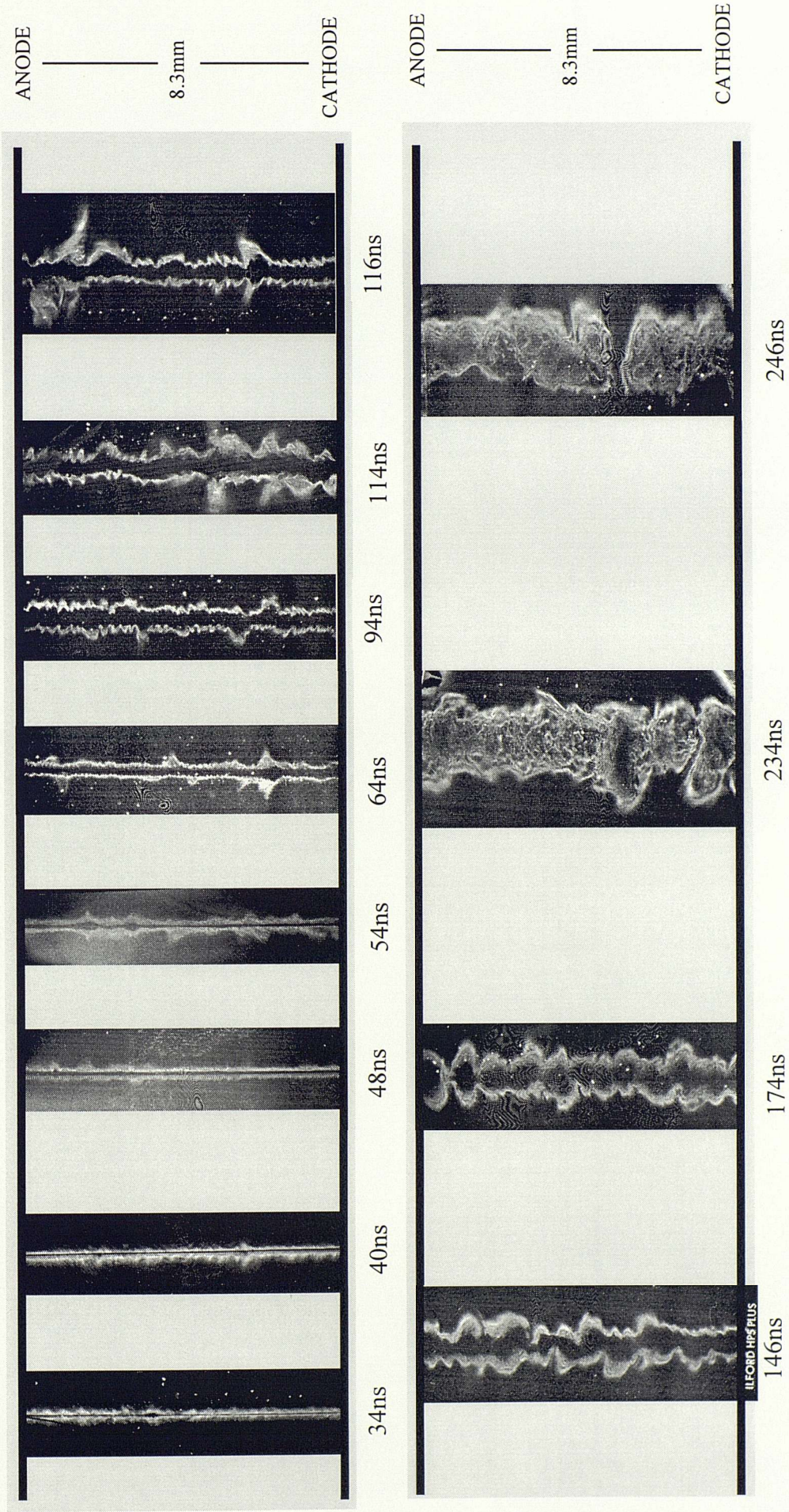


Figure 4.31. Side-on schlieren photographs of two parallel 7.5 μm tungsten wires separated by 1.5mm

The second phase (70ns – 120ns) was characterised by plasma streamers from both wires toward the axis, modulated by the instabilities on the wires. Different schlieren photographs taken in this time show that the wavelength of external coronal instabilities and streamer separation (along the axis) has the same magnitude. These plasma streamers are produced by the $\mathbf{J} \times \mathbf{B}$ force that drives the $m = 0$ -MHD instability, modulating either corona and core plasma towards the axis. It is important to mention that these plasma streamers were not observed both for other separations with tungsten wire and for two aluminium wire pinches. Furthermore, wire array experiments performed in MAGPIE [4.14] with 64 wire and wire separation of 1.5mm, showed experimental evidence that these plasma streamers are indeed produced by the $\mathbf{J} \times \mathbf{B}$ force.

In the third phase (145ns-175ns), the wire material is centred on the axis. During this phase, most of the core-wire material has been injected towards the central region. A completely unstable dense central-plasma was observed in this region.

Finally for $t > 235$ ns, the core plasma in the central region starts to expand, showing a $m = 1$ MHD instability. The simultaneous side-on photographs show that this MHD instability is contained mainly in the plane between wires (see Fig. 4.1).

Figure 4.32 shows the expansion velocities of coronal plasma in side-on and face-on directions for this wire separation. The ratio side-on to face-on of expansion velocities was 2.8, which can be interpreted as a low azimuthal symmetry of the coronal expansion.

Table 4.VII, gives the expansion velocities of core and coronal plasma for the three different wire separations of tungsten wire.

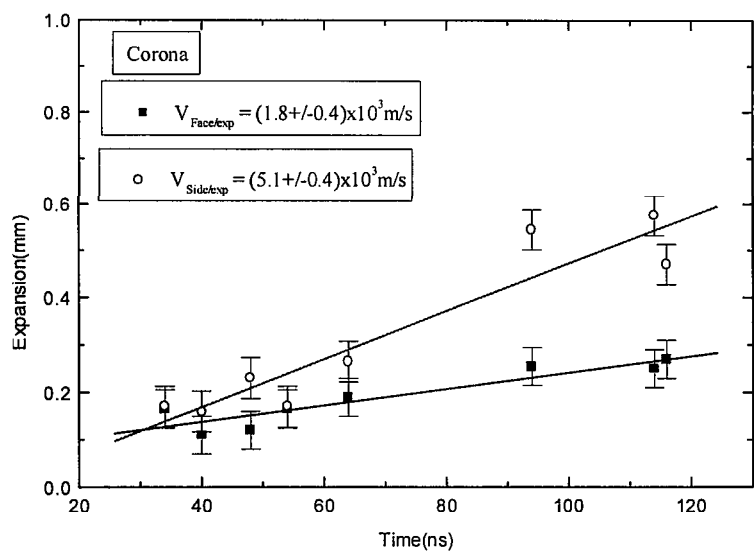


Figure 4.32. Face-on and side-on expansion velocities for 1.5 mm separation.

Table 4.VII. Coronal and core expansion velocities from schlieren photographs

Coronal Plasma						
Material	300μm separation		600μm separation		1.5mm separation	
	Face-on $\times 10^3 \text{ m/s}$	Side-on $\times 10^3 \text{ m/s}$	Face-on $\times 10^3 \text{ m/s}$	Side-on $\times 10^3 \text{ m/s}$	Face-on $\times 10^3 \text{ m/s}$	Side-on $\times 10^3 \text{ m/s}$
7.5μm Tungsten	6.4	8.9	3.8	4.2	1.8	5.1
	Core Plasma					
	-	5.0	-	3.5	-	3.0

4.4.2.- *Optical Emission Observations*

The optical emission from the tungsten pinch was observed simultaneously with an optical gated framing camera and an optical streak camera in radial mode. In general, the tungsten pinch showed a different behaviour compared with aluminium one. The central plasma was formed later, at 30, 35, 70 ns after the current start, for the three different separations (0.3, 0.6, and 1.5 mm) respectively. Results from both optical diagnostics are presented below:

4.4.2.1.- *Optical Framing Images*

4.4.2.1.1.- *Initial Separation: 0.3mm*

Figure 4.33 shows framing images for 0.3mm separation taken in the face-on direction. The optical emission from wires was detected after 20ns. At 35ns, the central plasma column was formed. Unlike the aluminium pinch, the central column showed a $m = 1$ MHD unstable structure and it was possible to distinguish emissions from wires and central column. At 45ns, the optical emission became brighter in the central region and there is a correlation of instability in both wires. At 75ns, a brighter column from accumulation of wire material was seen near to the axis. This material accumulation became more efficient compared with the 0.3mm separation aluminium pinch, resulting in a smaller diameter compared to the initial wire separation. For example, at 80 ns (near to the peak current), a column with a diameter of $200\mu m$ was observed with a duration of 5ns. By contrast, in the aluminium pinch, the plasma column increased in diameter like a thick wire before the density islands were formed. An expansion velocity of core plasma of $V_{core} = 2.5 \times 10^3 m/s$ was calculated from framing images. Comparison with core expansion velocity by schlieren photography shows that the expansion of the core from optical images is 19% less.

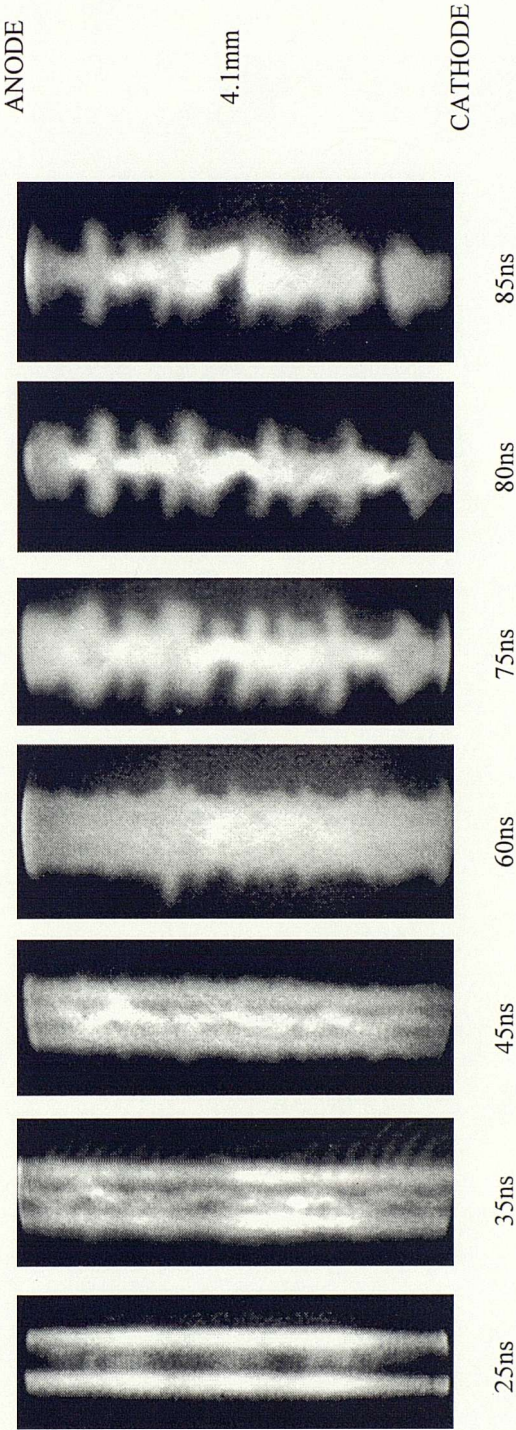


Figure 4.33. Framing images of two 7.5 μ m tungsten wire separated by 0.3 mm taken in face-on direction

4.4.2.1.2.- *Initial Separation: 0.6mm*

Figure 4.34 shows a series of optical images for 0.6mm separation. In contrast to the aluminium pinch, it was not possible to observe $m = 0$ and $m = 1$ MHD instabilities simultaneously. The plasma column did not show a regular structure of instabilities as observed for aluminium. The optical emission from individual wires is initially brighter than central plasma. After 35ns, emission from the central plasma becomes brighter.

As in 0.6mm separation aluminium pinch, the density islands were formed from a thick plasma column.

4.4.2.1.2.- *Initial Separation: 1.5mm*

Figure 4.35 shows four framing sequences from different shots which represent a full evolution of the tungsten pinch for 1.5mm separation. This evolution is summarised by four phases mentioned previously in Section 4.4.1.3:

1) **Wire emission** (20ns – 35ns), at early time, the emission from the wires is very uniform, without any instability formation.

2) **Flares of wire material toward the axis** (45ns – 60ns); the second set of framing images show flares from both wires injecting wire material towards the interwire region. This injection was not correlated axially; each wire shows a different flare structure. It is important to point out that these flares were not observed either for other tungsten separations or for aluminium pinches.

3) **Formation of central plasma column and plasma streamers** (70ns – 85ns); the first and second frame of the third set determine that the plasma streamers are formed at 70ns after current start.

4) **Accumulation of wire material around the two-wire axis** (105ns – 120ns); as a consequence of material injection by the streamers, a plasma column with a diameter of about $500\mu\text{m}$ was observed.

