

DIAGNOSIS OF FUSION PRODUCTS FOR REACTOR RELEVANT PLASMAS

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Abstract

Measurements of fusion products in the JET tokamak were performed and analysed with specially developed modelling codes. The reactions covered are listed below:

1. D-³He reactions were investigated with an escaping 14.7 MeV proton detector, the results indicating that fast particles are displaced from the plasma centre at a sawtooth crash and resolving issues left outstanding from experiments with a previous 14.7 MeV proton detector.
2. D-D reactions emitting 2.45 MeV neutrons have been investigated using two collimated arrays of neutron detectors and a fission chamber system. An analysis code was written to derive the neutron emission profile and was then used to calculate ion temperature profiles, deuterium dilution factors and correction factors for other neutron diagnostics. Results obtained using the analysis code are presented.
3. D-D reactions emitting tritons have been investigated using the secondary T-D reaction. The observations of neutron emission from the secondary reaction have been used to show that the energy loss rate of dilute populations of particles with energies in the MeV range is classical, within the errors of the measurement. This has been done by comparing the 14 MeV neutron emission rate with a time resolved model of the neutron emission. Results are also presented on the confinement of thermalising tritons. In addition, having demonstrated that the triton behaviour is essentially classical, the reaction has been employed in the determination of the deuterium dilution factor.

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1.0 Introduction

This thesis describes work performed over a three year period at the JET Joint Undertaking utilising fusion product diagnostics in order to identify and interpret some of the processes occurring in the JET plasma. This chapter contains background material which should make the remainder of the thesis more accessible to physicists from outside the fusion field. The first section of this chapter is concerned with nuclear fusion in general; the basic requirements for fusion to provide a commercially viable power source, the possible reactions which may be utilised and the proposed methods for confining the reacting particles. The next section covers the tokamak approach in more detail, as JET is such a device. The third section discusses the creation and detection of fusion products and how these may be used to diagnose the physical processes occurring in the plasma. The fourth, and final, section sets out the plan of the succeeding chapters.

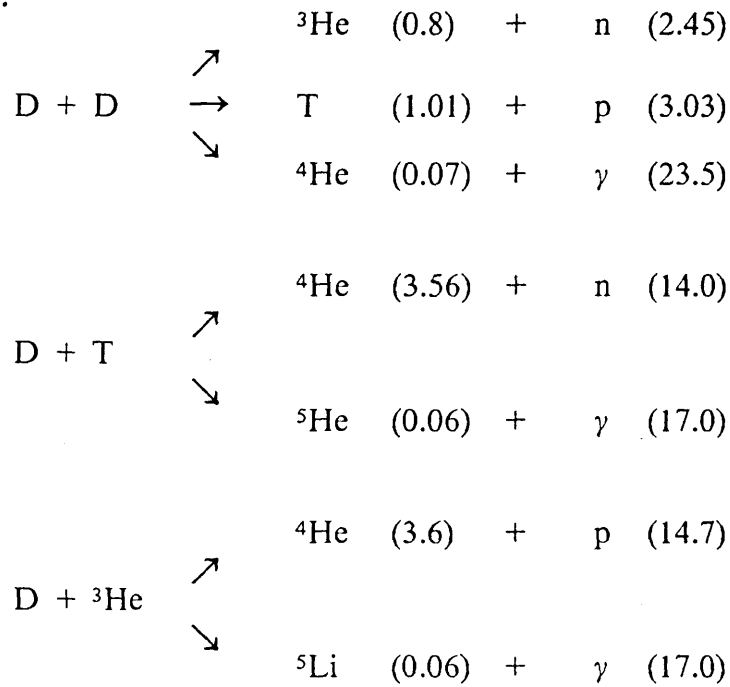
1.1 *Nuclear Fusion*

Nuclear fusion is the process by which two nuclei are joined to form a larger nucleus. By choosing appropriate nuclei, a large quantity of energy may be released by these reactions. In principle, it should be possible to use these reactions for commercial power production. However, the task of harnessing the energy from nuclear fusion reactions has proved extremely difficult. Only now, after approximately 40 years of research, are experiments approaching the point where fusion may be shown to be a practical energy source.

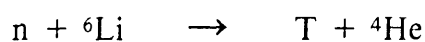
In order for fusion to occur between two nuclei, they must be brought close together, implying that the Coulomb repulsion must first be overcome. This

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effectively restricts the useful fusion reactions to those involving low Z nuclei. The three reactions most likely to be used in fusion reactors are shown below, with the average kinetic energy of each fusion product in MeV shown in parentheses:



In order to obtain fusion reaction rates high enough to be economically useful, the nuclei involved must have energies in the region of 10 to 1000 keV. These energies can be achieved in high temperature plasmas and the reactivity as a function of plasma temperature is shown in fig 1.1. The plasma temperature is usually given in units of keV, where 1 keV equals 11,600,000 K. It is obvious that the D-T reaction offers the easiest route to fusion power because of its large reactivity at relatively low temperatures. However, it does have some drawbacks. Firstly, the tritium nucleus is unstable, decaying by β^- with a half-life of 12.3 years, so it must be produced artificially. The following reactions with lithium are likely to be used in a reactor as, together, they produce more than one triton per D-T neutron. This is a necessary requirement if a reactor is to be self-sufficient in tritium, bearing in mind escaping neutrons and parasitic absorption in structural materials.



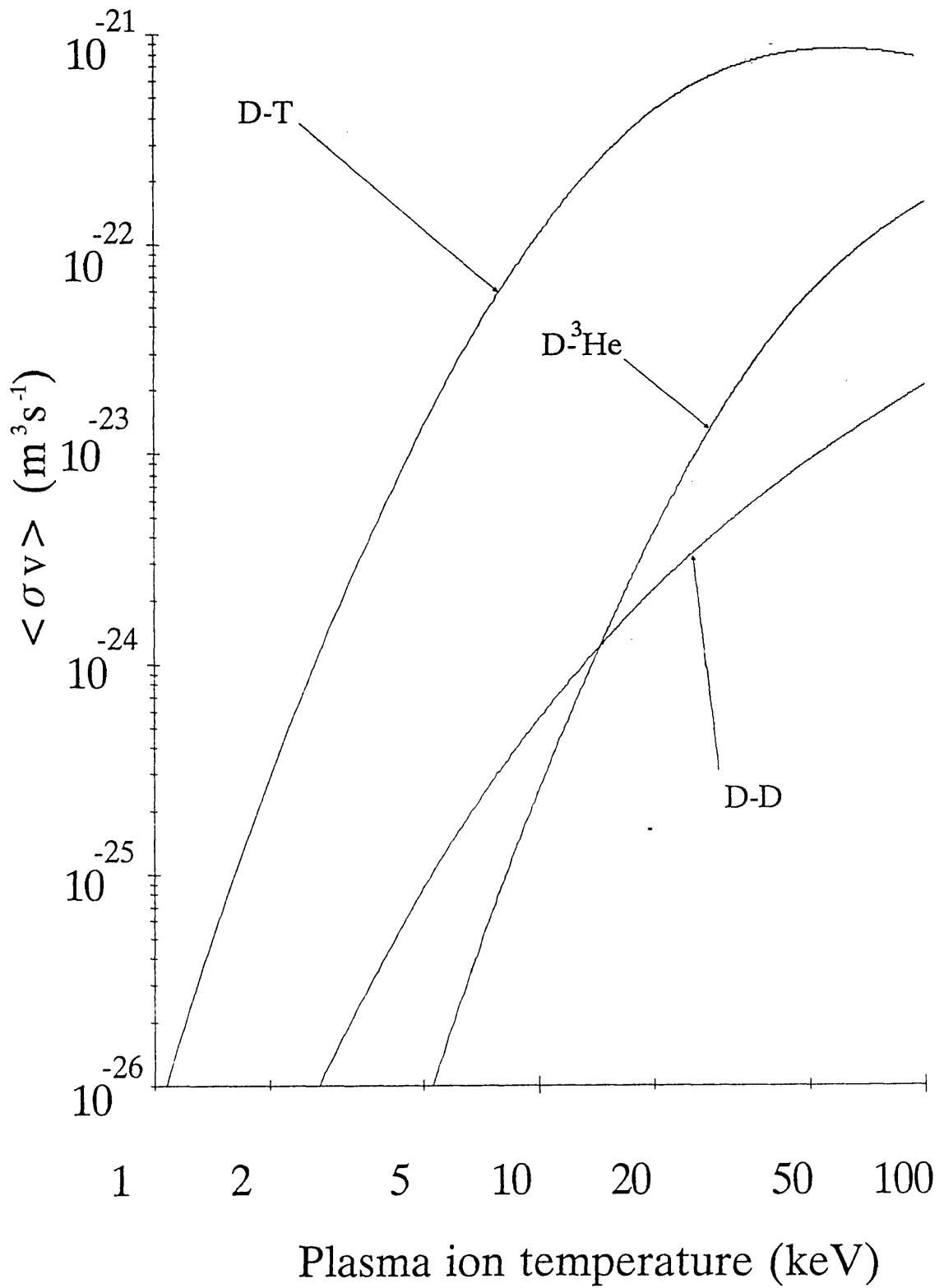


Figure 1.1. Fusion reactivities as a function of plasma temperature

Most proposed fusion reactors have lithium blankets surrounding the reaction vessel, partly to produce tritium and partly to extract the energy from the emitted neutrons. This entails solving engineering problems related to the structure and location of the lithium, as well as difficulties in removing the tritium from the lithium. Secondly, the 14 MeV neutrons produced by the D-T reaction are capable of activating the structure of the reactor vessel, necessitating the use of remote handling equipment for maintenance and posing a long term radioactive waste problem. Also, as the materials of the reactor vessel become activated, they lose their structural strength and need to be regularly replaced. These problems are not insuperable, but make aneutronic fusion reactions more desirable. The D-D reaction does not have a problem with fuel rarity, as 0.0015% of the hydrogen in water is deuterium. However, the higher reactor temperatures required make this a more difficult target than the D-T reaction. Also, although the activation problem with 2.45 MeV neutrons is smaller than that associated with 14 MeV neutrons produced by the D-T reaction, it is still enough to make operation of a D-D reactor difficult. The D- ^3He reaction would give a relatively clean reactor if the deuterium is dilute as most of the fusion products are then charged particles and should be contained by the plasma. However, even higher temperatures are required for this than for a D-D reactor due to the increased bremsstrahlung radiation losses. There is also a problem with fuel scarcity, as only 0.00013% of all helium on Earth is of the ^3He isotope and this is too small a fraction to be useful. Proposals have been made to mine the lunar surface for ^3He deposited by the solar wind over the previous 4 billion years [1.01].

One of the main problems with using high temperature plasmas is to confine the plasma for a long enough period so that a large number of fusion reactions occur. There are a number of methods proposed to do this, but only one will be discussed in this thesis. The magnetic confinement approach relies upon magnetic fields to contain the hot plasma. Numerous magnetic field configurations have been proposed, but all rely upon the fact that plasma elements in a magnetic field follow the field lines and should not drift far from

them. This allows energy to be added to the plasma from outside, increasing its temperature. In practice, diffusion across magnetic fields does occur in a plasma, but slowly enough to allow the temperature of the plasma to be raised enough for high fusion reaction rates to be obtained. The configuration which has been investigated more thoroughly than any other is the tokamak configuration; it is described in more detail in the next section.

1.2 Tokamaks

The tokamak design was developed in the late 1950's in the Soviet Union and by the late 1960's had been shown to give higher plasma temperatures than other approaches. Since then, tokamaks have become larger and more complex. Results have improved and the present generation of tokamak experiments are expected to be capable of reaching scientific break-even. This is when the power applied to the plasma for heating is equal to the fusion power generated.

1.2.1 Principles of operation.

This section aims to describe briefly the main features of a tokamak. For further details, reference [1.02] is recommended.

The distinguishing characteristic of a tokamak is its magnetic field configuration and this is shown in fig 1.2. It consists of two parts, known as the toroidal and poloidal magnetic fields. The toroidal field is generated by a set of coils which surround the plasma, while the poloidal field is supplied by the current flowing through the plasma and is typically an order of magnitude smaller than the toroidal field. The poloidal field is needed because a simple toroidal field induces a vertical drift in the charged particles of the plasma, causing a loss of confinement which the poloidal field counteracts. Also, the plasma current which provides the poloidal field is used to heat the plasma. The resultant field is helical, with the pitch of the helix varying throughout the plasma. If magnetic field lines in the plasma are traced around the torus, they are found to lie on nested surfaces referred to as flux surfaces. These surfaces

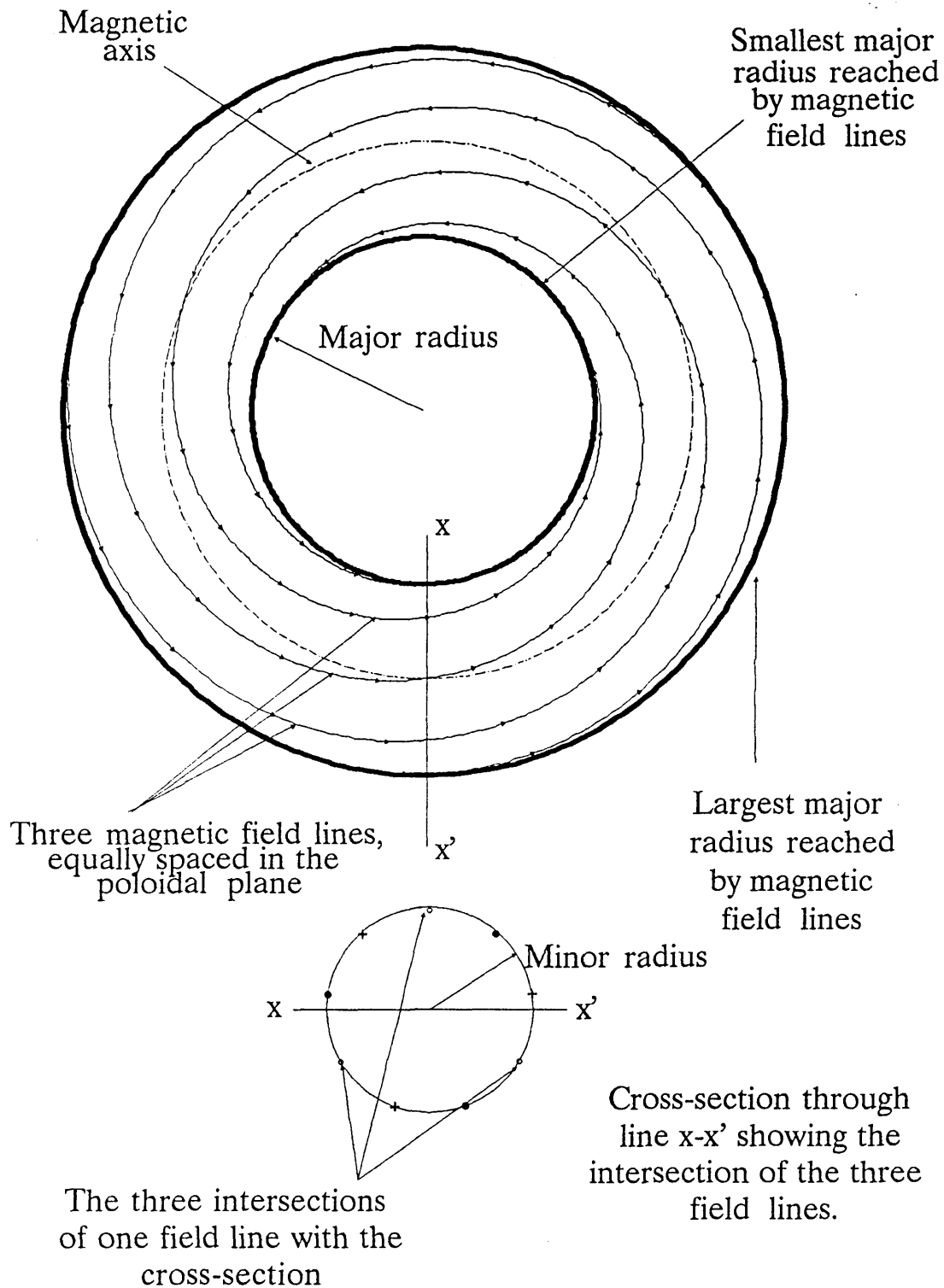


Figure 1.2. Magnetic field configuration of a tokamak:

are important in that transport, of energy or particles, is much faster along a surface than perpendicular to one. One of the standard approximations made throughout this thesis is that quantities such as particle density and temperature are uniform on these surfaces because of this fast transport.

The JET plasma can be heated in three ways, namely ohmic heating (OH), neutral beam heating (NBH) and ion cyclotron resonance heating (ICRH). Ohmic heating is due to the current passing through the plasma. The current is typically a few MA on JET and provides a few MW of heating. As the resistivity of the plasma drops with temperature, ohmic heating cannot be used to heat a plasma to the temperatures required for fusion. In order to obtain higher temperatures the other additional heating schemes must be used. Neutral beam heating relies upon accelerating ions to high energies (80 and 140 keV at JET) and then neutralising the beam. The uncharged atoms are not affected by the magnetic field of the tokamak and pass into the plasma, where they are ionised. The resulting high energy ions are confined by the magnetic field and deposit their energy. Deuterium beams are used at JET. As the fusion reactivity of these ions is much higher than that of thermal ions, the fusion reaction rate increases tremendously when neutral beams are applied to the plasma, often by more than two orders of magnitude. ICRH is more complex and relies upon the fact that ions in the plasma absorb energy from an electromagnetic wave if the frequency of the wave matches the local cyclotron frequency of the ion. This form of heating can increase the energy of a minority of the ions up to several MeV. At JET, 20 MW of NBH and ICRH are available to heat the plasma together with a few MW of ohmic heating. This allows the production of plasmas with high ion temperatures (e.g., over 20 keV) and high fusion reaction rates (up to 3×10^{16} neutrons s^{-1} in present D-D plasmas).

1.2.2 Plasma diagnosis.

In order to understand the processes occurring in the plasma, measurements of various physical parameters must be made. The parameters that are normally monitored are:

- The plasma energy,
- power input and output,
- temperature and density profiles of electrons and ions,
- magnetic field configuration and the current profile,
- impurity profiles,
- interactions between the plasma and the walls and limiters.

The devices used to diagnose these quantities have been described in great detail elsewhere [1.03,1.04], so only an outline of the physics of the diagnostics most commonly referred to in this thesis will be given.

The magnetic field configuration is determined primarily through measurements of the magnetic field near the edge of the plasma using a large number of coils. Given the magnetic field at the edge, the magnetic field further in may be calculated, although the error increases as the distance from the edge increases because of uncertainties in the plasma current density profile. The calculation at JET is performed by the IDENTC code and the estimated error on the location of the centre of the plasma is $\pm 7\text{cm}$. The flux surfaces derived from this code are used in calculations later in thesis.

The electron temperature profile (T_e) can be measured by two diagnostics at JET. The Light Direction And Ranging (LIDAR) diagnostic uses Thomson scattering of a short laser pulse to diagnose the temperature and electron density (n_e). The light scattered through 180° is measured, the time taken for the light to reach the detector being an indicator of the spatial location of the scattering position. Time resolved measurements of the scattered light intensity and spectral broadening of the laser pulse allow the calculation of the n_e and T_e profiles. The second technique uses the electron cyclotron emission (ECE) from

electrons in the plasma. The emission frequency varies across the midplane because of the varying toroidal field; by observing the intensity of the ECE at a range of frequencies a profile of T_e may be found, as the intensity of emission is proportional to T_e . Normally, the ECE value of T_e will be used in this thesis. This is because the LIDAR value is available at best once every 1.2 seconds, due to the low repetition rate of the laser used, whilst the ECE values are available at much higher rates. The systematic error on the LIDAR T_e is estimated at $\pm 5\%$, whilst that of ECE is $\pm 10\%$.

The n_e profile is normally measured with the LIDAR diagnostic, as described above, or through the use of the Far Infra-Red (FIR) interferometer. The latter works on the principle that a laser beam passing through the plasma will undergo a phase shift which is dependent upon the electron density integrated across the laser beam's path. By measuring this phase shift along 6 lines-of-sight and assuming that the density is constant upon flux surfaces, the n_e profile may be found. The error on the derived n_e profile is $\pm 5\%$ of the peak value for both diagnostics.

The impurity monitor normally used in this thesis is the visible bremsstrahlung diagnostic. This measures the continuum radiation in the visible part of the spectrum and, if the electron temperature and the electron density profiles are known, the Z_{eff} profile may be found. As the most common impurities are carbon and oxygen, Z_{eff} can be taken as a measure of their abundance in the plasma. The estimated error on the value of Z_{eff} from the visible bremsstrahlung diagnostic is $\pm 20\text{-}25\%$.

Ion temperature information is found from two sources (apart from the neutron diagnostics, which will be dealt with in sec. 1.3). The X-ray Crystal Spectrometer (XCS) is used to find the peak ion temperature by measuring the Doppler broadening of X-rays emitted by impurity atoms such as Nickel. The diagnostic suffers from a number of problems such as the burnout of the Helium-like Nickel line used at high T_e , the effect of profiles of T_i on the measured value on the observed T_i and the effect of profiles of toroidal rotation on the width of the line used. The Charge Exchange Recombination

Spectroscopy (CXRS) diagnostic also provides information on T_i . This works on the principle that when the neutral beams are ionised in the plasma, some of the beam particles transfer an electron to an impurity ion. The ion thus formed will normally be found in an excited state which will rapidly decay, emitting a photon which is detected by the CXRS diagnostic. By observing the Doppler broadening of these recombination lines, the temperature of the ions interacting with the beams may be found. This technique has an estimated accuracy of $\pm 10\%$, but does require the use of a beam of neutral particles to be available. At JET, the CXRS technique provides a profile of T_i as an array of detectors is used.

1.3 Fusion products

These can be used for diagnostic purposes, now that fusion reaction rates in tokamaks have become high enough. There are three general classes of fusion product:

- confined charged particles,
- unconfined charged particles and
- unconfined uncharged particles.

1.3.1 Confined charged fusion products

At JET, most charged fusion products are confined. They are born and move on an orbit around the tokamak, continually losing energy to the plasma. The duration of the slowing down ranges from 0.01 s to 10 s, depending upon the particle and the background plasma. Whilst slowing down, the fusion products may undergo a reaction with another ion in the plasma, causing the emission of secondary fusion products. These secondary reactions form the primary method of diagnosing the populations of confined charged fusion products on present day tokamaks, as some of the secondary reaction products may themselves be unconfined and therefore detectable outside.

The primary reason for studying the confined particles is that they have similar distribution functions and energies to the 3.56 MeV α 's produced by D-T reactions. Understanding of the behaviour of 3.56 MeV α 's is very important as it is the energy from the thermalisation of these particles which will be used to maintain the temperature of the plasma in a future reactor. Information on the behaviour of α 's can be obtained on present day machines by indirectly observing particles such as 1.01 MeV tritons. Chapter 5 of this thesis is devoted to such measurements.

1.3.2 Unconfined charged particles

Particles born on orbits which intersect the wall escape from the plasma without interacting, so the information which may be obtained from them relates to the fusion reaction rate profile and the energy distributions of the reacting particles. As the charged fusion products have energies of the order of MeV, these escaping particles can be detected by a number of methods. Also, as collimation is fairly easy, the solid angle from which the particles are detected can be made small and be known accurately. Unfortunately, the orbits of charged particles in a tokamak are fairly complex and a large amount of computation must be undertaken to find the point of origin of the particles. A diagnostic of this type, which uses 14.7 MeV protons from the D- ^{3} He reaction, is described in chapter 3.

1.3.3 Unconfined uncharged fusion products

This category basically refers to neutrons and γ rays, which have the advantage that they do not interact with the plasma after emission. The information obtainable is again the fusion reaction rate profile and the energy distribution of the reacting particles. However, detection, calibration and collimation are much more difficult than in the previous case.

1.3.4 Fusion product diagnostics at JET

An extensive set of fusion product diagnostics exist at JET and will be referred to throughout this thesis, so a short description of each diagnostic is presented here. Each diagnostic has a code name and this will be the usual method of reference.

- KH1, the hard X-ray monitors. There are 11 detectors positioned around the torus hall, each consisting of a scintillator and a photomultiplier tube. They are used for detecting hard X-rays produced by runaway electrons and disruptions.
- KN1, the time resolved neutron yield monitors. These consist of three pairs of fission chambers mounted on the transformer limbs of JET. Each pair consists of a ^{235}U chamber and a ^{238}U chamber. Fission events induced by neutrons emitted by JET are detected in each pair. Two fissionable materials are used in order to increase the dynamic range of the system, as the fission cross-sections for ^{238}U are much lower than those of ^{235}U . The current produced by the fission products is monitored with a normal time resolution of 6 ms, although a sampling rate of up to 100 kHz is possible. This is the major neutron diagnostic at JET and is estimated to have an absolute accuracy of $\pm 10\%$.
- KN2, the neutron activation system. Foils of known composition and mass are positioned near the tokamak and irradiated during a JET discharge. The γ rays emitted by the foils after the irradiation can be used to measure the total neutron yield of the discharge. For further information see chapter 5.2.2.
- KN3, the neutron profile monitor. This consists of 2 arrays of collimated neutron detectors which are used to measure the neutron emission profile as a function of time. For a more detailed description, see chapter 4.1.
- KN4, the delayed neutron counters. This is similar to the activation system KN2, except that it uses samples of fissile materials. The fission products

decay rapidly, with some of the daughter products emitting neutrons which are detected by KN4. This is used to monitor the total neutron yield and as the cross-sections of the fissile materials used are better known than those of the activation materials used in KN2, it is considered to have a higher accuracy than KN2 for 2.45 MeV neutrons.

- KM1, the 2.45 MeV neutron spectrometer. This consists of a number of neutron spectrometers inside a large radiation shield and is located in the torus hall. The spectrometers used are a ^3He ionisation chamber, an NE213 scintillator and an in-line proton recoil detector. The spectra are used to measure the peak ion temperature of the plasma and to look for the effects of high energy deuterons on the D-D neutron spectrum. More information on the KM1 spectrometer may be found in [1.05].
- KM3, the time of flight neutron spectrometer. This uses the time of flight of a neutron between two events to determine its energy. The detector is mounted in the roof laboratory, some 20 m above the tokamak. This diagnostic is used to measure the spectrum of neutrons emitted upwards from the torus, which can be different from the spectrum observed by KM1.
- KM7, the 14 MeV neutron monitor. This consists of a silicon diode positioned close to the tokamak and measures the time resolved 14 MeV neutron emission rate from JET. This is described in greater detail in 5.2.3.
- KP2, the escaping 14.7 MeV proton spectrometer. This consists of a 2.5 mm thick silicon diode positioned inside the vacuum vessel which detects the escaping 14.7 MeV protons. This is described in more detail in chapter 3.1.
- γ 1, γ ray spectrometers. These consist of a number of γ ray spectrometers mounted in the roof laboratory. γ rays are produced by the plasma and can be used to determine the energy distribution of high energy particles, such as those produced by ICRH.

1.4 *Thesis outline*

The work performed for this thesis mainly concerns three fusion products and each is dealt with in a separate chapter. These are preceded by a chapter on theory and summarised in a concluding chapter. The structure is as follows:

- Chapter 2. Theory. Theoretical material required for an understanding of the later chapters is introduced here for convenience. The main issues discussed are the slowing down of fast particles in a plasma, orbits of fast particles in a tokamak, sawteeth in the plasma and the spectra of fusion products.
- Chapter 3. 14.7 MeV protons. These particles are produced by the $D-^3He$ reaction and some escape from the plasma. A silicon diode near the plasma edge was used to detect these particles and to record their energy spectrum. This chapter describes the measurements made and the results derived.
- Chapter 4. 2.45 MeV neutrons. These particles are produced by the D-D reaction and are detected by a set of 3 fission chambers (KN1) and 2 collimated arrays of scintillation detectors (KN3). The data from these diagnostics are analysed with the aid of the code ORION, developed by the author, and some results are presented.
- Chapter 5. 1.01 MeV tritons. These particles are produced from the D-D reaction and slow down in the plasma over a period of up to 3 seconds. Whilst slowing down they have $\approx 1\%$ chance of undergoing the secondary D-T reaction and emitting a 14 MeV neutron. The 14 MeV neutron detector is described, together with some of its measurements. The data were analysed with the aid of 14 MeV neutron production simulation code developed by the author and the results are presented here.
- Chapter 6. Conclusions and future work. A general summary of the results obtained during the 3 years at JET, together with recommendations for further work.

- Appendices. Some of the work performed by the author does not fit readily into the overall structure of the thesis, but in order that it be documented is included in these appendices. These include a survey of α particle diagnostics for the D-T reaction and a user guide to the ORION code.

1.5 References

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2.0 Relevant physics

The purpose of this chapter is to describe some of the physics which will be needed for the later chapters.

2.1 *Theory of slowing down of fast charged particles*

Particles produced by fusion reactions typically have energies of the order of several MeV, considerably above the average particle energy for the background plasma. The charged fusion products which are confined in the plasma by the magnetic field are not in thermal equilibrium with the plasma and lose energy via collisions. The physics governing the slowing down process in the plasma has been theoretically investigated in great detail and the results appropriate to this thesis are summarised in this section, starting with a detailed formulation and working towards a more usable approximation.

2.1.1 Fokker-Planck equation

The Fokker-Planck equation [2.01] is a partial differential equation which is commonly used in plasma physics to calculate the evolution of a population of charged particles in time. The full derivation may be found in most plasma physics textbooks [2.02-2.04] and will not be discussed here. The general form of the equation is shown in eq. 2.1, where the subscript a refers to the test particles under study and the sum over the b subscript implies a summation over all the charged species present in the plasma.

$$\frac{df_a(\mathbf{v})}{dt} = - \sum_b \Gamma_a Z_b^2 \ln \Lambda_{ab} \frac{\partial}{\partial v_i} \left[f_a(\mathbf{v}) \frac{\partial H_b(\mathbf{v})}{\partial v_i} - \frac{1}{2} \frac{\partial}{\partial v_j} \left(f_a(\mathbf{v}) \frac{\partial^2 G_b(\mathbf{v})}{\partial v_i \partial v_j} \right) \right] \quad [2.1]$$

where

$$\Gamma_a = \frac{Z_a^2 e^4}{4\pi\epsilon_0^2 m_a^2} \quad [2.2]$$

$$G_b(\mathbf{v}) = \int d\mathbf{v}' f_b(\mathbf{v}') |\mathbf{v} - \mathbf{v}'| \quad [2.3]$$

$$H_b(\mathbf{v}) = \left(1 + \frac{m_a}{m_b} \right) \int d\mathbf{v}' \frac{f_b(\mathbf{v}')}{|\mathbf{v} - \mathbf{v}'|} \quad [2.4]$$

$$\ln \Lambda_{ab} = \ln \left[\frac{\lambda_D}{L} \right] \quad [2.5]$$

- and
- m_x = the mass of a particle of species x,
 - Z_x = the charge of a particle of species x,
 - n_x = the number density of species x,
 - f_x = the distribution function of species x,
 - h = Planck's constant,
 - λ_D = the Debye length = $\sqrt{\frac{\epsilon_0 T_e}{n_e e^2}}$
 - L = the larger of $L = \frac{Z_a Z_b e^2}{4\pi\epsilon_0 \mu \bar{v}_{ab}^2}$ or $L = \frac{h}{\mu \bar{v}_{ab}}$,
 - T_e = the electron temperature of the background plasma,
 - μ_{ab} = the reduced mass = $\frac{m_a m_b}{m_a + m_b}$,
 - $\bar{v}_{ab}$ = the relative speed averaged over species a and b.

Equations 2.1-2.5 can be solved if an accurate model of the slowing down of fast particles in the plasma is needed. For the purposes of this thesis, a time dependent solution of the equation is required and this is difficult. Programs to perform this are available, but are very slow. Approximations and assumptions can be made to simplify the solution and these are described in the next section.

2.1.2 Single particle approximation

Two assumptions may be made that make the Fokker-Planck equation much more tractable. The first is to assume that the species which is slowing down in the plasma can be modelled by an initial distribution function in the shape of a δ function. The initial energy of the δ function is given by the fusion reaction under study. This is suitable for modelling the slowing down of a single (test) particle in a plasma. The second assumption is that the background plasma is composed of species with Maxwellian distributions, which allows the G and H functions to be simplified. The derivation is shown in some detail in [2.04,2.05], but gives a solution in the form of :

$$\frac{dE}{dt} = -v_E E \quad [2.6]$$

where

$$v_E = \frac{2m_a \Gamma_a}{v^3} \sum_b \frac{n_b Z_b^2 \ln \Lambda_{ab}}{m_b} \left[\Phi\left(\frac{v}{v_b}\right) - \left(1 + \frac{m_b}{m_a}\right) \frac{v}{v_b} \Phi'\left(\frac{v}{v_b}\right) \right] \quad [2.7]$$

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2} du \quad [2.8]$$

and E = the energy of the test particle,
 v = the velocity of the test particle.

The expression 2.7 is true for a wide range of plasma conditions. In practice, the conditions normally encountered for MeV charged fusion products are $\frac{v}{v_e} < 0.3, \frac{v}{v_i} > 3$ which permits a further simplification of $\Phi(x)$ and the eqs 2.9-2.11 are then good approximations of 2.6-2.8.

$$\frac{dE}{dt} = \frac{-\alpha}{\sqrt{E}} - \beta E \quad [2.9]$$

$$\alpha = 1.81 \times 10^{-13} \ln \Lambda_{ab} A_a^{1.5} Z_a^2 \sum_b \frac{n_b Z_b^2}{A_b} \quad [2.10]$$

$$\beta = 3.18 \times 10^{-15} \ln \Lambda_{ae} \frac{Z_a^2 n_e}{A_a T_e^{1.5}} \quad [2.11]$$

and A_x = the atomic number of species x,
 $\ln \Lambda_{ae}$ = the Coulomb logarithm for collisions between the test particle and electrons,
 T_e = the electron temperature (in eV),
 b = the subscript for all ionic species.

The main advantage in using the approximate form of the test particle equation is that an analytic form for the energy as a function of time is available, if the α and β terms are assumed to vary slowly with energy and time, which is usually a valid assumption. The analytic form used is shown in eq 2.12.

$$E(t + \Delta t) = \left[E(t)^{3/2} e^{-3\beta\Delta t/2} + \frac{\alpha^{2/3}}{\beta} (e^{-3\beta\Delta t/2} - 1) \right]^{2/3} \quad [2.12]$$

This is referred to later in this thesis as the Batistoni form of the slowing down.

2.2 *Magnetic fields and particle orbits in a tokamak*

Knowledge of the behaviour of charged particles in the magnetic field of JET is necessary for the later chapters. The basic theory of particle orbits in a tokamak is well known [2.02,2.03,2.06] and so will only be briefly summarised below.

2.2.1 Basic theory

A charged particle in a magnetic field can be considered to have two velocity components. One parallel to the field ($v_{\parallel}$) and one perpendicular to the field ($v_{\perp}$), as shown in fig 2.1a. The pitch angle of the particle is defined as the angle between the magnetic field line and the velocity vector of the particle, with a pitch angle of zero implying a particle travelling along the field line. The particle gyrates at a frequency ω_L given by:

$$\omega_L = \frac{qB}{m} \quad [2.13]$$

where q = the charge of the particle,
 B = the magnetic field strength,
 m = the mass of the particle.

The radius of the orbit is also defined as $r_L = \frac{v_{\perp}}{\omega_L}$

It can be shown that the magnetic moment of the particle, μ (given by $\mu = \frac{mv_{\perp}^2}{2B}$), is a constant of motion of the particle. Also, particles following the curved magnetic field in a tokamak experience a drift in the vertical direction. If the drift is vertically upwards, then while a particle is in the top half of the tokamak there is a tendency for the particle to drift outwards across the flux surfaces and to drift inwards when in the lower half. Finally, the magnetic field strength in a tokamak rises as a particle approaches the major axis of the torus. These elements of basic theory imply that there are two classes of particle orbit in a tokamak, passing and trapped. These are explained in the next section.

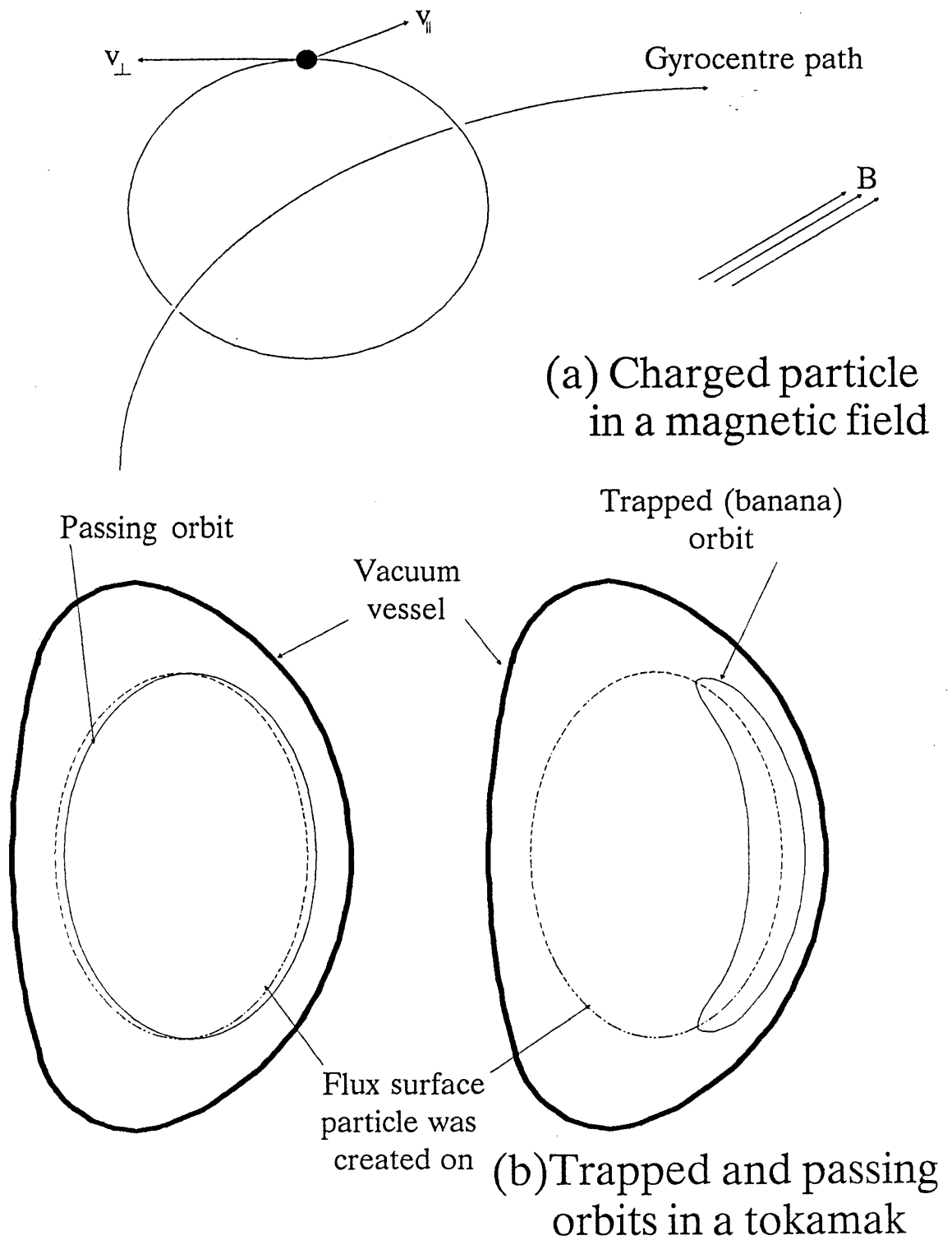


Figure 2.1. Charged particle orbits in a tokamak: Figure (a) shows the parallel and perpendicular velocity components of a charged particle in a magnetic field. Figure (b) shows the shape of passing and trapped gyrocentre orbits in a tokamak.

2.2.2 Passing and trapped particles

These two classes of orbit are illustrated in fig 2.1(b). A passing orbit usually follows a flux surface fairly closely. There is a small displacement radially outwards relative to the flux surface because of the effect of the vertical drift on the particle. A trapped orbit (also known as a banana orbit) has a very different shape. The particle may be considered to be born on a flux surface and, like a particle on a passing orbit, moves in towards the major axis. As it approaches the major axis, the magnetic field increases. In order to conserve μ , the value of $v_{\perp}$ increases. Hence, to maintain energy conservation, the value of $v_{\parallel}$ falls until it reaches zero at the tip of the banana orbit. The particle then starts to move radially outwards in major radius. The effect of the vertical drift on the particle is to transport the particle across the flux surfaces. As the average value of $v_{\parallel}$ is lower in this case than for a passing particle, the effect of the vertical drift is more pronounced. The time taken to cycle through a whole orbit is on the order of μs for the majority of fusion products.

The banana orbits allow a particle to make a large excursion from the flux surface of origin and a fraction of these orbits leave the plasma and intersect either the vessel wall or the limiters. Any particles on such an orbit are lost from the plasma. The range of pitch angles from which particles will be lost to the walls is known as the loss region. The loss region may be reduced by increasing the plasma current, experimenting with lower energy particles and by generating most of the fusion products near the plasma centre. For the case of 14.7 MeV protons, a significant fraction of the particles escape from the plasma, allowing an escaping proton detector to be used. This detector is described in the next chapter. For the case of 1.01 MeV tritons, to be discussed in chapter 5, almost all the tritons are confined, typically only a few percent escaping. The effect of the loss region may be enhanced by two further effects: pitch angle scattering and ripple trapping. Pitch angle scattering implies that the pitch angle of the fusion product changes as the particle slows down in the plasma. In general, this is quite a small effect until the particle reaches an energy of order 20 times the plasma ion temperature (expressed in keV). Even then, the fraction of particles

scattered into the loss region will normally be less than originally present in the loss cone and can be ignored for the purposes of this thesis. The effect of ripple trapping is described in [2.07] and refers to the ripple in the toroidal magnetic field introduced by using a finite number of coils. Particles undergo diffusion because of the ripple and are lost from the plasma. Again, the impact of this effect upon the results presented in this thesis is expected to be negligible.

2.3 *Fusion product spectra.*

For a fusion reaction of the type A(B,C)D the energy of the C particle is given by:

$$E_C = \frac{m_C V^2}{2} + \frac{m_D}{m_C + m_D} (Q + K) + V \cos \theta \sqrt{\frac{2m_C m_D (Q + K)}{m_C + m_D}} \quad [2.14]$$

where

- Q = the energy released by the fusion reaction,
- V = the centre of mass velocity,
- K = the kinetic energy of the reacting particles,
- θ = the angle in the centre of mass frame between the relative velocity and the fusion product,
- m_i = the mass of particle i.

For the case of Maxwellian populations reacting in a plasma, it can be shown that the resultant spectra from eq 2.14 are gaussian in shape with the FWHM of the gaussian being approximately proportional to the square root of the temperature of the ions [2.08]. Measurements of the energy spectra of fusion products can be used to determine ion temperatures for ohmic plasmas. However for non-Maxwellian distributions the spectra must be found numerically and the FPS code at JET is used for this purpose [2.09]. The most important case of this at JET is that of the anisotropic deuterium population introduced by the Neutral Beam Injection system. Reactions between beam particles and the background of plasma particles generate neutrons (called beam-plasma neutrons) with a spectrum similar to that of a plasma with an ion temperature of 20 keV. In order to analyse discharges with neutral beam

heating, the effect of this broadening of the neutron spectrum must be considered.

2.4 *Sawteeth*

During most discharges at JET, sawtooth activity is present. This phenomenon can be observed by viewing the axial electron and ion temperatures, which are seen to rise for ≈ 100 -200ms then abruptly crash to near their original value in $\approx 100\mu\text{s}$. As the total neutron emission rate is rather sensitive to changes in the ion temperature profile the effect of sawteeth on the total neutron emission rate may be pronounced, as shown in figure 2.2(a). Idealised electron temperature profiles before and after a sawtooth crash are shown in figure 2.2(b) and it can be seen that the profile flattens at the crash, redistributing the energy of the plasma. The reason that the electron temperature profile peaks during the ramp phase is that the effects of plasma heating are usually strongest on axis. However, the reason for the crash phase is not understood. It is generally considered to be a relaxation by the plasma to a lower energy state, although the trigger for it is not known. Several theories exist, but none are fully satisfactory at the time of writing [2.10,2.11]. The effect of sawteeth on fusion products will be discussed in the later chapters, although the effect on the production of 2.45 MeV neutrons has been reported in detail by other authors [2.12].

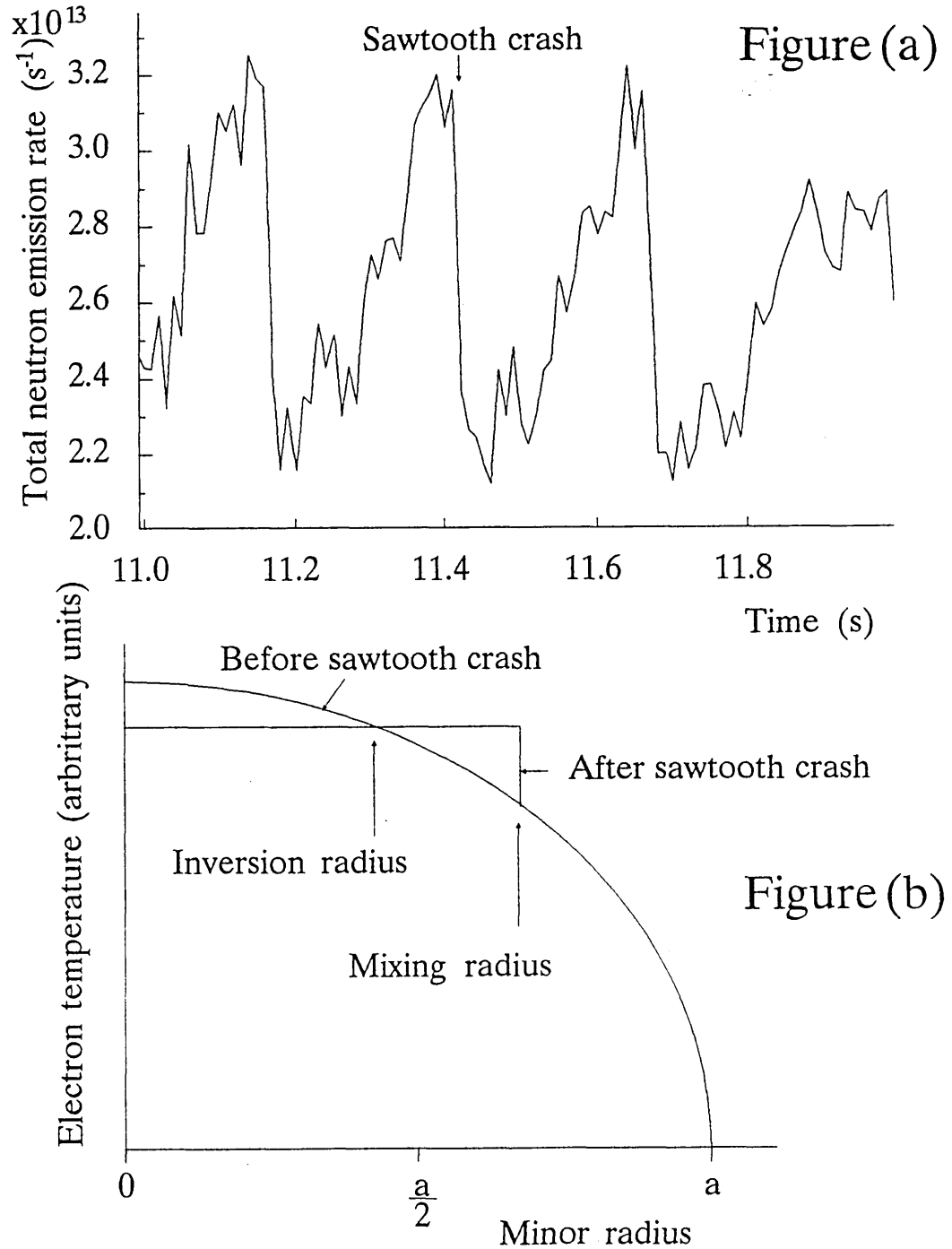


Figure 2.2. Diagrams illustrating the sawtooth phenomenon: Figure (a) shows the characteristic shape of the total neutron emission rate measured during sawtooth activity. Figure (b) shows idealised electron temperature profiles before and after a sawtooth crash. The profile flattens and the plasma inside the mixing radius homogenises.

2.5 *References*

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3.0 Escaping 14.7 MeV protons

This chapter concerns work performed in relation to the KP2 detector, which was used to observe escaping 14.7 MeV protons and was operated at JET for a period lasting from November 1987 to February 1988. The chapter opens with a brief history of the detection of escaping charged fusion products and an examination of the environment at JET showing why the 14.7 MeV proton is the only particle suitable for use with this class of detector. This is followed by a description of the detector used and the results obtained.

3.1 *Introduction*

Charged fusion products (CFPs) have been used extensively in the past as a means of probing magnetically confined plasmas [3.01-3.19]. The basic principle relied upon is that not all of the CFPs produced by the fusion reactions are confined in the plasma and some particles escape to hit the walls of the vessel. If a wall-mounted detector is capable of measuring the energy of the charged particles, then information on the nuclear processes occurring inside the plasma may be deduced. The normal detector used is a silicon surface barrier diode which is capable of measuring the energy of the charged particles with an energy resolution of better than 1%. This is adequate for spectroscopy of the charged particles to be used to determine information on the distribution functions of the reacting particles. If good collimation is available for the charged particles, then the paths of the orbits can be traced back into the plasma to define a small region from which the particles originated. If arrays of such detectors are employed, or one detector with pitch angle resolution, then profiles of ion temperature may be deduced. The detector used at JET was

constructed primarily to study the distribution function and spatial variations of RF heated ions.

Escaping CFP diagnostics have proved to be extremely useful on machines smaller than JET. However, at JET there are serious problems of implementation. As shown in Appendix A (Table 2), the region from which CFPs can escape is small for normal JET discharges. Combined with the fairly peaked CFP birth profiles, this means that the escaping fusion products such as 1 MeV tritons or 3 MeV protons must be born near the edge and only a few percent of the total production will escape from the plasma. For a fusion product to have a high probability of escaping when emitted from the centre of the plasma, a much larger energy is required and the 14.7 MeV proton from the $D(^3\text{He},p)^4\text{He}$ reaction is the best candidate. This conclusion is strengthened by the fact that silicon diodes operating near the JET vacuum vessel are sensitive to the low energy neutrons and γ rays, which produce a low energy background in the spectrum, making observations on charged particles with energies less than 6 MeV very difficult.

The first escaping proton detector at JET (KP1) was built and operated in 1985. It was intended for the study of RF heated populations of ^3He or deuterium, as the proton spectra reflect the energy distribution of the ions involved in the reaction. This role has since been taken over by studies of γ rays emitted from fusion reactions [3.20]. It was operated successfully and much useful information was obtained. It produced certain results which required further investigation. The most important of these was the appearance of dips in the detected proton signal, as shown in fig. 3.1, which could not be explained satisfactorily. In order to investigate this and to extend the observations made with KP1, an improved detector (KP2) was constructed and installed at JET. The next section describes the detector and its operation.

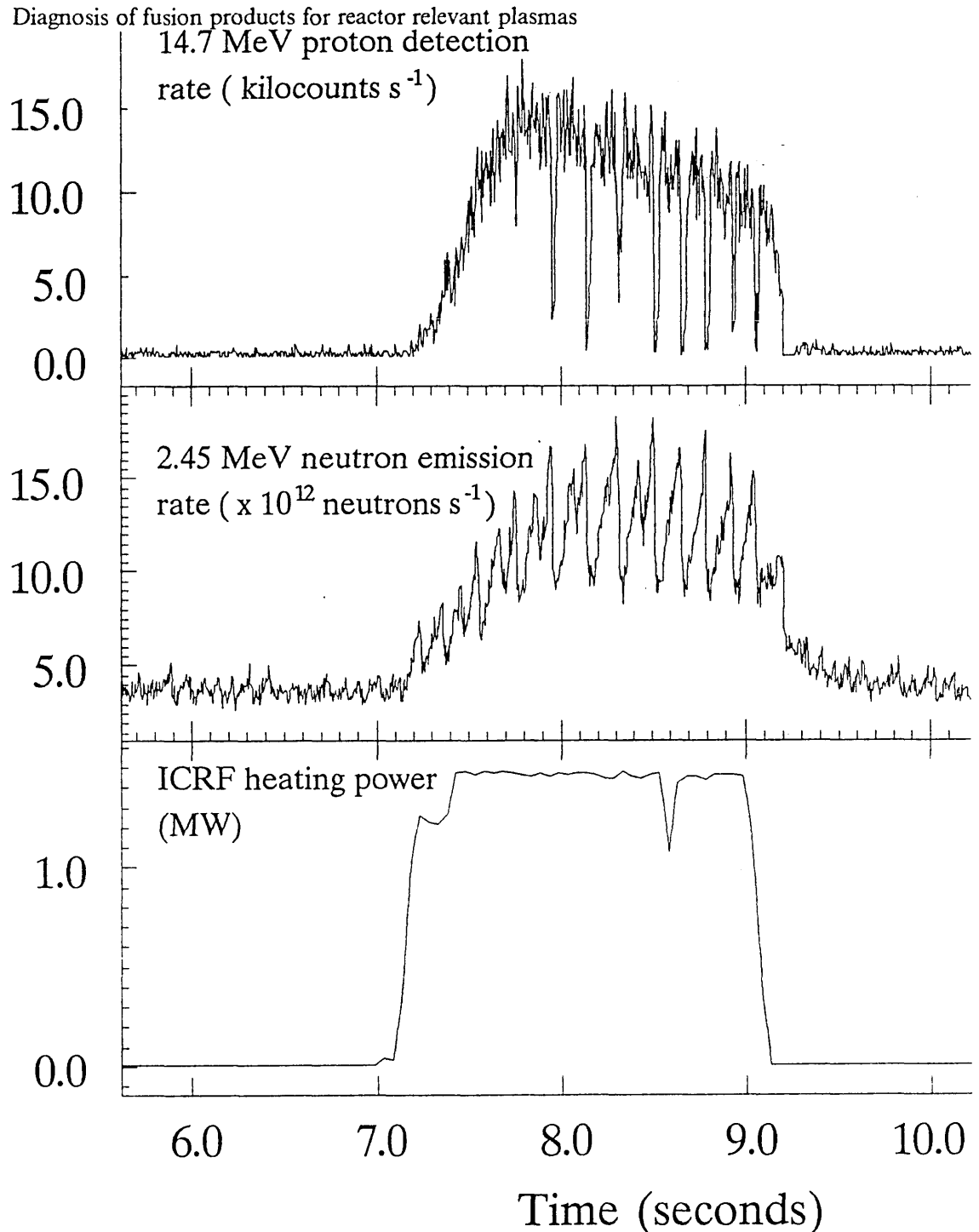


Figure 3.1. KP1 signal showing dips: Data obtained with the original 14.7 MeV proton spectrometer indicated the existence of dips in the proton emission rate correlating with the sawtooth crashes seen on other diagnostics. The cause for these dips was unknown and part of the motivation for building KP2 was to further characterise them.

3.2 *Detector design*

The major problems in the use of a silicon diode near the plasma relate to the temperature of the diode and the vacuum conditions. Silicon diodes operate at temperatures less than 20°C and require the temperature to remain constant for best results. The vacuum vessel into which the KP2 assembly is mounted, fig. 3.2, is at a temperature of $\approx 300^\circ\text{C}$ under normal operating conditions; hence, the device must be cooled. Water cooling was adopted. The inside of the KP2 tube also had to operate at a good vacuum, as the torus was separated from it by a $20\mu\text{m}$ thick stainless steel window and the diagnostic had to be designed so that it would not affect the torus vacuum in case of window failure. One of the consequences of the vacuum restriction was that a number of insulators, required to reduce the heat conduction from the vacuum vessel to the diode, had to be made out of ceramic materials. Unfortunately, ceramic materials tend to shatter when subjected to violent impacts and the failure of several of these ceramic components led to operational difficulties and the eventual demise of the diagnostic.

The lower end of the KP2 tube is shown in fig 3.3. The important features incorporated into the design are:

- Adjustable collimator. A rotatable cylinder surrounded the detector mounts. This cylinder had a range of collimators ranging from 0.3mm to 8mm in diameter built into it, any of which could be used to collimate the proton flux at the diode. The advantages of this system were twofold. Firstly, the variation in collimator size allowed the proton events at the diode to be kept to a level which the electronics were capable of handling. Secondly, by altering the position of a collimator relative to the centre of the diode, particles from different regions of the plasma could be detected, hence allowing the measurement of profiles if the discharges used were reproducible adequately.
- Two silicon diodes. These were lithium drifted silicon diodes with a surface area of 100 mm^2 and nominal depletion layer thicknesses of $2500\mu\text{m}$,

Diagnosis of fusion products for reactor relevant plasmas

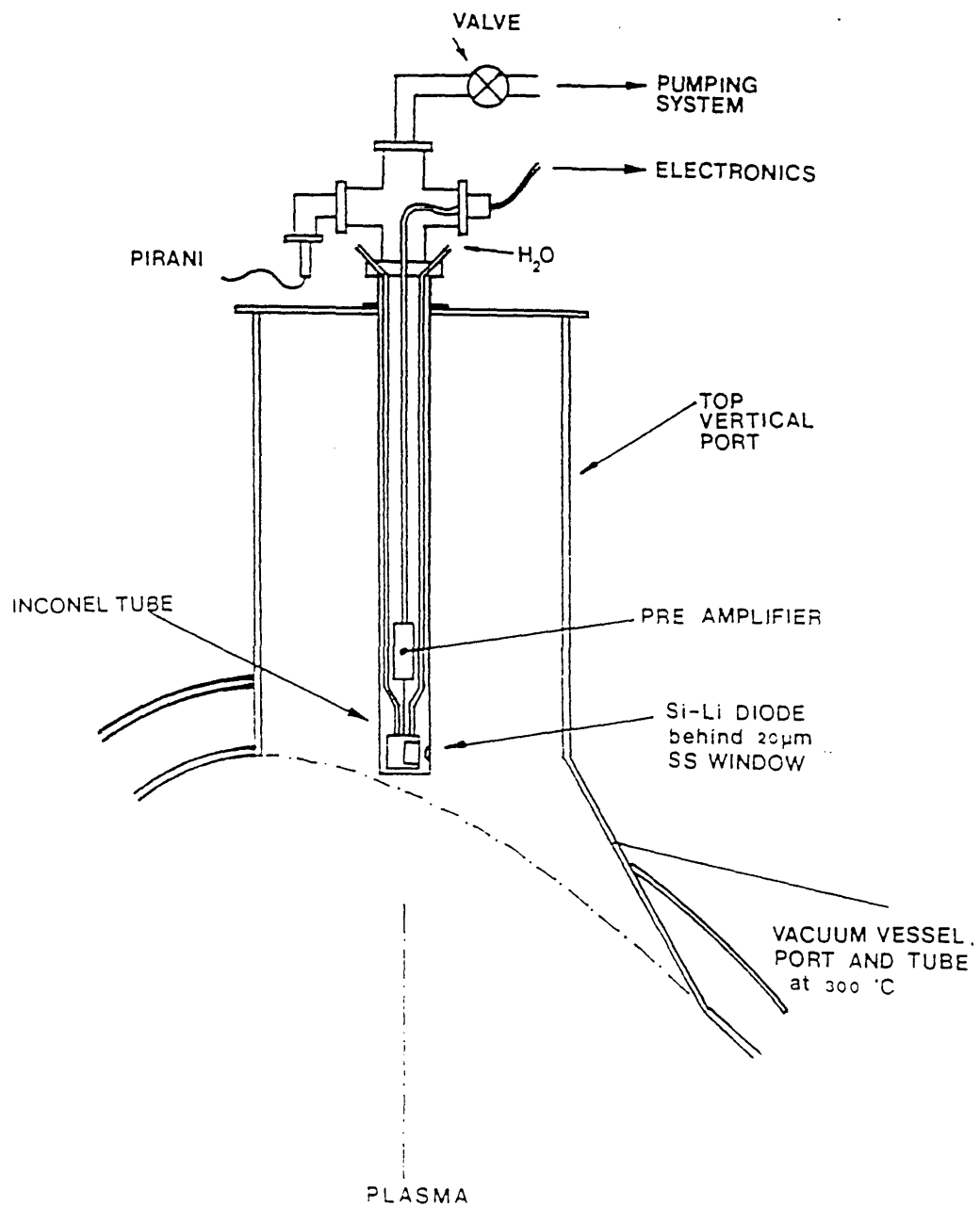


Figure 3.2. Picture showing KP2 construction and location

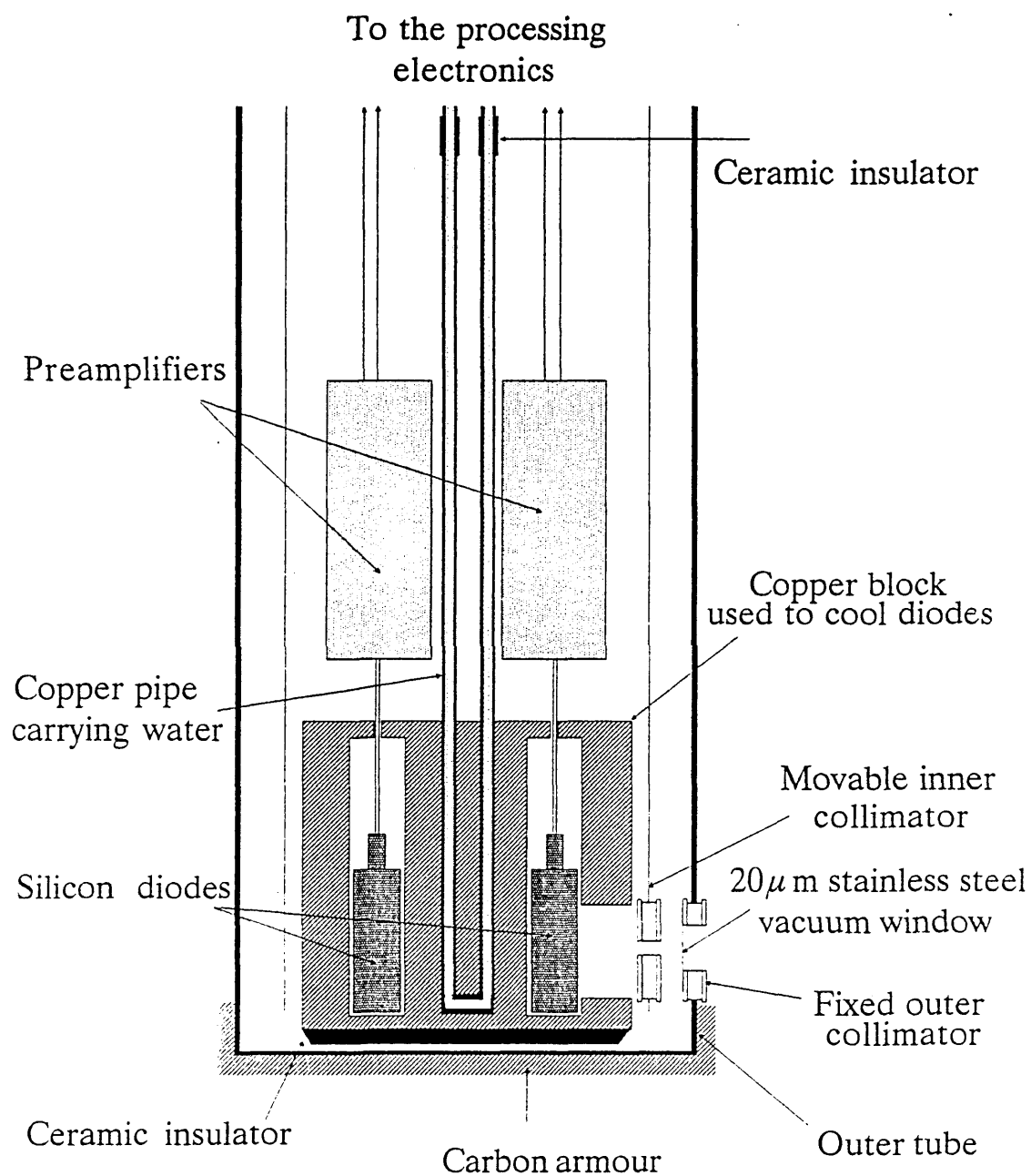


Figure 3.3. Detailed view of the end of the KP2 detector

sufficient to stop 20 MeV protons. One diode was open to the plasma, and protons interacted with this diode. The second diode was not open to the plasma, hence the only events detected by this diode were those attributable to interactions with neutron scattering and γ rays. The intention was to use the second diode to correct for background, although in most cases the proton signal was of sufficiently high energy to be easily distinguishable from the background.

- Preamplifiers. In order to obtain good energy resolution, the signal from each diode was put through a preamplifier, located as close as possible to the silicon diode to reduce distortion in the signal. The preamplifier operated with a $2\mu\text{s}$ time constant, limiting the total count-rate to 20 kHz before dead time corrections became significant.

The electronics used to process the signals from the diodes are shown in fig. 3.4. The pulser was used to monitor the stability of the system when the count-rates became high, as the pulser peak broadened due to pulse pile-up and the observed pulser peak count-rate decreased due to dead-time effects. By observing the pulser peak the effect of the broadening and the count-rate corrections for dead-time could be evaluated. A typical spectrum produced by the system is shown in fig. 3.5 where the proton peak, pulser peak and the low energy events due to neutrons and γ rays are shown.

One of the major problems in operating KP2 was the background of low energy events, as they constituted the majority of the signals in almost every discharge. These signals appeared whenever the neutron yields were high; for neutron emission rates in excess of $\approx 10^{15} \text{ s}^{-1}$, the low energy event count-rate exceeded 20 kHz and caused deterioration of the 14.7 MeV proton signal. The KP2 detector worked best for low current discharges with 1-2 MW of RF heating as large numbers of protons could escape from the plasma without the total count rate limit of the detector being exceeded. This is a regime in which JET operates rarely and it is for this reason that although approximately 2000 discharges were observed, very few gave results which could be analysed.

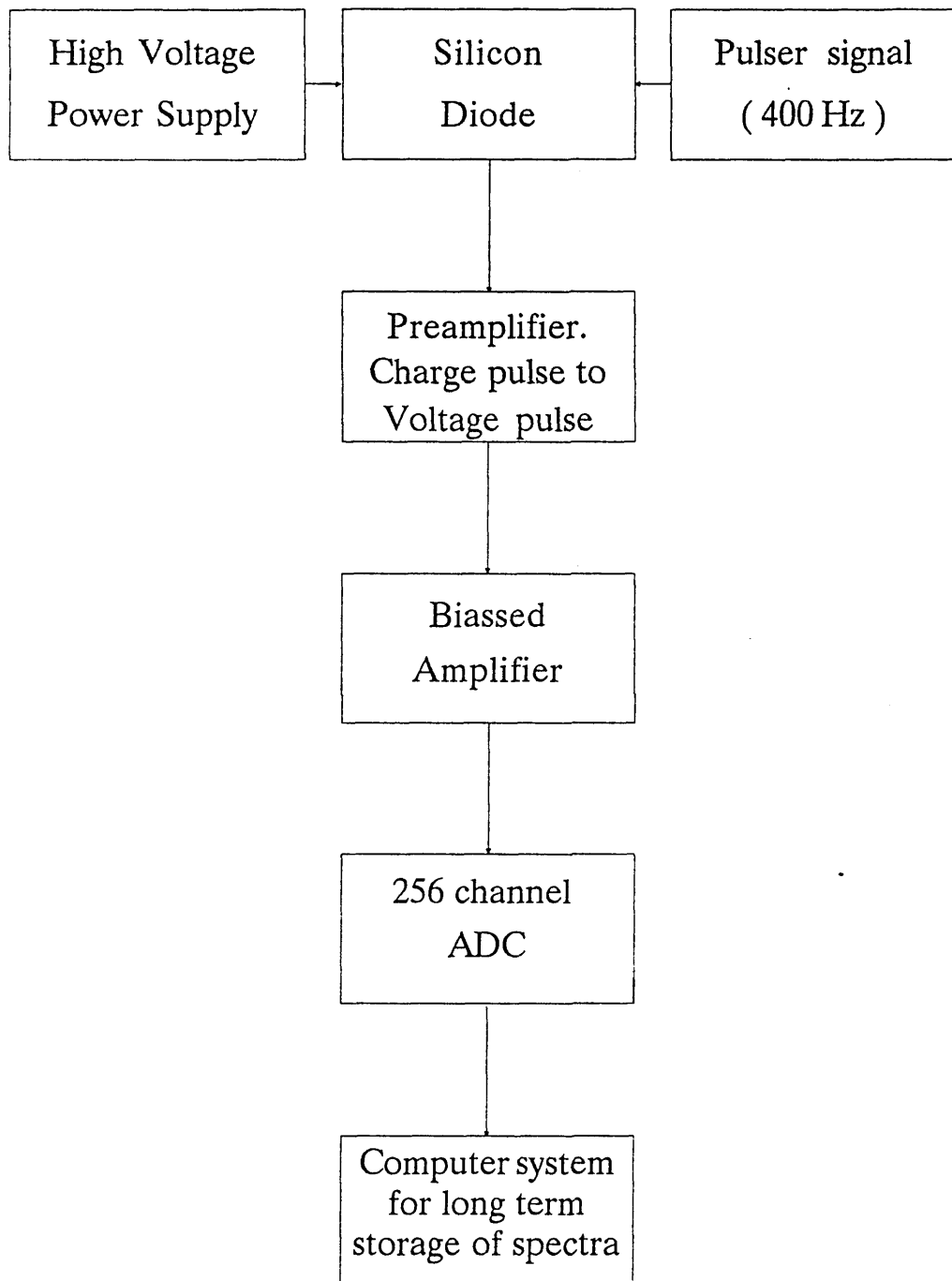


Figure 3.4. Pulse processing electronics used for each diode in KP2.

Events per energy bin

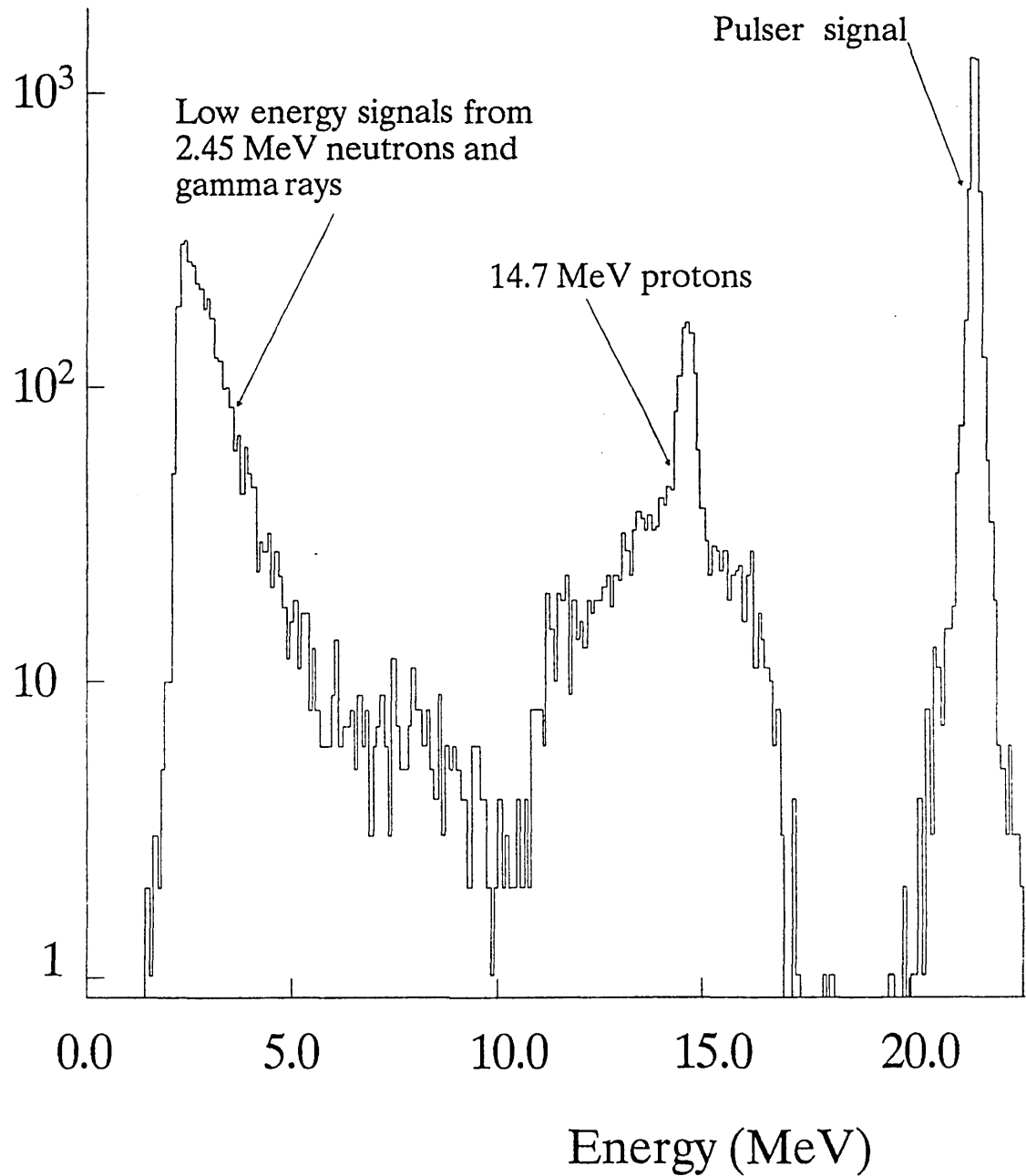


Figure 3.5. Typical energy spectrum from KP2 detector: The spectrum has been obtained by integrating over an entire discharge. The size of the energy bins is 89 keV.

In order to reduce the heating of the diode by the current passing through it, the voltage on the diode was increased to the operating value just before a discharge and was reduced to 50V just after a discharge. The 50V bias voltage was maintained to reduce the effects of radiation damage on the diode, as previous diodes had shown severe degradation of performance when left unbiased after exposure to neutrons. This operation was originally performed by hand, later it was automated. The diode performed well initially, until a disruption shattered some of the ceramic insulators, the remains of which fell into the collimator mechanism causing it to jam. After this point the rotation of the collimator became difficult, depending upon disruptions to jerk the collimation cylinder above the ceramic fragments. This method did not allow any great precision in the positioning of the collimators, so that the planned scans through pitch angle were not performed.

