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PLASMA MEASUREMENTS FOR JET

INTRODUCTION

An important requirement for a fusion experiment like JET is the accurate and reliable measurement of the plasma conditions. In a magnetically confined plasma there are many quantities to be measured in order to characterise the plasma and to compare experiment with theory. The most important quantities which are measured in JET include macroscopic parameters like the plasma position, shape, current, energy content etc. and spatially varying quantities like the densities and temperatures of each of the component species (ie. electrons, hydrogenic ions and impurity ions). Some of these quantities (current, position, shape and density) are measured in real time and included in feedback loops to control the discharge.

Measurements in high temperature plasmas are difficult because material probes cannot be used except at the extreme edge where the plasma is sufficiently cool ($\lesssim$ 100eV). For measurements in the hotter core of the plasma non-invasive techniques are required. These include passive methods which detect radiation or particles emitted spontaneously by the plasma and active methods where radiation or particles from an external source are used to probe the plasma. Many techniques make use of electromagnetic radiation and the spectral range covered in JET is shown in Figure 1. Use is also made of charged and neutral particles and neutrons.

In attempting to review these plasma measurement systems (or diagnostics as they are commonly called) in a systematic way, they can be grouped either according to the measurement technique (eg. laser scattering, X-rays etc) or according to the plasma parameter which is to be measured (eg. density, temperature etc). Neither classification method can be followed completely systematically since many measurement methods in fact give information on more than one plasma parameter, and conversely we usually use more than one method to measure each of the more important parameters. This overlap is very important for reliability and confidence in the measurements. It is important to stress that this duplication is needed not because the diagnostic equipment is unreliable but because in many cases the measurements themselves rely on complicated plasma physics effects whose interpretation may not always be straightforward. For example some of the measurement methods need cross-calibration against other measurements, some are restricted to certain ranges of plasma parameter and to cover the whole operating range of JET may be outside the scope of a single method, and in some cases there may be competing plasma effects which could confuse the interpretation. Clearly the accuracy of the measurements is important, particularly since most of the basic data is used to derive other plasma quantities, and therefore inaccuracies or errors in basic quantities can propagate down the entire analysis chain. It is generally accepted that most plasma measurements are accurate only to within ±20%, but by careful design and calibration we have been able to improve on this in JET (for example in the measurement of electron temperature) as will be discussed below.

The total number of diagnostic systems installed or being built for JET is around 30 and their present status is summarised in Table I. A schematic layout is shown in Figure 2. It will be seen that many of these systems have been built by the other fusion laboratories who are partners in the JET project. These systems have been specified and paid for by the JET project via a series of contracts placed with these other laboratories. This formal relationship was needed so that the work in the many different laboratories could be effectively coordinated and the complex systems could be built to uniform standards. This has been a particularly successful collaboration with the result that the diagnostic expertise of the European fusion programme has been concentrated in JET. Many skilled scientists, engineers and technicians have been involved and many of these have worked at JET for varying periods to install or operate these systems.

A deliberate policy has been to use diagnostics methods whenever possible whose principles have been demonstrated on other experiments. What is new in JET is the sophistication of the application of these methods and the complexity of the engineering. This has been necessitated by several factors including the large physical size of JET, the need to maintain compatibility with the very high standards of engineering on all other systems of the JET device, and by the hostile radiation environment which will occur in discharges with deuterium and tritium. Considerable emphasis has been placed on achieving much higher standards of reliability for the diagnostic systems than has previously been the norm in fusion research. All of the JET diagnostic systems are remotely controlled through a computer system and the more important diagnostics can be operated automatically with a minimum of skilled operators.

In order to make the most effective use of experimental time on JET and to improve the self-consistency of the data, a complete set of data is measured simultaneously on every discharge. In general we find that the measurements are reproducable from shot-to-shot for discharges with the same conditions. A large number of spatial channels is needed to measure profiles of plasma parameters with adequate spatial resolution (generally 5 - 10 cms) in these discharges with large poloidal cross-section (2.5 x 4.2 m). As the poloidal cross-section is non-circular, those measurements which integrate along a chordal line of sight have to be unfolded by tomographic inversion methods and thus the plasma must be viewed in orthogonal directions. In most cases the number and locations of the lines of sight are severely constrained by the access to the plasma through the available ports in the vacuum vessel. There are similar considerations in determining the time scales on which data should be recorded. The plasma parameters related to quasi-equilibrium processes (eg. energy balance) need to be recorded on time scales up to an order of magnitude shorter than the characteristic equilibrium times, eg. recording on time scales of ~ 10 ms is required for equilibrium times ~ 100 ms. Data is usually recorded at this rate throughout the 20s JET discharge, ie. about 2×10^3 data points per channel. There are however many transient plasma phenomena which take place on much shorter time scales (eg. instabilities and disruptions) and these data must be recorded on times scales of a few μs. Clearly it would be impractical in terms of data storage to record data on all the measurement channels at this rate throughout the JET discharge and so the fastest data taking rate is usually switched on for a limited number of time windows centred around the periods of interest in the discharge. These windows may be pre or post triggered in some cases by signals from other diagnostics.

Fairly stringent constraints have had to be applied to the data requirements of each diagnostic to keep the total data recorded per JET discharge within reasonable limits. Presently we record about 7×10^6 data points per discharge and this is expected to increase to ~ 1.5×10^7 when all planned diagnostics are operating. The data is recorded in local CAMAC memory during the discharge, and then read into the memory of one of a network of computers used for diagnostic and machine control and for data analysis. Initial analysis and display of results is carried out by these computers in the period between discharges and is used as a guide to the progress of the experiment. At the same time the complete raw data file is copied into the memory of a large mainframe computer where it can be used for higher level analysis and it is via this computer that retrospective analysis of JET data is carried out. An important feature of JET is that data for all JET discharges and from all the JET diagnostics is available to all of the JET team on this mainframe computer.

In this paper some of the JET diagnostics will be described. No attempt will be made to describe all the systems listed in Table I but rather a few typical systems will be selected to illustrate the range of measurements and the different techniques which are used.

MAGNETIC MEASUREMENTS

Measurements of the poloidal magnetic field outside the plasma are used to determine the discharge current, loop volts, ohmic power input, position and shape of the plasma boundary[1]. More detailed analysis of the data yields information on the total plasma energy and pressure, plasma inductance and the shape of the magnetic surfaces inside the plasma. The magnetic measurement coils are shown in figure 3. The component of the poloidal magnetic field perpendicular to the surface of the vacuum vessel is measured with a set of flux loops. There are two types of loops on the outer surface of the vacuum vessel; full flux loops which make a single turn in the toroidal direction are used in locations where there are no obstructions from ports etc, whilst saddle loops are used in places where there are obstructions. The component of the poloidal field parallel to the vacuum vessel surface is measured with small pickup coils which are located inside inconel protection tubes on the inside of the vacuum vessel. There are 18 of these coils distributed around the poloidal circumference and there is an identical set of coils on each of the octants. The signals from these coils are processed electronically and combined in various ways using both analogue and digital techniques to yield the various plasma quantities. For example the plasma current is obtained by adding the signals from all the internal pickup coils to simulate a continuous Rogowski Coil. The plasma position and the shape of the outermost magnetic flux surface are determined to a typical accuracy of ±10mm by a numerical solution of the Laplace equation for the poloidal field outside the plasma with the boundary conditions fitted to the field components measured by the magnetic diagnostics. The flux surfaces inside the plasma can be estimated by solving the Grad - Shafranov equation, and the integral plasma quantities such as total kinetic energy, pressure and inductance are obtained from the Shafranov integrals[2].

The plasma pressure is also determined by the diamagnetic effect on the toroidal magnetic field which is measured using coils supported on one of the toroidal field coils.

ELECTRON DENSITY

As in most other tokamaks the electron density is measured by interferometry with microwave and far infra-red radiation. The refractive index of an ordinarily polarised electromagnetic wave (ie. with the E vector of the wave parallel to the tokamak's B field) is a function of the local electron density. Thus $\eta = (1-n_e/n_c)$ where $n_c=4\pi^2c^2 E_o m_e/\lambda^2 e^2$ is the cut off density for propagation of the probing beam of wavelength λ. The microwave interferometer operates at a wavelength of 2 mm along a vertical chord through the major radius R = 3.12 m. The phase change in the transmitted beam due to the density dependent refractive index of the plasma is compared with the phase of a reference beam which has traversed a similar path length in air. The number of interference fringes is counted electronically and at this wavelength one fringe is equivalent to a change in plasma density integrated along the chordal line of sight of ~ $10^{20}m^{-2}$. Thus the single channel interferometer measures the integral of density times distance along the line of sight. In order to determine spatial profiles of the density we need to make simultaneous measurements along a number of different chords. If the poloidal cross-section is circular, the density profile is then obtained from the line integral measurements by Abel inversion. However, if the poloidal cross-section is non-circular, as in JET, it is necessary either to make measurements along orthogonal chords and use tomographic methods, or to assume that the surfaces of constant density coincide with the magnetic flux surfaces measured by magnetic diagnostics. The main interferometer on JET (figure 4) has 7 vertical and 3 lateral lines of sight[3]. The system works at a wavelength of 195 μm using a DCN laser. The shorter wavelength is not refracted as strongly as the microwave beam and this system can thus operate at higher densities. A problem with all interferonmeters, particularly those operating at short wavelengths, is that any mechanical vibrations of the optical components also produce changes in the optical path length which are indistinguishable from plasma density changes. The optical components of the vertical channels are mounted on a massive support frame which is mechanically independent of the rest of the JET machine but some of the components on the lateral channels cannot be so isolated and are thus sensitive to vibrations. The horizontal channels have been designed to operate simultaneous with a second wavelength (λ=3.39μm) which is affected more strongly by the mechanical vibrations than the main wavelength (λ=195μm). However this system has not proved satisfactory due to technical difficulties with the internal mirrors at the shorter wavelength and the second wavelength is presently being changed to 119μm.

