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R. Giannella

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R. Giannella

JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

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SPECTROSCOPIC DIAGNOSTICS AND MEASUREMENTS AT JET

R. Giannella
JET Joint Undertaking, Abingdon, Oxfordshire, UK

ABSTRACT A concise review is presented of activity in the field of spectroscopic diagnostic at JET during the latest few years. Together with a description of instruments, examples are given of the measurements conducted with these systems and some experimental result obtained with such activity are outlined. Emphasis is also given to the upgrading of existing apparatuses and the construction of new diagnostics ahead of the next experimental phase.

Introduction

A significant fraction of the energy employed in the production of thermonuclear plasmas in tokamak devices is released from those plasmas in the form of electromagnetic radiation. For high temperature devices such as JET, only a minor part of this radiation is emitted from the hot plasma core, although radiation levels up to 50 kW/m^3 and as much as 50 kW from a single emission line have been measured under certain circumstances in that region. At the periphery of the main plasma, in the scrape-off layer and in the divertor, where the emission per unit volume can be up to several MW/m^3, radiation is in most cases a major term in the power balance and can account, in some cases, for the exhaust of nearly 100% of the global heating power. The usefully observable spectrum is very wide: diagnostic applications have been made on JET using radiation emitted in a range extending from high frequency radio waves to γ-rays.

In this paper we give a concise review of spectroscopic apparatuses and measurements used so far for the diagnosis of the JET plasma in a narrower spectrum ranging from about 0.1 to 1000 nm. Emphasis will also be given to some new diagnostics, presently under construction, for the future experimental campaigns. Most of these systems are designed for routine operation and are generally used systematically in all the plasma pulses where they can produce significant data. Many of them have been operating for several years and producing extensive data sets that provide a virtually complete documentation on the different operation scenarios, confinement regimes, their development with time as well the influence of hardware modifications on the performance or the state of contamination of the tokamak.

Soft X-ray and VUV spectroscopy of the main plasma

Fruitful information can be obtained on every pulse and in all phases of the discharge by means of *passive monitors of radiation*, that detect photons spontaneously emitted by the plasma and do not rely on application of particle beams scanning the discharge. This is the widest class of spectroscopic devices used on JET. Although these systems intrinsically supply line integrated information, adequate space resolution could be achieved in JET by means of multi-chord apparatuses scanning the plasma with arrays of lines of sight from different points of view. Such is the case of *broad band detection systems* as the bolometry diagnostic and the soft X-ray diode cameras.

The former apparatus [1], in its fundamental configuration, consists of three arrays of detectors (cameras) with a total of 34 lines of sight covering most of the plasma cross section. It records most of the photon radiation in a wavelength range extending approximately from 0.1 nm to 300 nm. Its time resolution is 20 ms. A major rearrangement of this diagnostic (see fig. 1) is now in progress to adapt it to the new configuration of the plasma and of the vacuum vessel in the forthcoming pumped divertor experimental phase and to increase its space and time resolution. This upgrading requires the installation of the detectors inside the torus vacuum vessel. For this reason we had to develop new bolometric detectors capable to stand, without the aid of an active cooling system, the high temperatures (up to 400 °C) required for the baking of that vessel. The very thin (~ 35 nm) gold resistors used as sensitive elements in the cooled detectors previously used at JET suffered irreproducible and unstable modification of their resistance when heated at such temperatures. The new thicker gold and platinum resistors developed were proved to maintain, after a suitable thermal treatment, their resistance properties even after many heating cycles up to 450 °C [2]. Through a substantial increase of the total number of lines of sight (there will be 104 lines of sight built in 23 cameras located in two toroidal positions) an improved space resolution will also be achieved. The plasma between the X-point and the divertor plates will be crossed by more than 40 lines of sight as opposed to 4 previously; the outer 10% of the minor radius in the main plasma will be tangentially scanned by 12 instead of 3 channels.