After a shutdown, the shattered pieces of ceramic were removed and the insulators replaced with a more robust structure composed of ceramic and aluminium oxide. Then another disruption shattered the ceramic piece used as an insulating section of the water cooling. This ceramic insulator was necessary as the metal water pipes had to be electrically insulated from the diode and associated electronics inside the KP2 vacuum tube. When this broke, the water leaked out and caused damage although, fortunately, the thin window to the plasma did not rupture. After this, the probe was removed from the machine and has not been rebuilt because, simultaneously with this failure, access to the torus was severely restricted as an administrative action to encourage the development of systems which will function unattended for long periods of time, as will be essential during the D-T phase of JET operations. As KP2 required considerable maintenance, this effectively stopped further work. Fortunately, KP2 had already provided answers to the questions left over from KP1.

3.3 Data Analysis.

In order to perform an accurate quantitative analysis of the escaping proton data, a code is required to track the orbits of all the particles reaching the silicon

diode through its collimator, showing which regions of the plasma the protons may have come from and what the detection efficiency of KP2 is for these regions. Such a code has been installed at JET, but at the time of writing the results from it are not consistent with reasonable expectations. Until this is rectified the code cannot be used as a working tool; consequently, the results presented here are qualitative and preliminary. When the orbit-following code is improved, the analysis will be repeated. Fortunately, a code which calculates the orbits of single particles in the JET magnetic field is available and this can be used to estimate roughly the region of the plasma where detected protons originated from. This is performed by starting a few protons at the detector surface, with pitch angles appropriate to pass through the collimator, and tracing their orbits backwards in time, estimating by eye the minimum minor radius (at which the emission is supposed to occur). This should give the location of the region to which the detector is most sensitive to an accuracy of approximately $\pm 20\text{cm}$.

The first topics to be discussed are the three routes for the production of 14.7 MeV protons. The three prescriptions are:

- Maxwellian deuterium + Maxwellian ^3He (at the same temperature),
- Maxwellian deuterium + ^3He produced from D-D reactions,
- Maxwellian deuterium + RF heated ^3He .

These represent the three general classes of proton production, although the last could be expanded by including the possibility of RF heated deuterium in a ^3He plasma. The spectra of 14.7 MeV protons produced from each route are different, as illustrated in fig. 3.6, although the difference between the spectra from production routes 2 and 3 is small. The peak of the reactivity occurs near 600 keV (fig.3.7), hence the bulk of the reactions occur near the peak of the reactivity and the proton energy spectrum reflects this.

The spectrum of protons produced from Maxwellian populations of deuterium and ^3He is approximately gaussian in shape and the width of the

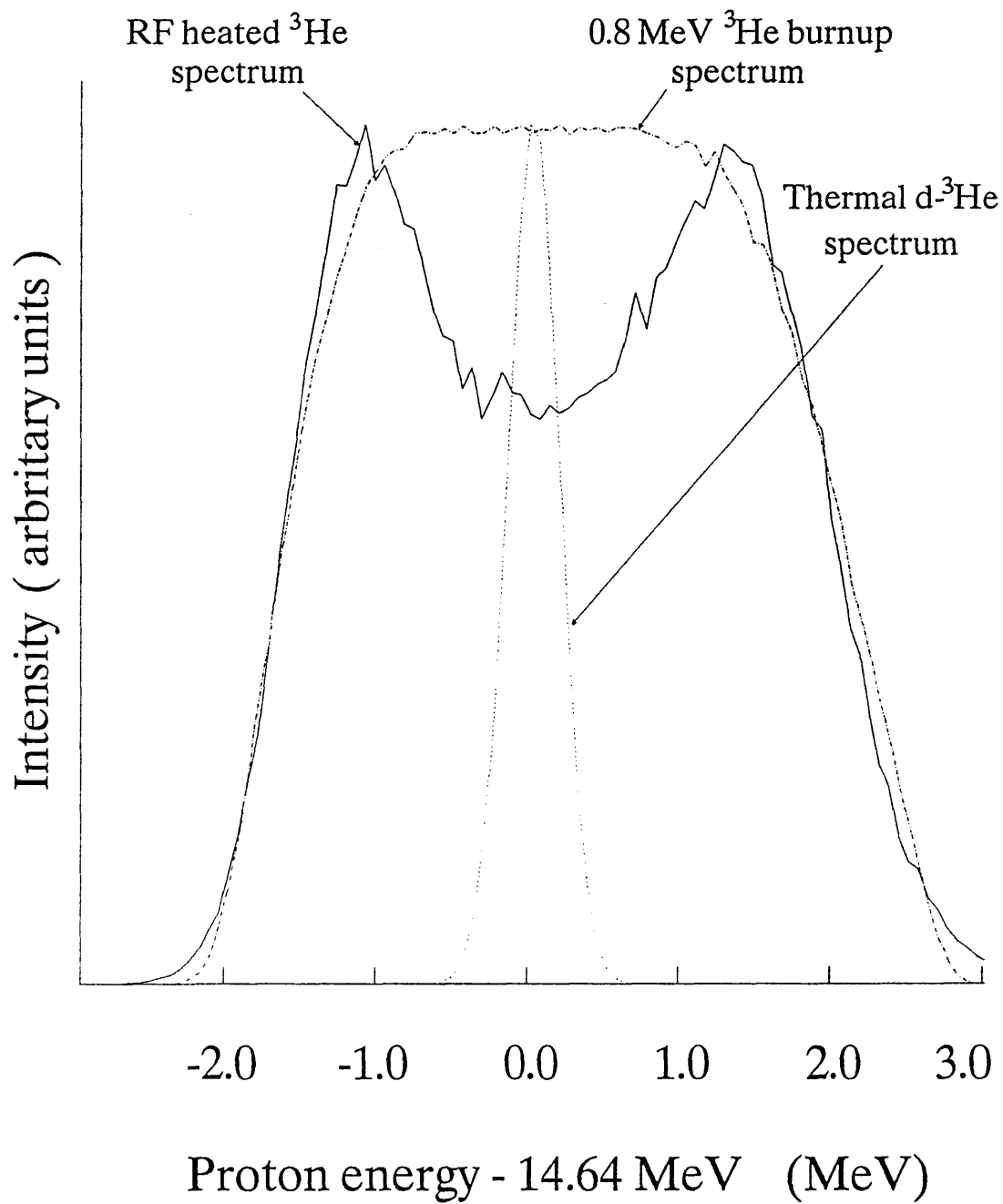


Figure 3.6. 14.7 MeV proton spectra from three production routes: The three spectra were calculated using the FPS code [3.21].

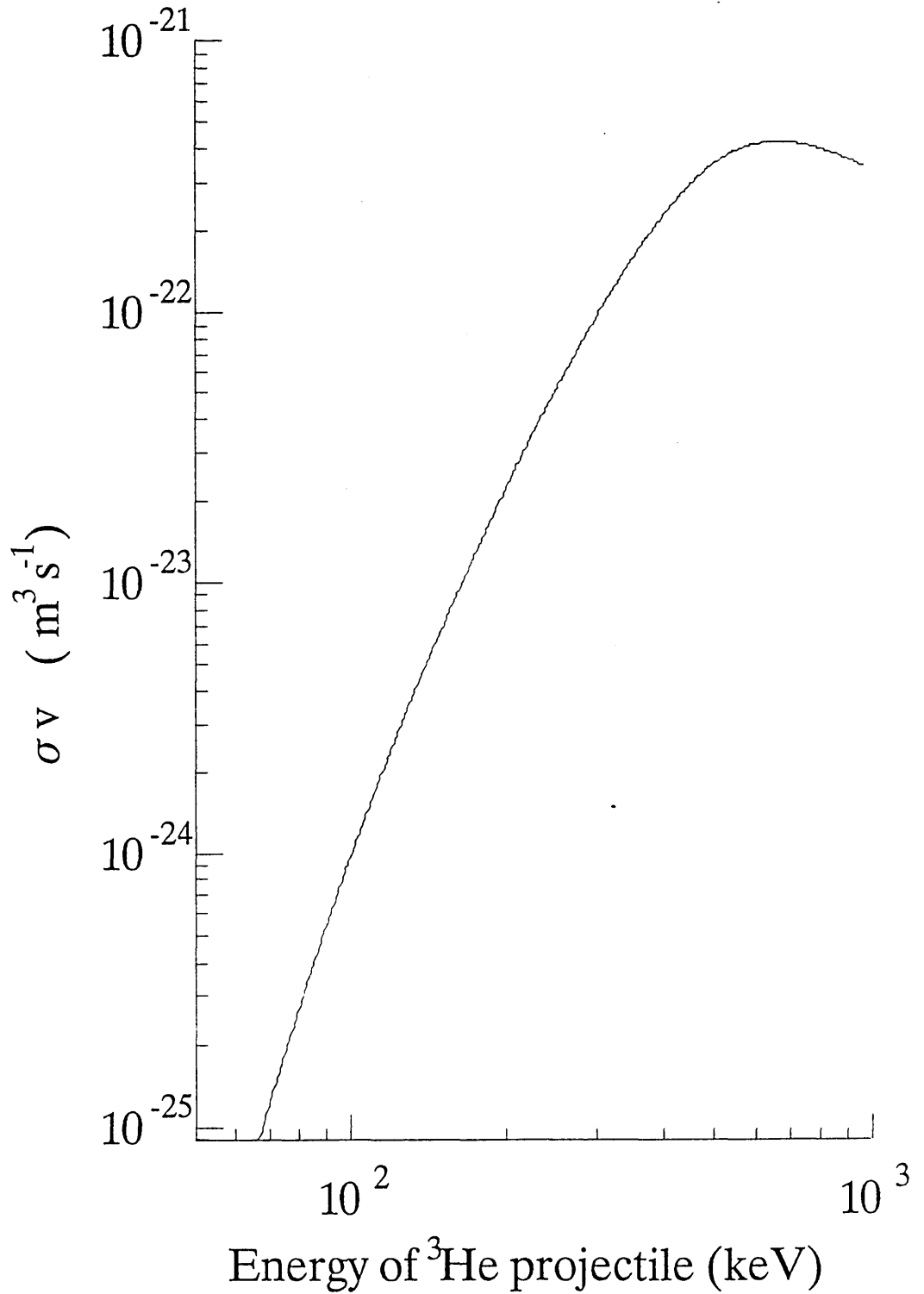


Figure 3.7. Reactivity for D-Helium 3: The reactivity is for a projectile ^3He nucleus passing through a cold deuterium plasma

gaussian gives the temperature of the ions [3.21]. The temperature of the plasma can be measured this way, although the associated errors are rather large because the width of the gaussian spectrum of the protons is similar to the resolution of the instrument. The formula used is :

$$T_i = \frac{W^2 - R^2}{182^2} \quad [3.1]$$

where T_i = the derived ion temperature in keV,
 W = the measured FWHM of the proton peak in keV,
 R = the measured detector resolution in keV.

The FWHM of the proton peak is measured by fitting a gaussian to the proton peak. The detector resolution is measured by fitting a gaussian to the pulser peak and measuring its FWHM. The pulser has an intrinsic width much narrower than a single channel of the spectrum, hence any broadening is due to the detector resolution. A spectrum where this can be used is shown in figure 3.8, where a discharge that had a large quantity of ^3He present was observed. From this spectrum, $W=477\pm40$ keV and $R=280\pm6$ keV, which gives an ion temperature of 4.5 ± 0.8 keV, a value roughly consistent with the X-ray crystal spectrometer value of 4.0 ± 0.5 keV for this discharge. The problem with this kind of measurement is that the exact location of the ion temperature measured on the radial profile is not known accurately and that it is not very accurate.

The other use for the peaks observed from route 1 is to calibrate the energy scale of the detector, as the energy of protons from the plasma will be simply their birth energies less the energy lost in passing through the thin window in front of the diode. By assuming that channel 1 corresponds to 0 keV and correcting the proton energy for the energy lost in the thin window, 0.5 or 1.5 MeV depending upon the window used, a reasonably accurate energy calibration can be obtained.

One of the principal aims of the KP2 detector was to study sawtooth activity. A series of discharges with plasma current 3.5MA and toroidal magnetic field

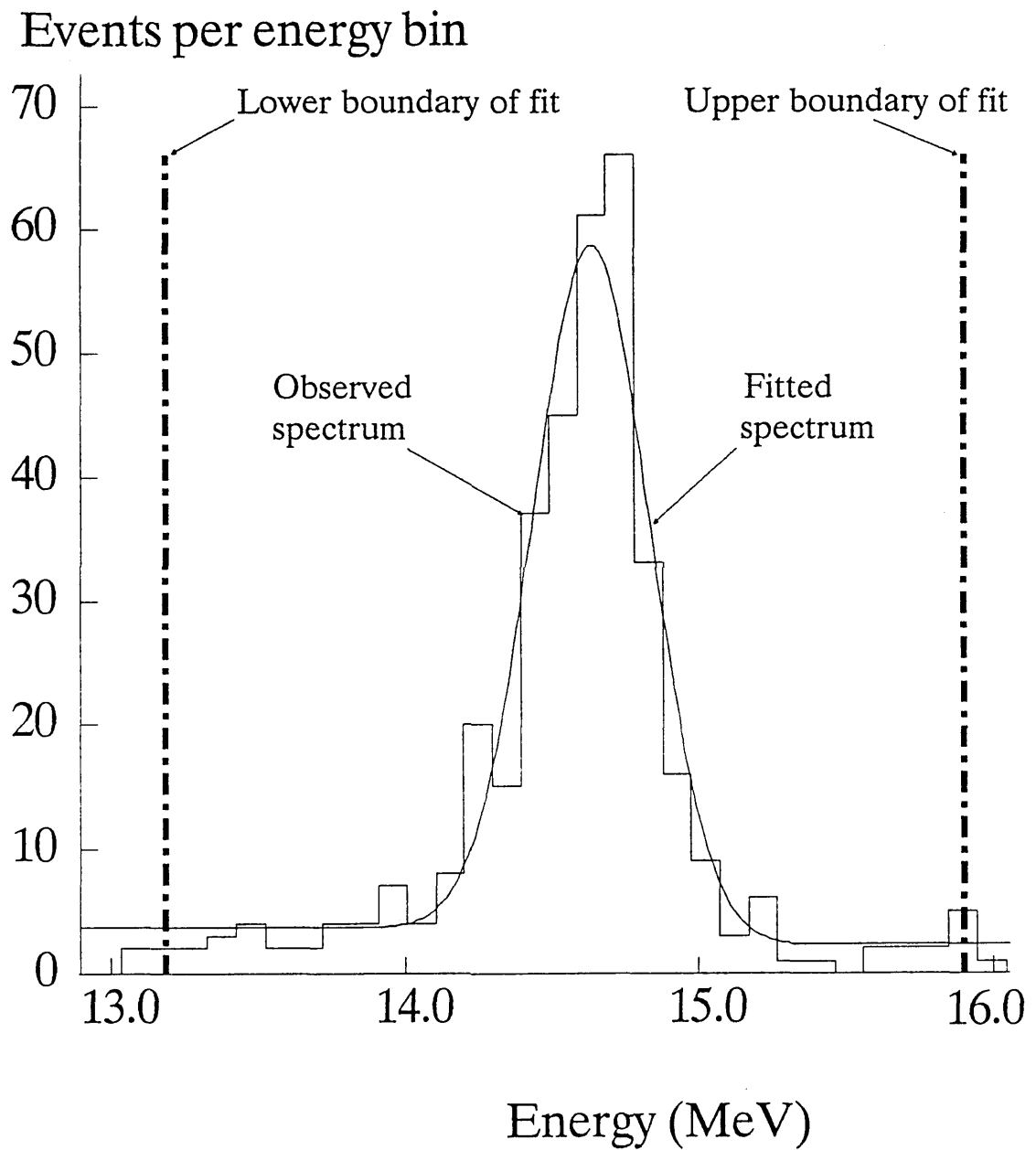


Figure 3.8. 14.7 MeV proton spectrum from JET discharge

3.5T have been examined in detail as these demonstrated a marked dependence upon the sawteeth. The discharges were mainly deuterium, with a minority ^3He component used for the RF heating. The RF powers were 1-2 MW and fig. 3.9 shows the proton count rate from the KP2 diagnostic during a typical discharge. The large spikes commence at the time of the sawtooth crash and last for typically 30-40 ms. If the proton spectra between spikes are compared to the proton spectra during spikes, then the spectra are seen to be similar (fig. 3.10) but, as the number of counts in the between-spikes spectrum is small, the details of the spectrum cannot be resolved. Further comments are: (i) that the width of the proton spectrum appears to be dependent upon the RF power input to the plasma and (ii) that full orbit code calculations show that the centre of the plasma cannot be observed with KP2.

The following model is suggested to account for these observations. The ^3He population develops a high energy tail during RF heating. Most of the energy is deposited near the centre of the plasma with a much lower amount deposited in the region accessible to KP2. At the crash phase of the sawtooth, the high energy ^3He near the plasma centre is displaced and during the mixing phase becomes more homogeneously distributed, populating the region of KP2 sensitivity. After the sawtooth crash, the ^3He slows down to thermal energies, as the RF power required to maintain the population at high energy is not available in the KP2 detection region. The slowing-down time of the ions should define the duration of the spike. In order to account for the spectrum of the protons increasing in width as the RF power is increased, the average energy of the deuterium and ^3He reactants must also increase.

This simple model accounts qualitatively for the features observed and can be tested by simulating the slowing down of populations of ^3He in the plasma and comparing the calculated proton production rate with the observed proton detection rate. This has been done using a variant of the TRAP-T code (a code described in more detail in chapter 5); the results of the comparison are shown in fig. 3.11. The duration of the spike does appear to be consistent with the slowing down time of a modelled population of RF heated ^3He . However, the position of the region sensitive to KP2 is not well known and only a rough

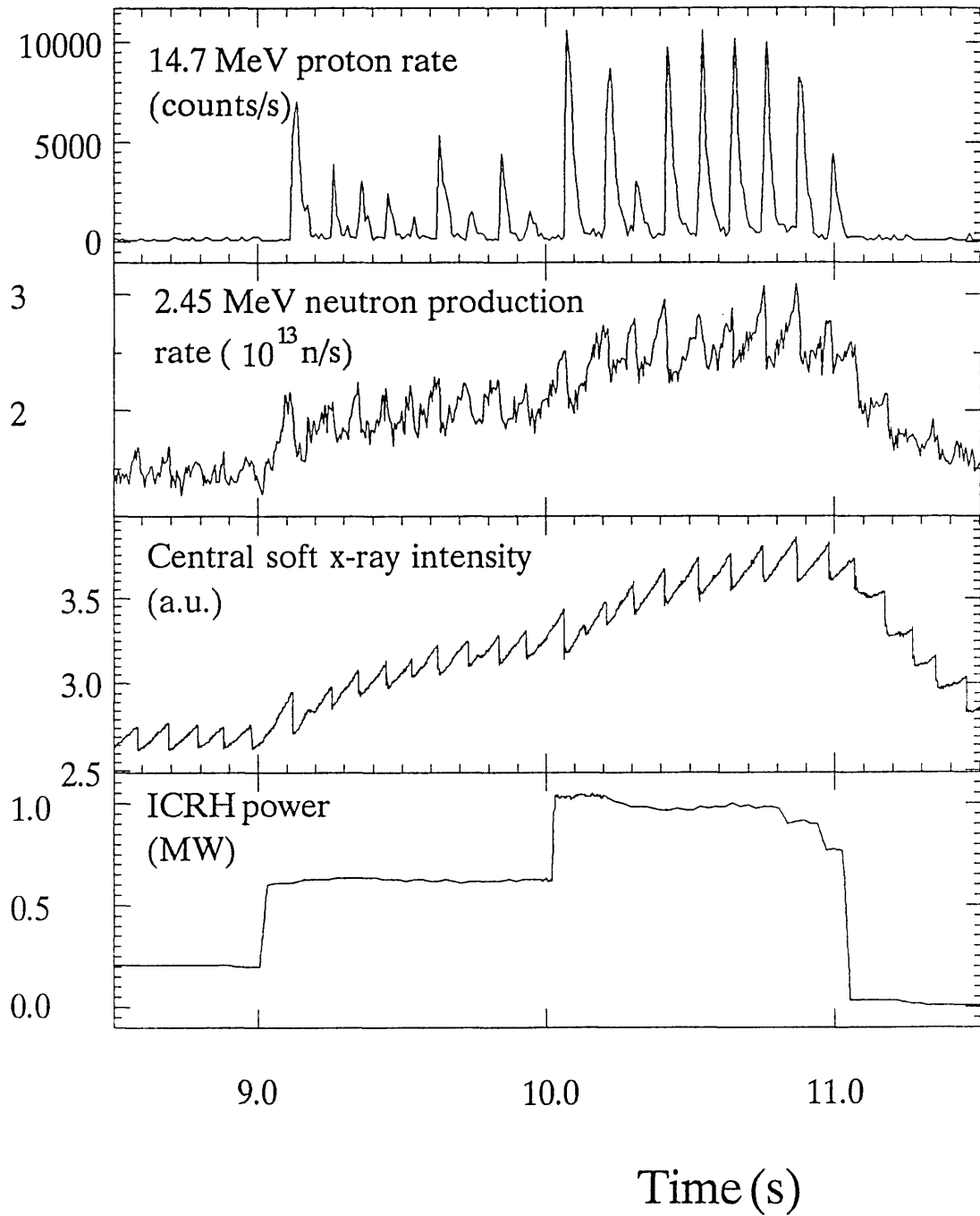


Figure 3.9. Time correlations during sawtooth activity

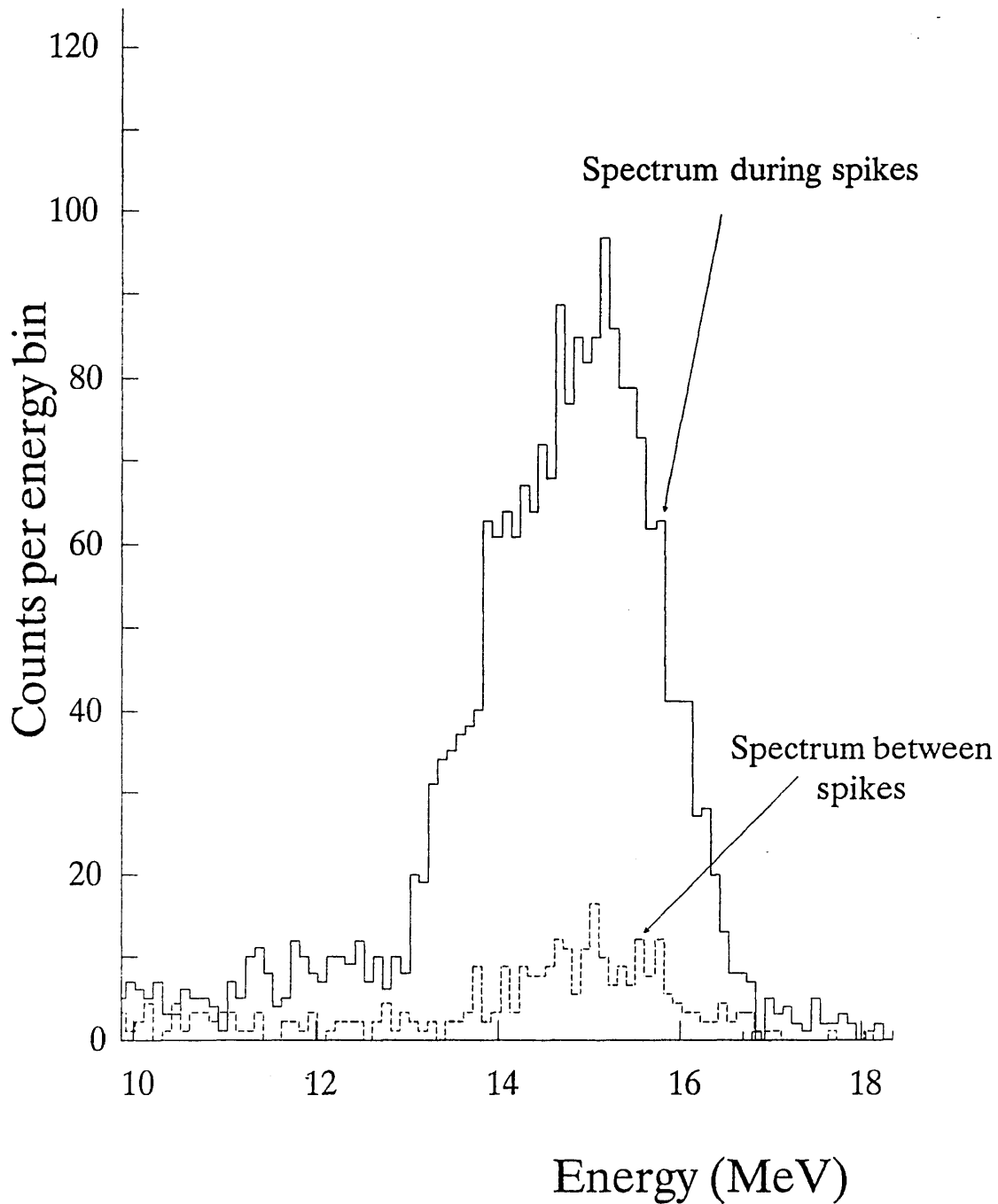


Figure 3.10. Proton spectra during spikes and between spikes: Each spectrum is obtained by summing a number of 50ms spectra acquired during one 2 second period of RF heating. The spectrum between spikes has poor counting statistics, but appears to be as wide as the spectrum produced during spikes.

estimate has been made of its location. As the electron temperature varies fairly rapidly across the plasma, this imprecision means that the selected value of T_e may be very inaccurate. The energy distribution function of the ^3He was assumed to be of the form :

$$f(E) = f_0 \exp\left(-\frac{E}{T_{tail}}\right) \quad [3.2]$$

where f_0 = a normalisation constant,
 E = the energy of the ^3He ,
 T_{tail} = the tail temperature.

This form is fairly widely used, but may well be inaccurate. A tail temperature parameter of 50-200 keV fits the observed duration of the spikes. This should be taken simply as indication that the spike duration could be consistent with the slowing down of the population.

From these observations it is possible to rule out some models of the spikes, such as the possibility that they were due to trapped 14.7 MeV protons being displaced from the plasma centre; this would require the pitch angle of the protons to alter during the displacement as a mere displacement causes few particles to become untrapped because of the slow increase in the size of the loss cone with minor radius. This cannot be a significant contributor as the protons should be lost on the timescale of 1 banana orbit, a few μs , whereas the observed time scale was of the order of 10-50 ms. If present, they would also be expected to have an energy spectrum downshifted in energy from the normal between-spikes spectrum and such an effect is not observed.

These measurements also provided the solution to the strange phenomenon of the dips in the proton emission rate at sawtooth crashes (fig. 3.1). It appears that the dips were due to massive spikes of protons being emitted by the plasma, the induced charge pulse in the silicon diode being sufficient to reduce the bias voltage across the diode for a short period of time. The effect on the diode is to reduce the width of the depletion layer of the detector, greatly reducing the pulse height due to protons. Hence, no signal was detected until the diode

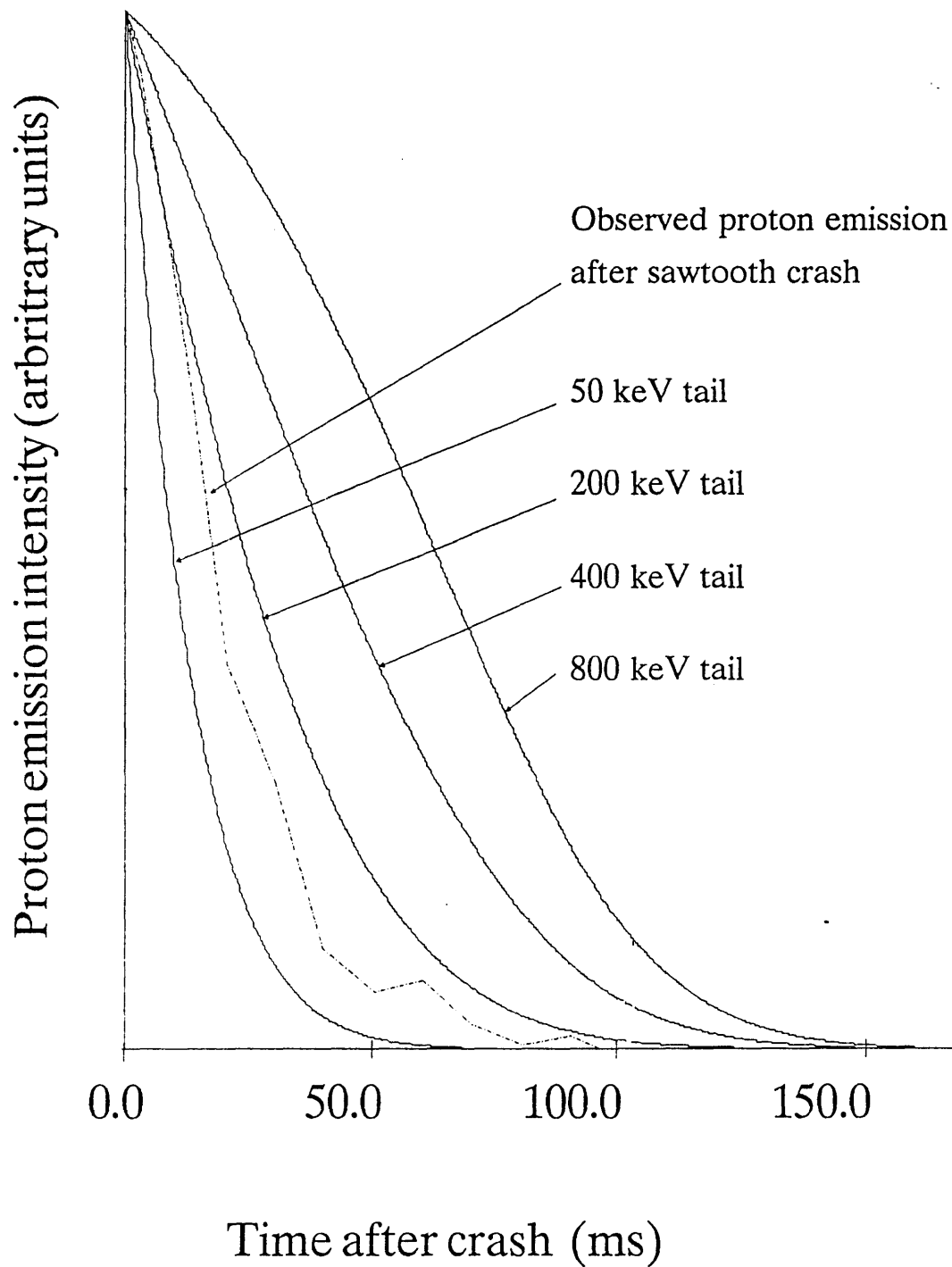


Figure 3.11. Proton emission from thermalising Helium-3: The time evolution of an RF heated population slowing down is modelled for different tail temperatures and the proton emission rate compared with that observed from the plasma. A tail temperature of 50-200 keV is deduced.

current returned towards normal. It appears that the time constant for this must have been some 10's of milliseconds.

When the code to calculate the detector efficiency becomes fully operational, a better analysis of this will become possible. However, even then there will remain certain pieces of information which will not be available so the improved analysis will still have large error bars. One of the principal areas of uncertainty concerns the distribution function of ^3He at the moment of the sawtooth crash, as this is needed in order to model the slowing down of the RF heated ^3He in the outer regions of the plasma. The distribution function used can be checked for consistency with the proton spectrum measured during the spike. However, this is of limited utility as the spectrum should change significantly during the spike for the low power RF shots under examination here. A further problem is the absolute concentration of ^3He in the plasma. No accurate measurement of this is made routinely at JET; only crude estimates of the ^3He concentration can be made from the gas inventory of the discharge.

3.4 Conclusions

14.7 MeV protons have been detected escaping from the JET plasma for discharges with low current (< 3.5 MA) through the use of a silicon surface barrier detector system mounted near the plasma. The diagnostic was fragile and suffered damage which reduced its effectiveness and eventually destroyed it. Whilst operational, spikes correlated with sawteeth were observed; these have been shown to be due to the displacement of RF heated ^3He from the centre to outside the inversion radius and into the KP2 region of sensitivity. The dips in the proton trace which caused interpretation difficulties with the original proton detector were found to be due to the diode effectively being switched off during times of intense proton detection.

For the immediate future, KP2 is not likely to be replaced, unless the main thrust of the JET program changes from producing high current, high neutron yield discharges. If such a turnabout did occur, then perhaps KP2 could be used

more effectively. The code to evaluate the detector efficiency must be improved in order for quantitative results to be obtained. Future versions of the escaping proton detector would require the ceramic breaks in the cooling lines to be more robust as their failure caused the end of the probe's operations. However, the recent addition of restraints to the vessel should reduce the effects of disruptions on the detector so it may be possible to achieve the required increase in strength of the ceramic breaks without great difficulty.

For the D-T phase of JET, an escaping α particle detector will be useful, but a different design from the present escaping proton detector is needed, as the radiation damage to silicon diodes mounted near the wall would be too severe to allow operations for any length of time and the preamplifiers could not be located near the diode. Plans are being made for a form of Faraday cup to be installed instead. This has the advantage of being very radiation resistant, but requires currents of the order of nA to be detected in an electrically noisy area. Further details can be found in Appendix A.

3.5 *References*

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4.0 2.45 MeV neutron emission profiles

The primary use of neutrons for diagnostic purposes has been the monitoring of the fusion reaction rate [4.01-4.03] and to a lesser extent, the calculation of peak ion temperatures. These relied upon measuring the total neutron emission rates from the plasma and such information is obtained at JET primarily from the fission chamber system, KN1 [4.04-4.05]. Neutron emission profiles provide more detailed information on the fusion reaction rates in the plasma and could be used to measure accurate temperature profiles under appropriate circumstances. The neutron profile monitor at JET has been designed to perform this task and this chapter is concerned with the interpretation of data from it.

4.1 Neutron profile monitor, KN3

This section discusses the KN3 design and its limitations, because in order to understand fully the software developed and the results obtained, an understanding of the hardware is essential.

4.1.1 Neutron detection and collimation

The neutron profile monitor is shown in fig. 4.1. It consists of two fanshaped collimator arrays, one mounted on the horizontal midplane and the other above the vessel. The collimators are made from mild steel and are surrounded by a high density ($\rho \approx 3.4 \text{ g cm}^{-3}$) concrete neutron shield. The horizontal array has 10 lines-of-sight and the vertical has 9. The dimensions of the collimators are individually known and can be altered by the addition of stainless steel inserts

placed at the entrance and exit points of each channel, altering the neutron fluxes at the detector by up to a factor of 25. Up to the present time the inserts have been mainly used in the horizontal array, although for the most recent discharges inserts have been used in three channels of the vertical camera. The collimator arrays have been positioned carefully and the location of each is known to an accuracy of a few millimetres and the orientation to better than a tenth of a degree. This is important as small errors in the positioning of the collimator arrays can lead to large errors in the estimation of the position of the centre of neutron emission.

The detectors are located at the end of the lines-of-sight through the concrete shield and a more detailed diagram of their housing is shown in figure 4.2. The neutron detector is a 19.6 cm³ volume of NE213 organic liquid scintillator, commonly used in neutron studies. This scintillator is used as it offers the possibility of discrimination between events due to γ rays and those due to neutrons, moderate energy resolution ($\approx 8\%$) and the capability of operation at high count-rates. The light pulses from the scintillator are detected using a photomultiplier tube, the signals from which are passed down approximately 65 metres of superscreened cable to the detection electronics in the diagnostics hall. The photomultipliers are triple screened against magnetic fields because the stray fields near the detectors can reach up to 0.1 Tesla; a residual field of 10 μ T is enough to have a detrimental effect upon the performance of the photomultiplier tubes.

4.1.2 Signal processing and corrections

The signals from each photomultiplier tube are processed by a modified Link 5020 pulse shape discriminator , PSD, [4.06], the pulses corresponding to proton recoil energies between 2.0 MeV and 3.5 MeV being counted. The PSD also monitors its live time (the fraction of all time that the PSD is available to process pulses), the number of γ ray events with energy in the range 0.7-1.4 MeV and the number of neutron events with energy higher than 3.5 MeV. The signals from the PSD are sent to latching scalars and then stored

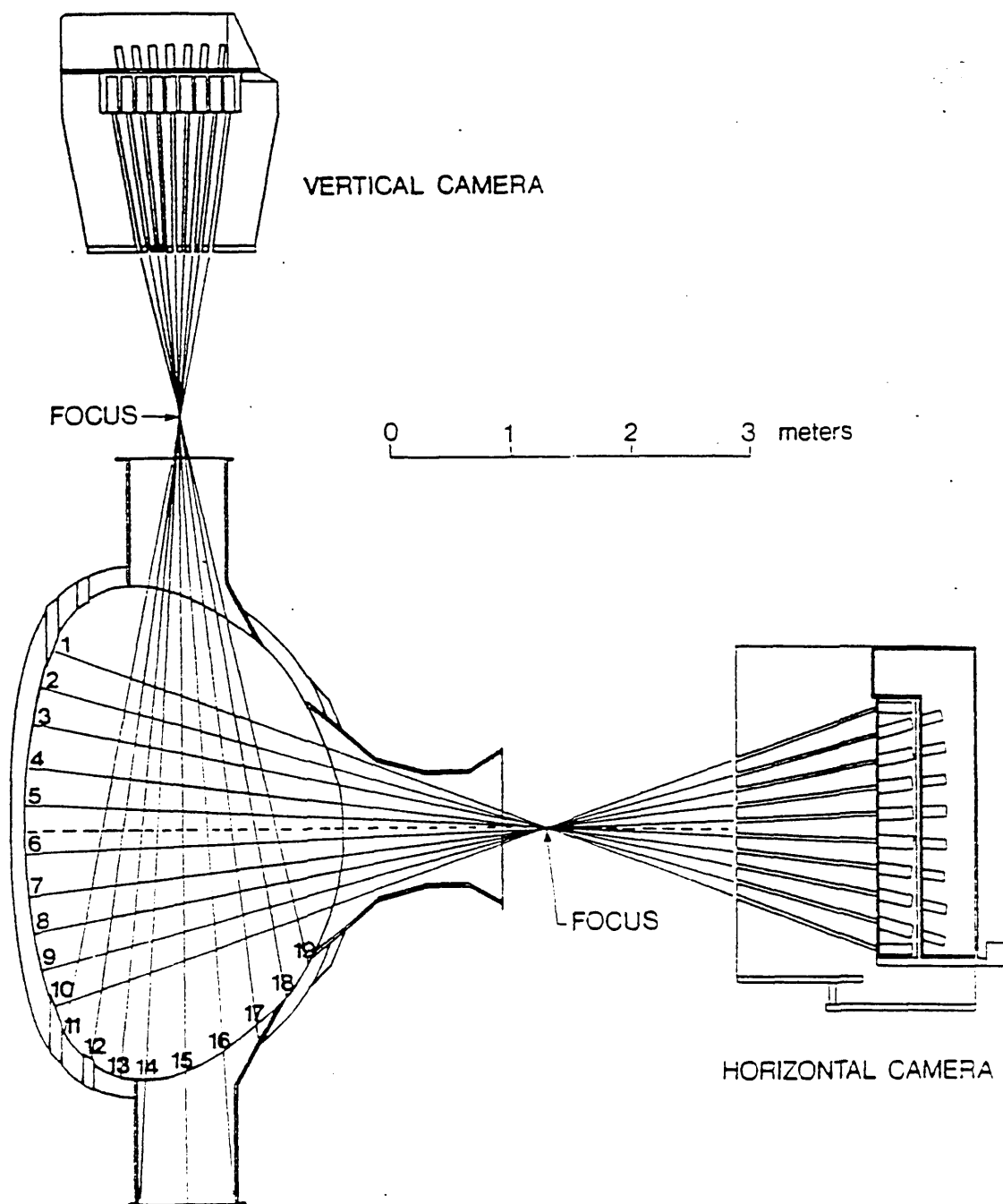


Figure 4.1. Neutron profile monitor, KN3: KN3 consists of two cameras positioned as shown above. The 19 lines-of-sight cover almost all the plasma, but with spatial resolutions of 18 and 22 cm for the vertical and horizontal cameras, respectively.

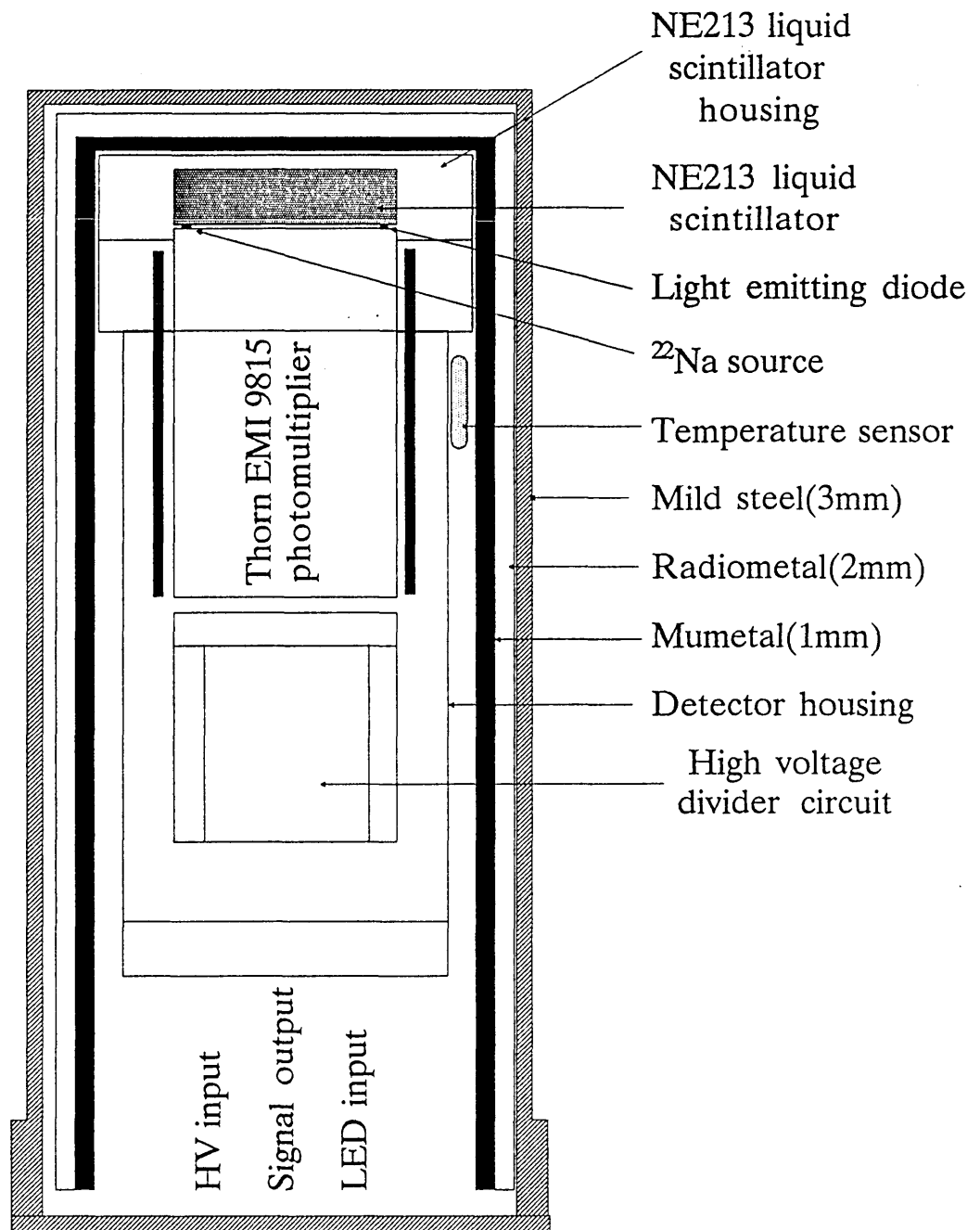


Figure 4.2. Neutron detector housing: The triple magnetic shielding is necessary to protect the PM tube from the large fields near the torus.

on the JET computer system. The PSD is capable of operating at total rates of up to 1 MHz with reasonable accuracy, corresponding to a 2.45 MeV neutron count-rate of a few hundred kHz, allowing good time resolution to be obtained.

The data are stored in the JET pulse file (JPF) in the form of a number of counts per time bin. Before analysis of the data is possible using physics codes, the raw data must first be converted into units of neutron brightness. This is performed by software, supplied with the KN3 hardware, which corrects the data for the following:

- γ ray counts from the built-in 200 nCi ^{22}Na sources used for estimating efficiency of each detector have to be subtracted from the γ ray data.
- The efficiency of each detector. This is typically 3%, but is measured prior to each shot by observations of the count-rate from the attached ^{22}Na source. This implies that the efficiency has a random error given by the square root of the number of ^{22}Na events detected, which typically gives a 2.2% random error. Unfortunately, the calculation of the efficiency increases the error to 7.6% per channel. This means that on average, 6-7 channels are 7-15% in error and 1-2 channels may be wrong by 15-23%. This could be improved by increasing the activity of the ^{22}Na sources used, or calculating the efficiencies by summing over a number shots, but at present it forms a limit on the accuracy attainable with the neutron profile monitor using the present correction software.
- The live time of each detector/PSD combination. This correction does not usually rise to more than 30%, except for discharges with unusually high count-rates with no inserts inside the collimators, or at the moment of disruption for some discharges.
- Cross-talk between detector channels. There exists the possibility that neutrons from one channel may be scattered into a neighbouring channel. The effect of this is small, measured to be less than 0.3% with an Am-Be neutron source, but necessary to take into account as the count-rate difference between channels can sometimes be large enough to cause an

observable increase in the count-rate in the channel with the lower count-rate.

- Solid angle effects. After correcting for efficiency and live-time, the neutron flux at the detector has been obtained. The solid angle correction is derived from the geometry of the collimators and is used to transform the flux into the specific intensity of neutrons (henceforward called the brightness). The reason for using a brightness is that it makes comparisons of the experimental data with modelled neutron emission profiles much easier as only line integrals through the plasma have to be evaluated instead of volume integrals.
- Attenuation and collimator scattering effects on the neutron signal. The neutron brightness of the plasma as seen by a line-of-sight is reduced by the materials between the detector and the plasma. The effect of the intermediate material has been calculated; the attenuation is typically 25% for the vertical camera and 15% for the horizontal camera. The effect of neutrons scattering from the walls of the collimator into the detector is also considered. Both effects are corrected for simultaneously, being calculated by the same neutron transport model.
- Back-scattered neutrons. The backscattering effect is illustrated in fig. 4.3, where neutrons from the bulk of the plasma are shown scattering off the vacuum vessel wall and into the line-of-sight of one of the KN3 channels. The number of neutrons scattered into each line-of-sight is nearly a constant multiplied by the total neutron yield, with only a slight dependency upon the plasma position. The flux of neutrons scattered into each line-of-sight has been estimated to be typically 2-3% of the total flux observed on the central channels [4.07], which corresponds to 50-100% of the flux in the outermost channels, depending on the type of discharge. The effect of this is considered more carefully in the section 4.3.4.

The corrections are all required in order to obtain the absolute neutron brightness for each channel. The estimated relative uncertainty between two

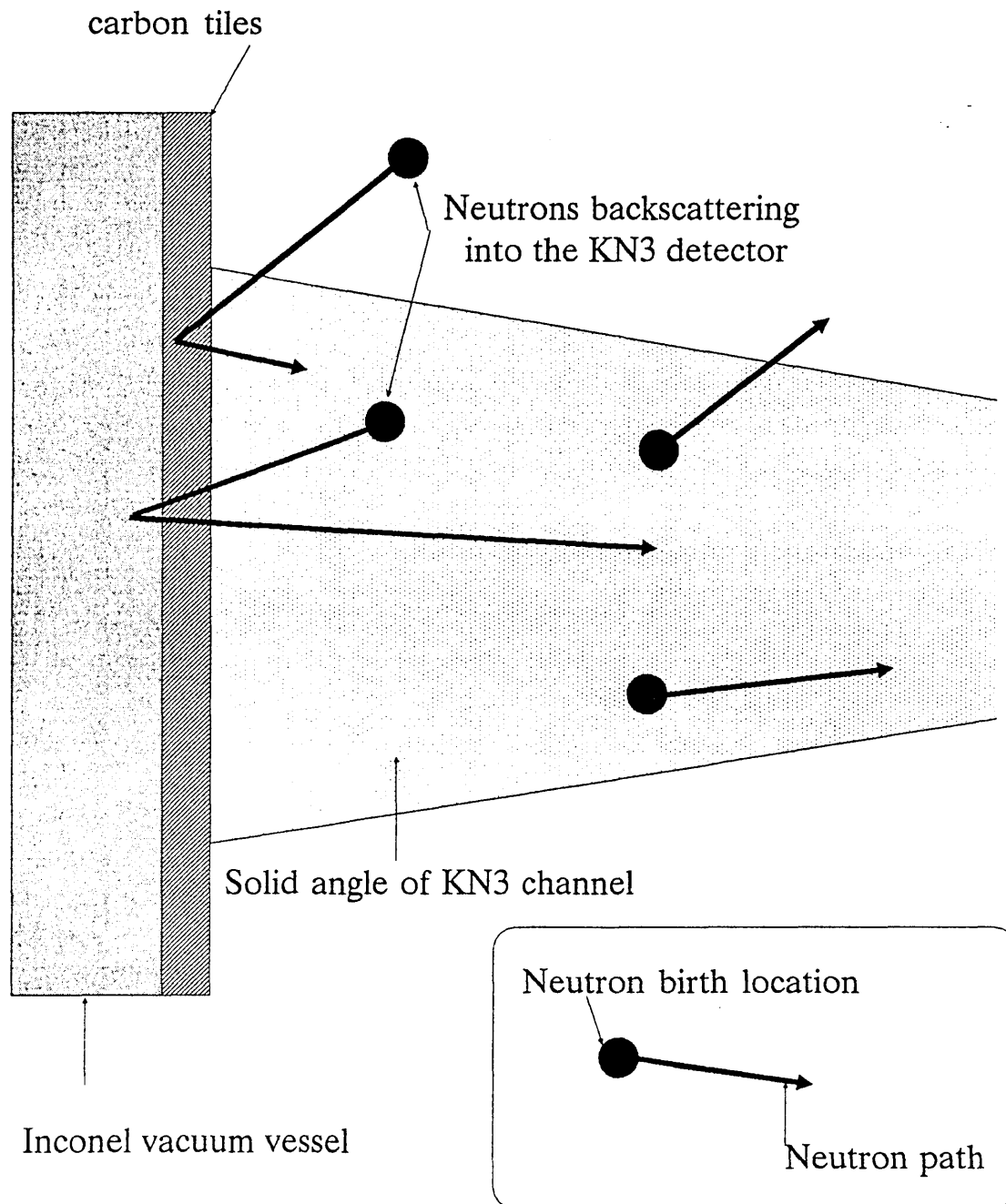


Figure 4.3. Diagram illustrating neutron backscatter process: Neutrons from outside the line-of-sight of the KN3 channel may interact with the vacuum vessel walls and be scattered into the KN3 line-of-sight. This is an important effect as 25-100% of the events detected in the outermost channels may be due to backscattered neutrons.

channels is estimated to be no greater than $\pm 10\%$. The accuracy of the absolute calibration of the neutron profile monitor is thought to be approximately $\pm 20\%$.

4.1.3 Summary.

The neutron profile monitor measures the neutron brightness along 19 lines-of-sight to an accuracy of $\approx \pm 15\%$. Neutron profile monitor data are available on most shots from 10582 onwards. This diagnostic has been thoroughly tested. The neutron brightnesses form the input to the interpretation code described in the next section.

4.2 *Analysis of the KN3 data*

The neutron brightnesses need to be further processed in order to obtain useful plasma information. The normal procedure involves deriving the two dimensional neutron emissivity function in the poloidal plane. There are currently 4 methods available to perform this at JET, namely: Cormack tomography, constrained tomography, generalised Abel inversion and a simple curve fitting technique. The first two are capable of fitting the data from the neutron profile monitor exactly, but have a tendency to generate fitted surfaces which make little physical sense, such as surfaces containing regions of negative neutron emissivity. By smoothing out the input data to some extent, the fitted solutions are more physical but are no longer very close to the original data. The third and fourth methods use flux surfaces supplied by magnetic equilibrium codes and assume them to be surfaces of constant neutron emission. The third method smoothes the data and then derives a unique neutron emission profile, whereas the fourth method finds the best fitting curve generated by an analytical source function with a small number of free parameters. The fourth method, using the program called ORION, is the one described in detail in this section. It was originally intended for a simple comparison between the neutron emission profiles which are assumed in the code TRAP-T (described in chapter 5) and the observed neutron emission profiles. It has since grown into an

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analysis tool in its own right (and is also used to estimate correction factors for other neutron diagnostics.)

4.2.1 Neutron source model used in ORION

The ORION code assumes that the contours of neutron emissivity in the JET plasma are described by the magnetic flux surfaces produced by the IDENTC or FAST magnetic equilibrium codes. These produce flux surfaces with the Lao-Hirshmann formalism, given by the parametric equations:

$$R = R_0(x) + ax \cos \chi + R_2(x) \cos 2\chi \quad [4.1]$$

$$Z = E(x)(ax \sin \chi - R_2(x) \sin 2\chi) \quad [4.2]$$

where

$R_0(x)$	= R coordinate of magnetic axis of each flux surface,
$E(x)$	= Ellipticity of each flux surface,
$R_2(x)$	= Triangularity of each flux surface,
a	= Minor radius of outermost flux surface,
x	= Normalised minor radius, $0 < x < 1$,
χ	= Parameter such that $0 \leq \chi \leq 2\pi$.

The centre of the plasma is estimated to be known to an accuracy of ± 7 cm, although the edge regions are thought to be known more exactly.

ORION uses 40 flux surfaces to model the plasma, with the intersections between the flux surfaces and the horizontal midplane being equally spaced. The sensitivity of the code to variations in the number of flux surfaces used has been tested and, even for highly peaked neutron profiles, the 40 flux surface prescription agrees well with versions of the code using up to 160 flux surfaces. Between each pair of adjacent flux surfaces, the neutron emissivity is assumed to be a constant given by the source function used. A variety of source functions are available to model the plasma and are detailed in Appendix B.

4.2.2 Neutron profile monitor model used in ORION

Each channel of the neutron profile monitor is modelled by 9 elements, as illustrated in fig 4.4. As the collimators are typically 40 times longer than they are wide, the approximation that the brightness of a single channel is given by eq [4.3] is valid.

$$Brightness = \frac{\sum_{i=1}^9 \text{elemental brightness}_i}{9} \quad [4.3]$$

It is necessary to use multiple elements per line-of-sight in order to model the large angles subtended by the neutron profile monitor channels, as shown in fig 4.5. In practice, this only introduces errors in regions where the second derivative of the neutron source profile with respect to minor radius is high and this implies that only very peaked discharges cause problems. The absolute magnitude of the effect is shown in figure 4.6, where the difference between calculations utilising only one element per line-of-sight and calculations made with more elements are shown.

The code calculates the distance between intersection points for each elemental line-of-sight and every flux surface. These values are stored in a matrix and used in the calculation of neutron brightness for each line-of-sight, as this is defined simply as the line integral through the plasma for each elemental line-of-sight. Hence, when calculating the response of the neutron profile monitor to a neutron emission profile, all that is required is a matrix multiplication of the matrix containing the simulated source profile with the matrix containing the intersection data, which allows the minimisation routine to operate quickly.

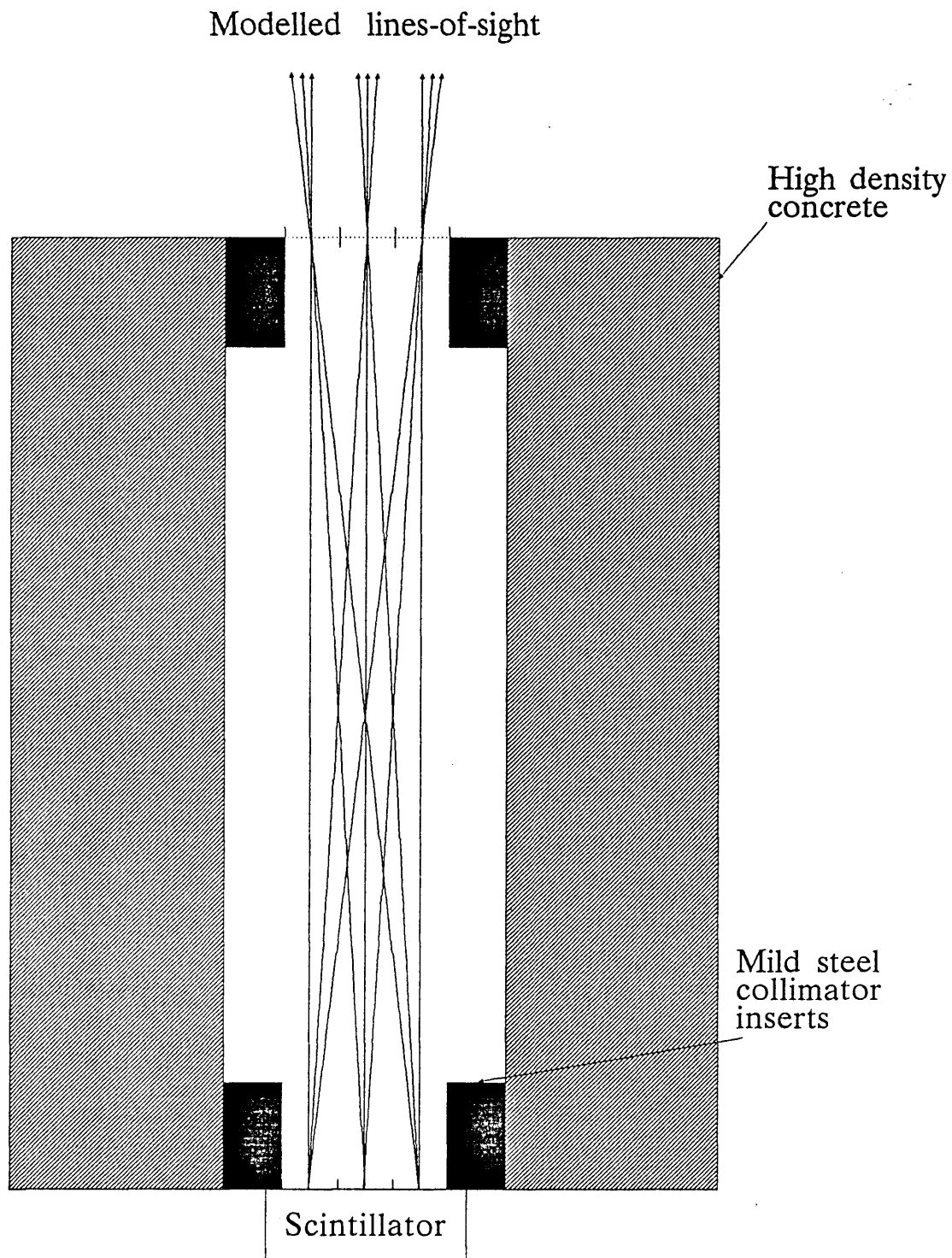


Figure 4.4. Multiple element model of KN3 collimator: The rectangular front and back ends of the collimator are divided into 3 strips and lines-of-sight drawn between the centres of them all.

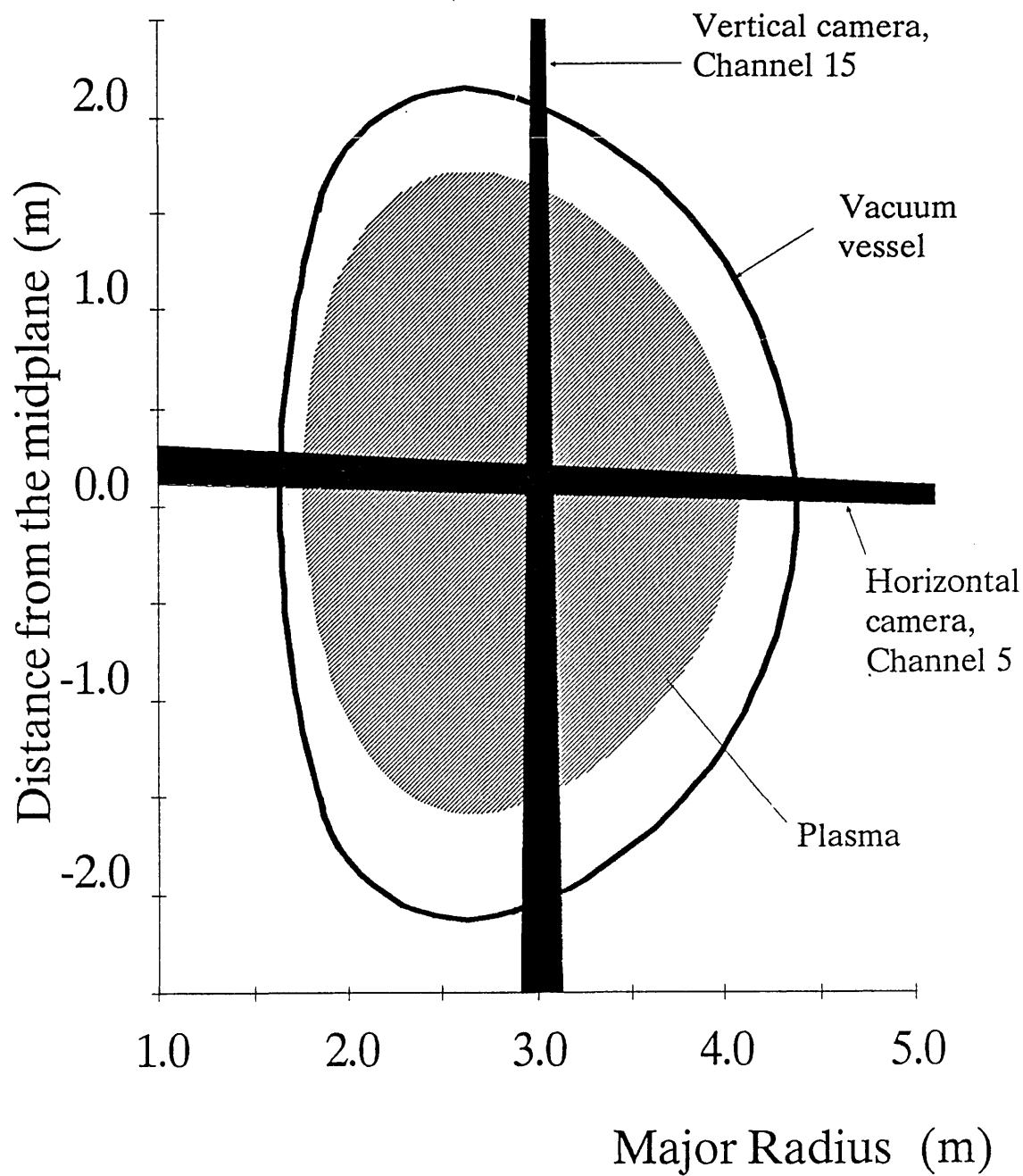


Figure 4.5. Divergence of collimation in plasma: Although the collimators used are 1 metre long and only up to 4 cm wide, the divergence causes an important error, as the plasma can show wide variations in neutron emissivity across the width of such a beam.

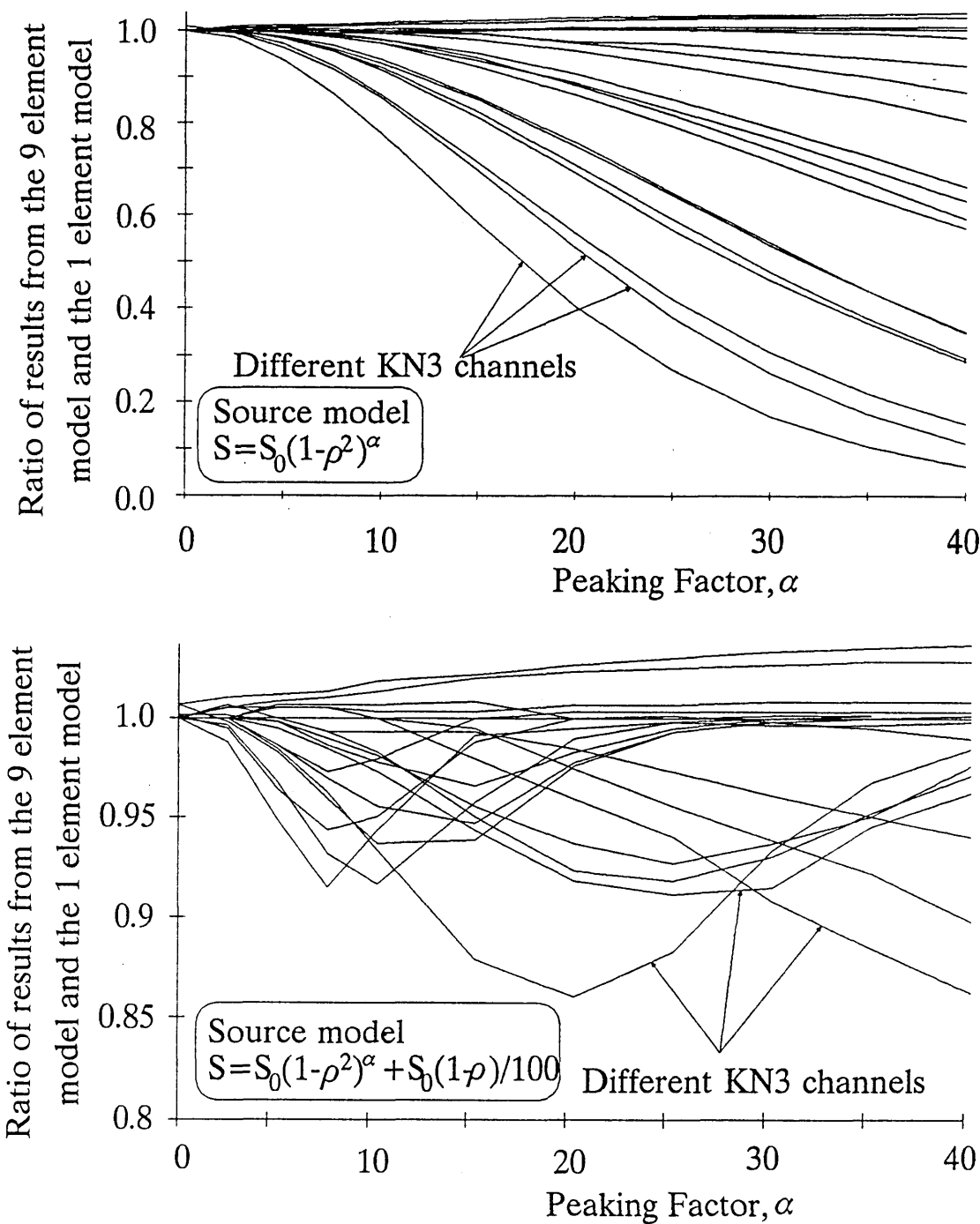


Figure 4.6. Comparison of line integrals evaluated using different numbers of elements: The deviation of the nine element collimator model from the one element model is shown as a function of the peaking factor of the source function. The deviation peaks where the second derivative of the neutron emissivity peaks. Note the different ordinates for the two graphs.

4.2.3 Profile fitting

The fitting functions have between 1 and 9 free parameters, although usually only functions with 5 or less are used. After the modelled response of the neutron profile monitor to a neutron source profile has been calculated, the minimisation parameter χ^2 is calculated as shown below:

$$\chi^2 = \frac{\sum_{i=1}^{19} \frac{(O_i - C_i)^2 W_i}{(\varepsilon_i O_i)^2}}{\sum_{i=1}^{19} W_i} \quad [4.5]$$

where

O_i	=	the observed neutron brightness of KN3 channel i,
C_i	=	the calculated neutron brightness of KN3 channel i,
W_i	=	the weight given to KN3 channel i in the fit,
ε_i	=	the fractional error on KN3 channel i.

This defines a weighted minimisation parameter, as experience with the code has shown that the fitted functions appear better when a weighting function of a similar shape to the observed neutron brightness is used. In theory, this should not be necessary as the errors on each channel should give rise to an effective weighting of a similar shape, but the errors on each channel are defined to be:

$$\varepsilon_i = \sqrt{(0.1)^2 + \frac{1}{N_i}} \quad [4.6]$$

where

ε_i	=	fractional error on channel i.
0.1	=	the error on the calibration of channel i,
N_i	=	the number of neutron events in channel i.

In practice, ε_i is usually nearly equal to 0.1 as the number of neutron events per channel is normally numbered in the thousands.

χ^2 is minimised with respect to the free parameters of the selected fitting function and the results are displayed. There are a wide number of options available to the user of the program to improve the quality of the fit achieved; for further details see appendix B. The only one that will be elaborated upon here is the option allowing the user to fit neutron emission profiles where the total neutron yield is a free parameter and is not constrained to be equal to that measured by the fission chamber system, KN1. This option is useful as the absolute calibration has an uncertainty of some 20% and so it seems likely that the best possible fits will be achieved with the ratio of the neutron profile monitor yield and the fission chamber neutron yield (this will be called the KN3 to KN1 ratio) not equal to 1.00. Instead, the KN3 to KN1 ratio would be expected to be a constant of the system, valid for all operating conditions.

4.2.4 Using the source profile

The ORION code calculates the neutron source profile that best fits the neutron profile monitor data. After this, the neutron source profile is used to calculate the ion temperature profile and certain correction factors for different neutron diagnostics. The ion temperature profile is obtained by assuming the following:

- The deuterium density profile is known. There are various deuterium density profile parameterisations available to the user of ORION. The simplest use the approximation that the n_D/n_e ratio across the plasma is constant. The next problem is to select the most appropriate of the 5 available electron density profile parameterisations. The charge exchange recombination spectroscopy (CXRS) diagnostic produces an n_D/n_e ratio which is not constant across the plasma, which adds another 5 possible profile parameterisations. (However, the CXRS diagnostic is only operational during NBI heating.) The evaluation of the ion temperature depends weakly on the deuterium density used, as the formula for the production of 2.45 MeV neutrons for Maxwellian plasmas is given by:

$$S = \frac{n_D^2 \langle \sigma v \rangle}{2} \quad [4.7]$$

where S = the 2.45 MeV neutron emission rate,
 n_D = the deuterium density,
 $\langle \sigma v \rangle$ = the reactivity for the $D(D,n)^3\text{He}$ reaction and is given by eq [4.8] from ref [4.08]:

$$\langle \sigma v \rangle = P_1 \theta \sqrt{\frac{\zeta}{T^3}} \exp - 3\zeta \quad [4.8]$$

where $\theta = \frac{T + P_3 T^3}{1 + T(P_3 - P_2)}$,
 $\zeta = \sqrt[3]{\frac{246.44}{\theta}}$,
 T = the deuterium temperature in keV,
 $P_1 = 5.574 \times 10^{-15}$,
 $P_2 = 3.329 \times 10^{-3}$,
 $P_3 = 2.949 \times 10^{-3}$.

- The fraction of neutrons produced by non-Maxwellian deuterium distributions, such as beam ions of RF heated ions, is a constant (which is set by the user) times the local neutron emission strength. Obviously, there is no problem when the plasma under investigation is ohmic, or has low power RF heating. However, this assumption is not very good when neutral beam heating is used, as the deposition profile of the beams and subsequent beam-plasma neutron emission are not well accounted for.

If eq [4.7] is used to find the ion temperature, the dependence upon the deuterium density goes as $T_i \propto n_D^{0.5-0.6}$ for the temperature range $3 \text{ keV} < T_i < 20 \text{ keV}$. Hence, the uncertainties of 20-40% on the deuterium density profile give uncertainties of 10-20% on the ion temperature profile. This is a reasonably accurate technique for measuring the ion temperature profile.

The deduced source profile is frequently used to calculate corrections to other neutron diagnostics for the position of the plasma. There are four diagnostics

for which corrections are calculated: the fission chambers (KN1); the activation system (KN2); the time of flight spectrometer(KM3) and the torus hall ³He spectrometer (KM1). The models used to calculate the corrections for each case will be described next.

4.2.4.1 KNI correction

The fission chambers have been absolutely calibrated in the past through the use of a strong neutron source moved around the inside of the JET vacuum vessel and the efficiency of each fission chamber measured at each point [4.09]. A consequence of this calibration was the production of a model through which the change in the calibration constant of a toroidal ring source of neutrons due to a change in its major radius or distance from the midplane could be calculated and using the formula in eq 4.9:

$$C = \frac{4.24911 \times 10^{-17} \{(464 - R)^2 + Z^2\}}{\{UR + V\} \{W - X \sqrt{640R - R^2 - 79296}\} \{464 - R\}^2} \quad [4.9]$$

where

C	= the correction to the KNI calibration,
R	= the major radius of the ring in cm,
Z	= the distance above the horizontal midplane in cm,
U	= 6.19×10^{-17} ,
V	= 5.94×10^{-17} ,
W	= 3.60×10^6 ,
X	= 1006.58

By subdividing each of the 40 flux volumes used in the code into 150 smaller ones (fig. 4.7) and approximating each small volume as a ring source located as shown in fig 4.7, the variation of the KNI emission rate due to the source profile can be evaluated by adding up the contributions of each small area weighted by its neutron source strength and normalised to the original total neutron emission rate. The neutron emission rate at each point on a ring is assumed to be constant (ie. toroidal symmetry is implicit).