An alternative method of density measurement which is being developed on JET is reflectometry, where a microwave beam directed into the plasma is reflected at the cut off density[4]. This technique is particularly suitable for measurements near to the edge of the discharge and for studying temporal fluctuations in the density.

ELECTRON TEMPERATURE

The traditional method of measuring electron temperature in tokamaks is by Thomson Scattering. An incident beam of laser light is scattered and doppler shifted by the electrons in the plasma. The scattered light is thus broadened in wavelength by an amount which corresponds to the velocity distribution of the electrons, and the temperature can be determined directly. This technique has a special place in the history of tokamak research, since its successful use by a joint British and Russian team on the T3 tokamak in Moscow in 1969 confirmed that tokamaks had high electron temperatures[5] and this stimulated a rapid development of tokamak research outside the USSR.

JET will have two Thomson Scattering Systems, one is already operating and the second is under construction. The first system[6], which we call the "Single Point Thomson Scattering System" is of conventional geometry ie. the scattered light is collected in a cone at 90° to the incident light. A schematic is shown in figure 5. A ruby laser is used as the source and can be operated in a variety of combinations of energy per pulse and repetition rate ranging from a single pulse of 25J to a series of pulses of 2.5J at 1Hz. The laser is located on the roof of the JET torus hall as shown in the schematic. The beam passes into the torus hall through a labyrinth to shield against neutrons, and into the torus through a quartz vacuum window. The scattered light leaves the torus through a cluster of seven windows each of ~ 200mm diameter which are arranged to have an effective apperture equivalent to that of a single window of ~ 500mm diameter. The light is collected by a large reflecting telescope and directed into the roof laboratory where the scattered spectrum is dispersed by a large prism spectrometer onto an array of photomultipliers. The Thomson Scattering diagnostic has the advantage that the local electron temperature is measured directly and unambiguously for the electron velocity distribution in a well-defined volume of plasma (typically 5 x 1 x 1 m) at the well defined instant when the laser is fired. It is however limited to a single spatial point measurement per discharge, (although the system can be moved to different major radii in between discharges) and to a maximum repetition rate of one measurement per second. The accuracy is determinated principally by the number of scattered photons. For typical JET discharge conditions an absolute accuracy of ±10% can be obtained using a laser pulse of ~5J at a repitition rate of 0.5Hz. The accuracy can be improved if necessary (for example in low density plasmas) by increasing the laser energy (ultimately to a single pulse of 20J) at the expense of repetition rate, or if required the repetition rate can be increased to 1Hz with a laser energy of 2.5J/pulse at the expense of slightly reduced accuracy.

A new type of Thomson Scattering system is being developed for JET and will be installed within the next year[7]. This system will use a laser with a much shorter pulse length (~ 250ps) than the conventional system (~ 20ns) and the scattered light will be recorded continuously as the laser light pulse travels across the plasma. Then the spatial profile will be determined from the time of flight of the laser pulse. Temperature and density will be determined respectively from the spectral width and intensity of the scattered light as in the conventional system. This new system, which is shown schematically in figure 6, will use much of the existing optics and both systems will be able to operate together.

Electron temperatures can also be measured by electron cyclotron emission (ECE). For a wide range of plasma conditions, the plasma emits as a black body for the extraordinary mode (ie. the E vector of the wave perpendicular to the B vector of the tokamak) at low harmonics of the electron cyclotron frequency $\omega_{ce}=eB/m_e c$. Thus the intensity of the emission gives the local electron temperature whilst the frequency is determined by the local magnetic field which is uniquely related to radial position in a tokamak. In this way spatial profiles of electron temperature can be measured by viewing the plasma radially with a suitably calibrated detector which can be swept in frequency to correspond to the electron cyclotron frequency at different radii along the line of sight.

In JET considerable effort has been invested into developing ECE as the main electron temperature diagnostic[8]. A poloidal section of the plasma is viewed along 10 different chords by an array of rectangular horn antennae. The ECE radiation, which for typical JET parameters is in the range 70 to 350 GHz is transmitted from the antennae to the detectors, which are located outside the torus hall, by oversized rectangular microwave waveguides. The distance along the route followed by the waveguides is of the order of 100m and the oversized waveguide is needed for low attenuation, but great care is needed in the design of bends etc to avoid serious problems with conversion between different waveguide modes.

Three types of detector are used. The complete spectrum of the ECE radiation over several harmonics is measured with scanning Michelson interferometers, and the relative amplitudes of the different harmonics are used to check that the emission is thermal. The spatial profile of temperature along different chords (figure 7) is measured with Fabry-Perot interferometers which are scanned over the second harmonic emission in a time of ~ 3ms. Each scan gives a temperature profile along the chordal line of sight with a spatial resolution ~ 10cm, and by combining the data from different chords a two dimensional temperature distribution can be constructed. The Fabry Perot instruments can be operated also at fixed frequencies so that the temperature at a selected position in the plasma can be recorded as a function of time with a sensitivity ~ 5eV and time resolution ~ 10μs. A twelve channel polychromator is also used to record the time dependence of temperature at 12 selected positions along a single chord. This is particularly useful for measurements of the propagation of heat waves through the plasma following the collapse of an internal 'sawtooth' instability.

The ECE diagnostics are absolutely calibrated by means of specially developed thermal sources of known temperature and emissivity. This technique has now been developed to the point where the absolute accuracy of the ECE measurements on JET is estimated to be within ±10% and the relative accuracy between different spatial points is within ±5%. These values are confirmed by comparison with the Thomson Scattering measurements. (Figure 8)

Other techniques eg. X-rays, can also be used to determine the electron temperature but are generally less accurate than the ECE and Thomson Scattering Systems.

ION TEMPERATURE

In general the temperature of the ions in a tokamak is different from that of the electrons. In ohmically heated discharges the primary power input is via the electrons, and thus they are hotter than the ions whereas in discharges with powerful additional heating of the ions the ion temperature may be higher than that of the electrons. Generally the methods for measuring the ion temperature have more difficulties and more limited ranges of application than the methods described above for the electrons and so this is an area where the overlap of several different diagnostics is particularly necessary.

The classic method is based on charge exchange neutrals[9]. Even in these highly ionised tokamak plasmas there is a finite but small density of non-ionised neutral atoms (typically ~ 10^{12}-10^{13} atoms m^{-3} in the centre of the discharge compared to ion densities in the range 10^{19} to 10^{20} ions m^{-3}). Charge exchange collisions between these neutrals and plasma ions produce neutrals with energies equal to those of the plasma ions but which can escape from the confining magnetic fields. The flux of these neutrals is small (typically 10^{14} atoms $m^{-2}sterad^{-1}KeV^{-1}$) and to detect them they are first reionised by a hydrogen gas stripping cell, and then passed through magnetic and electrostatic analysers to disperse them in momentum and energy onto an array of channelmultiplier detectors. In this way the energy spectra of hydrogen and deuterium neutrals can be measured simultaneously. In small low density plasmas the neutral energy spectrum has a characteristic shape which gives directly the ion temperature in the core of the discharge but in larger devices like JET the low neutral atom density in the core and the strong attenuation of neutrals escaping from the large diameter plasma introduces a severe distortion of the charge exchange spectrum so that a simple fit to the measured spectrum underestimates the central temperature. Transport code calculations are used to extrapolate to the central temperature. The neutral particle diagnostic system on JET has an array of 5 analysers viewing along different chords in the poloidal section, and the whole array can be scanned to view in different toroidal directions.

Neutron diagnostics are also used to measure ion temperatures in deuterium plasmas[10]. The neutron yield from a deuterium plasma with a maxwellian ion distribution is proportional to the square of the deuteron density and to a high power of the ion temperature. Thus the neutron yield ~ $n_d^2 T_i^\gamma$ when $4<\gamma<5$ for $T_i<10$keV. The neutron yield is dominated by the hot central core of the plasma and is relatively insensitive to the precise shape of the density and temperature profiles provided they are not too extreme. The ion temperature in the core of the discharge can therefore be deduced from the total neutron yield provided the deuteron density is known and the ions are maxwellian. The latter requirement is usually met in ohmically heated plasmas but is usually violated with powerful additional heating of the ions which results in a non maxwellian distribution.