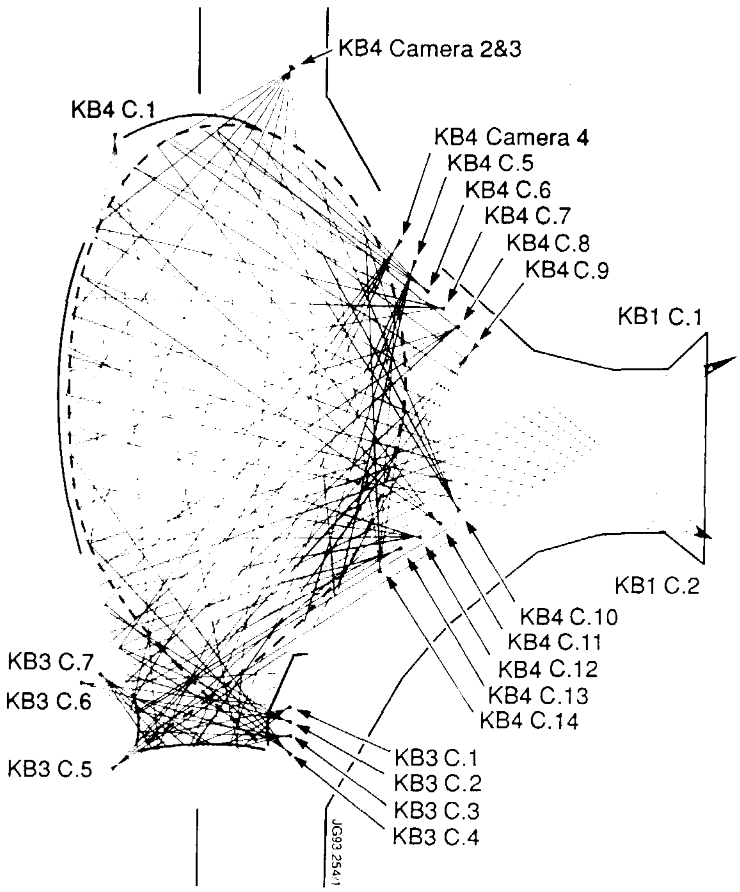

Fig. 1 New arrangement of the bolometric diagnostic for the upcoming pumped divertor experimental phase.

Due to the typical hollow radiation profiles of the JET discharges, the information gathered with bolometry is often limited to the outer layers of the main plasma and to the scrape-off and divertor region. High time resolution (highest sampling rate HSR = 200 kHz, band pass BP = 33 kHz) tomography [3] of the plasma emission from the plasma core is obtained with two soft X-ray diode cameras [4], with a total of 100 lines of sight. The radiation detected is in a wavelength range between 0.04 nm and a variable upper limit (< 4 nm) set by the metal filters used. The good space and time resolution afforded by this diagnostic make it precious for the analysis of rapidly varying phenomena such as the sawteeth collapses or MHD oscillations. Real time tomographic inversion of the integrated signals is performed 50 times per second by a network of four 20 MHz T800 transputers [5].

The diagnostic is now being upgraded for better space resolution. A total of 204 channels in 6 cameras will result in a radial resolution length Δr = 2.5 cm (three times better than previously) and allow resolution of angular harmonics of index up to 5 - 6. The time resolution will also be enhanced (HSR = 250 kHz, BP = 100 kHz).

Moderate *spectral resolution in the soft X-rays* $\lambda/\Delta\lambda$ = O(10) is obtained by a pulse height analysis system [6]. Better resolution is obtained with a number of crystal spectrometers. Taking advantage of the favourable dependence of the luminosity L of these systems on the distance D between the dispersing crystal and the photon source [7] ($L \propto D^{-1}$ and not $L \propto D^{-2}$ as in the case of grating instruments), it was possible to design several of these systems [7,8] such as to locate, without the use of relay optics, the analysing and detecting sections ~ 20 m away from the tokamak outside the hostile environment of the JET torus hall. These instruments provide survey monitoring of the 0.1 - 10 nm range as well as spectral resolutions up to $\lambda/\Delta\lambda \approx$ 20,000 and monochromatic spatial scanning of the discharge in a meridian plane [9]. Due to the relatively low crowdedness of this part of the spectrum and to the high energy involved in the transitions, suitable lines are available for the measure of the central ion temperature $T_i(0)$ that are not affected by the presence of high intensity edge-emitted neighbours or other isochromatic emission features. Such lines can be easily fitted by simple gaussians or Voigt

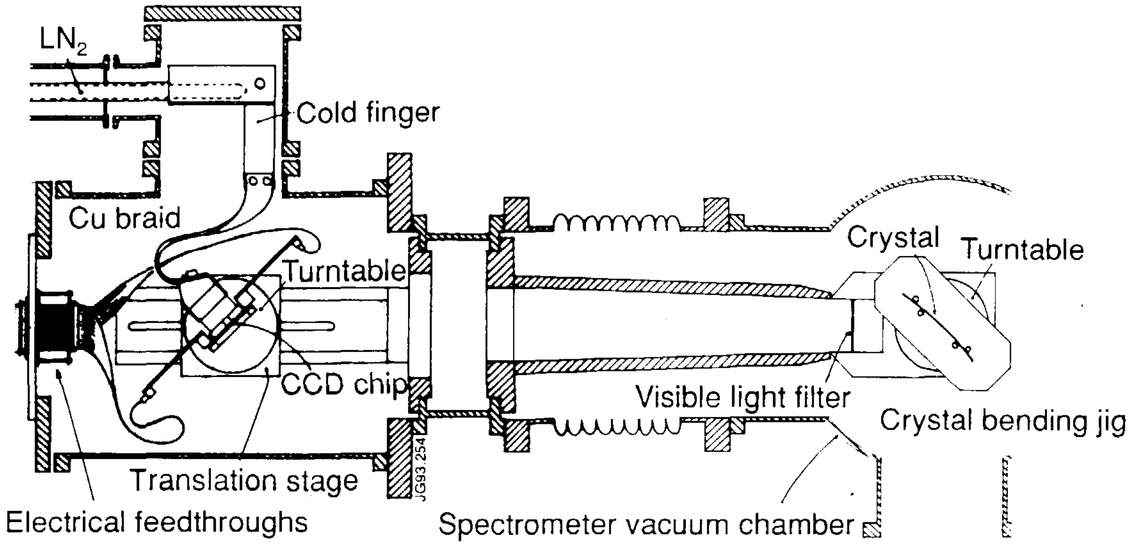

Fig. 2 Schematic of the curved cristal spectrometer equipped with a CCD soft X-ray detector recently tested on JET. Three such instruments will be mounted in 1994 for T_i measurements and transport studies