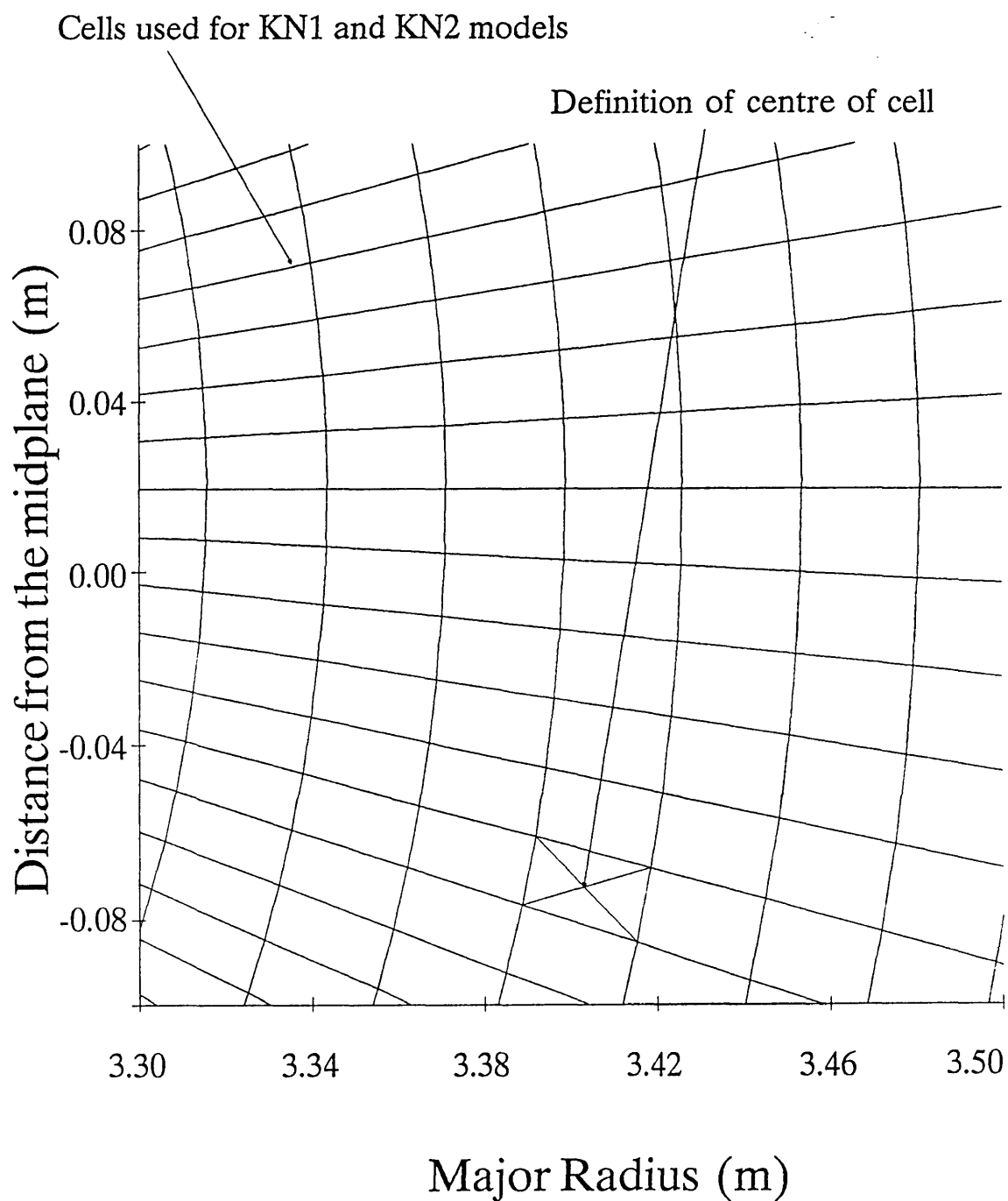


Figure 4.7. Diagram of the regions used to model the KN1 correction: The picture shows an enlarged view of the flux surfaces rendering the small regions used in the KN1 and KN2 corrections visible.

This is used as a standard correction to the total neutron emission rate. For most plasmas the correction is upwards by 8%, although the range of observed correction values is 3% (for a pellet discharge) to 16% (for a supershot discharge). Certain difficulties arise when using this correction with the KN3 to KN1 ratio set to 1.00 and not a free parameter, as the KN1 correction is calculated after the profile is derived. The effect of changing the total neutron emission rate will cause a different profile to be produced by ORION, but this change is usually very small, typically 1-3% variations in the values of the fitting parameters being observed. As the effect is so small, the ORION code does not iterate to a self-consistent solution. For the case where the KN3 to KN1 ratio is a free parameter, the KN1 correction is assumed to be part of the KN3 to KN1 ratio found by the fitting routine. Hence, the true KN3 to KN1 ratio may be found by dividing the fitted KN3 to KN1 ratio by the calculated KN1 correction factor.

4.2.4.2 KN2 correction

The activation of foils placed near the vacuum vessel is discussed in more detail in chapter 5. There is a correction to be made due to the deviation of the real plasma from the plasma modelled in the neutron transport calculations and this can be modelled by ORION. The plasma is divided up as before into 6000 small volumes and a ring source model used to calculate the variation in the foil activation yields. The ring source model is an extension of one used by Nicola and Pedretti [4.10] and is illustrated in figure 4.8. The neutron flux is calculated for each ring source by assuming that the only obstruction to the neutrons is the central column of JET, which is represented as a neutron opaque column of radius 1.49 m. This is given by:

$$F = \frac{S}{4\pi} \int_0^{\Phi_0} \frac{\exp\left(-\frac{l}{\lambda \cos \theta}\right) d\Phi}{r^2} \quad [4.10]$$

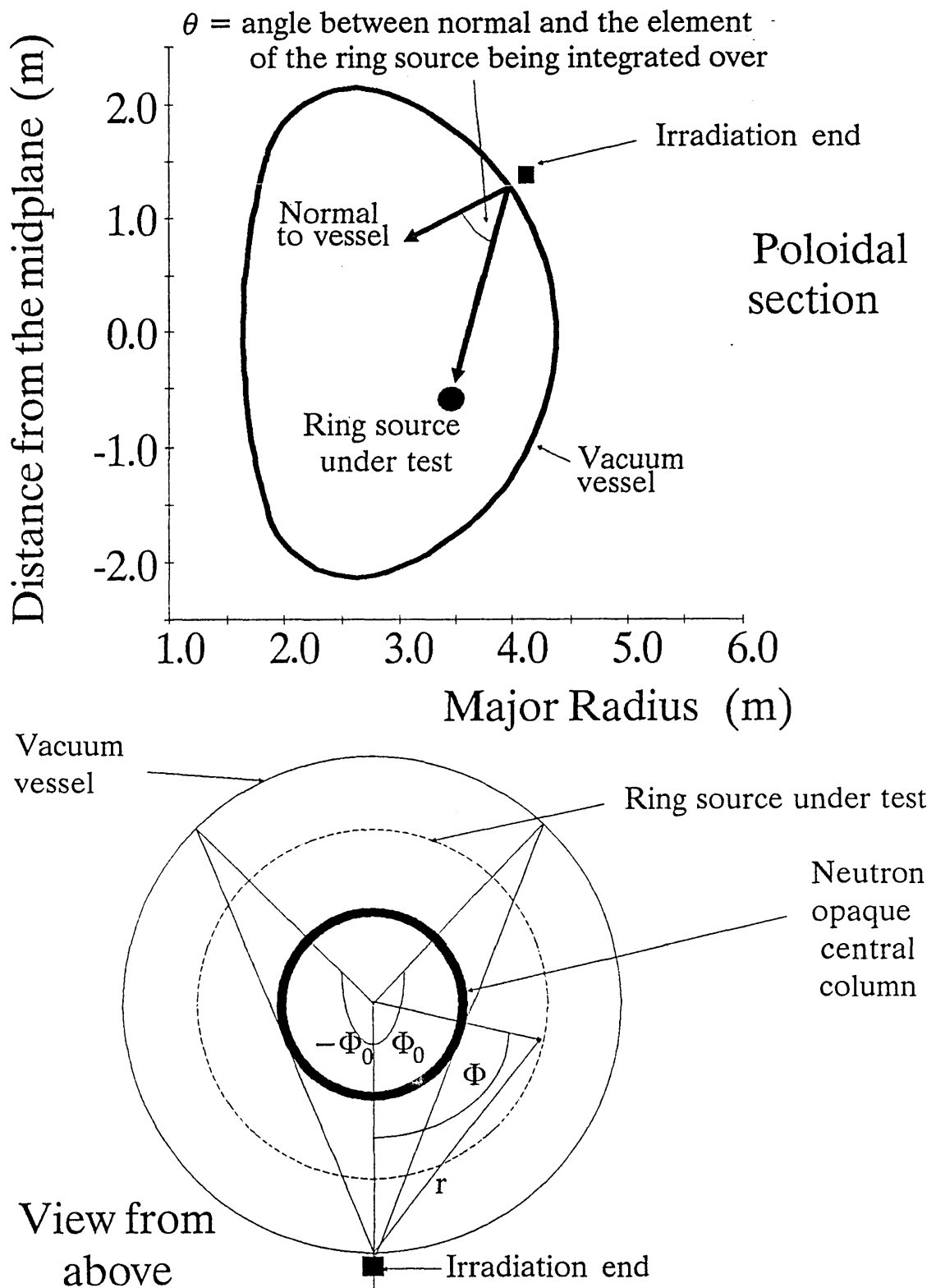


Figure 4.8. Model used to simulate the ring source for KN2 correction

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where S = the neutron emissivity per metre of the ring,
 l = the thickness of the vacuum vessel, $\approx 32 \pm 4$ mm,
 λ = the attenuation length for 2.45 MeV neutrons in the vacuum vessel, ≈ 32 mm,
 θ = the angle between the normal of the vessel at the irradiation end and the line to the ring element at Φ .

The correction factor, f , is then defined as

$$f = \left(\frac{F}{F_{reference}} \right) \left(\frac{Y_{reference}}{Y} \right) \quad [4.11]$$

where Y = the true neutron yield from the plasma under test,
 $Y_{reference}$ = the true neutron yield from the plasma model used in the neutron transport calculations,
 $F_{reference}$ = the flux from the plasma model used in the neutron transport calculations.

The model used in the neutron transport calculation is described in ref. [4.11]. The correction factor calculated here assumes that the only events detected at the irradiation end are due to virgin neutrons, ie. neutrons which have not been scattered. This is valid for activation materials with a high threshold energy.

4.2.4.3 KM3 correction

The KM3 diagnostic location is illustrated in fig. 4.9. The line-of-sight of the diagnostic is essentially a parallel beam, the width primarily being defined by the precollimator positioned on top of the vacuum vessel. This is modelled fairly easily by 27 equally spaced lines-of-sight, the exact position of the first and last being determined by the precollimator, fig. 4.10. The neutron brightness averaged across the beam is then calculated and this quantity can be used in comparisons of the total neutron yield of the plasma with the number of neutrons detected by the KM3 spectrometer, in order to check the linearity of the system. The neutron energy spectrum observed by the KM3 spectrometer can also be simulated, using the ion temperature profile calculated previously

and the fact that the spectrum from a Maxwellian plasma is well known [4.12]. The calculated spectrum is then analysed in the same manner that a real neutron spectrum would be analysed. Spectra from uniform temperature plasmas are compared with the calculated spectrum, until the ion temperature which gives the best fit is found. The ratio of this temperature to the known peak ion temperature gives a correction factor which can be applied to the ion temperature derived from real KM3 data in order to estimate the true peak ion temperature. The results of this procedure are described in section 4.3.2.

4.2.4.4 *KM1 correction*

The location of the KM1 spectrometer is shown in fig. 4.11. The correction factor generated for this diagnostic is similar to the temperature correction factor described in the previous paragraph. However, the calculation of the correction factor is a much more difficult problem as the simplification of only calculating intersections in the poloidal plane no longer applies and the more complex task of finding the intersections in the full 3-D toroidal geometry becomes necessary. The lines-of-sight used are shown in figure 4.12 and use the assumption presented earlier that the elemental lines-of-sight can simply be summed to include the effect of the finite solid angle of the spectrometer line-of-sight. The number of lines used is 625 as this seemed the minimum number necessary to model the large areas of the precollimator and the ^3He detector. One problem with using 625 lines-of-sight is that the computation time required to run the code becomes very high, typically 40s on the IBM 3090 mainframe computer used for every time slice. This means that the KM1 correction factor is never produced as a matter of course, but only for specially selected shots.

The lines-of-sight intersecting any one flux surface may be divided into 4 classes, as shown in fig 4.13. When calculating the line integrals, care must be taken to use the appropriate class. The intersection points of the line with the flux surface under test are required in order to calculate the line integral through the plasma. The routine used to find where the line intersects the flux surface finds two starting points along the line, one inside and one outside the flux

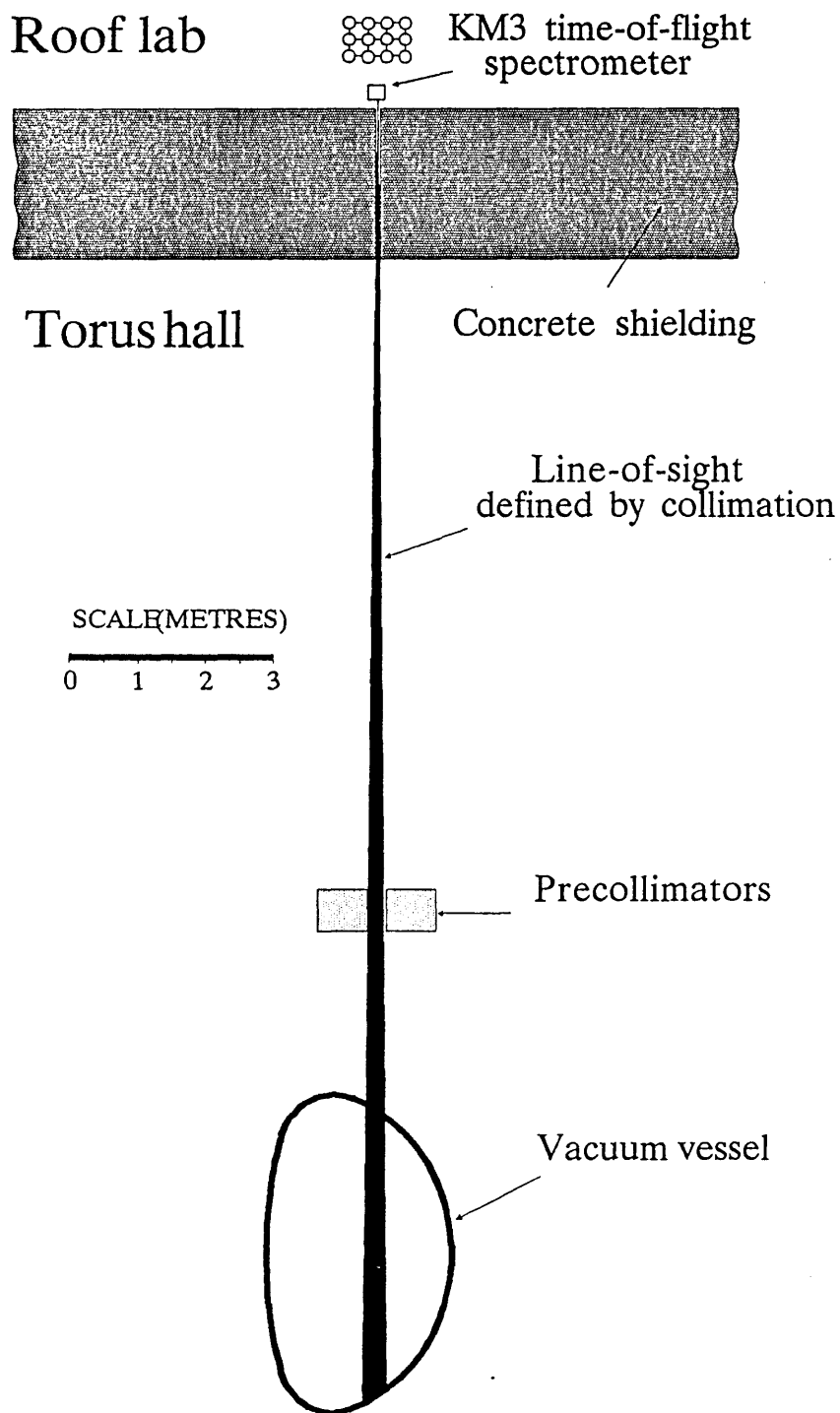


Figure 4.9. Location of time of flight spectrometer: The spectrometer is based in the roof laboratory at JET but the line of sight for it is defined by the precollimator mounted on the top of the torus.

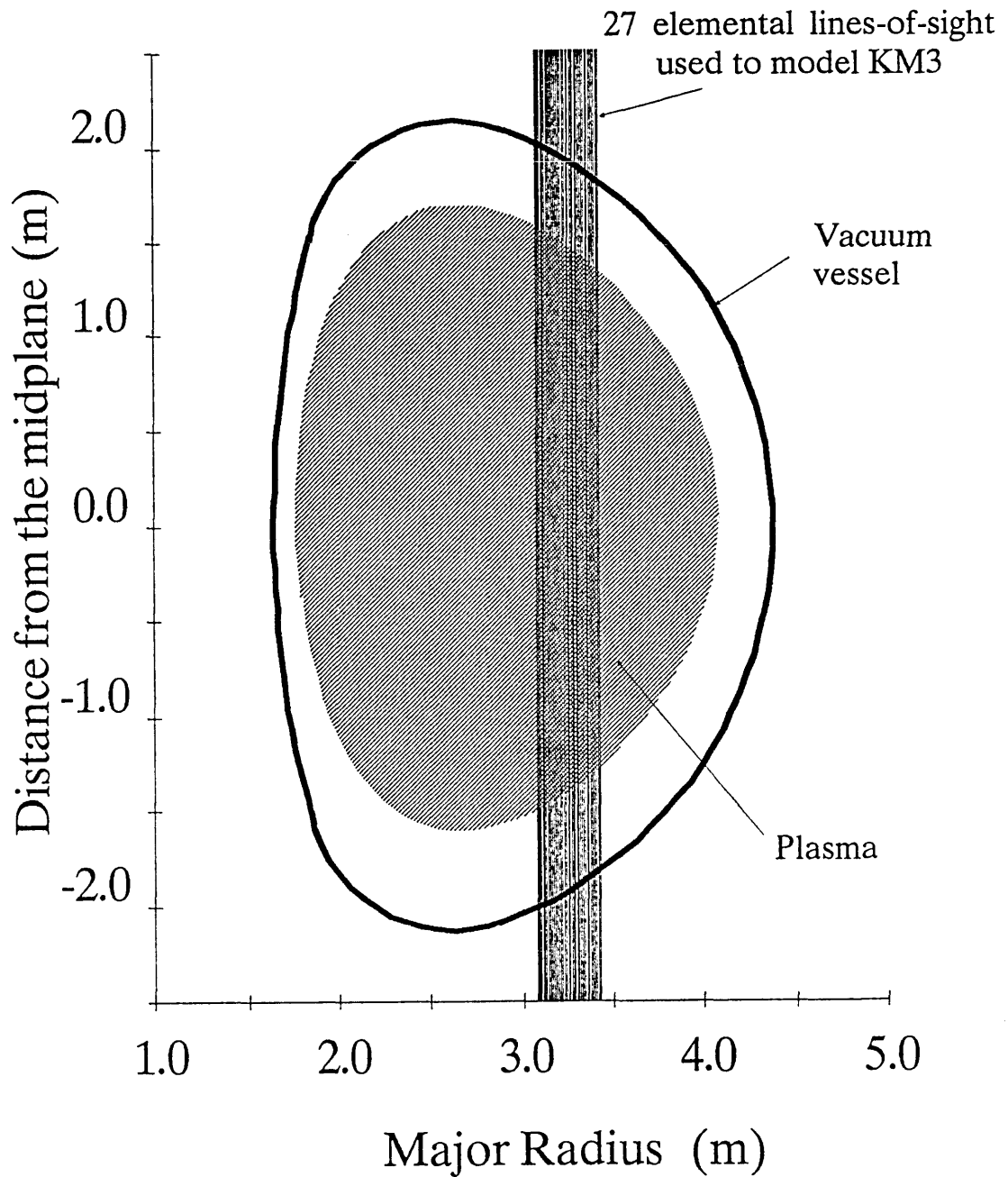


Figure 4.10. Lines-of-sight used to model KM3: As KM3 is in the roof laboratory, the lines-of-sight used to model it are approximated by the use of 27 vertical lines across a region defined by the positions of the precollimator jaws.

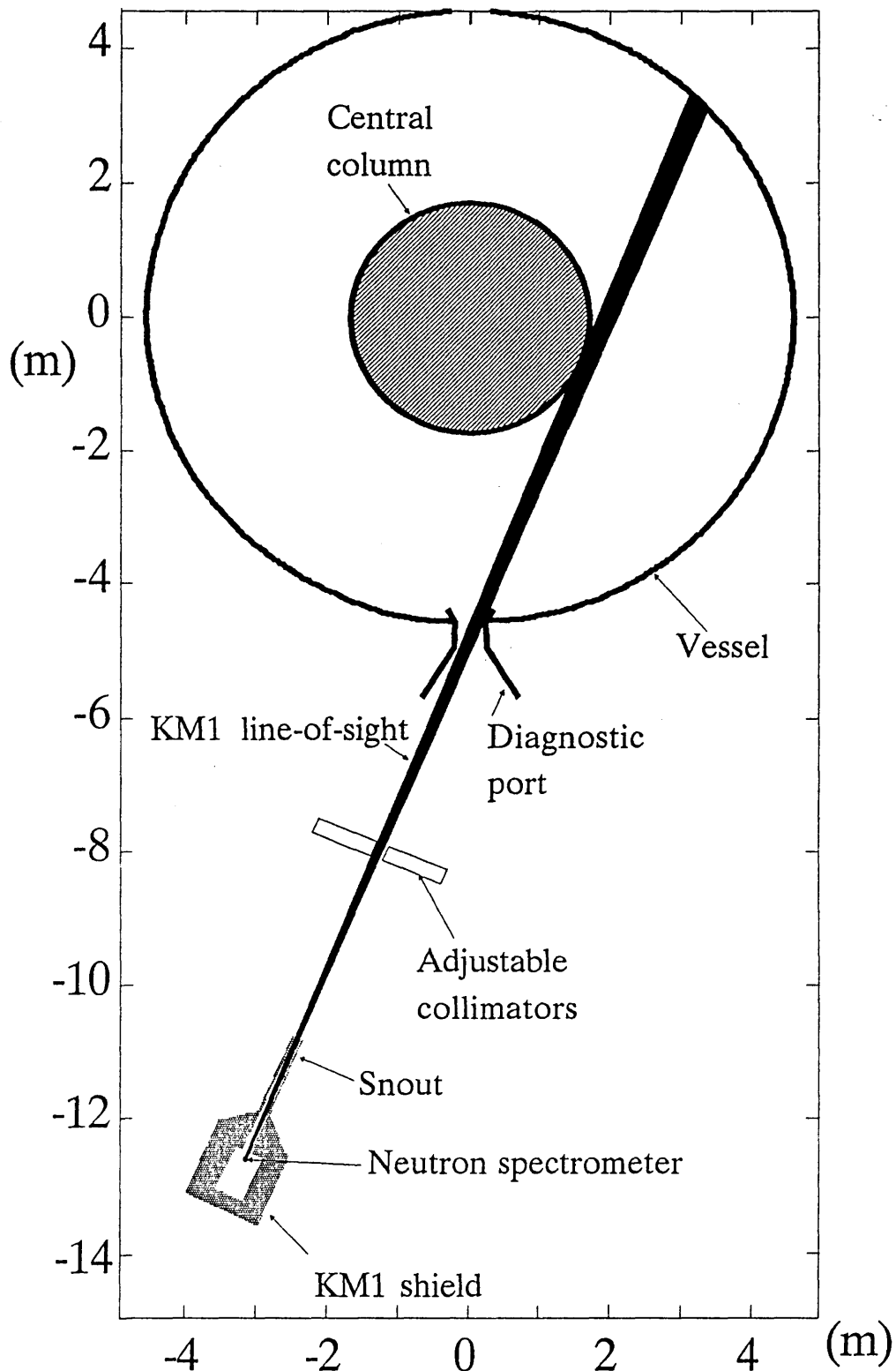


Figure 4.11. Location of KM1 spectrometer: KM1 is located in the torus hall and its line-of-sight is defined by a precollimator near the torus and by the structure of the port and the central column of the torus.

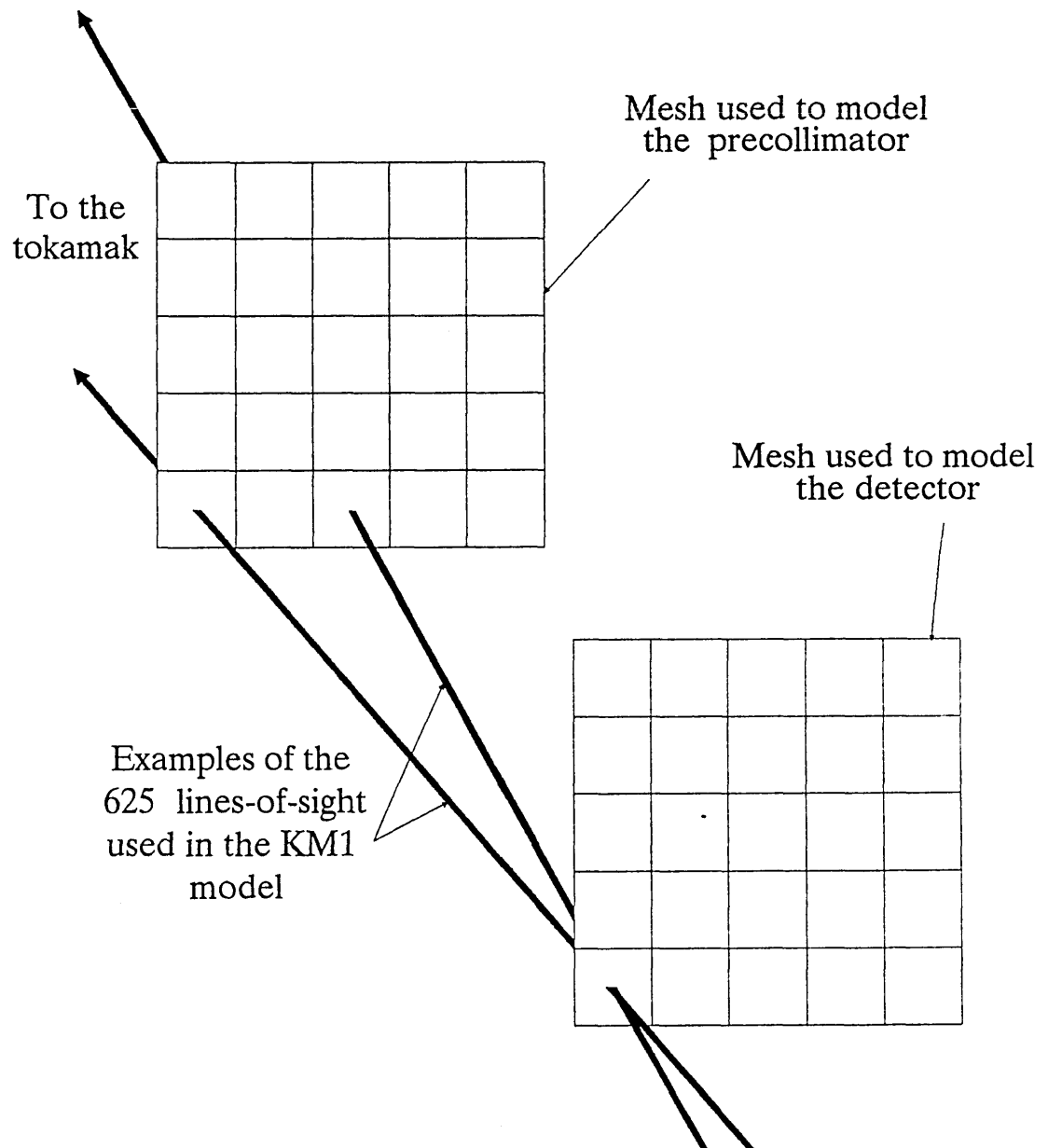


Figure 4.12. Model used to simulate KM1 lines-of-sight: The model is an extension of that used for the individual channels of KN3. The precollimator is represented by a 5x5 mesh, as is the detector. The resulting 625 lines-of-sight and their intersection with the flux surfaces are then calculated.

surface. The point midway between the two starting points is then tested to see if it lies inside or outside the flux surface. The midway point and one of the starting points are then chosen, such that one is inside and one outside the flux surface under test. The program then iterates, continually halving the toroidal angle the two points until the value of Φ at the point of intersection is known to an accuracy of better than $50 \mu\text{radians}$. The same procedure is followed for the second intersection point and then the distance between the two intersection points is calculated. If 4 intersection points are required (class c) then the remaining pair are found. From this point on, the KM1 line-of-sight is treated as another KN3 channel for purposes of obtaining line integrated information. The technique for correcting a measured ion temperature to give the peak ion temperature is the same as used in the KM3 correction described above.

The results from this section of the code are presented in section 4.3.3.

4.2.5 Assumptions and approximations

The major assumption built into ORION which can lead to errors is that the flux surfaces, which are contours of constant pressure, are also contours of neutron emissivity. For the case of ohmic plasmas this approximation should be extremely good and certainly adequate considering the errors on the input data from KN3 and the effect of other assumptions in the code. For NBI heated discharges, the question of flux surfaces becomes more relevant, as a large fraction of the injected beam ions perform banana orbits. The effects of this would be expected to appear primarily on the vertical camera, as a shift of the plasma radially outwards. In practice, a shift outwards when the NBI is active is noticed, although this could be due to the inaccuracy of the magnetic equilibrium codes in following the plasma centre in such conditions, so no hard conclusions may be drawn from this observation.

In principle, it should be possible to modify ORION in order to use surfaces which include the effect of the trapped particles, but there are several major obstacles, including:

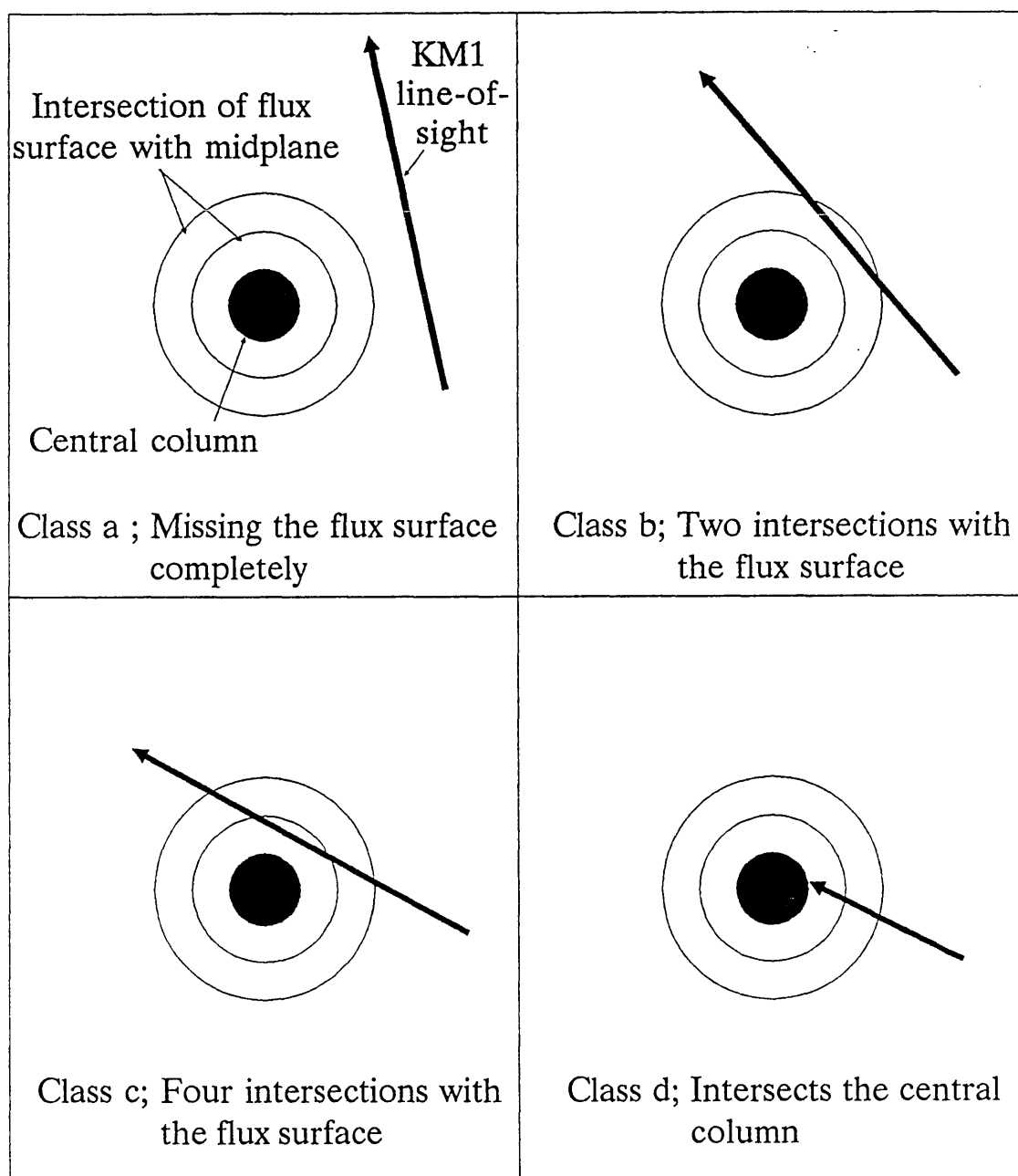


Figure 4.13. Classes of line-of-sight in KM1 correction: The four classes of line are shown above. Each must be taken into account when calculating the intersections of the lines-of-sight with the 3-D flux surfaces.

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- The beam deposition profile would need to be known in some detail, including the pitch angle distribution at the time of ionisation. While information on this is available, it does have large errors.
- The calculation of the neutron emission contours would require full orbit calculations for a large number of particles. There exist codes capable of the orbit simulation, but they are computationally expensive.
- The effect of the trapped particles on the neutron emission gets larger at higher beam powers in general, but the effect of beam-beam interactions also increases. These effects may be modelled by the code TRANSP [4.13]. However, TRANSP may require some 6-10 hours of computer time to run, making it an expensive pre-processing package to use.

The value of implementing such enhancements would seem to be questionable as the consequences for the neutron emission profiles would be expected to be slight and probably minor compared to those attributable to the experimental errors on the plasma parameters involved. Small regions of high or low neutron emissivity cannot be modelled. This could be a problem when interpreting discharges with 'snake' activity or strong sawtooth activity. However, as these phenomena occur on time scales such that the duration of any poloidal asymmetries is much shorter than the available time resolution they are unlikely to be of great importance.

When calculating the deuterium density from the visible bremsstrahlung diagnostic, the assumption is made that the plasma consists of deuterium, carbon and oxygen, the latter two in the ratio of 3 to 1. This assumption is not very accurate as it does not take into account the effects of the helium and higher Z impurities in the plasma, or the fact that the deuterium is diluted by hydrogen. These cause errors in the determined deuterium density ratio, the magnitude of which varies from 10 to 100%.

The input data from KN3 and from the other diagnostics used in the ORION code are not always in agreement. The most common problem is the centering

of all the profiles used in the program, particularly for discharges which are highly peaked, as discrepancies of a few cm between the centres of the density, flux surfaces and the KN3 neutron data result in quite large inaccuracies. There is little that can be done about this, apart from rigidly shifting the profiles until they centre on the same place. This kind of procedure is possible in the ORION code, but it is not very accurate.

The assumption that it is possible to average the neutron data over long periods (up to 5 seconds) has been made. If none of the data signals used by the program show signs of variation over the averaging period, then this assumption is probably valid. However, there are occasions when analysis is required for situations in which the plasma is changing quickly, such as the initial 200ms of neutral beam injection, where the signal may vary considerably throughout the time window and there is doubt over the accuracy of results from such investigations.

Apart from the major problem of the suitability of flux surfaces for the contours of neutron emissivity, the results obtained from ORION are insensitive to the approximations, if care is taken over the type of discharge analysed.

4.3 Results

There is an immense amount of neutron profile monitor data waiting to be analysed. Unfortunately, as shall become apparent in this section, there is a residual problem with the operation of the neutron profile monitor at this time, December 1989, which makes the analysis of data in any detail unproductive before the problem is resolved. What will be presented in this section is a selection of numerical results from the code and a limited amount of analysis of real data, concentrating on the areas where the neutron profile monitor misbehaves, in the hope of identifying the underlying cause.

4.3.1 Neutron emission rates from KN3

The neutron profile monitor can be used to measure the total neutron emission rate from the JET plasma. Using ORION, a source profile is found to reproduce the KN3 data and then a volume integration is performed to evaluate the total 2.45 MeV neutron emission rate. In principle, the emission rates obtained using this technique should be in good agreement with other neutron diagnostics and, in particular, with the KN1 fission chambers. As there are uncertainties in the absolute calibrations of both devices, perfect agreement between the two diagnostics would not be expected, but the ratio of the emission rates from KN3 and KN1 (the KN3 to KN1 ratio) should be a constant. Some small variations in the KN3 to KN1 ratio might be anticipated during beam heating, due to the anisotropy of the D-D cross-section in combination with the anisotropic pitch angle distribution. However, this effect would not be expected to be greater than 10%.

Unfortunately, the KN3 to KN1 ratio does not remain constant. For plasmas with low neutron emission rates ($< 5 \times 10^{14}$ neutrons s^{-1}), such as ohmic discharges and low power RF heated shots, the KN3 to KN1 ratio is found to be fairly constant with a value near 0.80. As the 2.45 MeV neutron emission rates increases, the KN3 to KN1 ratio increases as well, as shown in fig. 4.14. Two other observations can be made about the behaviour of the KN3 to KN1 ratio. The first is that for 2.45 MeV neutron emission rates greater than 5×10^{14} s^{-1} , the KN3 to KN1 ratio appears to be roughly proportional to the logarithm of the 2.45 MeV neutron emission rate, as shown in fig. 4.15. The second is that the KN3 to KN1 ratio does not seem to be closely tied to the neutron event rate in the scintillator. This is shown in fig. 4.16 where the KN3 to KN1 ratio is plotted against the average number of neutron events in channels 5 and 6 of KN3. The fact that the discharges appear to lie in two groups, one with collimator inserts and one without, implies that the deviation is due to the total neutron rate as opposed to the count rate of KN3.

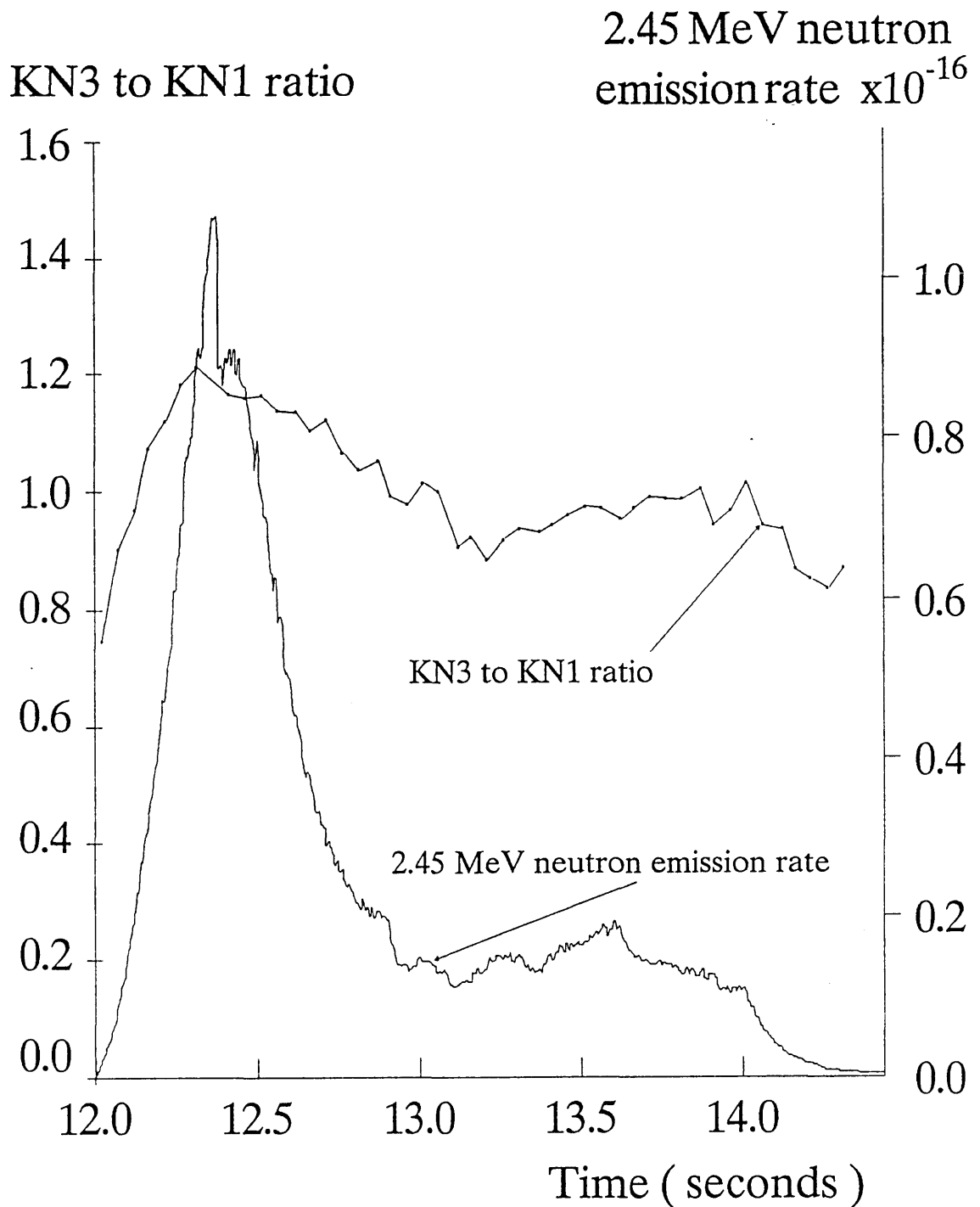


Figure 4.14. KN3 to KN1 ratio and KN1 rate as a function of time: During the NBI heating pulse, the KN3 to KN1 ratio varies between 0.8 and 1.2. The value should remain constant.

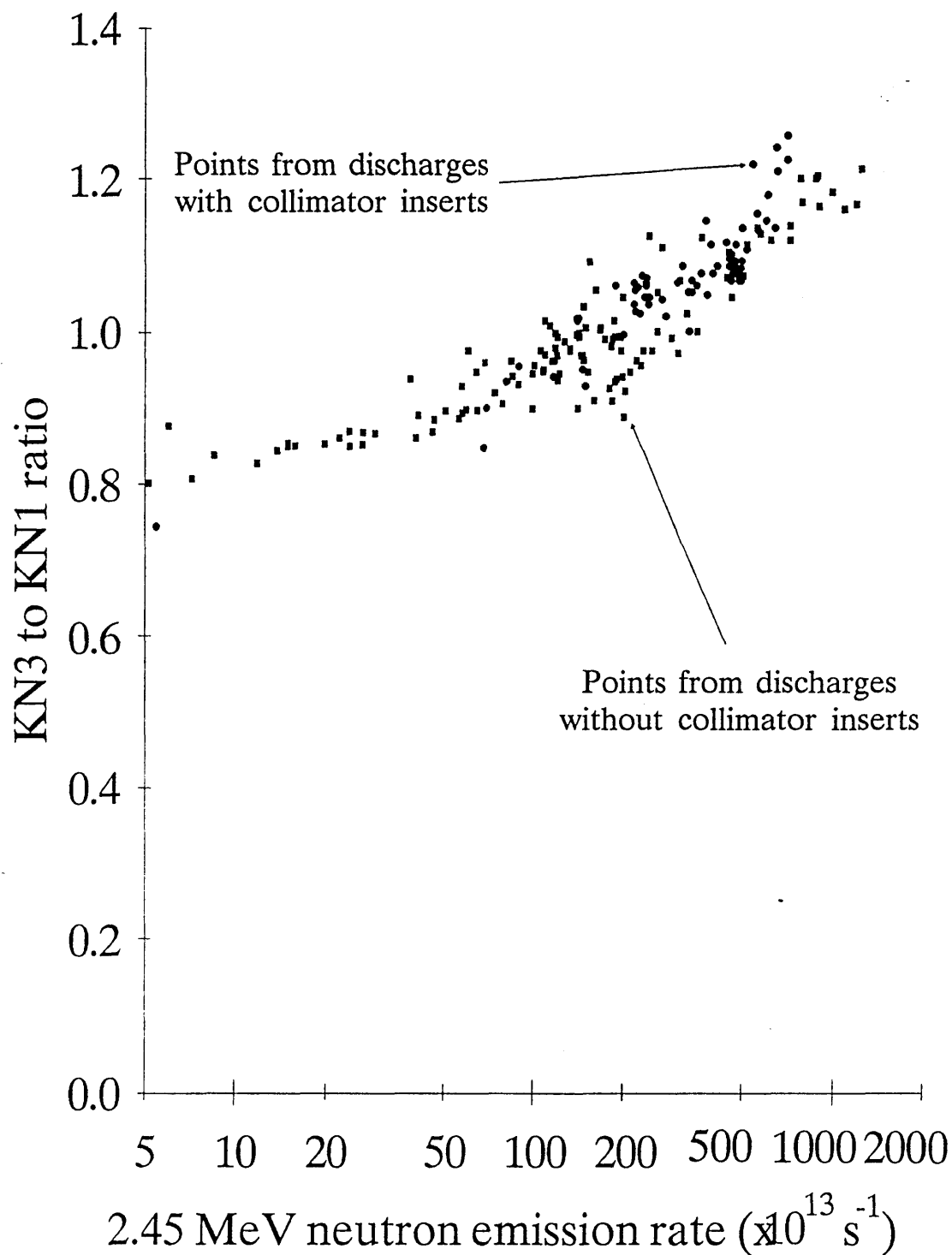


Figure 4.15. KN3 to KN1 ratio as a function of neutron emission rate: The ratio appears to vary linearly with the log of the neutron emission rate, a somewhat unexpected result.

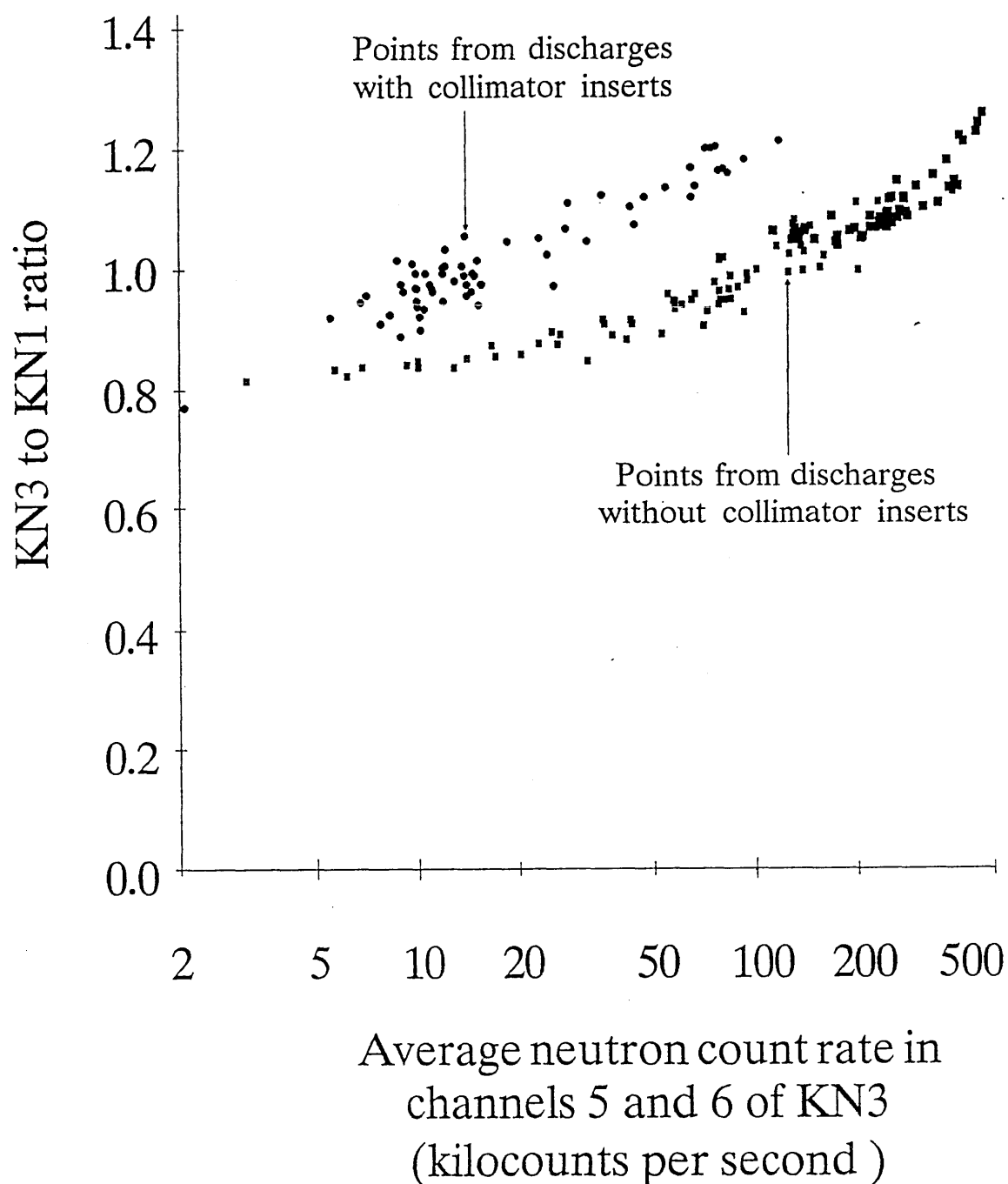


Figure 4.16. KN3 to KN1 ratio as a function of neutron event rate: The data clusters around two lines, corresponding to shots with collimator inserts and shots without. With fig 4.15 this implies that the KN3 to KN1 ratio is dependent upon the neutron yield and not the PSD count rate, which is highest in channels 5 and 6.

One of the favoured explanations of the variations in the KN3 to KN1 ratio is that the pulse shape discriminator (PSD) runs into difficulties at high total count rates. The PSD is thought to be capable of operating at total rates of up to 200 kHz reliably; however, for higher rates the effect of pile-up on the neutron signal is not well understood. It is possible to make this explanation fit the above observations if the deviation is due to γ rays created through neutron capture in the structure surrounding the torus. These γ rays then pass through the concrete shield to form the bulk of the total throughput of the detector. The logarithmic dependency upon the 2.45 MeV neutron emission rate is assumed to come from the pile-up of the γ pulses in the PSD, which would be recorded as neutron events. The total count-rate of the detector is not normally monitored, so it is possible that γ rays from neutron capture could be producing the bulk of the scintillator events, although the explanation does seem somewhat forced.

Whatever the cause, the fact remains that there exists a discrepancy between the neutron rates measured by KN1 and KN3. In order to make use of the KN3 data later in this chapter, the assumption has been made that normalising the source profile to the KN1 neutron emission rate removes the discrepancy. This allows some global information to be derived from the plasma, such as the deuterium density or correction factors for other diagnostics. It should be remembered that the discrepancy discussed here is only evident for the highest neutron emission rates.

4.3.2 Effect of backscattered neutrons on KN3

The backscattered neutron fluxes have been calculated by Verschuur [4.07] and can be represented as a neutron brightness given by the product of the total neutron emission rate of the plasma and a constant depending upon the line-of-sight. As the KN3 to KN1 ratio is not usually equal to 1, this implies that the backscattered neutron correction may be erroneous by as much as a factor of 1.4. Also, the estimated accuracy of the constants evaluated by Verschuur is

$\approx \pm 30\%$, so an investigation of the effect of this uncertainty on the magnitude of the backscatter correction seemed worthwhile.

It was investigated by multiplying the backscatter correction term by a factor M (the backscatter multiplier) and subtracting the product from the KN3 lines of sight instead of the normal backscatter correction term. Figures 4.17 and 4.18 show how the KN3 to KN1 ratio and the fitted peaking factor vary with respect to the value of M for a pellet discharge. The graphs are fairly linear for values of M below 2, which seems reasonable as a pedestal is slowly being removed from the KN3 lines-of-sight. At $M \approx 2$ the backscatter correction term exceeds the neutron brightness of channels 1 and 10, so some form of discontinuity would be expected at that point. The results show that an error of $\pm 30\%$ on the backscatter correction term translates to an error of $\pm 1.6\%$ on the KN3 to KN1 ratio and to an error of $\pm 2.5\%$ on the fitted peaking factor. The effect of the inaccuracy in the backscatter correction is small enough to be considered negligible.

4.3.3 KM1 corrections.

The response of the ^3He ionisation chamber (part of the KM1 spectrometer) in the torus hall to variations in the source profile has been extensively tested. The parameters that were thought to affect the measured T_i were the peaking factor of the neutron emission profile, the peaking factor of the temperature profile, the radial and vertical displacements of the plasma centre and the size of the precollimator. These were tested by using the magnetic flux surfaces from an ohmic plasma and fitting profiles of the form:

$$T_i(\rho) = T_i(0)(1 - \rho^2)^\alpha + 0.001(\text{keV}) \quad [4.12]$$

and

$$S(\rho) = S(0)(1 - \rho^2)^\beta + S(0) \frac{(1 - \rho)}{100} \quad [4.13]$$

where T_i = the ion temperature,

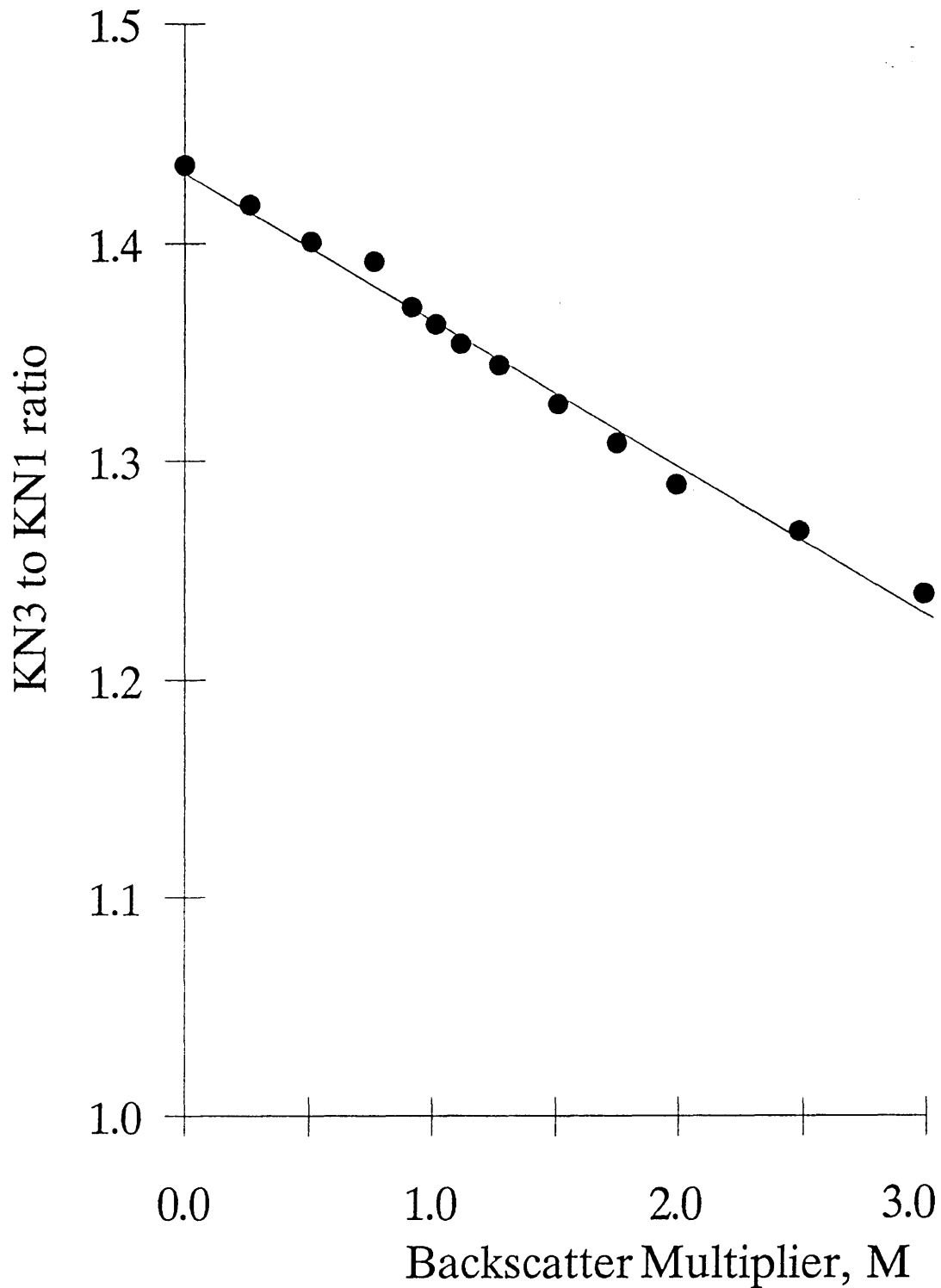


Figure 4.17. KN3 to KN1 ratio versus the backscatter multiplier, M : The discharge was heated by a combination of NBI and RF and had a pellet injected slightly before the time under test.

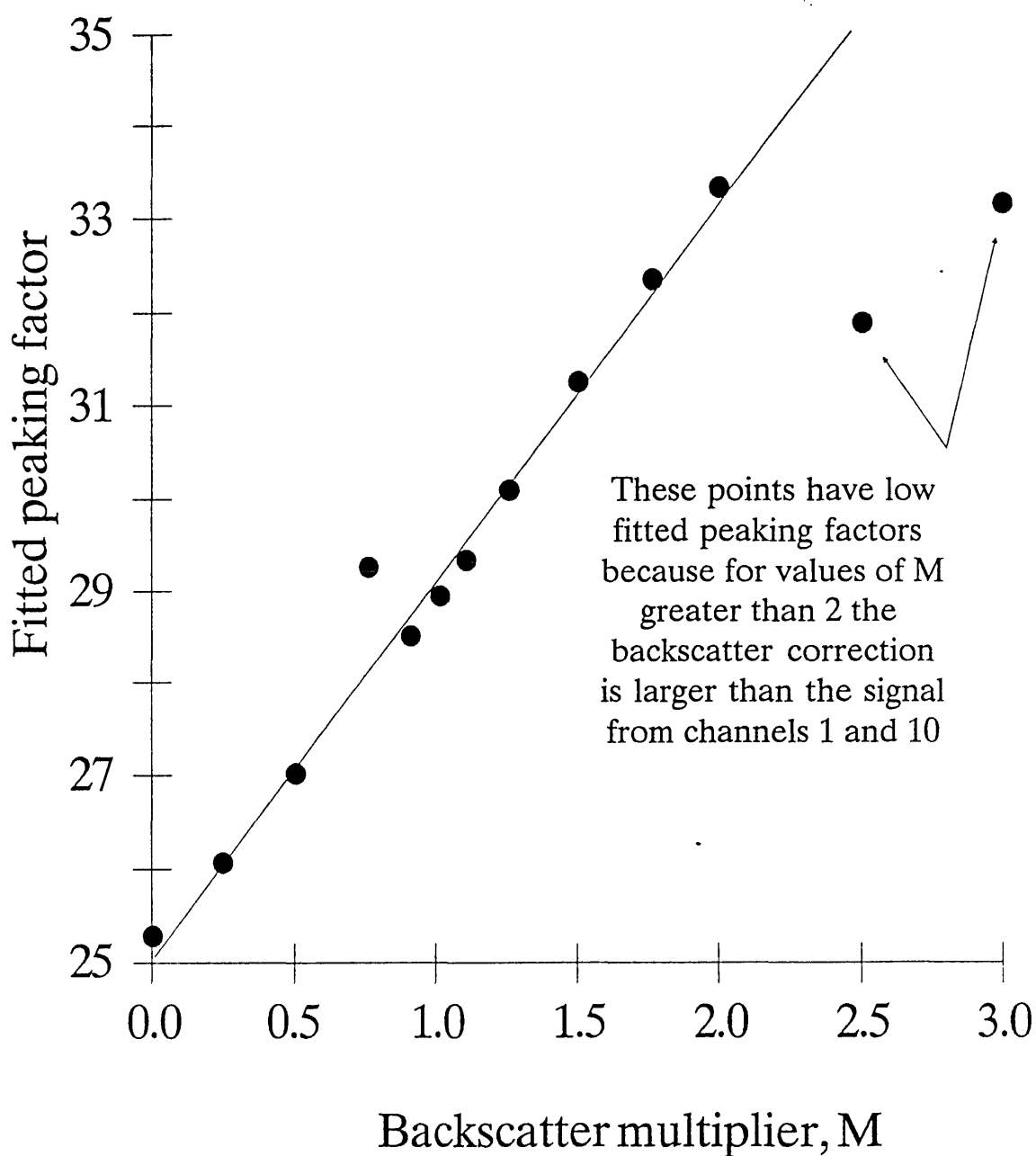


Figure 4.18. Peaking factor versus the backscatter multiplier: The fitted peaking factor appears to be a weak function of the backscatter multiplier.

S	= the neutron source emissivity,
ρ	= the normalised minor radius,
α	= the temperature profile peaking factor,
β	= the source profile peaking factor.

The temperature profile has a step of 1 eV in order to stop some numerical errors appearing in the code. The last term in eq 4.13 is usually called a wedge. The wedge on the neutron source profile is there because for peaking factors near 20, the second derivative of the neutron emissivity profile becomes large and errors due to variations in the profile across the finite solid angle of each line-of-sight enter into the ORION calculation, obscuring the effect under study. The addition of the wedge avoids this difficulty. In order to test the effects of the collimation, three different collimator sizes were used in the tests, a 60 mm x 60 mm, a 140 mm x 140 mm collimator and the last a 300 mm x 300 mm collimator. These values cover the normal range of collimator sizes.

Fig. 4.19 shows a typical spectrum as seen by KM1 and the fitted spectrum which minimises the sum of the squares of the differences between the spectra. Usually very good fits are obtained, but for unusual spectra, such as those produced with a strongly varying T_i profile and a weakly varying neutron emission profile, the fit can become quite poor. The output from these comparisons can be shown in the form of a 3-D graph with the deviation of the fitted temperature from the peak ion temperature used (5 keV) against the peaking factors of the ion temperature profile and the neutron source profile. Figure 4.20 shows the 3-D plot for the 6cm x 6cm collimator size. The graph includes regions where the plasma parameters probably cannot reach. A reasonable approximation is that the peaking factor for the ion temperature profile is about one quarter of that of the neutron emission profile. The graph then shows that as the peaking factors increase, the error between the peak ion temperature and the measured ion temperature increases, as expected. A section through such 3-D graphs can be drawn which is more applicable to JET discharges. The sections for the three collimator sizes are shown in fig. 4.21, showing that for normal discharges the correction should be 8-20%, depending upon the conditions. The sensitivity of the 60 x 60 mm collimator to changes in

the vertical position of the plasma centre is shown in fig. 4.22 and is generally small. The sensitivity to changes in the radial plasma position is not shown as it is negligibly small.

4.3.4 Correction to the ion temperature measured by KM3

The effect of the profiles of neutron emissivity and ion temperature on the ion temperature measured by spectrometers in the roof lab has previously been investigated for a single line-of-sight passing through the centre of the plasma [4.14]; this study showed that the correction was 8-12% for the most commonly encountered plasmas. The correction can be evaluated more accurately with ORION. Typical results are shown in figure 4.23, where the approximation that the ion temperature peaking factor is one quarter of the neutron profile peaking factor has been used. The line corresponding to the narrow collimation should be equivalent to the model used in [4.14] and the results appear to be very similar. The line corresponding to a larger collimator indicates a bigger correction, which is reasonable as a larger volume of low temperature plasma now lies in the detector's line-of-sight.

For real profiles the corrections are sometimes much larger than the 8-15% shown here, occasionally reaching as much as 30%. This applies to KM1 as well as KM3 and is usually due to plasmas with centres outside the line-of-sight of the spectrometer and for plasmas with unusual profiles, such as those with hollow density profiles. From the size and variability of the correction, it seems that the correction should be calculated for each plasma viewed by the spectrometer. Clearly, the neutron data from the two diagnostics should be checked for consistency.

4.3.5 Foil activation correction.

The results from this correction are given relative to the plasma model used by M. Pillon for an extended 14.1 MeV neutron source, which was a 1.1m minor radius circular plasma centred at a major radius of 3.17 metres. The use

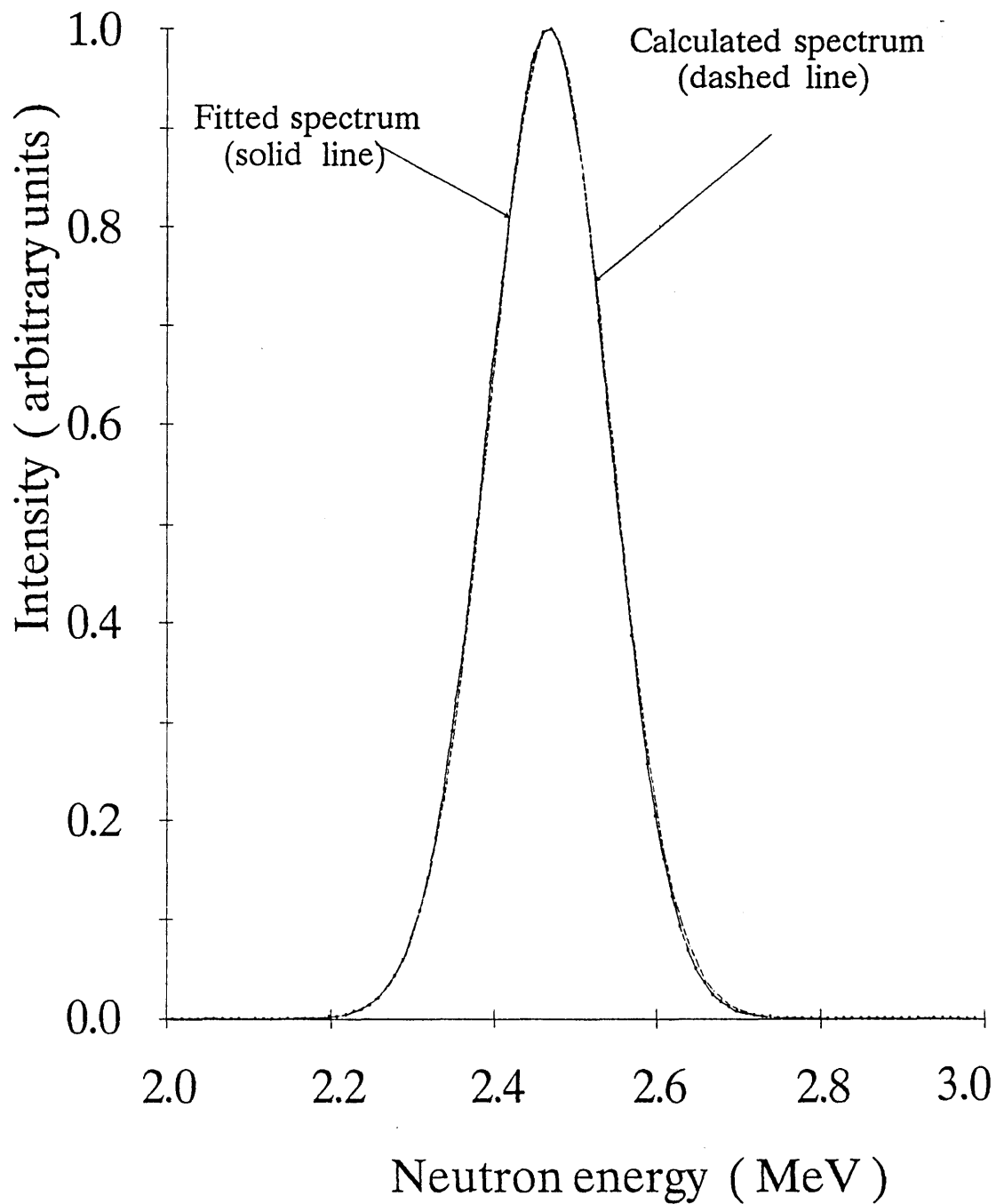


Figure 4.19. Modelled neutron spectrum at KM1 and the best fit to it: The neutron spectrum at the the KM1 spectrometer is modelled taking into account the variation of the spectrum across the plasma. The fitted profile corresponds to a spectrum from a source at a single temperature.

Effective temperature recorded
by KM1 less the assumed axial value

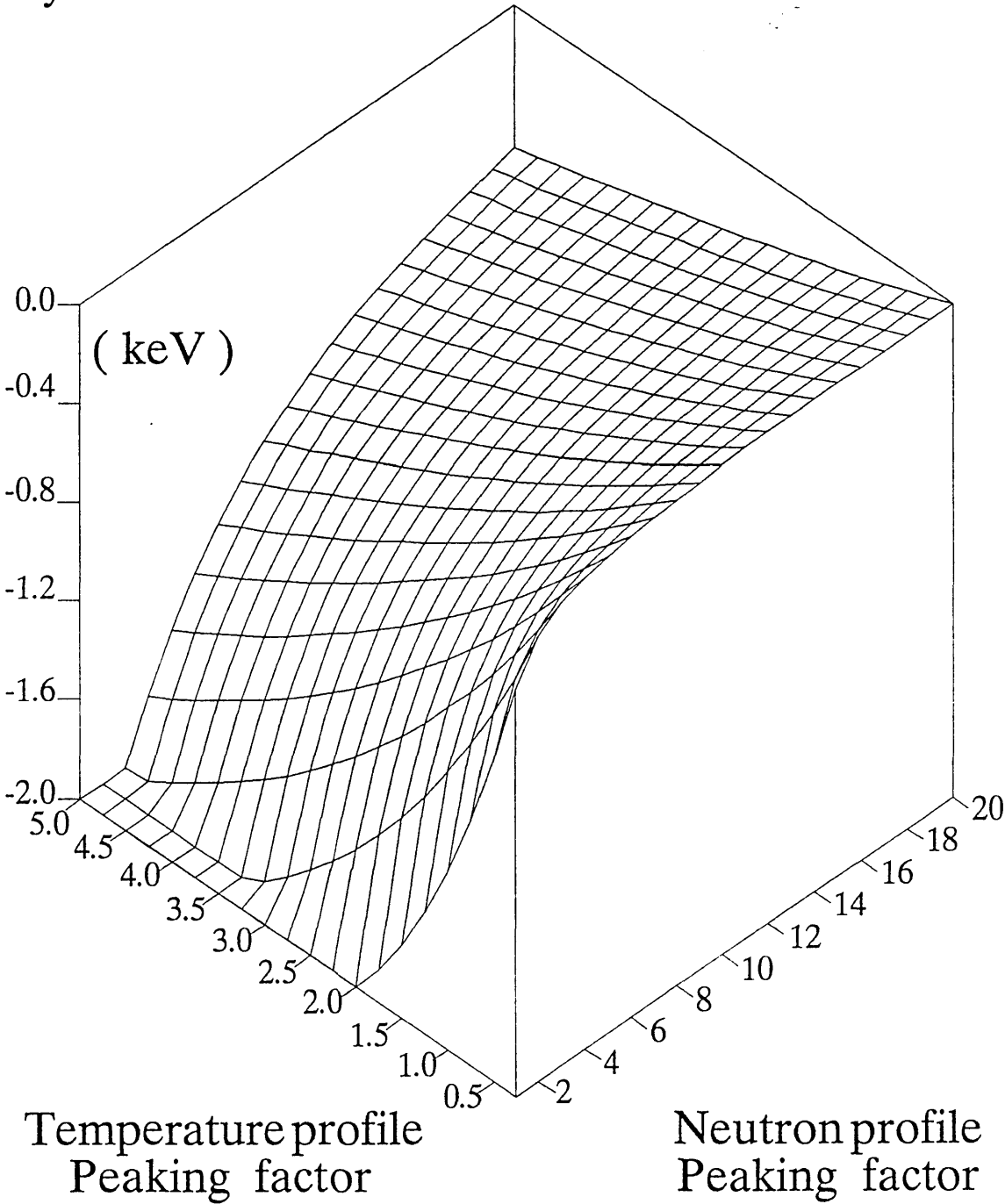


Figure 4.20. KM1 correction vs temperature and neutron profile peaking factor: The graph is for the case with 6cm by 6cm precollimator.

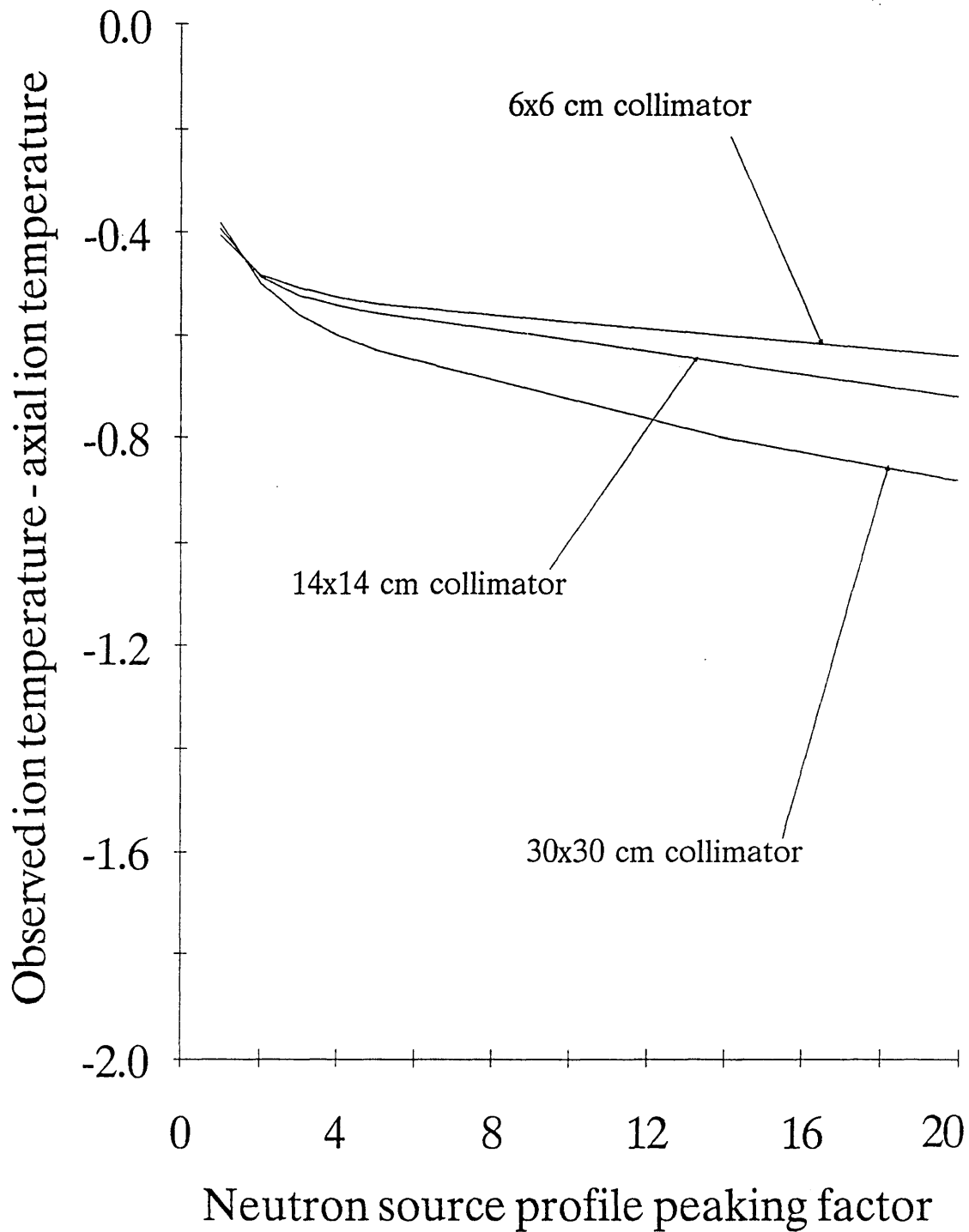


Figure 4.21. KM1 correction vs neutron emissivity peaking factor: The assumption that the neutron peaking factor is 4 times the ion temperature peaking factor has been made here.