However a more direct measurement of the ion temperature can be obtained by neutron spectrometry. The energy distribution of the neutrons is broadened about the fusion energy (2.4 MeV for D-D and 14.1 MeV for D-T) by the energy of the interacting ions. The broadening is relatively small ($\Delta E/E \lesssim 5\%$) and therefore very good energy resolution is needed for a neutron spectrometer. Good shielding and collimators are needed to reduce the background of lower energy neutrons which have been scattered from the material structures surrounding the plasma. The spectrometers also need to cover a very wide dynamic range of neutrons yields for typically 10^{12} neutrons s^{-1} in low temperature deuterium plasmas to typically 10^{19} neutrons s^{-1} in high temperature deuterium tritium mixtures. There is no single detector technique which will cover this wide range of fluxes with adequate energy resolution and thus JET has built several different instruments to cover the expected range. At low yields in deuterium plasmas we have used ^3He ionisation chambers located on the roof of the torus hall using the penetration hole through the roof as a collimator. A typical spectrum is shown in figure 9. At higher fluxes in deuterium plasmas we will use a variety of other methods including a novel time of flight technique which uses a pair of sintillators. Simultaneous measurement of the total neutron yield and of the ion temperature by a neutron spectrometer allows the determination of the deuteron density, which is generally significantly less than the electron density (typically $n_d/n_e \sim 0.5$) due to the dilution by impurities.

A typical comparison between the temperatures measured by the charge exchange and neutron diagnostics is shown in figure 10. In this case the ion temperature was relatively low and the neutron spectrum had to be integrated for 6s during the flat top phase of the discharge for good statistics, but more recent experiments with higher temperatures have allowed the time resolution to be reduced to about 1s. In the example shown there is good agreement between the different measurements, but this is not always the case, and in some discharge conditions there may be significant differences between the different measurements. The main source of difficulty is that all these methods are very sensitive to distortions of the high energy tail of the ion energy distribution, and in many cases the ions are no longer Maxwellian and therefore the simple concept of a plasma temperature is no longer valid. A particularly important quantity is the difference between the ion and electron temperatures which determines the coupling between the two species and is required for a detailed analysis of the energy balance. However in high density plasmas when the coupling is strong the difference in temperatures may be comparable to the accuracy (typically ±10% for Te and ±20% for Ti) of the measurements, and thus the relative accuracy of the temperature difference (and hence the coupling) is poor.

Ion temperature are also measured from the line widths of impurity emission lines. The impurity ions are of course in good thermal equilibrium with the hydrogenic ions and thus the measured impurity ion temperatures can be equated to the hydrogenic ion temperatures. These measurements can be made in different parts of the spectrum. In the X-ray region we use a high resolution crystal spectrometer to observe highly ionised stores of nickel from the centre of the plasma. The crystal and detector (a multiwire proportional counter) are located outside the torus hall behind the main radiation shield wall so that this system is hardened against neutrons and γ-rays. The first results are now being obtained with this system which can be used to measure bulk rotation of the plasma as well as temperatures.

IMPURITY DIAGNOSTICS

As discussed in the accompanying paper by Engelhardt[11] tokamaks are contaminated by impurities as a result of the interaction between the plasma and the surrounding material surfaces. Various diagnostic methods including spectroscopy are used to determine the processes which lead to this contamination and to study the effects of impurities in the plasma.

Spectroscopic diagnostics are the main methods for identifying the impurities in the plasma and for measuring their concentrations. The impurities are characterised by spectral line emissions over a very wide range from the visible (~6000Å) through the ultra-violet to the soft X-ray region (~1Å). Different instruments are needed to cover this very wide range. The resonance lines of the important low Z impurities (oxygen and carbon) and the lower ionisation stages of the high Z impurities (nickel) are in the ultra-violet and it is this region of the spectrum which has traditionally been used for quantitative measurements in smaller tokamaks. Unfortunately spectrometers in this part of the spectrum need to be placed in direct line of sight of the plasma as the reflectivity of surfaces is very low and, as there are no suitable window materials below ~1400Å, these instruments must be directly coupled to the tokamak vacuum system. The main system which has been built for JET will cover the wavelength range from 2000 to 100Å and is based on three identical duochromators. The plasma is viewed via grazing incidence mirrors which can be rotated to give a spatial scan of the plasma cross-section. These instruments are mounted horizontally - each viewing one half of the plasma whilst the third instrument views vertically. In this way it is intended to be able to unfold poloidally assymetric impurity distributions by tomographic inversion. This instrument gave its first data at the end of 1985, but due to vacuum problems in the rotary mechanisms its full implementation is likely to be delayed. There are subsidary vacuum ultraviolet spectrometers at longer (ie. > 2000Å) and shorter (20 - 100Å) wavelengths which view the plasma along fixed lines of sight.

Considerable effort has been invested into spectroscopy in the visible (ie. 6000 - 3000Å) and soft X-ray (20 - 1Å) regions of the spectrum since in both cases light relay systems can be used to place the spectrometers outside the radiation shielding wall. In the visible this is done with fibre optics whilst in the soft X-ray region a crystal spectrometer with two crystals in a periscope type arrangement is being built. Quantitative interpretation of the emission lines in the visible is more difficult, but in JET considerable use has been made of these techniques to view the limiter and walls and thus determine the flux of hydrogen and impurities which enter the plasma.

More direct measurements of the plasma interaction with material surfaces has been made by post mortem surface analysis of samples removed from the limiter and walls whenever the JET vacuum vessel has been opened for maintenance. These measurements necessarily give only an integrated picture over many months of operation, but probe drive systems are now being installed which will allow sample surfaces to be exposed near to the walls and limiters, and then transferred promptly under vacuum to an analysis system where a variety of surface analytical methods can be used. The same probe drive systems are also used to introduce electrical probes into the boundary regions of the discharge to measure the local plasma density and temperatures. These plasma data are required to interpret the spectrosopic measurements of impurity influxes at the plasma edge.

The degree of impurity contamination in tokamak plasmas is usually expressed by the average ionic charge $Z_{eff} = \sum_i n_i Z_i^2/n_e$ where n_i is the density of impurity ions with charge Z_i and the summation is taken over all impurity charge states. In JET we measure Z_{eff} by several methods including the enhancement of the continuum radiation from bremsstrahlung in a region of the visible spectrum where there are no strong emission lines, and from the enhancement of the continuum in the soft X-ray region. Generally there is agreement between these spectroscopic measurements of Z_{eff}, and with values of Z_{eff} derived from the plasma resistance enhancement to within an accuracy of about 20%.

The power radiated by impurities is measured by arrays of bolometers which view the plasma in orthogonal directions through small apertures. The horizontal camera has 20 channels and the vertical camera has 14 channels. Each detector consists of a pair of thin film gold resistors evaporated onto a mylar foil. One resistor receives plasma radiation and the other is shielded. The pair are connected in a bridge arrangement to cancel drifts in the substrate temperatures.

The temperatures of the surfaces of the limiters, rf antennae and vulnerable areas of the vacuum vessel wall are monitored with infra red television cameras. One system is based on CCD cameras and has good spatial resolution. It is sensitive to radiation ~ 1μm wavelength and has a minimum temperature threshold ~ 700°C. It is used primarily to monitor these surfaces for localised heating due to plasma interaction, although some information about limiter power fluxes can also be determined. The second system has low spatial resolution but operates at longer wavelengths

(~ 3-5 μm) and thus is sensitive to lower surface temperatures and can be used for more accurate power flux measurements.

FLUCTUATIONS

The discussion of JET diagnostics so far has concentrated on the measurement of quasi stationary plasma parameters, but most of these systems also have the capability to follow non-stationary plasma phenomena. Of particular interest at the moment in JET are the periodic density and temperature oscillations in the core of the discharge - usually called "sawteeth", and the complex chain of internal magneto-hydrodynamic oscillations which preceed the catastrophic termination of the discharge known as a "disruption". Amongst the most useful of the systems described already are the ECE diagnostics which have very good time resolution and sensitivity to record these events.

A diagnostic which has been installed on JET specifically to record these internal transitory phenomena is the X-ray diode array system[12]. Small semicondutor diode detectors are sensitive to soft X-rays emitted from the plasma and can therefore detect small localised temperature fluctuations. They are mounted inside the JET vacuum vessel in two arrays viewing the plasma cross-section in orthogonal directions as shown in figure 11. The wavelength range of the system can be changed by means of filters which can be introduced infront of the detectors and this has the effect of changing the sensitivity of the system to changes in plasma temperature. Each detector of course integrates the emission along its line of sight but with such a large number of sight lines (62 horizontal and 38 vertical) it is possible to unfold the integral signals numerically using tomographic methods to produce contour maps of the local emission density. This diagnostic has proved particularly powerful in observing the mechanism of the sawtooth oscillation. An example as shown in figure 12, and shows how the sawtooth collapse takes place on a very short time scale (< 100μs) and appears to involve a rapid outward convection of the hot core of the discharge often without any prior mhd activity. These measurements have substantially changed the understanding of the sawtooth which had been widely accepted previously and provides a clear example of the need for fusion experiments like JET to be well diagnosed.