profiles [10]. Space resolved T_i measurements have been obtained with these systems by simultaneous monitor of He- and H-like resonance lines from different impurities and purposely added trace elements [11]. The future implementation of three close coupled curved crystal instruments observing the plasma along different lines of sight, in addition to the two systems already available, is expected to supply virtually complete profile information on T_i from high resolution passive spectroscopy, useful for transport studies of those pulses or plasma phases where no active spectroscopy is available.

One such system has been tested recently on JET using a CCD detector optimised for direct detection of soft X-rays (fig. 2). The detector, consisting of an array of 1152x1242 22.5 μm square pixels, was developed by the Leicester University primarily for astrophysical applications [12]. Cooled at the liquid N temperature it detects single photons with a quantum efficiency larger than 20% between 0.7 keV and 12 keV. A He-like Cl resonance spectrum recorded by this instrument from a JET pulse is displayed in fig. 3.

Another recent addition to the family of JET crystal spectrometers is a Bragg rotor spectrometer. Its JET implementation, developed by the UKAEA-Euratom association of Culham, consists of two sections. The first one, devoted to continuous monitor of the main impurities, uses a side-by-side array of small diffractors (crystals and multi-layer mirrors) scanning small spectral ranges about representative lines of these contaminants [13]. The second section allows full coverage of the soft X-ray spectrum with a set of six diffractors scanned sequentially by a hexagonal rotor [14].

This instrument and the active phase double crystal monochromator (APDCM) [8], both located outside the torus hall, isolated from the torus vacuum by a 1 μm thick

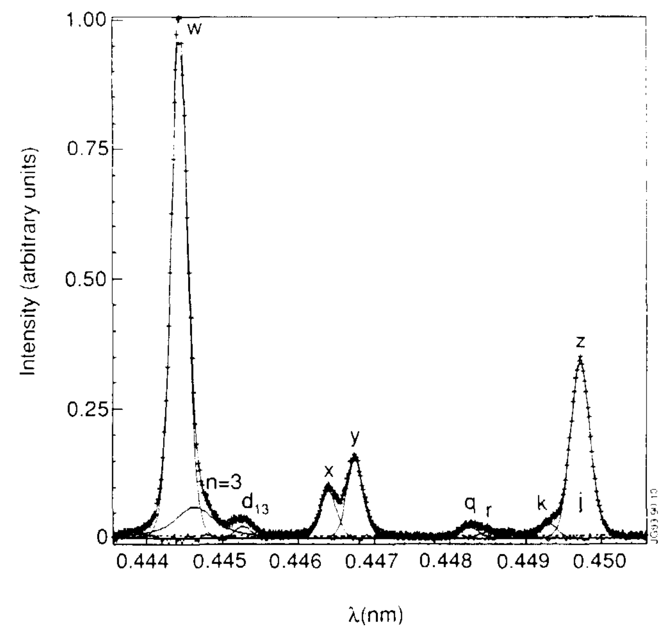

Fig. 3 He-like Cl resonance spectrum recorded on JET by the instrument shown in fig. 2

polypropylene window, and observing the plasma through the same observation beam-line, were operated throughout the JET preliminary tritium experiments (PTE) [15] in November 1991. They were used as monitors of the plasma contaminants, while the VUV/XUV grating spectrometers, located in the torus hall, could not be operated due to the high radiation-induced noise. The PTE test [16] demonstrated the good shielding properties of the APDCM, confirming its basic design as a good candidate for crystal spectroscopy [17] in the next generation of magnetic fusion devices, and supplied useful information on the radiation induced noise of gas proportional counters. The polypropylene window, with a useful transmission up to wavelengths $\lambda \approx 10$ nm, was shown to provide safe tritium isolation for the instruments' vacuum vessel.

In the VUV/XUV range two multichannel spectrometers, a SPRED survey instrument [18] and an XUV grazing incidence spectrometer (XGIS) [19], observe the main plasma along fixed or slowly moving lines of sight, with a practical spectral coverage from 1.7 to 170 nm. They allow regular monitoring of the H- and He-like resonance lines of the major light contaminants (a function also performed by the crystal instruments but with a lower spectral resolution) as well as the most prominent Li-, Be-, Na- and Mg-like $\Delta n = 0$ transitions of elements from the 2nd, 3rd and 4th periods. Using selected lines from the above set the elemental contributions to the total radiated power from the dominant impurities are determined for some operating regimes [20,21] (fig. 4). Knowledge of these contributions is crucial in accounting for certain operating limits (e.g. high density limits) and to allow optimisation of the machine operation. In addition to the low-Z impurities originating from the plasma-facing surfaces (Be and C), other impurities prove on occasions to be detrimental to the plasma performance (e.g. O, Cl, Ni).