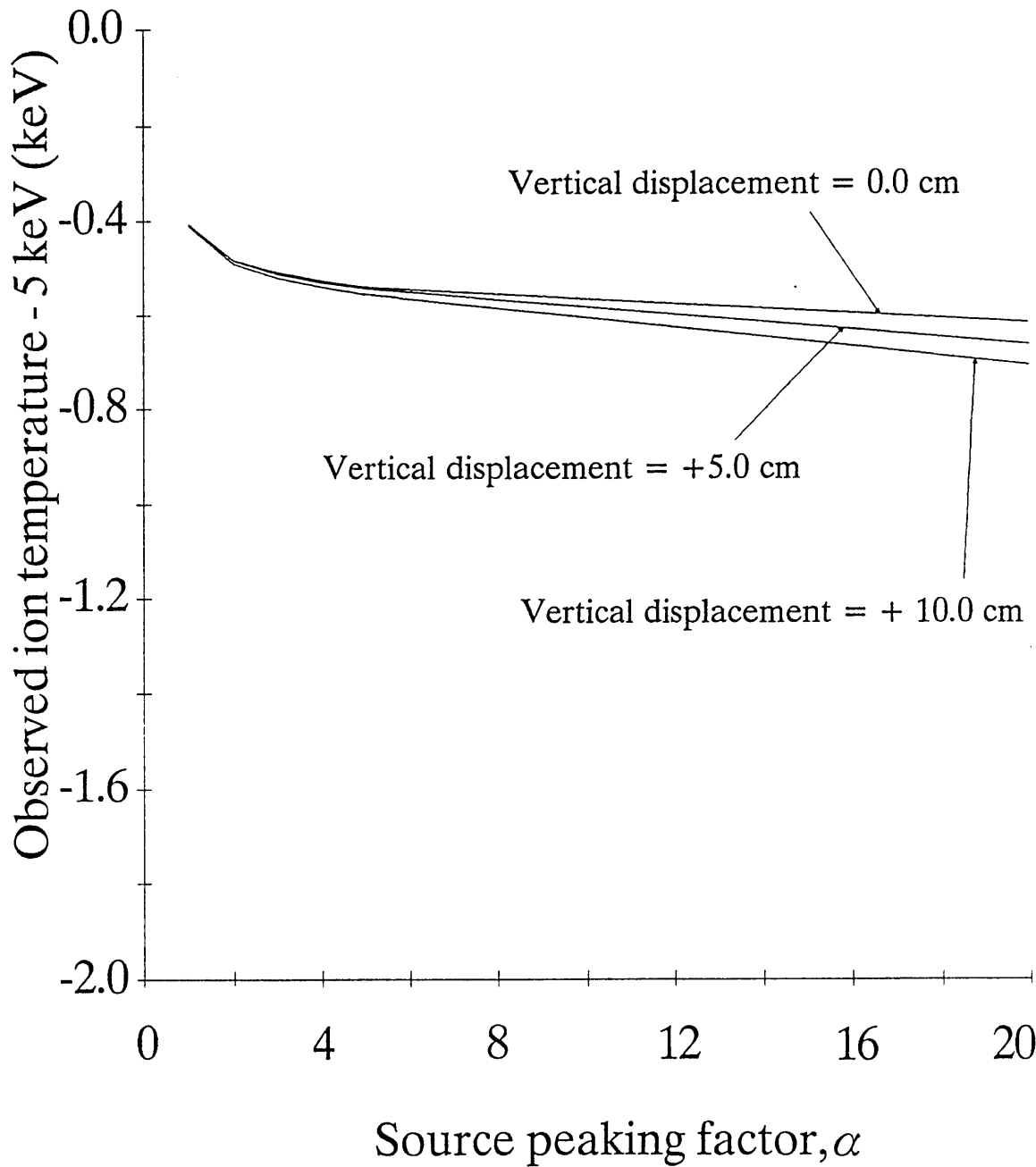
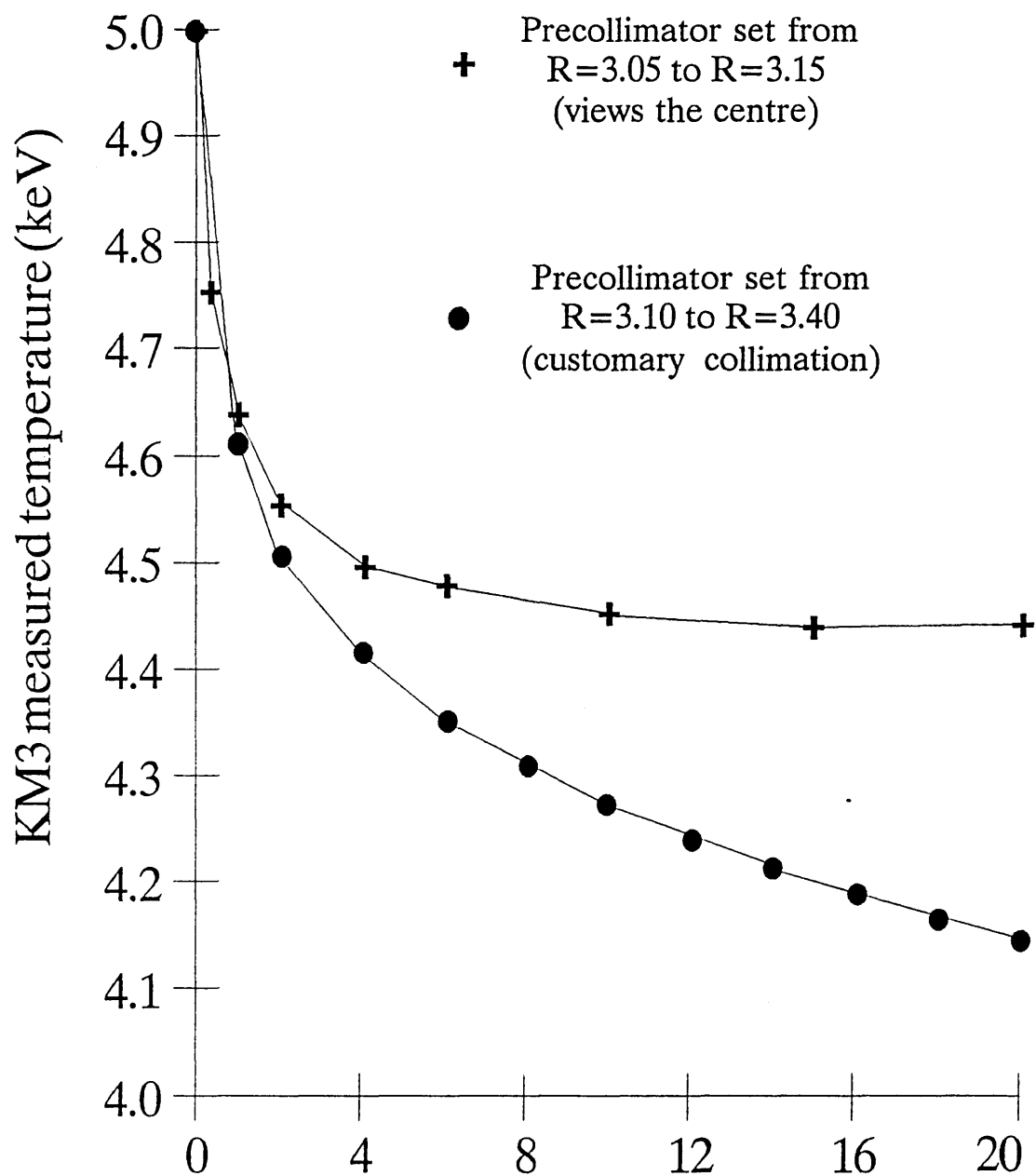


Figure 4.22. Sensitivity of KM1 correction to plasma position variations:



Neutron source profile peaking factor
Figure 4.23. KM3 ion temperature correction as a function of peaking factor:

of the model is reasonable for the purposes of this thesis, as the major interest is the triton burnup described in chapter 5, but it does reduce the general applicability of this correction.

The general magnitude of the correction is shown in figure 4.24, where the effect of variations in the source profile peaking factor and displacements in the vertical and horizontal directions of the plasma centre of a typical plasma are examined. The plasma was positioned on the midplane at a major radius of 3.14 m and had a source profile peaking factor of 5. This plasma was then rigidly shifted vertically and horizontally and the peaking factor varied whilst keeping constant the neutron emission rate from the altered plasma. The range of peaking factors and shifts cover the normal operating regimes at JET, although exceptional cases outside these regions are possible. The corrections are found to be consistent with those calculated in [4.15] which is encouraging. The only unexpected result was that from the radial position scan, which shows that the correction factor falls with increasing major radius for both the inboard and outboard irradiation ends. This suggests that the correction factor in this case is dominated by the increase in volume associated with increasing the major radius and the subsequent reduction of the peak neutron emission rate in the modelled plasma. All the variations produce corrections of up to 10% and can be considered as first order corrections.

4.3.6 Deuterium density ratio measurement

If the central ion temperature and the electron density profile are both well known, then the deuterium density may be estimated for a Maxwellian plasma, assuming that the impurity concentration remains constant across the profile. The ORION code is used to find the best fitting neutron source profile and the deuterium density fraction is then varied until the ion temperature deduced from the neutron profile is in agreement with that measured by another diagnostic, usually the ^3He neutron spectrometers (KM1) or the X-ray crystal spectrometer. The accuracy of the derived n_D/n_e ratio is typically $\pm 20\%$, due mainly to the error in the measured ion temperature. This technique has also

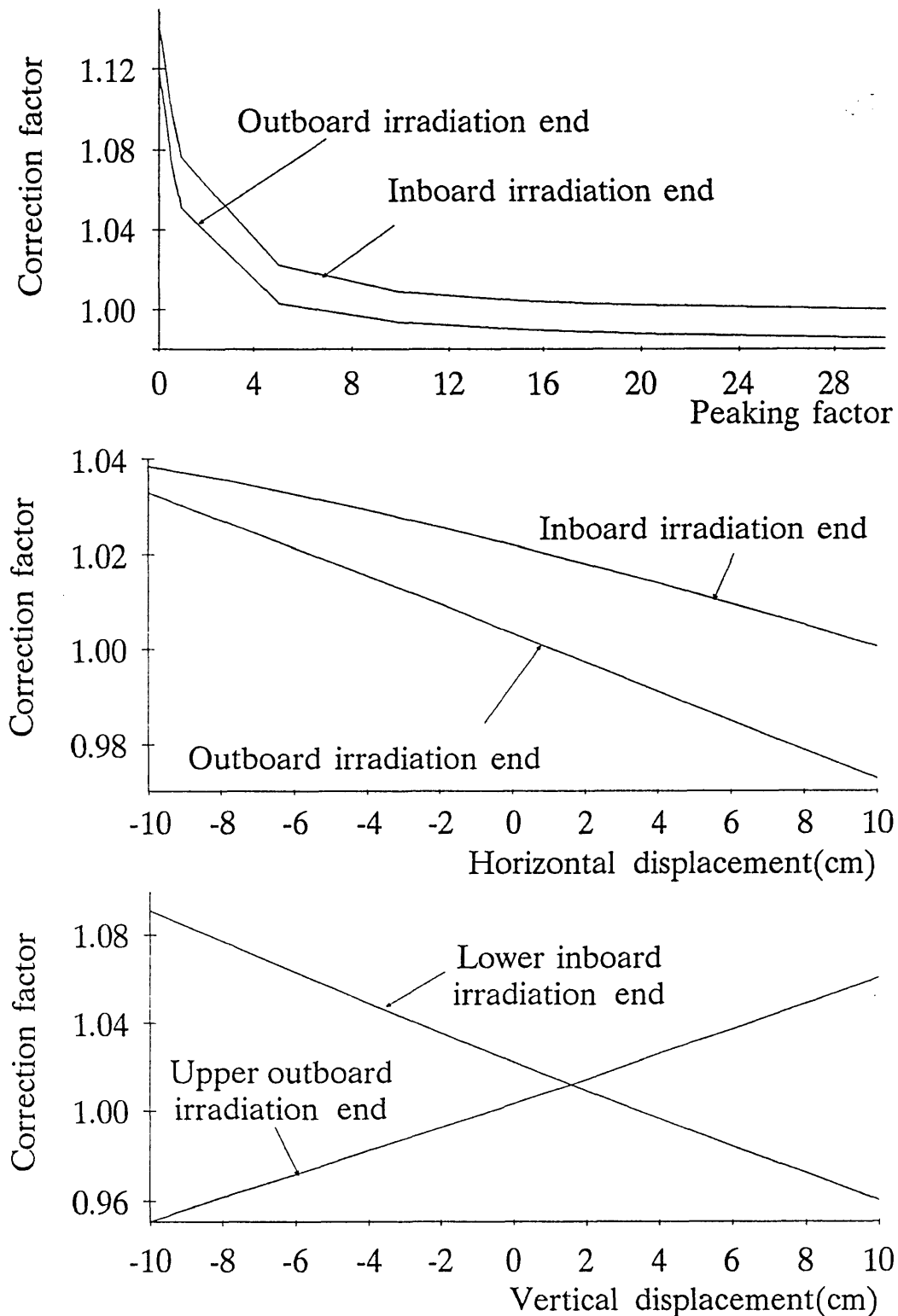


Figure 4.24. Typical magnitude of KN2 foil corrections: A typical flux surface configuration was taken and a neutron source with a peaking factor of 5.0 superimposed. The correction factors relate the measured neutron yield to the actual neutron yield.

been extended for use in discharges with neutrons from non-thermal sources by introducing a beam-plasma correction factor to the neutron yield and assuming that the profiles of the thermal and non-thermal neutron emission are similar. Figure 4.25 shows a comparison of the n_D/n_e ratio derived from this neutron technique and from other techniques which measure Z_{eff} then deduce the n_D/n_e ratio. The agreement appears to be within the errors of the various measurements and it should be noted that the two sets of n_D/n_e ratios are complementary in that the Z_{eff} techniques are more appropriate for values of high values of n_D/n_e and the neutron technique for low values. All the techniques are discussed in more detail in [4.16].

4.3.7 Neutron emissivity profiles

The ORION code produces radial profiles of neutron emissivity and results have been published [4.17]. Figure 4.26 shows the profile obtained from an ohmic discharge. Also shown, for comparison, are the profiles from the other two codes available for the analysis of data from the neutron profile monitor. It should be noted that none of the programs were capable of accurately reproducing the observed KN3 neutron emission. The derived ion temperatures show how the large discrepancies in the neutron emissivity propagate through the calculations into much smaller discrepancies on the ion temperature profile.

A source profile may be calculated as follows:

1. Rescale the electron temperature profile so as the peak matches the X-ray crystal spectrometer ion temperature (p 21) and use this modified profile as an ion temperature profile.
2. Approximate the deuterium density profile by the electron density profile measured by the far infra-red interferometer.
3. Calculate the neutron emissivity profile using eqs 4.7 and 4.8 and normalise the total neutron rate from the plasma to that measured by the KN1 diagnostic.

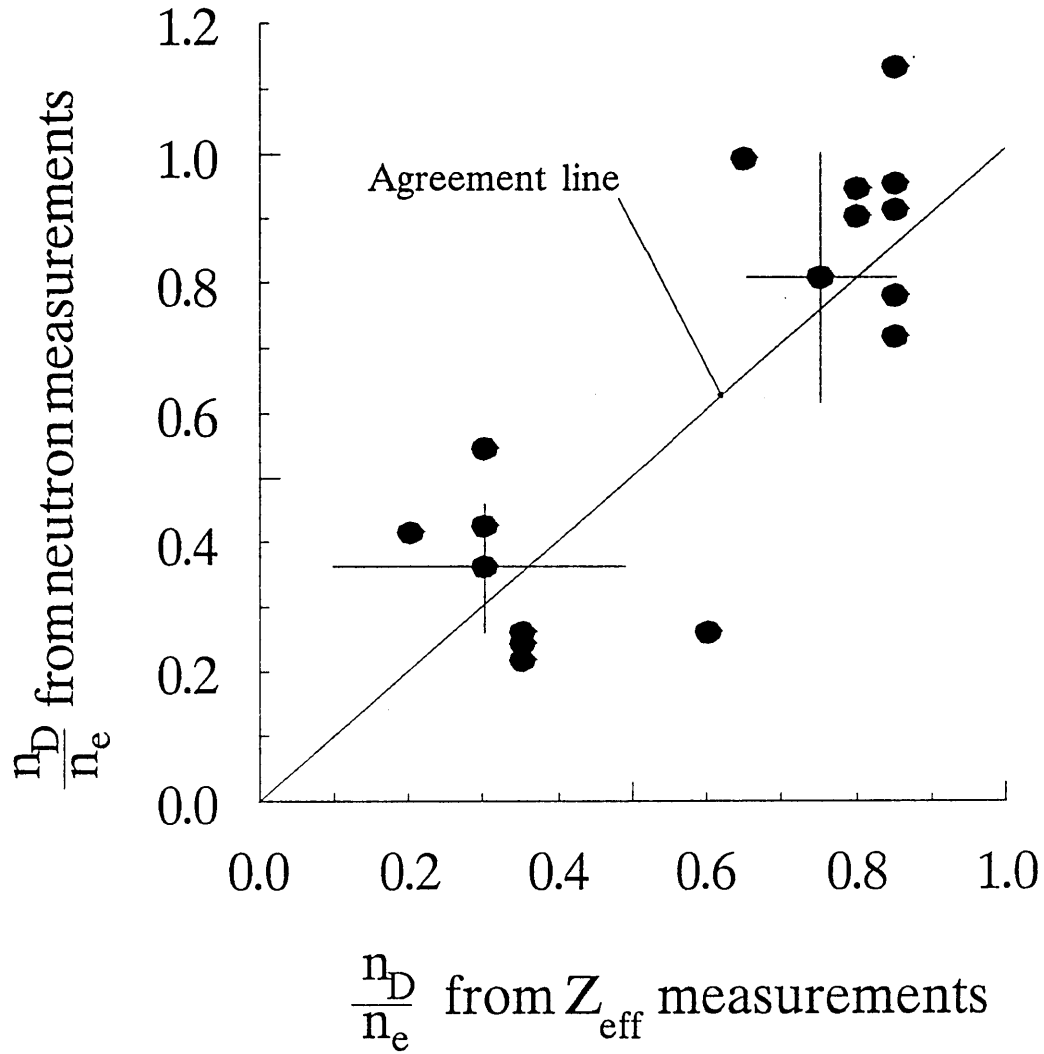


Figure 4.25. Deuterium density ratio from neutrons versus that from Z_{eff} : The n_D/n_e ratio from the neutron emission profile analysis is plotted against the n_D/n_e ratio from the Z_{eff} measurements. The neutron based method is of most use at low n_D/n_e ratios where the Z_{eff} techniques become unreliable.

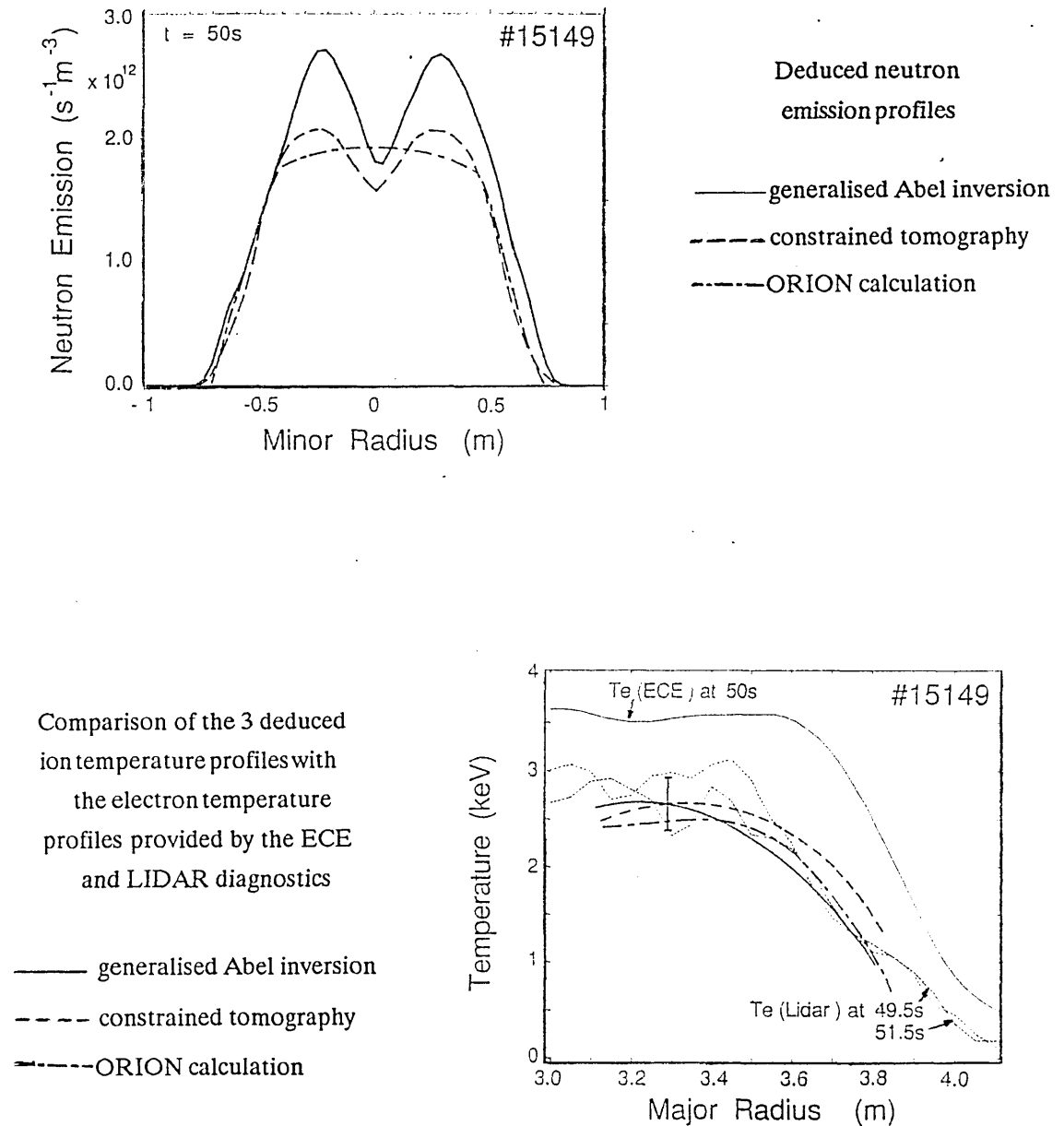


Figure 4.26. Emissivity and ion temperature profiles from KN3: An ohmic discharge was analysed by the three codes available at JET and the results are shown above. The neutron emissivity profiles show large discrepancies, whilst the ion temperatures derived from them are reasonably consistent.

The profile thus deduced is found to agree well with that derived from the KN3 data, even for additionally heated discharges. This observation is used later in chapter 5.

4.4 *Conclusions*

The neutron profile monitor is a large and complex diagnostic which, unfortunately, still does not operate entirely correctly at the higher neutron emission rates. Considerable effort has been invested by a large number of people but the cause of the problem has yet to be isolated. The principal manifestation of the problem is the variation of the KN3 to KN1 ratio, an analysis of which has shown that the problem appears to be tied to the number of neutrons emitted from the plasma as opposed to the number of neutrons passing through the collimators. The most probable cause of the effect is thought to be γ rays caused by interaction between the neutrons emitted by the plasma and the structure around the vessel, which give rise to pulse pile-up effects for high neutron emission rates.

A code has been written to assist in the analysis of data from the diagnostic and the production of correction factors for other neutron diagnostics. The code uses minimisation of a weighted χ^2 to fit neutron emission profiles to the observed data and works well. It has been used to obtain corrections to the KN1,KN2,KM1 and KM3 diagnostics and to determine deuterium densities in the plasma. Preliminary analysis of neutron emission profiles have been reported for discharges with low neutron emission rates.

4.5 *References.*

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5.0 Triton burnup studies

This chapter discusses the study of 14 MeV neutrons from the burnup of 1 MeV tritons. The chapter begins with a review of triton burnup studies and its relevance to prospective fusion reactors (sec. 5.1). This is followed by a discussion of the detection techniques used (sec. 5.2). The next section comprises the bulk of the chapter and consists of the analysis of the 14 MeV neutron data. It is subdivided into a description of the code used to analyse the data (sec. 5.3.1-5.3.2), a section on the global comparisons (sec. 5.3.3) and a section on the interpretation of specific issues, such as the confinement of fast particles (sec. 5.3.4). This is followed by the overall conclusions from this work.

5.1 *Introduction*

One of the major aims of the present generation of large tokamaks is to investigate the behaviour of α particles produced by D-T fusion reactions in the hope of confirming that fusion reactors can be self-sustaining. Unfortunately, due to a combination of high radiation levels and small α particle populations, the direct study of α particles will prove to be a difficult task (see Appendix A). It is possible to investigate some of the relevant physics using present machines by studying particles which have similar energies and gyroradii. There are two methods in use at JET, one involving RF heated minority populations [5.01] and the other utilising 1 MeV tritons from one branch of the D-D fusion reaction [5.02]. The first method employs ICRH to develop a high energy tail containing up to 20% of the plasma energy, allowing (to some extent) the simulation of the effects of a sizable population of thermalising α particles. This technique has the disadvantage that the energy

and pitch angle distributions of the population are not in close agreement with the expected α particle distributions. Triton burnup allows the study of a very dilute population of high energy tritons born with a unique energy and with the appropriate pitch angle distribution and spatial distribution.

Tritium nuclei (tritons) are produced from one branch of the deuterium-deuteron (D-D) fusion reaction. These have an initial energy of near 1 MeV and thermalise over a period of order 1.0 seconds (fig. 5.1). The slowing down triton may undergo a deuterium-tritium (D-T) fusion reaction, the most probable energy for this being 160 keV (fig. 5.2). The 14 MeV neutron produced by this reaction escapes from the plasma and may be detected. The production rate of the 1 MeV tritons can be monitored by observing the 2.45 MeV neutrons from the other branch of the D-D reaction and information on the energy loss processes of fast ions in plasmas may be obtained by examining the delay between the 2.45 MeV and the 14 MeV neutrons. From the absolute yield of 14 MeV neutrons, information concerning the confinement of tritons and the deuterium density in the plasma may be found. The rest of this chapter shows how these neutrons may be detected and how the 14 MeV neutron emission rates are interpreted.

5.2 14 MeV neutron detection

The 14 MeV neutron emission rate from JET has to be detected in the presence of large backgrounds of 2.45 MeV neutrons and γ rays. For a typical discharge, 14 MeV neutrons form approximately 1% of the emitted neutrons. The number of γ rays produced by JET is typically the same order of magnitude as the neutron yield, although this is dependent upon the plasma conditions and heating methods in use. There are three basic ways of performing the measurement in this background:

1. Use of detectors capable of measuring the energy of the detected neutrons. Adequate discrimination should be assured by selecting only events with energies greater than 5 MeV.

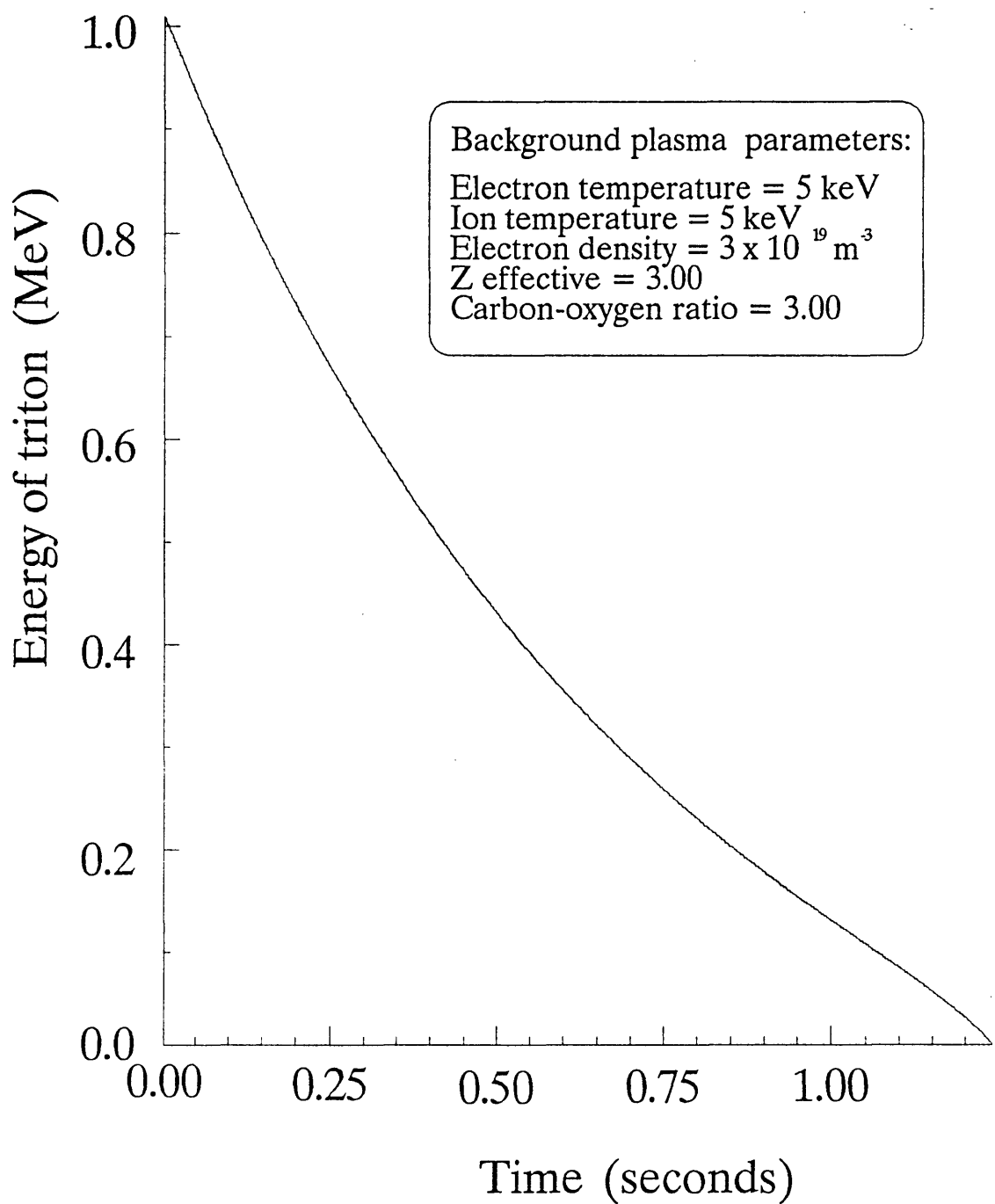


Figure 5.1. Graph of Triton energy as a function of time: The triton is slowing down in a background plasma consisting mostly of deuterium with the impurities being carbon and oxygen in the ratio 3 to 1, with a Z_{eff} of 3.

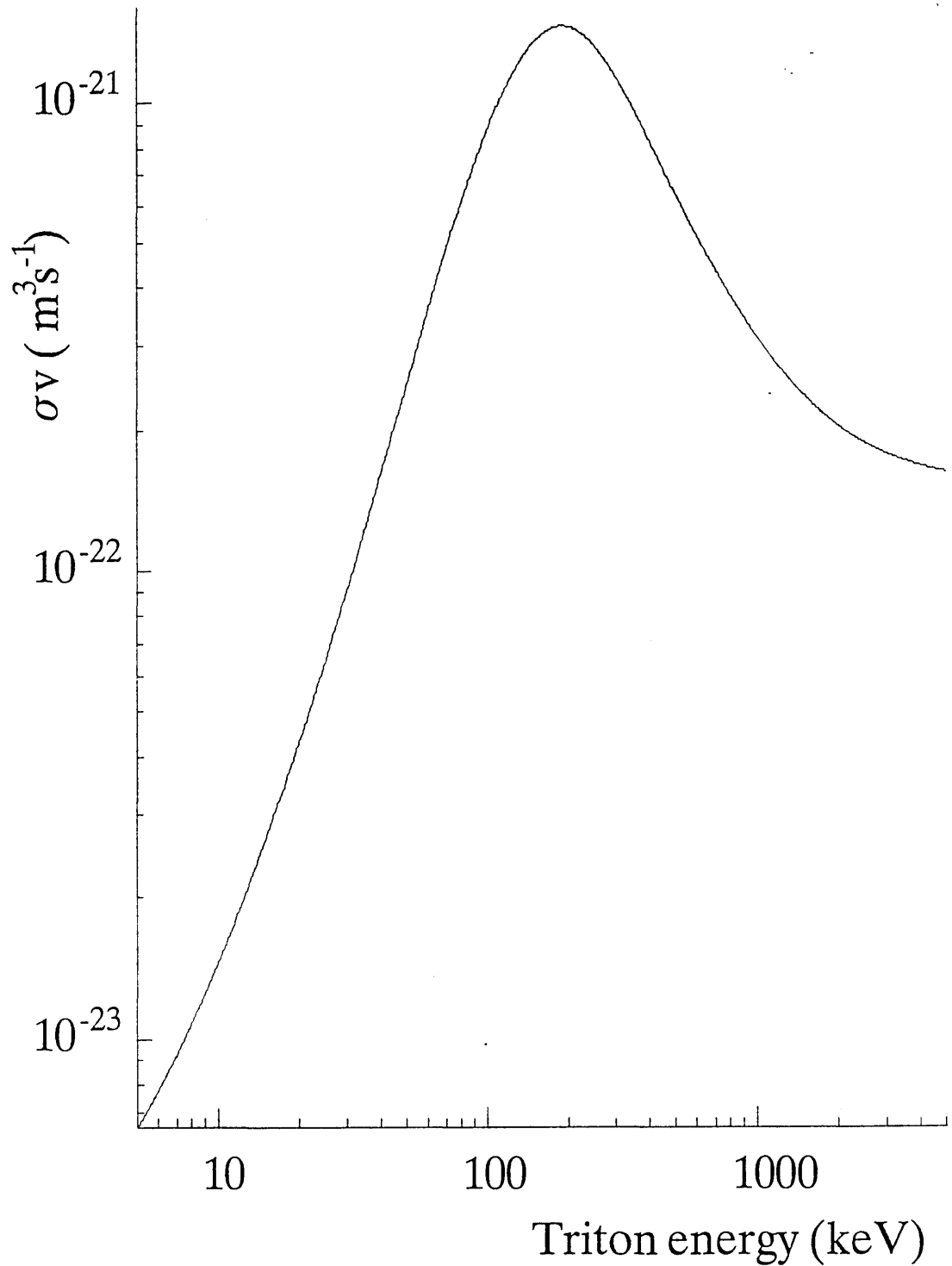


Figure 5.2. D-T reactivity as a function of energy: The information is drawn from two sources, the Peres formulation at high energy and the Sadler-van Belle formulation at low energies.

2. Use of threshold reactions, so only the 14 MeV neutrons are detected.
3. Operation of the detector in regimes where the background is much reduced.

All three techniques have been used in the past, with varying degrees of success and usefulness. At JET, variants on the second method are used and will be discussed in more detail later. First of all, an overview of the other possible systems will be given.

5.2.1 Alternative detection schemes not implemented at JET

The best time to observe 14 MeV neutrons is when there is no background of 2.45 MeV neutrons. This situation can be found after strong NBI heating of low density plasmas, where the 2.45 MeV neutron emission rate can fall several orders of magnitude on the timescale of the thermalisation time of a beam ion, say 50-100 ms. As the 14 MeV neutron emission rate changes little over such a short time interval, the bulk of the neutrons emitted from the plasma will have energies of 14 MeV. Standard neutron detectors (such as fission chambers) can then be used to detect the global neutron rate , which is interpreted as the 14 MeV neutron rate. This was the method employed by Jassby et al [5.03] to study the triton burnup in TFTR after the NBI heating of supershots and by Murphy to study the effects of pellets on the fast triton population [5.04,5.05]. This method has the advantage of being very straightforward to implement, but has the drawback of requiring a factor of 1000 (at least) drop in the 2.45 MeV neutron rate over a 0.1 second interval in order that the 14 MeV neutron rate be clearly distinguishable from the 2.45 MeV neutron rate. This situation is extremely unusual in JET and so could not be used.

A more complex method involves the use of energy discrimination to separate the 14 MeV neutron signal from the 2.45 MeV neutron signal. The main method which has been used in the past involves the use of an NE213 scintillator and photomultiplier as the neutron detector [5.06]. Such a detector can give an energy resolution of 8% for neutrons near 2.45 MeV, allowing easy

separation of the 14 MeV and 2.45 MeV neutrons detected. The results obtained were interesting in that they were the first to show that triton burnup did occur at approximately the classically expected rates in tokamak plasmas, but the time resolution and the counting statistics were poor because the fraction of 14 MeV neutron events was so low. More recent work using this type of detector has been attempted at TFTR [5.07] but again the results have poor time resolution and the absolute magnitude of the 14 MeV neutron emission is lower than the classically calculated yields by factors of 2-3. A possible future experiment at JET would involve using the neutron profile monitor to observe the spatial distribution of 14 MeV neutrons as the detectors in the profile monitor are NE213 scintillators. The results would also have poor time resolution but would provide a different test of the physics of slowing down particles in that, by comparing the profiles from the 2.45 MeV neutrons and the 14 MeV neutrons, the presence of any spatial diffusion of slowing down tritons should be easily observable. Also the effects of sawteeth on fast particle populations could be investigated more thoroughly. This experiment would require the simultaneous measurement of both the 2.45 MeV neutron profile as well as the 14 MeV neutron profile; unfortunately, this experiment has not yet been performed because of the difficulty in setting the PSD (pulse shape discriminator) to cover the required energy range with a single setting of the detector high voltage.

Another possible detection scheme involves the use of lithium-free glass scintillators [5.08]. This technique exploits the $^{28}\text{Si}(n,p)^{28}\text{Al}$ reaction; this has a Q value of -3.852 MeV so it should be insensitive to 2.45 MeV neutrons. The protons are produced with an energy of up to 10 MeV, generating a scintillation event as it slows down in the glass. This is detected by a photo-multiplier tube and the signal is processed by a standard pulse height analysis system. The method is still being developed at GA but does suffer from sensitivity to γ rays; in fact, it is easier to exploit the $^{28}\text{Si}(n,p)^{28}\text{Al}$ reaction by using a silicon surface barrier diode as the detector than by using a scintillator.

Because of the limited utility of the data from the above methods, a combination of two other techniques is used on JET, foil activation and silicon diode detectors.

5.2.2 Activation techniques

Neutron activation is a standard technique for measuring the time integrated fluxes of neutrons. It involves irradiating a sample of some material and then measuring the induced radioactivity, usually in a detector station some distance from the irradiation point. The cross-sections for these reactions are fairly well known, as are the decay routes and half-lives. The technique may be employed to study the 14 MeV neutrons only by using threshold reactions where the energy of the incoming neutron must be greater than 3 MeV.

5.2.2.1 *The JET activation system*

The activation system in use at JET [5.09] has 8 positions (irradiation ends) where activation occurs, a schematic of which is shown in fig 5.3. These are located on the torus as shown in fig. 5.4 and are designated as being either inboard or outboard. For the purposes of most of the results reported here, the outboard irradiation ends were used, as these are less sensitive to changes in the plasma position than the inboard irradiation ends and the results from neutron transport codes are more reliable. Each irradiation end is linked to a carousel by hollow plastic tubing. Compressed air is used to propel capsules, containing the samples to be irradiated, from the carousel to the irradiation end and back again via the plastic tubing. The carousel is also linked by plastic tubes to a set of detectors, which are used to measure the induced activity from the irradiated samples.

The system is capable of measuring the fluence of neutrons at a point near the JET vacuum vessel. To go from this measurement to a total neutron yield from JET requires a calibration factor. This could, in principle, be measured using a strong 14 MeV neutron source positioned at many points around the vessel, similar to the way in which the fission chambers are calibrated for

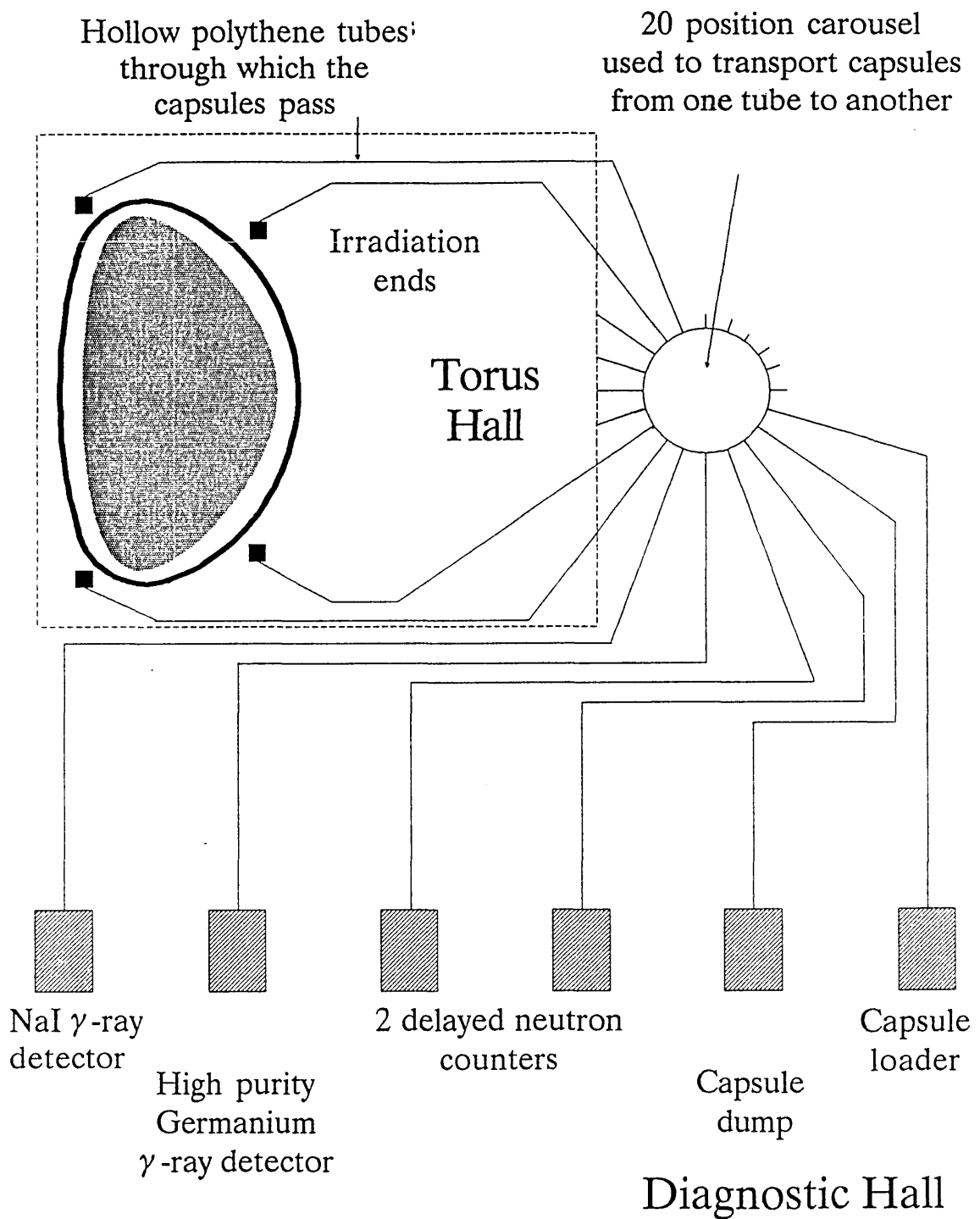


Figure 5.3. Schematic of KN2 foil activation system: Using this system, foils are activated near the vessel, rapidly transported via the carousel to the remote detector station, where the induced γ ray activity is measured by using a large NaI detector, or a high purity Germanium detector.

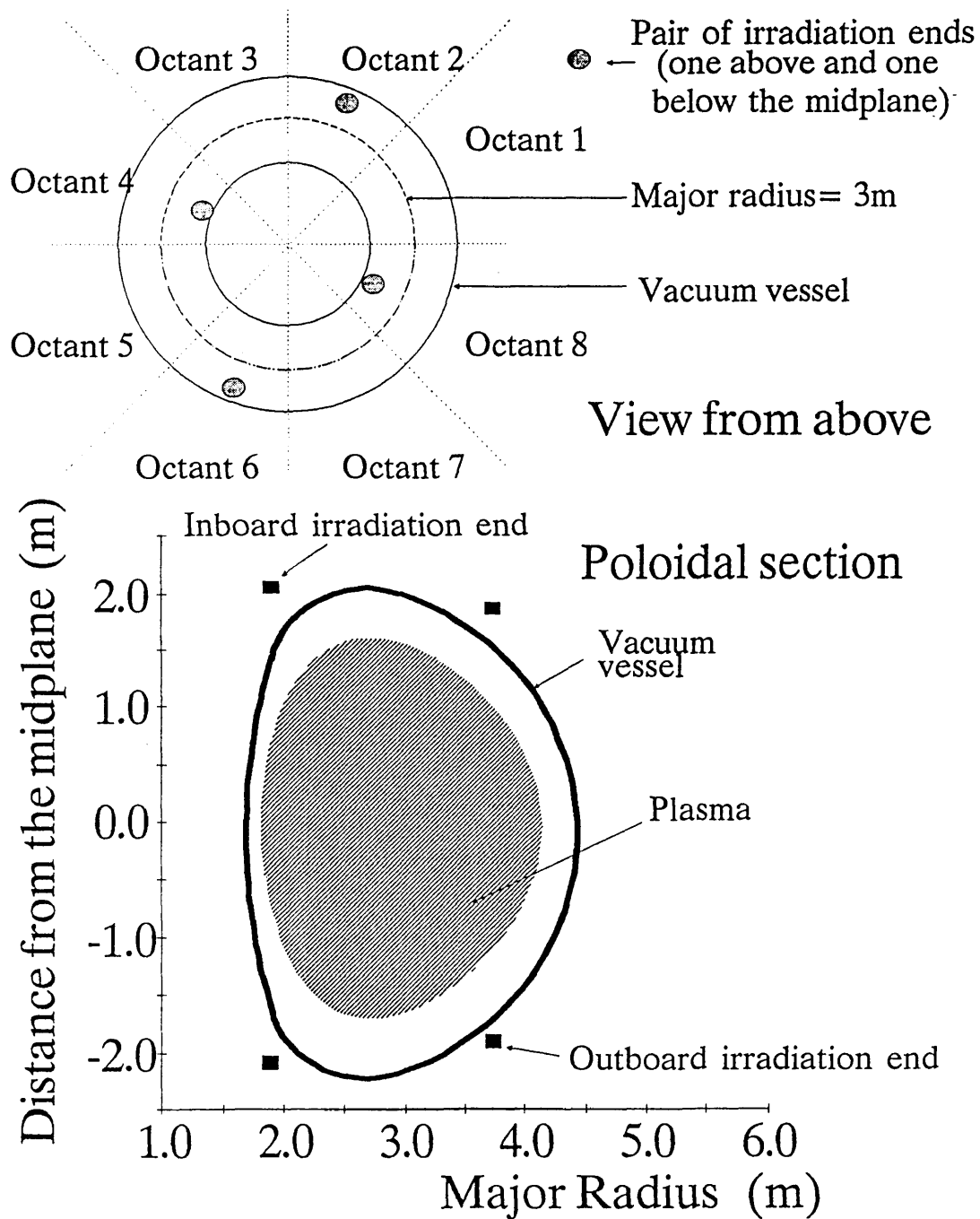
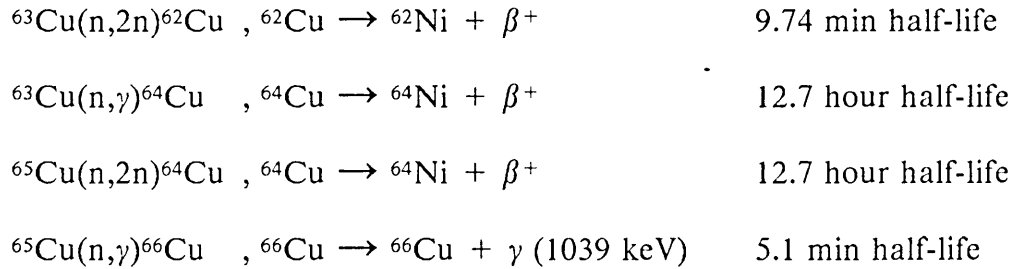


Figure 5.4. Location of the KN2 irradiation ends: The upper picture shows the toroidal location of the irradiation ends, each dot representing a pair of irradiation ends arranged as shown in the lower diagram. The outboard ends of octant 2 were most commonly used for the activations described in this thesis. This was because of the low sensitivity to variations in the position of the neutron source of the outboard irradiation ends.

2.45 MeV neutrons. As we lack such a source, the calibration constant is found using a neutron transport code to calculate the fluence at the irradiation ends for given neutron source profiles and plasma flux surfaces. The calculation used throughout this work was performed by M. Pillon [5.10] using the MCNP neutron transport code [5.11]. For 2.45 MeV neutron emission, this method gives good agreement with the absolutely calibrated fission chambers, giving confidence in the validity of the model used in the MCNP calculation. Also, multiple foil activation techniques can be used to check the neutron spectrum at the irradiation ends and these are found to agree well with the MCNP calculations [5.12].

5.2.2.2 *Activation materials*

A number of different materials have been used to measure the 14 MeV neutron yields at JET. The most important of these is copper but iron, silicon, magnesium and aluminium have been used as well. Copper is composed of two stable isotopes, ^{63}Cu and ^{65}Cu in the ratio 69 to 31, which undergo the following reactions:



The activation of the copper samples is measured with a γ ray detector, such as a NaI or a high purity Germanium detector. The observed spectrum has peaks at 511 keV (one of the two 511 keV γ rays produced by the annihilation of a β^+) and at 1039 keV (from the decay of ^{66}Cu), as shown in fig 5.5. The $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reaction has a threshold of approximately 10 MeV (the cross section is shown in fig 5.6 from [5.13]) and by observing the 511 keV γ from the annihilation of β^+ produced by the residual ^{62}Cu nucleus, the 14 MeV neutron yield may be assessed. Unfortunately, 511 keV γ rays are also produced

by the annihilation of β^+ from ^{64}Cu nuclei, created by other copper reactions. These may be subtracted by observing the activation of the copper over two time intervals, the first shortly after the exposure of the foil to 14 MeV neutron flux and the second some hours later. Hence, by using the formula:

$$\varepsilon N_{62} = \frac{C_1(e^{-\lambda_{64}t_2^c} - e^{-\lambda_{64}t_2^f}) - C_2(e^{-\lambda_{64}t_1^c} - e^{-\lambda_{64}t_1^f})}{(e^{-\lambda_{62}t_1^c} - e^{-\lambda_{62}t_1^f})(e^{-\lambda_{64}t_2^c} - e^{-\lambda_{64}t_2^f}) - (e^{-\lambda_{64}t_1^c} - e^{-\lambda_{64}t_1^f})(e^{-\lambda_{62}t_2^c} - e^{-\lambda_{62}t_2^f})} \quad [5.1]$$

where C_1 = number of counts in the 511 keV peak in the period $t_1^c \rightarrow t_1^f$,
 C_2 = number of counts in the 511 keV peak in the period $t_2^c \rightarrow t_2^f$,
 λ_{62} = decay constant of ^{62}Cu = $1.1861 \times 10^{-3} \text{ s}^{-1}$,
 λ_{64} = decay constant of ^{64}Cu = $1.5160 \times 10^{-5} \text{ s}^{-1}$,
 ε = the efficiency of the detector for 511 keV γ rays,
 N_{62} = Number of atoms of ^{62}Cu activated at $t=0$,
 $t = 0$ is defined as the time of activation of the sample.

it is possible to calculate the fluence of neutrons at the irradiation end and from this to calculate the total 14 MeV neutron yield from the plasma.

This is the most accurate way of removing the effect of the β^+ events due to ^{64}Cu . It is also possible to use the fact that the ratio of the 1039 keV line to the fraction of the 511 keV line produced by the ^{64}Cu decay is a constant value, to a good approximation. This ratio can be found by observing a number of discharges using the two time interval technique. Hence, it is possible to remove the ^{64}Cu component after only one measurement of the copper activation, making the experimental procedure easier and allowing more discharges to be examined. However, there is a higher error associated with this method introduced by the error on the ratio of the 1039 keV line to the 511 keV line and so in this thesis only activations analysed using the two measurement technique will be used.

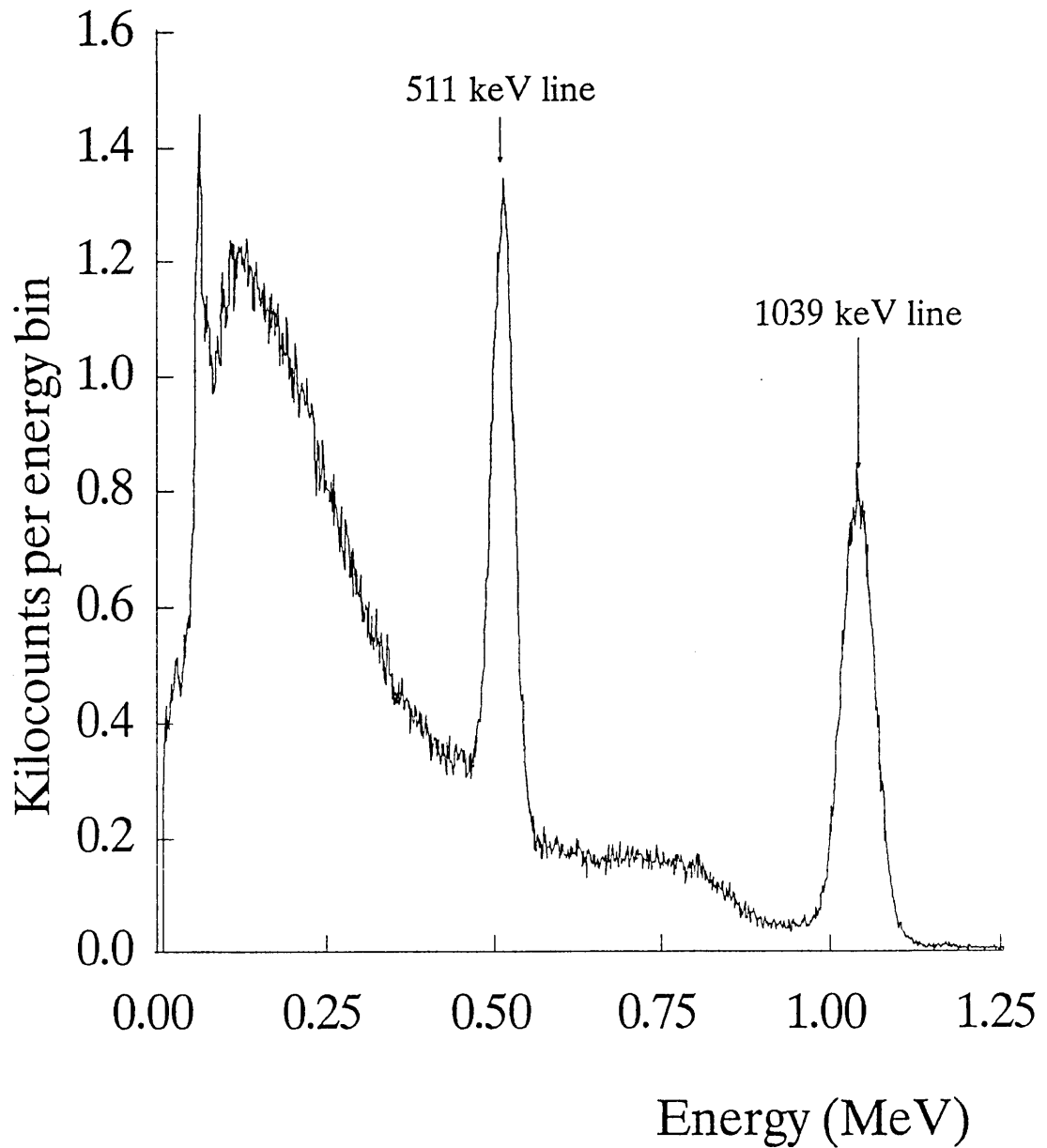


Figure 5.5. Gamma ray spectrum of copper activated at JET: The copper sample was activated by an NBI heated discharge and the γ ray spectrum measured using a high purity Germanium γ ray detector. The 511 keV and 1039 keV peaks from the (n,γ) and $(n,2n)$ reactions are clearly visible.

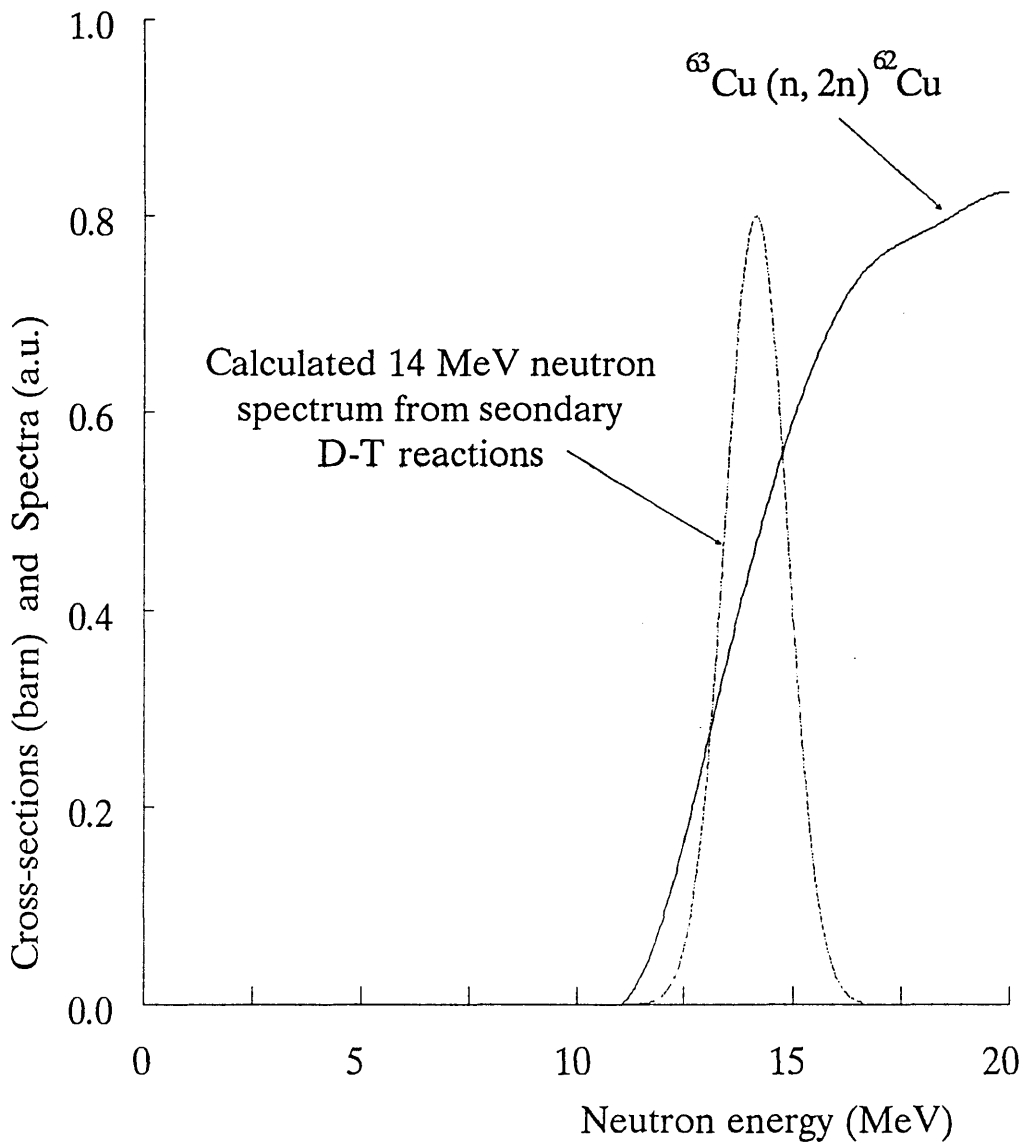


Figure 5.6. Cross-section of copper: The $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reaction has a threshold of approximately 10 MeV, making it suitable for use as a 14 MeV neutron activation material. The effect of the broad 14 MeV neutron spectrum produced by fast tritons must be included when absolute measurements are made, as the spectrum stretches from 12 to 17 MeV.

Copper was the original material used for measuring the 14 MeV neutron yield of the JET plasma because it has a large cross-section which is known to an accuracy of about 4% over the neutron energy range of interest. However, as the 14 MeV neutron yields have increased, other materials have become useful, such as magnesium. The $^{24}\text{Mg}(n,p)^{24}\text{Na}$ reaction is known to a similar accuracy as the copper reactions but has a much lower cross-section. The advantage of magnesium over copper is that the reaction used does not require two measurements and so is considerably easier to perform.

Silicon can also be used as an activation material, as silicon is known to have a threshold greater than 5 MeV for neutron activation and one of the resultant nuclei is a γ ray emitter with 2.24 minute half-life. A γ ray spectrum of an activated sample of silicon is shown in fig. 5.7. The cross-section for this reaction is poorly known, but it can be used to monitor the relative 14 MeV neutron yields from the JET plasma. As the γ ray emitting nuclei have a short half-life compared to the 15-20 minute period between discharges, one sample can be used repeatedly and the data taken automatically. This is useful for monitoring the calibration of the detector described in section 5.2.3 for deterioration due to radiation damage.

5.2.2.3 *Copper measurements*

The original measurements using copper as an activation material were made when the activation system was totally under manual control. A fully computer-controlled system has since been implemented.

A labelled capsule was filled with a known mass of 99.5% purity copper, typically 20 g being used. Shortly before a discharge, the capsule would be fired into the torus hall to a pre-selected irradiation end, usually the upper end on octant 2. The time the capsule was present in the torus hall was minimised in order not to leave the plastic capsule near to the 300°C vessel wall for a period long enough to cause deformation of the capsule and the possibility of the capsule getting stuck. After the discharge, the capsule would be retrieved from the torus hall and sent to the NaI detector, via the carousel. The NaI detector

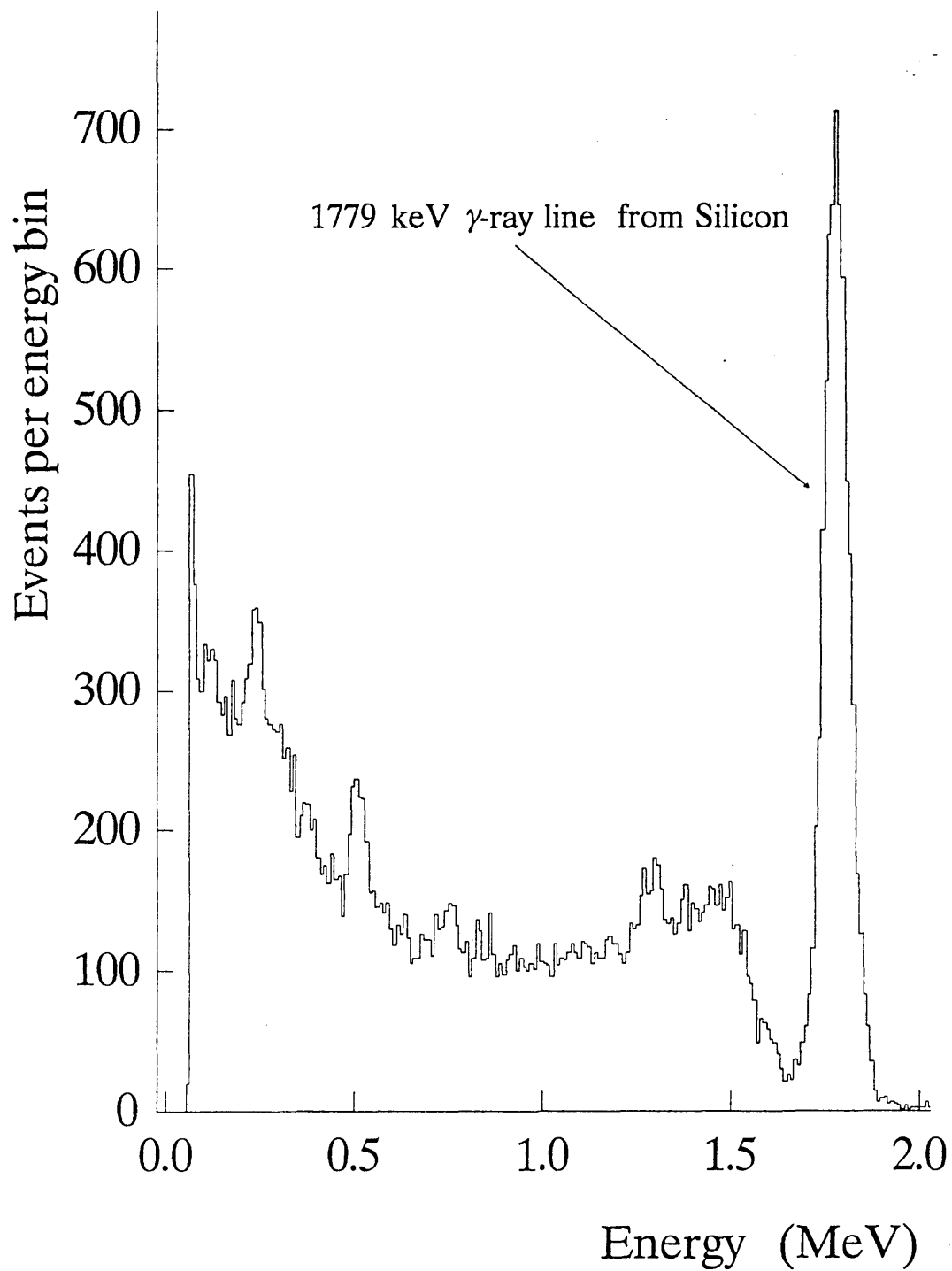


Figure 5.7. Gamma ray spectrum of activated Silicon: The number of counts in the single peak at 1779 keV is proportional to the 14 MeV neutron yield from the plasma.

was generally used because the capsule could be sent directly to it and the measurement made immediately, whereas, with the high purity Germanium detector, the capsule first had to be unloaded and the copper arranged on the surface of the detector in order to increase the γ detection efficiency. After a delay of some 5 minutes, to allow the very short lived nuclei to decay away, the γ ray spectrum would be taken for a period of 1000 seconds. The capsule would then be taken from the KN2 system and placed in a shielded storage area for a period of 1-3 hours before the second measurement was made, the exact length of time being dependent upon the operations program for JET as typically 3 or 4 copper measurements would be made concurrently. After the second measurement, the copper samples were stored and not used for several days, in order to allow the ^{64}Cu nuclei enough time to decay to a negligible level.

The number of counts in each peak was estimated using an algorithm built into the Canberra model 90 multichannel analyser used to collect the spectrum. These numbers would then be entered in a computer program which calculates the 14 MeV neutron yield from the JET plasma, taking into account the following effects; self-shielding by the copper; detector efficiencies; and the results of separate neutron transport calculations to relate the activity of the sample to the total 14 MeV neutron yield.

The statistical errors on the activation measurements vary from less than 1% to more than 50%, depending upon the number of γ rays detected. The systematic errors are estimated to be approximately $\pm 8\%$ in the case of copper using an outboard irradiation end. Small corrections, $\approx 1-5\%$, are needed because of the variation of the plasma position relative to the irradiation ends, but these can be estimated using the method described in Chapter 4. Another systematic error is introduced by the assumption made in the analysis that the $t=0$ time for the activation corresponds to the $t=52$ seconds point of a JET discharge. The peak neutron yield could be as much as 10 seconds away from this time and this introduces an error of δN_{62} in N_{62} given by:

$$\frac{\delta N_{62}}{N_{62}} = 1 - \exp \lambda_{62} \delta t \quad [5.2]$$

where δt is the error in the timing of the neutron emission. Even for an error of $\delta t = 10$ seconds, the fractional change in N_{62} is only 0.12% so it is considered to be unimportant.

Another problem in estimating the 14 MeV neutron yield with copper activation is the sensitivity to disruptions and photoneutrons created by runaway electrons interacting with the material of the vacuum vessel and its carbon tiles. If a discharge shows high runaway activity, such as is often seen in the so called 'supershot' operating regime, or if a disruption occurs whilst the capsule is near the plasma, then the results obtained can be extremely inaccurate and should not be used.

5.2.2.4 *Summary*

The activation system at JET allows the accurate measurement of 14 MeV neutron yields with errors of $\pm 10\%$ on the absolute yield attainable. This provides useful information on its own and several papers have been produced based simply upon the time integrated data available from such activation results [5.14-5.19]. However, it is impossible to distinguish between anomalous triton losses and anomalous energy loss rates using this technique. Also, the absolute 14 MeV neutron yield is proportional to the deuterium density in the plasma and, as this is usually a poorly known quantity (errors of $\pm 30\%$ are common), then any analysis based on the integrated yield must necessarily be inaccurate. By incorporating time-resolved 14 MeV neutron emission rates into the data, the slowing down of tritons is separated from the absolute yield, allowing a far more accurate examination of the behaviour of the tritons. The detector described in the next section is used for making time-resolved measurements, although the activation system is still required for calibration purposes.

5.2.3 Silicon diode detector

The activation system permits the determination of time-integrated neutron yields, but a time-resolved system allows a much more accurate estimation of

the slowing down properties of 1 MeV tritons. At JET, time-resolved data is obtained by using a silicon surface barrier diode as a detector.

5.2.3.1 Principles and limitations

Large volume silicon diodes are often used as charged particle detectors, because of the low energy required to form an electron-hole pair (3.2 eV). A charged particle that is totally stopped in a silicon diode will generate a large charge pulse, the magnitude of which is proportional to the energy deposited in the diode. The energy resolution attainable with such a device can be of the order of 1 keV. Silicon also undergoes several reactions with neutrons, the most important of which are shown below:



These Q values and the coulomb barrier to be surmounted by the escaping charged particles ensure that the signal from the 2.45 MeV neutron flux will be small. For 14 MeV neutrons, the bulk of the kinetic energy will be transferred to the p or α , which then slows down in the silicon diode generating a charge pulse. The path length for a 12 MeV α in silicon is approximately 100 μm , whilst for a 10 MeV p the path length is approximately 1.5 mm. The diodes used in these experiments had thicknesses between 1 and 2.5mm and surface areas of between 100 and 450 mm^2 , sufficient to contain almost all α 's produced and a large fraction of the protons as well.

The residual ^{25}Mg or ^{28}Al nuclei may be left in one of several excited states, implying that the α or p produced will have a much reduced energy, giving rise to the charge pulse spectrum shown in fig. 5.8 [from 5.20]. As all of these states are produced from interactions with neutrons with energy greater than about 3-4 MeV, the sum of them can be used as a signal proportional to the 14 MeV emission rate. This can be achieved by setting a threshold E_t corresponding to

a minimum energy deposited in the diode by an α or a p. The use of a threshold is necessary because the diode also detects elastic scattering recoil events due to 2.45 MeV neutrons and also γ rays (which generate a large number of events with low energies); by setting E_t sufficiently high, these events may be excluded.

A further possible application for silicon diodes involves neutron spectroscopy [5.21]. The peak with the highest energy in fig. 5.8 is broadened by a convolution with the incident neutron spectrum. With the high resolution attainable with silicon diodes, this broadening can be measured and the incident spectrum deduced. This would provide a simple method for obtaining neutron spectra in the D-T phase of JET operations, but cannot be used on slowing down tritons as the spectrum of 14 MeV neutrons produced from them is very broad, reaching from 12-16 MeV. The spectrum thus covers a larger energy band than the gap between peaks in the charge pulse spectrum and the details of the neutron energy spectrum cannot easily be deduced (fig. 5.9).

5.2.3.2 *System description*

The silicon diode system has undergone considerable changes during the past three years. The system that will be described here is the one in use at the time of writing. The silicon diode is mounted in a water cooled, airtight and lightproof box mounted some 50 cm from the face of the octant 6 port. The construction of the box is shown in fig. 5.10. The diode is connected by approximately 160 m of superscreened cable to a fast amplifier designed by G. Huxtable, Harwell Laboratory. The fast amplifier performs several functions:

- Application of the bias voltage to the silicon diode. The 300V HT power supply is connected to the diode in series with a $10\text{k}\Omega$ resistor via this module. The resistor has a low value compared to the $\approx 10\text{ M}\Omega$ of the diode and affords very little protection to the silicon diode against the application of excessive voltages. The advantage of using such a low resistance is that when the impedance of the diode changes due to radiation damage, the net

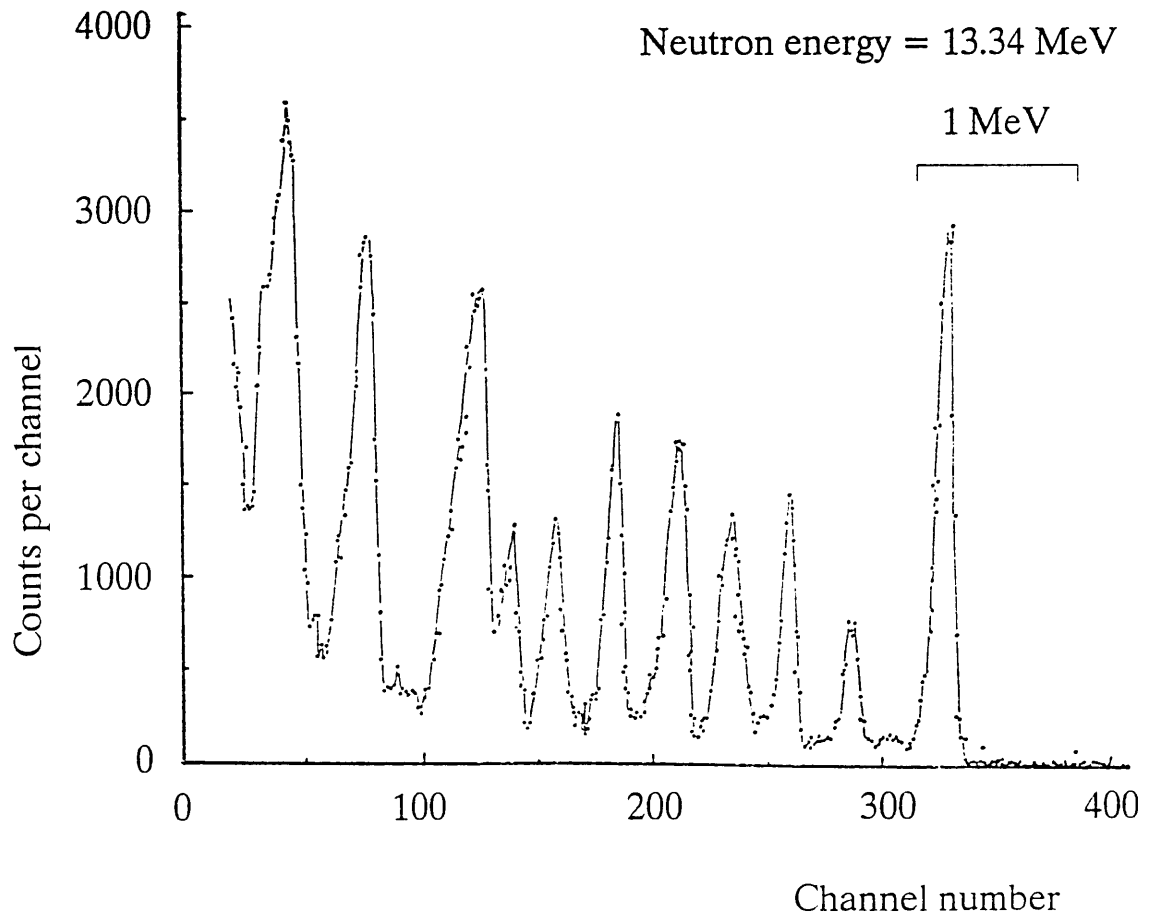


Figure 5.8. Charge pulse spectrum from a Silicon diode.: The charge pulse spectrum produced from a nearly monoenergetic neutron beam incident upon a silicon diode is shown here [5.20]. The structure of the spectrum is due to the variety of excited states in which the ^{28}Al or ^{25}Mg may be left after the reaction.