Conclusions

A considerable effort has been invested into providing the JET experiment with a comprehensive set of diagnostics. Particular emphasis has been placed on making measurements of the different plasma parameters simultaneously within a single discharge, in order to avoid problems of irreproducibility. Considerable care has been taken during the design and construction of these diagnostic systems to ensure that they are consistent with the high standards of engineering of the other systems of the JET machine. Many of the systems described in this paper were operated in a preliminary version for the first operation of JET in 1983, and since then they have been refined and brought into full operation. Most of these systems are now capable of reliable and automatic operation, allowing the scientific personnel to concentrate on interpretation of data. A few systems including the neutron systems specifically intended for the later phases of JET's programme are still in construction and will be installed within the next few years.

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References

1. Stott P E, Diagnostics for Fusion Reactor Conditions, EUR 8351-1 EN. Commission of the European Communities Brussels (1982) 403-418.

2. Mukhovatov V S & Shafranov V D. Nuclear Fusion II (1971) 605-633.

3. Veron D. Diagnostics for Fusion Reactor Conditions, EUR 8351-1 EN. Commission of the European Communities Brussels (1982) 199-224.

4. i) Hubbard A E, Costley A E, Gowers C W. A Simple Fixed Frequency Reflectometer for Plasma Density Profile Measurements on JET. (submitted to J. Phys. E : Sci. Instrum.)
   ii) Simonet F. Measurement of electron density profile by microwave reflectometry on tokamaks. Rev. Sci. Insts. 56 (5) (1985) 664.

5. Peacock N J, Robinson D C, Forrest M J, Wilcock P D and Sannikov V V (1968) Nature (London) 224 - 488

6. Nielsen P. Diagnostics for Fusion Reactor Conditions, EUR 8351-1 EN. Commission of the European Communities Brussels (1982) 225-259.

7. Salzmann H, Hirsch K, Gruber J, Röhr H, Bredelow G and Witte K. Rev. Sci. Inst. 56 (1985) 1030.

8. Costley A. Diagnostics for Fusion Reactor Conditions, EUR 83 51-1 EN. Commission of the European Communities Brussels (1982) 129-166.

9. Afrosimov V V and Kislykov A I. Diagnostics for Fusion Reactor Conditions, EUR 8351-1 Commission of the European Communities Brussels (1982) 289-310.

10. Jarvis O N, Gorini G, Hone M, Källne J, Sadler G, Merlo V and van Belle P.
Neutron Spectrometery at JET.
Proc. 6th Conf. on High Temperature Plasma Diagnostics, Hilton Head Island, S.C. March 1986 (to be published in the Rev. Sci. Inst.)

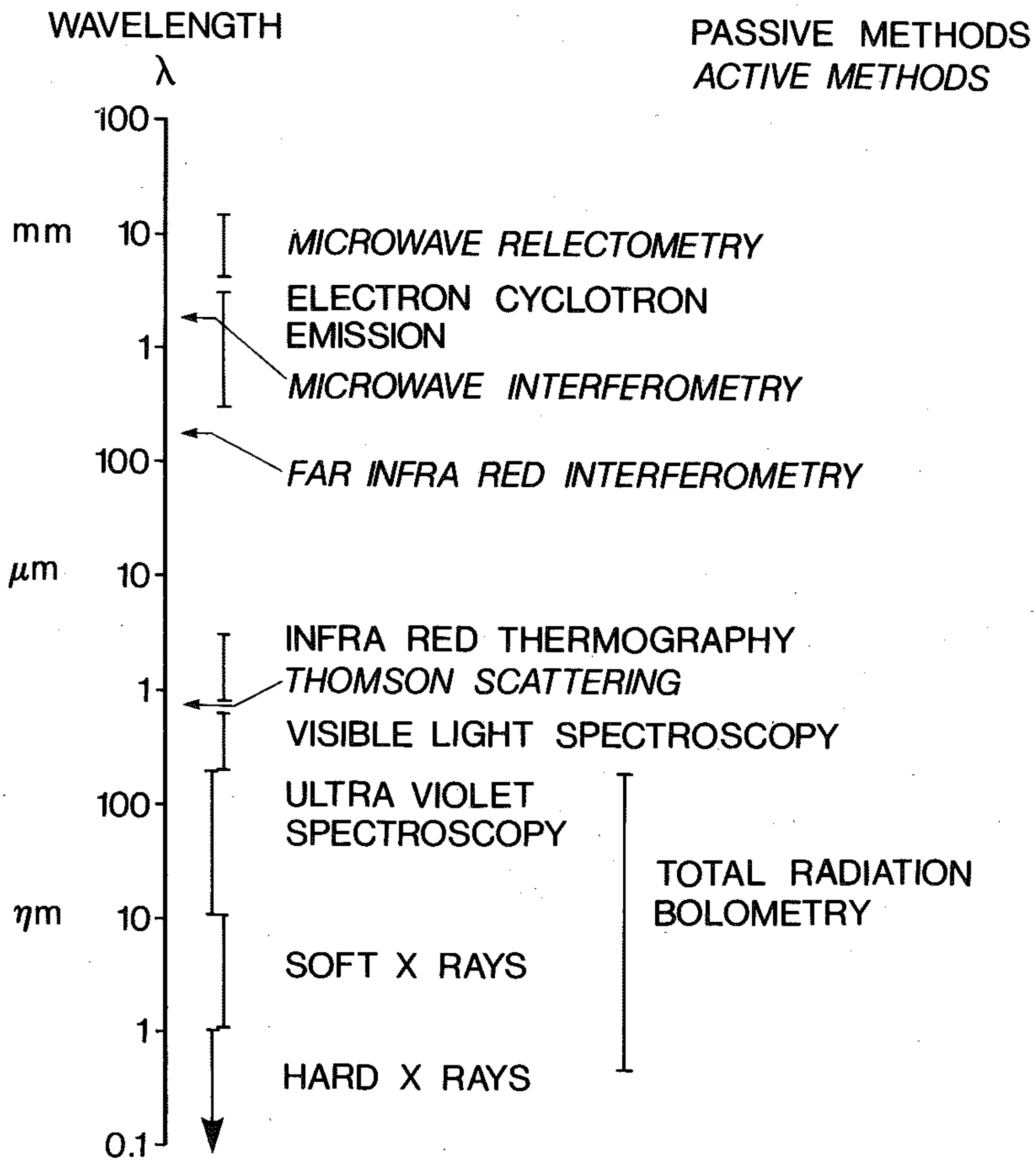
11. Engelhardt W.
Wall Effects and Impurities
(This conference).

12. Edwards A, Fahrbach H-U, Gill R D, Granetz R, Oord E, Schramm G, Tsuji S, Weller A, Zasche D.
The JET Soft X-ray Diode Array Diagnostic.
6th Conf. on High Temperature Plasma Diagnostics, Hilton Head Island, S.C. March 1986. (to be published in the Rev. Sci. Inst.)

