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Edge density profiles in high-performance JET plasmas

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Abstract

Detailed electron density profiles of the scrape-off layer in high-performance JET plasmas (plasma current, $I_p < 5$ MA, neutral beam heating power, $P_{nbi} \sim 17$ MW) have been measured by means of a lithium beam diagnostic system featuring high spatial resolution [K. Kadota et al., Plasma Phys. Controlled Fusion 20 (1978) 1011]. Measurements were taken over a period of several seconds, allowing examination of the evolution of the edge profile at a location upstream from the divertor target. The data clearly show the effects of the H-mode transition — an increase in density near the plasma separatrix and a reduction in density scrape-off length. The profiles obtained under various plasma conditions are compared firstly with data from other diagnostics, located elsewhere in the vessel, and also with the predictions of an 'onion-skin' model (DIVIMP), which used, as initial parameters, data from an array of probes located in the divertor target.

Keywords: JET; Boundary plasma; Plasma density diagnostic

1. Introduction

Density profiles in the edge of JET plasmas are key data for the understanding of a wide range of issues from the performance of hot ion H-modes [1] to the determination of scrape-off layer transport [2]. An important diagnostic technique for measuring electron density profiles in the boundary employs an energetic neutral lithium beam [3] which is injected into the plasma. These lithium atoms are either ionised in the edge region, or are excited by collisions with electrons. Lithium ions so created are deflected out of the beam path by the magnetic field, but the excited atoms promptly relax to their ground state, emitting radiation at a characteristic wavelength (corresponding to the 2s–2p resonant line at 670.8 nm). The intensity of this emission is a measure of the local electron density and by spatially resolving this intensity, the variation of the electron density along the path of the lithium beam may be deduced. Since the stopping cross-section for lithium is large, the beam intensity rapidly decreases at higher density. Hence the technique is particularly applicable for density profile measurements in the scrape-off region outside the separatrix. The intensity of the injected beam is low enough to cause negligible perturbations even in the outermost region of the scrape-off plasma. Thus, the technique is essentially non-invasive and can be applied for the whole plasma pulse duration.

From the emission profile, the electron density may be obtained via the rate equations describing the level populations in the lithium. Since the lithium beam is mono-energetic this may be written as

$$\frac{\mathrm{d}n_i}{\mathrm{d}x} = \sum_{j=1}^{n} \left(n_e \cdot n_j \cdot a_{ij} + n_j \cdot k_{ij} \right), \tag{1}$$

where x is the beam penetration distance, n_e is the electron density, n_j are the level population densities, a_{ij} are all electron collision rate coefficients, k_{ij} are all other collision rate coefficients and the spontaneous emission coefficient. All electron, proton and impurity ion cross-sections have been taken from a critical compilation by Janev et al. [4] and Schweinzer et al. [5].

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The evolution of the 2p-level in Li is given by:

$$\frac{\mathrm{d}n_2}{\mathrm{d}x}=n_e(x)\cdot\sum_{j=1}^{n}(n_j\cdot a_{2j})+\sum_{j=1}^{n}(n_j\cdot k_{2j}) \qquad (2)$$

from which $n_e(x)$ can be calculated using measurements of the 2p–2s emission ($\sim n_2$). Details of the method employed to calculate density profiles from the intensity data may be found in Ref. [6].

At JET the Li-beam measurements were made at a location near the top of the plasma. In order to provide comparison with data from other techniques, use was made of the EFIT magnetic equilibrium code to provide details of flux surface contours and this allowed scale lengths obtained from data taken at any particular poloidal position to be converted to values at any other.

2. Experimental details

A lithium beam system has recently been installed at JET and is shown schematically in Figs. 1 and 2. The source, similar to that used at ASDEX [7], was arranged to inject $\sim$ 60 keV lithium atoms vertically into the torus and has been designed to provide beams of $\sim$ 0.6 mA equivalent current with a diameter < 2 cm for periods up to 30 s. However, for the measurements reported here, the beam intensity was only $\sim$ 0.1 mA equivalent. There are practical advantages in the use of sodium vapour ($Z = 11$) as a neutraliser, but for vertically-injected beams, there is a danger that sodium droplets may fall into and contaminate the plasma. To reduce this possibility, baffles are located in the beam flight tube and lithium vapour ($Z = 3$) is used as a neutraliser.