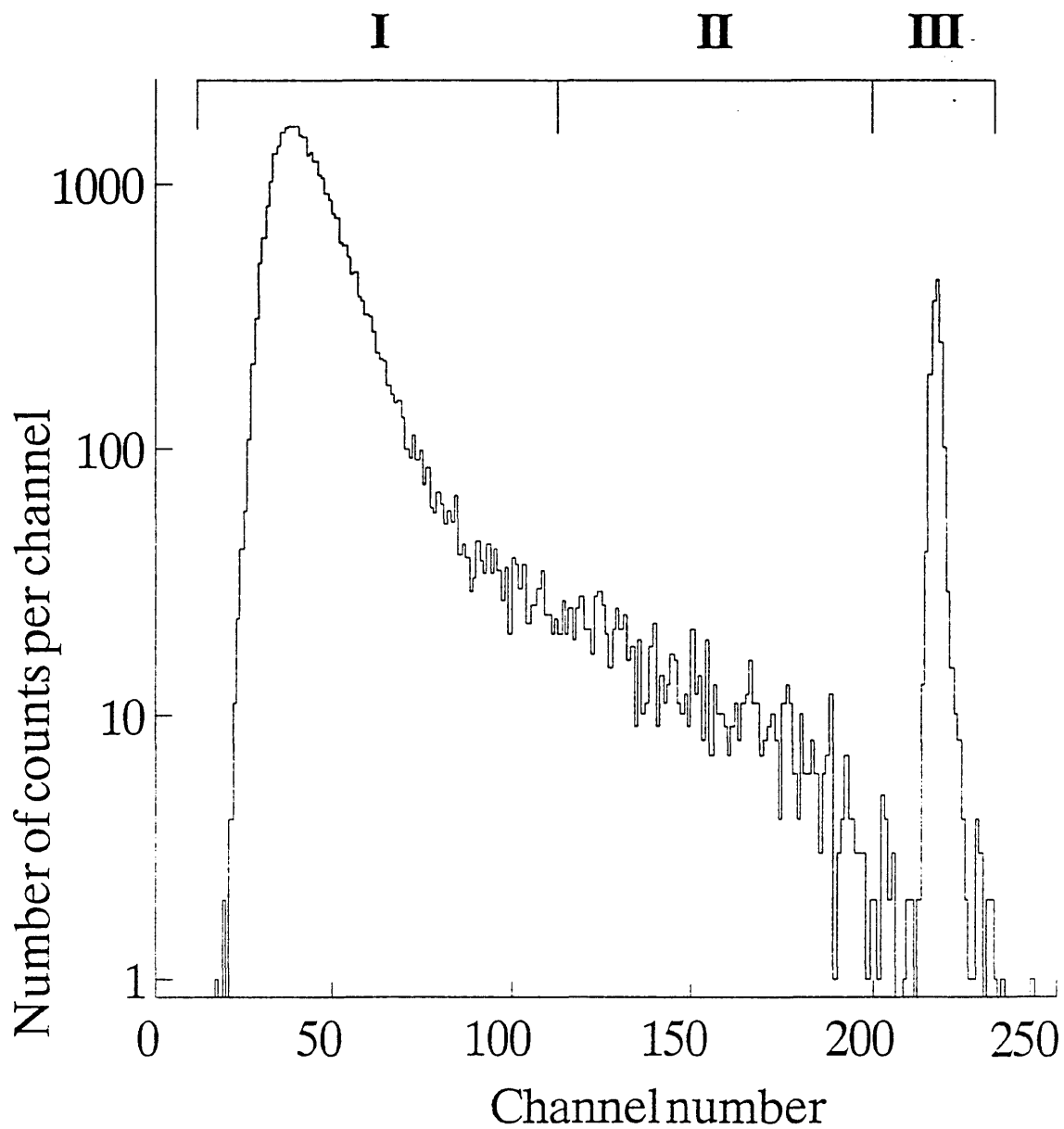


Figure 5.9. Charge pulse spectrum from a diode at JET: The majority of pulses are at low energy and are due to inelastic scattering of neutrons and interactions with γ rays. The region marked II is the 14 MeV neutron signal and the pulser used to monitor the stability of the system is at position III. None of the structures visible on fig. 5.8 are present here as the spectrum of the 14 MeV neutrons is wider than the gap between peaks, hence all the details are lost.

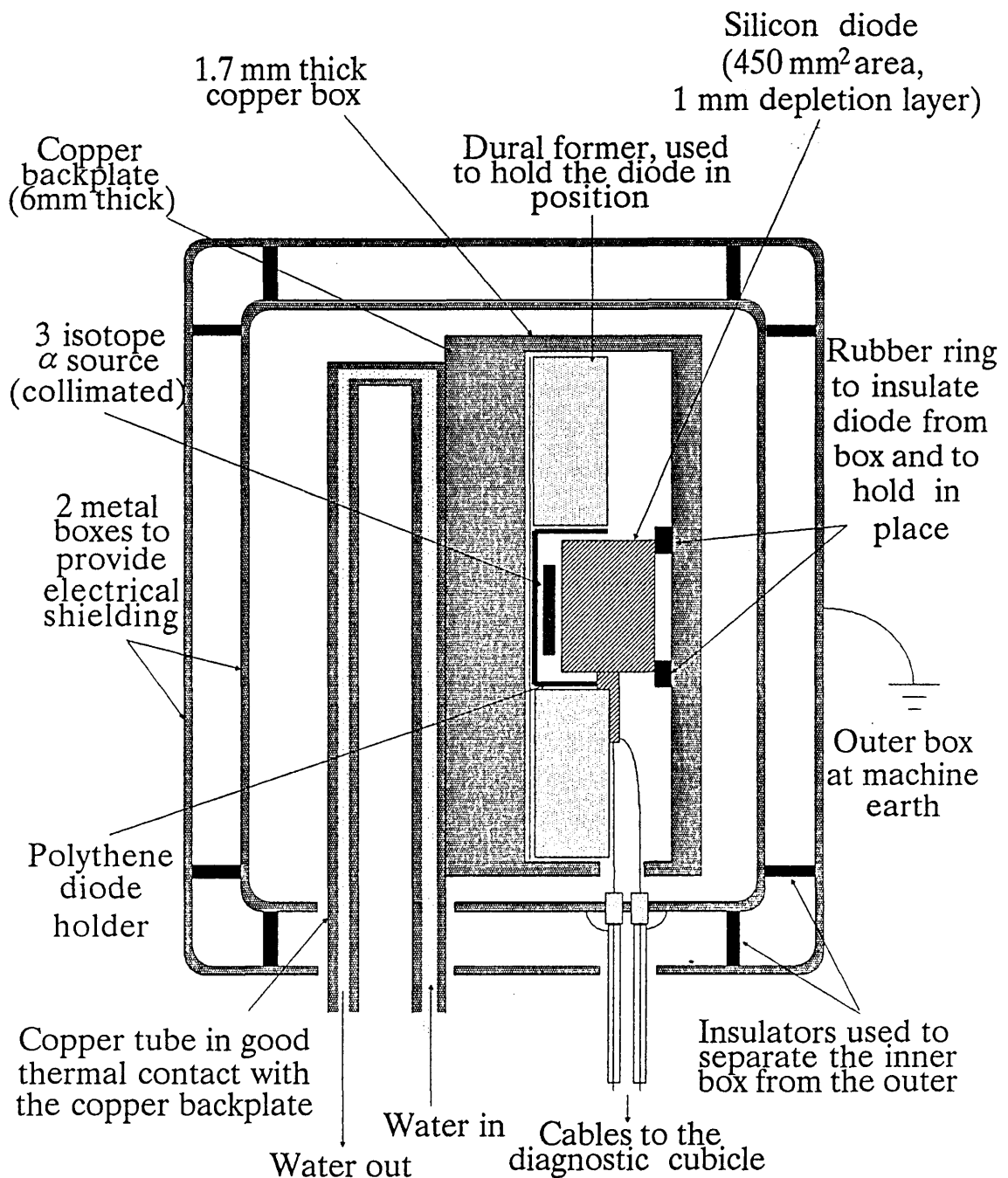


Figure 5.10. Silicon diode detector housing: The electrical shielding is required as the Torus Hall is an electrically noisy area. The water cooling maintains the diode temperature at a constant 10°C in order to reduce the chance of the diode current running away. Also, without water cooling the diode current is observed to vary by up to 100% during a day's operations, introducing potential errors and making comparisons between discharges less accurate.

voltage change across the diode is small and does not require the continuous resetting of the HT applied.

- Discrimination against low amplitude signals with longer rise-times than those of the neutron induced events.
- Amplification of the charge pulse. The signals from the diode typically correspond to several million electronic charges. The amplifier converts this charge pulse into a voltage pulse which retains the shape of the charge pulse. The voltage pulses typically have amplitudes of 20-300 mV, large enough for the later elements of the signal processing chain.
- Application of the pulser signal to the diode. A pulse generator set to produce 1000 pulses per second is connected to the fast amplifier. The duration and height of the pulse has been chosen so that the voltage spike applied to the diode corresponds to an event in the diode with a slightly higher energy than any signal attributable to 14 MeV neutrons. The purpose of the pulser is to monitor the stability of the electronic pulse processing at high count-rates and the dead-time of the whole processing chain.

A typical signal from the fast amplifier has a pulse length of only 100ns. The signals from the fast amplifier are then passed to a fast signal splitter which generates five copies of the original signal, allowing the data to be analysed using two techniques (fig. 5.11). The first route integrates the pulse using a LINK 5020 module with an integration time of 120 ns. The integrated signal is passed to an ADC which gives a number between 0 and 255 proportional to the height of the integrated signal. A 256 channel spectrum is then incremented by one in the channel number given by the ADC. A 256 channel spectrum is taken every 250 ms during the discharge and stored on the computer system. This allows the presentation of the data as a spectrum of charge pulses, as shown in fig 5.9. This formed the original processing technique for the silicon diode when it was first implemented in 1986. However, the spectra thus obtained are now used primarily for checking the consistency of the second route of signal processing, to be described below.

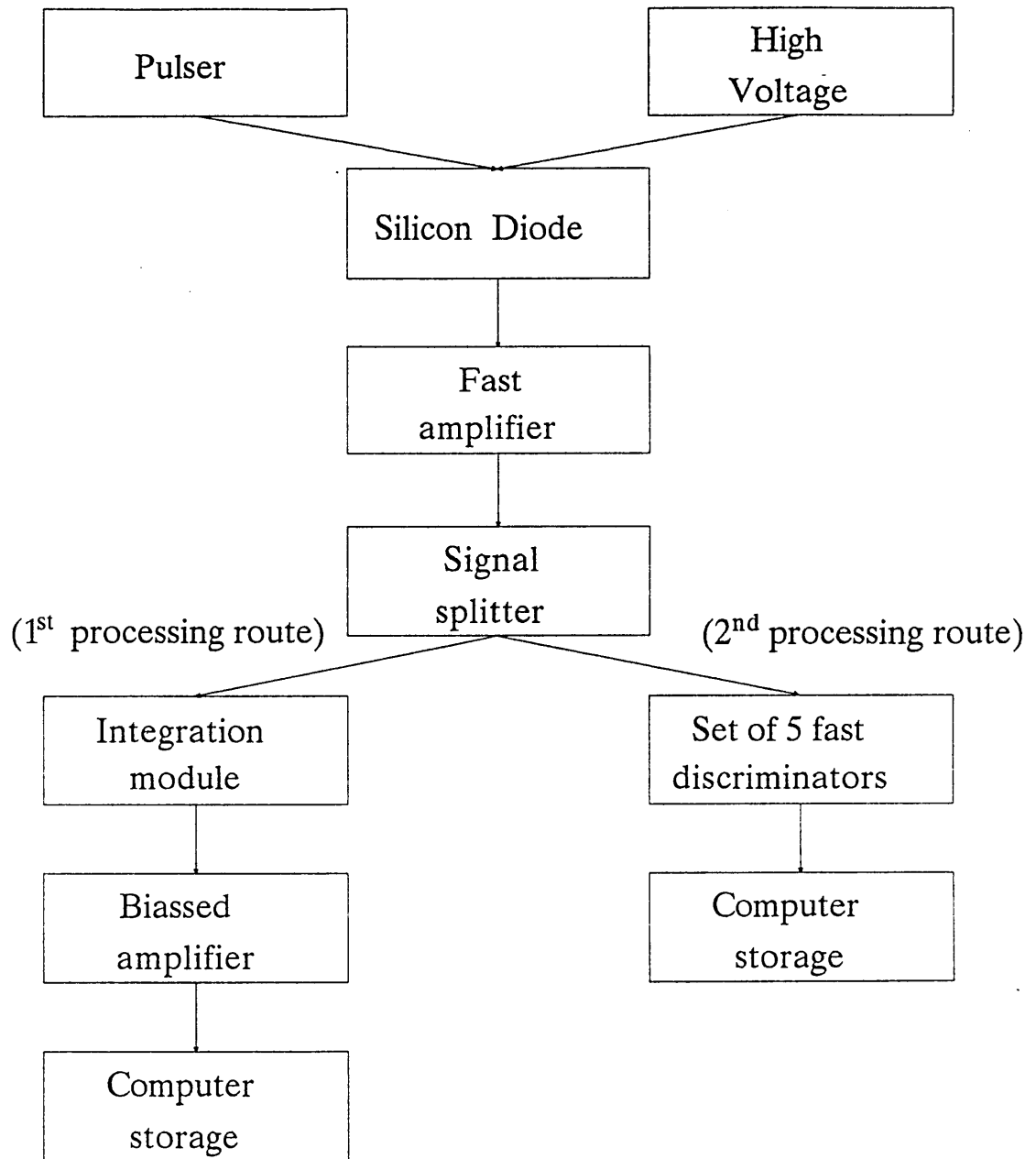


Figure 5.11. Silicon diode signal processing schematic: The components used in the signal processing are shown here. The route involving the integration of the signal from the fast amplifier constituted the original pulse processing system but is at present used mainly to monitor the diode's performance because of the low rates (< 50 kHz total, ≈ 500 Hz useful counts) attainable with it compared to the fast discriminators route.

The use of the LINK module also permits the energy resolution of the silicon diode to be tested by collecting spectra between discharges. The only signals present at this point are from the alpha sources positioned near the reverse face of the silicon diode. The alpha sources are ^{239}Pu , ^{241}Am and ^{244}Cm with energies of 5.157, 5.488 and 5.806 MeV, respectively. The spectra are collected using a Canberra model 30 MCA using 1024 channels. Fig 5.12 shows the three peaks, which are clearly distinguishable. From such spectra, it is deduced that the resolution of the silicon diode is of the order of 100-200 keV, far better than required for the present purpose.

In the second route, the assumption is made that all the pulses have a similar shape. This has been checked using an oscilloscope to compare the shapes of high energy and low energy pulses. Hence, the amplitude of each pulse determines its energy and a pulse-height discriminator may be used to separate the 14 MeV neutron pulses from the low energy pulses. This allows the processing of pulses at high counting rates, as the individual electronic modules are all capable of operating at several MHz. One problem is the tendency for the calibration of the diode to drift in time due to radiation damage. The pulse length of the first diode used for detecting 14 MeV neutrons deteriorated from 60-70ns to 100-250ns over the course of its exposure to the neutron flux. This would cause a major drift in the calibration of the second processing route using peak-sensing fast discriminators in the present system (it did not affect the original system which used the charge integration method only). This means that the calibration of the diode using the activation system must be an ongoing exercise. This is where the use of the silicon capsules in the activation system is helpful, as the drift of the calibration can be followed quite accurately and relatively easily with this technique. In practice, no drift has been observed whilst the discriminator system has been in use as the radiation damage threshold has not yet been reached.

Fig. 5.13 shows how several discriminators with increasing threshold levels are used to monitor the signals. The lowest level is used to monitor the throughput of the system. The uppermost level is used to monitor the pulser peak for any deterioration in the performance of the system because of dead

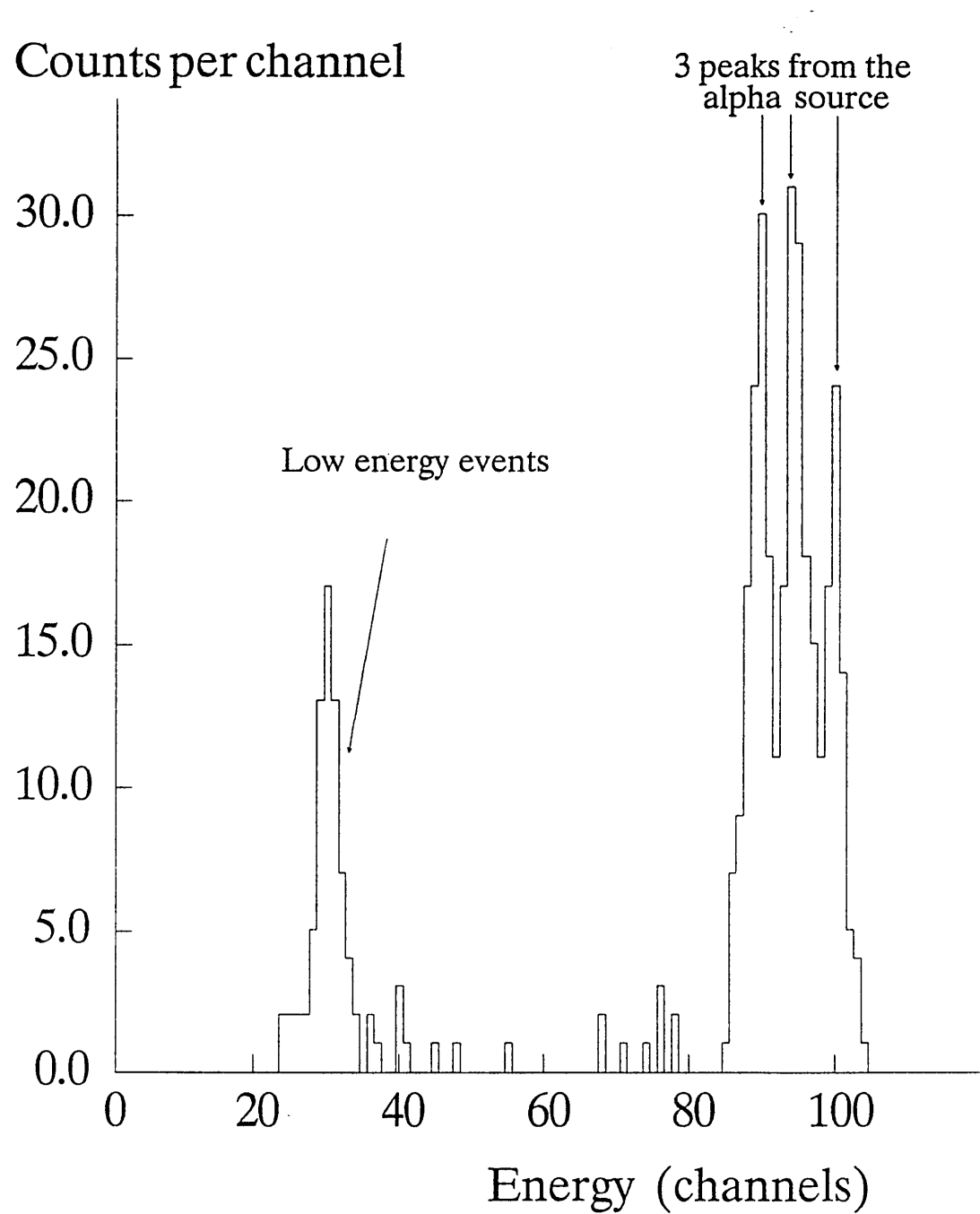


Figure 5.12. Alpha particle spectrum from diode: The three peaks from the α particle source near the silicon diode are seen to be resolved here. This is used to give an approximate energy calibration for the diode.

time difficulties and is also used to remove the signals due to the pulser from all the other discriminator levels. The middle three levels are used as signals proportional to the 14 MeV neutron emission rate. The level preferred for subsequent analysis depends upon the discharge under study. The lower the level used, the better the statistics and hence the finer the time resolution obtained. However, at high counting rates, or when an unusually high number of γ rays is produced, the pile-up of the low energy signal can falsely contribute to the 14 MeV neutron signal and in such cases a higher discriminator level must be used. Such a discharge is shown in fig. 5.14.

5.2.3.3 *Operational difficulties*

The major problems in operating a silicon diode detector are its sensitivity to e.m. interference and radiation damage. The inside of the torus hall is an electrically noisy environment, so the diode has to be well shielded against picking up stray noise. In the final system two Faraday cages surround the diode and the diode signal is carried down the cores of two superscreened cables, the screens of the cables being connected to the innermost Faraday cage.

The problem of radiation damage is unavoidable. In order to use the diode to detect 14 MeV neutrons, the neutron fluxes must be high. A lifetime dose of 10^{12} neutrons cm^{-2} is estimated to cause significant radiation damage in silicon surface barrier diodes [5.22], while lithium drifted surface barrier diodes are an order of magnitude more vulnerable. The original silicon diode system was positioned as shown in fig. 5.15, where the solid angle subtended by the plasma was much greater than in the present position. Also the neutron attenuation was lower as less structure was present between the detector and the plasma. As the diode was lithium drifted, the system was likely to suffer severe radiation damage and this turned out to be the case. This manifested itself as an increase in the current drawn by the diode and a degradation of the charge pulse duration. The original pulses were some 60-70ns long but towards the end of the diode's lifetime, the duration increased to 150 ns for the bulk of the pulses with some lasting up to 250 ns. This did not affect the data processing to a great extent, as the integration of pulses was the only technique in use at the time.

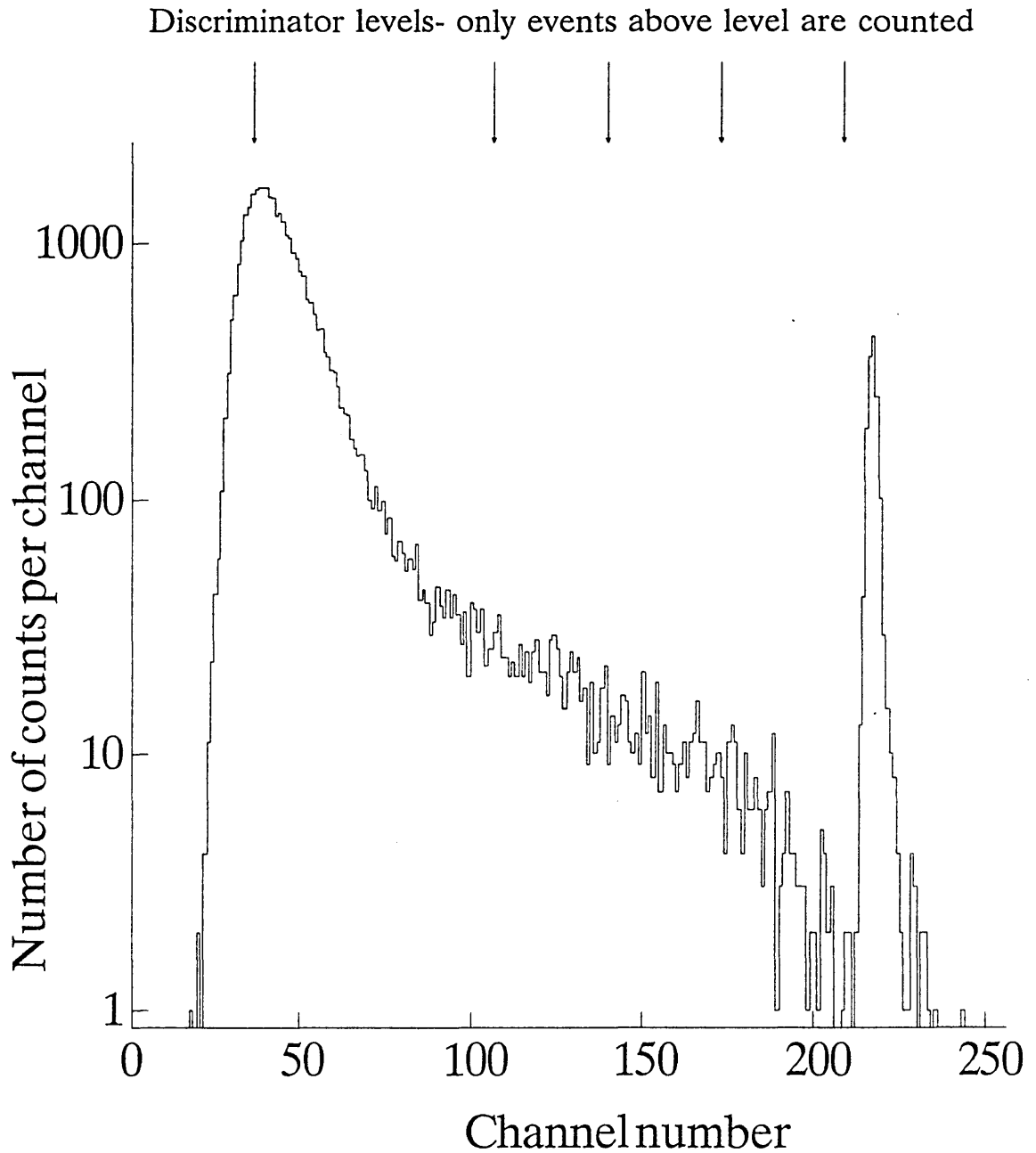


Figure 5.13. Discriminator settings on charge pulse spectrum: This figure shows the position of the cutoff for each of the fast discriminators used in the second processing route. For most data analysis purposes, the discriminator with the second lowest threshold is used.

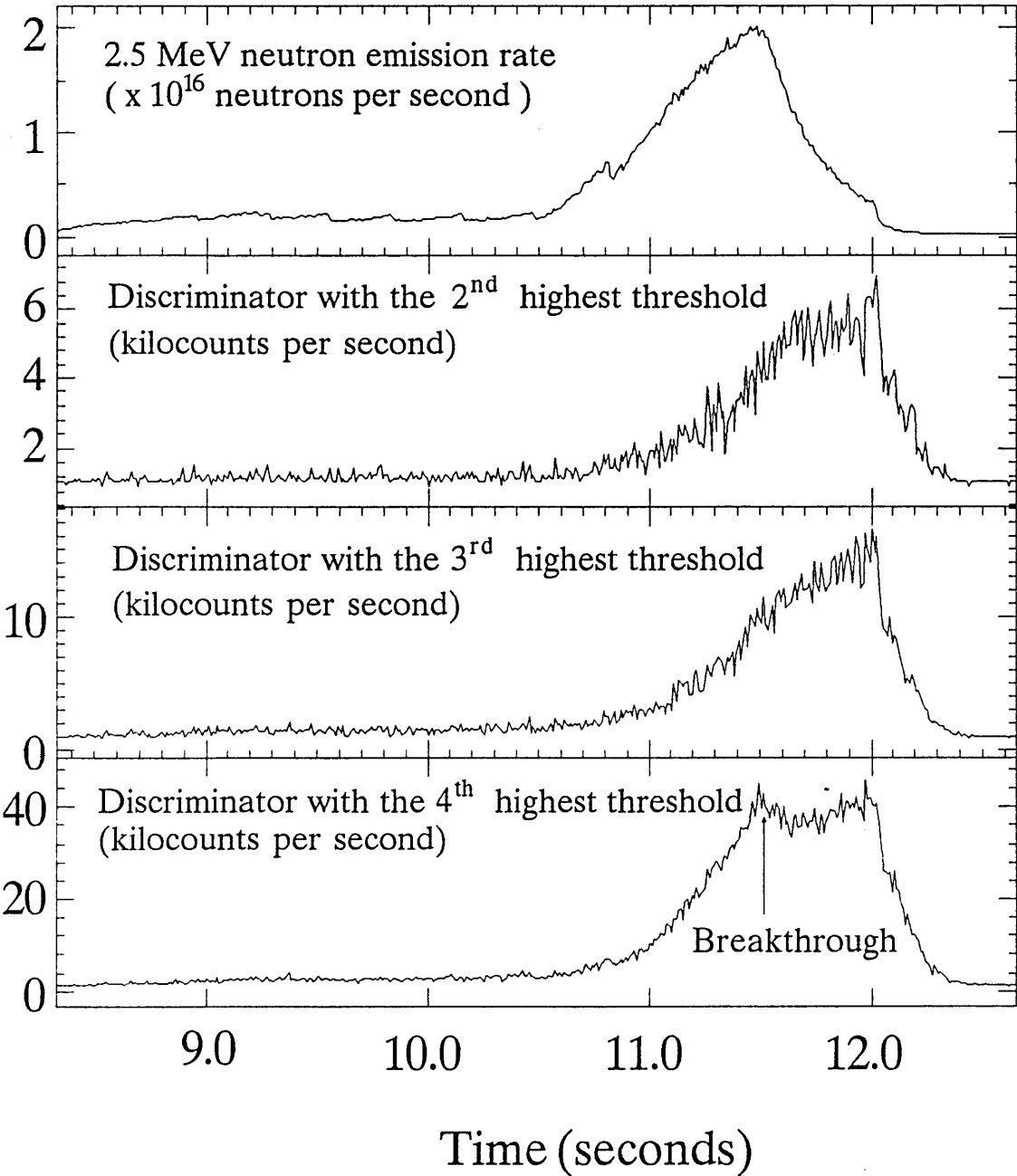


Figure 5.14. 14 MeV neutron signal showing breakthrough by 2.45 MeV neutrons: The top graph shows the 2.45 MeV neutron rate from the fission chambers. The bottom graph shows the discriminator exhibiting breakthrough, while the middle pictures show data without breakthrough.

However, the results are less reliable than those obtained using an undamaged diode.

5.2.3.4 Calibration with activation measurements

The foil activation system was used to provide an absolute calibration of the silicon diode system. This calibration was carried out for four distinct periods of silicon diode operation and the results for the most sensitive measurement are shown in table 5.1.

Period	Shot range	Diode volume (mm ³)	Calibration constant (n/count)	Estimated error
1	10800-11100	200	2.56 x 10 ⁹	±10%
2	15500-16518	450	2.85 x 10 ⁹	±10%
3	16518-18790	450	3.30 x 10 ⁹	±10%
4	19900-21030	450	9.62 x 10 ⁹	±20%

Table 5.1. Calibration constants for the silicon diode detector: All periods of operation of the silicon diode detector to date are shown.

During period 1 the diode was mounted near the vacuum vessel, whilst periods 2-4 correspond to the midplane position. It can be observed that the calibration constant changed little despite the change in location and resultant reduction in neutron fluxes. The increase in the size of the diodes approximately compensated for the loss in flux. Period 4 has a much larger calibration constant and this is attributable to a number of factors; the diode had more neutron shielding, was 50 cm further from the horizontal port than in periods 2 and 3 and the discriminator settings were slightly different.

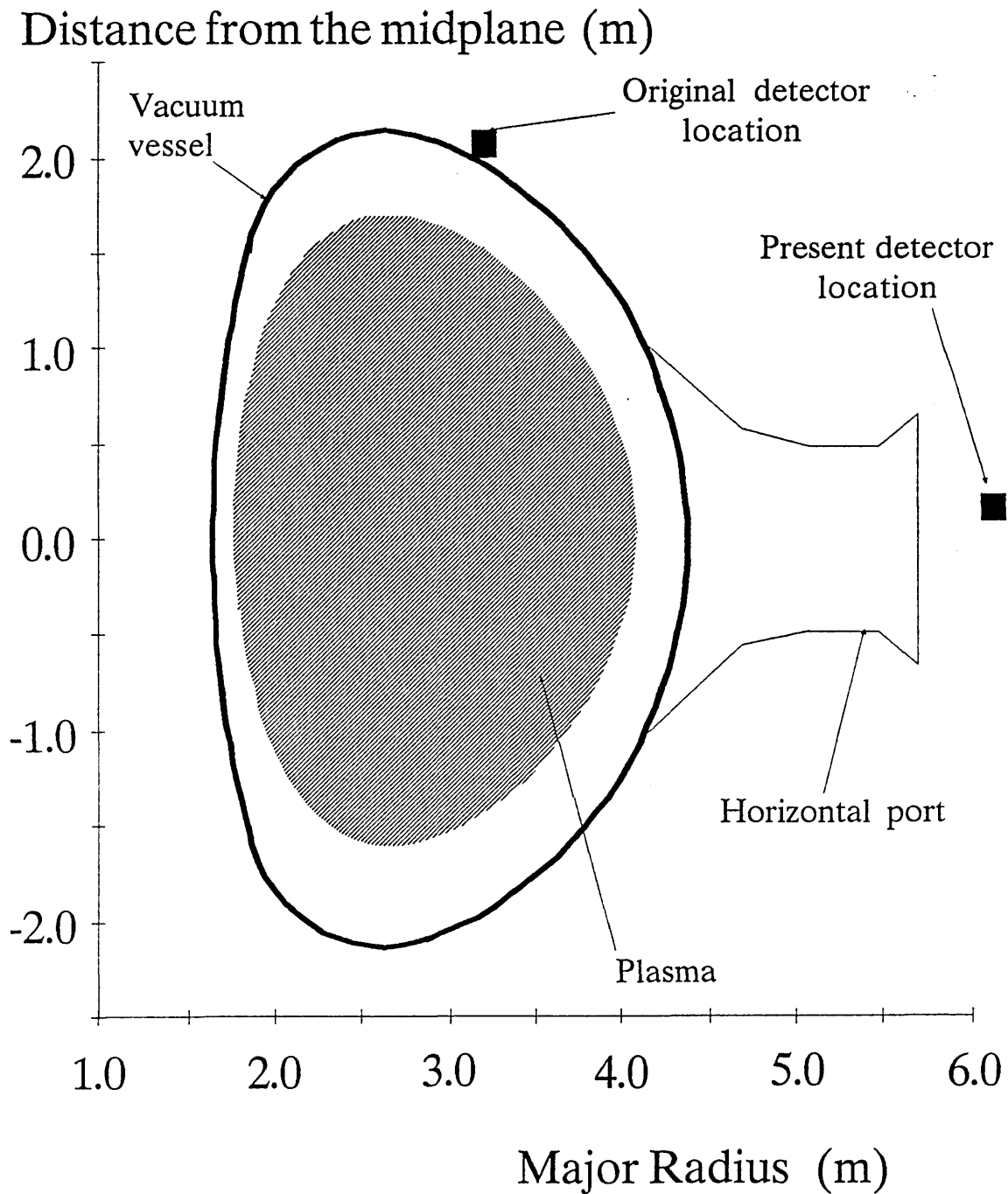


Figure 5.15. Location of the silicon diode detectors: The original silicon diode used for 14 MeV neutron detection was mounted in the old KPI housing, in order to position the diode as close to the plasma as possible. Later versions of the detector have been mounted outside the vessel to reduce radiation damage and to increase accessibility.

The calibration constants for periods 2-3 were obtained by comparing foil activation results with the number of counts registered by the silicon diode for the same shot. The results of these comparisons are shown in figures 5.16-5.17. Silicon activation data was available for periods 3 and 4 and were used to deduce the diode calibration in period 4 from the period 3 calibration (fig. 5.18), which explains the much increased estimated error. The calibration constant for period 1 was obtained in a different manner, as very few shots were available where both the foil activation system and the silicon diode system were simultaneously operational. A computer code, TRAP-T, was used as an intermediary between the two for purposes of interpolation. The code will be described in more detail in section 5.3.2 but, basically, it simulates the 14 MeV neutron emission from the plasma. The comparisons of the code with both the foil activations and the silicon diode counts are shown in figures 5.19-5.20. The code overestimates the foil yields by some 17% and this factor, when applied to the gradient from fig. 5.20, gives the calibration factor of 2.56×10^9 .

5.2.4 Summary

The use of a silicon diode as a 14 MeV neutron detector is, in principle, a fairly simple task, although it has taken three years for the system to reach its present state. The system offers good time resolution and can operate over a fairly wide range of 14 MeV neutron emission rates. There are disadvantages in using silicon diodes, such as their sensitivity to γ rays and to runaway electrons. The latter are produced at disruptions (and when the plasma has a low density) and can be confused with tritons under certain conditions. The diodes are expensive ($\approx$ £2000). The necessity of replacing them regularly because of radiation damage is inconvenient, as is the continuous monitoring with foil activation to detect calibration drifts.

5.2.5 Further developments.

The system at present works very well, but some improvements could still be made. The ratio of useful counts to total counts is fairly low at about 1-5%,

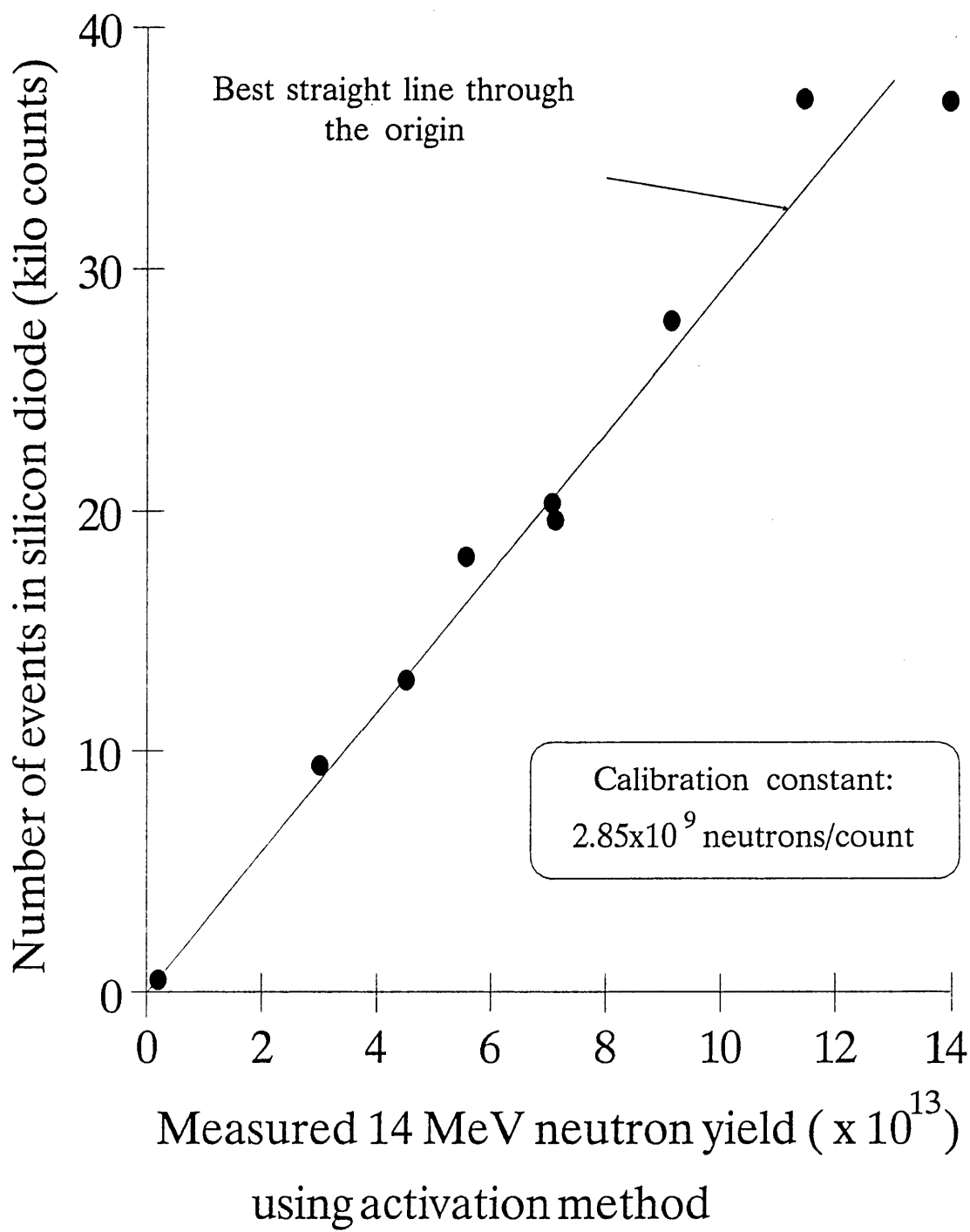


Figure 5.16. Silicon diode calibration graph, period 2:

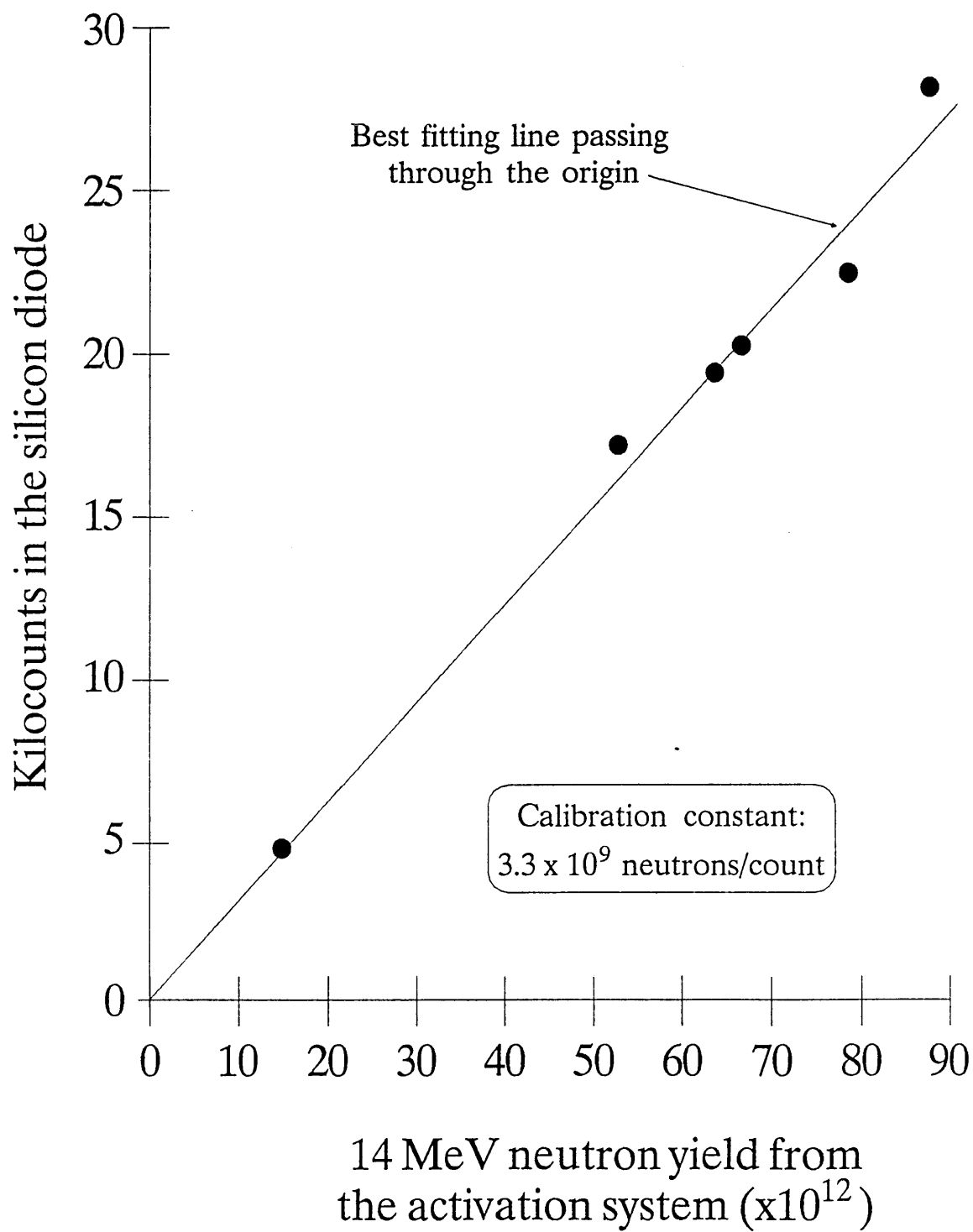


Figure 5.17. Silicon diode calibration graph, period 3:

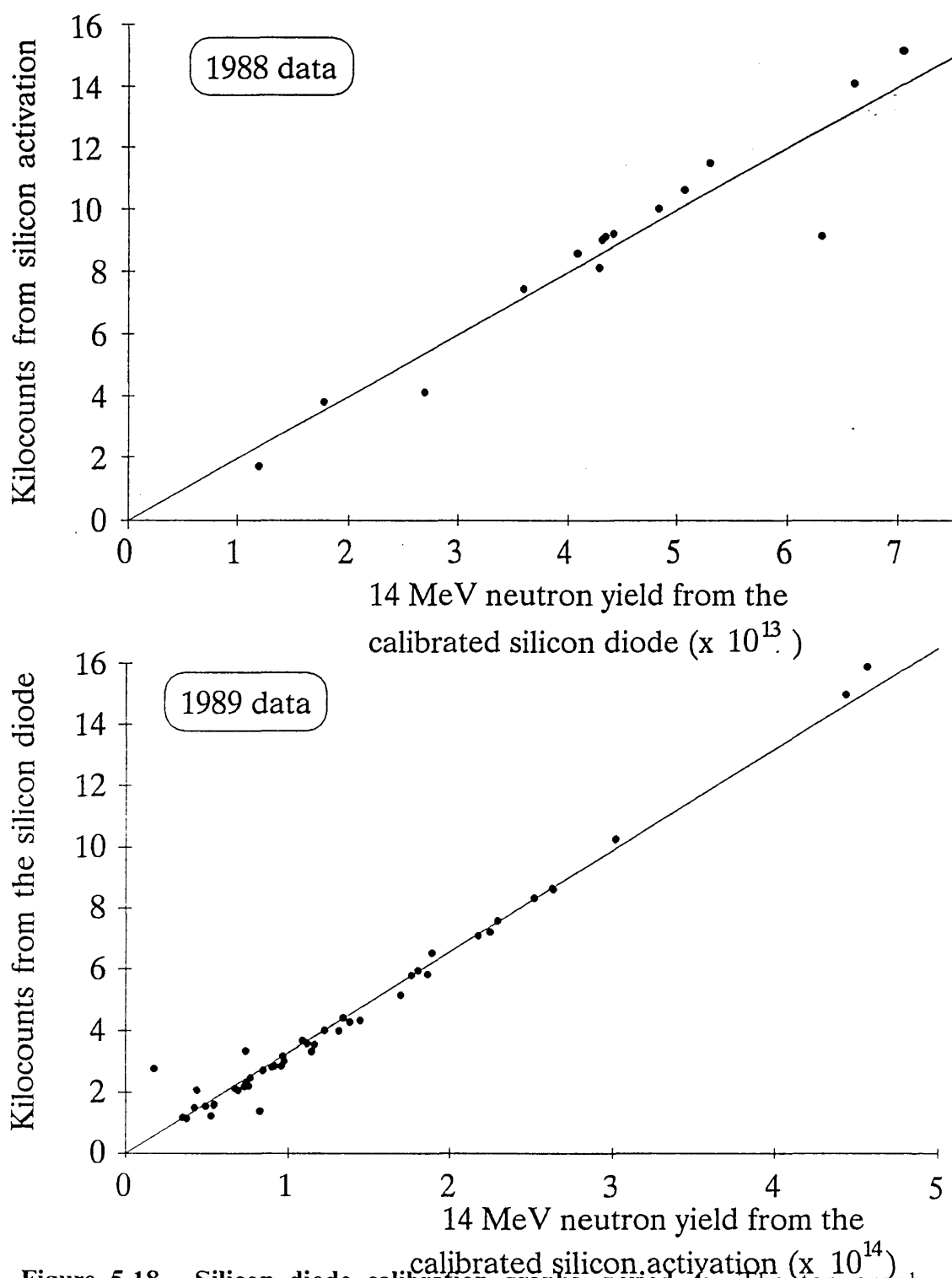


Figure 5.18. Silicon diode calibration graphs, period 4: The top graph shows the cross-calibration used to define the calibration of the silicon activation system. The lower graph shows the cross-calibration of the period 4 silicon diode system with the silicon activation system.

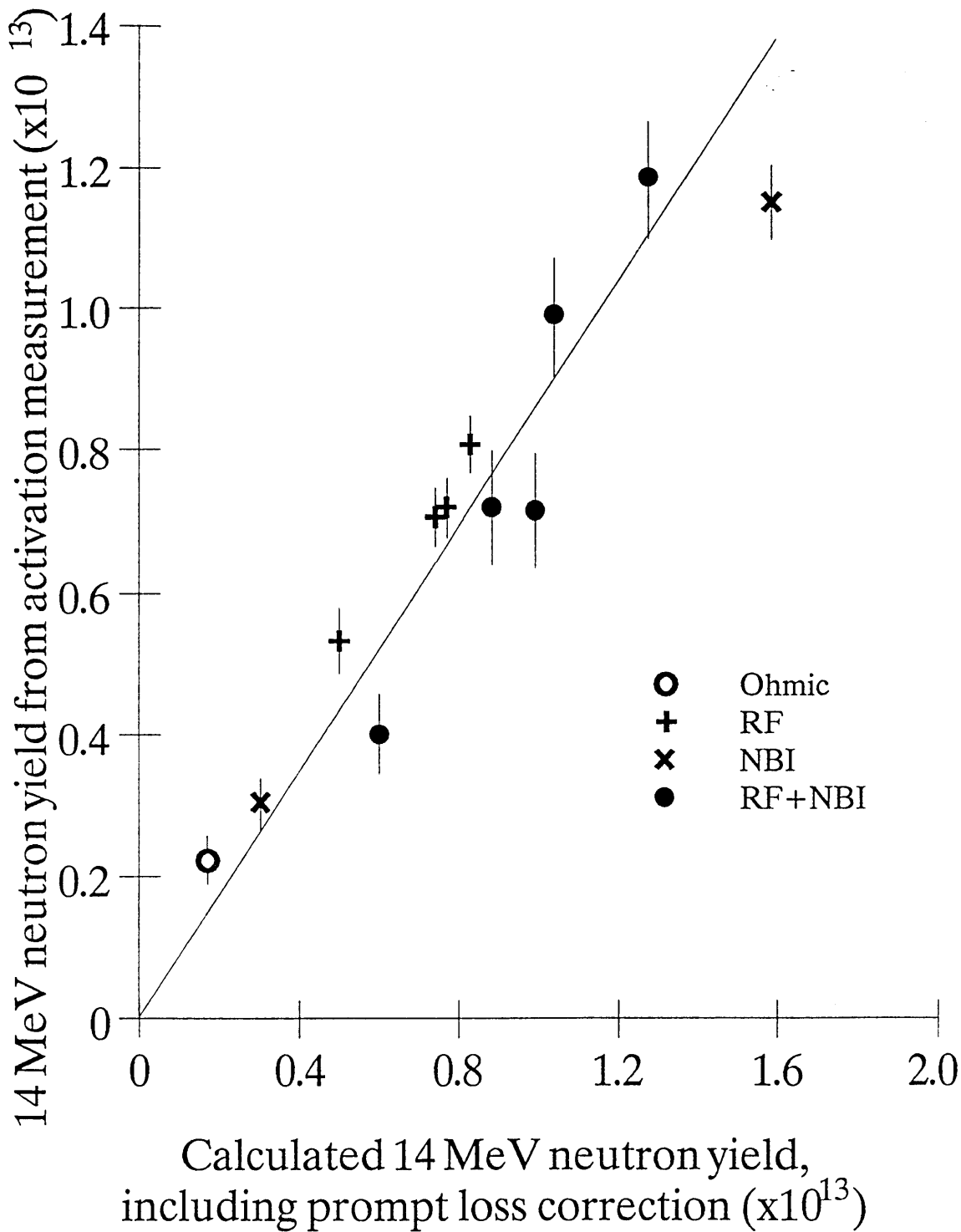


Figure 5.19. Calculated 14 MeV neutron yield vs KN2 measurement, period 1: The calculation overestimates the yield by 17%, which lies within the errors.

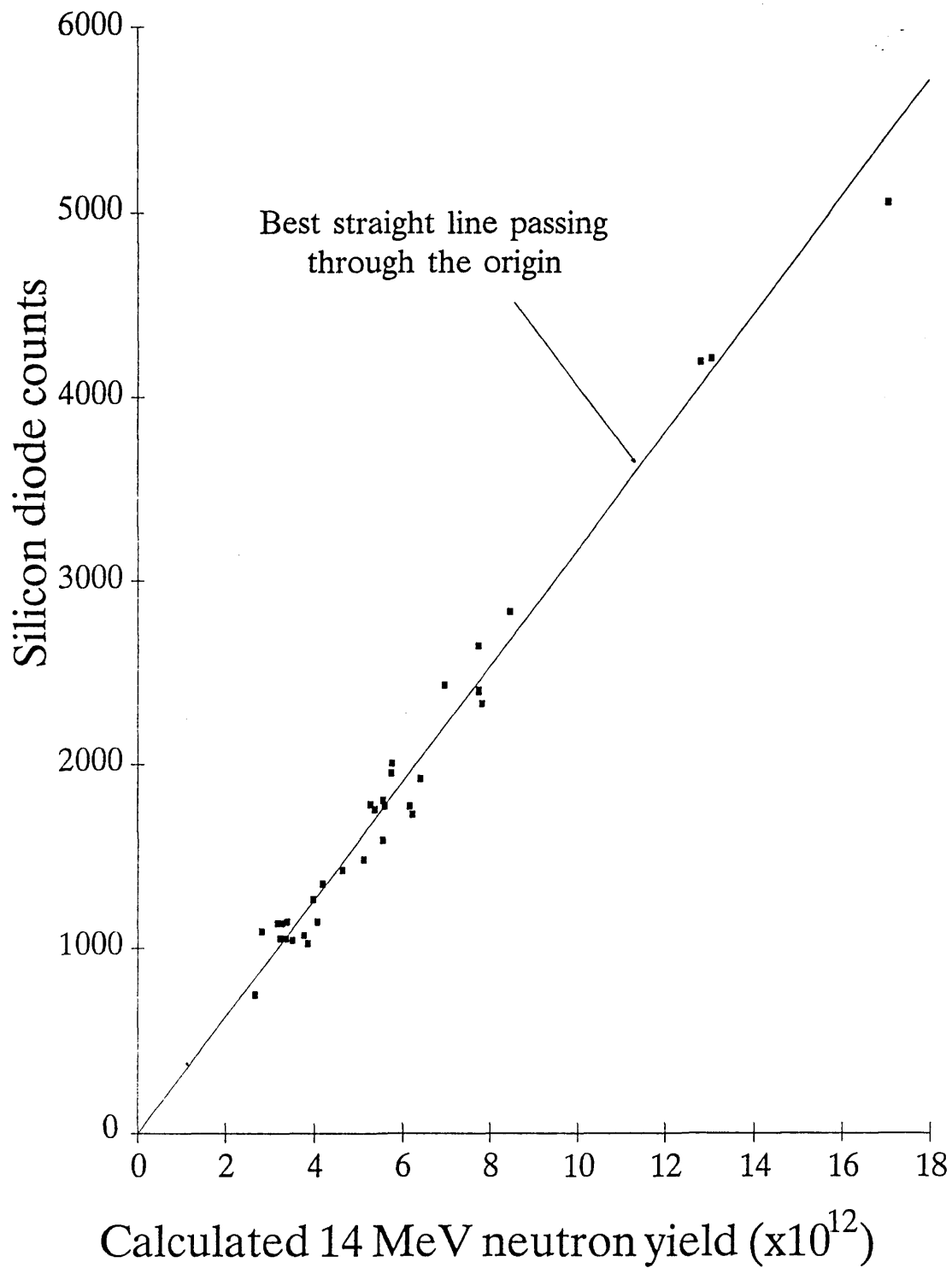


Figure 5.20. TRAP-T 14 MeV neutron yield vs silicon diode counts, period 1:

depending upon the type of discharge under study. An increase in this ratio would allow better time resolution. There are two techniques which may provide this. The first involves improving the γ ray shielding around the diode, reducing the number of spurious counts, by surrounding the detector by a lead, or lead-tungsten alloy, shield. This should work, although it will also attenuate the 14 MeV neutron flux to a lesser extent. The second method was suggested by M. Pillon [5.23] and is illustrated in fig. 5.21. The polythene block acts as a source of protons for elastic collisions with all incident neutrons. The protons from the block will be produced mainly from interactions with 2.45 MeV neutrons, but some 1% will be due to 14 MeV neutrons. The knocked-on protons pass into the aluminium foil, which is thick enough to absorb all protons incident with energies less than 3 MeV. This leaves protons knocked-on by 14 MeV neutrons as the only protons capable of passing through the foil to be detected by the surface barrier diode, which is approximately a 100% efficient detector of protons incident upon its surface. This system has been tested at Harwell by the author and G. Huxtable, where it was found that the resultant charge pulse spectrum is very similar to the charge pulse spectrum normally obtained, with the exception that the efficiency of the diode is increased by a factor of two. The system tested at Harwell was a simple one, as illustrated in fig 5.21; the spectrum of the protons incident upon the detector included a large component of low energy protons below the discriminator settings due to energy attenuation in the polythene block and because of the wide range of angles through which the protons could be scattered and still be detected by the diode. By using a thinner polythene block and by taking more care with the acceptance angles, both the diode efficiency and the ratio of good counts to total could be improved. The gain in efficiency alone probably makes this a worthwhile improvement as this could allow the diode to be used in a position with a lower neutron flux, thereby increasing the time between replacements due to radiation damage.

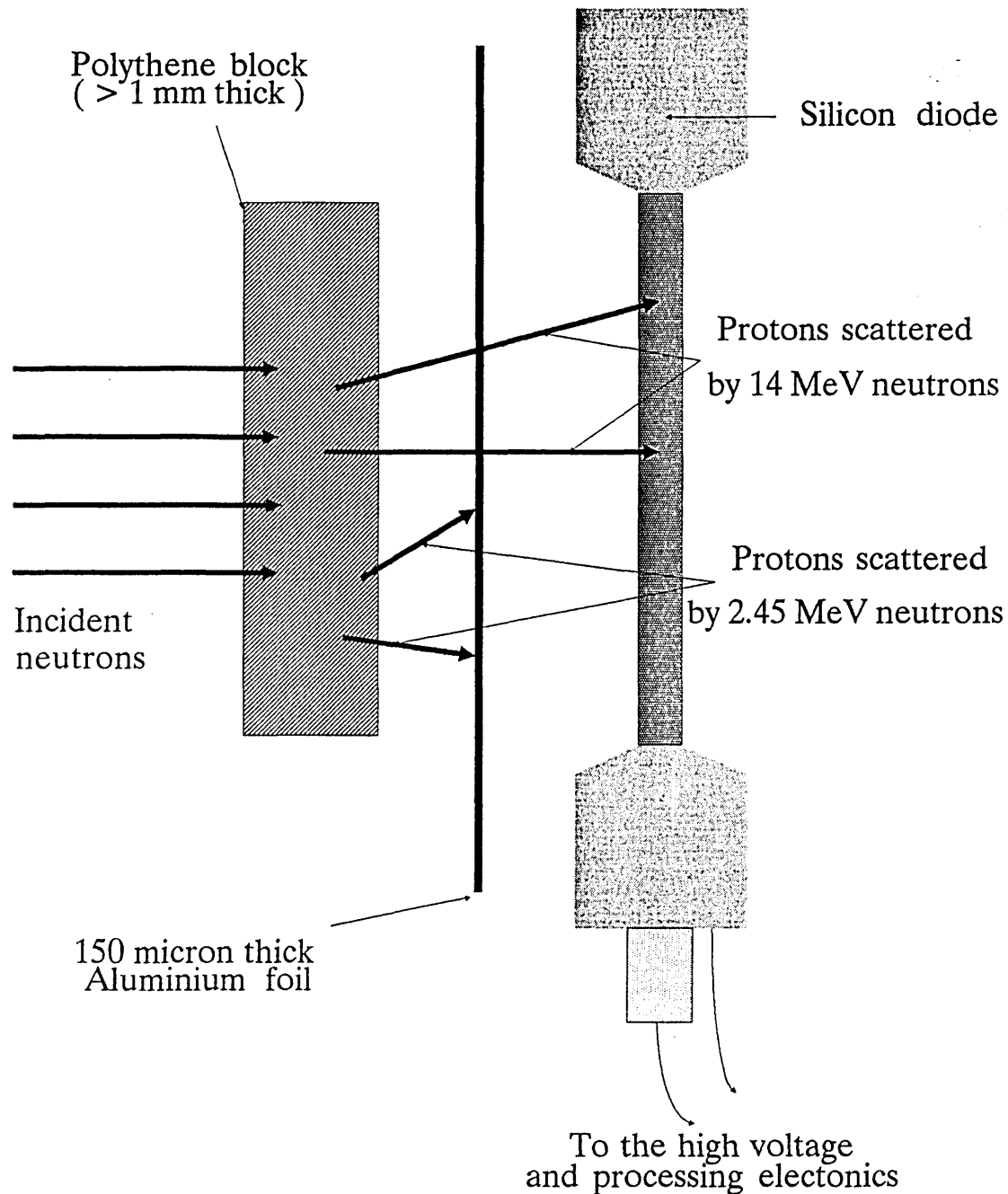


Figure 5.21. Polythene and foil used to enhance diode detection efficiency: Protons in the polythene are knocked on by neutrons, with energies up to the neutron energy. The foil is thick enough to stop all protons with energy less than 3 MeV, hence only protons produced by 14 MeV neutrons will pass through the foil and hit the diode.

5.3 *Data Analysis*

The equipment described in the previous section produces an absolutely calibrated time-resolved 14 MeV neutron emission rate. This section describes how this signal is interpreted and what useful information may be derived from it.

5.3.1 Description of the problem

The classical theory of fast particles slowing down in a plasma was presented in sec. 2.1. Unfortunately, it is not practical to test this theory by simply plotting an observed quantity (such as the instantaneous 14 MeV neutron emission rate) against temperature, T_e , because under most circumstances the 14 MeV neutron emission rate is dependent upon the value of T_e over the previous 0.5-1.0 seconds, during which period T_e will probably have varied considerably. This makes comparisons with key plasma parameters of limited use, although, for discharges where the triton burnup reaches an equilibrium (fig. 5.22), it is possible to plot the burnup ratio against the product of the slowing down time and the deuterium dilution factor (fig 5.23). In order to make full use of the data obtained from the silicon diode, it is necessary to model the full time-dependence of the 14 MeV neutron emission rate from the plasma for comparison with the observed data.

Any model which simulates the 14 MeV neutron emission rate must be both time and space resolved, as strong variations in the triton burnup are possible in both. The model should use as much real data to characterise the plasma as is possible, relying on assumptions and approximations only if no suitable experimental signal is available. It should also be computationally inexpensive, as the model should be used to interpret hundreds of discharges. Such a model has been produced and the following section describes the assumptions and approximations which went into its formulation.

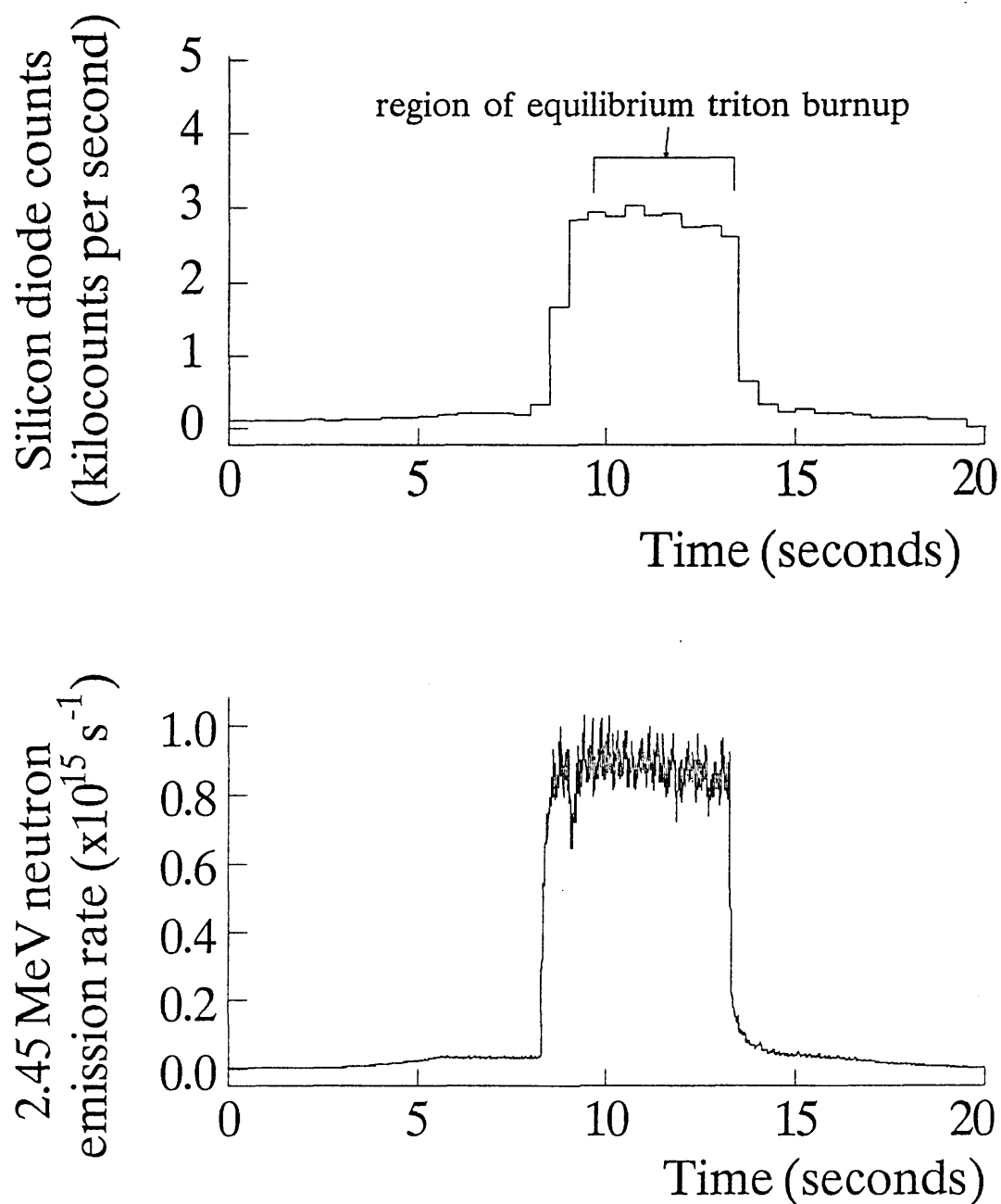


Figure 5.22. Discharge with an equilibrium triton burnup: This figure shows a discharge where the plasma conditions were steady for a long enough period that a steady state triton population was formed at $T = 13.0\text{s}$. This type of discharge is suitable for analysis with a time-independent analysis method.

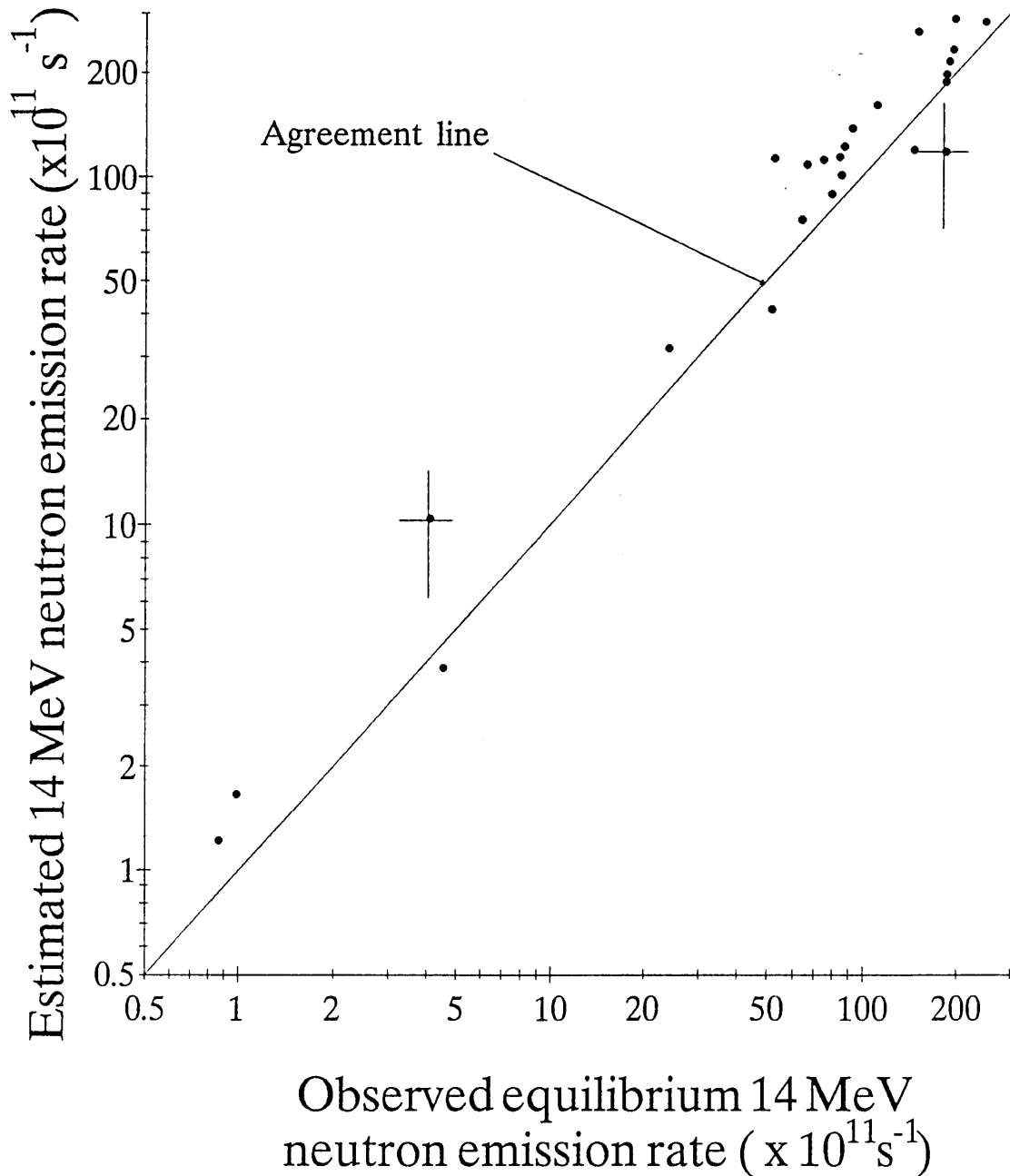


Figure 5.23. 14 MeV neutron rate against the calculated equilibrium rate.: In a discharge where the burnup reaches an equilibrium value, an estimate of the 14 MeV neutron emission rate may be made using simple time independent burnup codes. The large scatter in the points is due to the fact that the discharges do not usually attain such an equilibrium state.

5.3.2 Computer simulation of 14 MeV neutron emission

A program, TRAP-T, was written in order to model the 14 MeV neutron emission from the JET plasma. In the model, the plasma is divided into 10 nested volumes, bounded by flux surfaces represented in the Lao-Hirshmann form, as shown in figure 5.24. The parameters which model the flux surface (such as ellipticity and triangularity) are produced by the FAST program [5.24] and form one of the inputs to the program. TRAP-T is not very sensitive to errors in the evaluation of the flux surfaces (sec 5.3.2.2) for most types of discharge; however, for discharges with very peaked neutron source profiles the faithfulness of the flux surfaces becomes rather important and , unfortunately, questionable.

The triton birth profile as a function of time is calculated by assuming the following:

1. The deuterium density profile is obtained by multiplying the measured n_e profile by the n_D/n_e ratio. The value of n_D/n_e is derived from visible bremsstrahlung measurements of Z_{eff} and by assuming that the only impurities present in the plasma are carbon and oxygen in a known ratio set by the user.
2. The T_i profile is given by:

$$T_i(r) = \frac{T_i(0)T_e(r)}{T_e(0)} \quad [5.3]$$

where $T_i(0)$ is obtained from the X-ray crystal spectrometer (p. 21) and $T_e(r)$ is obtained from the ECE diagnostic.