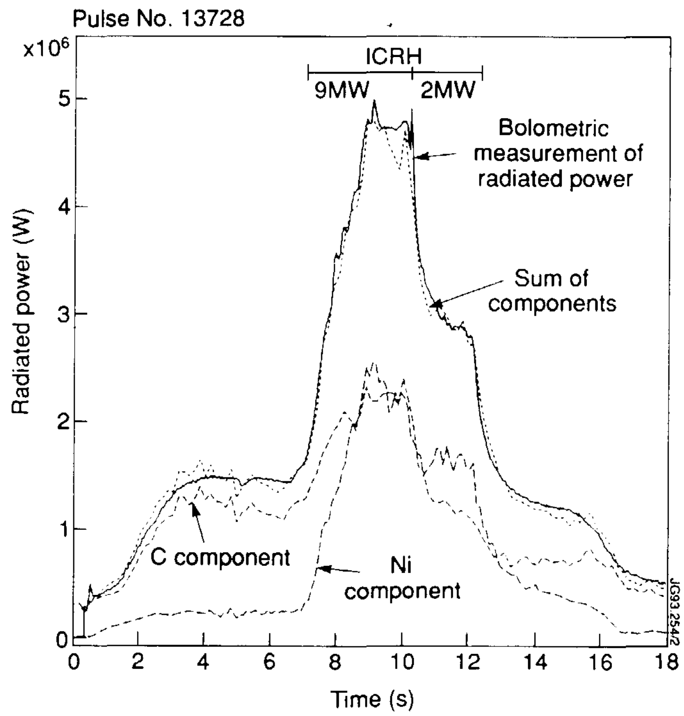

Fig. 4 Elemental components of radiated power derived from line intensities measured by the SPRED and XGIS spectrometer. Their sum is compared to the total bolometric radiated power.

Integrated information from the whole range of diagnostics described above is used for impurity transport studies during transient phenomena such as central or peripheral accumulation of impurities as in the cases of sawtooth-free pellet fuelled discharges [22] and of ELM-free H-modes [23,24] respectively; or in laser blow-off experiments [25,26]. The space resolution supplied by the bolometers and/or soft X-ray tomographic system, together with the selective information on individual ion states from the line monitors, reveal the existence of structures in the radial profiles of the diffusivity D of these impurities or in the convection field that these particles are subjected to. Clear evidence was found with these studies, for instance, of the existence, in the centre of the discharge, of a region of slow transport (RSL) [22,26], where D can be as low as to be comparable with the neoclassically predicted values. A very similar effect was subsequently found in the particle transport of the electrons in sawtooth free discharges [27,28]. The analysis of these data is mainly performed by checks of consistency between the different experimental data and simulations performed with transport codes [24,26]. The codes in turn require the use of large amounts of reliable atomic data in order to model accurately the kinetic processes of excitation/de-excitation and ionisation/electron capture involving the

different populations of particles and determining the ionisation equilibrium and the spectral emission. For this reason a structured computational tool and data-base, Atomic Data and Analysis Structure [29], was developed at JET. This structure consists of generalised collisional radiative programs for the production and easy upgrading of derived rate coefficient data used in analysis. The data base of such coefficients is accessed directly by the utilisation codes.
Analysing the time evolution of the perturbation in the soft X-ray emissivity induced by the injected impurities in dedicated experiments where the plasma current and toroidal magnetic field, as well as the average electron density and the heating power, were scanned from pulse to pulse [30], it was possible to identify a correlation between the size of the RSL and that of low magnetic shear [31].

VUV spectroscopy of the divertor

Two identical VUV spectrometers, out of an original group of three, observing the plasma through rotating double faced mirrors supply spatially resolved information on line intensities from the upper half of the tokamak cross section. This system has been recently used to observe line radiation of deuterium and low ionisation states of carbon (C II, C III and C IV) from the upper X-point region in discharges performed in open divertor configurations (single upper null or double null). The data obtained gave information on the carbon fluxes Γ_C from the upper divertor target plates on both sides of the poloidal magnetic field null, on the dynamics of that impurity in the scrape-off layer, as well as on the radiation and localisation in the poloidal plane of MARFE's. It was found that, at moderate heating power, Γ_C is higher on the ion drift side of the null, especially when this coincides with the outer side (that is when the ion ∇B drift is directed upwards). Increasing that power, Γ_C becomes higher on the opposite side until a precipitous increase of its growth develops leading to the eventual complete dilution of the main plasma (carbon bloom). The onset of such a condition was found to be critically dependent on the surface temperature of the target plates reached under the effect of the power conducted to them from the main plasma. To prevent such occurrences, strong gas puffing was found useful, but above a certain level this same tool resulted in the development of MARFE's in the proximity of the X-point but well separated from the plates near the separatrix [32,33].