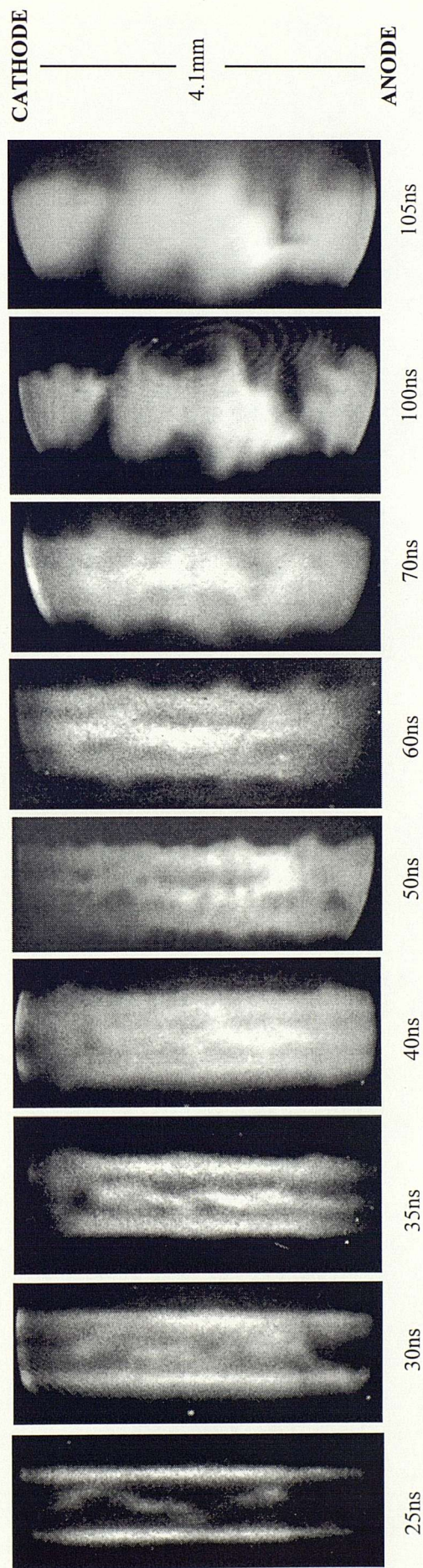


Figure 4.34. Framing images of two 7.5 μ m tungsten wire separated by 0.6 mm taken in face-on direction

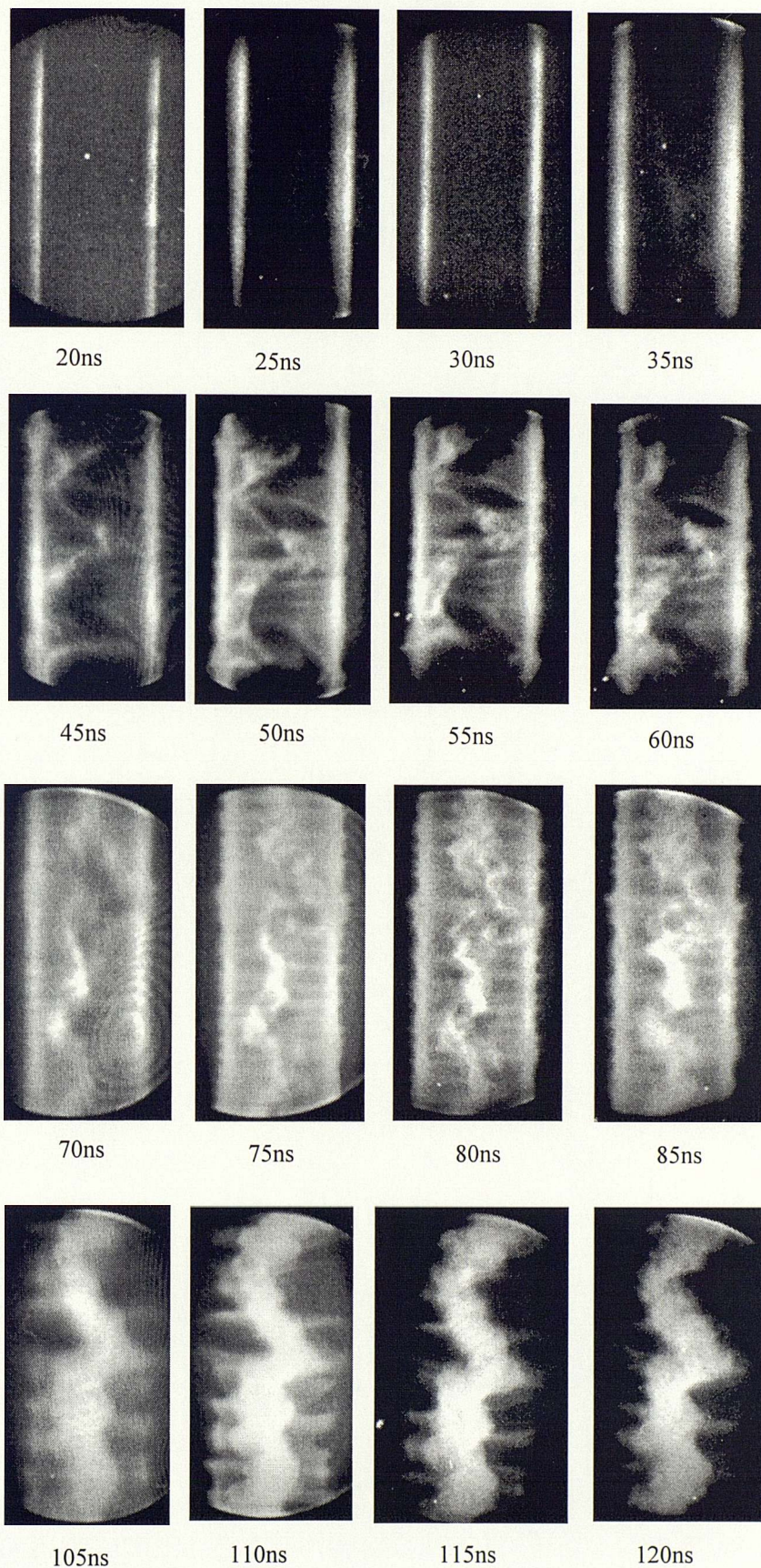


Figure 4.35. Framing images of two 7.5μm tungsten wire separated by 1.5 mm taken in face-on direction

4.4.2.2.- *Optical Streak Camera Observations*

The tungsten pinch showed both a low rate of external coronal expansion (compared with the aluminium pinch) and a longer pinch duration. A streak speed of 7.5 ns/mm with a $300 \mu\text{m}$ slit gave a time resolution of 2.5 ns. A magnification of plasma image of 6.5x was used, giving a spatial resolution of $15 \mu\text{m}$.

Figure 4.36 shows optical streak photographs of two $7.5 \mu\text{m}$ tungsten wires for different separations. For 0.3mm separation (see Fig. 4.36.a), the emission from each wire was observed initially up to 30ns. After that time, the emission from the interwire region became brighter, in agreement with observations of the central plasma formation by the GOI camera. The plasma column does not expand even later in time, evidencing the existence of the $\mathbf{J} \times \mathbf{B}$ force. For 0.6mm separation (see Fig. 4.36.b), the pinch shows a dense region with a diameter of about the wire separation. As with 0.3mm separation, this column did not expand much, showing a constant diameter for about 200ns. For 1.5mm separation (see Fig. 4.36.c), the emission is only from individual wires initially. A central plasma emission was evident at 70ns. The pinch did not expand larger than wire separation. At 240ns, implosion of the plasma column was seen. This observation is in agreement with previous schlieren photograph and GOI images for 1.5mm separation tungsten wires.

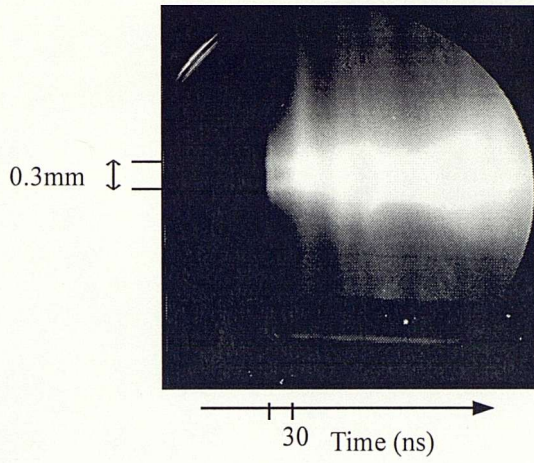


Fig. 4.36.a
Wire separation: *0.3mm*

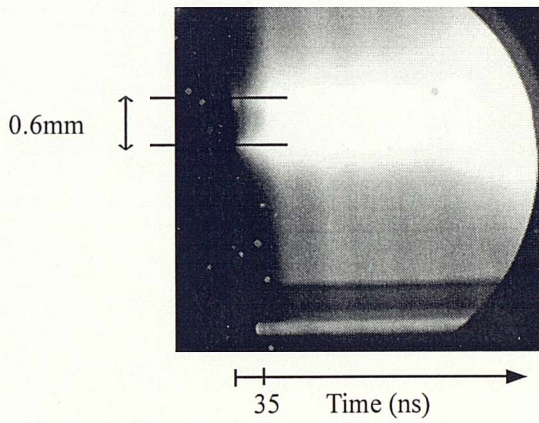


Fig. 4.36.b
Wire separation: *0.6mm*

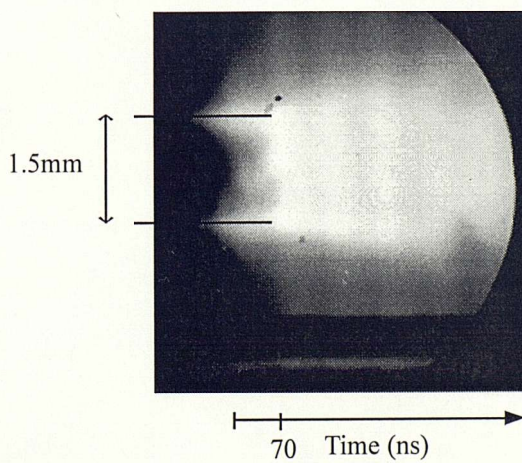


Fig. 4.36.c
Wire separation: *1.5mm*

Figure 4.36. Optical streak photographs of two $7.5\mu\text{m}$ tungsten wire for different wire separations.
Streak speed: 7.5ns/mm .

4.4.3.- X-Ray Emission Observations

A filtered time integrated pinhole camera and a PIN diode monitored the x-ray emission from the pinch. These diagnostics were used simultaneously to obtain time and space resolved information. Table 4VIII shows filters and pinhole apertures used for tungsten pinch.

4.4.3.1.- Time Integrated Pinhole Camera

Figure 4.37 shows time integrated x-ray pinhole photographs for three different separations. Fig. 4.37.a shows emission for 0.3 mm separation. Image 1 was filtered with 1.5 μm aluminised Mylar ($h\nu > 240\text{eV}$), bright spots are situated between the two wires and emission from some of them is very intense. Also a faint emission from the whole column can be seen. Image 2 was taken with a 300 μm pinhole size and filtered with a 25 μm Mg foil ($h\nu > 4.4\text{keV}$). This was faint. Image 3 is with a copper filter ($h\nu > 6\text{keV}$). Image 4 shows that emission in the 1-2keV range is intense from bright spots, and is also seen from individual wires.

X-ray images for 0.6mm separation show similar trend (see Fig. 4.37.b), but fewer bright spots were seen.

For 1.5mm separation (see Fig. 4.37.c), the x-ray emission in the soft x-ray range ($h\nu > 240\text{eV}$) (see image 1) is intense and does not allow are to distinguish between the central plasma and individual wires. For $h\nu > 4.4\text{keV}$ (image 2), intense emission from the central plasma may be seen, it has a $m = 1$ -MHD structure as seen in schlieren and optical framing images. Image 3, 4, 5, and 6 shows faint emission from individual wires. Interestingly, bright spots were not observed for 1.5mm separation.

Table 4.VIII. Pinhole diameters and filters used in the x-ray pinhole camera.

Pinhole size/ Filter & Thickness	cut-off Energy
1: 50 μm /1.5 μm aluminised Mylar	$h\nu > 240\text{eV}$
2: 300 μm / 25 μm Magnesium	$h\nu > 4.4\text{keV}$
3: 300 μm /10 μm copper	$h\nu > 6\text{keV}$
4: 200 μm /20 μm Aluminium	$h\nu > 5.0\text{keV}$
5: 200 μm /2 μm Aluminium	$h\nu > 880\text{eV}$
6: 200 μm /12 μm Beryllium+12 μm Mylar	$h\nu > 1.9\text{keV}$

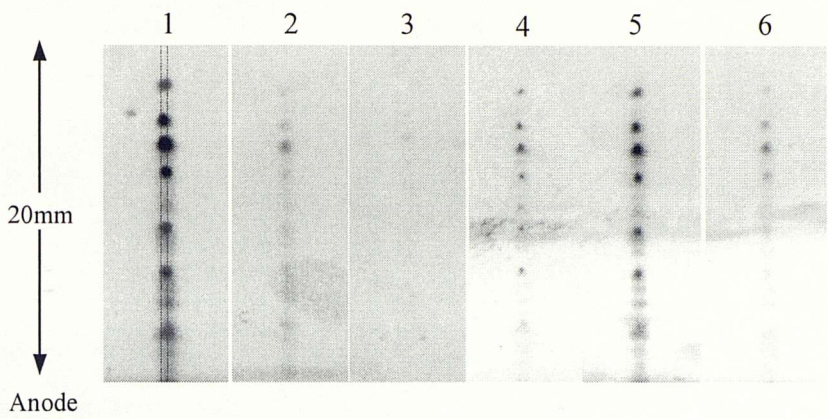


Fig. 4.37.a.
0.3mm separation

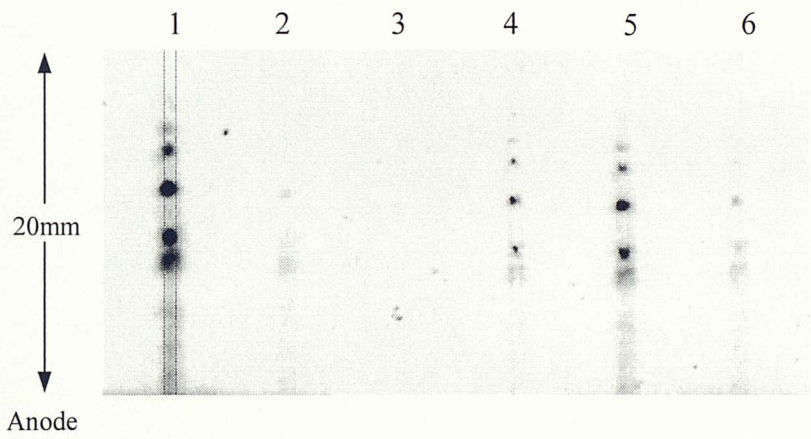


Fig. 4.37.b.
0.6mm separation

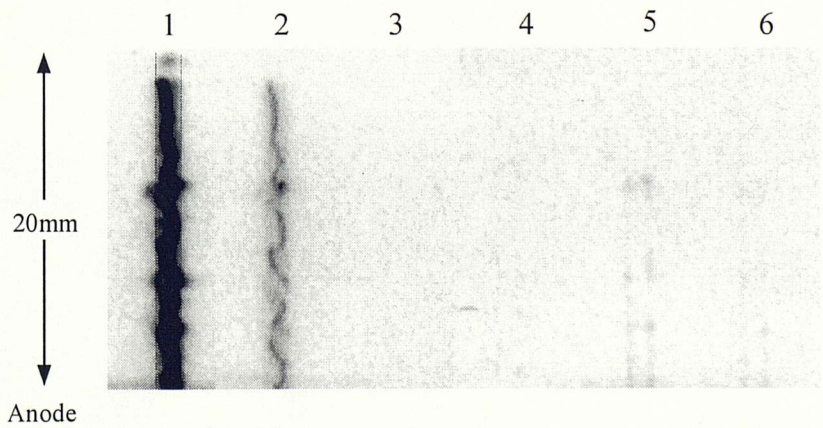


Fig. 4.37.c.
1.5mm separation

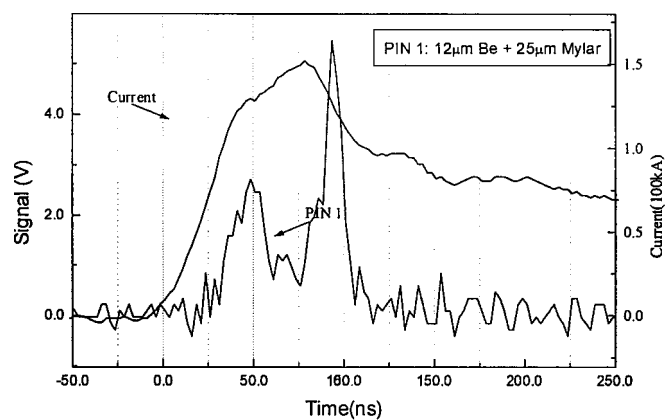
Figure 4.37. Time integrated X-ray pinhole photographs for different wire separations