3. The broadening of the profile due to the random distribution (of the phase) of the tritons around their Larmor orbits as well as the effect of banana orbits on the particle's guiding centres has been estimated from observations made using the code ORBIT [5.25]. The effect may be modelled by a

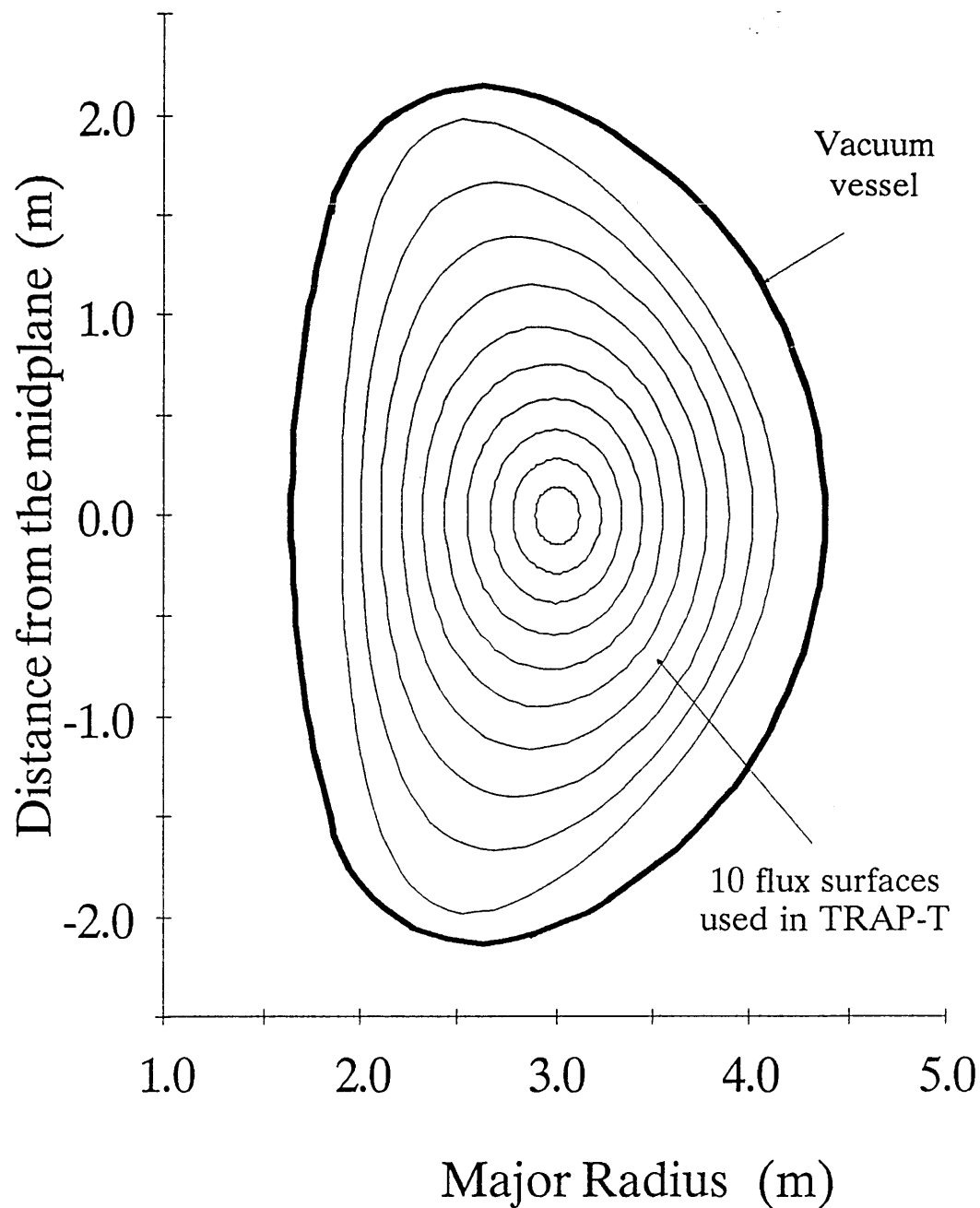


Figure 5.24. Flux volumes used in TRAP-T: A poloidal section of the torus showing the volumes into which the plasma is subdivided in the TRAP-T program. Plasma parameters are assumed constant in each volume and no transport of particles from one volume to another is allowed.

convolution of the source profile with a narrow gaussian (FWHM of 1 volume element).

4. The total triton birth rate at each time is normalised to the measured 2.45 MeV neutron emission rate at that time.

As has been shown in chapter 4, the approximation made by using the ECE temperature profile normalised to the X-ray crystal spectrometer temperature is usually quite good. The effect of the broadening of the triton source profile through assumption 3 is usually of the order of a few percent and therefore relatively unimportant. One further effect upon the triton source profile should be taken into account, namely sawteeth. Typically two to four sawteeth will occur during the slowing down of any given triton, causing the relocation of tritons inside the plasma. Due to the way the code is structured, no transport between flux volumes of the plasma is allowed while the tritons slow down, so it is not possible to redistribute the tritons at each sawtooth crash. However, using the model it is possible to show that sawteeth will have relatively little effect upon the triton burnup if their only effect is to transport particles inside the inversion radius to just outside the inversion radius. This can be performed by altering the triton source profile by moving all the tritons that would normally be born and slow down on the inner volume elements so that they are born and slow down on the volume element just outside the inversion radius, given by the empirical formula [5.26]:

$$r_{inv} = \frac{a\kappa}{1.6q_{cyl}^{0.82}} \quad [5.4]$$

The assumption implicit in using this model of the sawtooth crash is that the sawtooth period is much shorter than the slowing down time of the tritons, so that all tritons will be affected by a sawtooth before they reach the peak of the reactivity. This means that the actual crash cannot be simulated, but the effect of the crash on the overall burnup may be estimated. Figure 5.25 shows the comparison of the triton burnup obtained with and without the sawtooth model. Even with a model as severe as the one used here, no great variation in the triton burnup is obtained. In practice, a smaller effect should be expected, as at the

crash tritons just outside the inversion radius are presumably swept into the centre, partially compensating for the loss of tritons from the inside to outside the inversion radius region.

After calculating the time-resolved source profile, the program has normally generated 4000 groups of tritons, each with their own start time and minor radius on which to slow down. They are assumed to act independently of each other as they slow down and burn up. The Batistoni formulation of the slowing down is used to model the physics of the slowing down, rearranged somewhat in order to optimise the speed of the code. Each group is slowed down in steps of approximately 10 ms and at each step the fraction of the group lost through burnup is calculated using:

$$S_{14}(t) = \sum_{i=1}^{\text{every group}} n_D(r,t) n_i \sigma_{DT}(v_i(t)) v_i(t) \quad [5.5]$$

where S_{14} = the 14 MeV neutron emission rate. S_{14} is then compared with the observed 14 MeV neutron emission rate

5.3.2.1 Assumptions and input data

There are certain assumptions built into the slowing down section of the code which are as follows:

1. Magnetic flux surfaces do not vary quickly, or more specifically, the slowing down time of the tritons is shorter than the time for the flux surfaces to alter significantly. This implies that current ramping discharges should be treated with some caution, although this is not thought to be a large effect.
2. No spatial transport of tritons occurs while they are slowing down in the plasma. This assumption excludes the possibility of accurate modelling of the sawtooth phenomenon, or any other particle transport mechanism. However, as the discussion on sawtooth crash modelling earlier showed, the effect of particle transport on a fairly large scale is of order 10%. A larger

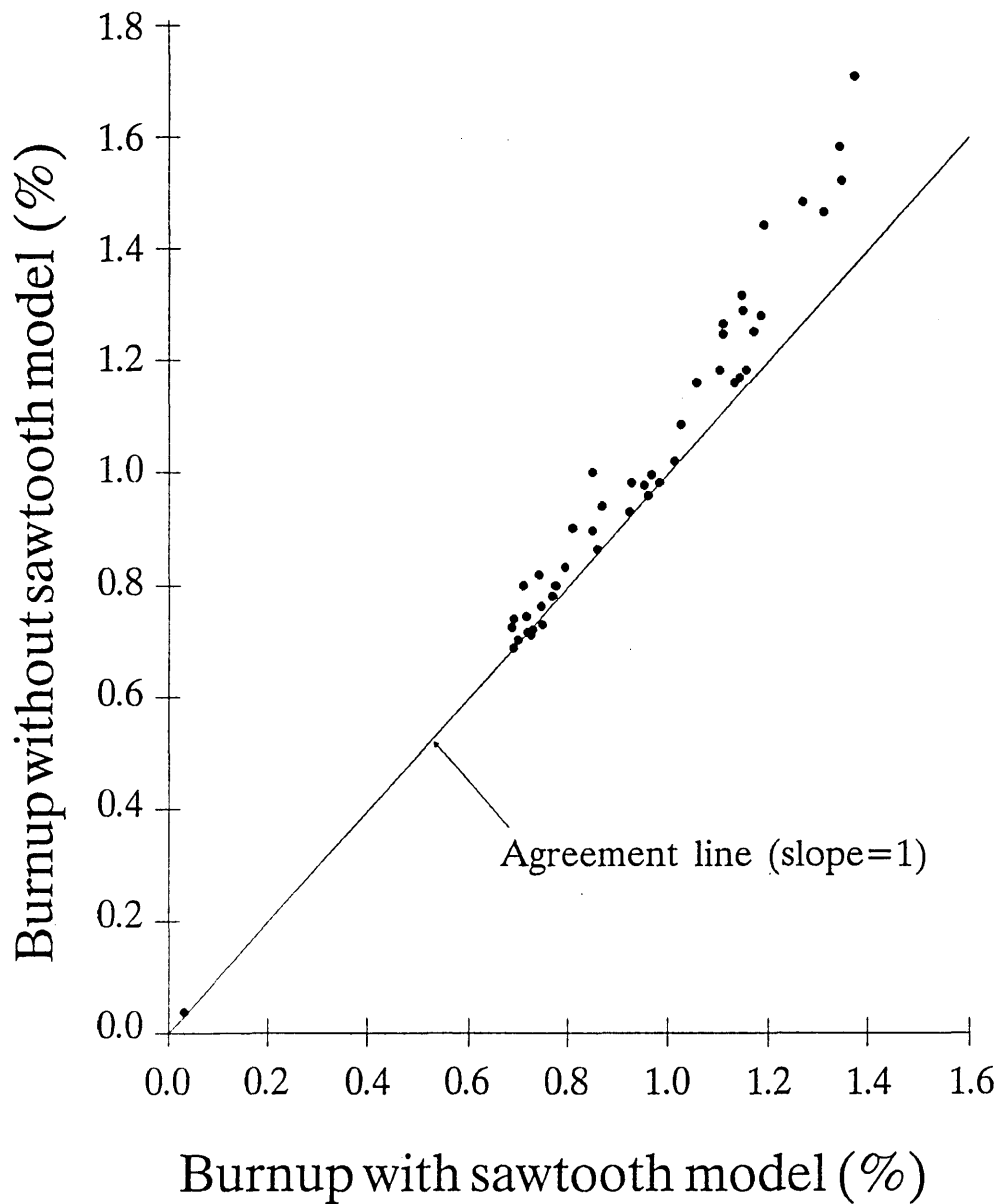


Figure 5.25. Modelled 14 MeV neutron emission with and without sawteeth: The sawtooth model used causes a small change to the 14 MeV neutron emission on average. Therefore, as the model overestimates the effect of sawteeth, the influence of classical sawteeth on the 14 MeV neutron production rate should be small and is ignored.

effect could only be due to a mechanism capable of altering the minor radius by more than 50 cm during one second and such a transport mechanism is not observed, apart from monster sawteeth.

3. The triton population is assumed to be accurately modelled by the single particle approximation. The main effect missed by the single particle approximation is that of energy diffusion. This is a phenomenon that occurs primarily when ion-ion collisions dominate the energy loss rate and this usually occurs at energies lower than the maxima in the D-T reaction cross-section, so the effects of this should be small on the 14 MeV neutron emission rate. Pitch angle diffusion into the triton loss cone is also mainly due to ion-ion interactions and hence the effects of this should be small, an observation born out by calculations using the HECTOR code [5.27]. Instabilities are unlikely to be excited by the tritons as only a very dilute population is available, up to 1 part in 10^6 at the most.
4. It is assumed that 10 flux volumes are sufficient to model the plasma. This has been checked by varying the number of flux surfaces used up to 40 and very little change was observed, less than 10%. This is only true for normal discharges where the triton birth profile is moderately peaked (up to peaking factors of approximately 10). For very peaked profiles the model requires more flux volumes for accurate modelling; in addition, a number of other assumptions fail in this regime and the input data become unreliable. For this application a specially modified version of TRAP-T is used which has more flux volumes and a more general slowing down formula (see item 5 in this list).
5. The slowing down formulation used in TRAP-T assumes that $v_e > 3v_t$, which holds for plasmas where $T_e > 1$ keV. In JET plasmas, this is not usually a problem as even for ohmic plasmas the axial electron temperature is in the region 2-3 keV and electron temperature falls to 1 keV only in the outermost regions of the plasma, where the triton production level is usually fairly low, making this assumption reasonable. Pellet discharges form an exception to this as, at the time of pellet injection, the electron temperature

can fall to a few hundred eV across the plasma, before recovering quickly to several keV. It is possible to model the slowing down accurately in this region, but the computation time increases drastically.

6. A flat n_D/n_e profile is assumed. This is an assumption that is known to be wrong and can give rise to quite large errors, up to 30 %. However, there are no deuterium density profiles available on a regular basis and so an assumed profile must be used in most cases. The simplest assumed profile is the flat one.
7. It is assumed that there are no prompt or delayed losses of tritons from the plasma. The calculation of the prompt loss fraction of tritons would require an orbit calculation for each of the 400 triton start times, which would be a computationally expensive calculation for a correction which is usually very small because of the high plasma currents associated with most JET discharges. The guiding centre code SOCRATE [5.28] was used for approximately 100 discharges with $I_p > 3$ MA and the prompt loss fraction was always found to be less than 5%. The delayed losses, as shown by the code HECTOR are typically of the order

$$f_{delayed} = 0.1 Z_{eff} f_{prompt} \quad [5.6]$$

where f_{prompt} is the prompt loss fraction. Hence the effect of tritons being lost from the plasma under classical conditions is less than 5% and may reasonably be ignored.

8. The triton birth rate is assumed to be given by the 2.45 MeV neutron emission rate. This assumption is also known to be invalid, but again only a small error should be introduced by it. The branching ratio of the D-D reaction is shown in fig 5.26 from [5.29] and the ratio can be seen to be dependent upon the energy of the reacting deuterons. For tritons produced by Maxwellian deuterium populations, the difference between the two branches is never more than 10% in the region of interest of 2 keV to 20 keV. For tritons produced from beam-plasma or beam-beam reactions, the majority of the tritons are produced by deuterons near the beam

Diagnosis of fusion products for reactor relevant plasmas

injection energy and so the the ratio of tritons to 2.45 MeV neutrons also is equal to 1.0 ± 0.1 . The ratio is a slowly varying function across this interval, so that a systematic error on the absolute 14 MeV neutron yield would not affect the time dependence, nor the shot to shot comparisons.

The assumptions in the above list are all capable of giving rise to small errors in normal use of the code but the largest sources of error in the calculation are thought to be the errors in the input data. The most important data with their associated errors are shown below:

	Absolute error	Spatial error
• Magnetic flux surfaces		± 10 cm
• Electron temperature profiles	$\pm 10\%$,	± 7 cm
• Electron density profiles	$\pm 15\%$	
• Z_{eff}	$\pm 30\%$	

The magnetic flux surfaces are important in that they determine where on the T_e and n_e profiles the T_e and n_e data are taken, as these profiles are quoted as functions of major radius and must be converted to plasma coordinates for use in TRAP-T. The magnitude of the errors likely to be introduced here depends on the peaking factors of the various profiles, flat profiles implying little or no error and highly peaked profiles implying large errors. The other input quantities have associated uncertainties, those on T_e and n_e mainly affecting the slowing down rate of tritons while Z_{eff} is the major source of uncertainty on the absolute magnitude of the 14 MeV neutron emission. The effect of these experimental uncertainties on the predictions of the 14 MeV neutron emission is discussed in more detail in the next section.

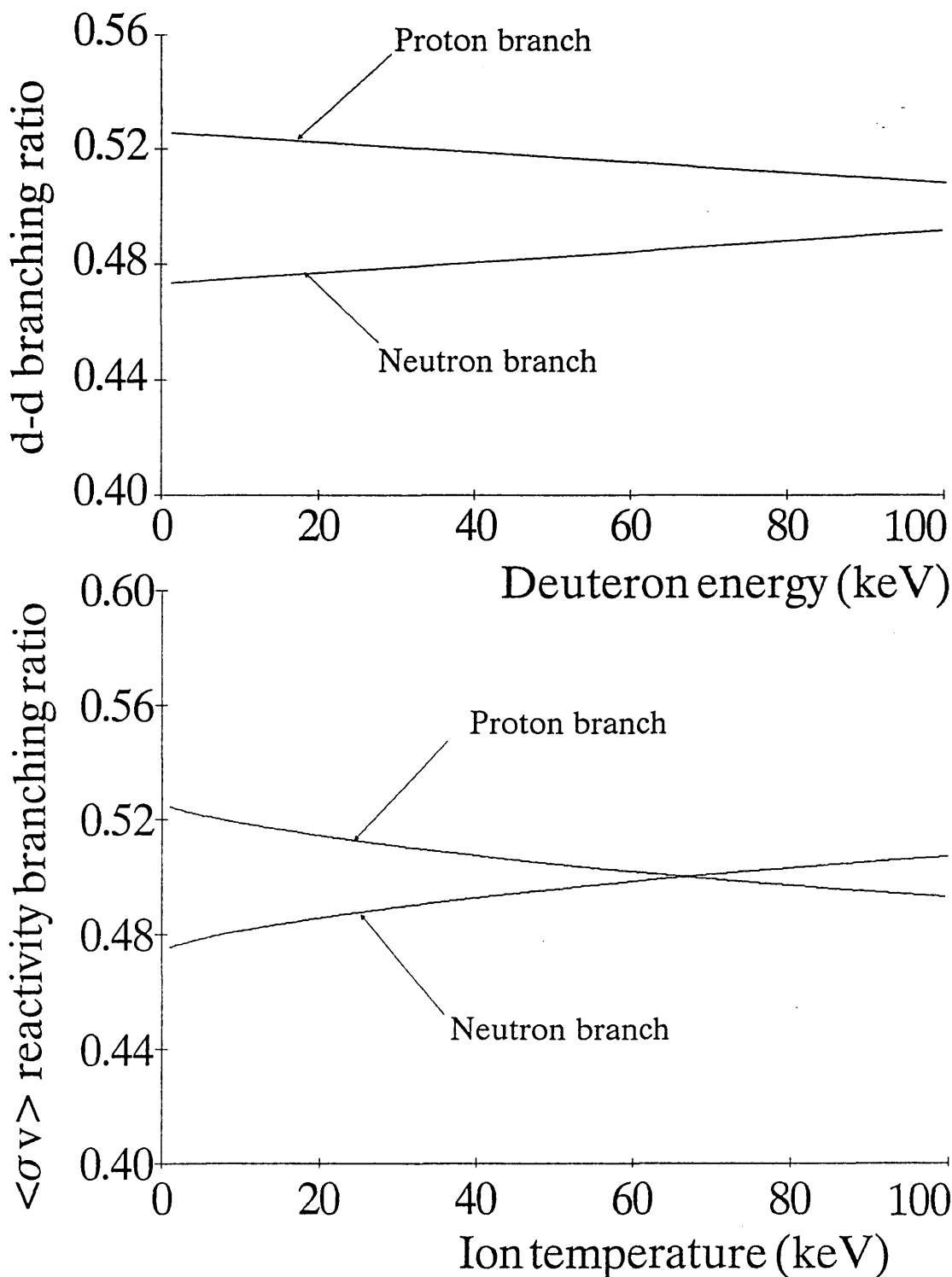


Figure 5.26. D-D branching ratios: The upper figure shows the relative probability of the branches as a function of deuteron energy. The lower graph shows the branching ratios as a function of plasma temperature. The graphs have been drawn from [5.29].

By treating the triton population as a large number of groups of independently slowing down particles, a significant simplification of the problem is achieved at the expense of being able to model such processes as spatial diffusion of the tritons. The physics of the code has been checked by comparing the results with SOCRATE in time-independent cases, as illustrated in fig 5.27. The agreement between the two codes is very good, except for a few cases with high temperature plasmas. One important difference between the codes lies in their handling of interpolation between data points in the input data, which meant that for time-independent cases with identical input data, the values of T_e and n_e used to model the plasma were slightly different. Upon further inspection, most of the points showing a large deviation from the line of equality turned out to be due to sawteeth, with one code using data from low side of the crash and the other code using data from the high side of the crash.

It seems reasonable to conclude that for a wide range of discharges, the approximations and simplifications made in TRAP-T do not introduce large inaccuracies and that, for the majority of JET discharges, orbit effects upon the triton burnup are trivial. There are exceptions to this, such as pellet discharges, where the peaking of the triton source profile and the the associated temperature and density profiles cause large inaccuracies to be introduced into the calculation.

5.3.2.2 *Sensitivity analysis.*

Uncertainties in the input data lead to errors in the calculated fraction of tritons which burnup. In order to estimate the effects of these uncertainties, the values of T_e , n_e and Z_{eff} were altered by up to $\pm 30\%$ and the changes in the burnup ratio noted. The results of this study are shown in fig. 5.28, when it can be seen that the greatest sensitivities of the absolute triton burnup ratio are associated with the parameters T_e and Z_{eff} . T_e affects how fast the tritons are slowing down; if the modelled and observed time dependence are in good agreement, the experimental T_e can be assumed to be reliable. The sensitivity to Z_{eff} appear to be of a similar magnitude to that for T_e when $Z_{eff} \approx 2.5$, which is usually the case in the shots analysed. When Z_{eff} is smaller than 2.5, the error

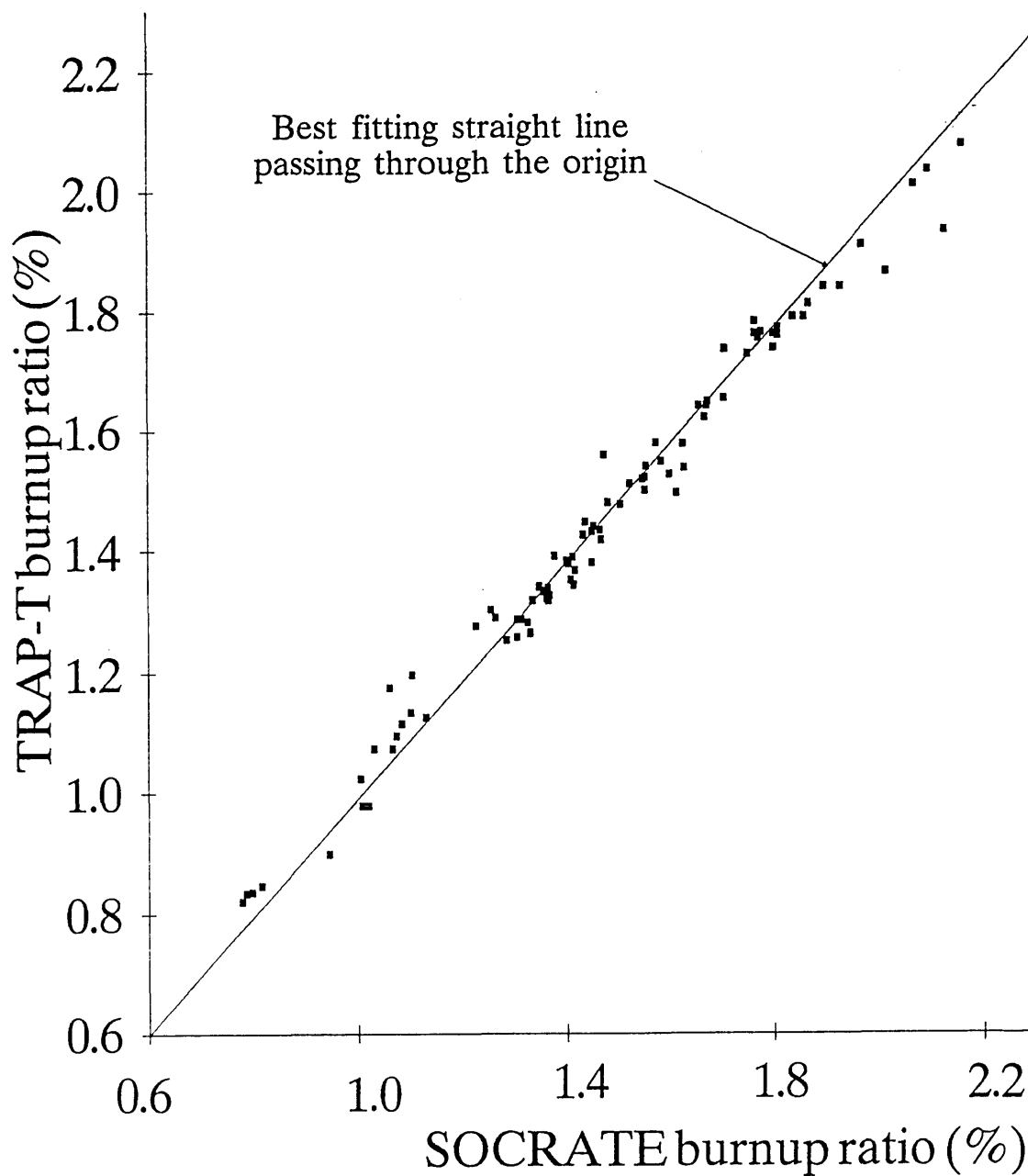


Figure 5.27. Comparison of calculated triton burnups from TRAP-T and SOCRATE: The guiding centre code and TRAP-T were compared for approximately 100 times from a number of JET discharges. The agreement between the two codes is very good, except for a few discharges with high burnup ratios. This result implies that orbit effects have little importance on the burnup ratio, as SOCRATE includes the orbit effects, whereas TRAP-T does not.

introduced by an error in Z_{eff} is smaller. This can be shown from the formula used to calculate the deuterium density from the Z_{eff} value:

$$n_D = \frac{(18 + 32f_i - 3Z - 4f_i Z)n_e}{(1 + f_f)(15 + 28f_i)} \quad [5.7]$$

where f_f = the ratio of hydrogen to deuterium in the plasma,

f_i = the ratio of oxygen to carbon in the plasma

The values of f_f and f_i are taken from other diagnostics and are typically 0.00 and 0.33, respectively. The fractional change in the calculated deuterium density caused by a change in Z_{eff} for these typical conditions is given by:

$$-\frac{\Delta n_D}{n_D} \approx \frac{\Delta Z}{6.6 - Z} \quad [5.8]$$

$\frac{\Delta Z}{Z}$ is estimated to be $\pm 20\text{-}30\%$ from the visible bremsstrahlung diagnostic, so in order to keep the fractional error in n_D at a similar level, shots having Z_{eff} values higher than 3 are rejected.

5.3.2.3 Summary and future developments

The code TRAP-T meets the targets specified at the beginning of this section for a program to simulate the 14 MeV neutron emission rates. The program has been well tested and is used routinely to assist in the analysis of 14 MeV neutron data from JET. It contains a number of approximations and assumptions which are reasonably valid on a large device such as JET, although for smaller devices this would not hold true. In fact, the major source of inaccuracy is the data used to model the plasma. The code runs fast enough to be used for all shots for which adequate data exist in order to model the plasma.

TRAP-T is fairly well developed at this moment. No major upgrades to the program are planned. Variations on TRAP-T are sometimes required, such as the version used to model the slowing down of ^3He used in chapter 3, or the version used to study the production of γ rays from the population of ^3He as it

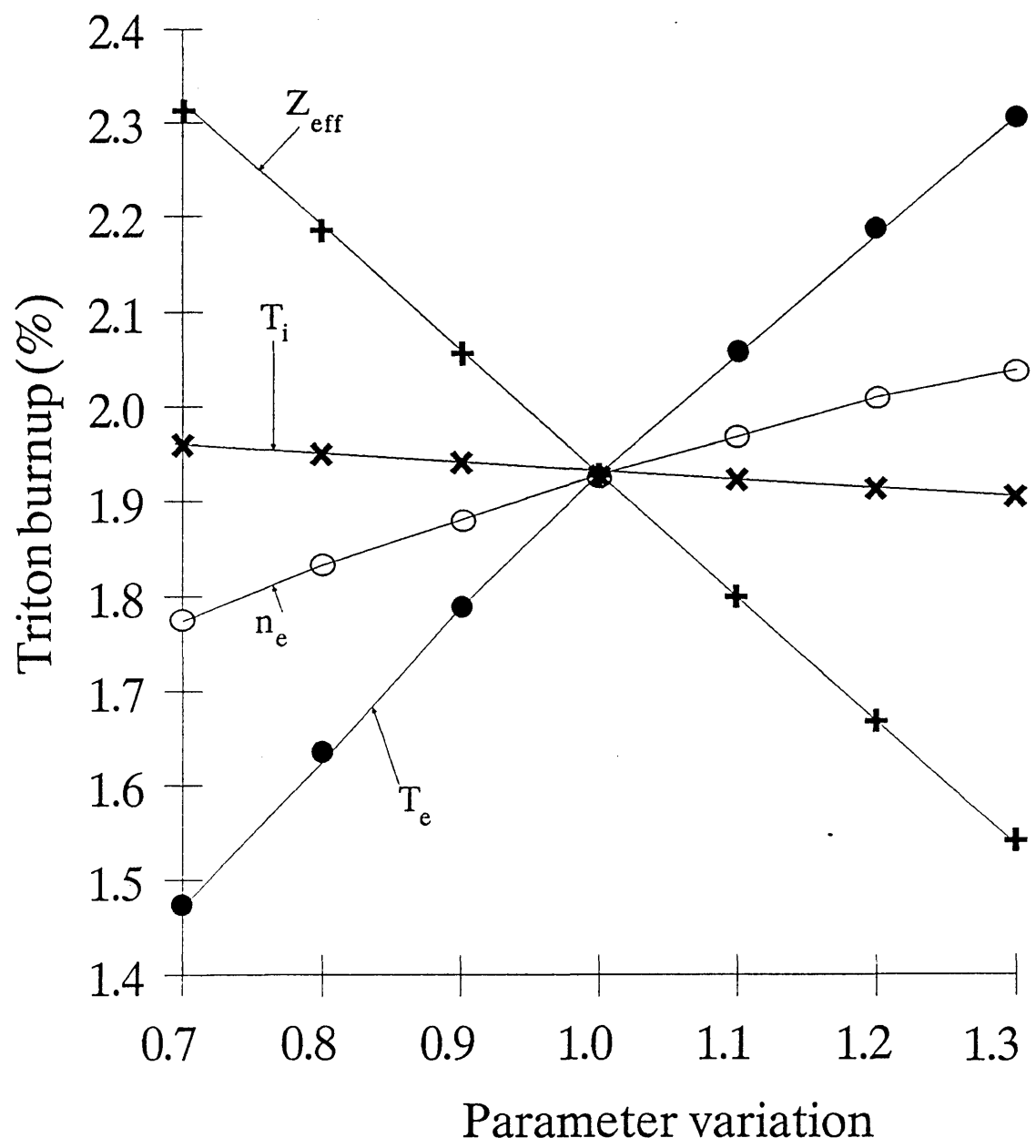


Figure 5.28. Burnup ratio dependence upon input parameters: By altering the values of T_e , n_e , Z_{eff} and T_i the sensitivity of TRAP-T to errors in the input data is estimated.

thermalises after RF minority heating on the ^3He . The only class of discharge with which TRAP-T experiences difficulty is that of pellet injection, for which a version of TRAP-T exists which, in principle, can manage the low electron temperatures and the high gradients although, in practice, the experimental uncertainties associated with the input data are usually the limiting factor on the accuracy of the predictions. In order to obtain a more accurate 14 MeV neutron emission rate, a new program would have to be written, probably along the lines of HECTOR or SOCRATE, but with time resolution.

5.3.3 Data overview

14 MeV neutron emission data have been taken at JET during the last three years. Out of the 10^4 discharges in this period, a few hundred are suitable for further analysis. The selection criteria used for foil activation measurements are:

- statistical error $< 30\%$,
- no disruptions during the discharge,
- very low runaway production levels,
- only copper activations with 2 measurements per activated foil are to be used.

For the silicon diode detector, the requirements are less stringent as disruptions can simply be excluded from the time interval examined. The following are the criteria used to judge the acceptability of silicon diode data:

- more than 100 events due to 14 MeV neutrons.
- no contribution to the 14 MeV neutron signal from pile up of the low energy events,
- low runaway production.

There are some difficulties associated with determining whether the second of the conditions is valid for the silicon diode detector. The normal way to test for it is to observe the ratio of the signals from the various discriminators. If the pulser count rate is subtracted from each channel, then the discriminators set to above the low energy signal should be proportional to each other. If the ratios of these discriminators alters from the known value, then the lowermost discriminator is discarded in favour of the next higher discriminator level.

For the TRAP-T analysis of a shot to proceed , a further set of selection criteria must be applied in order that the code may operate accurately:

- $Z_{\text{eff}} < 5$ throughout the main 14 MeV neutron emission times, (shots 10200-11100),
- $Z_{\text{eff}} < 3$ throughout the main 14 MeV neutron emission times, (shots 11100-21030),
- good electron density data from the FIR available,
- good electron temperature data from ECE available,
- magnetic flux surface data available.

The Z_{eff} criterion has been relaxed for the first period of silicon diode operation in order that one or two particularly interesting shots could be analysed. From the good results obtained from these high Z_{eff} shots, it seems that the systematic error on the Z_{eff} value was rather smaller than that quoted.

After applying all the selection criteria, the following data regions are available from the foil activation system and the silicon diode detector:

Period	Shot range	Number of shots
A	10500-11000	≈ 15
B	12000-13000	≈ 100
C	15500-18790	≈ 20

Table 5.2. Foil activation data regions

Period	Shot range	Number of shots
1	10800-11100	≈ 40
2	15500-16518	≈ 50
3	16519-18790	≈ 50
4	19900-21030	> 200

Table 5.3. Silicon diode data availability

For the foil activation system, periods A and C contain too few discharges to make any detailed analysis of trends worthwhile, although the observation that the measurements appear to be near classical can be made. Period B has enough shots to allow scalings with various parameters to be derived [5.18], although the lack of any silicon diode data does make the data more open to misinterpretation. For the silicon diode data, periods 1 and 2 were quite fruitful, however, period 3 suffered from high impurity levels and this limited the number of discharges available for analysis. At the time of writing, measurements have just commenced on period 4 and this looks to be the best period of operations so far, as the impurity levels in the plasma are low.

Two methods of comparing the observed with the calculated 14 MeV neutron emission are employed. The first is to sum the neutron emission rates over the shot and compare the integrated neutron yields. This is the only comparison available for the foil activation measurements and, to a lesser extent, is also used for the silicon diode measurements. Such comparisons are shown in figs 5.19-5.20, 5.29-5.31. 14 MeV neutron yields are shown from plasmas with very different operating regimes, from pure ohmic to 35 MW of additional heating and from 3 to 7 MA plasma currents, yet the agreement between the code and the experimental determined yields is remarkably good. These comparisons show that the calculated and experimental yields are linearly related (to within 10%) but the slope may differ from unity by as much as 30%. This may be understood in terms of the absolute error of 30% on Z_{eff} . For the values of Z_{eff} normally encountered (typically 2-3) this implies a similar error on the derived n_D/n_e ratio and hence the calculated 14 MeV neutron emission rate. The scatter of the points around the lines is thought to simply be due to random errors in all the input data used by the program.

The second type of comparison is used only for the silicon diode data, as it is a comparison of the calculated time-resolved 14 MeV neutron emission rate with that measured. To simplify such comparisons, the calculated 14 MeV neutron yield for the discharge is often normalised to the observed 14 MeV neutron yield. A discharge which had two periods of neutral beam heating is shown in figs. 5.32-5.34. The agreement between the calculation and the observed values is fair if purely classical slowing down theory is used, although the calculated peak in the 14 MeV neutron emission rate falls some 200 ms after the observed peak. This may be easily modelled in the code by introducing an energy loss factor, A , defined as:

$$\left(\frac{dE}{dt} \right)_{\text{model}} = A \left(\frac{dE}{dt} \right)_{\text{classical}} \quad [5.9]$$

where E = the triton energy. Using a factor $A=1.2$ in the code produces fig. 5.34. Here the time dependence can be seen to be better modelled than in the previous case. The value of 1.2 is used as it optimises a χ^2 test between the

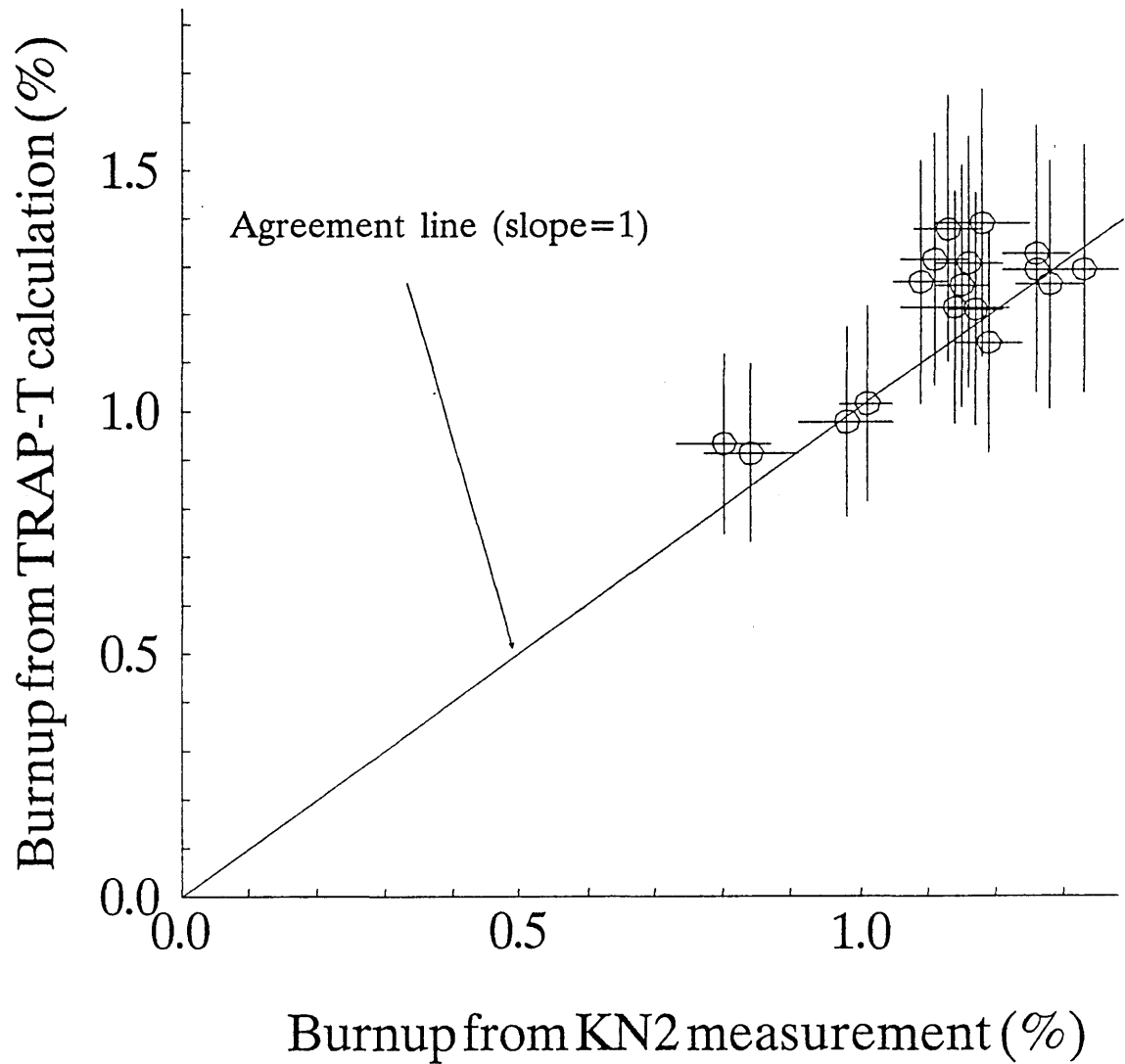


Figure 5.29. Comparison of calculated 14 MeV yields with KN2 yield, period B: The yields are obtained by integrating over the whole discharge, hence each point corresponds to one shot.

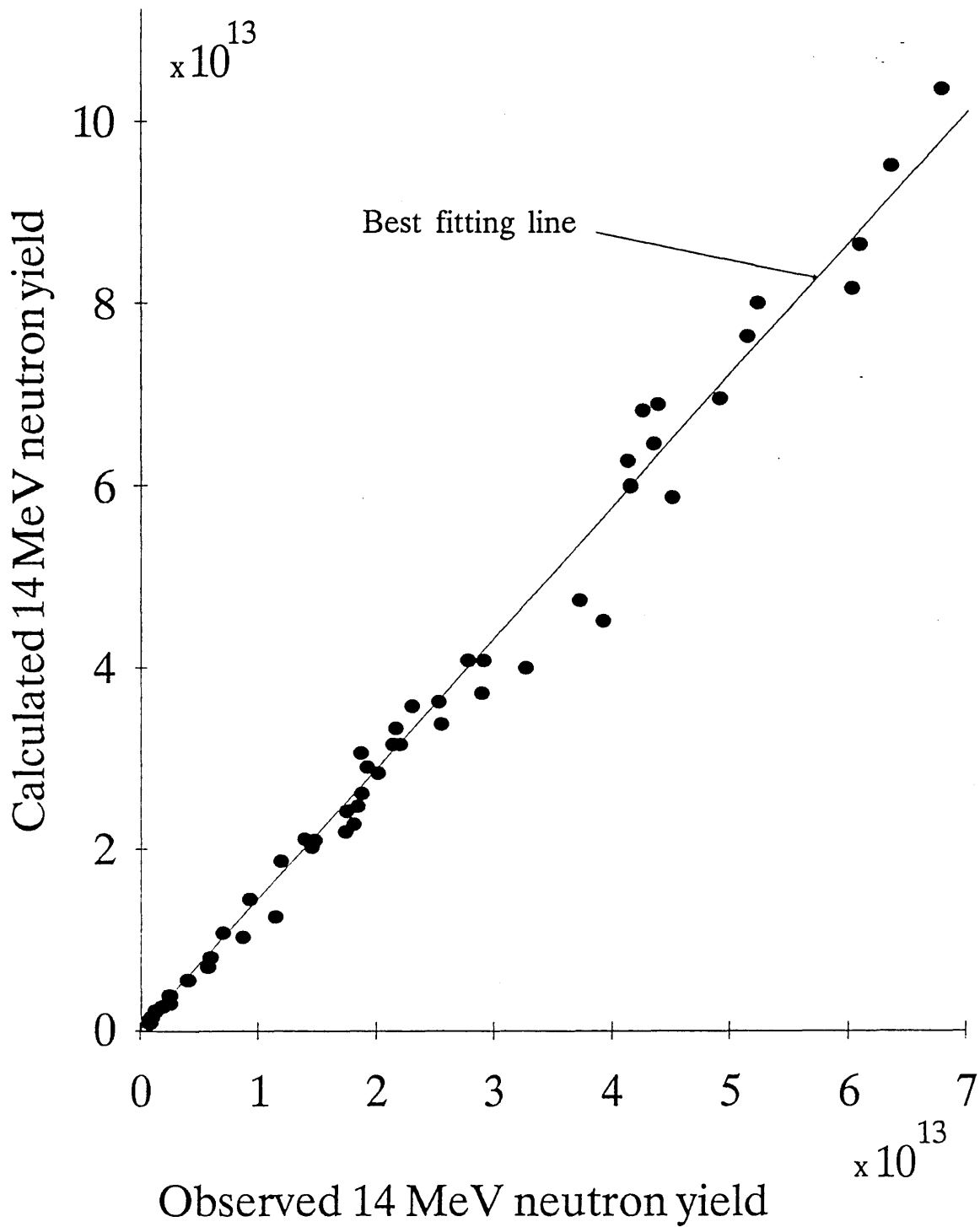


Figure 5.30. Comparison of TRAP-T 14 MeV yields with diode counts, period 2: The yields are obtained by integrating over the whole discharge, hence each point corresponds to one shot.

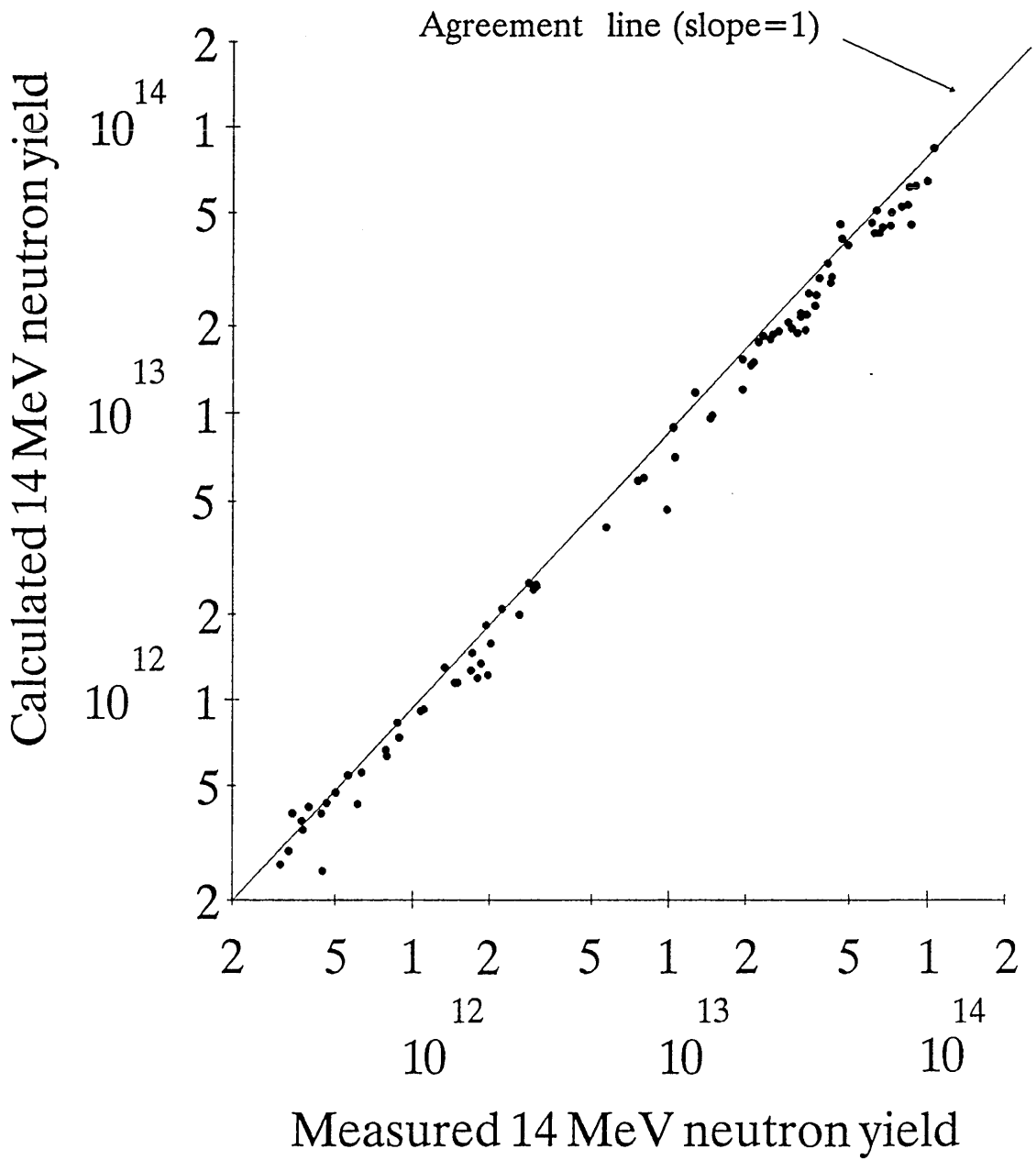


Figure 5.31. Comparison of TRAP-T 14 MeV yields with diode counts, period 3: The yields are obtained by integrating over the whole discharge, hence each point corresponds to one shot.

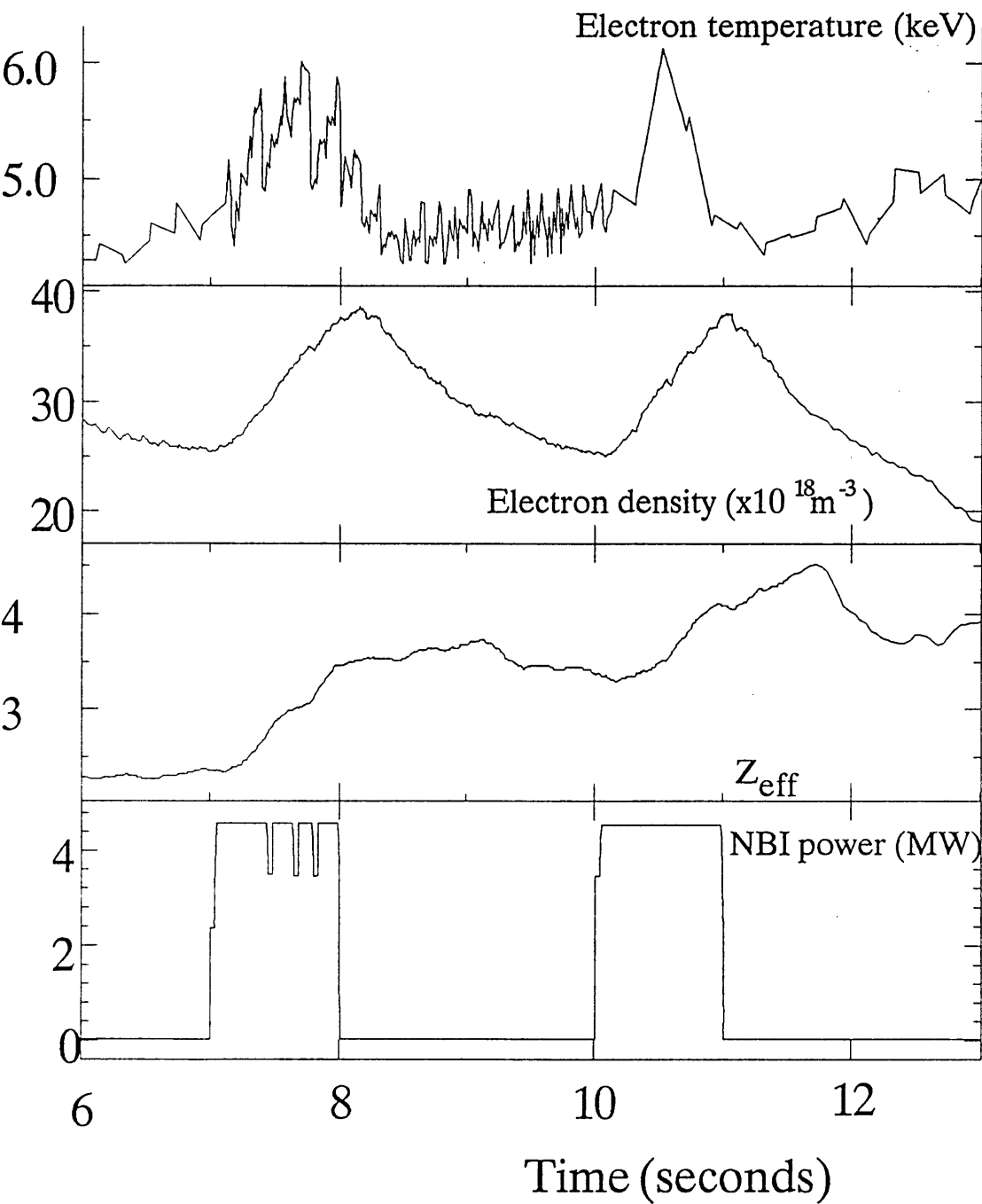


Figure 5.32. Key plasma parameters for discharge illustrated in figs 33-34.

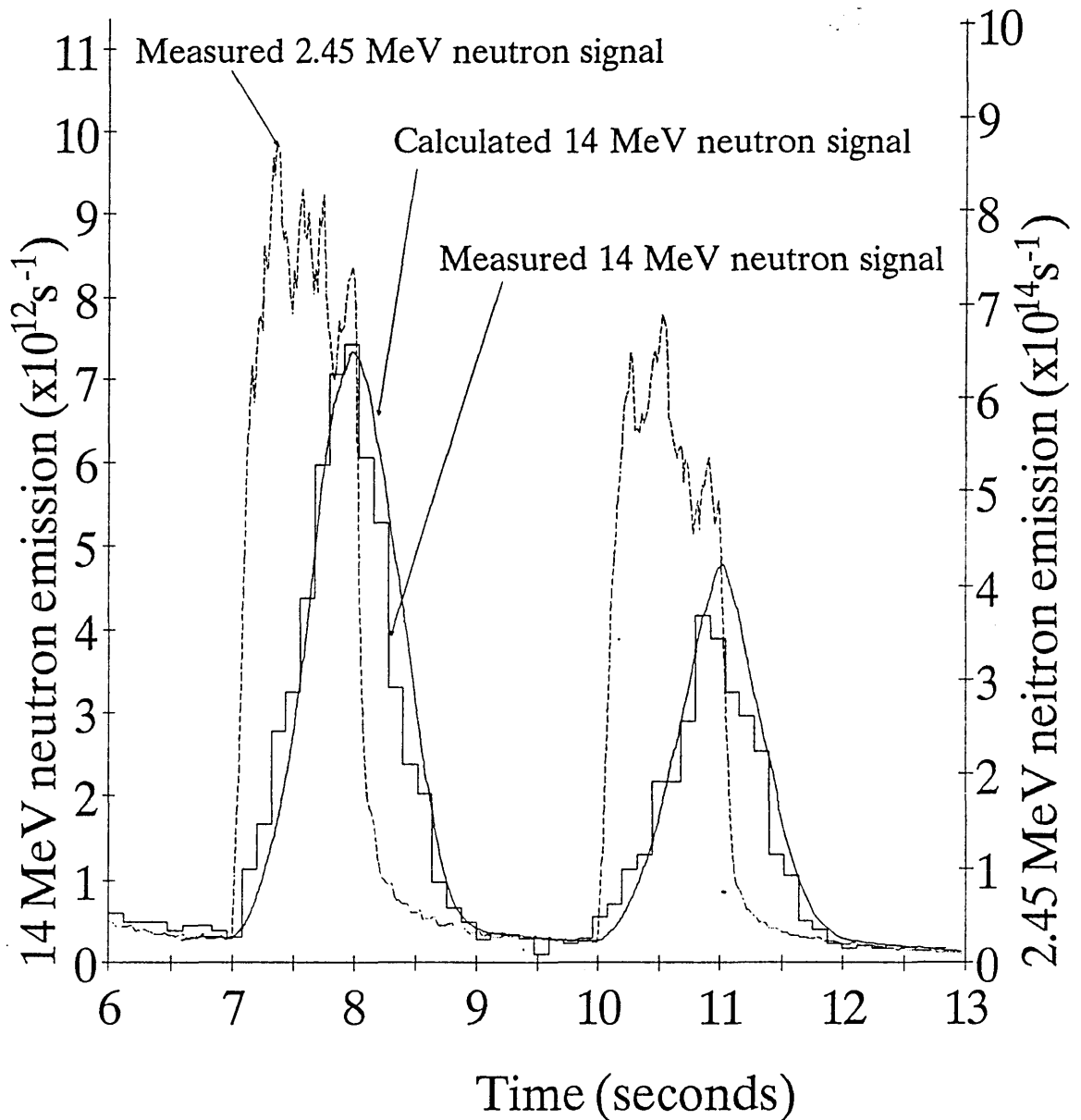


Figure 5.33. Comparison of TRAP-T calculation with experiment, $A = 1.0$: The code TRAP-T was used for this discharge with $A = 1.0$. The areas of the calculated and the observed 14 MeV neutron emissions have been normalised to highlight the time evolution features. The code is close, but not quite accurate, the observed 14 MeV neutron emission appearing to precede the calculation by about 0.2 seconds.

modelled and the observed data. This factor does not necessarily imply that the energy loss rate of slowing down tritons is non-classical as the error on the $\left(\frac{dE}{dt}\right)_{\text{classical}}$ term is $\approx \pm 20\%$ because of errors in the absolute calibration of the electron temperature diagnostics. The shot illustrated is from period 1. For periods 2 and 3 the value 1.15 is used. These A values are used throughout the time-resolved analyses. The A value is also dependent upon the electron temperature diagnostic used. If the ECE data is rescaled to approximate the LIDAR temperature values at the LIDAR times, then the A values required to obtain good agreement approach 1. The LIDAR temperatures are not available with a sufficiently high time resolution to allow their use as the only electron temperature input and the rescaling process is somewhat arbitrary, so the ECE data with a non-unity A factor is used for most discharges.

To summarise this section, the observed triton burnup averaged over a shot and the time dependence of the 14 MeV neutron emission rate both appear to be classical, within errors. There are systematic discrepancies between the absolute yields and the energy loss rates of the calculation and the observations, but these could be caused by errors in the input data of the code. The next section examines the individual shots in more detail, in order to look for departures from classical behaviour on short timescales which might not appear on the large scale comparisons described above.

5.3.4 Specific issues

5.3.4.1 Confinement of tritons

The confinement of tritons is an important issue as it relates directly to the confinement of α particles from D-T reactions in a fusion reactor. Poor confinement of α particles would imply that the efficiency of α particle heating will be somewhat less than the near 100% expected, making the achievement of a self-sustaining fusion plasma more difficult. Also the power loading on the first wall would be increased, causing problems with impurity influxes and also the provision of adequate cooling for the first wall. Therefore, demonstrating that tritons are well confined is an important result.

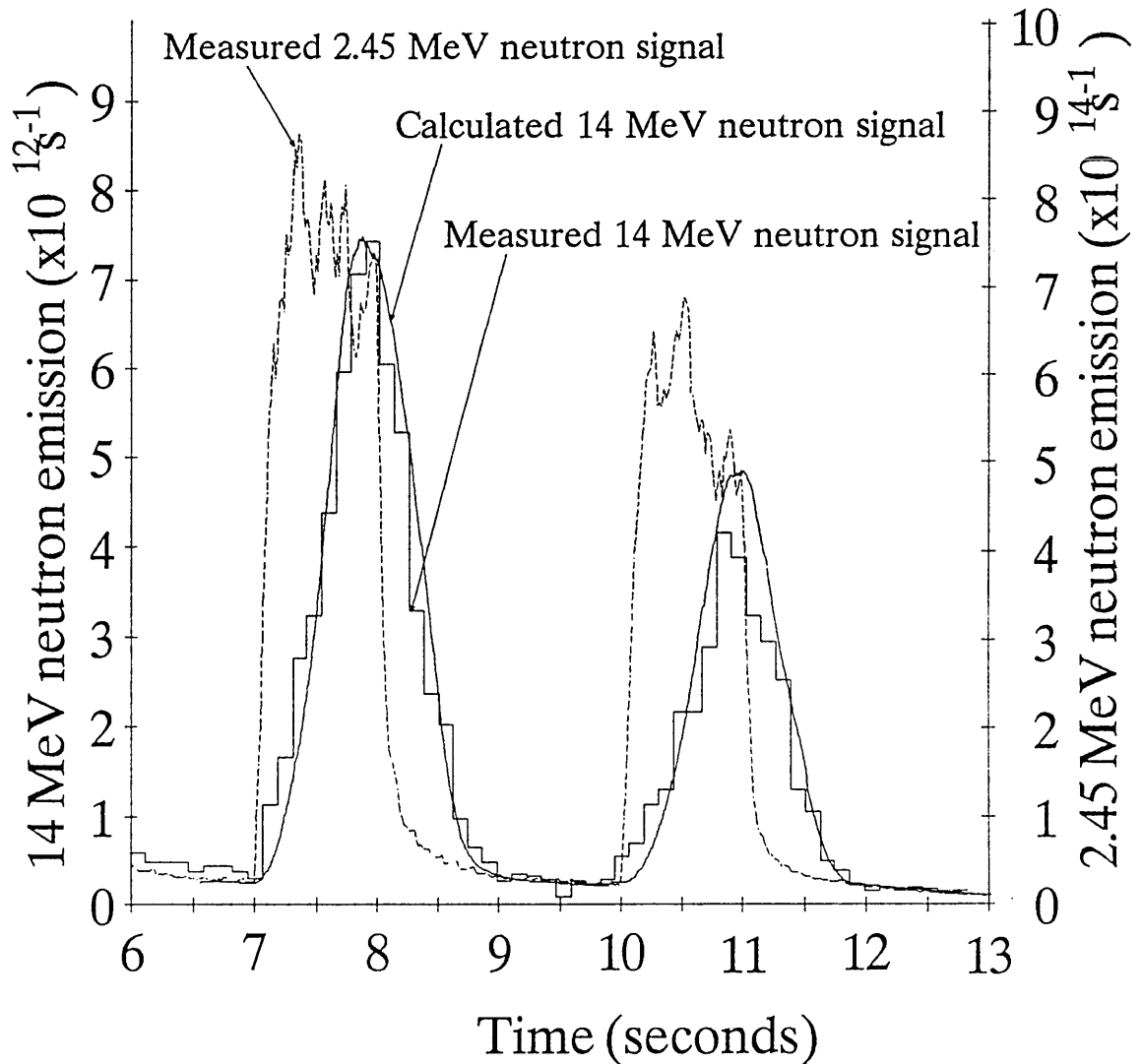


Figure 5.34. Comparison of TRAP-T calculation with experiment, $A = 1.2$: The agreement here is better than in the previous figure. The enhanced A factor could be due to a genuine anomalous energy loss process, or errors in the input data used to model the plasma. The latter explanation seems the most likely.

Comparisons of the calculated and measured integrated neutron yields are the principal test of triton confinement. After the model has been optimised by the adjustment of the A factor, any discrepancies must be due to either lack of confinement of tritons or to errors in the evaluation of the deuterium density. The fact that the calculated and measured 14 MeV neutron yields are linearly related over a wide range of plasma currents is compelling evidence that the confinement is near perfect and that the systematic discrepancy between the calculation and the measurement is due to errors in the evaluation of the deuterium density. It is thought that the systematic discrepancy is unlikely to be due to poor confinement of tritons, as a mechanism by which a constant 30% of all tritons are lost from the plasma is very hard to invent.

Sudden loss of triton confinement could occur on short timescales during the large events which occur in JET plasmas. The obvious events to investigate are sawteeth, monster sawteeth, infernal modes and pellet injection. These events are quite violent and could possibly cause the loss of tritons from the plasma. Such a loss would be observed as an abrupt fall in the 14 MeV neutron emission rate, although a similar drop could be produced without actual loss of tritons by their sudden relocation from one plasma region to another region with a lower deuterium density. Without a wall-mounted escaping triton detector, it is very difficult to distinguish between the two effects.

5.3.4.2 *Effect of sawteeth*

As described in chapter 2, the sawtooth phenomenon is a well documented but little understood process commonly found in JET plasmas. The effect of one sawtooth crash is to relocate plasma from the inside to the outside of the inversion radius, with plasma from outside this radius being transported inwards. It has the overall effect of flattening the temperature profile.

If the only effect of the sawtooth is this relocation, then its effect on the 14 MeV neutron emission rate should be small, of the order of 10%, as shown earlier in section 5.3.2. After examination of a large number of discharges for drops in the 14 MeV neutron emission rate coincident with sawtooth crashes,

it was concluded that sawteeth do not normally have a large enough effect on the total 14 MeV neutron emission rate to be detected. A typical set of sawteeth and the associated 14 MeV neutron emission rates are shown in fig. 5.35.

One possible way of extending this measurement would be to use the neutron profile monitor as a 14 MeV neutron detector. Neutron sawteeth show up much more clearly on the neutron profile monitor than on total neutron detectors and a similar effect would be expected for 14 MeV neutron emission rates. The major problem expected with such an experiment would be the counting statistics required. The count rate for 14 MeV neutron events would at best be a few hundred counts per second. In order to be able to detect a 10% change in the counting rate N against the statistical fluctuations of order $\sqrt{N}$, $N > 400$ would be required over a time bin no more than 50 ms long and preferably shorter. This would necessitate the summing up of numerous sawteeth from similar discharges. Such a procedure has not yet been undertaken.

5.3.4.3 *Effect of monster sawteeth*

Monster sawteeth are superficially similar to long duration normal sawteeth but they also have much larger inversion radii associated with them. A typical monster sawtooth and the associated 14 MeV neutron emission rate are shown in fig. 5.36; no drop in the 14 MeV neutron emission rate is observed coincident with the sawtooth crash, although a change in the gradient is. This is consistent with the abrupt change in the electron temperature and the subsequent decrease in the slowing down time of the tritons.

This behaviour is repeated throughout all monster sawteeth observed, with only one possible exception. This discharge is illustrated in fig. 5.37, where an apparent drop of some 30% in the neutron emission rate is observed at the sawtooth crash. As can be shown by the 2.45 MeV neutron profile monitor, the crash caused an unusually large change in the 2.45 MeV neutron emission profile, suggesting that particle transport had occurred. The discharge was also undergoing the 'carbon catastrophe' at the time of the crash, implying that a

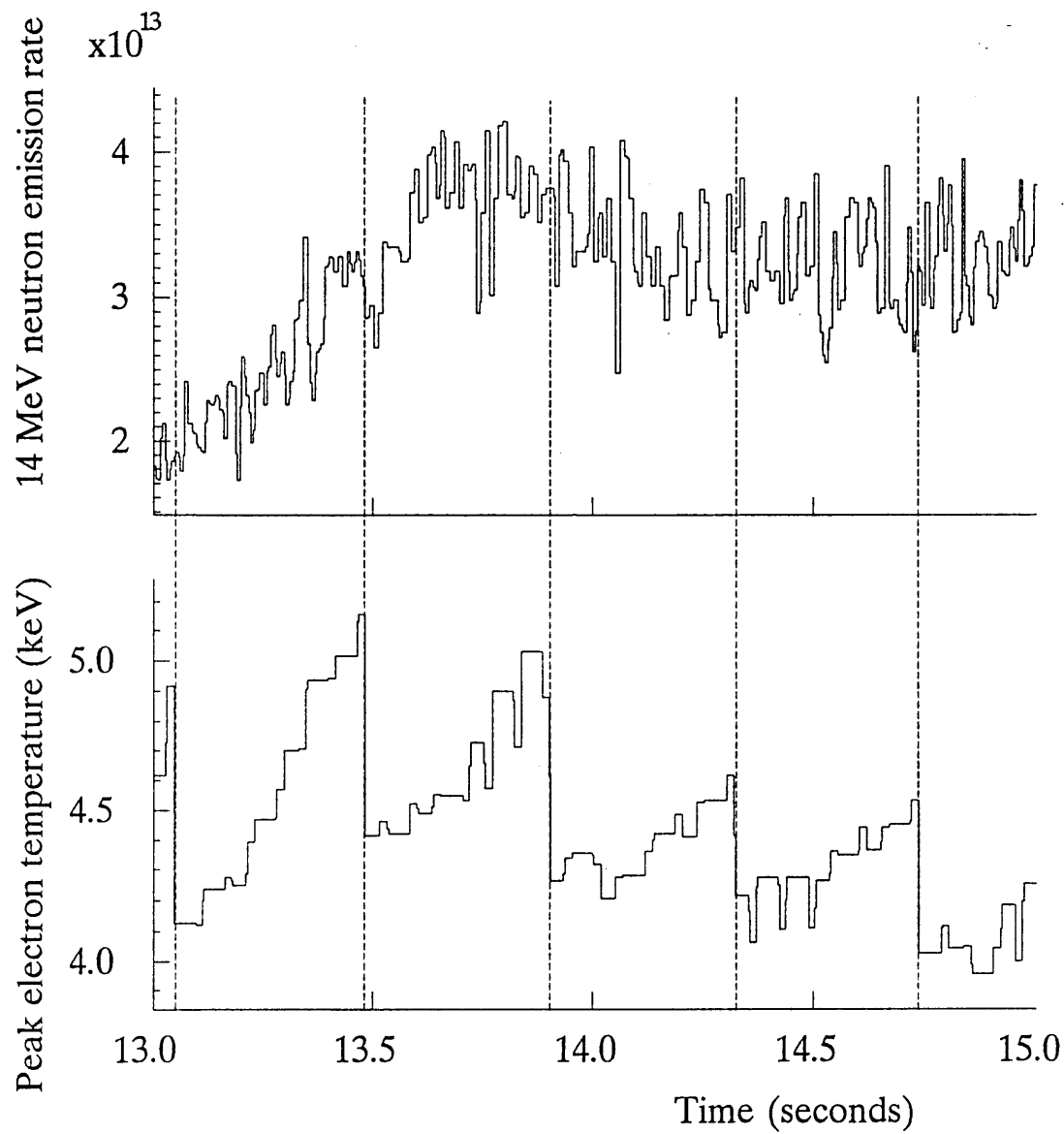


Figure 5.35. 14 MeV neutron signal from discharge exhibiting sawteeth: The lower graph is from the ECE electron temperature diagnostic and show the plasma to be exhibiting obvious sawteeth. The upper graph shows the 14 MeV neutron signal at the same time and no obvious sawteeth are seen.

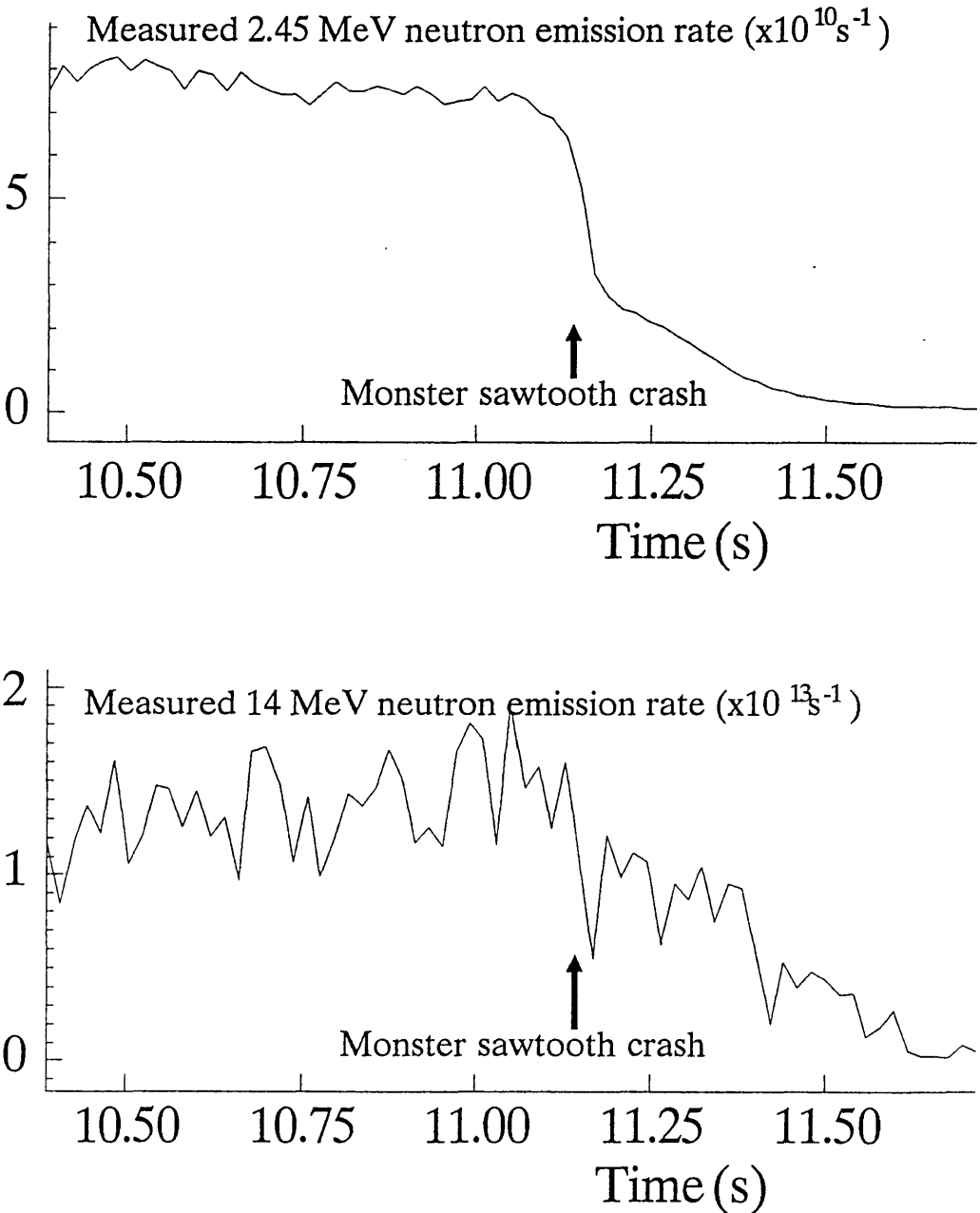


Figure 5.36. 14 MeV neutron emission rate during monster sawtooth activity: The indicated time shows when the monster sawtooth occurred and no effect can be seen on the 14 MeV neutron emission signal.

very low value of n_D/n_e existed near the edge of the plasma. The simplest explanation for the drop in the 14 MeV neutron rate is that the tritons had been transported to outside the sawtooth inversion radius, where the low n_D/n_e ratio caused an instant drop in the triton burnup ratio. The possibility still exists that the tritons had been lost from the plasma but this would have required a larger shift of the tritons and so is less likely. As stated earlier, to differentiate between tritons lost from the plasma and tritons transported to regions of the plasma with low n_D/n_e requires an escaping triton detector, which is not available on JET.

5.3.4.4 *Effect of infernal modes*

The infernal mode is an event which occurs in pellet fuelled discharges. A typical discharge showing this feature is shown in figure 5.38. Opinion on the physics of the event is divided but for the purposes of triton confinement what matters is the large change in the plasma conditions at the event. As can be seen from fig. 5.38, the 14 MeV neutron emission rate appears to be unaffected and maintains the same level for 0.4 seconds after the crash.

This is a somewhat puzzling result because the peaked density profile associated with pellet discharges collapses during the infernal mode and so a large change in the 14 MeV neutron emission rate might be anticipated. One possible explanation for this involves the position of the triton source profile. Whilst the KN3 2.45 MeV neutron emission profile is very peaked for this discharge, the tritons will effectively slow down on a broader profile because of the random gyrophase and bounce averaging effects. As the number of tritons present in each flux volume scales as the square of the minor radius of the volume, this implies that the bulk of the tritons which burnup will do so not on axis, but somewhat further out. Thus, the decrease in the deuterium density at the centre of the plasma and its local effect on the tritons slowing down could be countered by the increase in density further out, where the bulk of the tritons slow down. It is possible, though surprising, that the two effects cancel each other out as far as the 14 MeV neutron emission rate is concerned.