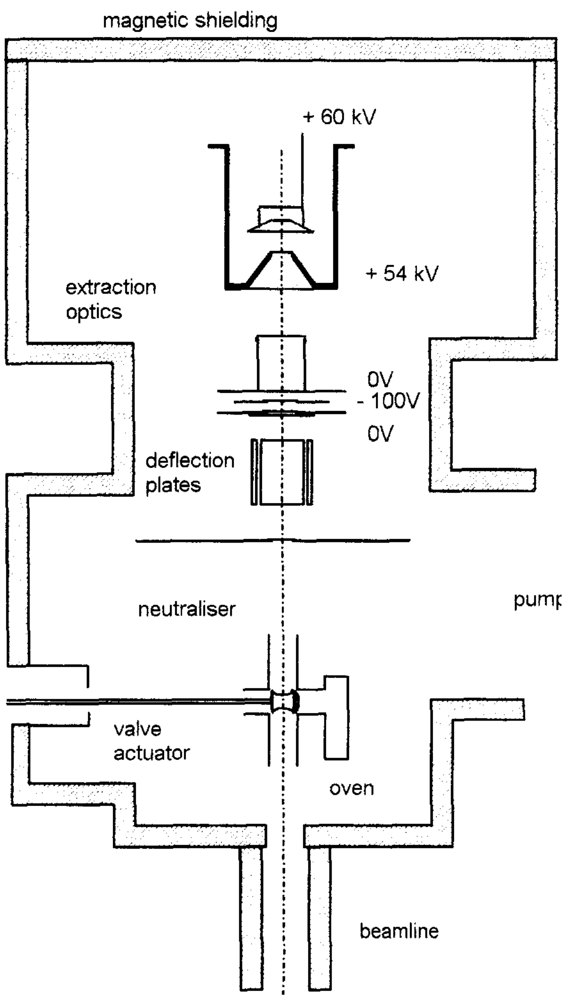

Fig. 1. Details of the Li-beam source.

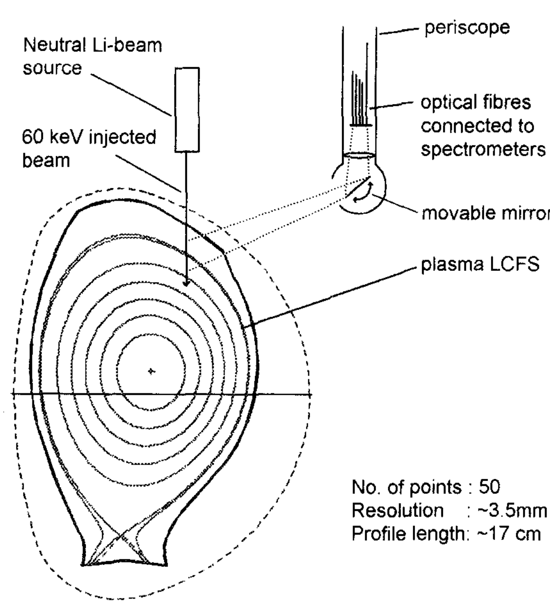

Fig. 2. Diagnostic overview.

Emission from the beam–plasma interactions is collected using a periscope located some 70 cm toroidally from the beam axis and positioned so as to avoid the possibility of contact with the plasma. Its mirror is rotatable so that data may be taken from different sections of the beam path, thus allowing measurements on plasmas of various minor radii.

Within this periscope a lens directs light onto an array of 50 optical fibres located at the focal plane. By this means, emission from a 17 cm long section of the beam path can be sampled with a spatial resolution of $\sim$ 3 mm. Fig. 2 shows details of the arrangement. The optical fibres extend outside the torus hall to spectrometers fitted with CCD arrays as detectors, allowing simultaneous measurement of signals from all 50 fibres. A useful feature of this arrangement is the ability to distinguish between radiation from plasma interactions with energetic lithium atoms, those with thermal lithium from the neutraliser and other plasma radiation. The emission due to the energetic atoms is Doppler-shifted by a few Å which can be resolved within the spectrometers and is used for spatial calibration.