4.4.3.2.- *PIN Diode Signals*

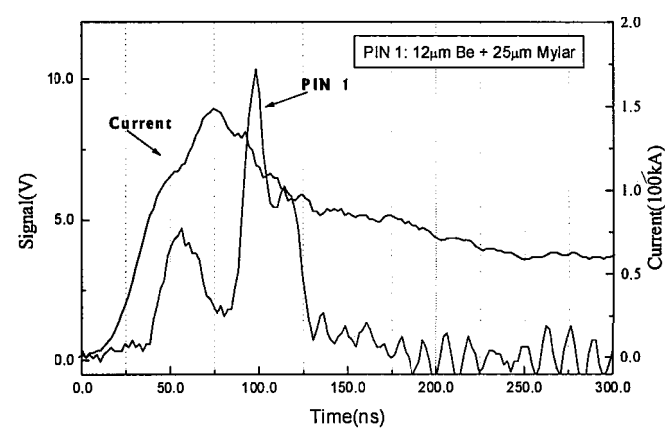
A filtered PIN diode ($h\nu > 2keV$) was used to obtain temporal information of x-ray emission. Fig. 4.38 shows the PIN diodes signals along with the current waveform for three different wire separations. These signals showed two x-ray peaks for all wire separations.

For 0.3 mm separation (see Fig. 4.38.a), the first peak was at 50 ns. This is due to the emission from individual wires. The second relatively higher peak was recorded at 90 ns, presumably from the central plasma column. Comparison of times of the second x-ray peak and framing optical images (see Fig. 4.33) shows that effectively at about 80 ns a large accumulation of wire material is located in the region between wires.

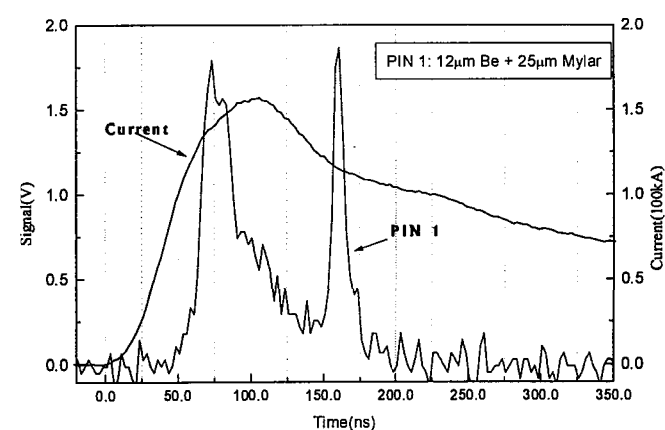
For 0.6 mm separation (see Fig. 4.38.b), the first peak was delayed by about 10 ns relative to the 0.3 mm separation. This was recorded at 60 ns, while the second intense peak occurs at 100 ns, presumably from bright spots and the central plasma. For 1.5 mm separation, the first peak occurs at 70 ns and the second peak was recorded much later than for other separations. It occurred at about 160 ns. It is interesting to note that the bright spots were not observed for the 1.5 mm separation (see Fig. 4.38.c). By contrast, a stronger x-ray emission from central plasma along the whole pinch was recorded. Schlieren photographs (see Fig. 4.30) and framing images (see Fig. 4.35) show for this wire separation the injection of wire material towards the axis by plasma streamers.



(a)



(b)



(c)

Figure 4.38. X – ray PIN diode signals for: (a) 03.mm, (b) 0.6mm and (c) 1.5mm separation.

Chapter 5

DISCUSSION AND CONCLUSIONS

The experimental results described in chapter three and four are discussed in this chapter and interpretations of some results are given. It is divided into two main discussion sections. Section 5.1 is about single wire results and section 5.2 about two-wire results.

These two different load configurations of z-pinches were chosen to simulate the initial conditions of wire explosion from cylindrical arrays driven by Z accelerator [5.1] and SATURN [5.2] at Sandia National Laboratories (SNL).

5.1.- Single Wire Z-Pinches

5.1.1.- Summary of Observations

Tungsten wires of various diameters were used and the results compared with 15 μm diameter aluminium wire. The expansion of the pinch is studied as a function of wire diameter and material. This information is relevant to understanding the behaviour of wire-array z-pinches, as proposed in the heuristic model by Haines [5.3]. The $m = 0$ perturbations appear at about 8 ns for the aluminium pinch compared with 20 ns for the tungsten one. The wavelength and diameter of the perturbations increase with time for both types of wires, but is relatively faster for the aluminium pinch. The short wavelength perturbations ($\sim 200 \mu\text{m}$) persist for a longer time for larger diameter tungsten wires. Bright spots are seen to appear after 60 ns from current start for tungsten wires, whereas for aluminium wires, bright spots appear after 40 ns. The decay time of bright spots is 40 ns for the smallest diameter tungsten wire compared with only a few nanoseconds for larger diameter wires. Hard x-ray emission above 6 keV was observed from tungsten wire pinches, but it was not observed from either bright spots or the plasma column for the aluminium pinch. However, hard x-ray emission from the anode due to an electron beam was observed for wires of both materials.

Expansion velocities obtained from radial streak photographs and optical probing agree well. The initial expansion velocities for different diameters of tungsten wires are similar, but aluminium expands by a factor of two faster than tungsten.

Schlieren observations show that the coronal plasma of tungsten wires of various diameters expands with the velocity of $(9.4 \pm 1.0) \times 10^3 \text{ m/s}$. Observations show that the expansion of the coronal plasma is independent of the wire diameter, but is dependent on the wire material. Furthermore, variations shot-to-shot were observed in the coronal structure for the different diameters of tungsten wires.

5.1.2.- *Comparison with Simulations*

Two-dimensional (r,z) resistive MHD simulations [5.4] for carbon fibres show that the expansion velocity is independent of the wire diameter. The early instabilities are the same for all wire sizes, but density islands depend on wire size.

J. Chittenden (private communication) has performed computer simulations for single $15\mu\text{m}$ aluminum wire with a length of 20mm. The 2D(r,z) resistive MHD code [5.4] was used with the addition of a modified Thomas-Fermi equation of state and dense plasma transport model [5.5] to allow the phase transitions from solid to plasma to be approximated.

The coronal and core expansions from the code can be compared directly to experimental results obtained by schlieren photography. The refraction angles between 1.3 mrad and 78 mrad (determined by the size of the stop and the f-number of the imaging lens) were used respectively as cut-off contours in the low-density corona and in the high-density plasma inside the core. These limits permit us to detect electron densities in the range $3.0 \times 10^{18} \leq \int \frac{dn_e}{dx} d\ell \leq 1.8 \times 10^{20} [\text{cm}^{-3}]$. Interestingly, it was possible to detect low-density coronal plasma at 8 ns after current start for aluminium wire, with a radial width of $110 \mu\text{m}$. This was $m = 0$ (MHD) unstable with a wavelength of $350 \mu\text{m}$.

The simulation and experimental results are compared in Fig. 5.1. The initial coronal expansion and then contraction is evident in the simulation. The delay with reference to current start, of the core expansion and instability development often referred as the “dwell time”, is reproduced in simulation and is associated with the self-pinching time of the corona. Both experiment and simulation show a rapid expansion of the coronal plasma during the first 17ns. After that time, the code predicts plasma compression of the low-density plasma, reaching a minimum radius

of $120\mu\text{m}$ at 24ns . Then, at this time, the high density region starts to expand (see Fig. 5.1).

The coronal plasma initially expands with a velocity of $V = 1.6 \times 10^4 \text{ m/s}$. After the pinching, this zone bounces and then expands with a velocity of $V = 1.7 \times 10^4 \text{ m/s}$, whilst the dense region expands with a velocity of $V = 1.1 \times 10^4 \text{ m/s}$. These values show close agreement with those predicted by the model. Like the model, there is an initial coronal expansion with a velocity of $V = 1.8 \times 10^4 \text{ m/s}$, and then compression takes place, reaching a minimum at 24ns . Then, the corona and the core expand with velocities of $V = 7.0 \times 10^3 \text{ m/s}$ and $V = 1.9 \times 10^4 \text{ m/s}$ respectively. The different coronal expansions may be because for the two-dimensional simulation the values are for the necks of the $m = 0$ instability, whereas the experimental data is for the bulges.

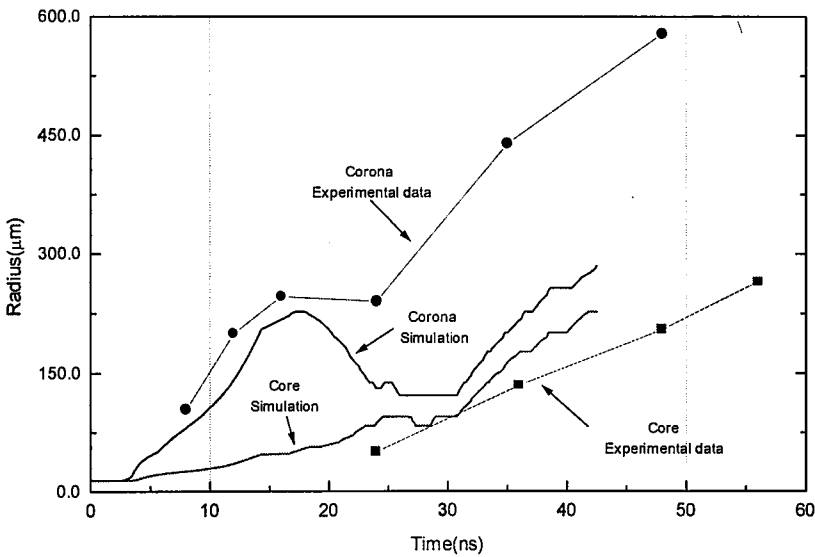


Figure 5.1. Comparison of radius vs. time from experimental and computer simulation data of corona and core plasma for $15\mu\text{m}$ aluminium wire.

Another simulation performed by Gene McCall [Los Alamos National Lab., private communication] using a one-dimensional Lagrangian code (RAVEN) also predicts a rapid coronal expansion early in time. According to McCall this expansion is due to heating by the skin current. However, when the magnetic pressure is greater than the kinetic pressure the corona plasma will be compressed. Results from this computer simulation code are shown in reference [5.6].

5.1.3.- *Comparison with previous experiments*

Comparisons of x-ray backlighter [5.7] and black-field schlieren observations show that due to the sharp plasma boundary both techniques can be used to diagnose its expansion velocity. However, black field schlieren enables observation of both boundaries between core region–coronal plasma and coronal plasma–vacuum at the same time. This feature makes schlieren photography a powerful technique, because one may obtain information about the coronal and core plasma simultaneously and at the same axial position.

According to Lindemuth [5.8], the $m = 0$ behaviour begins very early in the discharge at the outer radial boundary of the coronal plasma as a result of ablation from the cold central fibre. It is found that the wavelength and the amplitude of the perturbation increase with time relatively faster for aluminium than for tungsten pinches. The fast development of instabilities is presumably due to the higher temperature in the aluminium coronal plasma. For aluminium, after 40 ns , there is a long wavelength and large amplitude $m = 0$ instability in the coronal plasma, whilst in the core region this instability shows a short wavelength and small amplitude. Schlieren images show an expansion velocity of $(7.0 \pm 2.0) \times 10^3\text{ m/s}$ in the core region, in agreement with the value found by Kalantar and Hammer [5.7] using an x-ray backlighter. However, contrary to Kalantar and Hammer, the expansion of the coronal plasma starts early in the current compared with the core region. In their experiments a rapid expansion and compression of coronal plasma in the firsts 20ns of current discharge was observed. After that expansions both in the coronal and the core plasma were observed. The difference in results is probably due to the difference in sensitivity of the techniques used in the two experiments.

5.1.4.- *X-ray Emission and bright spots Formation*

X-ray diagnostics also show different characteristics for the tungsten z-pinch. X-ray emission from tungsten is hard ($h\nu > 6\text{ keV}$) from the plasma column, and the intensity of x-rays decreases with increasing wire diameter. The number of bright spots also decreases as the diameter of the wire is increased, and as the current is reduced. Bright spots appear later in the current rise (at 100ns). Schlieren (see Fig. 3.3) photographs and x-ray axial streak photographs (see Fig. 3.15a) show the formation density islands and bright spots for $5\mu\text{m}$ tungsten wire at 130ns. The

physics of bright spot formation has been discussed by Mosher and Colombant [5.9] for high atomic Z wire material. The mechanism of formation of bright spot is by the disruption of the unstable ($m = 0$) pinch column into density islands, which produces a high electric field between islands so that electrons and ions are accelerated in opposite direction in the gaps.

Hard x-rays were not observed either from the aluminium plasma column or the bright spots, but only those emitted from the anode were seen in both pinches. The intensity of the x-rays from the anode and the pinch was of the same brightness in tungsten, but for aluminium the intensity from the anode was comparatively lower than the pinch. PIN diode signals for tungsten wires showed two peaks, the first one corresponding to the emission in the soft x-ray range. The second peak appears at about 60 ns depending on the wire diameter and is coincident with the emission from the bright spots. For an aluminium pinch, PIN diode signals showed multiple peaks coincident with the bright spots in x-ray streak photographs.