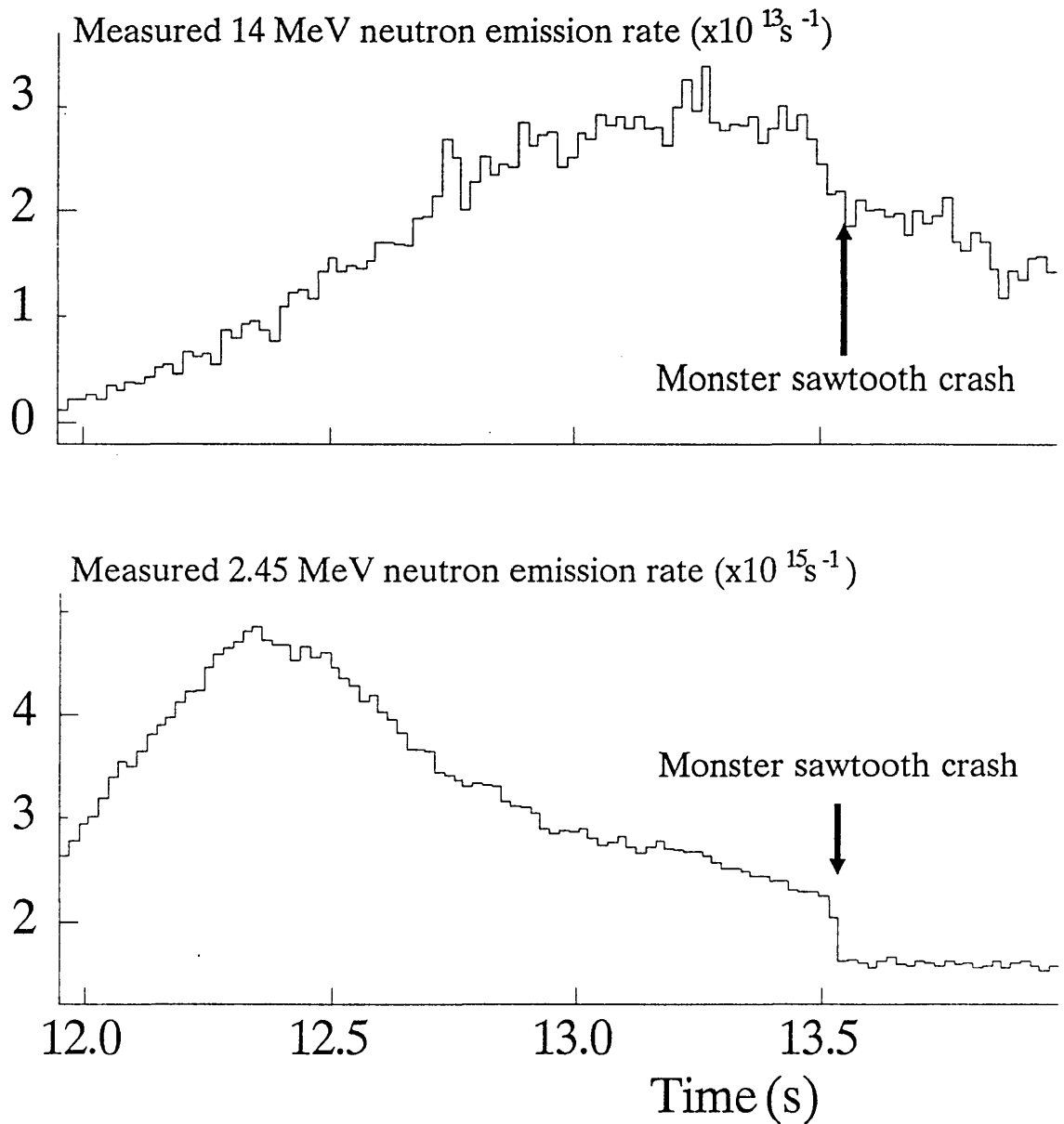


Figure 5.37. 14 MeV neutron emission correlated to monster sawtooth activity: This is the only case seen so far where a drop in the observed 14 MeV neutron emission rate correlates with the crash phase of a monster sawtooth.

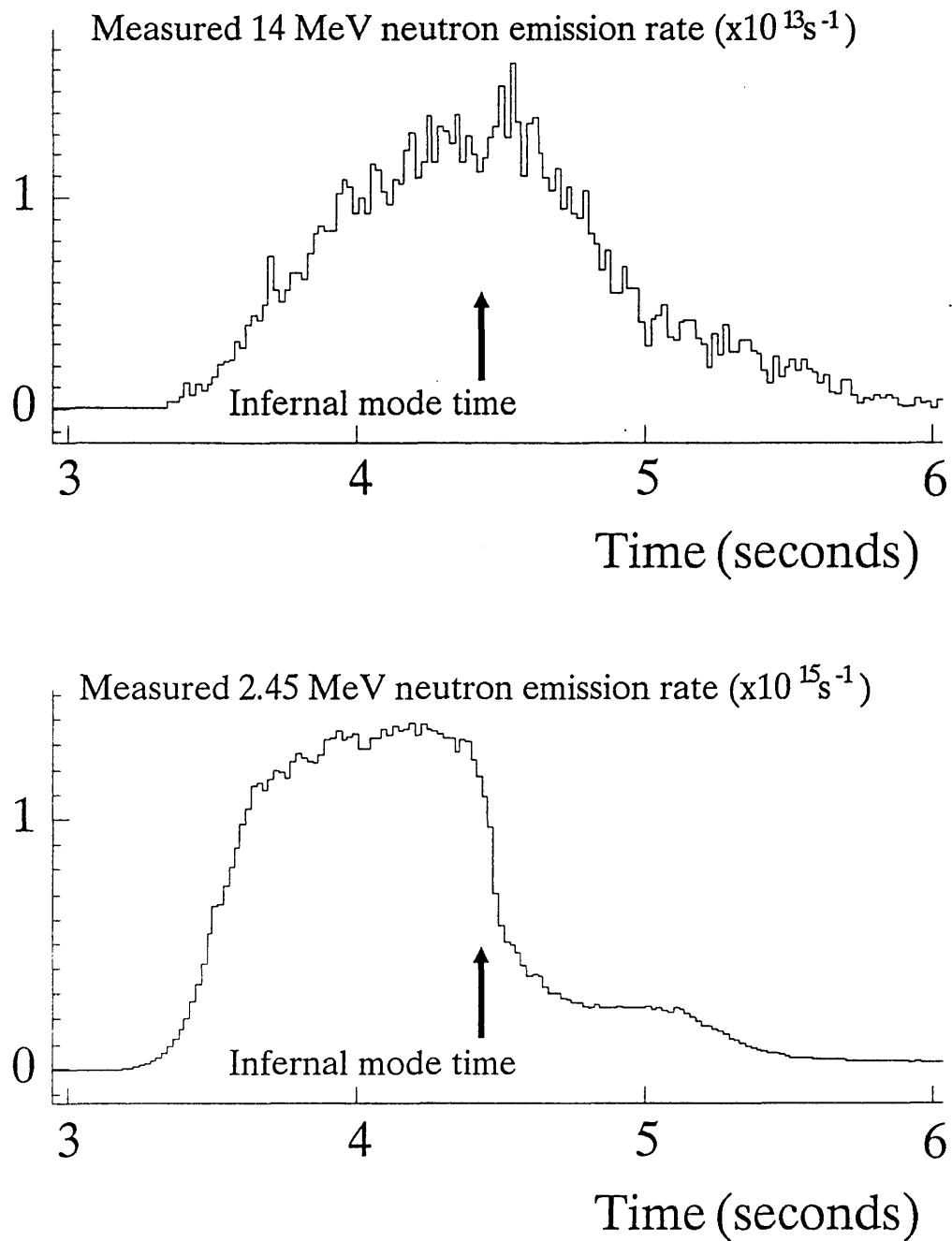


Figure 5.38. Typical infernal mode effect on the 14 MeV neutron emission

5.3.4.5 *Effect of rapid density reduction*

A set of unusual discharges where the electron density falls rapidly, even during the beam heating phase, have been observed (fig 5.39). For these discharges, beryllium tiles were being used inside the vessel and were thought to be responsible for the high pumping observed. The 14 MeV neutron emission rate computed using the classical model with the normal enhanced energy loss term is shown in fig 5.40; there is a considerable difference between the prediction and experiment. The discharge does have a low density and high electron temperature, so the delay between the 2.45 and 14 MeV neutron emission rates would have been expected to be greater than 1.5 seconds, as observed, but some 2/3 of the tritons appear to be missing at the end of the discharge. This has been modelled by including an exponential loss term in the TRAP-T code with a time constant of 0.9 seconds over the time interval from $T = 6.5$ to 8.5 seconds. The results are shown in fig 5.41 and the agreement is excellent. This discharge would appear to show two contradictory features: the longest slowing down times observed on JET and the poorest triton confinement properties.

The probable explanation for the loss of confinement is that the tritons were swept out of the plasma along with the rest of the bulk plasma ions, a somewhat discouraging result as this implies that ^4He ash removal schemes in future reactors will also sweep out the thermalising α particles, reducing the efficiency of the reactor.

5.3.4.6 *Deuterium density measurements*

One of the most restrictive limitations placed on the analysis of data using TRAP-T is that $Z_{\text{eff}} < 3$, as JET often operates with much higher Z_{eff} than this. The reason high Z_{eff} discharges cannot be used is that small errors on the Z_{eff} value lead to very large errors in the derived $n_{\text{D}}/n_{\text{e}}$ ratio. The errors become so large that it becomes worthwhile turning the problem around by assuming that the calculation (for $Z_{\text{eff}} = 1$) is correct and then using it to calculate the $n_{\text{D}}/n_{\text{e}}$ ratio of the plasma. A version of TRAP-T has been constructed which performs

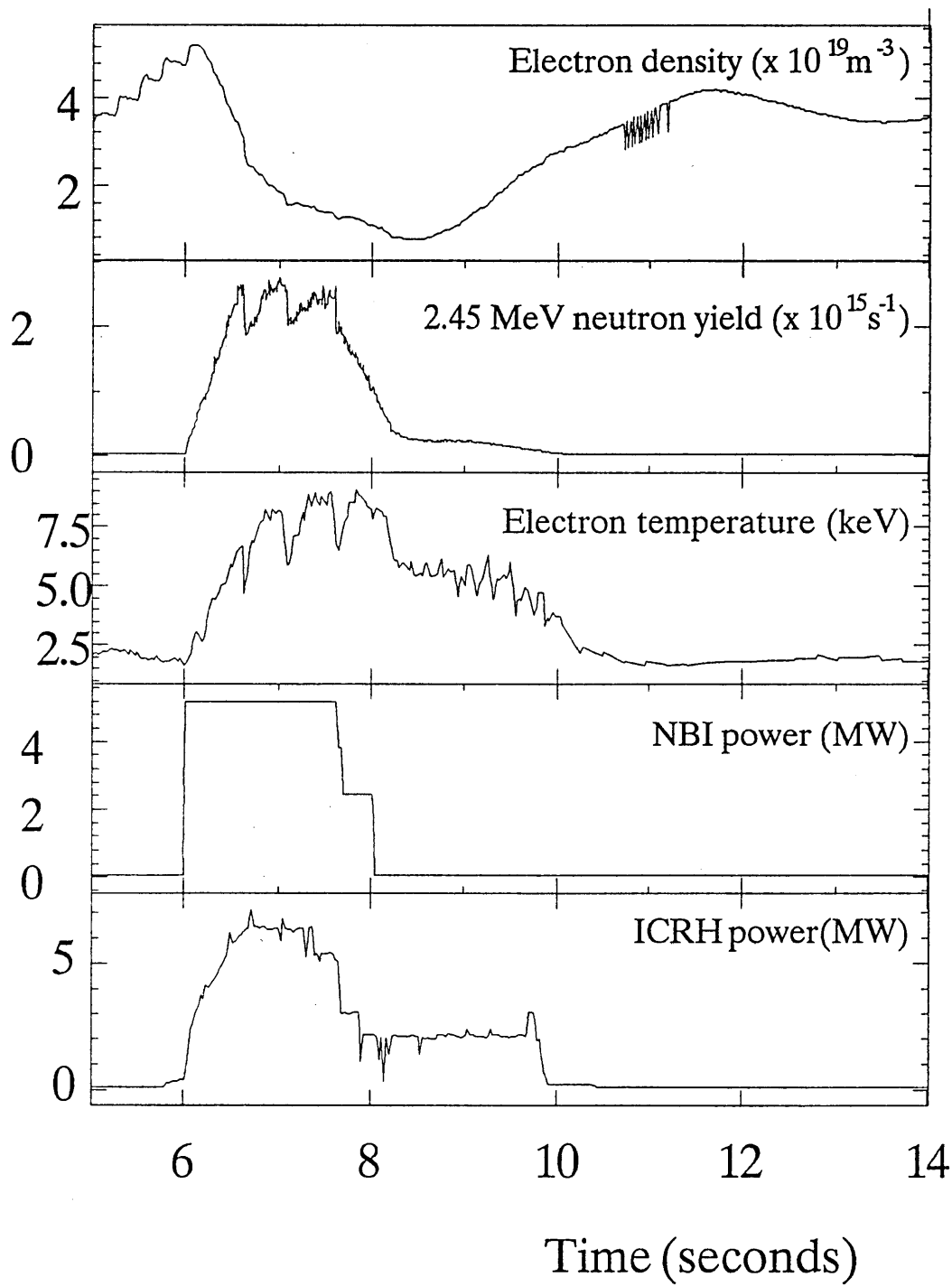


Figure 5.39. Plasma parameters for discharge with poor triton confinement

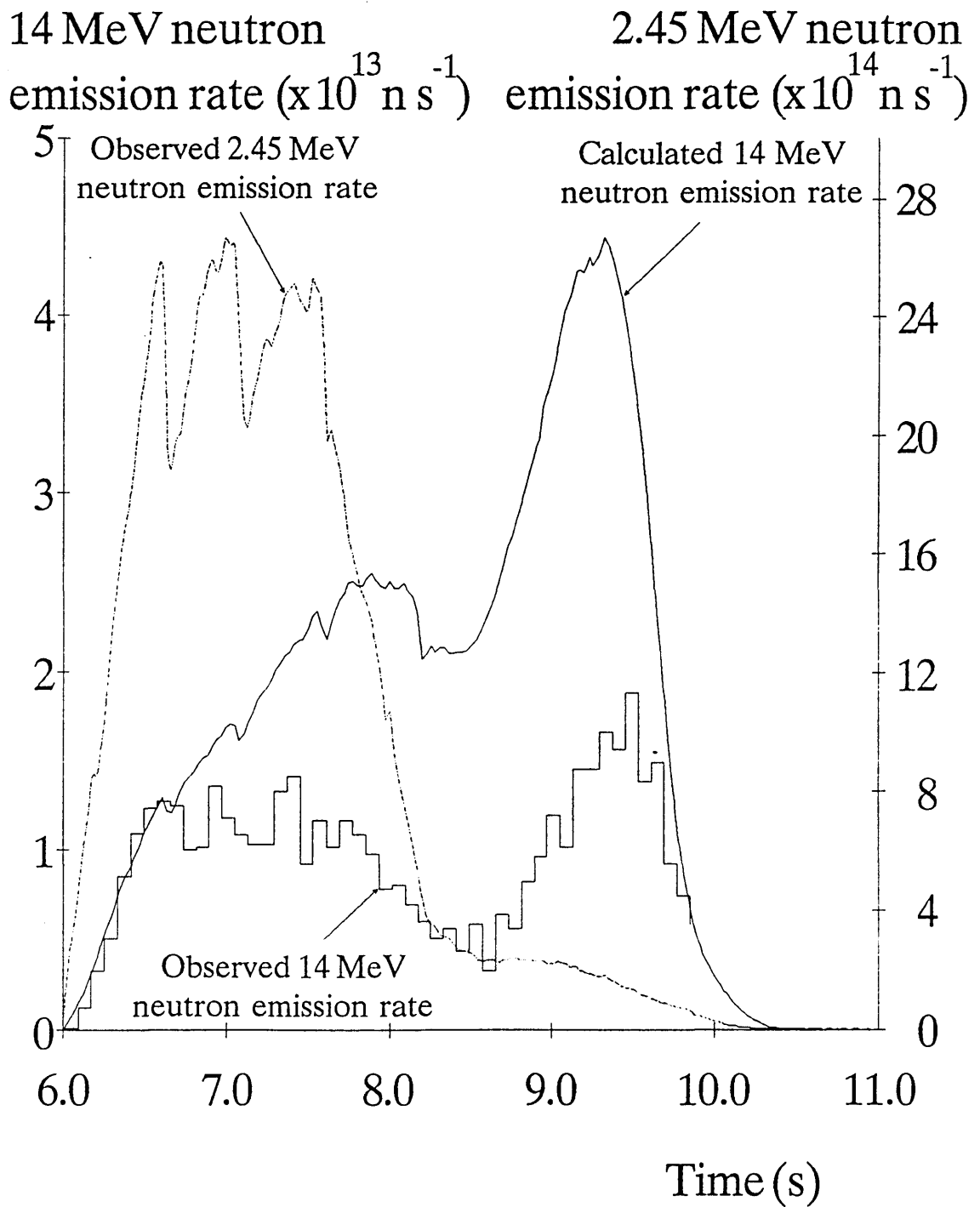


Figure 5.40. Classical TRAP-T run for low density discharge

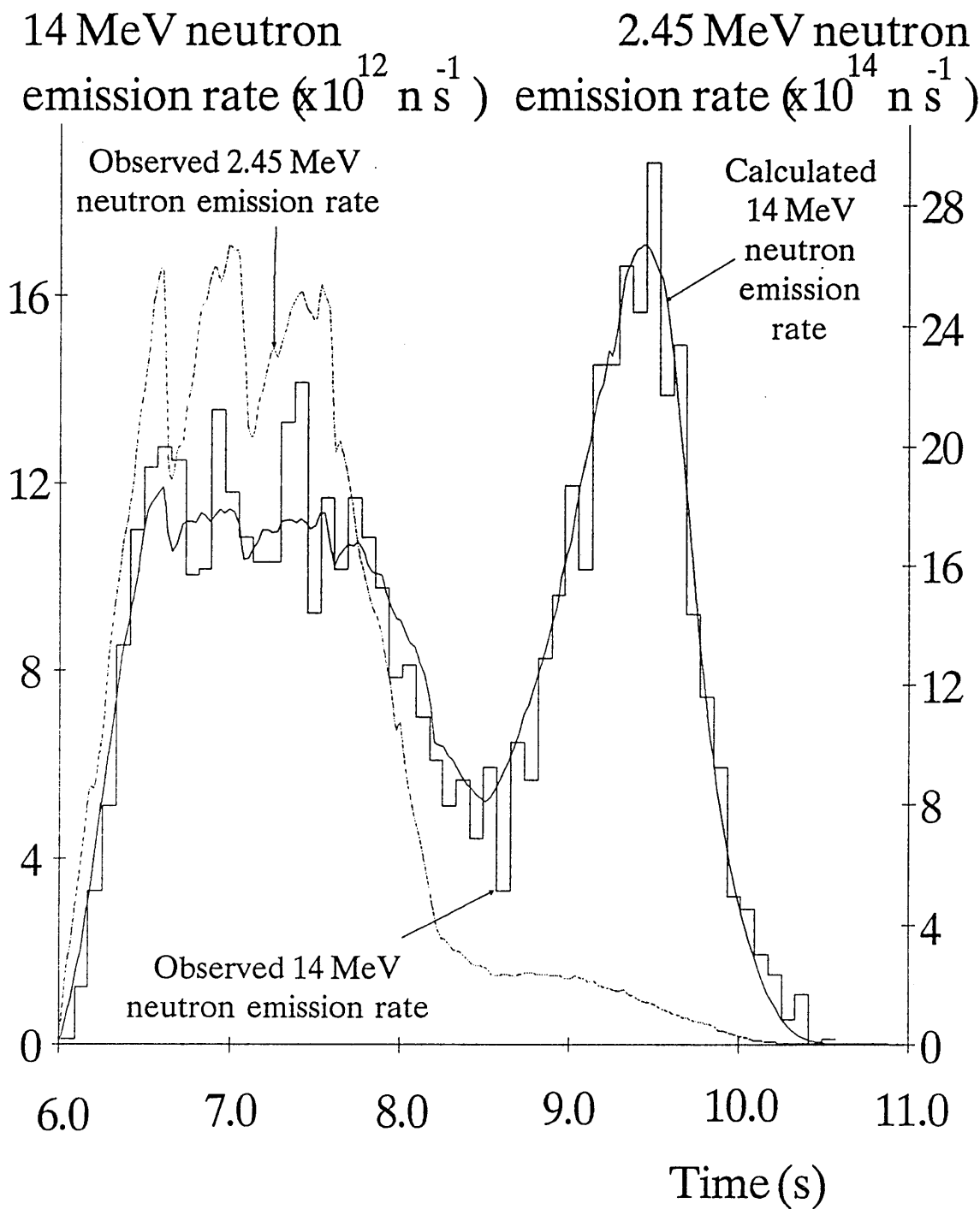


Figure 5.41. TRAP-T run with anomalous losses for low density discharge

this calculation and some typical results from it are shown in fig. 5.42 where the deuterium density was well known (ie, it had low Z_{eff}).

The method used in the program is very simple. It relies upon the observation that for plasmas consisting of isotopes with an atomic mass to atomic number ratio of 2, the slowing down of the tritons is nearly independent of the value of Z_{eff} . This means that the n_D/n_e ratio can be calculated from:

$$\frac{n_D(t)}{n_e(t)} = \frac{S_{14}^{\text{observed}}(t)}{S_{14}^{\text{calculated}}(t)} \quad [5.10]$$

where $S_{14}(t)$ is the time-resolved 14 MeV neutron emission rate. This works well for regions where S_{14} is a near constant value. For time intervals where it varies strongly, such as at the beginning and ending of a neutral beam pulse, the accuracy is poor as the time dependence must be followed extremely accurately in such intervals. The other disadvantage of this technique as an n_D/n_e diagnostic is that it is limited to discharges with a high 14 MeV neutron emission rate, as only they will have sufficient detected events to make the technique viable.

A more detailed comparison of this method with other deuterium density evaluation techniques is found in [5.30]. The general result found there is that the measurement is in good agreement with the other diagnostics and is particularly suited to discharges with $Z_{\text{eff}} > 4$.

5.4 Conclusions

The most important conclusion from this chapter is that the slowing down of tritons in a plasma is classical, even when the plasma is undergoing violent changes. The only evidence for unusually high prompt losses has been found in discharges with very low density and high T_e , an unusual operating regime. Hence the prospect for α particle heating of plasmas appears good, although possible collective effects have not been tested because the population of tritons is ≈ 1000 times too dilute to excite them.

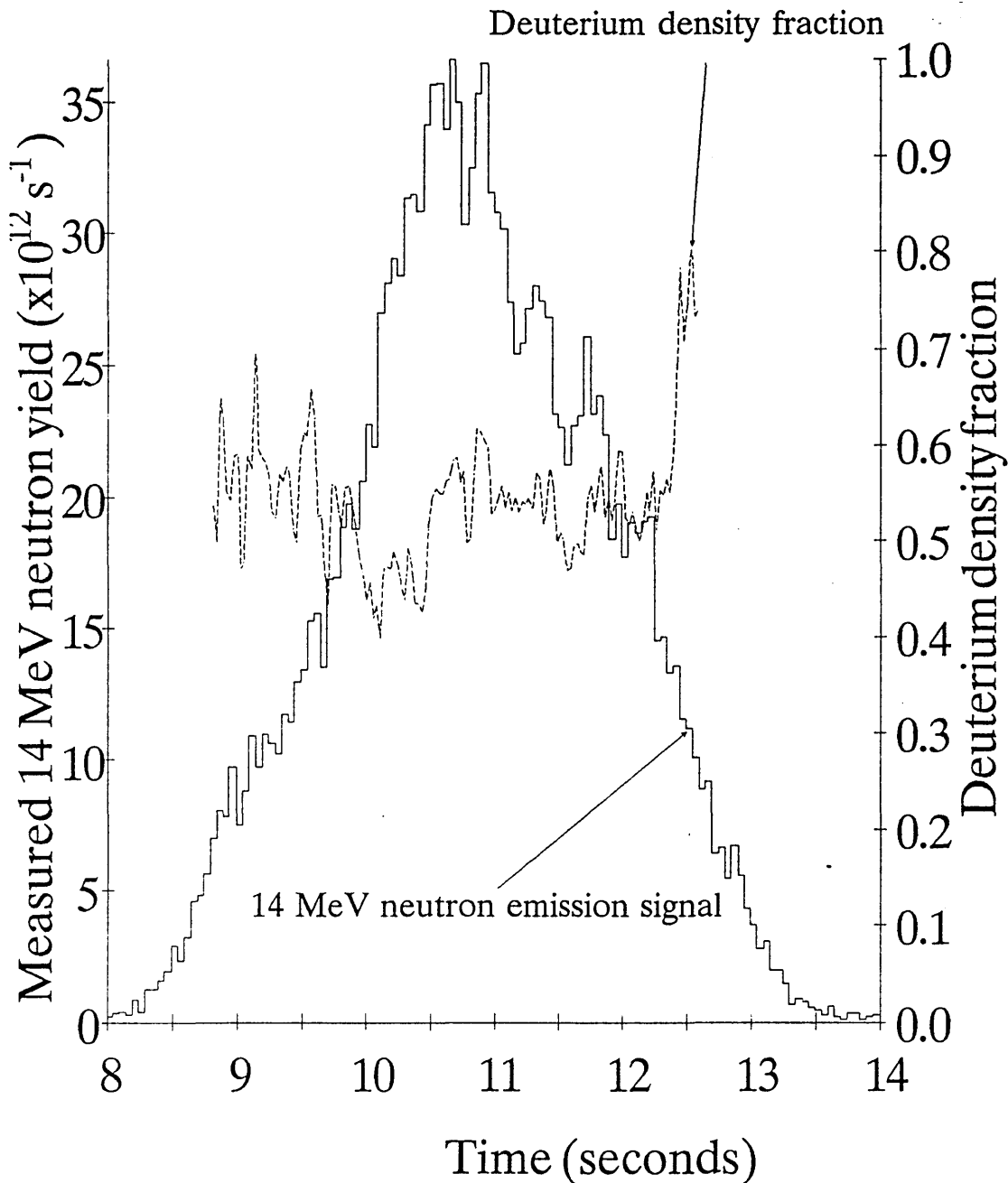


Figure 5.42. Calculated deuterium density traces during NBI heating phase: Using TRAP-T to calculate the deuterium concentration, the above diagram is produced. The agreement with other diagnostic techniques is good, although the method is unreliable for regions where the triton population is altering rapidly.

The code developed to calculate the 14 MeV neutron emission rate works well and has been modified for use in areas other than triton burnup and has passed all tests performed so far. Perhaps the most significant fact deduced from the operation of the code is that for particles in the MeV energy range, the effect of the finite size of the orbits on the triton burnup is minimal.

The code has been modified to produce n_D/n_e ratios which are in good agreement with other diagnostics and forms one of the most accurate techniques for measuring the n_D/n_e ratio for high Z_{eff} plasmas.

For the future, the upgrading of the shielding around the detector and the possible addition of a polythene radiator with a thin foil appear to be useful. The observation of 14 MeV neutron emission rates should be continued so that any discharges exhibiting unexpected triton burnup problems may be recognized. Profiles of 14 MeV neutron emission would be extremely useful, although difficult to obtain during D-D operations.

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6.0 Conclusions and future work

Work for this thesis has primarily involved the analysis of data from three diagnostics and the important results drawn from them are shown below.

For the 14.7 MeV proton spectrometer:

- For low power ICRH discharges, the escaping proton signal can show large spikes coincident with sawtooth crashes. This is interpreted as the expulsion of fast particles from the centre of the plasma into the viewing region of KP2, where they react to produce 14.7 MeV protons which are lost from the plasma.
- The “dips” observed on the KP1 diagnostic were due to very strong proton emission reducing the voltage across the diode, effectively switching off the diode for a short period
- The spectrometer used was too fragile and if further measurements were to be made, it would have to be made more robust.
- The present operational aims for JET of high neutron emission rates and high heating powers are incompatible with the operation of such a diagnostic, as the large background signal overwhelms the protons. Unless there is a change in these aims or a detector insensitive to neutrons and γ rays is used, a replacement for KP2 would not seem prudent.

For the 2.45 MeV neutron profile monitor , KN3:

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- A code, ORION, has been developed to aid in the analysis of data from this diagnostic. ORION has been used both for the analysis of data from KN3 and to obtain general results relating to the operation of KN3.
- A disturbing result is the observation that the ratio of the neutron emission rates from KN3 and KN1 is not constant and varies as a function of neutron emission rate. However, this is thought to be a problem for high neutron emission rate discharges. The source of this variation is not confirmed at the time of writing.
- The effect of the estimated error on the backscatter subtraction on the derived profile has been found to be small, as a 30% error in the subtraction propagates through the analysis to an error on the total emission rate and peaking factor of the order of 3%.
- Neutron spectrometers measure an ion temperature averaged over the whole line-of-sight. In order to find the peak ion temperature, a correction factor must be applied and this has been shown to have a larger value than previously thought. The correction lies between 10 and 40% of the measured ion temperature.
- The effect of the plasma position on the total neutron yield measured with the outboard irradiation ends of KN2 has been shown to be small enough to be negligible.
- Utilising ion temperature data from other diagnostics, estimates of the deuterium dilution factor across the plasma may be obtained.
- Profiles of 2.45 MeV neutron emission have been produced and reported upon.

For the 14 MeV neutron detector:

- A 14 MeV neutron detector has been developed which is capable of making time-resolved measurements of a 14 MeV neutron emission rate some two

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orders of magnitude smaller than the 2.45 MeV neutron emission rate. The diagnostic offers time resolution down to 10 ms with a statistical accuracy of better than 10%.

- A code has been developed to model the time-resolved 14 MeV neutron emission rate from the JET plasma. The code has been tested against more complex guiding centre codes and has shown that the effect of orbits on the slowing down and burnup of tritons is small ($< 10\%$).
- The code is found to be in good agreement with the observed 14 MeV neutron emission rate if the energy loss rate is increased by approximately 20% from its classical value. This discrepancy lies within the errors of the measurement, so the tritons appear to lose energy classically in the JET plasma.
- The confinement of tritons in JET plasmas appears to be extremely good in the majority of discharges studied, but for some unusual cases departures from the classical picture have been observed.
- The 14 MeV neutron emission rate has also been used to deduce the deuterium dilution and results are in good agreement with the technique outlined in chapter 4.

For the future, the following suggestions are made:

- The full orbit code needed for the quantitative analysis of the KP2 data should be made operational and used to fully analyse the escaping 14.7 MeV proton data.
- The 2.45 MeV neutron profile monitor should continue to be investigated to discover the cause of the non-constant KN3 to KN1 ratio.
- 14 MeV neutron emission profiles from the neutron profile monitor would be very useful in determining the diffusive properties of slowing down tritons and should be investigated as soon as possible. The use of these profiles to

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investigate sawteeth and their effects on the triton population would appear to be a very difficult measurement but would be very valuable.

- The ORION program is satisfactory for the present accuracy of KN3 but in future a more accurate profile reconstruction technique will be required. To further this end the addition of an inversion technique to ORION would be most useful. Also further consideration of the effects of orbits on the contours of neutron emissivity should be undertaken, as it seems that these are non-negligible.
- With the corrected KN3 and improved ORION a study of neutron sawteeth could be undertaken.
- The silicon diode detector should be upgraded by adding further shielding and perhaps including a polythene radiator plus foil combination to enhance efficiency.
- The analysis of the period 4 triton burnup data should be completed as this will double the number of shots analysed and also contains discharges of considerable interest.
- The TRAP-T code should be upgraded in order to model discharges with pellet injection. These discharges are more difficult to model because of the highly peaked profiles involved, but offer the chance of extending the triton burnup measurements into a new regime of plasma conditions, ie. cold and dense.
- Alternate routes for the modelling of the 14 MeV neutron emission rate should be considered, as the TRAP-T code is limited in the range of phenomena which can be simulated well. A code which can model the diffusion of the triton population and the effect of pitch angle scattering would be useful, although mainly in the more exotic plasma regimes. For the bulk of discharges encountered in JET operations, the TRAP-T code is sufficient.

Appendix A. Charged particle diagnostics

A.1 Introduction

Charged fusion products (CFPs) include a wide variety of particles, as shown in table A.1, but the behaviour of the 3.5 MeV alpha particles from the D-T reaction is of most interest as the first fusion reactor will probably use them to heat the plasma. Hence the heating and confinement properties of alphas are of considerable use and must be well diagnosed. Numerous proposals have been made as to how this may be achieved and the primary aim of this appendix is to review and assess these proposals.

Diagnosis of 3.5 MeV alpha particles in a burning D-T plasma is difficult because the operating environment is very hostile with high neutron and gamma fluxes. One way of getting round this problem is to make use of the fact that other CFPs have similar properties to 3.5 MeV alpha particles and by studying them in present-day devices useful information about the confinement and slowing down of fast charged particles may be found. This approach gives an insight into the problems associated with very dilute populations of alpha particles and has the advantage of a much less hostile environment. This appendix includes a survey of the techniques which are used in present day machines to study CFPs.

CFPs are produced with much more energy than the background plasma particles (typically 100-1000 times as much) and so execute much larger orbits than thermal ions. A non-negligible fraction of these particles will have orbits which intersect the vessel wall and hence are unconfined. The unconfined particles may be used to investigate the confinement of the CFPs as well as

profiles of ion temperature and current density. The rest of the particles slow down in the plasma, setting up a non-Maxwellian distribution which may be susceptible to instabilities. Fig. A.1 shows the classically expected time evolution of the alpha population in a plasma and deviations from this would indicate the presence of some anomalous energy or particle loss process with the exact deviation giving information on the anomalous process involved.

Techniques used to study the unconfined CFPs are simpler than those to diagnose confined CFPs and are described in section A.2. The techniques to study the confined CFPs are described in section A.3, but few of these methods have been tried experimentally and most need considerable development in order to give reliable information.

A.2 Unconfined charged fusion product diagnostics

A.2.1 Causes of particle losses

For a charged particle in an axisymmetric tokamak there is a range of pitch angles (the loss cone) for which the orbits intersect the vessel wall and all the particles born on these orbits are lost immediately. If a point on the vessel wall is specified (as in fig. A.2) then there is a range of pitch angles at that point for which a particle's orbit, if traced backwards in time, passes through the plasma. Each pitch angle corresponds to an orbit passing through a different region of the plasma. Therefore, if multiple pitch angles can be resolved then orbits passing through different regions of the plasma may be identified. By use of a technique similar to Abel inversion it is then possible to build up an emission profile of the plasma.

Non-uniformities in the toroidal magnetic field (ripples) due to the discrete nature of the toroidal field coils lead to two further loss mechanisms; ripple trapping and ripple diffusion. In ripple trapping the particle is caught in a magnetic well and the vertical drifts, due to the gradient and curvature of the magnetic field, cause it to leave the plasma. In ripple diffusion the ripple causes

small, random radial excursions at the bounce points of banana orbits leading to radial diffusion and an increase in the number of lost particles. On TFTR and JET ripple trapping effects should be negligible but ripple diffusion losses could be greater than the prompt losses due to the loss cone. The exact size of the ripple diffusion losses in tokamaks is disputed at this time [A.01-A.03].

As the confined CFPs slow down they may be pitch angle scattered into a loss region. This should be significant only at low energies because plasma ions are responsible for pitch angle scattering of CFPs. So for CFP energies more than about $20T_i$ very little pitch angle scattering occurs [A.04]. Hively [A.05] estimates that the total pitch angle scattering loss fraction is of size $0.1Z_{\text{eff}} f_1$ (where f_1 is the prompt loss fraction) so the total loss will be fairly small and at low energy. Instabilities may also cause the expulsion of CFPs, which can be detected at the wall as an increase in the escaping particles, often correlating with MHD activity [A.06].

A.2.2 Uses of escaping CFP detectors

The primary use for an an escaping alpha diagnostic would be to monitor the alpha losses and to check that they are not anomalously large. However, if a large number of CFP detectors are available, then more information about the plasma may be obtained. Karulin and Putvinskij [A.05] show how the ion temperature, the ion density and the poloidal magnetic field may be found using an array of these detectors. They also show that for 3.5 MeV alpha particles the information will be limited to the outer regions of the plasma due to the presence of a 'dead zone' at the centre of the plasma from which the alpha particles may not escape. Table A.2 shows the 'dead zone' for a circular plasma which for JET at 5MA gives a value of r/a of approx. 0.6. This restriction to regions of the plasma near the edge casts doubt on the usefulness of studying escaping 3.5 MeV alpha particles at JET. The 14.7 MeV proton is more suitable for this task as it may escape from almost the whole plasma but, in the D-T phase, few of these will be produced relative to the 3.5 MeV alphas and the noise induced by the 14 MeV neutrons is likely to overwhelm the detectors.

The following sections detail existing CFP experiments and the proposals for the future 3.5 MeV alpha particle diagnostics are reviewed.

A.2.3 Time resolved escaping CFP detectors: previous work

Silicon diode based systems

A large number of these detectors have been used [A.06-A.23, A.70, A.71] but most are similar in design to the detector shown in fig. A.3. The CFPs drift out of the plasma and through the collimator onto a silicon surface barrier diode. In some designs there is also a thin foil (approx 1 μm thick) before the diode to stop low energy particles and to shield the diode from light. The diode generates a charge pulse proportional to the energy of the incident CFP, which can be collected and measured. The time resolution ($< 50\text{ns}$) and the CFP energy resolution ($< 1\%$) makes the surface barrier diode the ideal detector for CFPs. Unfortunately the diode is also sensitive to gamma rays and to nuclear reactions with 14 MeV neutrons so will be unusable near a burning D-T plasma. Detectors of this type have been used for 1 MeV tritons, 3 MeV protons, 3.6 MeV alphas and 14.7 MeV protons. Information has been derived on the effect of fishbone instabilities on CFPs [A.06], the effects of lower hybrid heating and ion cyclotron resonance heating on minority species [A.07,A.08], sawtooth instability effects [A.09,A.10], fusion product emission profiles [A.11-A.13], ion diffusivity profiles [A.14], ion temperatures [A.71] and ^3He transport in tokamaks [A.15]. Clearly this is a useful technique and if similar results can be obtained in a D-T plasma it is worth pursuing. On TFTR the anticipated plasma current is 2.5-3MA, giving a dead zone of less than 0.1 (for 3.5 MeV alpha particles), so for them the development of radiation hardened detectors is a worthwhile exercise while at JET the usefulness of the technique seems limited.

Improvements to the basic detector may be made. One method is to use an array of detectors and derive profile data from them as described above [A.11-A.14]. Similar data may be obtained if pitch angle resolution is used but

as yet only simple attempts have been made towards this end [A.13;A.72]. Another method involves using two separate detectors operating to accept only coincident events from associated particles. A great increase in the spatial resolving power may be made as when tracing orbits from the each of the detectors back into the plasma there can only be a small region where they cross. This technique is suitable for the D-³He reaction but only on small tokamaks such as TEXT and even then the count-rates are estimated to be low (15.3 s^{-1}) with a poor signal to noise ratio of 5 to 1. In principle it is also possible to detect a neutron and an escaping CFP in coincidence but this too suffers from a lack of count rate and a high random coincidence rate.

Radiation hardening of existing detectors

For alpha particles produced in a burning D-T plasma new versions of these detectors are being designed [A.24-A.27]. The obvious modification is to replace the silicon surface barrier diode with some other detector which is radiation hardened (figs. A.4,A.5). At present there is only one candidate for this, ZnS based scintillators. This material scintillates when an alpha is incident and has a low sensitivity to neutrons and gamma rays but has poor energy resolution and will not operate at temperatures in excess of 100 centigrade. ZnS also suffers from radiation damage due to the alpha particles after a flux of order 10^{13} alphas cm^{-2} when the scintillation efficiency decreases by a factor of two.

The detector in fig. A.4 , designed by Zweben [A.24], is capable of good pitch angle resolution and a prototype has already been tested at TFTR [A.25]. The first results suggested that the neutron and gamma backgrounds were 100 times higher than anticipated which would rule out the use of ZnS as a useable material because even with the backgrounds as low as anticipated the detector would expect noise problems. However, the high backgrounds appear to have been due to inadequate shielding of the diode from soft X-rays scattering from (and emitted by) the vessel wall and if this can be rectified, the detector is probably capable of measuring the escaping alpha particles on

TFTR. If the high backgrounds are due to neutrons or gammas, then the viability of the detector is open to question.

A.2.4 Time resolved escaping CFP detectors: proposed systems

Radiation hardening of existing detectors

The detector illustrated in fig. A.5, proposed by Miley and Kislev, should provide more pitch angle information than Zweben's and has better radiation shielding as well. However, the distance between the alpha entrance slit and the ZnS screen is approx 10cm while the alpha gyroradius (TFTR, 5T toroidal field) is at best 5.4cm. Few, if any, alphas will get through this collimation. From fig. A.6 it is clear that the designers believe that the alpha gyroradius is larger than the detector so it appears that the designers of the device have either incorrectly evaluated the alpha Larmor radius or have consistently published their design with the wrong scales.

New detection methods are being considered. One suggestion is that the high alpha particle fluxes may make the use of a Faraday cup possible but as yet no detailed analysis of the viability of such a system has been attempted. A technique known as foil neutralisation has been proposed as a candidate for the measurement of escaping alphas by Gerdin et al [A.28-A.33]. This is described below.

Foil neutralisation of escaping alpha particles

Fast unconfined alpha particles pass through a carbon foil, which is of known thickness, as in fig. A.7. The alpha particles lose energy in the foil, the exact amount being dependent upon the thickness of the foil (see fig. A.8), and a fraction of those leaving the foil may be neutralised by a charge exchange process. Neutralised alphas travel straight down a drift tube to a second foil of thickness 0.1 μm where another charge exchange may occur. Any particles which are ionised in the second foil are deflected onto a detector by magnetic

fields. The probability of an alpha particle performing this sequence of actions (neglecting solid angle effects) is shown in fig. A.9 and is typically 1-7% for a foil exit energy of $< 500\text{keV}$.

The principal advantage of this system is that the charged particle detector is removed from the first wall and may be shielded from the neutrons and gammas. Using a 1m thick shield of borated limestone, the signal to noise ratio in a ZnS detector is calculated to be 10 to 1 [A.33]. Count rates are estimated to be from 10^5 to 10^8 Hz so good time resolution may be obtained. Also pitch angle resolution of $< 1^\circ$ is possible (due to the length of the drift tube) The proposed energy resolution system involves the use of multiple copies of the above system with differing first foil thicknesses. Energy resolution of 10%-20% may be obtained in this way.

The main disadvantage of the system is its fragility. Gerdin [A.32] estimates that the heat, radiation, neutron and neutral particle fluxes are too small to damage the foils but that during a soft disruption ($\Delta I/I = 10\%$, $I = 2.5\text{MA}$) on TFTR $0.1\text{ }\mu\text{m}$ of the foil could be lost. For the projected 100 shot D-T phase on TFTR this would probably be satisfactory for $10\text{ }\mu\text{m}$ foils but not for JET where a considerably longer D-T phase is planned. The proposed energy resolution system appears unworkable as the unconfined alpha population in the region 1-3 MeV is expected to be fairly low so the count rates in detectors tuned to that region will be at least a factor of 10 down on the detector tuned to the 3.25-3.75 MeV region. Hence, the signal to noise ratio for lower energy alphas at best would be 1 to 1. Also, the first foil will be 1-5 μm thick for low energy alpha particle detection so will be more seriously affected by disruptions than the $10\text{ }\mu\text{m}$ foils.

Proof-of-principle tests have been carried out at TFTR using a silicon surface barrier diode as the particle detector instead of ZnS. However, due to bad positioning of the diode, the signal was overwhelmed by soft X-ray emission [A.31] and the tests were inconclusive. The detector could, in principle, be used to detect other CFPs in present day tokamaks but there seems to be no good reason to do so as the wall mounted surface barrier diode based systems provide

more data and are easier to implement. In the D-T phase this system would provide less data than those described earlier and so could only be justified if the wall mounted systems were found to give poor results because of the high neutron and gamma fluxes.

Time resolved nuclear track detectors

Nuclear track detectors can be obtained which are sensitive to alpha particles but not gammas or neutrons. By mounting them on a rotatable probe, such as the Fast Transfer System or the Plasma Boundary Probe [A.33], the detectors can be passed behind the collimator with only a small part of the detector seeing the plasma at any one time. If the probe is removed, the detector etched and then analysed under a microscope, the energy (from the length of the tracks), the pitch angle (from the direction of the track) and the time of the alpha emission (from the position on the detector) may be found.

The disadvantage with such a system is that the removal and analysis of the detector is time consuming and a new detector is required for each experiment. However, the quality of the data should be good and the experiment looks straightforward to implement.

A.2.5 Time integrated escaping CFP diagnostics: previous work

Emulsions and nuclear track detectors

The original measurements of unconfined CFPs were made using nuclear emulsions positioned near the plasma to collect 1 MeV Tritons and 3 MeV protons [A.34,A.35]. Similar experiments occur today except now other CFPs are collected as well [A.7,A.36]. The experiment performed by Murphy and Strachan [A.36] shows the potential of such measurements. CFPs pass through a pinhole, then a slit and onto a plastic nuclear track detector (fig. A.10) . On the plastic, pitch angles are resolved parallel to the slit and energy perpendicular to the slit (due to the magnetic field). The plastic was exposed to the plasma for

one shot and then removed and analysed. The emissivity profile derived from it is shown in fig. A.11 and an emissivity profile from an array of time resolved detectors is shown for comparison in fig. A.12. The errors from the former technique are considerably lower and the emission profile shows more detail. As noted earlier, the main problem is the time consuming analysis though the quality of the results probably makes it worthwhile.

Activation measurements

Longer term measurements have been made via activation of the vessel by CFPs. On PLT 14.7 MeV protons activated titanium samples on the wall via the $^{48}\text{Ti}(p,n)^{48}\text{V}$ reaction [A.18]. This reaction has a threshold energy of 4.9 MeV, a half-life of 16 days and emits 0.983 MeV and 1.312 MeV gamma rays which are easily identified in a high purity Germanium detector. Knowing the time-integrated flux at a point, it is then possible to calculate the time-integrated 14.7 MeV proton yield for the whole plasma. Also observed was the activation of stainless steel by 14.7 MeV protons via $^{56}\text{Fe}(p,n)^{56}\text{Co}$, a reaction with a 5.3 MeV threshold. This was observed at various poloidal points and the poloidal profile was found to be consistent with calculations. Reactions could be found for other fusion products so as they could also be monitored this way.

A.2.6 Time integrated escaping CFP detection: proposed systems

Proposed systems have concentrated upon the detection of 3.5 MeV alpha particles and simplicity of design.

Foil stacks

The system proposed by Langley [A.37] involves the use of a stack of thin foils (fig. A.13) upon which the alpha particles are incident, presumably after some collimation. The alphas slow down in the foils and stop with the position of the alpha in the stack of foils being a measure of its initial energy. The foils

Diagnosis of fusion products for reactor relevant plasmas

are then removed from the vessel and heated to release the helium stored in them. The quantity of helium released by each can be used to generate an energy spectrum and the sum gives the incident alpha flux. The method is quite sensitive (10^{10} - 10^{12} atoms cm^{-3}), supplies a crude energy resolution, seems fairly inexpensive and appears likely to work.

JET long term sample system

A system in use on JET involves the use of 96 probes (fig. A.14) fixed to the vessel walls with 12 in each octant [A.33]. These probes have carbon, nickel or inconel surfaces and they absorb the alphas which hit them. The fast alphas will penetrate to a depth of up to 10 μm and will be trapped. Particles near the surface may be lost to thermal desorption processes but the alphas deeper than 200nm should be trapped. After an extended operating period, the probes may be removed and the amount of helium present measured to find the time integrated alpha flux. By using all the detectors, detailed poloidal and toroidal alpha fluxes may be found. This measurement is relatively easy but the information derivable appears limited and the system will be accessible only after the final shutdown.

Liquid activation by escaping alpha particles

A technique proposed by England [A.38] has the fast, unconfined alpha particles pass through a collimator and a 1 μm thick Nickel window into a liquid containing Boron (fig. A.15). Boron undergoes the $^{10}\text{B}(\alpha, n)^{13}\text{N}$ reaction generating ^{13}N which is unstable to positron emission ($T_{1/2} = 10$ minutes). The liquid is forced by a high speed gas stream to a NaI(Tl) well counter where the e^+ annihilation may be observed. The number of counts is proportional to the time integrated fast alpha flux at the detector.

The advantages of this system are its relative simplicity and inherent lack of sensitivity to neutron and gamma induced events. This system could act as a calibration check for the more sophisticated time resolved detectors (if present).

With a suitable choice of liquids other fusion products could also be tested for but no examination of this possibility has been made.

Potential difficulties include the effects of the boundary layer of the fluid, which England estimates to be $10\text{ }\mu\text{m}$ thick for B_5H_9 flowing at 22 ms^{-1} , while the range of alpha particles in B_5H_9 is approximately $17\text{ }\mu\text{m}$ so care must be taken to remove all the fluid in the boundary layer when transporting it to the counting station. Also if the counting station is a considerable distance from the torus (say 50m) then volume of liquid stuck to the walls of the tubing will exceed that in the above detector. Leaks from the system could be hazardous as the suggested chemical spontaneously combusts with air.

A.3 Confined CFP diagnostics

A.3.1 CFP energy loss in a plasma

If a CFP orbit is such that it is confined by the tokamak then (under normal circumstances) it will lose energy to the plasma and slow down. The classical energy loss mechanism is through Coulomb collisions with the ions and electrons which make up the plasma. The transfer of energy from one species to another works best when the ratio of the velocities is close to 1. Hence, at birth the electrons dominate the CFP energy loss rate, as electrons are typically 1 to 5 times faster than the CFP while the CFP is typically 20 to 30 times faster than the ions. Electrons have a low mass relative to the CFP so they do not deflect it appreciably from its trajectory (low pitch angle scattering). When the CFP slows down to near thermal velocities the contribution of the plasma ions to the energy loss increases and, below a critical velocity, v_c , becomes dominant. The ions have a similar mass to the CFP and so pitch angle scattering becomes important at low CFP energies and CFPs may pitch angle scatter from confined orbits into the loss regions of phase space.

The equilibrium distribution function for CFPs in an infinite plasma has been solved [A.39] in the range $v_e > v_{\text{CFP}} > v_i$ for a Coulomb collision energy loss term. The solution has the form :

$$f(v) = \frac{\tau_{se} R(v)}{v^3 + v_c^3}$$

where

$$\tau_{se} = \frac{3m_p \varepsilon_0^2 (\pi k T_e)^{1.5}}{\sqrt{\frac{m_e}{8}} e^4 n_e \ln \Lambda}$$

and

$$v_c = \left(\frac{3R_{cl}}{n_e} \sum \frac{Z_i n_i}{A_i} \right)^{1/3} \left(\frac{2kT_e}{m_p} \right)^{1/2} \left(\frac{\pi m_p}{m_e} \right)^{1/6}$$

and

$$R_{cl} = \frac{\ln \Lambda_i}{\ln \Lambda_e}$$

The symbols used above have the following meanings:

$R(v)$ = the production rate of CFPs with velocity greater than v ,

m_e = electron mass,

m_p = proton mass,

n_e = number density of electrons,

n_i = number density of species i in the plasma,

Z_i = charge of species i in the plasma,

A_i = atomic number of species i in the plasma,

T_e = electron temperature,

ε_0 = permittivity of free space,

$\ln \Lambda_i$ = the Coulomb log for ion-ion collisions,

$\ln \Lambda_e$ = the Coulomb log for ion-electron collisions.

The possibility exists that instabilities may occur which can cause different energy or momentum transfer rates and hence distort the distribution function. If the gradient of the distribution in velocity space is greater than zero at some velocity v then free energy will be available to drive instabilities with phase velocity v . If the distribution is as shown above, then this will not happen as the above distribution has a negative gradient at all velocities. Instabilities may occur while the system approaches equilibrium (fig. A.1) as then the gradient may be positive. For example, Alfvén waves may be excited by alpha particles and considerable theoretical effort has gone in to finding out if this will happen. If it does, the effects need not necessarily be bad. High frequency Alfvén waves are predicted to enhance the energy loss rate of the CFPs, which is useful. However, low frequency Alfvén waves are predicted to enhance the pitch angle scattering of CFPs and this would have serious consequences upon the use of alpha particles to heat plasmas as the efficiency of the heating will decrease and the heat loading on the wall will increase.

To test for the presence of instabilities or anomalous energy loss processes, a good knowledge of the distribution function of the CFP is required so a great deal of effort has gone into devising diagnostic techniques which will do this. This section covers the techniques which have been used in the past and new methods being developed.

A.3.2 Confined CFPs: previous work

This has concentrated upon the burnup of CFPs. While CFPs slow down a large fraction of them may undergo a further reaction as the cross-sections for fusion reactions tend to increase with energy. For example a 1 MeV triton, produced by a D-D reaction, when slowing down in a typical JET plasma has roughly a 1% chance of undergoing a D-T reaction while for a thermal triton the reaction probability is several orders of magnitude lower. By observing the reaction products produced by the burnup of CFPs it is possible to obtain information on the slowing down and confinement of the CFPs themselves [A.41].

1 MeV Triton burnup measurements

Several measurements have been made on the 1 MeV Triton undergoing the $T(d,n)^4\text{He}$ reaction [A.42-A.49]. The D-T fusion reactivity peaks at a triton energy of 180keV so the burnup is weighted towards the end of the slowing down period. This combined with the long slowing down time (approx 1 second) means that this reaction is a fairly sensitive test of both the confinement and slowing down properties of fast charged particles but is insensitive to short timescale changes in the plasma.

Each triton has a 2.45 MeV neutron associated with it from the second branch of the D-D reaction so the number of tritons produced can be found quite accurately. The 14 MeV neutron from the D-T reaction gives the number of tritons burnt up. The original measurements used activation of aluminium foils via $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ to monitor the burnup as the reaction has an energy threshold of 3.25 MeV so is insensitive to 2.45 MeV neutrons. 2.45 MeV neutron production can be monitored by Indium foil activation [A.42], BF_3 chambers [A.44] or fission chambers [A.45]. From these measurements the confinement and deceleration of tritons were found to be consistent, within a factor of 2, with classical predictions. More recent measurements have included time resolution [A.47-A.49] from which a more accurate assessment of the triton slowing down properties may be made. Three experiments have been performed; one uses an NE213 scintillator with discrimination against 2.45 MeV neutrons; another uses fission chambers to detect 14 MeV neutrons after the 2.45 MeV flux has fallen by several orders of magnitude just after NBI heating of a low density plasma [A.42]; and the last uses a threshold reaction in Si(Li) diodes to monitor the 14 MeV neutrons (A.43). These measurements have found no conclusive anomalous slowing down or anomalous loss processes. Considerably more detail on triton burnup may be found in chapter 5 of this thesis.

Burnup of 0.8 MeV Helium3

The ^3He ion produced by one branch of the D-D reaction has also been used in burnup studies. The escape of 3.6 MeV alpha particles and of 14.7 MeV protons from the plasma has been monitored using devices described in section A.2.3. ^3He is not suitable for the study of the long term stability of confined fast particles, as the peak of the burnup is reached within 50 ms, but is useful for studying the effect of rapid instabilities on fast confined particles. The burnup of ^3He has been previously reported to be nonclassical [A.12]. Sawteeth, low toroidal fields, fishbone instabilities and large $m=2$ oscillations have all been shown to affect the burnup. All the effects have been interpreted as a loss of confinement instead of anomalously high deceleration of the CFPs.

A.3.3 Confined CFPs: proposed diagnostics

Nuclear diagnostics

There are several proposals in this field [A.50-A.56] but all use the same principle. The plasma is seeded with a low Z impurity (1-10) and the reaction products of a CFP and the impurity are monitored from outside the vessel. The cross-sections for these reactions tend to increase with increasing alpha energy so these diagnostics are most sensitive to the high energy alpha particles (with one exception). A problem shared by all these systems is that of impurity density and impurity transport. If the seeding impurity is not confined well by the plasma, then a continuous source of the impurity will be required. Beryllium limiters have been proposed to improve Z_{eff} in plasmas and this could supply the impurity for one scheme; otherwise, the impurity must be added by pellet or some other means. Also the impurity density profiles will have to be diagnosed for analysis of the data.

The first proposal [A.50] was to seed the plasma with 1-10% of ^{10}B as this undergoes the $^{10}\text{B}(\alpha, n)^{13}\text{N}$ reaction. The ^{13}N would be absorbed by a probe at the plasma boundary and its decay via positron emission would be observed to

find the quantity of ^{13}N present in the probe at the end of the plasma pulse. The difficulty with this system lies in the relating the quantity of ^{13}N in the probe to that produced in the plasma which will require careful calibration. Also, the information provided is time-integrated and so rather limited in use. In its favour is that the experiment could be performed using existing systems and should be simple to perform.

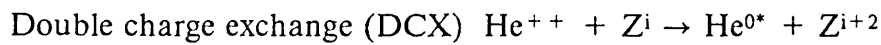
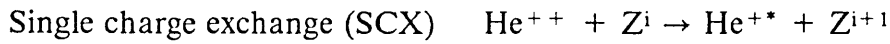
A proposal by Slaughter [A.51] suggests that approximately 1% of ^9Be interacting via the reaction $^9\text{Be}(\alpha, n)^{12}\text{C}$ would give an observable neutron spectrum, from 4-8 MeV, which could be interpreted to give the distribution function of the alpha particles. The neutron flux produced by this reaction would be two to three orders of magnitude lower than the 14 MeV neutron flux. Calculations by Verschuur [A.57] find that for JET the scattered 14 MeV neutron flux at those energies is larger than this, making the accurate observation of the neutron spectrum hard. The experiment appears to be difficult but could be attempted with the neutron spectrometers planned for JET. If the plasma was observed after a period of NBI heating then the 14 MeV neutron background should be reduced. The alphas, however, will still be slowing down and the 4-8 MeV neutrons should be produced against a much lower background. This is known as the delayed counting method of observation [A.46].

Cecil et al [A.52, A.53] propose to use a resonance in the $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$ reaction at an alpha energy of 0.958 MeV which results in the emission of a 4.825 MeV gamma ray. The 14 MeV neutron rate will give the alpha production rate and by observing the gamma rays produced with an energy of 4.825 MeV the number of alphas with energy 0.958 MeV can be found. The main problem for this measurement is the background. Calculations have been performed, taking the expected gamma ray background into account; it was found that a single detector will need 110,000 seconds of counting to make an observation on the 4.825 MeV line with an accuracy of 25% if a 1% ^7Li seeding is used. This time may be reduced by using multiple detectors or higher impurity densities but by using the delayed counting method the counting time is estimated to be 18ms. The model used for the gamma ray background has been tested recently

[A.56] and found to give good agreement with experiment but doesn't take into account any line spectra which may exist near 4.825 MeV and this should be checked. By using the delayed counting method and equipment which is already installed at TFTR and JET, a measurement of the alpha particle density at an alpha energy of 0.958 MeV may be made.

Charge exchange based techniques

Several systems have been proposed [A.58-A.61] which use charge exchange processes in the plasma to observe the alpha distribution. Two charge exchange processes are of interest:



where Z = atomic number of electron donor, i is its charge state and $*$ denotes an excited state.

SCX processes leave the He^+ ion in an excited state which radiates a photon of known frequency. The velocity of the alpha causes a Doppler shift in the frequency of the photon. By observing the intensity and shape of the line, information on the ion distribution may be obtained. DCX results in a neutral helium atom which drifts out of the plasma and may be detected by modified neutral particle analysers. Possible problems for SCX include bremsstrahlung, which may be large enough to conceal the radiated photons, and design of detectors to operate near the plasma. For DCX, the main problem is the reionisation of helium atoms as they escape from the plasma.

In order for charge exchange to be viable, a source of Z^i must be provided. Charge exchange processes work best when the Z^i and the He^{++} have similar velocities, as the interaction cross-section drops off rapidly when the relative velocities increase. Because of this Z^{+i} sources must provide either fast neutrals at low densities or slow neutrals at high densities to give the same signal strength. The two candidates at present are neutral beam injection (NBI) and pellet injection (PI).

NBI systems would have to provide the Z^0 at energies of 600-900keV/amu in order to match the velocity of the alpha particles. This is well beyond the capabilities of present systems. Proposed systems include $^3\text{He}^0$ at energies from 1.7-2.6 MeV [A.58-A.60] and $^7\text{Li}^0$ at 6 MeV [A.58] with beam currents near 10mA. All require considerable developmental work before they could be used and would favour DCX for diagnosis. Analysis of the data seems to be feasible. As an alternative to these beams, the use of heating beams as a source of neutrals is a proven technique and should be very useful in diagnosing the low energy alpha distribution [A.61].

PI based systems use pellets of some low Z material injected at high speed into the plasma to provide a high density source of neutrals to undergo charge exchange processes with the alpha particles [A.31,A.60]. In order for the pellet to reach the centre of the plasma in a tokamak, it must be injected at speeds of 10^4 - 10^5 ms $^{-1}$ which is beyond today's system's abilities. Most low Z materials could be used and detection would primarily be of the SCX process as the cross-sections are larger. The pellet should be well localised in space and background levels should be low. Apart from the development of a pellet launcher, the problem with this system will be in the data analysis as the cloud of material ablated from the pellet will have a significant effect upon the alpha particle distribution because it will be thick enough to slow down the alpha particles. Detailed modelling of the effect of the cloud would have to be undertaken to derive the original alpha distribution from the distribution of alphas inside the cloud and this appears to be a difficult task.

CX based systems could prove very useful in diagnosing the alpha distribution in burning plasmas if the problem of getting sufficient neutrals far enough into the plasma can be overcome. The easiest to interpret should be NBI based systems but these appear to be the hardest to implement. The acceleration of pellets to high speeds also looks difficult but here there is the possibility of embedding impurities within fuel pellets. This should enable the impurity pellet to penetrate much further at the cost of making the analysis of the data more difficult, as well as perturbing the plasma rather severely.

Wave damping by fast alpha particles

Proposed by Wong [A.62], this method involves the damping of Lower Hybrid (LH) waves which have been projected into the plasma from outside the plasma. Calculations show that a 1% population of fast alpha particles should cause extensive damping of the LH waves which could be observed by an FIR laser scattering system. Good spatial and temporal resolution should be possible. The analysis of the data appears to be very difficult and will require much more work before this method is feasible. At the moment, the presence of a large population of fast alpha particles might be detected but more information would be hard to get. A similar proposal using ion Bernstein waves [A.63] also suffers from this problem.

Ion Cyclotron Emission

CFPs in a magnetic field spontaneously emit electromagnetic radiation at the ion cyclotron frequency and its harmonics. This radiation may be observed easily by the use of a simple loop antenna at the vessel wall. The shape and intensity of the received spectrum will depend upon the CFP distribution. Tests by Cottrell et al. [A.64] show that the signal can be related to the production of CFPs but, again, trying to derive the CFP distribution function appears to be a formidable task. This technique is not easily compatible with the use of ion cyclotron resonance heating. It may be used to monitor roughly the size of the CFP population and Zweben has suggested that it may be possible to look for the effect of high frequency instabilities on the CFP population using this technique [A.65].

Thomson scattering techniques

Electromagnetic waves propagating in a plasma may be scattered by fluctuations in the electron density. If the wavelength of the wave is long enough and the scattering angle is small, then the motion of individual electrons contributes little to the scattering with the collective motion of electrons near ions contributing most. The scatter in frequency is proportional to the velocity

of the scattering ion so the fast alpha population will be separable from the rest of the plasma ions as in fig. A.16, where the alpha feature may be clearly seen. Two systems have been proposed, by Hutchinson et al [A.66] and by Woskoboinikow et al [A.67].

The system proposed by Hutchinson uses a pulsed 100MW CO₂ laser at a wavelength of 10.6 μm . The scattering angle used is 0.7° and the scattered radiation is detected by the use of a group of heterodyne detectors set at different frequencies to give frequency resolution across a 22GHz band. The apparatus has been constructed [A.68] and should be tested in the near future. Problems associated with the design centre on the alignment of the system, as better than 0.1 degree accuracy will be required. Also the exact angle at which to view is inversely proportional to the Debye shielding length, hence variations in that distance will force the system out of alignment for some shots.

The other system uses a 100kW gyrotron at 140GHz as the source and almost any viewing angle allowed by the vessel is acceptable because of the longer wavelength. Detection and alignment are not considered problems in this design; choice of the frequency is restricted because it is only just higher than the plasma frequency (hence refraction will be a problem) and lies between the first and second ECE harmonics. The large ECE and black body radiation background levels at JET will apparently force long counting periods upon the detector in order to gain a satisfactory signal to noise ratio. The exact time depends on the plasma conditions but a period of the order of seconds appears necessary [A.73]. Higher power gyrotrons appear to be the best solution to this problem and these are now available so this problem should be soluble.

Both systems have problems and need more work to be done on them before they can be said to be viable.

A.4 Conclusions

The study of CFPs in the past few years has yielded much information, primarily from unconfined CFP diagnostics. In non-ignition devices, this situation is likely to continue but, in ignition devices, the hard radiation backgrounds will make measurements more difficult. This, coupled with high toroidal currents, will mean that these detectors will play a reduced role in ignition experiments. However, these diagnostics should still be useful for observing instabilities which lead to the loss of confinement for CFPs.

The study of confined CFPs is still in its infancy and much work needs to be done in this field in order to produce accurate CFP velocity distribution functions. Measurements which integrate over most of the distribution have been made which show that confined CFPs at low concentrations behave more or less classically. Diagnostics are being developed in order to study the distribution of alphas produced by D-T reactions. The number of high energy alphas produced can be monitored by use of 14 MeV neutron measurements and estimates of the population at high energy should be obtainable using a number of techniques. The nuclear reaction diagnostics could be used in a similar fashion but these would require the addition of impurities to the plasma which is not conducive to high fusion yields. If beryllium limiters are used, then nuclear diagnostics may be possible but the backgrounds to be measured against seem high. The first systems to produce good alpha distribution functions are likely to be the Thomson scattering systems as these appear to be the easiest to construct and interpret. The measurements based on charge exchange with a neutral beam might give information of a similar standard but the extensive beamline development required and the high cost seem prohibitive. For charge exchange measurements using pellet injection, the problems of interpretation seem high but if these can be overcome this could work well. For low energy alphas ($<200\text{keV}$), a combination of neutral particle analysers and charge exchange recombination spectroscopy using heating beams looks likely to give good information.

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61. von Hellermann, Alpha particle diagnostics workshop, JET (1986)
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64. Cottrell et al, EPS Schliersee (1986) vol 10C part II p37
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72. Lovberg, Thesis (1987) Princeton
73. Salmon, Imperial College, Private Communication (1987)

D + D	50%	<u>T (1.01 MeV) + p (3.02 MeV)</u>
	50%	<u>³He (0.82 MeV) + n (2.45 MeV)</u>
D + T		<u>⁴He (3.5 MeV) + n (14.1 MeV)</u>
D + ³ He		<u>⁴He (3.6 MeV) + p (14.7 MeV)</u>
T + T		<u>⁴He + 2n + 11.3 MeV</u>
³ He + T	51%	<u>⁴He + p + n + 12.1 MeV</u>
	43%	<u>⁴He (4.8 MeV) + D (9.5 MeV)</u>
	6%	<u>⁵He (2.4 MeV) + p (11.9 MeV)</u>
p + ⁶ Li		<u>⁴He (1.7 MeV) + ³He (2.3 MeV)</u>
p + ⁷ Li	20%	<u>2 ⁴He + 17.3 MeV</u>
	80%	<u>⁷Be + n - 1.6 MeV</u>
D + ⁶ Li		<u>2 ⁴He + 22.4 MeV</u>
p + ¹¹ B		<u>3 ⁴He + 8.7 MeV</u>
n + ⁶ Li		<u>⁴He (2.1 MeV) + T (2.7 MeV)</u>

Table A.1

Common fusion reactions, from the NRL formulary. CFP's are underlined.

ρ/ρ_0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
$\frac{J \text{ (MA)} Z_i}{\sqrt{1+A^{-1}} \sqrt{\frac{m_i}{m_p}} E_0 \text{ (MeV)}}$	1.55	1.66	1.8	2.0	2.3	2.8	3.7	5.4

ρ_0 = tokamak minor radius
 J = toroidal current
 Z_i = Atomic number of the CFP
 A = the aspect ratio
 m_i = mass of CFP
 m_p = mass of a proton
 E = energy of CFP in MeV

Table A.2 - dead zone radii (ref. A.5)

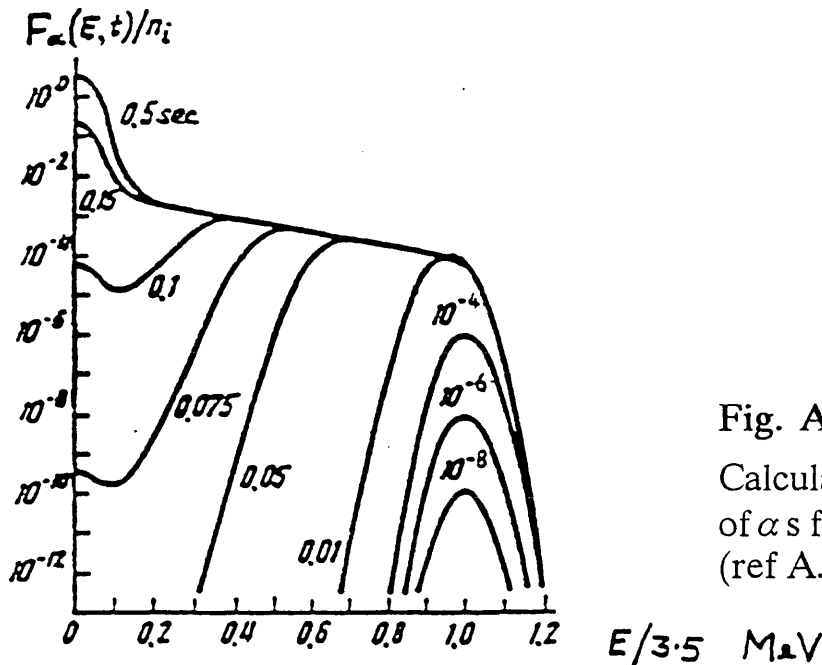


Fig. A.1.
Calculated time evolution of α s from the D-T reaction (ref A.69)

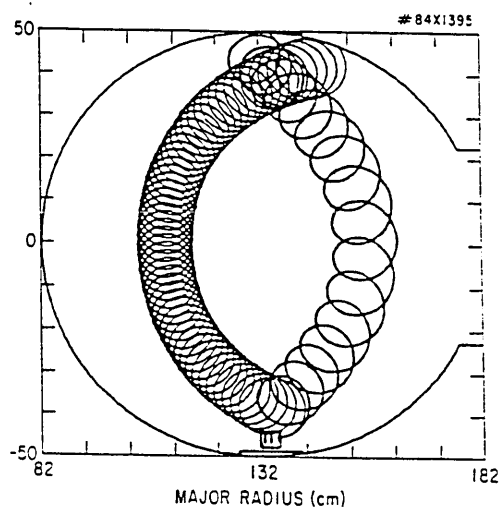


Fig. A.2

Effect of pitch angle on CFP orbits in PLT. The orbits both pass through the same point at the bottom of the vessel, but with different pitch angles. By varying the pitch angle of the observed orbits at a detector, it is possible to obtain different 'lines of sight' through the plasma, hence obtaining profile information (ref. A.36)

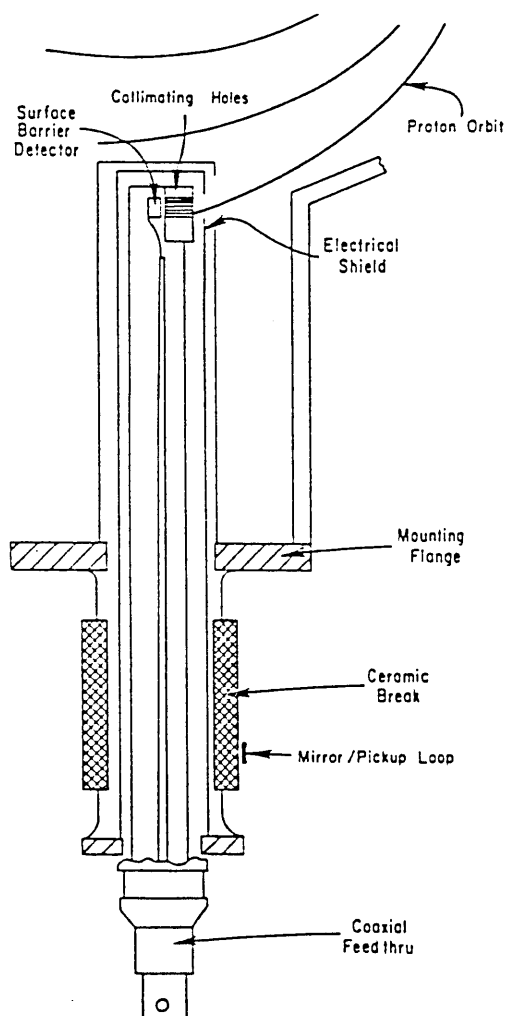


Fig. A.3

Basic design of the time resolved escaping CFP detectors. CFPs from the plasma pass through a collimator to hit a silicon surface barrier diode (ref. A.70)

ESCAPING ALPHA CAMERA

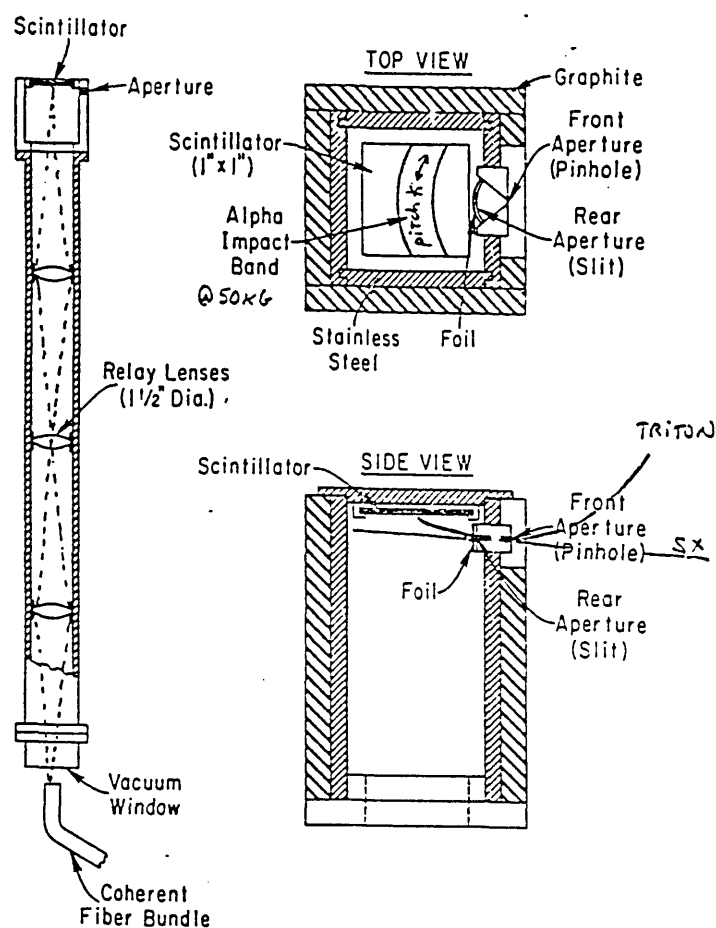


Fig. A.4 Radiation hardened escaping CFP detector (ref. A.25)

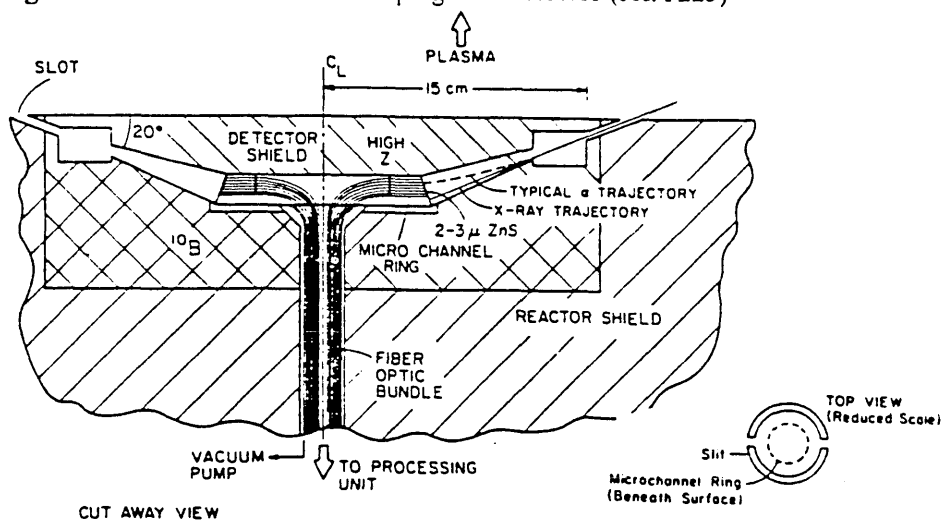


Fig. A.5 Radiation hardened escaping CFP detector (ref. A.26)

Fig. A.6
Radiation hardened escaping CFP detector
with incident alpha particle orbit shown. The
estimated alpha orbit radius is 40 cm (ref. A.27)

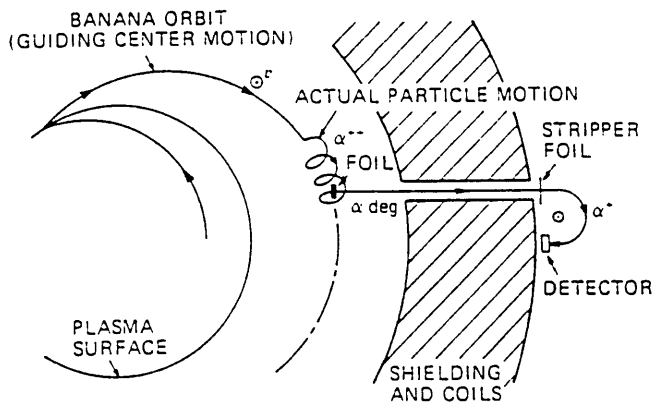
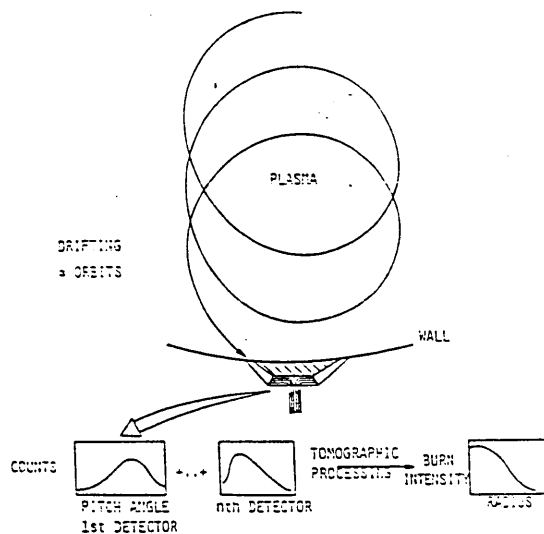


Fig. A.7
Conceptual design of the foil neutralisation
detector proposed by Gerdin et al (ref. A.32)

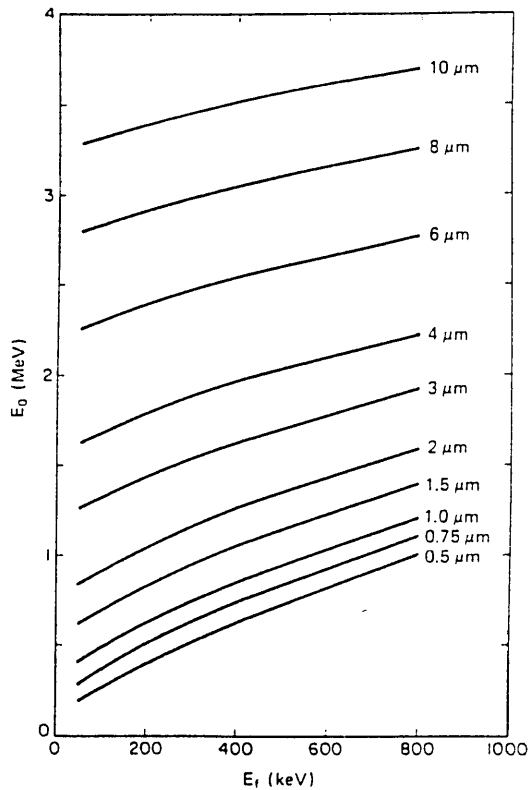


Fig. A.8
Relation of incident alpha energy E_0 to exit
energy E_f for carbon foils of varying
thicknesses (ref. A.32)

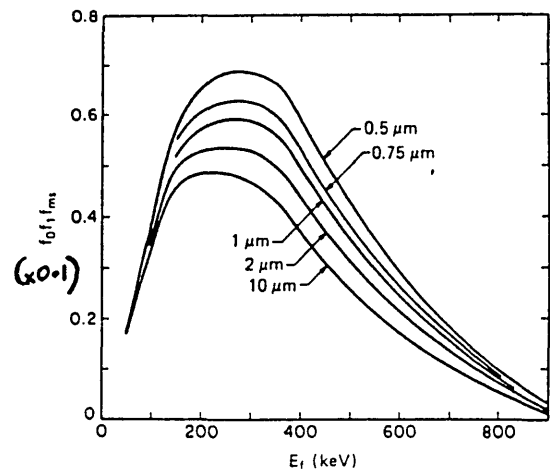


Fig. A.9
Probability of an alpha particle passing through two carbon foils, where the first foil neutralises it and the second ionises the neutralised alpha. Also included is the effect of multiple scattering causing the loss of some particles. The drift tube has length 0.7 m and diameter 1cm (ref. A.32).