3. Results

Since this was the first application of the Li-beam technique at JET, comparison was made initially with other diagnostics in modest plasma conditions. For example, in low-density L-mode plasmas, such as pulse No. 35171, with $I_p = 1$ MA, the measured profiles showed good correspondence with data from the reciprocating probe (RCP) which made a brief (200 ms) excursion into the plasma edge during the Li-beam measurement period from a similar poloidal position. The values obtained were: edge density, $n_{es} = 1.6 \times 10^{18}$ m^{-3} (1.45×10^{18} m^{-3}); density scrape-off length, $\lambda_{ne} = 3.0$ cm (3.15 cm), where the first values shown are from Li-beam data and the values in brackets are those from the reciprocating probe (λ_{ne} values are referred to the vessel mid-plane). Fig. 3 shows the comparison of data from the two diagnostic systems for this pulse. The face of the RCP includes 4 separate Langmuir probe heads and data from all 4 are plotted. The stroke of the RCP has a duration of 250 ms and takes place during two subsequent exposure times of the Li-beam diagnostic, both of which are shown. The figure also shows the position of the separatrix as calculated with the DIVIMP code, with boundary conditions provided by data from the target Langmuir probes. Although the RCP and Li-beam data were taken from well outside the separatrix, in the region of overlap between the measurements and calculations the correspondence is remarkably good. Due to the combined effects of low beam intensity and low plasma densities, it was necessary to sample over periods of 500 ms. One result of this is that the data integrates the effects of 'sweeping' of the X-point (the magnetic null of the divertor configuration).

In order to limit the temperature rise at the target surface and therefore increase the total power handling

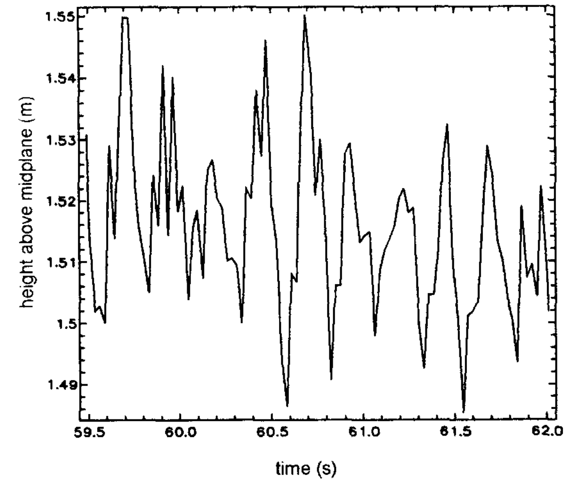

Fig. 4. Vertical movement of separatrix at Li-beam position as recorded by magnetics in 1 MA plasma pulse #35373. The amplitude of the oscillation should be compared with those at 5 MA (see Fig. 8).

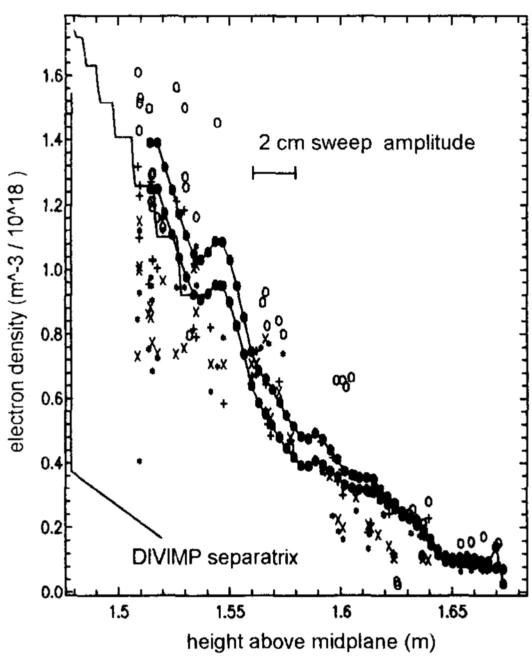

Fig. 3. Comparison of measured electron density profiles from Li-beam (•), reciprocating probe (RCP) (○, +, ×) and DIVIMP code (————) for 1 MA plasma (#35373). The RCP stroke takes place during two periods of the Li-beam data.