5.1.5.- *Relevance to wire array results*

Observations show that single aluminium and tungsten wires behave differently as far as the initial expansion is concerned. The instability wavelength evolves faster for aluminium pinch, emitting x-rays in a lower energy range ($h\nu < 2\text{keV}$) than tungsten ($h\nu > 6\text{keV}$). However, using the same current rise time for different tungsten diameter wires, the expansion velocities are similar. The wire diameter plays a role later in the current, for example for $5\text{ }\mu\text{m}$ tungsten the pinch changes into density islands, but for larger diameter wires an inaccessible dense region persists long after current maximum. These observations indicate that these factors can play an important role in the physics of wire arrays at an early stage. Sanford *et al.* [5.10] conjecture from wire array results that a sharper x-rays pulse is obtained with a smaller diameter wire. When larger diameter wires are used to build the array, the x-ray pulse was broadened and the final diameter of the pinch was larger. On the other hand, according to the heuristic model [5.3], the broadening of the soft x-ray pulse when fewer larger diameter aluminium wires are used can be due to broadening of the shell at merger of the wires.

5.2.- *Two-Wire Z-Pinches*

5.2.1.- *Summary of the Observations*

A series of experiments on two-wire pinches were performed. The dynamics of the pinch was studied as a function of wire material (aluminium and tungsten) and separation (0.3, 0.6, and 1.5 mm). Initially the wires expand independently. The time of formation of central plasma column and correlation of coronal plasma instability (indicating the existence of a global magnetic field surrounding the wires) depends on wire material and separation. An asymmetric expansion of the coronal plasma was observed in the face-on direction (perpendicular to the wire plane), it being faster in the interwire region than in the external one. In the side-on direction (parallel to the wire plane) both expansions have the same magnitude. The central plasma column formed by accumulation of wire material became a current channel, conducting a large fraction of the total current. For a 1.5mm separation tungsten pinch, plasma streamers were observed from each wire towards the geometrical axis. These were modulated by the instability formed in the coronal plasma. Furthermore, it enabled a higher accumulation of material in the central plasma column. Implosion of the wire material, as predicted by theory, was not observed for aluminium at all. This can be explained by both the faster plasma expansion of 2.5×10^4 m/s (twice faster than for tungsten), and for the early formation (at 30ns) of the current channel. 2D simulations for both materials are only partially in agreement with the experimental observations. For example, it predicts wire implosion for both wire materials, but such implosions were not observed. The main reason why the simulation results do not agree with the experiments is, in fact, due to that the model used in it is not complete and does not include all the physics involved in the two-wire z pinch dynamics.

In the following section results from two-wire experiments for different wire materials and separations between wires are discussed. Also a discussion about the formation of the central current channel is presented. Comparison with early expansion dynamics of aluminium wire arrays driven by MAGPIE [5.11] generator is presented.

5.2.2.- Two-wire z-pinch dynamic

The dynamics of a two-wire pinch can be divided into three different phases, which depend on the current rise and the attraction effect produced by the $\mathbf{J} \times \mathbf{B}$ force generated between the wires.

Along with these phases, the two-wire z-pinch shows also topological changes in the magnetic field configuration. The duration of each phase is dependent on both the load characteristics (mass and separation) and the energy transferred from generator to the load. These phases are discussed in detail below

5.2.2.1.- Individual wire expansion

In this phase, each wire carrying a rising current behaves individually, where the growth rate and wavelength instabilities in the coronal plasma are not correlated. Initially the wires have a symmetrical expansion for both materials (aluminium and tungsten). Then the expansion starts to be asymmetric, being faster in the interwire region (y^- direction) compared with the external expansion (y^+ direction). In the x^- and x^+ directions, the expansions have the same magnitude. The coronal expansion velocities are such as $|v_{y-}| > |v_x| > |v_{y+}|$, see Fig. 5.2.

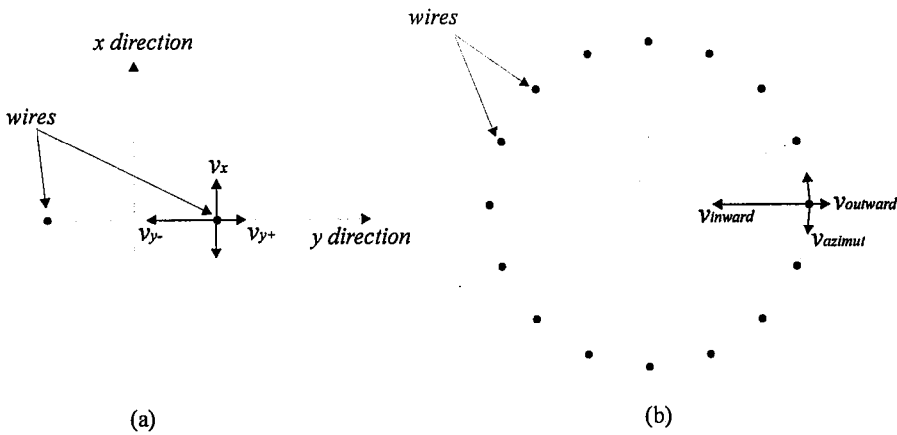


Figure 5.2. Velocity configurations of: (a) two-wire z-pinch and (b) wire array.

For 1.5mm separation aluminium wires, the velocities are: $v_{y-} = 2.5 \times 10^4 \text{ m/s}$, $v_x = 1.4 \times 10^4 \text{ m/s}$, and $v_{y+} = 6.3 \times 10^3 \text{ m/s}$ respectively.

A similar relationship between the velocities was observed in wire array experiments on MAGPIE generator [5.12]. The expansion velocities of the coronal plasma in inward and outward radial directions were $v_{inward} = 3.2 \times 10^4 \text{ m/s}$ and $v_{outward} = 2.0 \times 10^3 \text{ m/s}$, while in azimuthal direction, it was $v_{azim} = 1.3 \times 10^4 \text{ m/s}$. It is important to note that for a wire array, the velocities have the same relation as for a two-wire configuration as shown by Fig. 5.2.

5.2.2.2.- *Central Plasma Column Formation*

The second phase is related to the formation of the central plasma by accumulation of wire material in the interwire region. This formation was observed for both wire materials and for all separations. The time of appearance of the central plasma depends on wire separation and wire material as was described in experimental result section.

Optical framing images for aluminium and tungsten wires show that the central plasma emission is brighter than wire emission. The time-integrated pinhole photographs also show that the bright spots are formed in the central plasma before current maximum.

These experimental observations show that this plasma column is $m = 1$ MHD unstable. Simultaneous side-on and face-on schlieren photographs show that this instability is contained in the plane between wires. The structure of this central column does not change too much (during the discharge) after it had been formed. However, it was different shot to shot for both wire materials and for all separations.

A compressional z-pinch experiment performed at Imperial College by Choi *et al.* [5.13] conjectured that the $m = 1$ MHD instability formed on the axis is due to a peak density distribution on the pinch during the discharge. Although this conjecture was made for a different z-pinch configuration, we suppose that for a two-wire z-pinch the instability formation is caused by the transfer of current to the central plasma column, which has a peak density on the geometrical axis produced by the injection of material from wires. This process of current channel formation has been investigated by other authors [5.14, 5.15 and 5.16]; however they do not give a satisfactory explanation about how the channel is formed.

5.2.2.3.- *Global magnetic field Formation*

This phase introduces a correlation of the growth rates and wavelengths of the coronal plasma instabilities for both wires. Simultaneous face-on and side-on schlieren photographs, taken at different laser time, enabled determination of the expansion velocities in the core and corona plasma. Two different expansion velocities of the external coronal plasma were observed, it being faster in the x direction compared to the y direction, see Fig. 5.2.

Simultaneous with the external correlation of $m = 0$ -MHD mode in the coronal plasma instability, the face-on schlieren photographs showed a $m = 1$ -MHD mode in the central plasma column. This is in agreement with previous observations of two-wire z-pinch experiments using a time-integrated x-ray pinhole camera [5.17, 5.18].

In contrast to previous two-wire experiments which conjectured that this column has a single helix-like behaviour [5.19], simultaneous side-on and face-on schlieren photographs enabled us to observe that these instabilities are contained in the plane between wires. The perpendicular schlieren frames gave us a 3-D view of the pinch. By contrast, the conjecture of reference [5.19] was supported by observation in the face-on direction only.

5.2.3.-*Difference between Aluminium and Tungsten two-wire z-pinches*

Comparison of optical framing images of aluminium and tungsten wires for 1.5mm separation shows a time difference of 40ns in the formation of central plasma column (see Figs. 4.18 and 4.35). The two wire materials have different formation processes for this plasma column.

For aluminium, it was possible to distinguish the emission from wires and central plasma column at 30ns after current start for 1.5mm separation. Optical images did not show emission from the gap between wires and central column, see Fig. 5.3. It may be that the camera sensitivity did not permit detection in those regions. However, for tungsten pinch, the central plasma column is formed later at 70ns. It was possible to observe clearly the emission from the wires and how this material starts to accumulate in the interwire region at 45ns, before formation of the central plasma as is shown in Fig. 5.3. It is important to note that the $\mathbf{J} \times \mathbf{B}$ force moves wire material toward the axis without any correlation between the two wires.

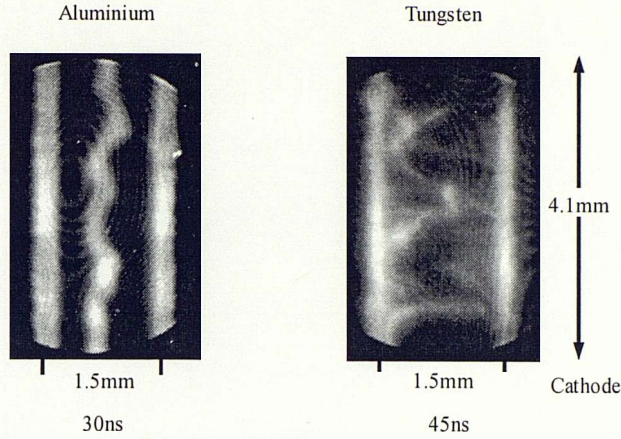


Figure 5.3. Comparison of optical framing images of two-wire for 1.5mm separation.

Another important difference in the pinch dynamics of a two-wire z-pinch for these materials was the plasma streamers, which were observed only for the 1.5mm separation tungsten pinch (see Fig. 4.30). These plasma streamers were formed as a consequence of the time delay in the formation of the current channel between the wires. This delay permitted the current in each wire to rise until the $\mathbf{J} \times \mathbf{B}$ force (between wires) was sufficiently intense to attract wire material toward the axis. The plasma streamers were modulated by the coronal plasma instability of the wires. That means, the separation between plasma streamers along the pinch and the wavelength of $m = 0$ MHD instability in core and coronal wire plasma are correlated. This is interpreted as follows: the $m = 0$ MHD instabilities on the wires are the seed of the streamer formations. Correlation of MHD instabilities in both wires results in a correlation of plasma streamers from both wires as well. This observation for two-wires (the simplest wire-array configuration) can be related to wire array observation by Deeney [5.20], who state that the initial perturbation that seeds the Rayleigh-Taylor instability in a z-pinch is produced by the individual wires that form the array.

5.2.4.- *Calculation of wire implosion*

Figure 5.4 shows the magnetic field lines and force directions of a two-wire z-pinch configuration, which corresponds to a magnetic quadrupole. In order to determine the implosion time of the wires onto the axis, by the action of the attraction force between wires, we just have to consider the $\mathbf{J} \times \mathbf{B}$ force assuming that the wires are very thin.

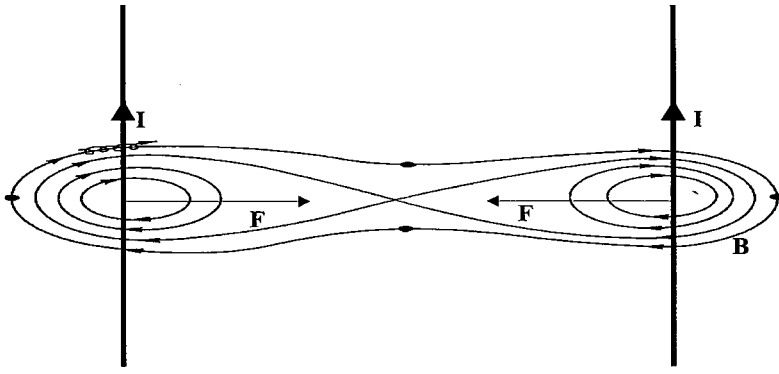


Figure 5.4. Attraction force between two parallel wires carrying current I .

The equation of motion is given by Eq. 5.1, where m is the wire mass per unit length, r is the separation between wires and I is the total current.

$$m \frac{d^2 r}{dt^2} = - \frac{\mu_0 I^2}{8\pi r} \quad 5.1$$

This can be rewritten in terms of dimensionless variables (x, τ) as follows:

$$\frac{d^2 x}{d\tau^2} = -A \frac{i^2}{x} \quad 5.2$$

where $x = r/r_i$; $\tau = \frac{2Z_0 t}{\mu_0 l / 2\pi}$; $i = (Z_0 / V_0)I$ and $A = \left(\frac{l}{16}\right) \left(\frac{\mu_0}{2\pi}\right)^3 \frac{V_0^2 l^2}{Z_0^4 r_i^2} \frac{1}{m}$.

Where r_i represents the three different wire separations (0.3, 0.6, and 1.5mm), l is the wire length ($l = 20\text{mm}$), Z_0 is the line impedance of the generator ($Z = 4\Omega$) and V_0 is the voltage across the pinch ($V_0 = 550\text{kV}$). It is important to point out that the current waveform used in this calculation corresponds with an experimental trace monitored with the Rogowski coil.

Substituting parameters related with the load (mass and wire separation) and the generator (line impedance, voltage) we can get a numerical solution of Eq. 5.2. Table 5.I shows the implosion time and inductance of two $15\mu\text{m}$ aluminium and $7.5\mu\text{m}$ tungsten wires for different wire separations.

Table 5.I. Implosion time and inductance of a two-wire z-pinch for different wire separations.

Load	Separation (mm)	Inductance (nH)	Implosion Time (ns)
<i>Two 15μm aluminium</i>	0.3	34.0	20
	0.6	32.6	40
	1.5	30.8	110
<i>Two 7.5μm tungsten</i>	0.3	35.4	28
	0.6	34.0	55
	1.5	32.2	138

These numerical results predict that the attraction force between the wires is enough to produce an implosion of the wires on the axis. However, experimental observations show that the pinch implosion is diminished by the formation of the current channel midway between the wires, which takes a large fraction of the total current.

For aluminium, the implosion was not observed at all. This was probably due to the fact that the MHD instabilities in the wires and the central column develop faster than for tungsten. Moreover, the expansion velocities for aluminium are two or more times faster than with tungsten.