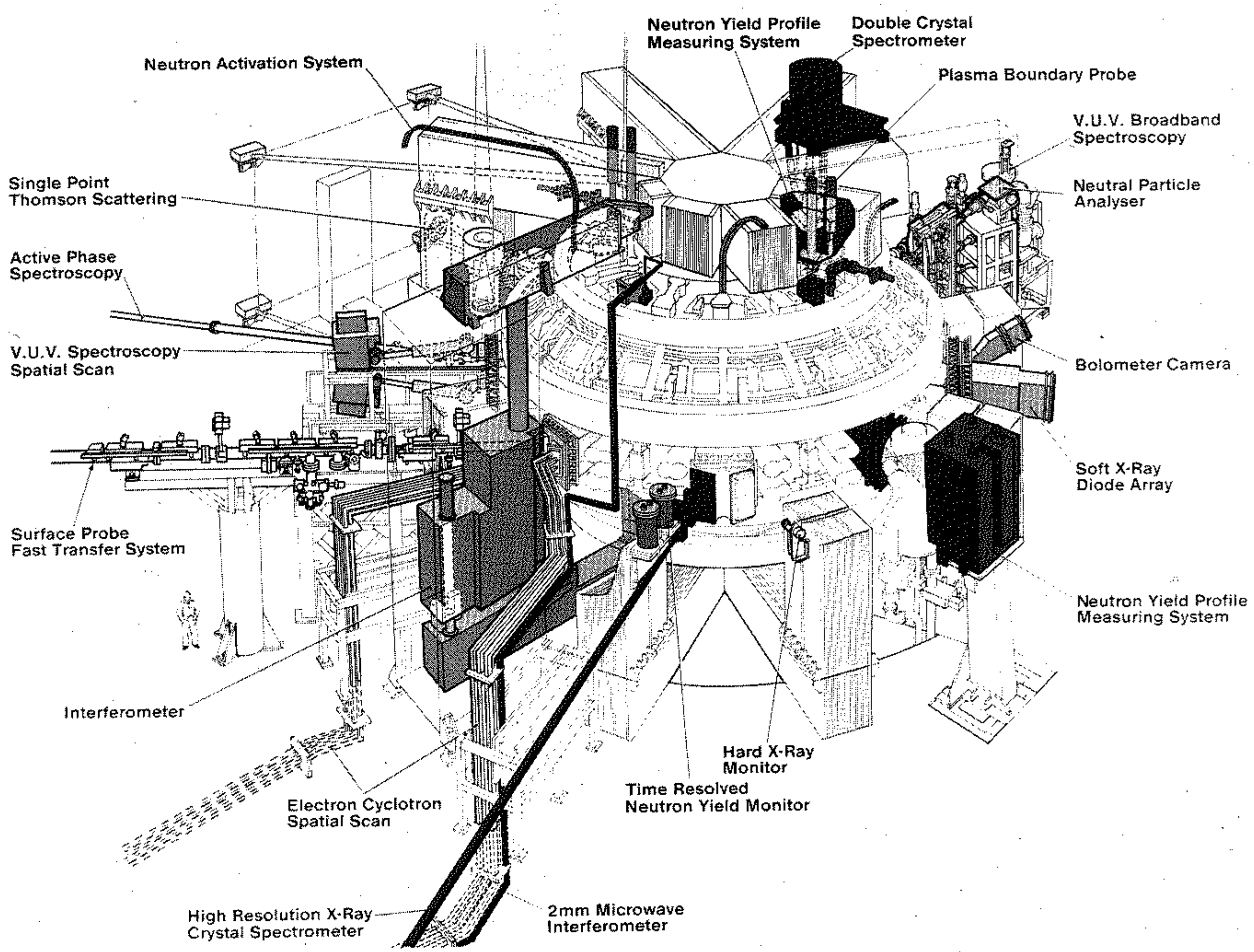
Table 1

STATUS OF THE JET DIAGNOSTICS SYSTEMS

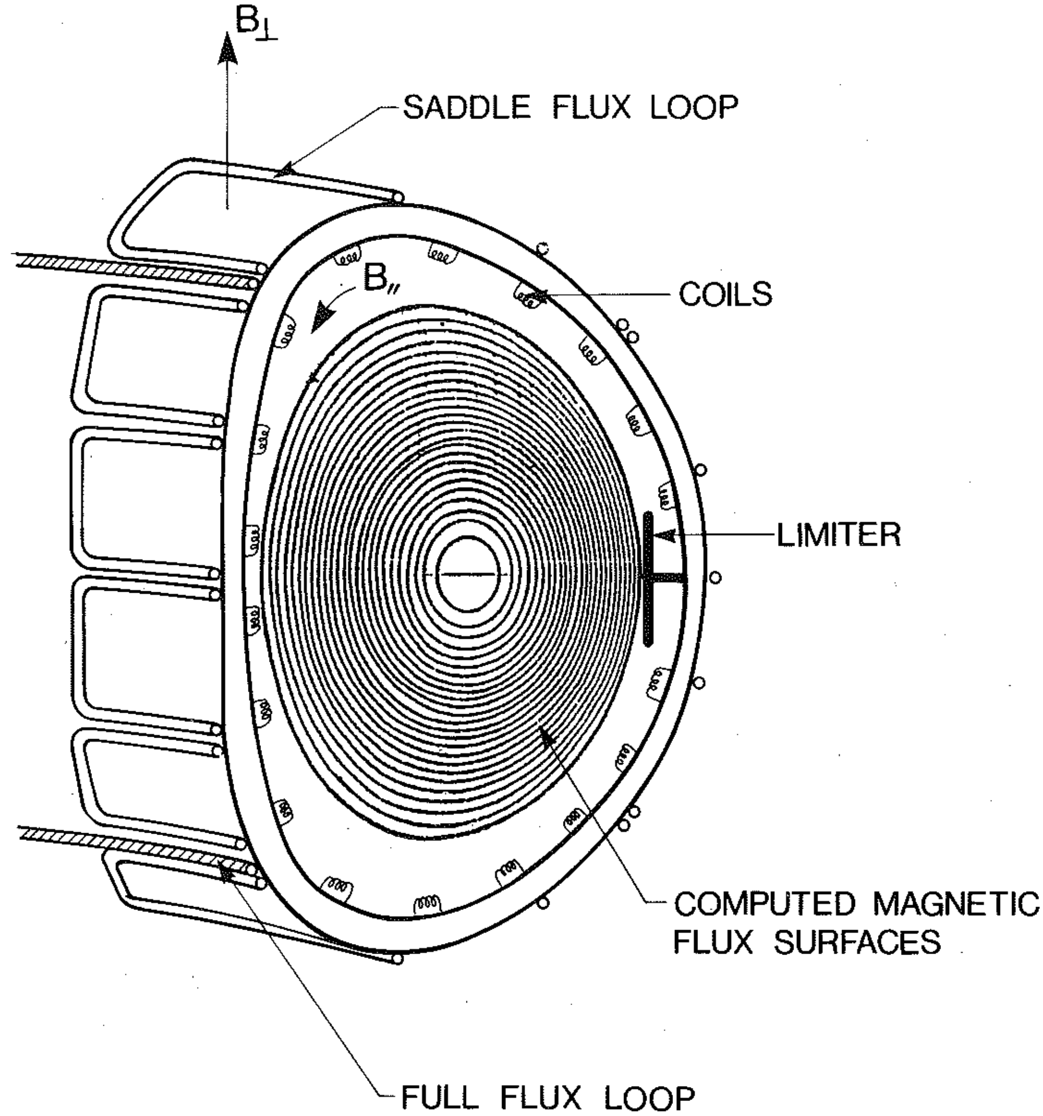
Diagnostic System	Diagnostic	Purpose	Association	Status Dec. 1985	Date of Operation in JET
KB1	Bolometer Scan	Time and space resolved total radiated power	IPP Garching	Operational	Mid 1983 partly Early 1984 fully
KC1	Magnetic Diagnostics	Plasma current, loop volts, plasma position, shape of flux surfaces	JET	(1) Operational (2) Enhanacement	Mid 1983 Late 1985
KE1	Single Point Thomson Scattering	T_e and n_e at one point several times	Risø	Operational	Mid 1984
KE3	Lidar Thomson Scattering	T_e and n_e profiles	JET and Stuttgart University	Construction	Early 1987
KG1	Multichannel Far Infrared Interferometer and Polarimeter	(1) $\int n_e ds$ on 7 vertical chord and 3 horizontal chords (2) $\int n_e B_p ds$ on 6 vertical channels	CEA Fontenay-aux-Roses	(1) Operational (2) Under construction	Mid 1984 partly Early 1985 fully Early 1987
KG2	Single Channel Microwave	$\int n_e(r) ds$ on 1 vertical and 3 horizontal chords in low density plasmas ($<10^{20} m^{-3}$)	JET and FOM Rijnhuizen JET	2mm Operational Extension to 1mm	Mid 1983 Not proceeding
KG3	Microwave Reflectometer	n_e profiles and flucutations	JET	(1) Prototype system operating (2) Multichannel system being designed	Mid 1983 Mid 1987
KH1	Hard X-ray Monitors	Runaway electrons and disruptions	JET	Operational	Mid 1983
KH2	X-ray Pulse Height Spectrometer	Plasma purity monitor and T_e on axis	JET	Installed	Early 1986
KJ1	Soft X-ray Diode Arrays	MHD instabilities and location of rational surfaces	IPP Garching	Operational	End 1985
KK1	Electron Cyclotron Emission Spatial Scan	T_e (r,t) with scan time of a few milliseconds	NPL, Culham Lab. and JET	Operational	Late 1985
KK2	Electron Cyclotron Emission Fast System	T_e (r,t) on microsecond time scale	FOM, Rijnhuizen	Operational	Early 1985
KL1	Limiter Surface Temperature	(i) Monitor of hot spots on limiter and RF antennae (ii) Temperature of wall and limiter surface	JET and KFA Jülich	Operational Development	Mid 1984 1986
KM1	2.4MeV Neutron Spectrometer		UKAEA Harwell	Construction proceeding	1986
KM3	2.4MeV Time-of-Flight Neutron Spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	NEBESD, Studsvik	Commissioning	1986
KM4	2.4MeV Spherical Ionisation Chamber		KFA Jülich	Commissioning	1986
KM2	14MeV Neutron Spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distributions	UKAEA Harwell	Design completed	
KM5	14MeV Neutron Spectrometer		NEBESD, Gothenberg	Decision on construction under review	
KN1	Time Resolved Neutron Yield Monitor	Time resolved neutron flux	UKAEA Harwell	Operational	Mid 1983
KN2	Neutron Activation	Absolute fluxes of neutrons	UKAEA Harwell	Installation	1986
KN3	Neutron Yield Profile Measuring System	Space and time resolved profile of neutron flux	UKAEA Harwell	Construction proceeding	1986
KN4	Delayed Neutron Activation	Absolute fluxes of neutrons	Mol	Awaiting delivery	1986
KP1	Fusion Product Detectors	Charged particle produced by fusion reactions	JET	Prototype operational Upgrade	1985 1986
KR1	Neutral Particle Analyser Array	Profiles of ion temperature	ENEA Frascati	Operational	Mid 1984 partly End 1985 fully
KS1	Active Phase Spectroscopy	Impurity behaviour in active conditions	IPP Garching	Under construction	Mid 1986
KS2	Spatial Scan X-ray Crystal Spectroscopy	Space and time resolved impurity density profiles	IPP Garching	Under construction	Early 1986
KS3	H-alpha and Visible Light Monitors	Ionisation rate, Z_{eff}, Impurity fluxes	JET	Operational Poloidal Scan	Early 1983 Early 1986
KS4	Active Beam Diagnostics (using heating beam)	Fully ionized light impurity concentration $T_i(r)$ rotation velocities	JET	Provisional system Under construction	Early 1986 Early 1987
KT1	VUV Spectroscopy Spatial Scan	Time and space resolved impuritiy densities	CEA Fontenay-aux-Roses	Operational	Mid 1985
KT2	VUV Broadband Spectroscopy	Impurity survey	UKAEA Culham Lab.	Operational	Early 1984
KT3	Visible Spectroscopy	Impurity fluxes from wall and limiters	JET	Operational	Mid 1983
KT4	Grazing Incidence Spectroscopy	Impurity survey	UKAEA Culham Lab.	Under construction	Early 1986
KX1	High Resolution X-ray Crystal Spectroscopy	Ion temperature by line broadening	ENEA Frascati	Installed	Early 1986
KY1	Surface Analysis Station	Plasma wall and limiter interations including release of hydrogen isotope recylcing	IPP Garching	Commissioning	Mid 1986
KY2	Surface Probe Fast Transfer System		UKAEA Culham Lab.	Commissioning	Mid 1986
KY3	Plasma Boundary Probe	Vertical probe drives for electrical and sur face collecting probes	JET UKAEA Culham Lab. IPP Garching	Both units installed	Mid 1984-86
KZ1	Pellet Injector Diagnostic	Particle transport, fueling	IPP Garching	Partly installed	Early 1986