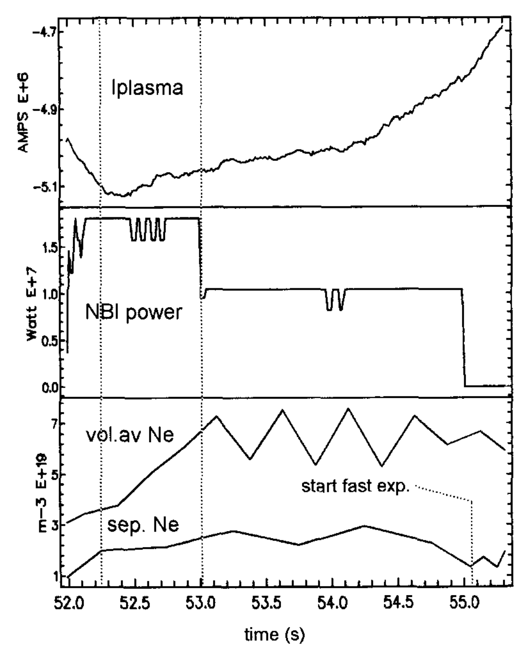

Fig. 5. Overview of 5 MA plasma pulse #35703. The vertical dotted lines indicate the two times of the DIVIMP calculation. The volume average density is taken from LIDAR and the edge density is the Li-beam result at the separatrix.

capability in JET, the position of the X-point is swept radially at a rate of 4 Hz, by control of the coil currents. The effect of this sweeping is to cause a corresponding movement of the separatrix, the magnitude of which depends on the plasma current. At $I_p = 1$ MA, this movement has an amplitude of ~ 2 cm as may be seen in Fig. 4. The Li-beam profile in Fig. 3 shows a ripple which is attributable to this movement, with the peaks corresponding to the limits of the motion.

In plasmas with $I_p = 5$ MA, such as pulse No. 35703, the RCP was not operated and Li-beam data were compared with those from other techniques. For this pulse, 18 MW of neutral beam heating (NBI) was injected for 1 s at peak current and 10 MW for the subsequent 2 s (Fig. 5). Data were taken in 500 ms samples during the heating phase and in 100 ms samples after the heating was switched off. The measured edge density rose to $n_{es} \sim 4 \times 10^{19}$ m^{-3} during the neutral beam heating phase and during H-modes, the e-folding length, λ_{ne}, was reduced to 1.0 cm (referred to the mid-plane), consistent with data from Langmuir probes in the divertor target. For these steep profiles, detailed comparison with the LIDAR Thompson scattering diagnostic (resolution ~ 10 cm along a mid-plane radial line) was not possible, but, as Fig. 5 shows, the development of the edge density follows reasonably well the volume-average measurement. At various times during the heating period, the profiles were compared with the output from the DIVIMP code. Fig. 6 shows measured and computed profiles during the heated phase of 35703.

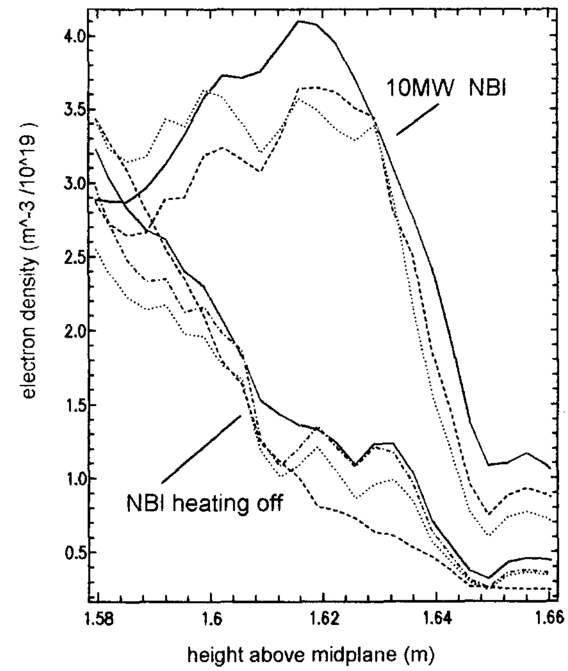

Fig. 7. Edge electron density profile evolution during and after 10 MW NBI heating.