However, for a tungsten pinch, a prominent accumulation of wire material was observed around the geometrical axis. For 1.5mm separation, as is shown in Fig. 4.35, the optical emission from the core-wire was not observed longer after 120ns. A $m = 1$ unstable plasma column of thickness $650\mu\text{m}$ exists in the interwire region for about 30 ns.

Interestingly, face-on schlieren photographs taken later in time, at 234ns and 246ns, (see Fig. 4.30 and 4.31) show a final low-density $m = 1$ unstable column with wavelengths of $\lambda = 2.2\text{mm}$ and $\lambda = 4.1\text{mm}$ respectively. However, the simultaneous photographs taken side-on did not show such a MHD structure. It is important to mention that these instabilities were only observed in the face-on direction. It tells us that the instabilities develop mainly in the y direction. This is in agreement with Felber and Roskoter [5.21], who presented a study about the oscillation modes and instabilities of cylindrical wire arrays with a small number of wires. They found that

there exist two types of modes: medial modes (contained in the r - z plane), and lateral modes with only azimuthal deformation. Recently, Hammer and Ryutov [5.22] presented a similar study for cylindrical wire arrays with a larger number of wires compared to Felber and Roskoter.

Figure 5.5 shows optical framing images of 0.3mm separation tungsten and aluminium pinches. The tungsten pinch shows a greater material accumulation on the axis (at the midway between wires), while aluminium behaves as a thick single wire. The external global magnetic field and the current channel formation enable the remaining wire material, located at the initial wire position, to be injected into the interwire region. By contrast, this material injection was not seen for any aluminium pinch.

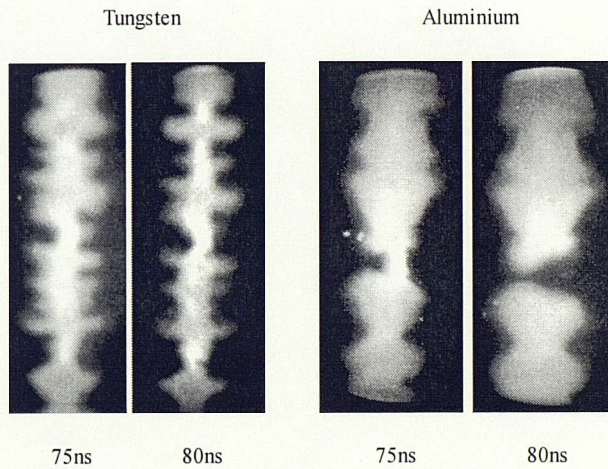


Figure 5.5. Comparison of axial framing images of the z-pinch plasma for aluminium and tungsten wires for 0.3mm separation.

In addition, comparison of filtered time-resolved x-ray PIN diode signals ($h\nu > 8\text{keV}$) of two aluminium wires for different separations (see Fig. 4.24) shows that for 0.3mm separation, the PIN diode signal (PIN 2) is small compared with the signals for other separations. This PIN diode signal looks like that for a thick single wire ($200\mu\text{m}$) z-pinch [5.23]. That means, that for a smaller separation (0.3mm) of aluminium wires there was evidence of the presence of a current channel early in the current discharge (at 15ns), which conducts a large fraction of the current.

5.2.5.- *Simulation of the dynamics of two-wire z-pinch*

Chittenden et al [5.24, 5.25], used a 3D resistive magneto-hydrodynamic code to model the two-wire experiments. This code was limited to two-dimensions (2D) in the x-y (or r- θ) plane. The code was evolved from an ideal MHD code used to model galactic jet formation [5.26].

The simulation was initialised with only 1% of the wire mass forming the corona plasma and the remaining 99% in the dense core. These initial conditions are based on 1D “cold start” calculations of individual wire explosions, which model the early stages of wire plasma ionisation and expansion. A computational grid of 60×60 $50 \mu\text{m}$ square cell is used. Figure 5.6 shows contour plots of electron density, electron temperature, current density, and magnetic field intensity at 10ns after the current discharge for 1.5mm separation aluminium wires. The energy necessary to evaporate the wires ($\Delta E = Q_{\text{boil}} + Q_{\text{melt}} + Q_{L,F} + Q_{L,E}$, where Q_{boil} is the boiling heat, Q_{melt} is the melting heat, $Q_{L,F}$ is heat latent of fusion and $Q_{L,E}$ is heat latent of evaporation) is 256 mJ for aluminium and 168 mJ for tungsten. The generator gives this amount of energy in the firsts 2 nanosecond of the discharge.

A series of plot of mass density, current, temperature and magnetic field lines of two $15 \mu\text{m}$ aluminium and two 7.5 mm tungsten wires for 1.5mm separation at 10ns, 20ns, 30ns, 50ns, 70ns, 90ns, and 110ns are shown in figures 5.6, 5.7, 5.8, 5.9, 5.10, 5.11, 5.12 respectively.

The initial independent coronal expansion (Fig. 5.6), at 10ns, is $2.5 \times 10^4 \text{ m/s}$, which is in agreement with the experiment value. The density of the surface region drops sufficiently due to ionisation. At 20ns (see Fig. 5.7), it is possible to observe the asymmetric expansion both for aluminium and tungsten. For aluminium, the current is mainly flowing through the internal coronal plasma. The central plasma is already formed, with the fully ionised material. The temperature of this central plasma is about 100eV. However, for tungsten the evolution is slower compared with aluminium at this time. The central plasma is not formed yet, but the coronal expansion is asymmetric. The current is flowing uniformly in each wire, and the temperature is higher in the internal region of the coronal plasma. A slight difference between either configuration is in the magnetic field distribution. For aluminium, due to the central current channel, the magnetic field is more elliptical, with a lower

intensity in the two-wire plane. But, for tungsten, the magnetic field has not changed too much compared with of 10ns.

At 30ns, the central plasma material is full ionised ($Z=13$), reaching an electron density of $1.1 \times 10^{21} \text{ cm}^{-3}$ (see Fig. 5.8). Furthermore, at that time, a current of 50 kA is conducted through the central plasma, while that for each wire is 20 kA . In addition, the estimated temperature is 250 eV in the central plasma, which is higher than in the coronal wire plasma ($\sim 15 \text{ eV}$). This theoretical result is in agreement with x-ray spectroscopy measurements performed by I. Ross (private communication) using a crystal spectrometer, who estimated temperatures and densities in the range $300 \text{ eV} - 400 \text{ eV}$ and $10^{20} - 10^{21} \text{ cm}^{-3}$ respectively. However for tungsten, the current density in the central plasma is still lower than for aluminium. At 50ns (see Fig. 5.9), the aluminium pinch behaviour becomes mainly dominated by the central plasma column, where the current is 115 kA . But, for tungsten, the central column only conducts 60 kA . At 70ns (see Fig. 5.10), the mass distribution is more uniform for tungsten in the plane between wires than for aluminium. This is in agreement with the plasma streamers observed experimentally. At 90ns, the magnetic field distribution for aluminium is cylindrical (see Fig. 5.11). However, for tungsten it is still elliptical, showing a region with higher mass density in the plane between wires.

The simulation results predict that the attraction force between wires is enough to produce an implosion of the wire material on the axis at 110ns. Fig. 5.12 shows density, current, temperature and magnetic field lines of two $15 \mu\text{m}$ aluminium and two 7.5 mm tungsten wires for 1.5 mm separation. A plasma column of $500 \mu\text{m}$ diameter is predicted. However, experimentally no such collapse of the wires was observed. This is probably due to the theoretical model used in the code is not complete and does not include all the physics involved.

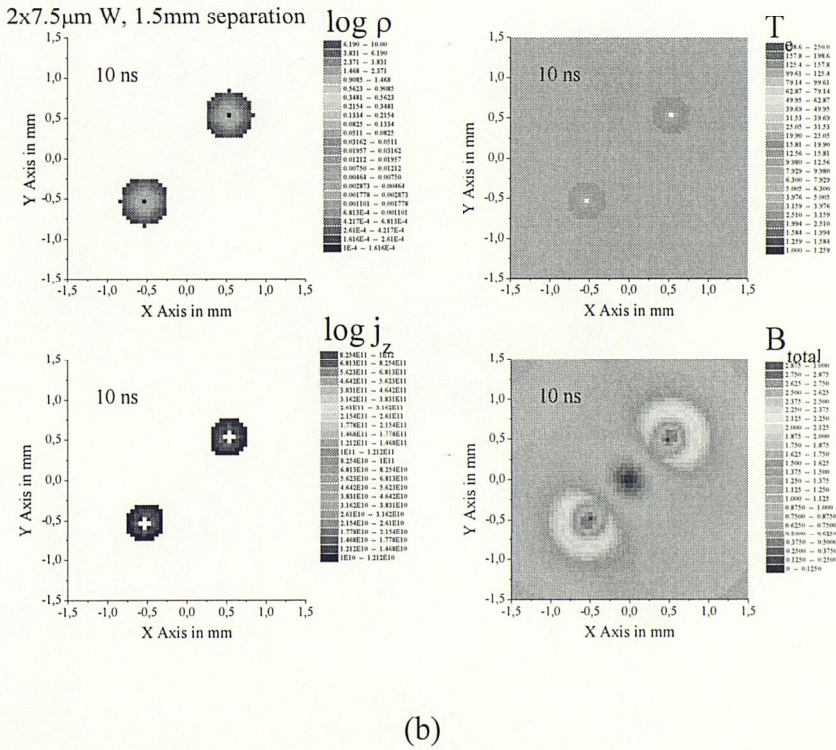
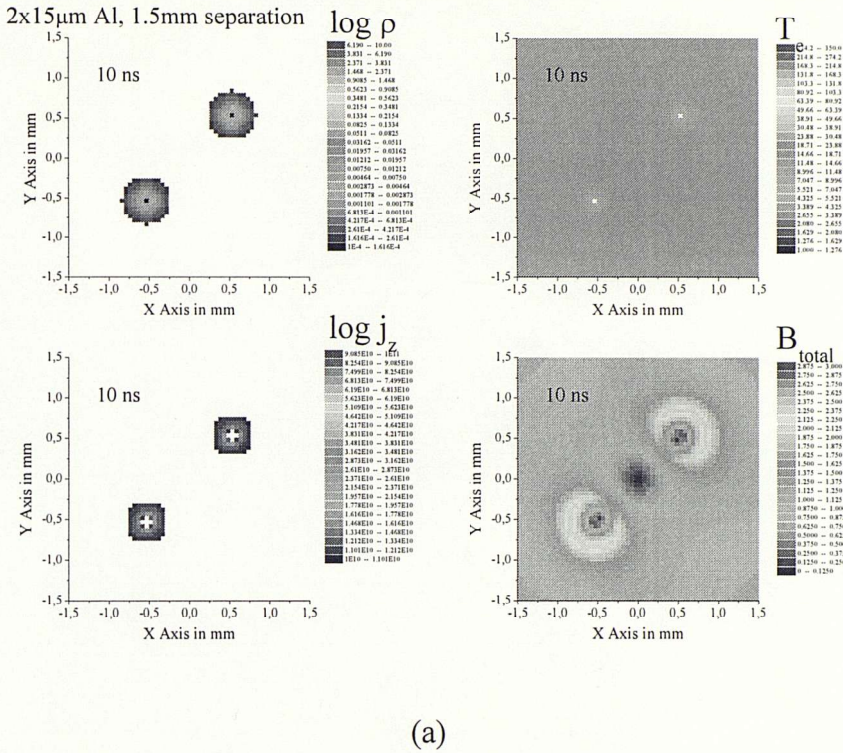


Figure 5.6. Simulation of mass density, temperature, current density and magnetic field distribution of: (a) Two 15 μ m aluminium wire and (b) Two 7.5 μ m tungsten wire z-pinchs for 1.5 mm separation at 10ns after current start.

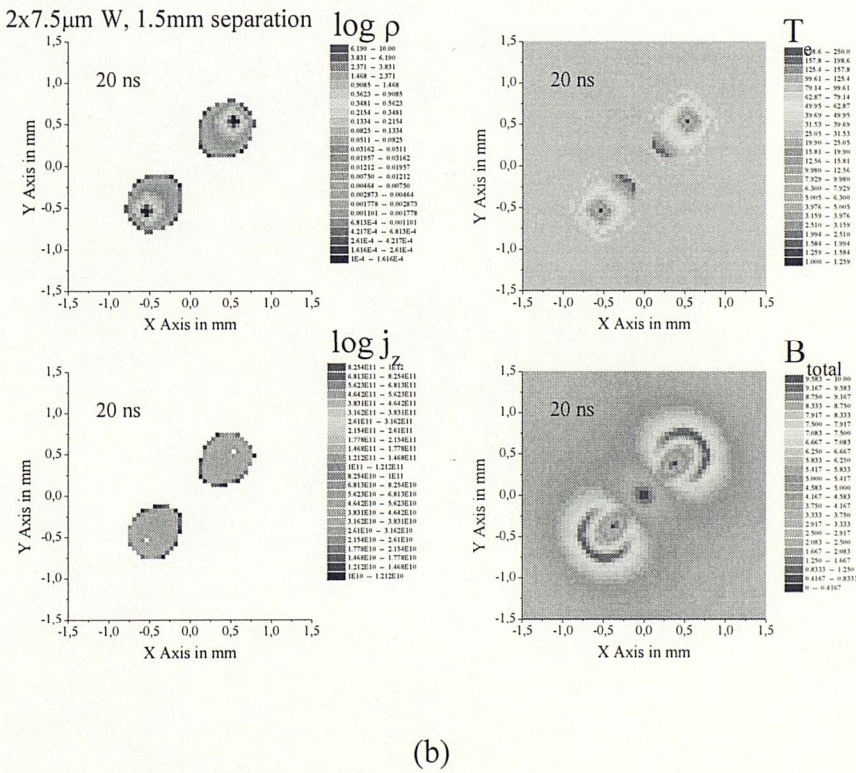
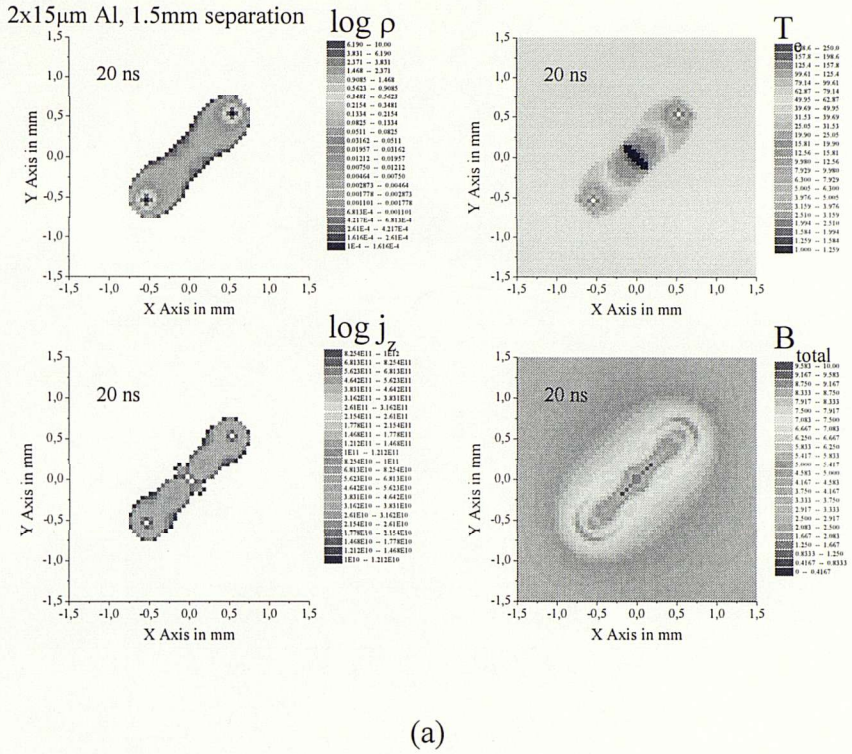


Figure 5.7. Simulation of mass density, temperature, current density and magnetic field distribution of: (a) Two 15 μ m aluminium wire and (b) Two 7.5 μ m tungsten wire z-pinchs for 1.5 mm separation at 20ns after current start.