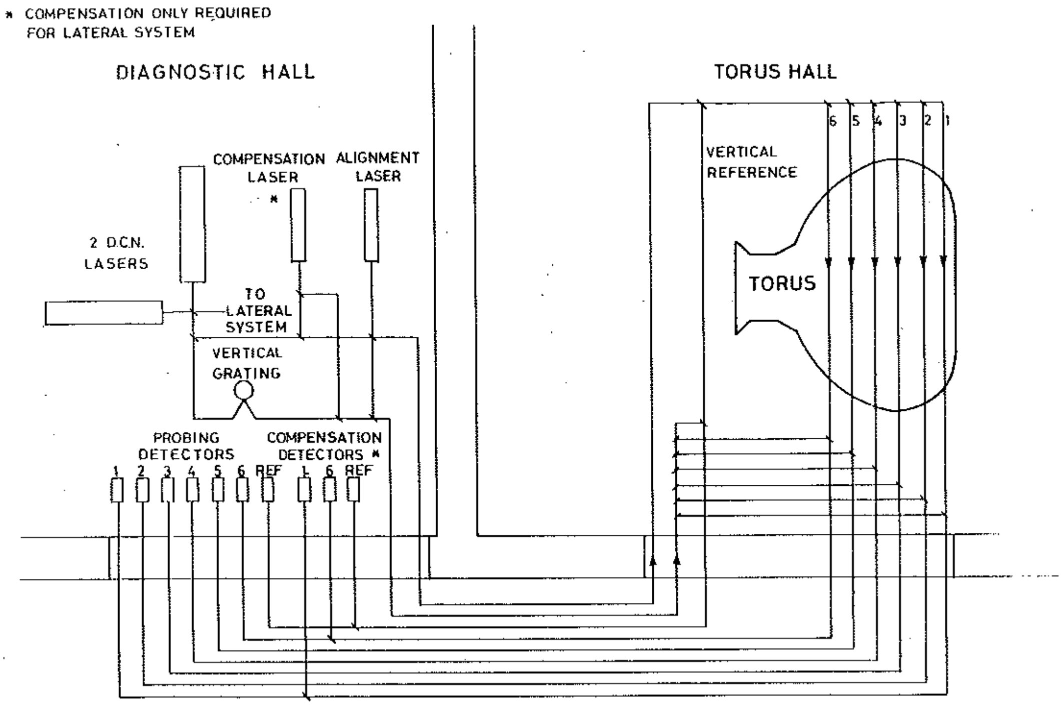
1. Spectral range covered by JET diagnostics.