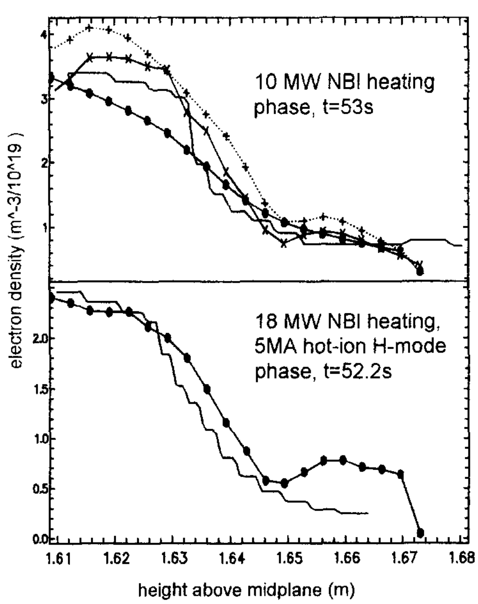

Fig. 6. Comparison of electron density profiles of Li-beam diagnostic (+, ×, •) with DIVIMP calculations (————) based on target probe data for 5 MA plasma pulse. The full dots (•) in the upper graph correspond to measurement at the NBI step-down transition.

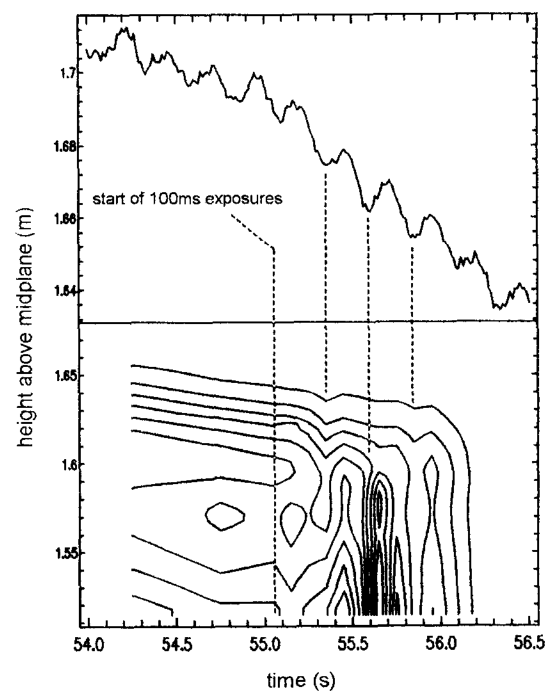

Fig. 8. Vertical plasma boundary movement due to sweeping of divertor plasma, as measured by magnetics and in Li-beam contours.

At the end of the heating period, the plasma current began to decay and the Li-beam data showed the edge density gradient to decrease and the separatrix to move inwards, as the plasma column contracted (Figs. 7 and 8, upper).

Although at this value of I_p the X-point sweeping moves the boundary by only a few mm, at the higher sampling rate the effect can be resolved, as may be seen in Fig. 8, which shows density contours varying with the oscillation of the separatrix position.

4. Conclusions

- Edge density profiles in JET have been measured using a Li-beam technique.
- At low density and $I_p = 1$ MA, the profiles agree well with data from the reciprocating probe.
- At higher densities with $I_p = 5$ MA and neutral beam heating, good agreement is found with target probe data and the time behaviour of the edge density corresponds with the Lidar measurements of the volume-average density.
- The technique is shown to be capable of resolving small changes in separatrix position and with higher beam currents, faster sampling rates will enable resolution of fast edge events.
- Good agreement with the DIVIMP code predictions is found at both values of plasma current.

Acknowledgements

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