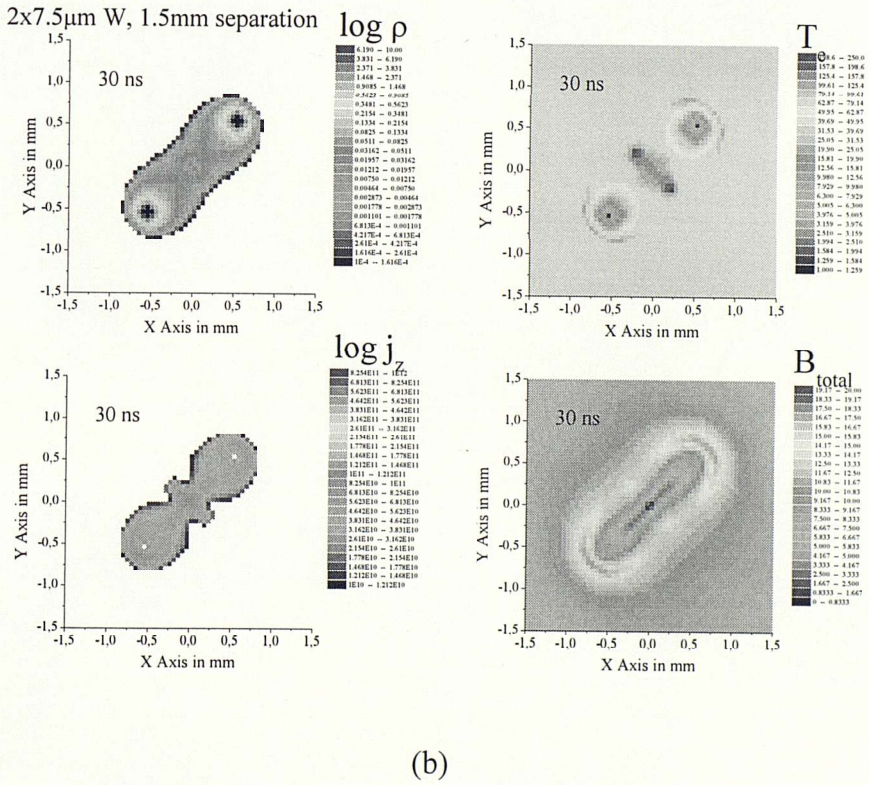
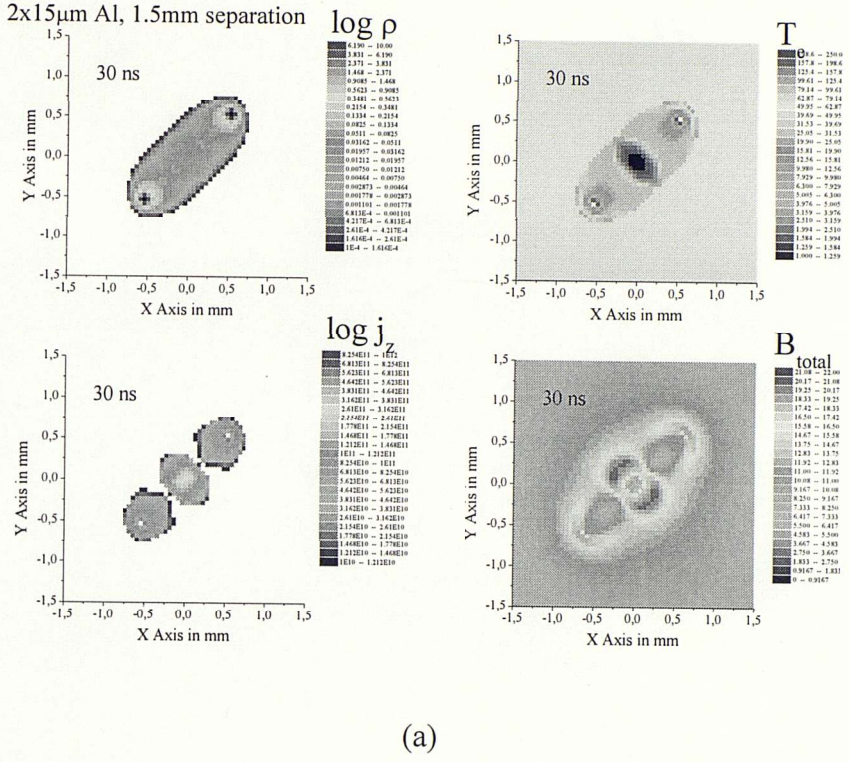


Figure 5.8. Simulation of mass density, temperature, current density and magnetic field distribution of: (a) Two 15 μ m aluminium wire and (b) Two 7.5 μ m tungsten wire z-pinch for 1.5 mm separation at 30ns after current start.

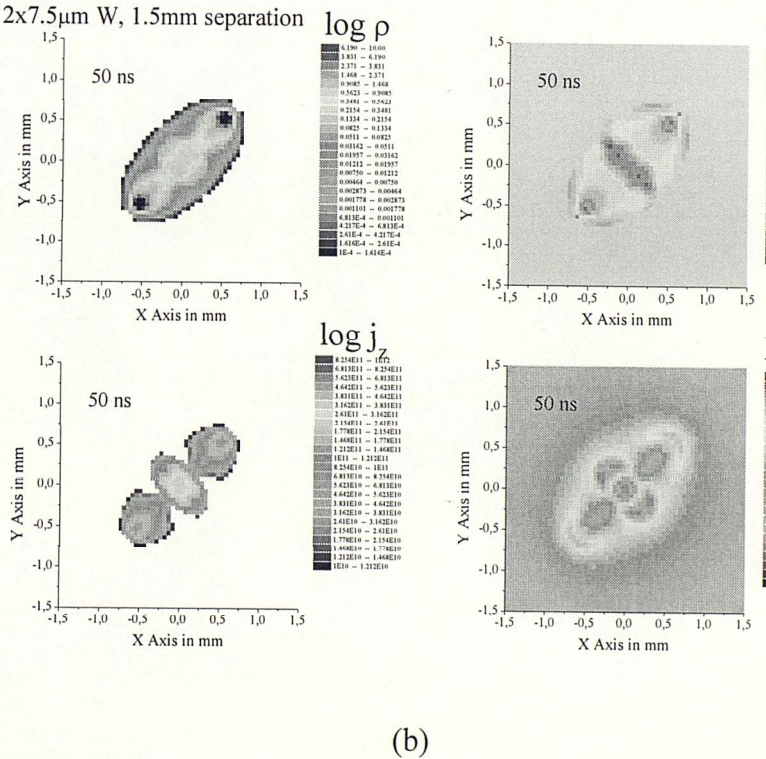
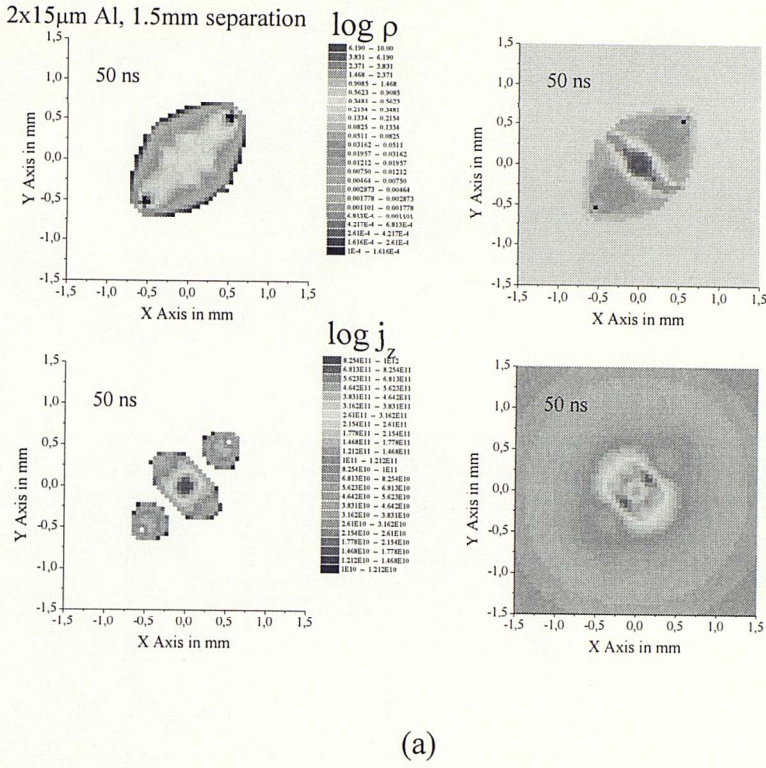


Figure 5.9. Simulation of mass density, temperature, current density and magnetic field distribution of: (a) Two 15 μ m aluminium wire and (b) Two 7.5 μ m tungsten wire z-pinch for 1.5 mm separation at 50ns after current start.

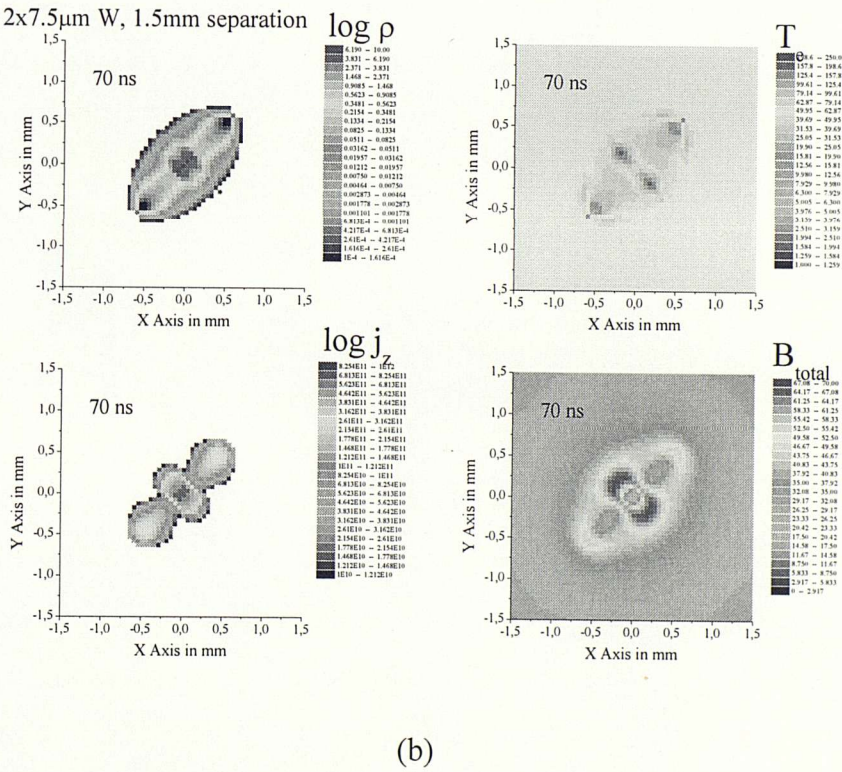
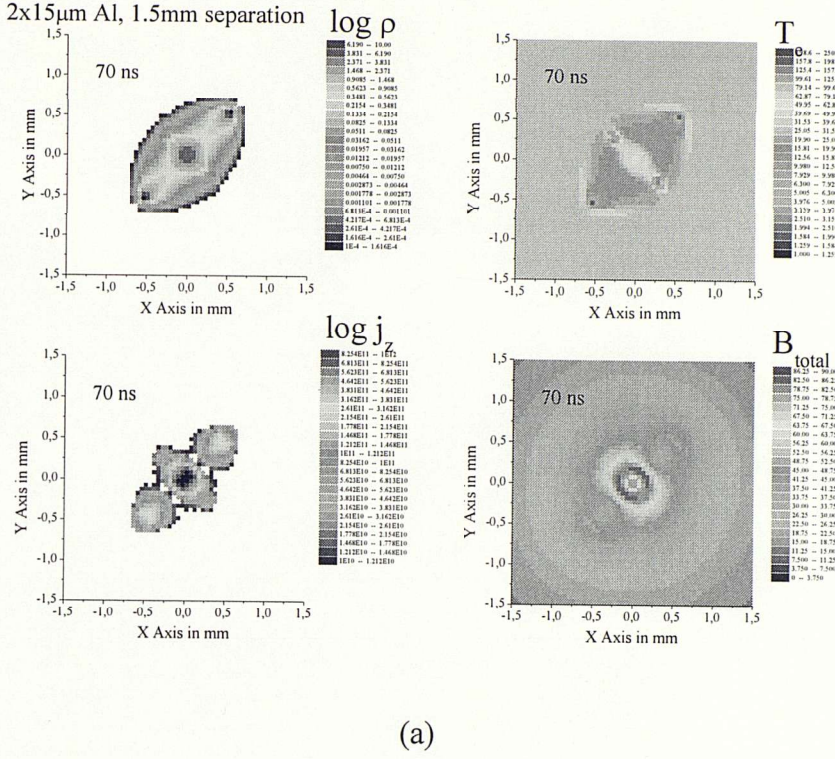


Figure 510. Simulation of mass density, temperature, current density and magnetic field distribution of: (a) Two 15 μ m aluminium wire and (b) Two 7.5 μ m tungsten wire z-pinch for 1.5 mm separation at 70ns after current start.