The data of this diagnostic have been used in the initial experimental studies for validation of divertor plasma models. This analysis is based on the integrated use [34] of a fluid code simulating the energy and particle transport in the background divertor plasma [35] and two Monte Carlo codes describing the particle transport of the impurities [36] and of the neutrals [37] respectively. Preliminary results of this investigation, based on spatial profiles of the 90.4 nm C II and the 31.2 nm C IV lines suggest that, in the open divertor configuration used in the latest experimental campaign, the carbon originating from the inner wall is still an important source of contamination of the main plasma [38,39].
These studies will be extensively carried out, in the upcoming pumped divertor experimental phase, using a large variety of spectroscopic data from a comprehensive range of diagnostics. As an example we describe in the following the rearrangement of the existing VUV/XUV spectroscopic diagnostics and the new ones in preparation. Various modifications are being made to the mirror scanning VUV spectrometers described above. Their original slit-channeltron detectors were converted, in 1990, to polychromatic detectors consisting of 2 microchannel plates (MCP's) in chevron assembly closely coupled to a multi-anode array covering with 10 anodes a spectral range of 0.3 to 0.9 nm [40,41]. 32-channel anode arrays have now been implemented for the present upgrade to cover a three times larger range for a better measure of the continuum background about the monitored emission lines. The signals from each array, converted to ECL pulses by two 16 channel amplifier-discriminator cards mounted inside the instrument's vacuum vessel, are sent via 32 50 MHz optical transmission lines to the acquisition system some 70 m away. This will allow a capability to detect up to $\sim 10^7$ photons/s per channel before saturation effects become significant. Two such detectors, movable on the 1 m diameter Rowland circle are mounted in each instruments. The whole system of three spectrometers will be restored. One will view vertically, from the top of the machine, the divertor area. The other two will observe from a horizontal port the divertor inner strike zone through the lower half of the main plasma and the upper half of the tokamak meridian cross section (see fig. 5). With a new assembly of the

scanning mirrors mounted on eight sided supports a scanning repetition rate of 40 spatial profiles per second will be obtained. These three instruments will only be able to observe two narrow spectral regions at a time in a limited range (useful wavelength range 20 - 200 nm). To compensate for this limitation additional space resolved information from wide band multi-channel VUV/XUV instruments with a slower time resolution will be available on the same tokamak's octant. The XGIS, viewing from the horizontal port (fig. 5) will be scanned at a slower rate (≤ 2 scans per second). Another pivoted support for spatial scanning, to be swept across an angle of 7° (fig. 5) twice a second, will be located above the tokamak. It will carry, for vertical observation of the divertor area, one more XGIS together with a new double SPRED.

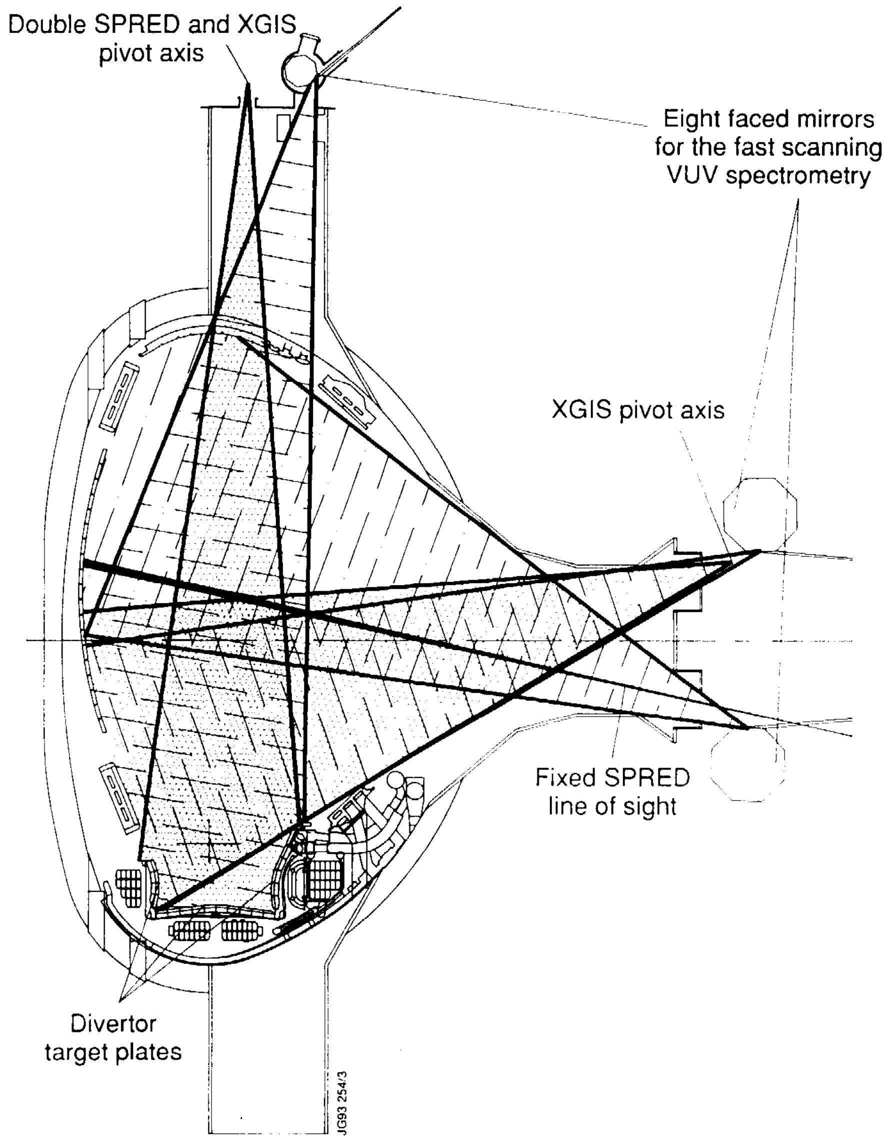

Fig. 5 Lines of sight of the VUV/XUV diagnostics for the pumped divertor experimental phase.