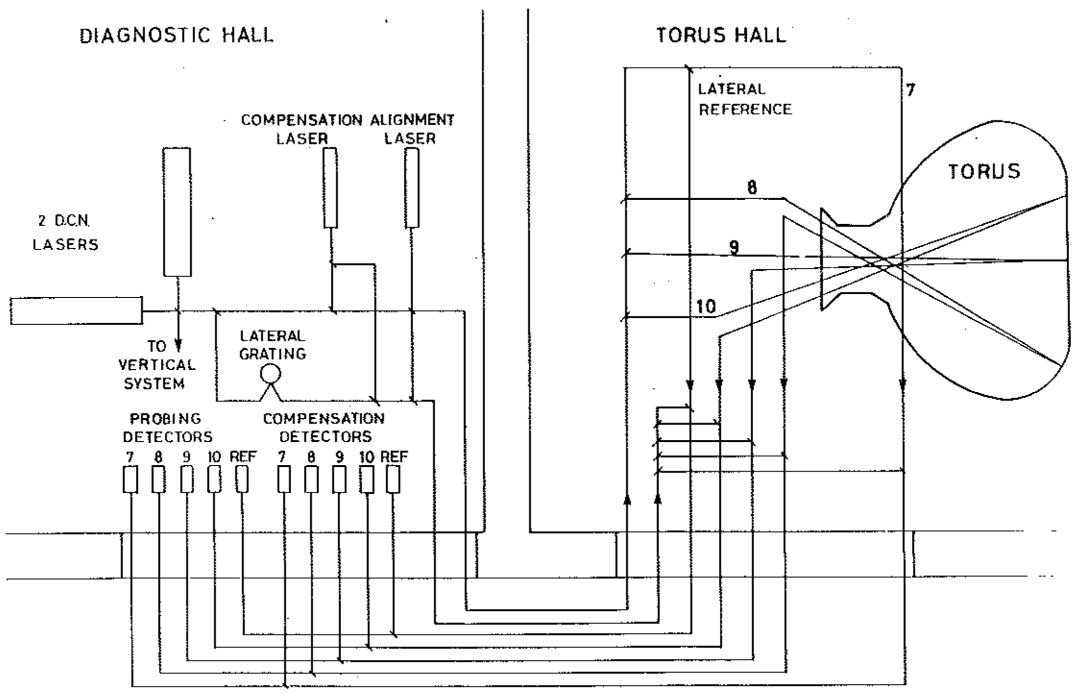


2. Schematic showing the location of JET diagnostic systems.

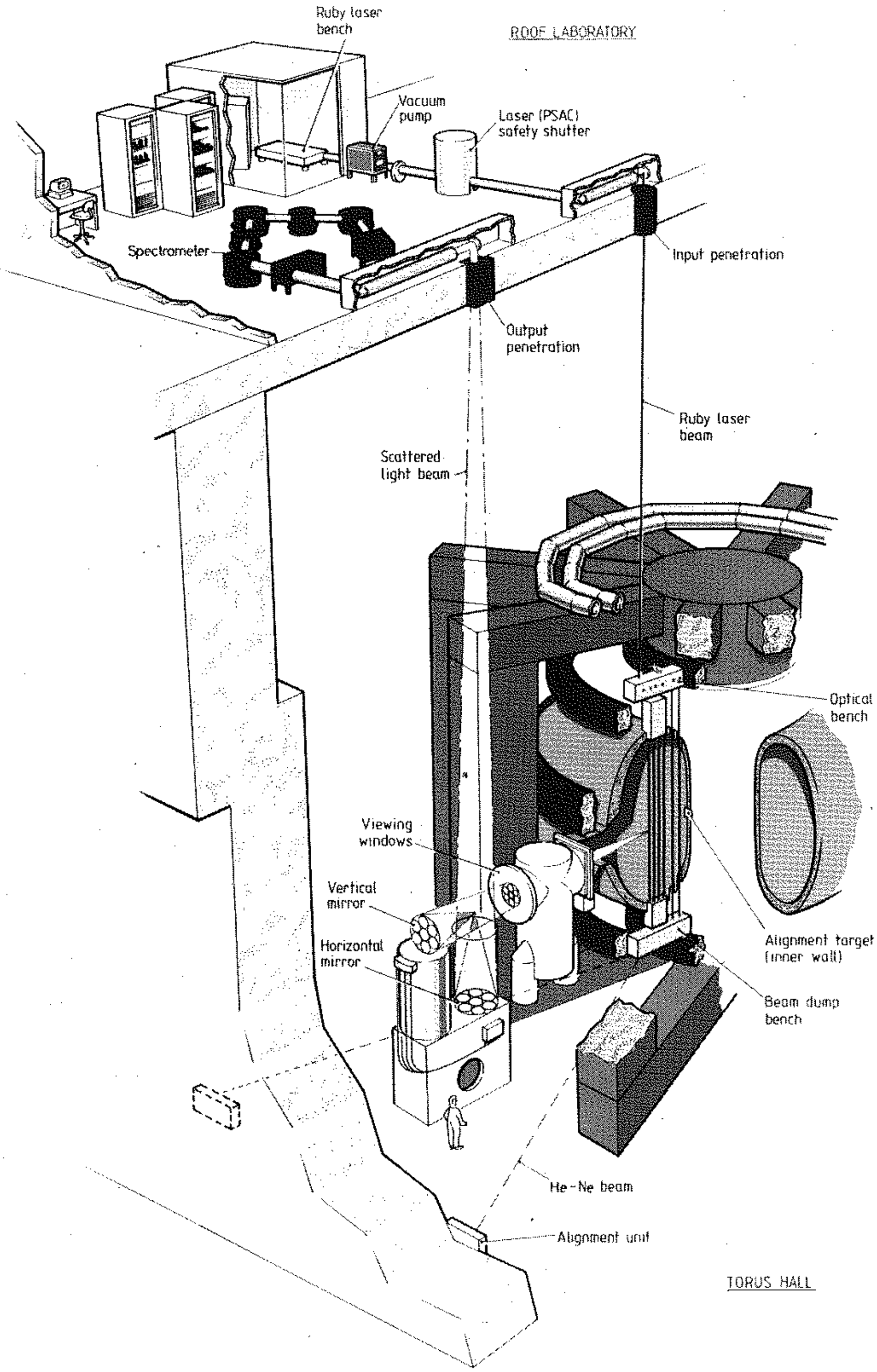


3. Magnetic diagnostics.

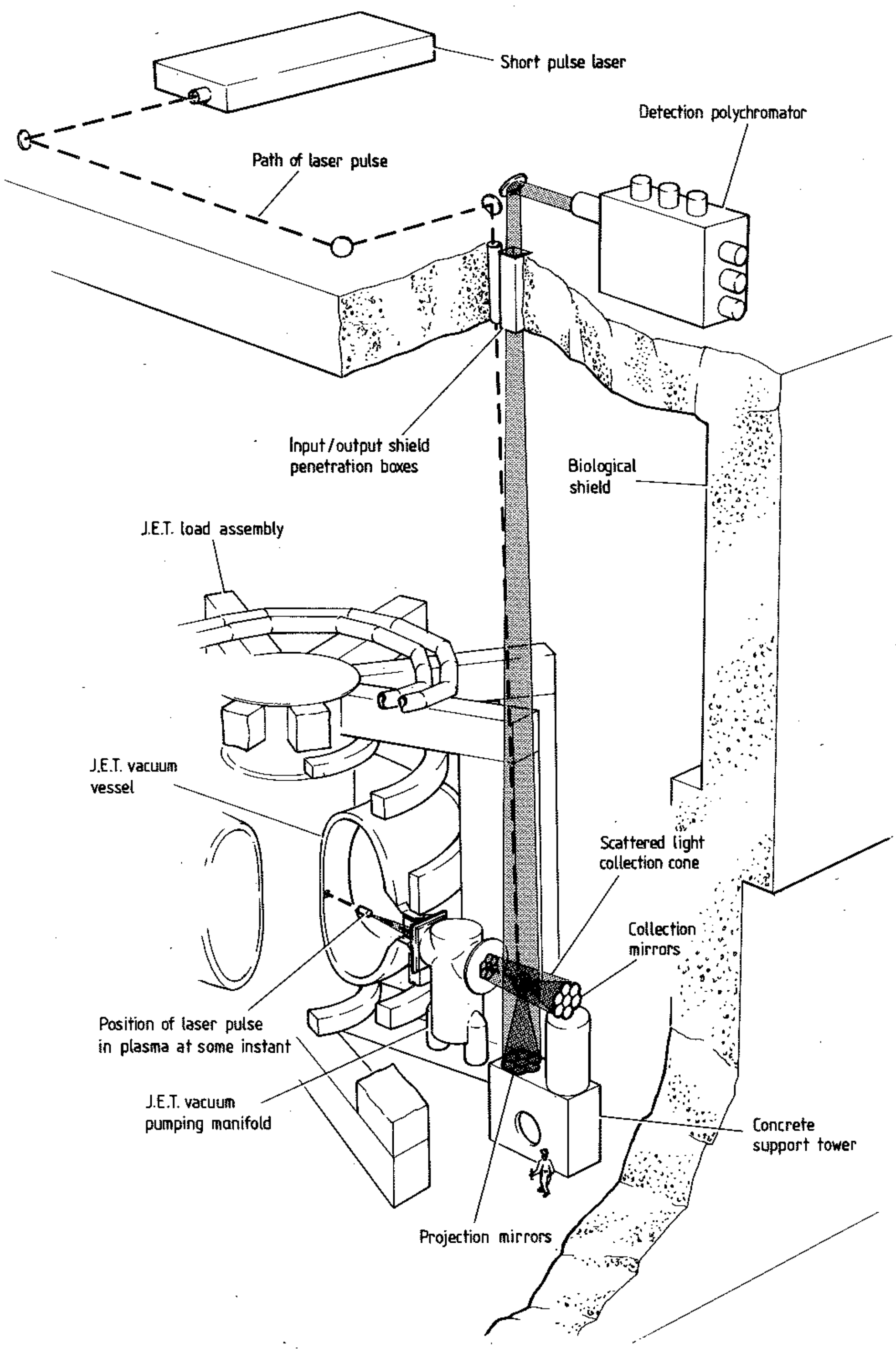




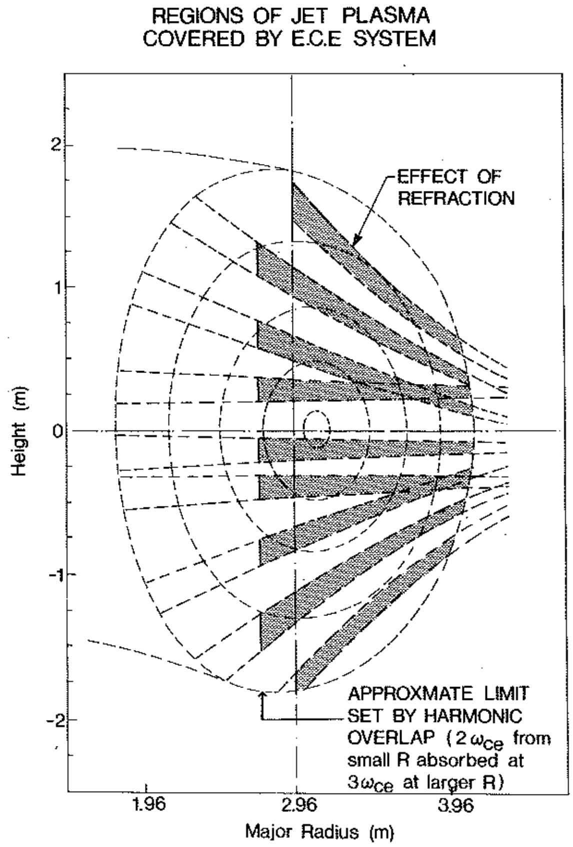
4. Schematic of the multichannel interferometer.



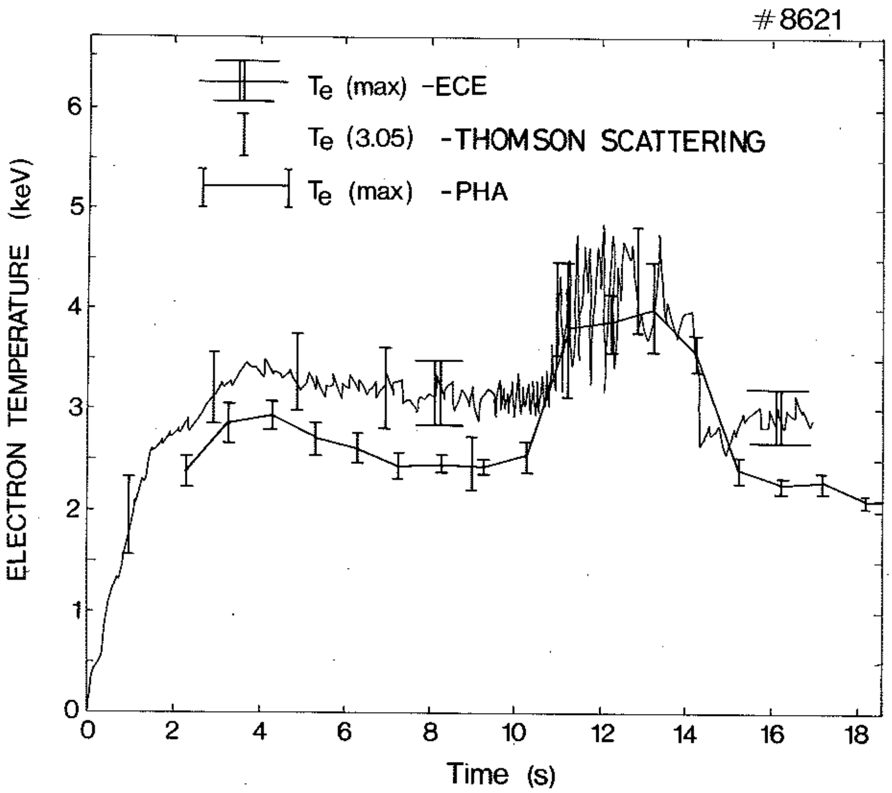
5. Schematic of the Single Point Thomson Scattering Diagnostic.