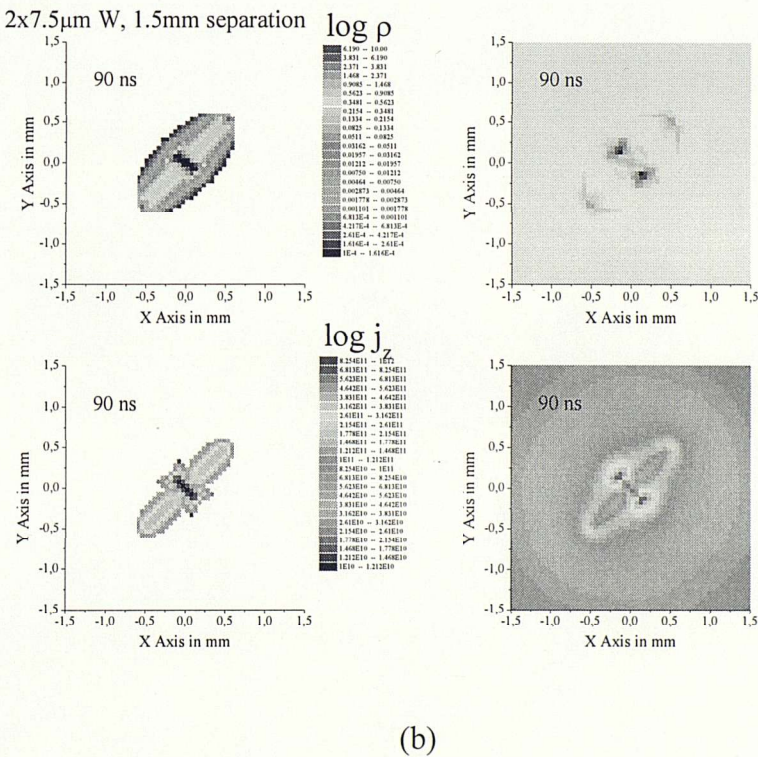
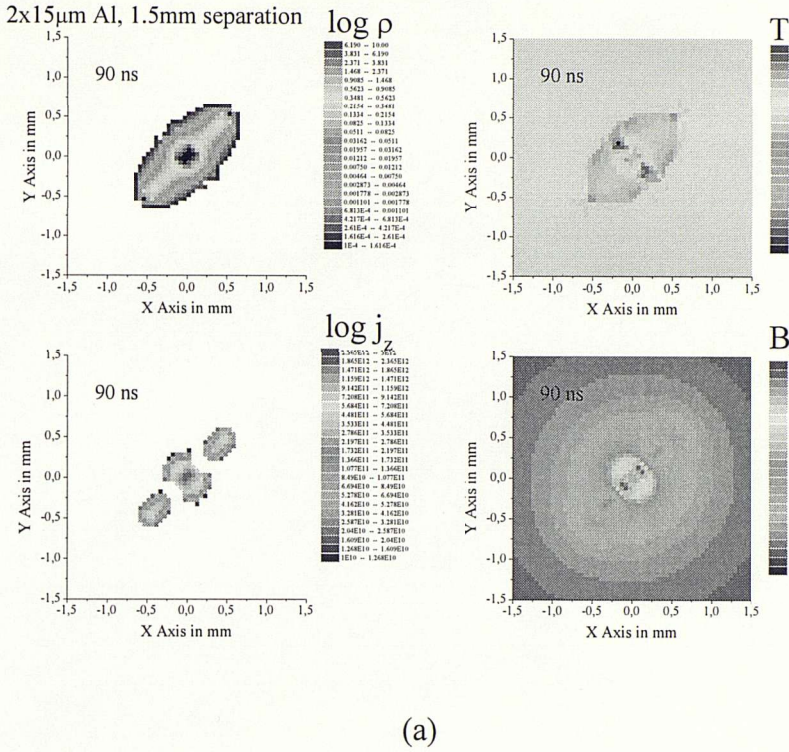


Figure 5.11. Simulation of mass density, temperature, current density and magnetic field distribution of: (a) Two 15 μ m aluminium wire and (b) Two 7.5 μ m tungsten wire z-pinchs for 1.5 mm separation at 90ns after current start.

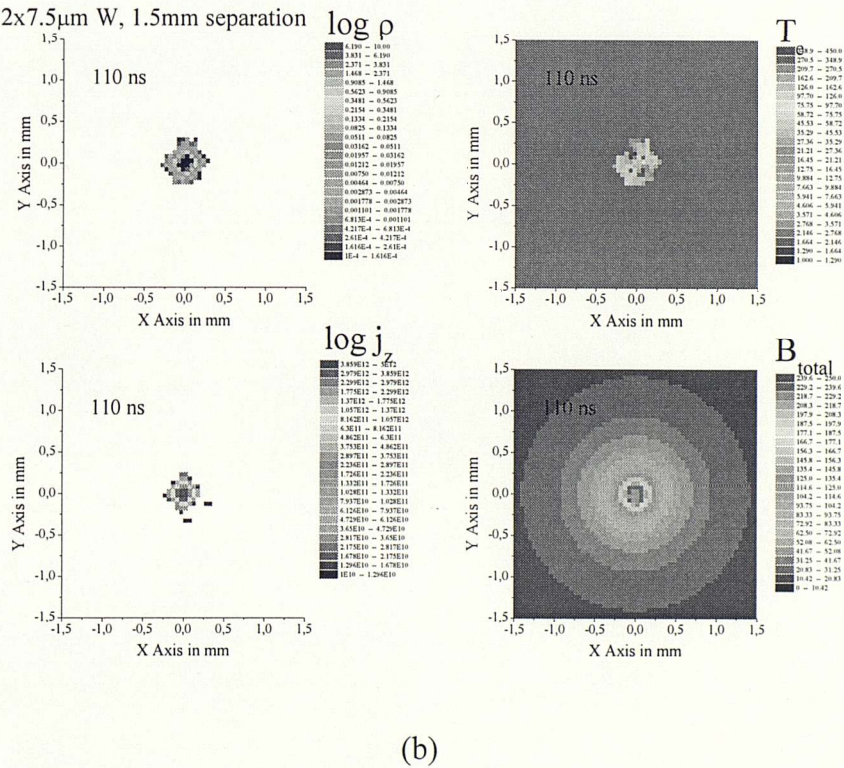
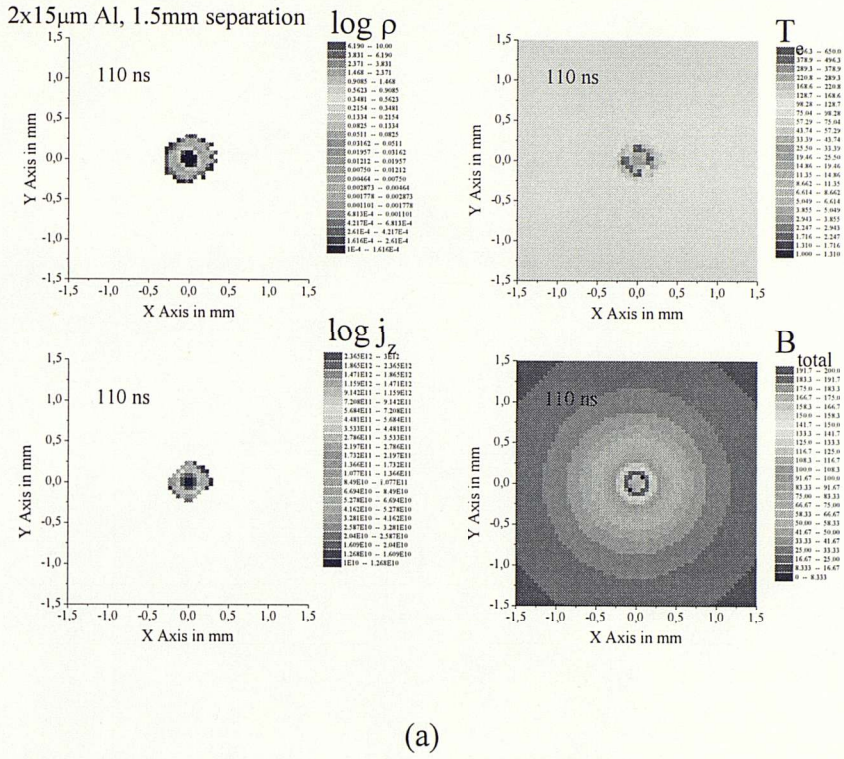


Figure 5.12. Simulation of mass density, temperature, current density and magnetic field distribution of: (a) Two 15 μ m aluminium wire and (b) Two 7.5 μ m tungsten wire z-pinchs for 1.5 mm separation at 110ns after current start.

5.2.6.- Laser Absorption

Figure 5.13 shows simultaneous schlieren and optical framing images of two aluminium wires 1.5mm apart, taken at 65ns after current start. From schlieren, the coronal plasma (white region) is not dense enough to be optically thick. However, the black regions (core) corresponds with the image seen with the optical framing camera. They correspond to the core of each wire and the current channel formed between wires.

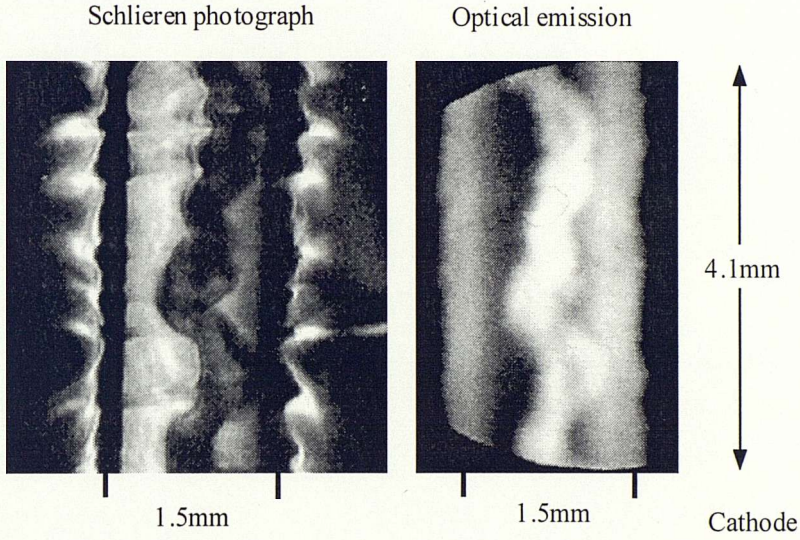


Figure 5.13 Simultaneous schlieren photographs and framing image of two 15µm aluminium wire for 1.5mm separation, taken at 65ns after current start.

To find out whether the core observed in schlieren is due to refraction or absorption, we consider the case where refraction is neglected. In this case, the absorption of the ruby laser can be used to place a lower limit on the electron density within the core region. For a ruby laser ($\lambda = 694.3nm$, $70mJ$) the critical electron density is $n_c = 2.31 \times 10^{21} cm^{-3}$.

The light absorption by plasmas at densities below cut-off is given by $I = I_0 e^{-\kappa \ell}$, where κ is the absorption coefficient and ℓ is the plasma column thickness. The absorption coefficient, also known as inverse bremsstrahlung absorption coefficient, is given by [5.27]:

$$\kappa = \frac{3.1 \times 10^{-7} Z n_e^2 \ln \Lambda}{T^{3/2} \omega^2} \left(1 - \omega_p^2 / \omega^2\right)^{-1/2} [cm^{-1}] \quad 5.3$$

where T is the electron temperature in eV , Z the average ionisation, ω is the laser frequency, ω_p is the plasma frequency, n_e the electron density in $1/cm^3$, and $\ln \Lambda$ is the Coulomb logarithm. The Coulomb logarithm varies only slightly with the plasma conditions and was taken to be 10 for these calculations.

Assuming $\ell = 0.05cm$ we find that for $\kappa\ell > 1$, $n_e > (1.7 \times 10^{19}) \cdot (T^{3/2}/Z)^{1/2}$. Figure 5.14 shows the density at which, absorption becomes significant as a function of temperature for a variety of Z . From simulation, the temperature of the central column is $250eV$ and $Z=13$ at 30ns. So, absorption is important for $n_e > 3.0 \times 10^{20} [cm^{-3}]$. For our set up, this is greater than the maximum density detectable due to the numerical aperture of the imaging lens (see Section 2.5.3). Hence we can assume that the core observed is due to the refraction not absorption. This will change through with temperature and ionisation.

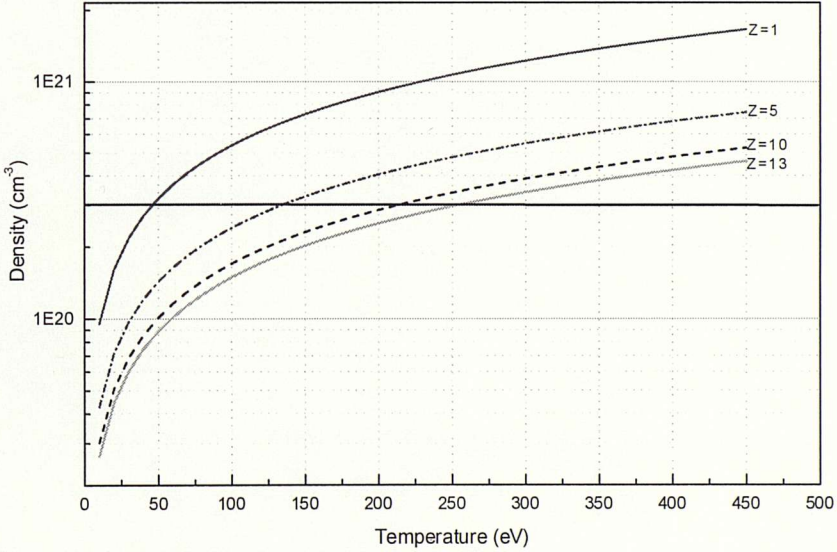


Figure 5.14. Absorption of laser light for different ionisation stages of a plasma column of $500\mu m$.