The latter instrument, whose construction has just been completed, will cover continuously the wavelength range from 10 to 150 nm. Its vacuum vessel, housing the two platinum coated holographic toroidal gratings, is carved in a solid stainless steel block that will provide shielding against hard X- and γ–rays to its two detectors, each one consisting of a 50 mm diameter HOT MCP (high current MCP) proximity focused onto a phosphor coated fiber optic coherent bundle. This fiber bundle is the vacuum interface of the detector and is coupled to a 2048 pixel diode array. The minimum read-out time of a full spectrum with 16 bit dynamic range will be 10 ms, resulting in the acquisition of 50 spectra per spatial scan. Through the same stainless steel body, passing between the gratings, is the vacuum line of sight of the XGIS whose detector, of similar construction, is also shielded by it.

Visible and active beam spectroscopy

Extensive use is made of diagnostic systems working in the wavelength interval from 250 to 1000 nm. Among them are several CCD and CID video cameras for narrow- or wide-band two-dimensional imaging of plasma facing components, or of the low temperature plasma in front of them [42]. In addition to them a number of single or multi-chord viewing devices are linked by 50 to 100 m long

optical fibers, or by mirror relay optics when low attenuation in the near UV range is required, to various analysis/detection stations [43,44] located outside the torus hall. The latter range from the simple interference filter-photomultiplier assembly to high resolution spectrometers equipped with two-dimensional CCD cameras providing spectral resolution for the different viewing lines.
An important application of such devices, the active beam spectroscopy, relies on emission from the region of plasma probed by the heating neutral beams. The complex spectra observed contain features (mainly excited by charge exchange recombination or CXR) emitted in that region by ions or atoms from the background plasma together with other features due to the beam emission (BE) and other passive features emitted by colder ion populations at the plasma edge. From the analysis of CXR signatures of the spectra, this powerful diagnostic [45, and refs. therein] supplies, for beam heated plasmas, space profiles of the temperature, toroidal velocity and density of different thermal ion populations (D^+, He^{2+}, Be^{4+}, C^{6+}). BE spectroscopy provides local measurements of the beam density and of the magnetic field.

The latest addition to this family of diagnostic tools is a new multi-chord spectrometer for velocity measurements at the plasma edge [46]. The choice of CXR-excited, high n number transitions allows the convenient use of fiber optics relay and high resolution visible spectroscopy. From the spectral profiles of a given line (e.g. C VI 529.1 nm), as obtained looking at the same portion of plasma on a neutral beam's path along two non parallel lines of sight, the poloidal and toroidal velocity components of the radiating impurity are obtained. The same two line profiles also provide a measurement of its density and temperature. The light from 10 pairs of lines of sight is fed to a stack of four rows of five slits at the input of a 1.33 m Czerny-Turner spectrometer and then recorded by a single two-dimensional detector. To avoid overlap of spectra from adjacent slits the light is pre-analysed by a low dispersion spectrometer used as a band pass filter ($\Delta\lambda$ = 1.5 nm). The detector is a 40 mm image intensifier, using an MCP providing a luminous gain of 10^5, coupled by fiber optics bundles to four diode arrays with 1024 pixel and total read-out time of 1 ms, with 12 bit dynamic range. Measurements with this apparatus, made on several JET H-mode discharges, have shown no evidence of strong poloidal velocity of the C^{6+} population near the separatrix, contrary to the findings of experiments performed on other machines, but revealed the presence of a thin layer of strong negative radial electric field in agreement with those experiments [47]. Studies on the dependence of the L-H transition on collisionality at the separatrix were also performed with the same instrument [48]. It was found that the collisionality of the main ions is not the critical parameter for the occurrence of the transition and that it is necessary to include the effect of impurities in the expression of viscosity.

Conclusion

A wide variety of spectroscopic devices and techniques are used on JET for the diagnosis of its hot core, the outer layers of the main plasma, the scrape-off layer and the divertor plasma. Progress in the phenomenological description of the different processes, the measurement of specific physical parameters and the validation of theoretical predictions has been achieved employing space resolving systems and by integrated use of the information from a range of diagnostics together with extensive use of simulation codes describing the transport and the atomic processes governing the ionisation equilibria and emission processes.
Acknowledgment Systems and measurements described here are due the work of many years by a large number of JET staff. Several apparatuses were designed and built by the National Euratom Associations of France, Germany, Italy, Sweden and UK that also helped with the operation of these diagnostics and the data analysis. The author is grateful to P. Thomas for the support received in the preparation of this paper, as well as to R. Barnsley, I. Coffey, R. Gill, E. van der Goot, N. Gottardi, J. Hancock, N. Hawkes, M. von Hellermann, H. Jäckel, G. Janeschitz, L. Lauro-Taroni, K. Lawson, C. Maggi, P. Morgan, H. Morsi, R. Reichle, H. Summers for their useful suggestions and criticisms.

