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Strong Asymmetries in Impurity Distributions of JET Plasmas

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INTRODUCTION

A general feature observed during hot-ion H-mode discharges in JET has been a pronounced poloidal asymmetry in the soft X-ray (SXR) emission profiles with a distinct excess emission occurring on the outboard, low-field side. A tomographic reconstruction of one such plasma, using data from the new multi-camera SXR diagnostic[1] with 210 lines of sight and six independent views at one toroidal location, is shown in Figure 1. This figure clearly demonstrates this feature with a pronounced peak in the SXR emissivity beyond a major radius (R) of 3.5m. A similar phenomenon has been observed, in a less dramatic form in earlier JET plasmas [2], the effect being attributed to the centrifugal force on heavy (metal) impurities as a result of toroidal plasma rotation [3]. This feature is strongest at high toroidal velocities, which approach or even exceed the impurity ion thermal speed. These conditions occur in the hot-ion H-mode plasmas in which plasma rotation, driven by the neutral beams, reaches frequencies in excess of 18 kHz and where nickel impurities with temperatures in the range 10 - 15 keV are found. Also seen in Figure 1, in addition to this outboard peak, a second narrow peak is seen at, or close to, the magnetic axis. This is attributed to neo-classical diffusion of the metal impurities.

LASER ABLATION OF NICKEL

The peak in SXR emission at large major radii, shown in Figure 1, is attributed to line emission from metal impurities. A more quantitative study of this effect has been possible with controlled injection of nickel by laser blow-off during high performance discharges. In one such case, shot 34476, the nickel injection was performed early in the high performance phase of a hot-ion H-mode discharge. Figure 2 shows time traces of the concentration of nickel, together with its angular frequency and ion temperature from a high resolution X-ray crystal spectrometer.

The rise in nickel concentration is clearly seen at the time of laser ablation and reaches 4 parts in 10^4 . The Ni^{26+} emission used in these measurements is also the dominant source of line emission contributing to the SXR diode data. At the time of peak nickel concentration (12.96s) the nickel temperature is 11 keV corresponding to $v_{thermal} \sim 1.3 \times 10^5$ m/s with an angular frequency of 110 krad./s corresponding to $v_{rot.} \sim 4x10^5$ m/s (at a radius of 3.6m). Thus the rotational velocity of the nickel is more than a factor of 3 greater than the thermal velocity.

Tomographic reconstruction of the SXR emission during this event has been performed using a pixel technique developed initially by C. Fuchs for JET bolometer data. In Figure 3 the SXR emissivity along a horizontal line through the magnetic axis is shown for several time slices. The background emission at 12.91s has been subtracted. The inward progress of the nickel occurs very rapidly following the ablation over a period of about 10-15ms and then essentially stops. The last time slice, over 400ms later, shows the development of a secondary peak at the plasma axis (probably due to neo-classical diffusion) with a minimum in emission occurring between the two peaks. This two peaked structure also often develops late into a conventional hot-ion H-mode discharge (e.g. Figure 1). In Figure 3 the peak emission is centred on the outboard equator at a major radius of ~3.6m; (the magnetic axis being at ~3.0m). Figures 4 shows a 3-dimensional view of SXR emission corresponding to the '+30ms' trace of Figure 3. Note that no up-down asymmetry is observed, unlike reference [3].

THEORY OF THE ASYMMETRY

The asymmetry in the SXR emission distribution arises because the impurities take up the toroidal rotation of the plasma and the resulting 'centrifugal force' throws the impurity ions outwards. The behaviour is complicated by the electrostatic field which arises to maintain quasi-neutrality in the plasma. Nevertheless, it is possible to set up simple equations to describe the system and in the case of low impurity content, to solve for the poloidal distribution of each impurity species. The feature which makes this problem tractable is that the poloidal distribution of impurities on a flux surface depends only on the equation of pressure balance parallel to the magnetic field in the poloidal plane. The balance of forces, in the simple case of a trace species with charge Z in a hydrogenic plasma, arises from the pressure gradient, centrifugal force and electrostatic field in a magnetic surface (Ψ). This can be represented by

$$T_Z \frac{dn_Z}{dR} = n_Z\left(m_Z\omega^2 R - eZ\frac{d\phi}{dR}\right)$$

where the derivatives are taken at constant Ψ.

Solving the set of equations for a pure deuterium plasma with a small addition of impurity (s) yields the ratio of impurity concentration between the outboard-(o) and inboard-(i) sides

$$\frac{n_s^o}{n_s^i} = \exp\left\{\frac{m_s\omega^2(R_o^2 - R_i^2)}{2T_s} f\right\} \text{where } f = \left(1 - \frac{T_e}{T_i + T_e}\frac{m_i}{m_z}Z_s\right).$$

At the radius of peak nickel emission for shot 34476, T_e is ~5.5 keV at 12.94s and taking $T_i = T_s$ a value for f ~0.7 is obtained. This yields a value for the ratio of concentrations of 5.5±1:1. A further correction for the presence of other impurities in the plasma (carbon and beryllium) reduces this ratio by around 20%. (See [2] and references therein). Experimentally, from Figure 3 a value of 4±1 : 1 is found, in good agreement with theory.