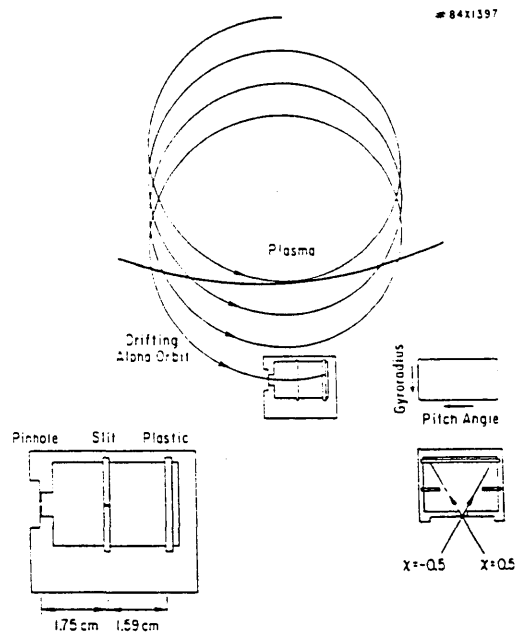


Fig. A.10
Schematic of the nuclear track detector. The effect of the CFP gyroradius and pitch angle are shown (ref. A.36).

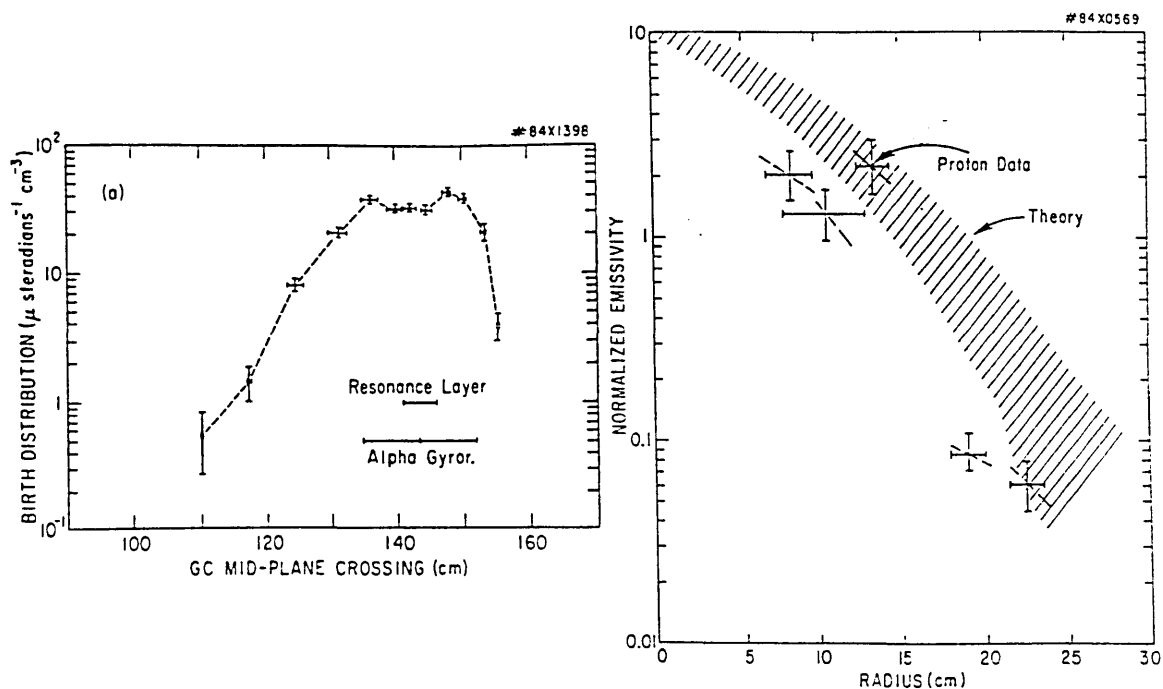


Fig. A.11
Emissivity profile from PLT obtained using a nuclear track detector (ref. A.36).

Fig. A.12
Emissivity profile from PLT obtained using an array of escaping CFP detectors (ref. A.70).

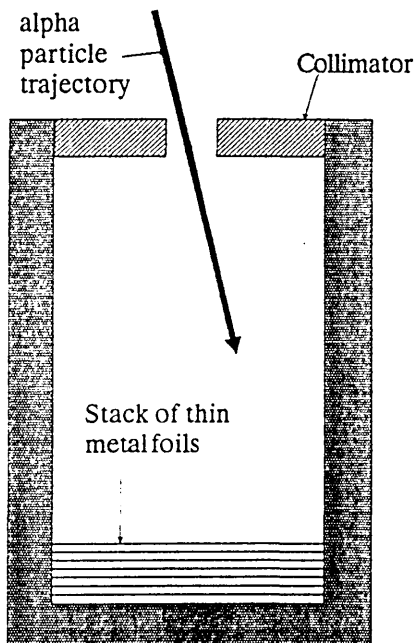


Fig. A.13
Schematic of proposed foil stack long term sample system (ref. A.37).

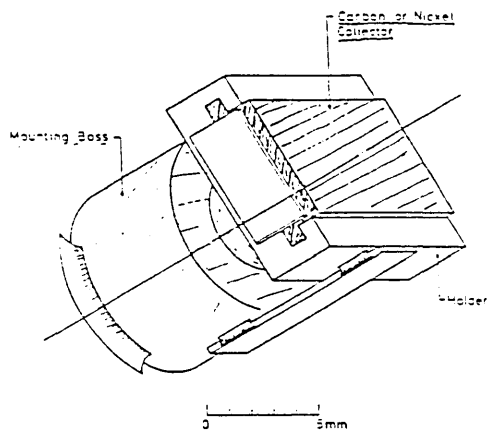


Fig. A.14
Detector used in the long term sample system at JET (ref. A.33).

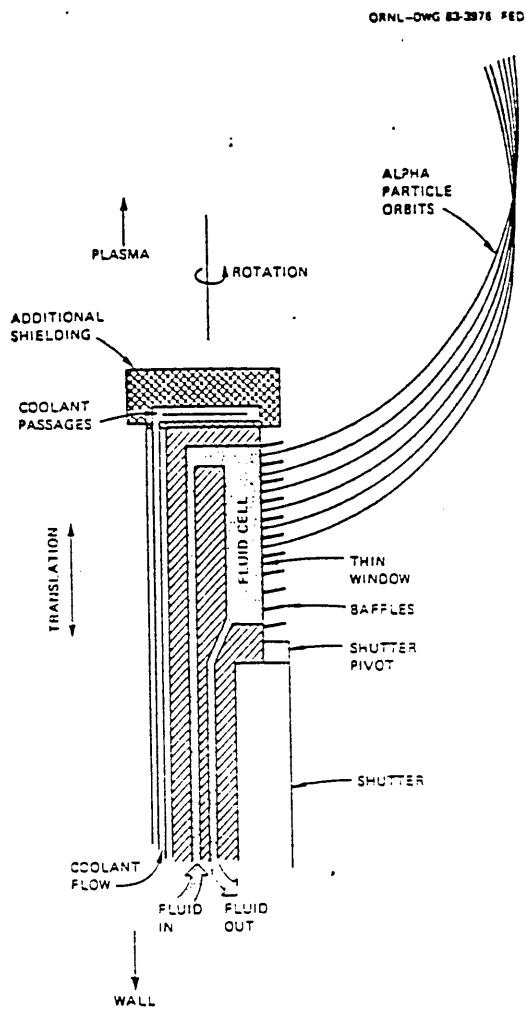


Fig. A.15
Proposed liquid activation system to study the time integrated escaping alpha flux (ref. A.38).

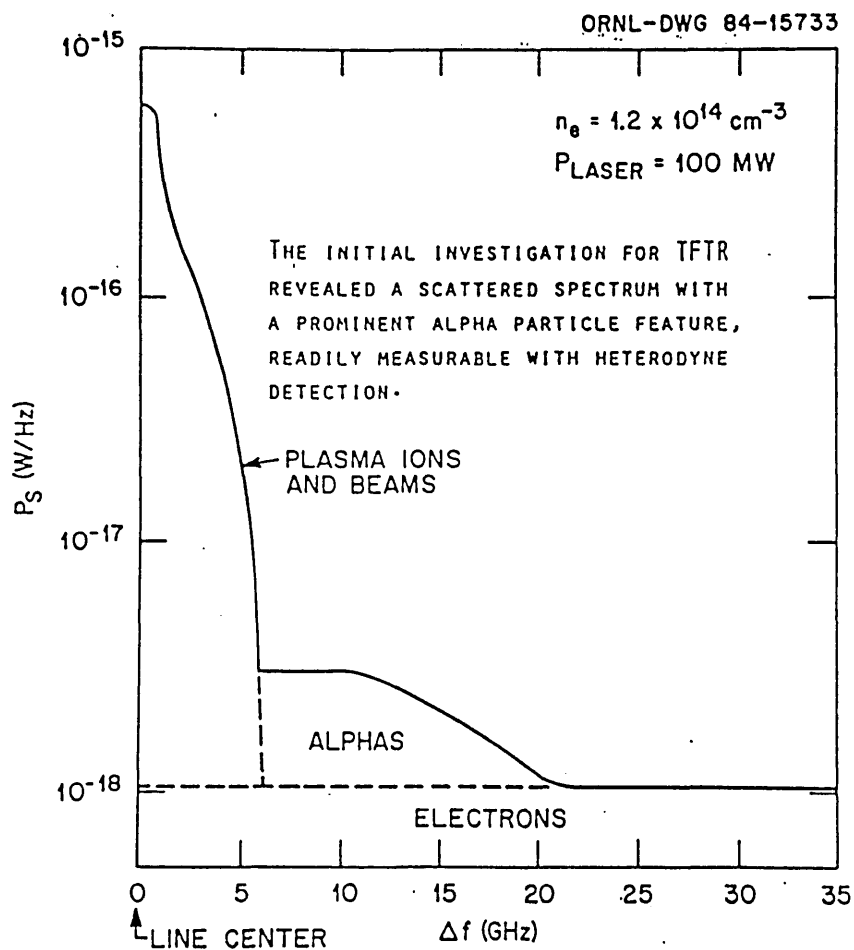


Fig. A.16

Graph showing the expected line broadening for $10.6\mu\text{m}$ light scattered through approximately 1° by a plasma. The contributions from the various species which make up the plasma are labelled (ref. A.68).

Appendix B. ORION user manual

B.1 Introduction

ORION is a computer code written to facilitate analysis of data from KN3. The aim of this guide to ORION is to show the important assumptions and approximations which have gone into this code, as well as to show how to use it.

The program is straightforward to use, but must be called by use of a CLIST. To install the CLIST, copy the file to be found in

JETLPA.CMDPROC.CLIST(ORION)

into your own command CLIST. The only alteration you then need to make is on the second line, changing the name of the DATA file to one which exists on your userid. Then typing ORION in SPF option 6 should start the program.

For those who are curious to see the original FORTRAN (perhaps to look for errors), it may be found in

JETLPA.ORION.FORT(ORION)

This manual comes in two parts. The first covers the description of the plasma and KN3 models used by the code, along with a description of the fitting technique used, whilst the second covers the actual use of the code.

B.2 Neutron source model

The plasma is modelled in 2-dimensions by a set of 40 nested Lao-Hirshmann flux surfaces. These are represented by the parametric formulae

$$R = R_o(x) + ax\cos\chi + R_2(x)\cos(2\chi)$$

$$Z = E(x)(ax\sin\chi - R_2(x)\sin(2\chi))$$

Where

$R_o(x)$ = The R magnetic axis for each flux surface

$E(x)$ = The ellipticity for each flux surface

$R_2(x)$ = The triangularity for each flux surface

a = The minor radius of the outermost flux surface

x = The normalised minor radius ($0 < x < 1$)

χ = a parameter such that $0 < \chi < 2\pi$

The parameters used to construct these surfaces are read from the PPFs, either from the IDENTC or the FAST programs. Of the two, the IDENTC data is to be preferred as the code is considered to give a more accurate picture of the plasma than FAST.

The neutron emission source profile is modelled by a variety of functions of x , ie flux surfaces are assumed to be surfaces of constant neutron emission rate. There are 10 different types of function available, but the ones which seem to give good results are the simple parabolic and the so called Nigel function. The actual functions available are:

Parabolic $S = S_o(1 - x^2)^{F1}$

Parabolic with a step $S = S_o((1 - x^2)^{F1} + F2/100)$

Parabolic with a wedge $S = S_o((1 - x^2)^{F1} + F2 (1 - x)/100)$

Parabolic with a parabola $S = S_o((1 - x^2)^{F1} + F2 (1 - x)^2/100)$

Nigel function $S = S_o(1 + \tanh(F2(1 - x) - 2.3))^{F1}$

Topless parabola $S = S_o(1 - F2^2)^{F1}$ for $x < F2$
 $S = S_o((1 - x^2)^{F1}$ for $x > F2$

Polynomial fit $S = S_o(F1 - F2(x + F3(x - F4(x + F5(x - F6(x + F7(x - F8))))))))$

Flexycurve fit
 $S(x = 0.0) = S_o$
 $S(x = 0.2) = S_o F1$
 $S(x = 0.4) = S_o F2$
 $S(x = 0.6) = S_o F3$
 $S(x = 0.8) = S_o F4$
 $S(x = 1.0) = 0.00000$
 Then a smoothed line is drawn through the points

Two parabolas $S = S_o((1 - x^2)^{F1} + F3 (1 - x^2)^{F2}/100)$

Off-centre parabolic $S = S_o(1 - (x + F2/10)^2)^{F1}$

All references to F1, F2, etc are to the free parameters which are found by the program. The term S_o is a normalisation constant such that the total neutron yield from the modelled source profile is equivalent to that given by KN1, after correction for the geometry of the source profile.

There is one more optional free parameter, the KN3 divisor. If the program is not constrained to give the same neutron emission rate as KN1, then it usually finds a best fit giving a higher neutron emission rate than KN1. The ratio of these two rates is known as the KN3 divisor. This can be used to give dramatic

improvements in the quality of the fit obtained, but the reason for the discrepancy between KN1 and KN3 is not known at this time.

B.3 KN3 model

KN3 is modelled by 19 lines of sight, the directions of which are obtained from the most recent survey. Each line of sight is broken into 9 elements, as shown below in figure B.1:

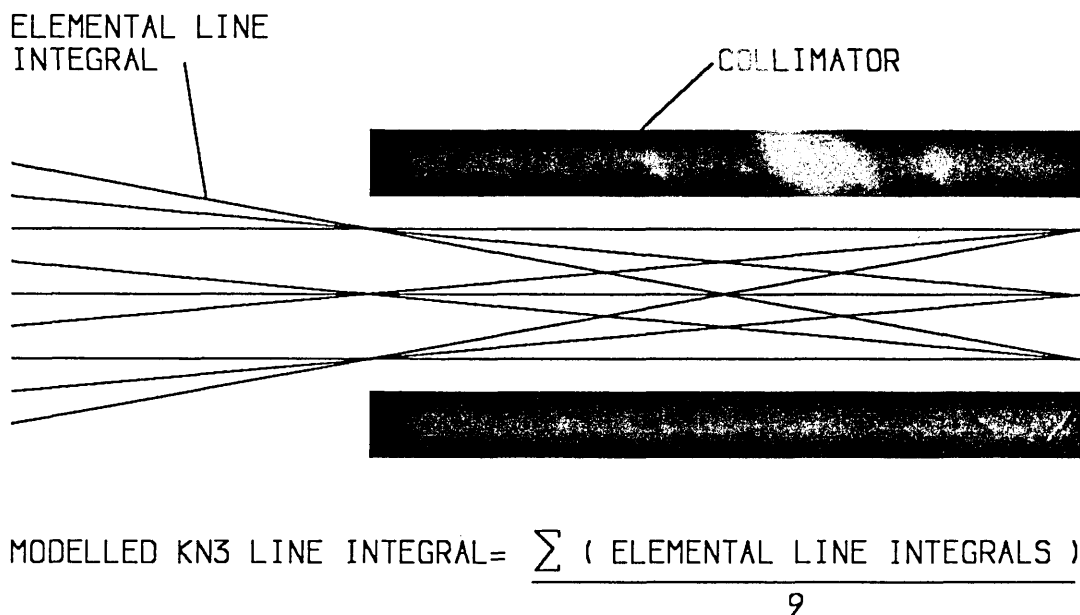


Figure B.1

This was performed in order to allow for variations in the observed neutron brightness across the width of the collimator. Tests of the magnitude of this effect, for reasonable profiles, give a variation of order 5-10%.

The intersection points of these 171 lines with each of the flux surfaces are found and the average distance between the intersection points for each KN3 line of sight and each flux surface is stored, for use in the calculation of the line integrals. The routine that finds these intersections is not terribly fast and is one

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of the bottlenecks in the program, using about 1 s of CPU time. The use of this routine is kept to a minimum in the program and is only calculated when the plasma flux surfaces change or are moved around. One consequence is that it is not very practical to include the R and Z position of the plasma as free parameters in the fitting routine.

B.4 Fitting

This is done using a standard NAG library fitting routine. The routine is used to minimise χ^2 , defined as:

$$\chi^2 = \frac{\sum_{i=1}^{i=19} (O_i - C_i)^2 W_i / (\varepsilon_i O_i)^2}{\sum_{i=1}^{i=19} W_i}$$

Where:

- O_i = The observed brightness of KN3 channel i
- C_i = The calculated brightness of KN3 channel i
- W_i = The weight given to KN3 channel i
- ε_i = The fractional error on KN3 channel i

This basically defines a weighted χ^2 . The observed brightness is obtained from Nigel Watkins' KN3 routines, with a minor modification to the backscatter correction. The weights are set by the program to be all equal to 1, but the user is allowed to change these. There is no justification for changing these weights, other than it really does seem to improve the fit if a set of weights roughly proportional to the KN3 data are used. The fractional error is calculated to be the larger of two numbers, one being the statistical error on the channel and the other being a number set by the user as an estimate of the systematic error on the KN3 calibrations, typically 10%.

B.5 Other calculations

Once the source profile has been calculated, the ion temperature profile may be found, given the deuterium density profile and the plasma-plasma fraction of the neutrons. The deuterium density profile is assumed at present to be proportional to the electron density profile, which is given either by LIDAR or by the FIR interferometer. The deuterium density fraction is calculated from the Z_{EFF} PPF known as HAL EHZ with the assumption of carbon and oxygen impurities in the ratio 3:1 as the only impurities, although the deuterium density fraction is directly alterable by the user. The program then uses the Asher Peres cross-section formulation to calculate the ion temperature at each flux surface. This is displayed as a graph.

The program also calculates other quantities, such as the KN1 geometric correction factor for the calculated source profile which is then labelled as TRUE/KN1.

The total 2.45 MeV emission rate that would be observed if the ion temperature profile was given by the ECE temperature profile normalised to the XCS T_i is found and displayed as XCS RDD.

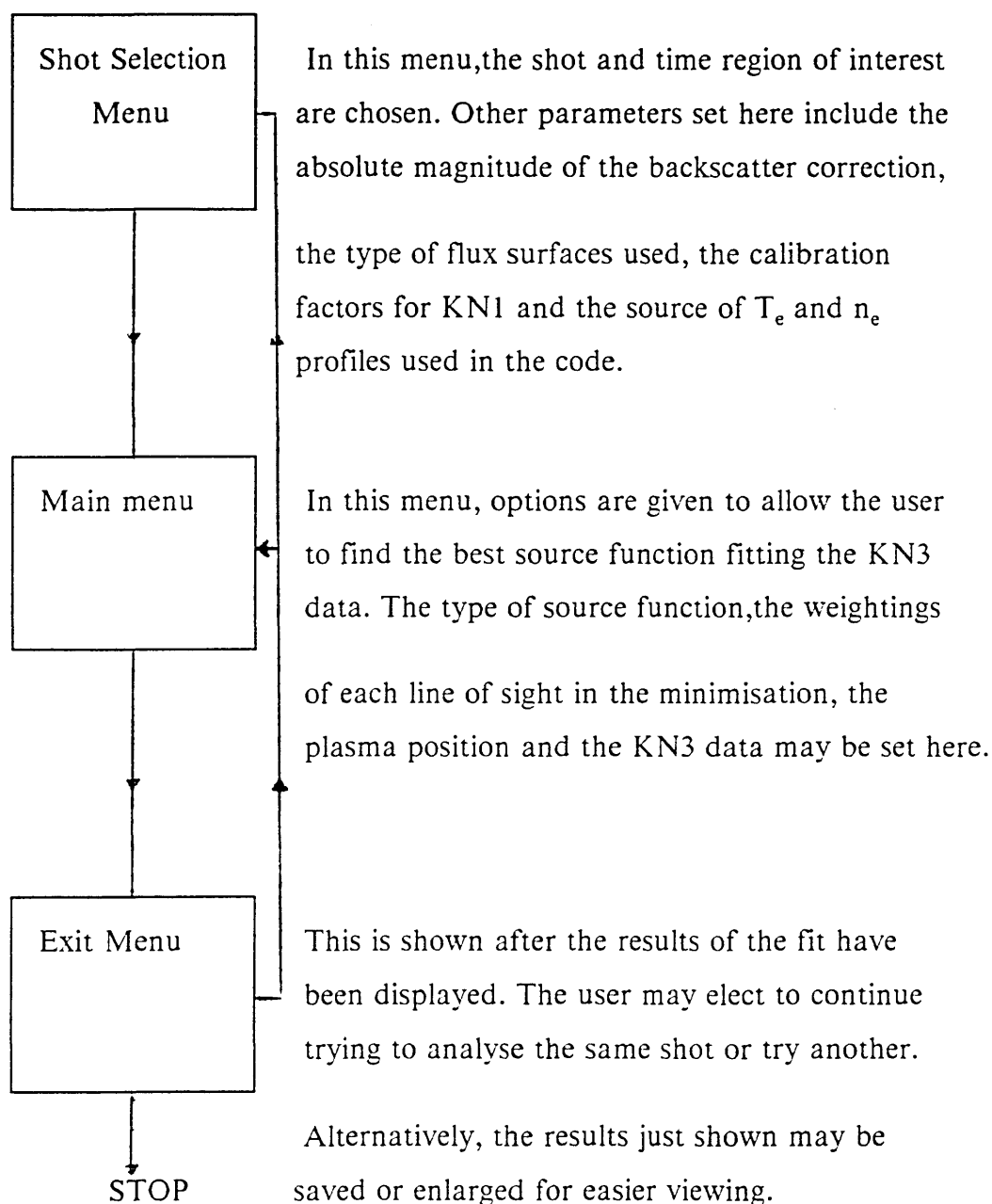
Using the line-of-sight for KM3, the line integrals through the fitted source profile and the source profile associated with the ECE profile normalised to the XCS T_i are found. These are called KM3 FIT and KM3 THER, respectively, and their ratio is called M3 TH/FI. An estimate of the neutron yield in a D-T scenario is also obtained. By assuming that the present deuterium fraction would correspond to a 50:50 mix of deuterium and tritium and that the ion temperature profiles would be the same and that all neutrons are thermally produced, then the 14 MeV neutron emission rate may be found. This is not put out on the interactive part, but may be found in the autosave dataset (if used).

B.6 Using ORION

ORION is a fairly easy code to run. The program is driven through a series of menus, which allow various options to be brought into play. Output is mostly

by graphical display, which will be saved in a gridfile if required. The raw numbers may be written in a dataset if required, the dataset being the one which was specified in the CLIST used to run ORION.

The structure of the menus is illustrated below:



The following subsections deal with these menus in turn.

B.6.1 Shot selection menu.

Figure B.2 shows a screen dump of this menu. Shot number is where the user specifies the shot required. All parameters read by the program from the PPFs (such as the flux surfaces, n_e , T_e , etc.) are averaged between the start and end times specified on this panel. If the exact times required are not known, then the Shot Summary option should be invoked by entering Y on that line. This then displays the neutron rates measured by the fission chambers, the peak electron temperature, the peak electron density and the Z_{EFF} from Vis. Brem. measurements. This information should allow a good choice of the time interval to be made.

Entering Y on the automatic run line causes the panel in figure B.3 to be displayed. On this panel the user has the option of configuring the code to run through a sequence of time slices in one shot automatically. Only one fit will be done per time interval and very little optimisation will be possible. To cause the automatic run to occur, type Y in the first line. The time interval for each slice is decided next. The start and finish times are given by:

$$T_{START} = (\text{Initial Time}) + (N-1) * (\text{Gap between intervals})$$

$$T_{FINISH} = T_{START} + (\text{Integration period})$$

and N is the number of the time interval between 1 and the Number of Intervals. The next two terms refer to any additional shift of the magnetic flux surfaces the user wishes to introduce. The source number parameter defines which of the available source profiles is to be used for the fitting and the numbers correspond to :

1. Quasi-parabolic
2. Quasi-parabolic with a step
3. Quasi-parabolic with a wedge
4. Quasi-parabolic with a parabolic
5. Nigel function

6. Topless parabolic
7. Polynomial fit
8. Flexycurve fit
9. Offset parabolic
10. Two quasi-parabolics

The region type refers to which camera the fit is over and is explained more fully under section B.6.2.5. The weights line sets the weighting to be flat (N) or proportional to the KN3 line integrals and is more fully explained under 6.2.3. The last line makes the total yield from fitted neutron source function a free parameter (Y) or limits it to the value from KN1 (N). The automatic run option should be used with some care as it burns up a lot of CPU time and does not usually result in good quality fits. However, if the user wishes to scan through a shot in a crude way, it is very useful.

The program reads the data from the neutron profile monitor for the shot chosen above, then tries to calculate the statistical error on each channel (including the statistical error on the backscatter correction). To allow for an error in the relative calibration of the KN3 channels, this statistical error is added in quadrature to the quantity entered as the minimum error for KN3 channels on this panel. The χ^2 calculated by the program later on is strongly dependent upon this term.

The backscatter correction multiplier is the number by which the backscatter correction is multiplied. This is potentially needed because the ratio of the neutron yields from KN1 to KN3 appears not to be constant and the backscatter correction is defined as being proportional to KN1. It may be that the appropriate backscatter correction is proportional to KN3 and this term allows it to be set that way.

The autosave option allows (or disallows) the production of a dataset containing most of the numbers calculated within ORION. The output is shown in figure B.4 and is written to the dataset the user specifies in the CLIST used to run ORION. The dataset shows what the optional settings were for the run,

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but also includes various profiles. The first table of numbers shows parameters varying across the minor radius of the plasma . They are :

- Rho : The normalised minor radius of the plasma.
- Int-emiss : The volume integral from the centre to this rho value of the fitted source profile.
- Density : The electron density at each value of rho.
- Te : The electron temperature at each value of rho. This value has been normalised such that the axial temperature is that of the X-ray crystal spectrometer (or the users own value).
- Ti : The ion temperature derived from the neutron source profile.
- Source : The fitted source profile in units of neutrons m⁻³.
- XCS Source : The source profile if the electron temperature profile normalised to the XCS ion temperature is used as the deuterium temperature profile, and the electron density profile (multiplied by n_D/n_e) is used as the deuterium density profile.
- SigmaV(Ti) : the sigmav profile derived from the fitted neutron source profile and the assumed deuterium density profile, from which the ion temperature profile is derived.
- R values : The value of the major radius where the flux surface for this rho value has its maximum value.
- Volume : The volume of the flux surface associated with this rho value.

The other table of values contains information on the lines of sight of KN3. The columns correspond to the following:

- Fit Value : The value of the line integral through the fitted source function for each line of sight. This value takes into account the finite width of the collimator.
- KN3 Raw : The number of neutron events detected in each line of sight.

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- KN3 (-bs) : The KN3 data after correction for detector efficiencies, solid angles, live time, attenuation and collimator scattering.
- KN3 (+bs) : The same as KN3 (-bs), but now the backscatter correction term has been included.
- KN3 (Orig) : The neutron brightness as observed by KN3 per line of sight (neutrons m⁻²).
- KN3(modif) : The KN3 data after the data has been modified, either by the user or by the program. These are the values which the program attempts to reproduce with fitted profile (Fit Value).
- Chi-squ : The value of the weighted χ^2 per point.
- Effic : This is the table of numbers by which the user multiplies the KN3 data. There is no good reason for changing these numbers from their default values of 1.000, other than the data sometimes looks like it requires it in order to give a good fit.
- Weights : The weights used in the minimisation process. By increasing the weight for one channel, the program tries harder to get a good fit to that channel, at the expense of other channels. As with the efficiency table, there is no reason for playing with these, other than that they work.
- Errors : This column shows the calculated statistical error on each channel.

There are a few more calculated numbers, but they are all obvious enough, except for the KM3 related parameters. As an extension to the program, line integrals along the KM3 line-of-sight are found and a few quantities calculated. The intention was that these parameters could be used to correct the b-p estimates from KM3 for the fact that KM3 does not see the entirety of the plasma.

Returning to the shot selection panel, the next item is the magnetic flux surface type selection. The recommended flux surfaces are those provided by IDENTC, but sometimes these are not available and the surfaces generated by the FAST code must be used. If the FAST flux surfaces are used, then the type of ellipticity used for them must be set. Entering a value of A means that the ellipticity at the edge will be used all the way in to the centre of the plasma. Option B means that the ellipticity will change from the edge value until the axial value is 1.2 (this is the recommended value for the for plasmas with $E(a) > 1.3$). Option C forces the ellipticity to a value of 1.0 on axis and is recommended for near circular plasmas ($E(a) < 1.3$).

The next two rows on the panel set the width of the KM3 line of sight. The default values correspond to the settings throughout 1988. When the program calculates the KM3 line of sight, it uses 27 rays through the plasma in order to account for spatial variation across the width of the KM3 line sight.

The final two rows of the panel lead to further panels. The first allows the user to change the calibrations used for KN1 inside the program and is shown in figure B.5. The second row leads onto a panel (figure B.6) where the electron temperature and density profiles to be read by the program may be specified. As a general guide to choosing which type of density profile, the bigger the number available, the better the profile. The exception to this is the LIDAR case, which can give some very strange results. If the LIDAR form of temperature and/or density is chosen, then yet another panel is revealed, figure B.7.

As the LIDAR is available (at the time of writing) as a 0.5-1 Hz diagnostic, this program will not average over the data, as this seems particularly meaningless. An actual time slice must be selected by the user through this LIDAR selection panel. It is generally recommended that the user select a time slice which lies inside the time zone that they are looking at, but this is not forced by the program.

B.6.2 The Main Menu

The main menu is that part of the program where the user selects the source profile in order to find the best fit to the KN3 data. The plasma can be pushed around, the source profiles changed, the KN3 data modified, the KN3 cameras moved and the fitting procedure altered. The menu is shown in figure B.8 and consists of a list of options and one data entry position. Entering the number of the required option leads to yet another panel.

B.6.2.1 *Altering the plasma position*

The panel is shown in figure B.9. Its purpose is to allow rigid shifts of the magnetic flux surfaces in the poloidal plane. The codes which produce the formulations do not claim an accuracy of greater 5-7cm for their positioning of the magnetic axis, so it seems plausible that some kind of shift be allowed by the program. The simplest shift is the rigid one in the poloidal plane, but the disadvantage is that you lose the accuracy of the flux surfaces near the edge of the plasma. In most cases this will be unimportant as the 2.45 MeV neutron source profile is effectively zero in the outermost regions of the plasma, but this is a limitation which should be considered when applying the program to shots with very flat profiles (eg. H-modes and high current ohmic discharges).

The panel requires the shift of the flux surfaces from the midplane (the vertical shift) and the shift of the flux surfaces from the magnetic axis given by FAST or IDENTC (the horizontal shift). It should be noted that the original value of the vertical shift parameter is set to the value derived from the FAST or IDENTC codes. At the foot of the panel, guesses for both shifts are displayed which are derived from the position of the centroids of the KN3 lines of sight from each camera.

The last feature on this page is the entry to the fast spatial scan option. Typing Y on that line leads to the panel displayed in figure B.10. The purpose of this panel was to speed up the search for the best shift of the magnetic flux surfaces, being defined as the shift resulting in the lowest value of χ^2 . To use

the panel, merely enter the values of the R and Z shifts to be tested. The recommended way is to vary first the R values, say from 0 to +100mm in steps of 20mm. Pressing PF3 returns the user to the main menu. If the option 9 (Perform the fitting routine) is chosen, then instead of the usual graphical output, figure B.11 will be displayed. This shows the selected R and Z values which were tested, along with the values of χ^2 calculated for each. Going back to the fast scan panel the user should then set the R values to the R value where the minima in χ^2 appears to be and then vary the Z values, say from -40mm to +60mm, again in steps of 20mm. This should allow an accurate determination of the best centre of the neutron emission centroid. There is one warning about the use of this facility. It uses a lot of computer time to find a good centroid position and if the autosave option is on, then the user will probably generate a large quantity of output which is not very interesting.

B.6.2.2 Altering the camera position (options 2 + 3)

These two options are very similar and basically allow the user to push the horizontal and vertical cameras around in the poloidal plane so as they point in any direction, from any position. They were originally installed before good surveys of the KN3 cameras were available and now have a rather limited use. The panel is illustrated in figure B.12 and is self explanatory.

B.6.2.3 Changing the minimisation weights.

Equal weights should be used on each line-of-sight. However, if a set of weights is used that is peaked in the same way as the data, not only does the human eye see the fits as being better, but the best χ^2 is reduced as well (in general). Option 4 allows the weights to be adjusted. The panel is illustrated in figure B.13. Each channel may have its weight set individually or, by use of the 5 data entry points on the right, some broader approximations may be made. HOR and VER simply set the entire horizontal or vertical array to the value entered at that point. If YES is entered at the AMP point, then the weights are made equal to the actual value of the KN3 lines of sight, then all divided by the largest value. This is the one which is used most commonly. The

DEF data entry point allows the user to set the default weightings to be proportional to KN3, as opposed to the normal default of all even. The last data entry point on the right causes the weights to be set to a preset group. This was defined to be a set of weights representing a moderately peaked plasma. Using these would be more systematic than using the values from AMP, but does not really allow for the wide range of profiles seen by KN3.

B.6.2.4 Changing the source profile or the deuterium dilution

This menu (fig B.14) is the most important of all those accessible from the main menu. It allows the user to vary the source profile and certain other important parameters. The mathematical forms of the different source profiles have been described earlier in section B.2.0. Options 1-5 and 6.1-6.5 allow the user to choose between them. The default source profile shape is the simple parabolic (option 1). Choosing the best function for a given KN3 profile is largely a matter of trial and error, augmented by experience. The profiles 1 and 5 tend to give good results, accounting for peaked and flat source profiles. The flexycurve (option 6.3) sometimes gives good results as well, but the minimisation often fails when using it.

The other trick which allows for good fits to the KN3 data to be obtained is making the absolute value of the KN3 data a free parameter. This allows ORION to take account of the overall systematic error in the estimation of efficiencies for the 19 lines-of-sight. It is enabled by selecting option 9 on the list. When the option is in use, selecting 9 again will cause the option to be disabled. Using this option, it is generally observed that the more peaked the profile, the larger the number that KN3 must be divided by in order that the derived source function have the neutron emission rate derived from KN1 (including the effect of the geometry factor). This is observed in the case of beam and RF and pellet shots. Unfortunately, for ohmic shots, the dependency seems to go the other way, with flatter plasmas causing a higher KN3 divisor (the name given to the free parameter).

The other two options selectable from the menu refer to the starting values adopted for the free parameters to be optimised. The program has one default set for each type of source function, but it is possible that by choosing a different set, an improved fit may be made, as the fitting routine supposedly works better if a really good initial guess is made for the shape of the profile. Option 7 allows the user to set up a table of values from which to start the minimisation process (fig. B.22) and option 8 makes the program actually use these values.

The other information on this panel refers to values stored by the program and used when performing calculations after the optimum source function has been found. The value of N_d/N_e refers to the deuterium dilution factor used across the plasma. This is originally derived from the visible bremsstrahlung measurements, but may be modified here if the user finds it necessary. The value of $T_i(0)$ refers to the value of the X-ray crystal spectrometer derived ion temperature, which is assumed to correspond to the ion temperature on axis. In some cases the value from the XCS is wrong, or perhaps the ion temperature derived from another diagnostic is required, in which case the value may be entered manually at this point. This value is used to normalise the electron temperature profile. The final value which can be set on this panel is the P-P fraction, referring to the fraction of neutrons which originate from thermal deuterium reactions. The default value is 1.00, but if beams are used then this must be reduced, the exact value coming from PENCIL or from the neutron spectrometers. This term has been inserted in order to make calculations of the n_D/n_e ratio easier during NBH shots.

B.6.2.5 Specifying a fitting region

This panel is included to allow the user to generate fitted profiles from the horizontal camera, the vertical camera or from both cameras simultaneously (the default setting). The panel is illustrated in figure B.15 and the number of the required fitting region is entered on the data entry line.

In principle, fitting separately to the vertical camera and to the horizontal camera should result in the same profile being generated. Unfortunately, this

is rarely the case. There seems to be a discrepancy of 10-20% in the absolute yields of the vertical and the horizontal cameras and quite often the shapes seem to be almost unrelated, but some of this could be due to banana orbits.

B.6.2.6 Defining the fitting parameters.

If the user wishes to set up a source model and see what the results from KN3 should be, this is the option to use. It allows the user to specify all the free parameters of the source function which is in use at the moment and then by selecting option 9 on the main menu, the results will be displayed. This is mostly useful for testing purposes.

B.6.2.7 Changing the KN3 efficiencies

This option, illustrated in figure B.16, allows the user to enter a number to multiply the KN3 data by, on a channel by channel basis. As with the weighting tables, the option of setting the entire vertical and entire horizontal array is offered.

B.6.2.8 Performing the fitting routine

When this option is selected, the minimisation routines are called to find the best fit, given all the settings and options the user has selected. The output is displayed graphically, as in figure B.17. There is a lot of information on this display, including most of the options used in the fit. The various parts of the figure correspond to the following:

1. A picture of the flux contours used in the program, inside a boundary defined by the vacuum vessel. The numbers show the shift of the cameras, if any. Also shown are the lines of sight of the KN3 cameras. This is not a very useful picture and if speed is important the user is recommended to suppress it.
2. A graph showing the weights assigned to each of the KN3 lines of sight. As with many of the graphs, the first 10 lines-of-sight correspond to the

horizontal camera and the next 9 lines-of-sight to the vertical. The actual channel referred to by a number may be seen in graph 1, as the n^{th} KN3 channel corresponds to the n^{th} channel encountered crossing the axes, in an anti-clockwise direction from the top of the Z axis.

3. The errors graph shows the calculated error for each KN3 channel.
4. The χ^2 per channel is shown here. Useful for showing where the fit is poorest and thereby aiding the selection of a more appropriate source function.
5. The KN3 multiplier graph shows how much the KN3 data has been modified by the using option 8 from the Main menu.
6. The total fit graph shows how the fitted source function appears using KN3 to view it.
7. The total KN3 graph shows the data from KN3, after it has been modified by the user, in histogram form. The vertical line in the middle of each horizontal bar of the histogram indicates the difference between the KN3 data and the fitted source profile.
8. The source graph shows the fitted 2.45 MeV neutron source function as a histogram of 40 vertical bars. Also shown is the source function derived from assuming that the ion temperature profile is the same as the ECE profile, if normalised to the XCS ion temperature, and the deuterium density profile is the same as the electron density profile multiplied by one global deuterium dilution factor. This second graph is shown as a solid line.
9. The last graph shows the derived ion temperature from the fitted source function, again as a set of vertical bars. Also shown is the ECE temperature profile, after normalisation to the XCS ion temperature. These are both displayed using the left hand axis. The third graph, consisting of a line formed by crosses, shows the electron density profile employed and uses the right hand axis.

The last remaining part of the graphical display is the written section. This section displays a lot of information, so each line will be explained here. The written section has been blown up in size in figure B.18 and the numbering of the lines there is used in the following list.

1. The program title and the author's initials.
2. The shot which the user was examining is listed here.
3. The start of the time region the user was examining is listed here.
4. The end of the time region the user was examining is listed here.
5. These three lines are used to describe the free parameters used to fit the data. The first line corresponds to the free parameter F1, the second to F2 and the third to F3. If more free parameters are used then nothing is displayed. As a legacy from the past, the label "alpha index" is often used for F1 and "Step value" for F2. The error quoted on these numbers is usually not very helpful.
6. This line (if present) shows the number by which the KN3 values have been divided. It is a free parameter. Effectively, this is the ratio of the neutron emission rates of KN3 to KN1
7. Z position is defined as the distance above the horizontal midplane of the magnetic flux surfaces.
8. R position is defined as the major radius of the magnetic flux surfaces.
9. KN1 rate is defined as the averaged neutron emission rate as measured by KN1 between the start and finish time. It does not include the correction for the geometry of the neutron source.
10. True/KN1 is defined as the geometrical correction factor which must be applied to the measured KN1 yield to give the true 2.45 MeV neutron yield.

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11. KN3 maxima is defined as the value from the KN3 channel which has the highest neutron brightness. (This is of limited value and may be replaced soon.)
12. Fit maxima is defined as the highest value from the KN3 model of the fitted source profile.
13. Ne(0) shows the value of the electron density on axis.
14. Ne(a) shows the value of the electron density at the plasma edge.
15. Density type shows the name of the source of the electron density profile.
16. Temperature type shows the name of the source of the electron temperature profile.
17. Source fun shows the name of the source function used in the fit
18. This line shows whether IDENTC flux surfaces or FAST flux surfaces have been used to model the plasma shape.
19. This line shows the deuterium dilution factor employed by the program.
20. Volume shows the volume confined within the outermost magnetic flux surface.
21. Chi square shows the calculated value of χ^2 per point for this run.
22. IFAILS shows the error codes from the minimisation and error analysis subroutines, respectively. The first number can range from 0 to 8 and these correspond to :
 - 0: Good fit.
 - 1: Terminal error in input.
 - 2: Could not minimise in time limit, but may if continued.
 - 3: Lowest value of χ^2 found, but it is not a true minimum.

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- 4: Error in some associated subroutine.
- 5: Minimum found, but not a good minimum.
- 6: Minimum found, but a poor one.
- 7: Minimum found, but a very poor one.
- 8: Minimum found, but probably unacceptable.

and the result codes from the error subroutine stand for:

- 0: No errors found.
- 1: Terminal error in input.
- 2: All errors zero. Routine failed.
- 3 or more : Linear dependencies found in parameters.

- 23. HKN3/KNITRUE is the sum of the line integrals from the horizontal camera divided by the true 2.45 MeV neutron rate
- 24. VKN3/KNITRUE is the sum of the line integrals from the vertical camera divided by the true 2.45 MeV neutron rate
- 25. SC d/e,T(0) shows the deuterium dilution fraction consistent with the peak ion temperature given by the X-ray crystal spectrometer diagnostic. The value of 3.155 listed here indicates that the neutron emission rate is higher than accountable for with Maxwellian plasmas. This is reasonable as the discharge under study has a large beam-plasma fraction.
- 26. XCS Ti is the ion temperature used to normalise the electron temperature profile. Originally it comes from the XCS diagnostic, but may be set by the user.
- 27. XCS YDD is the 2.45 MeV neutron emission rate obtained if the ion temperature profile is given by the electron temperature profile normalised to the XCS Ti value and the deuterium density profile is given by multiplying the electron density profile by a global deuterium dilution factor.

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28. XYDD/KN1 is the value shown above (XCS YDD) divided by the true 2.45 MeV neutron emission rate.
29. KM3 TEMP is the ion temperature which would be measured by KM3 if the ion temperature and neutron emissivity profiles are as deduced from the KN3 data. Essentially, this shows the KM3 correction.
30. The date and time of the run.

B.6.2.9 Setting the graphics switches

Selecting this option leads to figure B.19. The purpose of this panel is to save the user some time when using ORION by toggling the production of the graphs plotted. In order to allow a graph to be plotted, enter Y next to its name and to disallow it enter N.

B.6.3 The exit menu

After the display of the fitting routine results, the program moves onto the exit menu (figure B.20). If the user wishes to perform further work with the present shot and time slice, then select option 1. If a different shot, or a different time slice in the same shot is required, then option 2 should be selected. Option 3 merely saves the last displayed picture to a gridfile, the name of which is specified on the title page of ORION. Option 4 leads onto another panel (figure B.21) which allows the expansion of graphs on the previous display. Option 0 causes the program to terminate.

B.7 Hints on use.

This is a program with many options and when using it in a serious way, certain simplifications are found to make life easier.

- If you are interested in ion temperatures, or deuterium densities or the like, use the Abel inverted density profiles if at all possible.

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- Use the AMP form on the weighting table. If you really don't like the edge channels, remove them by weighting with zeros.
- The source profiles of most use are:
 1. The simple parabolic(ohmics, some pellets, some beams).
 2. The parabolic with a wedge (pellets or high power RF).
 3. The Nigel function(H-modes, some pellets, perhaps for sawtooth studies).
 4. The flexycurve (no particular strengths, it sometimes works)
- Make the absolute magnitude of KN3 a free parameter.
- Add 10% to the horizontal camera and remove 10% from the vertical. This makes the fit easier, but you may have problems with giving a good explanation of what causes the discrepancy.
- Move the plasma around using the fast spatial scan option. It is astonishing what shifting the plasma centre by 20 mm can do to the value of χ^2 .
- Don't try too hard to make a fit. There are some classes of profile which cannot be fitted with this code; eg. KN3 profiles that have 3 peaks, profiles where the magnetic axis appears to be oscillating in the vertical plane and shots where the channels 11 and/or 19 are greater than their neighbours.

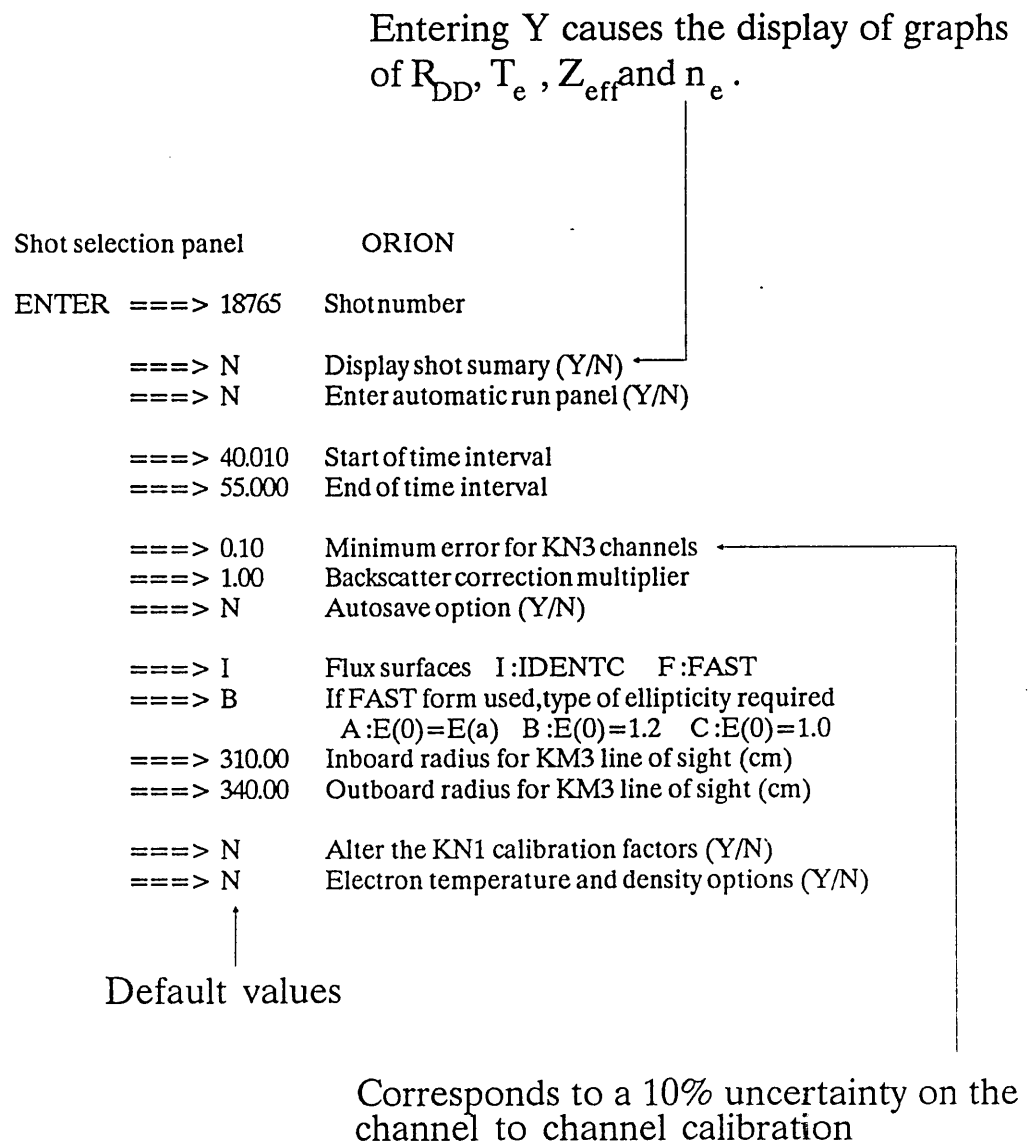


Figure B.2

Shot selection panel

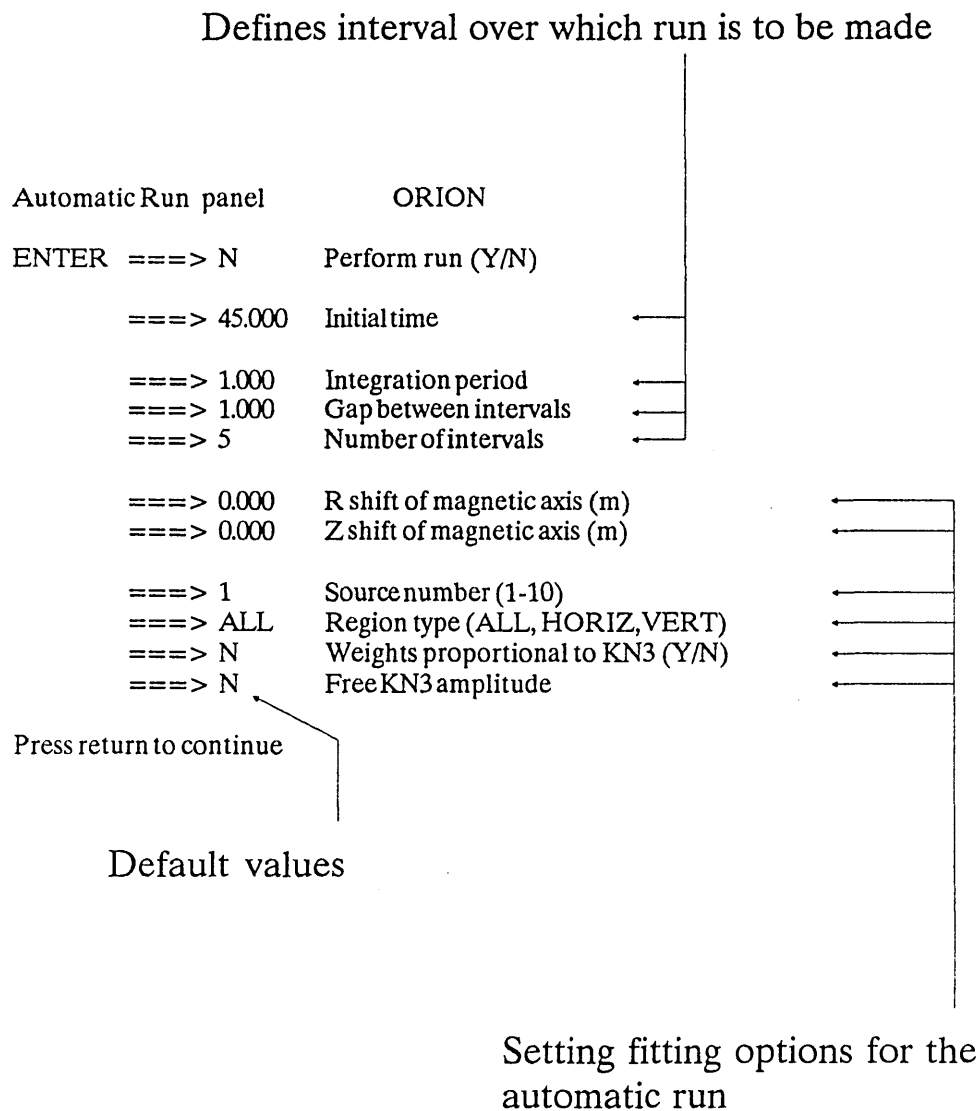


Figure B.3
Automatic run panel

[illegible]

Figure B.04: ORION output file

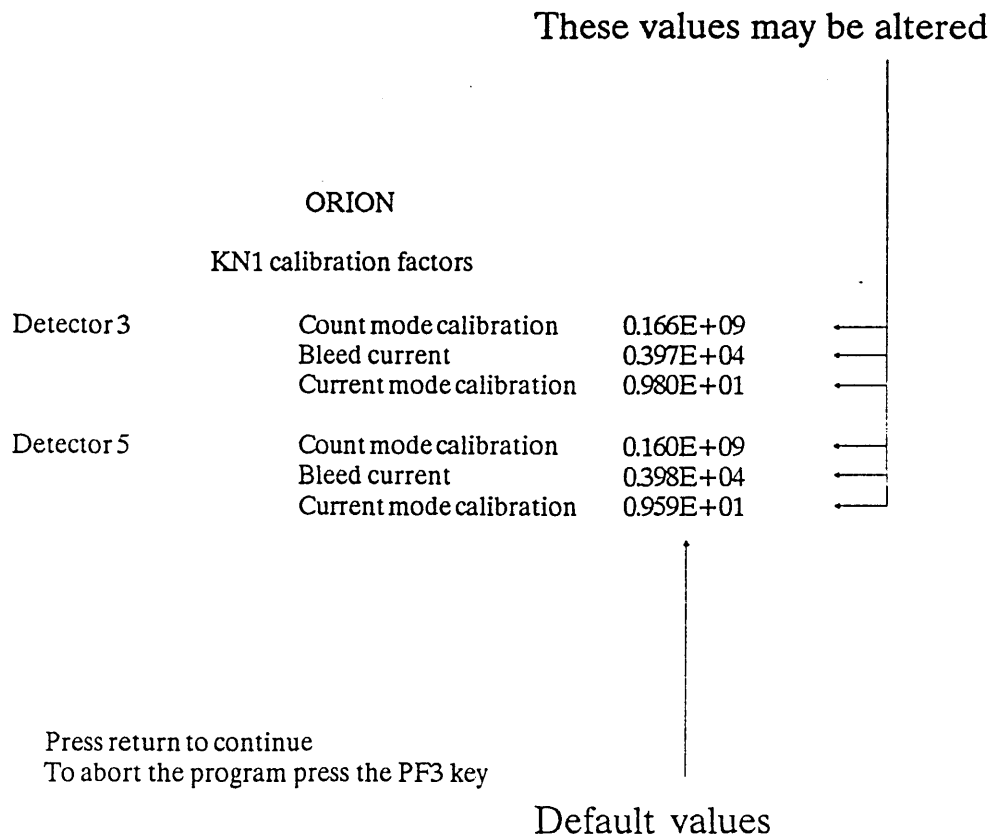


Figure B.5

KN1 calibration panel

ORION
Temperature and density selection panel Shot Number=18765

Density profile type	Availability
0 : Parameterized (NEX AX)	YES
1 : Abel inverted (Public)	YES
2 : Abel inverted (JETSEJ)	NO
3 : Abel inverted (JETRSG)	NO
4 : LIDAR version	YES

Temperature profile type	Availability
0 : Electron cyclotron emission	YES
1 : LIDAR version	YES

ENTER ==> 0 Density trace required
ENTER ==> 0 Electron temperature trace required

To abort the program press the PF3 key

Different temperature and density profiles are available at JET. This panel displays those available and allows the user to select one.

Figure B.6

Temperature and density profile panel

```

                                ORION

                                Available LIDAR time slices

1====> 42.799                11====> 0.000
2====> 44.799                12====> 0.000
3====> 46.799                13====> 0.000
4====> 48.799                14====> 0.000
5====> 50.799                15====> 0.000
6====> 52.799                16====> 0.000
7====> 54.799                17====> 0.000
8====> 56.799                18====> 0.000
9====> 58.799                19====> 0.000
10====> 0.000

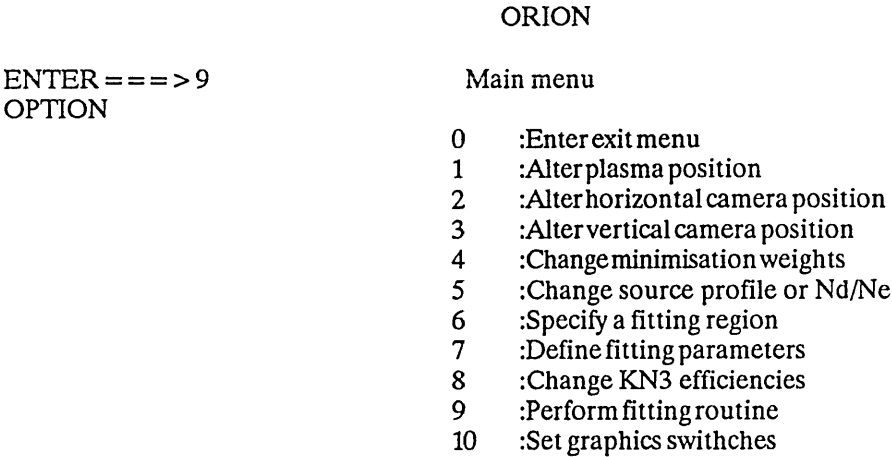
ENTER====> 0                Required timeslice

To abort the program press the PF3 key
To leave this panel press return

```

This panel lists the time slices at which LIDAR temperature and density profiles are available. The slice required by the user is selected by entering the number of the slice on the `====>` line.

Figure B.7
LIDAR time slice panel



To abort the program press the PF3 key

This panel lists the options available to the user to improve the quality of the fit to the data.

Figure B.8

ORION main menu

ORION

Plasma centre position

ENTER == => 3.0	Verticalshift (mm)
ENTER == => 0.0	Horizontalshift (mm)
ENTER == => N	Fast spatial scan option (Y/N)
KN3 estimate of the plasma centre: Horizontal : 27.3	
	: Vertical : 12.5

To abort the program press the PF3 key
Press RETURN to go back to the main menu

Figure B.9

Plasma central position selection panel

ORION		
	R change	Z position
1	0.0	0.0
2	0.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0
7	0.0	0.0
8	0.0	0.0
9	0.0	0.0
10	0.0	0.0
11	0.0	0.0
12	0.0	0.0
13	0.0	0.0

Panel for the selection of the spatial positions to be used in the fast spatial scan.

If a row is unaltered, then it will not be included in the spatial scan.

To abort the program press the PF3 key

Figure B.10

Fast spatial scan panel

ORION			
Fast spatial scan results table			
	R change	Z position	Chi square
1	1.0	0.0	19.0
2	20.0	0.0	18.8
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0
8	0.0	0.0	0.0
9	0.0	0.0	0.0
10	0.0	0.0	0.0
11	0.0	0.0	0.0
12	0.0	0.0	0.0
13	0.0	0.0	0.0

To continue press ENTER

Figure B.11

Fast spatial scan results panel

ORION	
Position of horizontal camera	
ENTER == => 0.00	Vertical shift (mm)
ENTER == => 0.00	Horizontal shift (mm)
ENTER == => 0.00	Camera rotation (degrees)

To abort the program press the PF3 key
Press RETURN to go back to the main menu

Figure B.12

Camera position panel

ORION

Weights table

1====>1.00	11====>1.00	HOR====>0.00
2====>1.00	12====>1.00	VER====>0.00
3====>1.00	13====>1.00	
4====>1.00	14====>1.00	AMP====>NO
5====>1.00	15====>1.00	DEF====>NO
6====>1.00	16====>1.00	
7====>1.00	17====>1.00	PRE====>NO
8====>1.00	18====>1.00	
9====>1.00	19====>1.00	
10====>1.00		

HOR sets all the horizontal channels, VER sets all the vertical channels
 AMP sets weights proportional to the line integrals (YES/NO)
 DEF sets the default weighting to AMP instead of 1.0 (YES/NO)
 PRE sets a preset shape over the minimisation weights (YES/NO)
 To leave this panel press the PF3 key

Figure B.13

Minimisation weights selection panel

ORION

ENTER====>9
 OPTION

Source function selection menu

	0	:Return to the main menu
	1	:Parabolic profile
	2	:Parabolic with a step at r=a
	3	:Parabolic with a wedge
Nd/Ne====>0.382	4	:parabolic with a parabola
	5	:Nigel function
Ti(0)====>3.83	6	:Further functions
	7	:Set minimisation start points
P-P====>1.000	8	:Usedefault minimisation starting points
Fraction	9	:Free the total neutron yield parameter
	10	:Return to the main menu

To abort the program press the PF3 key

Figure B.14

Source function selection panel

```
ORION

ENTER===>1          Select fitting region

0   :Whole profile
1   :Horizontal profile
2   :Vertical profile

To abort the program press the PF3 key
Press RETURN to go to the main menu
```

Figure B.15
Fitting region selection panel

```
ORION

Weights table
1===>1.00    11===>1.00    HOR===>0.00
2===>1.00    12===>1.00    VER===>0.00
3===>1.00    13===>1.00
4===>1.00    14===>1.00
5===>1.00    15===>1.00
6===>1.00    16===>1.00
7===>1.00    17===>1.00
8===>1.00    18===>1.00
9===>1.00    19===>1.00
10===>1.00

HOR sets all the horizontal channels, VER sets all the vertical channels
AMP sets weights proportional to the line integrals (YES/NO)

To leave this panel press the PF3 key
```

Figure B.16
KN3 efficiency selection panel

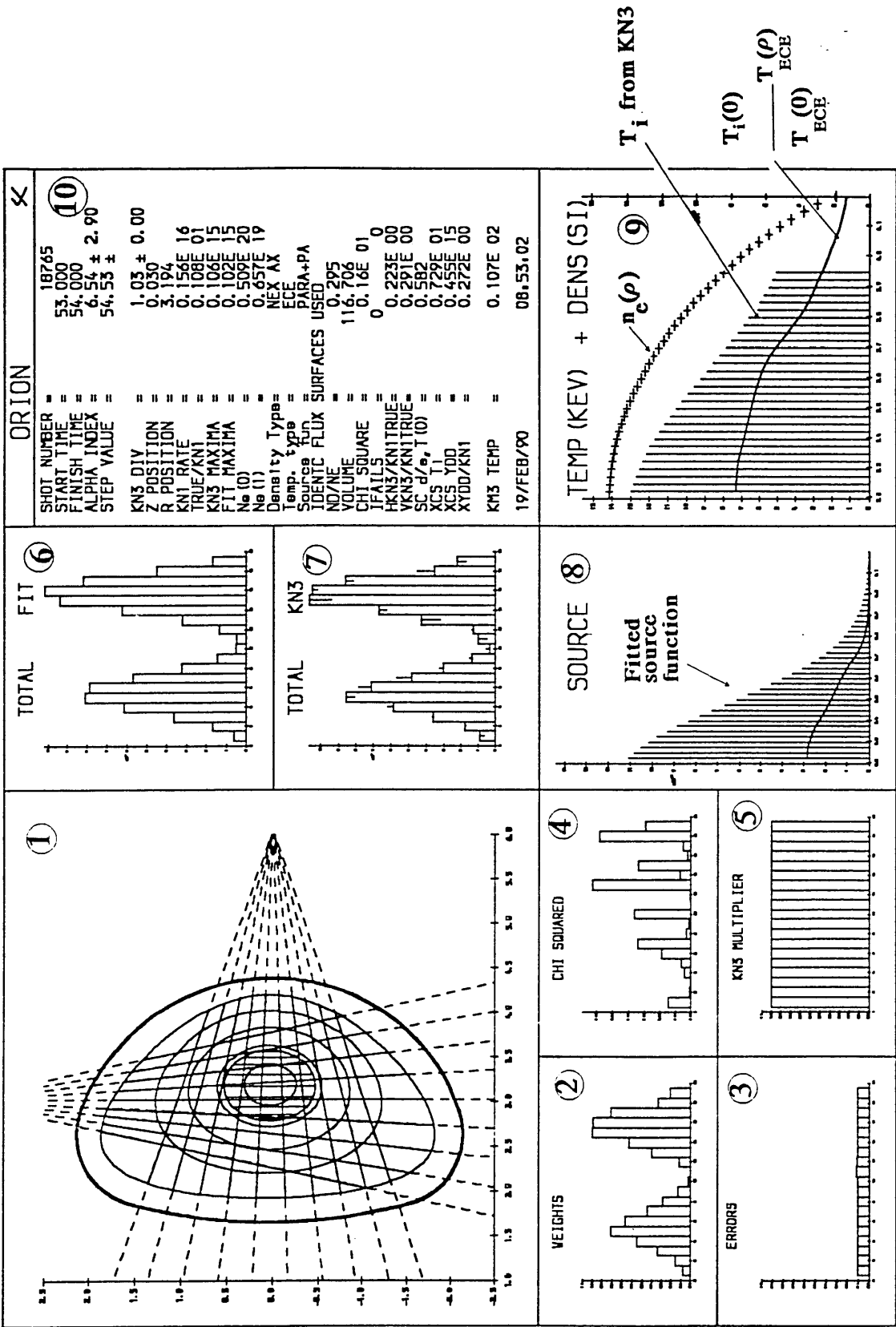


Figure B.17: ORION graphical output

ORION				ORION	
1					
2	SHOT NUMBER =	18765			
3	START TIME =	53.000			
4	FINISH TIME =	54.000			
5	ALPHA INDEX =	6.54 ± 2.90			
	STEP VALUE =	54.53 ±			
6	KN3 DIV =	1.03 ± 0.00			
7	Z POSITION =	0.030			
8	R POSITION =	3.194			
9	KN1 RATE =	0.156E 16		SHOT	=18765
10	TRUE/KN1 =	0.108E 01			
11	KN3 MAXIMA =	0.106E 15			
12	FIT MAXIMA =	0.102E 15			
13	Ne (0) =	0.509E 20		TIME	=53.00
14	Ne (1) =	0.657E 19			
15	Density Type =	NEX AX			
16	Temp. type =	ECE			
17	Source fun =	PARA+PA			
18	IDENTC FLUX SURFACES USED			TO T	=54.00
19	ND/NE =	0.295			
20	VOLUME =	116.706			
21	CHI SQUARE =	0.16E 01			
22	IFAILS =	0 0			
23	HKN3/KN1 TRUE =	0.223E 00			
24	VKN3/KN1 TRUE =	0.291E 00			
25	SC d/e, T (0) =	0.582			
26	XCS T1 =	0.729E 01			
27	XCS YDD =	0.455E 15			
28	XYDD/KN1 =	0.272E 00			
29	KM3 TEMP =	0.107E 02			
30	19/FEB/90	08,53,46			

Figure B.18: Expansion of written material from figure B.17

ORION

Graphical setup page

STATUS

Y	Flux surface picture
Y	Fitted line integrals
Y	KN3 line integrals
Y	Error graph
Y	Chi squared graph
Y	Weights graph
Y	Efficiency graph
Y	Temperature profile
Y	Numerical information
Y	Source profile graph

STATUS must be either Y or N

Y means the picture will be included in the main display

N means that it will not be included

To leave this panel press the PF3 key

Figure B.19

Graphical setup panel

ORION

ENTER == => 1
OPTION

Exit menu

- | | |
|---|---|
| 1 | :Further work with the same time interval |
| 2 | :Return to the shot selection menu |
| 3 | :Save last picture |
| 4 | :Expand last picture |
| 0 | :Exit the program |

To abort the program press the PF3 key

Figure B.20

Exit menu

ORION	
ENTER == => 0	Graph expansion options
OPTION	
0	Return to exit menu
1	Flux surface picture
2	Weights graph
3	Error graph
4	Chi squared graph
5	Source profile graph
6	Temperature profile
7	Fitted line integrals
8	KN3 line integrals
9	Efficiency graph
10	Numerical information
STATUS must be either Y or N	
Y means the picture will be included in the main display	
N means that it will not be included	
To abort the program press the PF3 key	

Figure B.21
Graphical output expansion panel

Source function for this panel is a flexycurve, with a free KN3 neutron emission rate	
ORION	
Setting the starting fitting parameters	
PARAMETER	VALUE
HEIGHT :RHO = 0.2	0.900
:RHO = 0.4	0.500
:RHO = 0.6	0.100
:RHO = 0.8	0.050
KN3 DIVISOR	0.930
To abort the program press the PF3 key	

Figure B.22
Initial minimisation parameters panel