References

[1] K.F. Mast, H. Krause, K. Behringer, A. Bulliard, G. Magyar, Rev. Sci. Instr. **56** (1985) 969.
[2] N. Gottardi, K.F. Mast, R. Wirth, *Development of a High Temperatuere Bolometer with Platinum on Mica Support* Physicalisch-Technische Studien GmbH, Freiburg, 1992.
[3] R.S. Granetz, P. Smeulders, Nucl. Fus. **28** (1988) 457.

[4]A.W. Edwards, H.U. Fahrbach, R.D. Gill, R. Granetz, E. Oord, G. Schramm, S. Tsuji, A.Weller, D. Zasche, Rev. Sci. Instr. **57** (1986) 2142.
[5]E. van der Goot, A.W. Edwards, J. Holm JET-P (89) 45.
[6]D. Pasini, R.D. Gill, J. Holm and E. van der Goot, Rev. Sci. Instr. **59** (1988) 693.
[7]R. Bartiromo, F. Bombarda, R. Giannella, S. Mantovani, L. Panaccione, G. Pizzicaroli, Rev. Sci. Instr. **60** (1989) 237.
[8]R. Barnsley, U. Schumacher, E. Källne, H.W. Morsi, G. Rupprecht, Rev. Sci. Instr. **62** (1991) 889.
[9]U. Schumacher, E. Källne, H.W. Morsi, G. Rupprecht, Rev. Sci. Instr. **60** (1989) 562.
[10]F. Bombarda, R. Giannella, E. Källne and G. Tallents, J. Quant. Spectrosc. Radiat. Transfer **41** (1989) 323
[11]I. Coffey, PhD Thesis, Queens University Belfast, 1993.
[12]E.G. Chowanietz, D.H. Lumb, A.A Wells, SPIE **597** (1985) 381.
[13]R. Barnsley, J. Brzozowski, I.H. Coffey, K.D. Lawson, I.M. Melnick, A. Patel, T.K. Patel, N.J. Peacock, Proc 19th Conf. on Contr. Fus. and Plasma Phys., Innsbruck 1992, Vol 1 p. 291.
[14]R. Barnsley, K,D. Evans, N.J. Peacock and N.C. Hawkes, Rev. Sci. Instrum. **57** (1986) 2159.
[15]The JET Team, Nucl. Fus. **32** (1992) 187.
[16]R. Barnsley, J. Brzozowski, I.H. Coffey, K.D. Lawson, A.Patel, T.K. Patel, N.J. Peacock, U. Schmacher, Rev. Sci Intr. **63** (19920 5023.
[17]V. Mukhovatov, H. Hopman, S. Yamamoto, K.M. Young et al., ITER Diagnostics, IAEA Vienna, 1990.
[18]R.J. Fonk, A.T. Ramsey and R.V. Yelle, Applied Optics **21** (1982) 2115.
[19]J.L. Schwob, A.W. Wouters, S. Suckewer, M. Finkental, Rev. Sci. Instrum. **58** (1987) 1601.
[20]K. Lawson, R. Barnsley, R. Giannella, N. Gottardi, N.C. Hawkes, F. Mompean, T.K. Patel, N.J. Peacock, Proc 17th Conf. on Contr. Fus. and Plasma Phys., Amsterdam 1990, Vol 3 p. 1413.
[21]K. Lawson, R. Barnsley, R. Giannella, L. Lauro-Taroni, M.G. O'Mullane, N.J. Peacock and P. Smeulders, Proc 20th Conf. on Contr. Fus. and Plasma Phys., Lisboa, to be published 1993.
[22]K.Behringer, B. Denne, N. Gottardi, M. von Hellermann, D. Pasini, in Pellet Injection And Toroidal Confinement IAEA-TECDOC-534, Vienna, 1989, p. 167.
[23]R. Giannella, K. Behringer, B. Denne, N. Gottardi, N.C. Hawkes, M. von Hellermann, K.D. Lawson, P.D. Morgan, D. Pasini, M.F. Stamp, Proc 16th Conf. on Contr. Fus. and Plas. Phys., Venezia 1989, Vol 1 p. 291.
[24]R. Giannella, L. Lauro-Taroni, R. Barnsley, N. Gottardi, N.C. Hawkes, K. Lawson, F. Mompean, H. Morsi, D. Pasini, D. Stork, Proc 17th Conf. on Contr. Fus. and Plasma Phys., Amsterdam 1990, Vol 1 p. 291.
[25]N. Hawkes, Z. Wang, R. Barnsley, K. Behringer, S. Cohen, B. Denne, A. Edwards, R.Giannella, R. Gill, G. Magyar, D. Pasini, N. Peacock, U. Scumacher, C. Vieider and D. Zasche, Proc 16th Conf. on Contr. Fus. and Plasma Phys., Venezia 1989, Vol 1 p. 79.
[26]D. Pasini, M. Mattioli, A.W. Edwards, R. Giannella, R.D. Gill, N.C. Hawkes, G. Magyar, B. Saoutic, Z. Wang, D. Zasche, Nucl. Fus. **30** (1990) 2049.