A numerical simulation of the poloidal distribution of the nickel emission has been carried out for one time slice using these equations. The outboard radial distribution through the magnetic axis was taken from the data at 12.94s. The model results are shown in Figure 5 and compare well to the data of Figure 4.

SUMMARY AND CONCLUSIONS

Strong in-out asymmetries are observed in the soft X-ray emission from JET hot-ion H-mode plasmas, a peak being observed on the outboard side. The key feature of the asymmetry can be explained by the effect of the centrifugal force on metal impurity ions in these rapidly rotating plasmas, where their rotational velocities exceed their thermal velocities by a factor of three. A simple model developed for the poloidal distribution produces quantitative agreement with data from a discharge in which there was laser ablation of nickel into the plasma. The radial distribution of impurity ions with a stationary peak at R~3.6m and the subsequent development of a secondary peak on axis is less well understood.

REFERENCES

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[2] Giannella R. et al, 19th EPS Conference on Controlled Fusion and Plasma Physics, Innsbruck, 1992, Vol. I p279

[3] Smeulders P., Nuclear Fusion Vol.26 (1986) 267

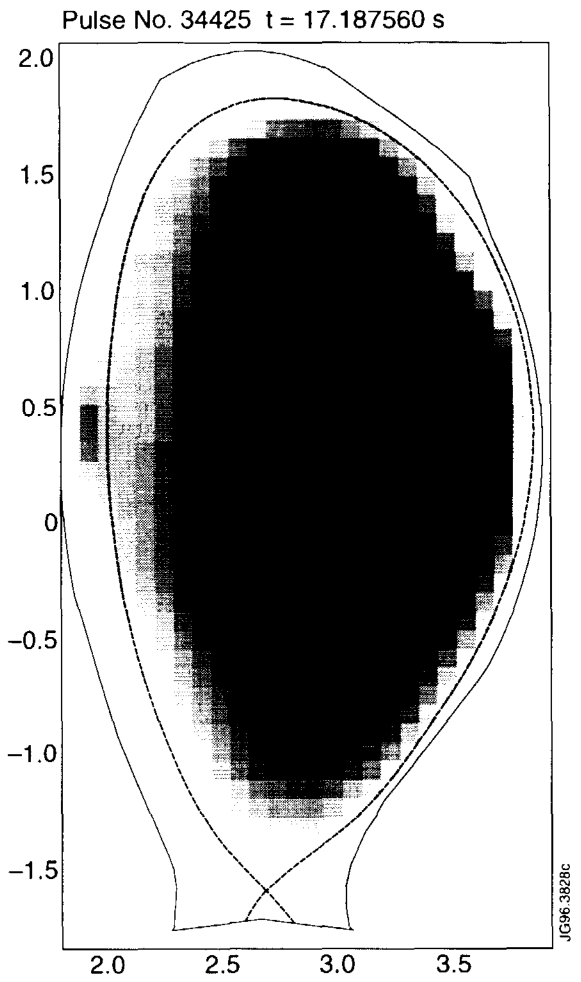

Figure 1. SXR emission during the high performance phase of a hot-ion H-mode discharge 34425

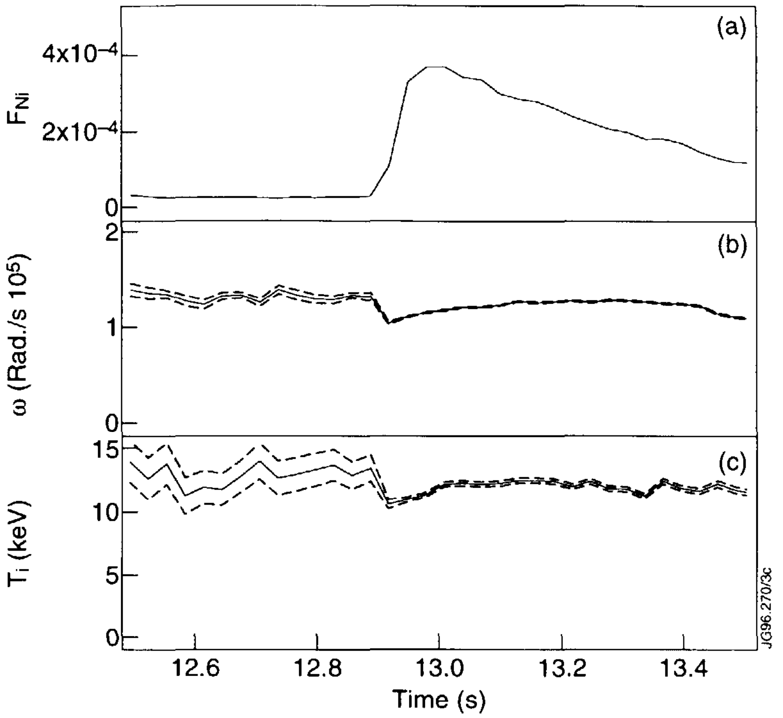

Figure 2. (a) Ni concentration, (b) Ni^{26+} angular frequency and (c) the ion temperature of Ni^{26+} with errors for shot 34476.