5.3.- *Conclusions*

5.3.1.- *Single Wire Z-pinches*

1. - Observations show that the expansion of the coronal plasma is independent of the wire material, but is dependent on the wire material. This is because it is determined by MHD instability and hence the Alfvén velocity in the coronal plasma. The heats of vaporization and ionization energies are very different for tungsten and aluminium wires. In the early expansion phase, radiation loss does not play a significant role due to the low density of the coronal plasma.
2. - The $m = 0$ -MHD behaviour begins very early in the discharge at the outer boundary of coronal plasma as a result of ablation from the cold central fibre. It is found that the wavelength and the amplitude of the perturbation increase with time relatively faster for aluminium compared with tungsten pinches. The fast development of instabilities is presumably due to the high temperature in the aluminium coronal plasma.
3. - The amplitude of instabilities in the coronal plasma and in the core region varies. After 40 ns , there is a long wavelength and large amplitude $m = 0$ instability in the coronal plasma, whilst in the core region this instability shows a short wavelength and small amplitude.
4. - The density islands were observed only for $5\text{ }\mu\text{m}$ tungsten and $15\text{ }\mu\text{m}$ aluminium pinches. The inaccessible region is visible for all wire diameters, and its diameter increases with time.
5. - X-ray diagnostics also show different characteristics for the tungsten z-pinch. X-ray emission from tungsten is hard ($h\nu > 6\text{ keV}$) from the plasma column, and the intensity of x-rays decreases with the increase in the wire diameter. The number of bright spots also decreases as the diameter of the wire is increased, and as the current is reduced. Bright spots appear later in the current rise for larger diameter wires, and these were not observed at all for $18\text{ }\mu\text{m}$ tungsten wire. This is consistent with the observations of density islands with the optical probing for $5\text{ }\mu\text{m}$ tungsten wire.
6. - Hard x-rays were not observed either from the aluminium plasma column or the bright spots, but only those emitted from the anode were seen in both pinches. The intensity of the x rays from the anode and the pinch was of the same brightness in

tungsten, but for aluminium the intensity from the anode was comparatively lower than the pinch.

7. - PIN diode signals for tungsten wires showed two peaks, the first one corresponding to the emission in the soft x-ray range. The second one appears at about 60 ns depending on wire diameter and is coincident with the emission from the bright spots. For aluminium pinch, PIN diode signals showed multiple peaks coincident with the bright spots in x-ray streak photographs.

5.3.1.- *Two-Wire Z-pinches*

1. - The pinch dynamics for aluminium and tungsten are different.
2. - The coronal expansion of the wire-plasma is asymmetric, being faster in the interwire region (toward the axis) than for the external region.
3. - A global magnetic field surrounding the wires is observed through the axial correlation of the coronal plasma instabilities.
4. - The time of appearance of the central plasma column depends both on the wire material and separation.
5. - The central plasma column is $m = 1$ - MHD unstable and it is mainly contained in the plane between wires.
6. - Plasma streamers in the interwire region were observed for 1.5mm tungsten pinch. The $m = 0$ -MHD instability in the core wire-plasma modulates the plasma streamers. These plasma streamers were formed as a consequence of the time delay in the formation of the current channel between the wires. That means the separation between plasma streamers along the pinch and the wavelength of $m = 0$ -MHD instability in core and coronal wire plasma are axially correlated. Correlation of MHD instabilities in both wires results in a correlation of plasma streamers from both wires as well. This observation for two-wires (the simplest wire-array configuration) can be related to wire array observations, which show that the initial perturbation that seeds the Rayleigh-Taylor instability in a z-pinch is produced by the individual wires that form the array [5.28].
7. - The implosion predicted by theory and simulation was not observed in these experiments. The main reason why the simulation results do not agree with the experiments is, in fact, due to that the model used in it is not complete and does not include all the physics involved in the two-wire z pinch dynamics.

5.4.- *Future Work*

At the conclusion of these experiments on single and two-wire z-pinches, new two-wire experiments have been planned to investigate in more detail the central plasma column formed between the wires. **X-ray spectroscopic measurements** with spatial and/or time resolution will gather information about the temperature and ionisation of the central column, and how these parameters change during the current discharge. Another important diagnostic is **multiple-frame Moiré deflectometry** (see Appendix A) to estimate electron densities in the central plasma, so that one can infer how much mass is accumulated in it. Another important experiment that needs to be studied is the effect of a prepulsed current on the formation of the central plasma column.

APPENDIX A

MOIRE DEFLECTOMETRY

Moiré Deflectometry is a technique that maps the deflection of a collimated beam as it passes across a phase-test medium [1]. This deflection is proportional to the gradient of the refractive index transverse to the optical path.

A Moiré pattern is in the form of a series of straight parallel equidistant fringes, separated by $p' = p/\theta$, where p is the grating pitch, and θ is the angular rotation between the gratings, c.f. Fig. A.1.

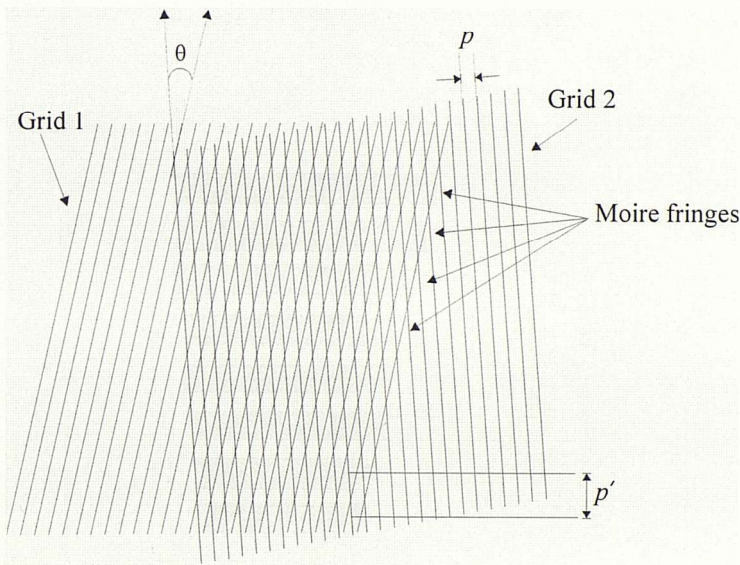


Figure A.1. Moiré fringes pattern produced when two identical ruling gratings of uniform pitch p are overlaid with a rotational mismatch angle θ . The pitch of the Moiré fringes $p' = p/\theta$.

A basic set-up for a Moiré deflectometer is shown in Fig. A.2. A collimated laser beam passes through the plasma and then across a pair of transmission gratings, G_1 and G_2 , producing a Moiré pattern with different orders. A lens L images the plasma into an image plane. An aperture D , located at the focal length (Fourier plane) of the imaging lens, selects a single diffracted order. A filter F may be necessary to reject plasma light.

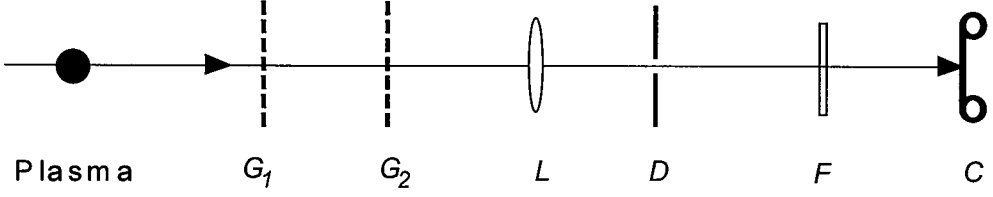


Figure A.2. Schematic of a basic Moiré deflectometer.

As the light passes through the plasma, the rays will be deflected by an angle φ given by:

$$\varphi = \frac{1}{2n_c} \int \nabla n_e \cdot d\ell \quad (\text{A.1})$$

$d\ell$ is a element of the optical path. For an object with axial symmetry, φ can be rewritten in cylindrical co-ordinates as:

$$\varphi(x, z) = \frac{2x}{n_o} \int_x^{r_{\max}} \frac{\partial n}{\partial r} (r^2 - y^2)^{-1/2} dr \quad (\text{A.2})$$

Using the inverse transform of Eq. (A.2), we can obtain the electron density n_e as

$$n_e(r, z) = \frac{2n_c}{\pi} \int_r^{r_{\max}} \varphi(y, z) (y^2 - r^2)^{-1/2} dy \quad (\text{A.3})$$

The deflection, φ , distorts the Moiré pattern and from it, the electron density can be obtained directly. Due to it, the deflectogram's information is used in *Abel transformation* directly. For interferograms we need to calculate the derivative of the fringe shift, introducing errors in the final calculation.

In a z-pinch the density gradient is mainly radial, thus the laser beam is passed transversely to the pinch axis. To facilitate interpretation of the fringe distortion, these are aligned to be perpendicular to the pinch. If the z-axis is along the pinch and the y-axis along the laser, then the deflection $\varphi(x, z)$ in the $x - y$ plane will produce a fringe shift $h(x, z) = \varphi \, d/\theta$. From Eq. (A.3), we see that the deflection depends on the density gradient along the x-axis, i.e., dn_e/dx .

The relative fringe shift $\alpha(x, z) = h(x, z)/p' = \varphi(x, z)d/p$ is fixed by measuring accuracy of the $\alpha \approx 0.2$, we thus see that the minimum deflection angle that can be detected depends on the ratio of grating pitch p to the distance d between gratings. However, due to the uncertainty principle, $\delta\varphi \cdot \delta x \geq \lambda/2\pi$, where $\delta\varphi$ is the angular resolution and δx is the spatial resolution, increasing the sensitivity decreases the spatial resolution [2].

The spectral width of the laser, the beam divergence, the size of the beam relative to the grating pitch and grating imperfection [3] determine the fringe visibility. In addition, if the second grating is positioned at the Talbot planes [4], i.e., $d = lp^2/\lambda$, where l is an integer, the fringes have maximum contrast. Indeed, if the second grating is midway between the Talbot planes, the fringe pattern is totally blurred.

The Moiré deflectometer set-up that was used to study electron density distribution on single wire z-pinch. The beam size of the laser that pass across the plasma is reduced using a telescope ($m < 1$) on emerging from the plasma is with the lenses L_1 (50cm) and L_2 (30cm). The lenses are separated by the sum of their focal lengths and the plasma position is at the focal plane of L_1 . The plasma image, at the focal plane of L_2 , is in front of the first grating G_1 ($p=33\mu m$). The first order diffracted by G_1 is passed at normal incidence through the second grating G_2 ($p=33\mu m$) to produce the Moiré pattern. The aperture D (Diameter: 3mm) is at the focal distance from L_3 (57cm), and is adjusted to select the zero order beam from G_2 . The film position is at the image of the plasma generated by lens L_3 .

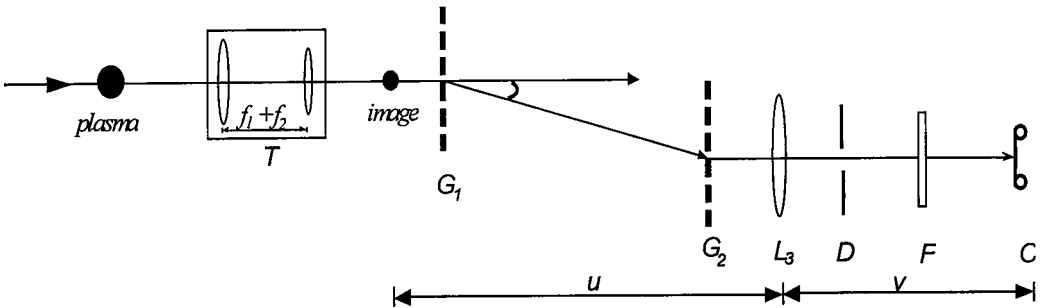


Figure A.3. Schematic of a modified Moiré deflectometer

The advantage of this system is that since the angular deflection is increased by $M = f_1/f_2$, the minimum measurable deflection angle is decreased by a factor M . Now, substituting $\varphi_{min} = \alpha p/Md$ in Eq. (A.4), it is possible to determine the electron density.

$$n_e(r, y) = \frac{2n_c}{\pi} \frac{p}{dM} \int_r^{r_{max}} \alpha(x, y) (y^2 - r^2)^{-1/2} dy \quad (A.4)$$

The term p/dM can be adjusted, representing the tuneable factor of our Moiré Deflectometer. Adjustable sensitivity is the main advantage of Moiré deflectometer over an interferometer.

Moreover, using other lens, L_3 (60cm) we can compensate for the reduction in size of the image introduced in the system by the telescope. Care should be taken to ensure that the image of the plasma produced by the telescope is in front the first grating. By operating only with the first order diffracted beam produced by the first grating, blurring of the Moiré fringes due to the Talbot effect is eliminated.

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CONTRIBUTED PAPERS

During my PhD course I participated in the following journal articles:

- 1.- **Plasma formation in metallic wire Z pinches.** J. P. Chittenden, S. V. Lebedev, **J. Ruiz-Camacho**, F. N. Beg, S. N. Bland, C. A. Jennings, A. R. Bell, M. G. Haines, S. A. Pikuz and T. A. Shelkovenko and D. A. Hammer, Phys. Rev. E **61**, 4370 (2000).
- 2.- **Radiative properties of high wire number tungsten arrays with implosion times up to 250 ns.** C. Deeney, C. A. Coverdale, M. R. Douglas, K. W. Struve, R. B. Spielman, W. A. Stygar, D. L. Peterson, N. F. Roderick, M. G. Haines, F. N. Beg, and **J. Ruiz-Camacho**, Physics of Plasmas **6**, 3576 (1999).
- 3.- **Z-pinch Discharges in aluminium and tungsten wires.** **J. Ruiz Camacho**, F. N. Beg, E. Clark, I. Ross, A. E. Dangor and M. G. Haines Physics of Plasmas **6**, 2579 (1999).
- 4.- **Titanium K-shell x-ray production from high velocity wire array implosions on the 20-MA Z accelerator**, C. Deeney, C.A. Coverdale, R.B. Spielman, M.R. Douglas, T. Nash, W. Thornhill, K. Whitney, J. Apruzese, J. Davis, D. Patterson, R. Schneider, F.N. Beg and **J. Ruiz-Camacho**, Physics of Plasmas **6**, 2081 (1999).
- 5.- **Influence of prepulse current on fibre Z-pinch.** A. Lorenz, F.N. Beg, **J. Ruiz-Camacho**, J. Worley and A. E. Dangor, Phys. Rev. Lett. **81**, 361 (1998).
- 6.- **Z-pinch discharges – Bare and plastic coated copper wires**, F. N. Beg, **J. Ruiz-Camacho** and A. E. Dangor, p. 333, Dense Z pinches, AIP Conference Proceeding **409**.
- 7.- **Laser probing of fibre z-pinch plasmas.** **J. Ruiz-Camacho**, F. N. Beg and A. E. Dangor, p. 407, Dense Z pinches, AIP Conference Proceeding **409**.
- 8.- **Carbon Fiber z-pinch with current prepulse.** A. Lorenz, F.N. Beg, **J. Ruiz-Camacho**, J. Worley and A. E. Dangor, p. 315, Dense Z pinches, AIP Conference Proceeding **409**.

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