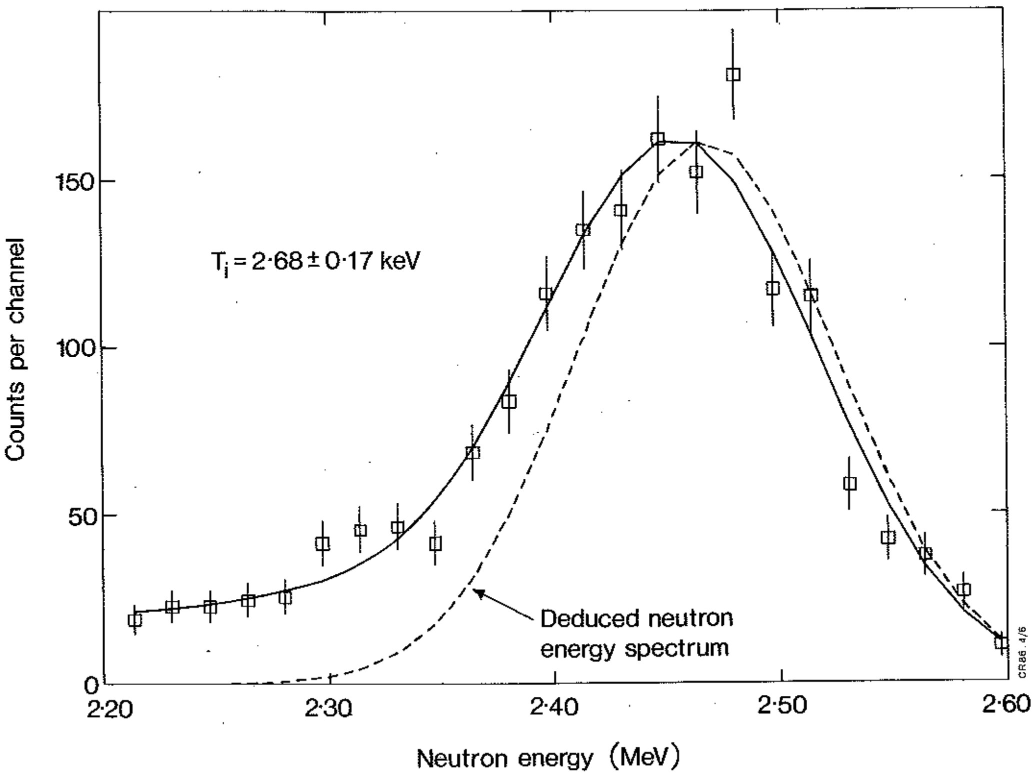
6. Schematic of the LIDAR Thomson Scattering system.



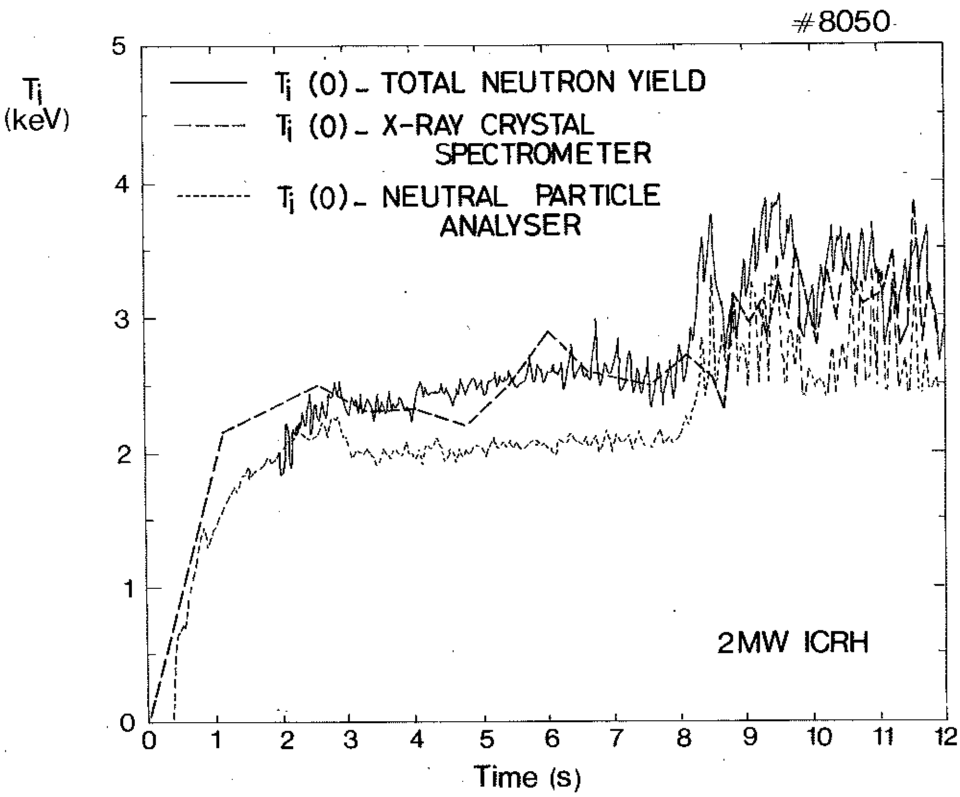
7. The multichord ECE system. The shaded areas show the regions of the plasma covered by the ECE measurements.



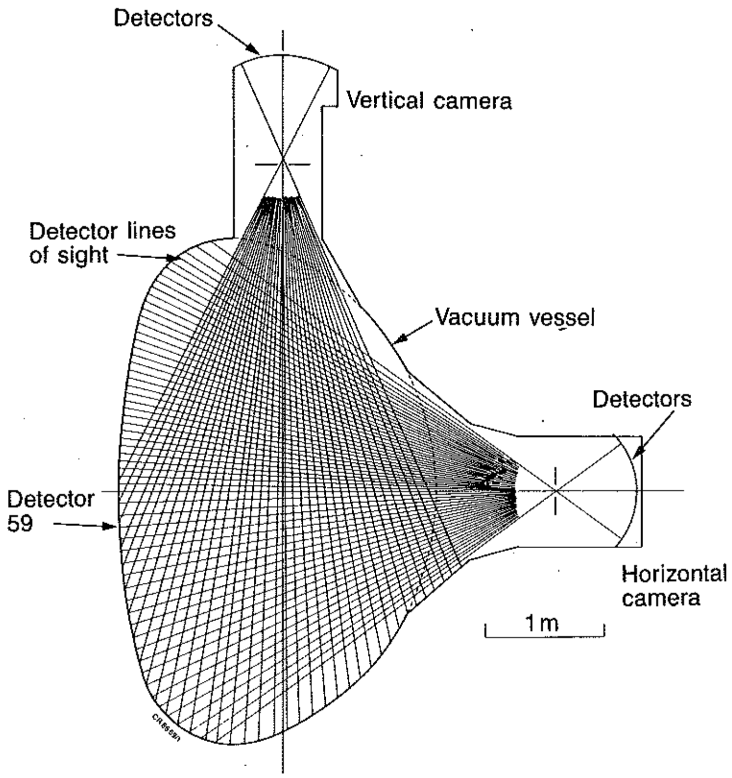
8. Comparison of electron temperatures measured by different JET diagnostics. The data from the different diagnostics are all based on independent absolute calibrations, and have not been normalised in any way.



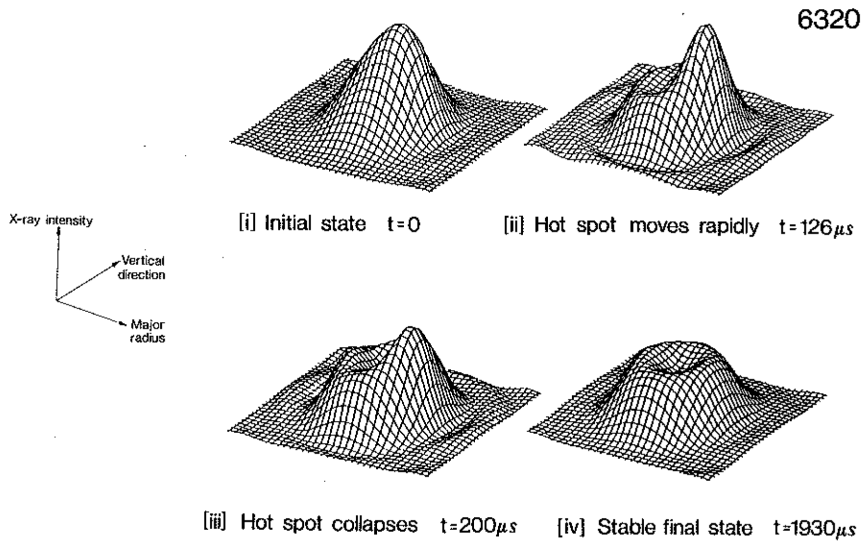
9. Typical spectrum of neutrons emitted from a deuterium plasma.



10. Comparison of ion temperatures measured with different methods. The data from the different diagnostics are all based on independent absolute cailbrations and have not been normalised in any way.



11. Soft X-ray diode arrays.



12. X-ray emission during a sawtooth crash.