[27]R. Giannella, N.C. Hawkes, L. Lauro-Taroni, M. Mattioli, J. O'Rourke and D. Pasini, Plasma Phy. and Contr. Fus. **34** (1992) 687.
[28]L. Lauro-Taroni, R. Giannella, Proc 19th Conf. on Contr. Fus. and Plasma Phys., Innsbruck 1992, Vol 1 p. 287.
[29]H.P. Summers and M. von Hellermann, in *Atomic and Plasma-Material Interaction Processes in Controlled Thermonuclear Fusion*, edit. R.K. Janev, ELSEVIER, Amsterdam 1993
[30]D. Pasini, R. Giannella, L. Lauro-Taroni, G. Magyar, M. Mattioli, Proc 19th Conf. on Contr. Fus. and Plasma Phys., Innsbruck 1992, Vol 1 p. 283.
[31]R. Giannella, B. Denne-Hinnov, L. Lauro-Taroni, G. Magyar, M. Mattioli, Proc 20th Conf. on Contr. Fus. and Plasma Phys., Lisboa, to be published 1993.
[32]H. Jäckel, R. Giannella, N. Gottardi, P.J. Harbour, G. Janeschitz, R. Reicle, D.D.R. Summers, T. Tagle, Bull. Am. Phys. Soc. **36** (1991) 2367.
[33]H. Jäckel, S. Clement, M. Lesourd, J. Lingertat, C.F. Maggi, G.F. Matthews,D.D.R. Summers, H.P. Summers, Proc 19th Conf. on Contr. Fus. and Plasma Phys., Innsbruck 1992, Vol 2 p. 823.
[34]C.F. Maggi, Laurea Thesis, University of Milan, 1992.
[35]R. Simonini, A. Taroni, M. Keilhacker, G. Radford, J. Spence, G. Vlases, M.L. Watkins, S. Weber, J. Nucl. Mat. **196-198** (1992) 369.
[36]P.C. Stangeby, J.D. Elder, J. Nucl. Mater. **196-198** (1992) 258.
[37]E. Cupini, A. De Matteis and R. Simonini, NET Report EUR XII, 1984, 324/9.
[38]G. Matthews, P.C. Stangeby, J.D. Edler, N.A.C. Gottardi, P.J. Harbour, L.D. Horton, H.J. Jäckel, L. de Kock, A. Loarte, C.F. Maggi, D.P.J. O'Brien, R. Simonini, J. Spence, M.F. Stamp, P.E. Stott, H.P. Summers, J. Tagle, M. von Hellermann, J. Nucl. Mat. **196-198** (1992) 374.
[39]G. Janeschitz, R. König, L. Lauro-Taroni, J. Lingertat, G. Matthews, M. Stamp, G. Vlases, D. Campbell, S. Clement, L. de Kock, W. Eckstein, J. Ehrenberg, N. Gottardi, P. Harbour, L. Horton, H. Jäckel, M. Lesourd, A. Loarte, C. Lowry, J. Roth, G. Saibene, D. Summers, J.A. Tagle, P.R. Thomas, M. von Hellermann, J. Nucl. Mat. **196-198** (1992) 374.
[40]C. Breton, C. De Michelis, J.L. Dumay, W. Hecq, M. Mattioli, J. Ramette, B. Saoutic, J. Phys. E **20** (1987) 679.
[41]J-P. Coulon, H. Jäckel, G. Janeschitz, R. Giannella, *Diagnostics for Contemporary Fusion Experiments*, Proc. of Worksh. at Varenna, edit. P.E. Stott, D.K. Akulina, G. Gorini, E. Sindoni, Editrice Compositori, Bologna 1991.
[42]D.D.R. Summers, K. Erents, M. Hugon, A. Huang, P.H. Rebut, R. Reichle, M.F. Stamp, P.C. Stangeby, J. Nucl. Mat. **176-177** (1990) 593.
[43]P.D. Morgan, K. Beringer, P.G. Carolan, M.J. Forrest, N.J. Peacock, M.F. Stamp, Rev. Sci. Instr. **56** (1985) 862
[44]M.G. von Hellermann, W. Mandl, H.P. Summers, H. Weisen, A. Boileau, P.D. Morgan, H. Morsi, R. König, M.F. Stamp, R. Wolf, Rev. Sci. Instr. **61** (1990) 3479.
[45]M.G. von Hellermann and H.P. Summers, in *Atomic and Plasma-Material Interaction Processes in Controlled Thermonuclear Fusion*, edit. R.K. Janev, ELSEVIER, Amsterdam 1993.
[46]N. Hawkes, N.J. Peacock, Rev. Sci. Instr. **63** (1992) 5164
[47]N. Hawkes, Proc 20th Conf. on Contr. Fus. and Plasma Phys., Lisboa, to be published 1993.
[48]N. Hawkes, P. Thomas, Proc 20th Conf. on Contr. Fus. and Plasma Phys., Lisboa, to be published 1993.