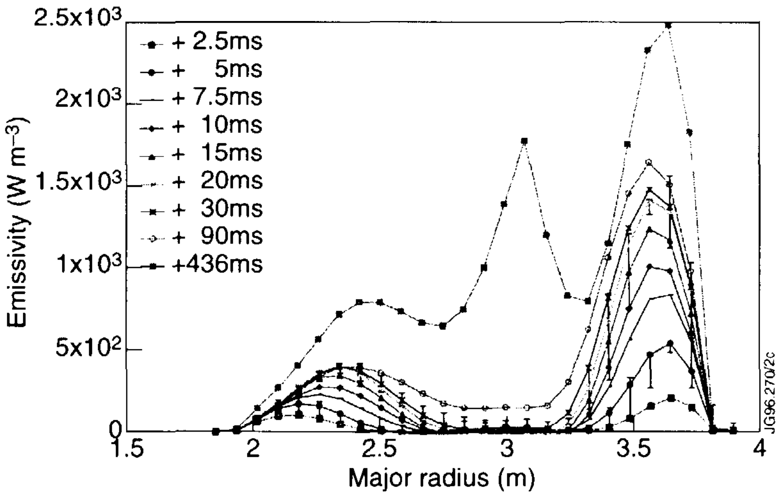

Figure 3 Emissivity projected onto a horizontal line through the magnetic axis after subtraction of the first - pre-ablation time slice for shot 34476.

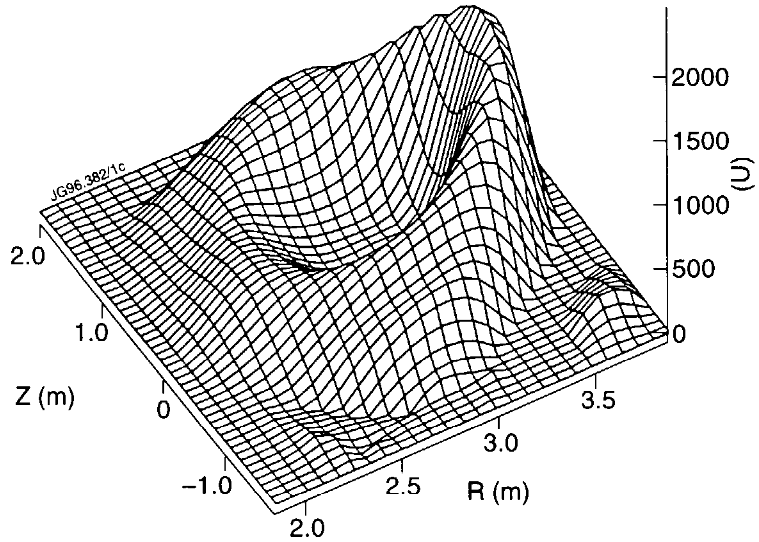

Figure 4 Tomographic reconstruction 30ms after nickel injection with background emission subtracted.

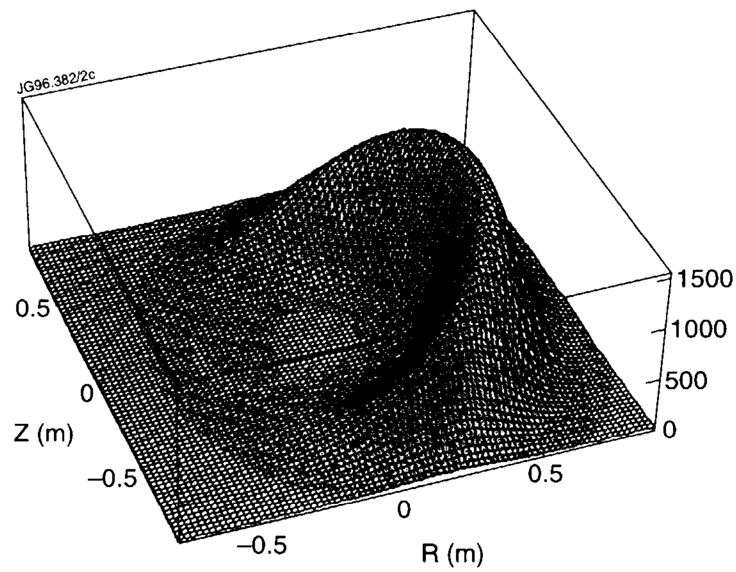

Figure 5 Simulation of the poloidal distribution of the Ni emission for shot 34476. The outer equatorial intensity from Fig. 3 at +30ms was used as input and circular geometry assumed