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ABSTRACT.

The determination of the power conducted and/or convected to the scrape-off layer (SOL) of tokamaks is usually based on two types of measurements: Main plasma characteristics (Power input and radiated) and SOL measurements (Langmuir probes and thermocouples on the limiters).

The power flow to the beryllium toroidal limiters in JET, determined by Langmuir probes, is lower than the input power to the plasma edge, $P_{INPUT}^{EDGE} = P_{INP} - P_{RAD}$. This difference is partly explained if account is taken of the excess of ion temperature over electron temperature and partly by systematic errors associated with uncertainties in the area of Langmuir probes and that they provide a measurement which ignores variations in axisymmetry due to field ripple effects etc. However at high densities, which concern us here, it has become apparent that the power losses associated with recycling have not been properly accounted for in JET and this is the subject of this paper.

When an atom of beryllium enters the plasma from the limiter, it is ionized rapidly to Be^{+}(~1µs) and to Be^{2+}(~1µs) and mor slowly thereafter. Significant radiation occurs during the transient charge stages towards full ionization, because the low charge states have a concentration greater than the equilibrium one and are in a plasma with relatively high T_e. hence their excitation cross sections are large. Because the beryllium ions are in a cloud of recycling hydrogen atoms, they could undergo charge exchange with them ($Be^{n+} + H \rightarrow Be^{(n-l)+} + H^{+}$), the population of lower charge estates would be enhanced and the radiation losses increased. These processes are described by a transient ionization code which follows the ionization of an impurity atom in a uniform plasma with a uniform neutral hydrogen density.

To study these losses requires a model of the beryllium and hydrogen behaviour which takes into account the geometry of the recycling region and shows why the bolometer in JET ignores this radiation (sensitivity at relevant wavelengths and geometrical constraints due to the fact that the bolometer looks through a gap in the toroidal belt limiters). One model would be the LIM code, but we describe here a flexible analytical approach which accounts readily for variations in plasma profile and geometrical effects.

AN INVESTIGATION OF THE POWER BALANCE ASSOCIATED WITH RECYCLING IN JET OHMIC LIMITER DISCHARGES

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1. Introduction

The determination of the power conducted and/or convected to the scrape-off layer (SOL) of tokamaks is usually based on two types of measurements : Main plasma characteristics (Power input and radiated) and SOL measurements (Langmuir probes and thermocouples on the limiters).

The power flow to the beryllium toroidal limiters in JET, determined by Langmuir probes, is lower than the input power to the plasma edge, $P^{EDGE}_{INPUT} = P_{INP} - P_{RAD}$. This difference is partly explained if account is taken of the excess of ion temperature over electron temperature [1] and partly by systematic errors associated with uncertainties in the area of Langmuir probes and that they provide a measurement which ignores variations in axisymmetry due to field ripple effects etc. However at high densities, which concern us here, it has become apparent that the power losses associated with recycling have not been properly accounted for in JET and this is the subject of this paper.

When an atom of beryllium enters the plasma from the limiter , it is ionized rapidly to $Be^{+}(\sim 1\,\mu s)$ and to $Be^{2+}(\sim 10\,\mu s)$ and more slowly thereafter. Significant radiation occurs during the transient charge stages towards full ionization, because the low charge states have a concentration greater than the equilibrium one and are in a plasma with relatively high T_e, hence their excitation cross sections are large. Because the beryllium ions are in a cloud of recycling hydrogen atoms, they could undergo charge exchange with them ($Be^{n+} + H \rightarrow Be^{(n-1)+} + H^{+}$), the population of lower charge estates would be enhanced and the radiation losses increased. These processes are described by a transient ionization code which follows the ionization of an impurity atom in a uniform plasma with a uniform neutral hydrogen density [2].

To study these losses requires a model of the beryllium and hydrogen behaviour which takes into account the geometry of the recycling region and shows why the bolometer in JET ignores this radiation (sensitivity at relevant wavelengths and geometrical constraints due to the fact that the bolometer looks through a gap in the toroidal belt limiters). One model would be the LIM code [3], but we describe here a flexible analytical approach which accounts readily for variations in plasma profile and geometrical effects.

2. The Impurity model

The time scale on which radiation losses due to recycling occur depends on the range of the impurities and the time scales for radial transport to the limiter and for transport along the field line, which amongst other effects, takes the impurities out of the neutral hydrogen cloud.

The impurities are assumed to be produced by sputtering from the limiter. The production mechanism determines the speed normal to the plasma of the incoming impurity atom v_{Be} and therefore the range of this atom. Here the typical energy $\bar{E}_{Be}$ for the sputtered impurities is calculated using the Thompson energy distribution [4] and the corresponding values for beryllium from [5].

The sputtering yield is taken from measurements of the Be^{+} (436.1 nm) and D_{α} (656.3 nm) intensities giving the relative influx of beryllium to deuterium [6].

For the discharges studied the mean free path, in the SOL, of the emitted Be atoms is typically $\sim 10 - 20\ cm$ and so for these conditions only a few percent are ionized in the SOL. These are ignored in our study.

The distance x_{ion} of the ionization point in the main plasma, from the limiter, is calculated using the profiles for n_e, T_e inside the separatrix. These are obtained using the values for n_e, T_e at the separatrix from Langmuir probe measurements and the outermost reliable value for n_e from interferometry and T_e from ECE measurements : several interpolations between these values have been used. This distance x_{ion}, is derived from

$$v_{Be} = \int_0^{x_{ion}} n_e(x) < \sigma_i v_e >_{Be} (x)\, dx \ , \tag{1}$$

where $< \sigma_i v_e >_{Be} (x)$ is the electron ionization rate for beryllium at a radial distance x from the limiter.

After the first ionization the impurities are subject to two diffusive processes :

- Diffusion along the field line, described here by classical transport, with characteristic collision time [7]

$$t_Z^c = \frac{3(kT_i)^{\frac{3}{2}}\, m_Z^2}{4\sqrt{2\pi m_i}\, e^4 Z^2 n_i (m_i + m_Z) \ln \Lambda} \ . \tag{2}$$

This diffusion determines the poloidal transport away from the neutral cloud and the toroidal axisymmetry of the impurities. The time scale, $t_Z^{\parallel}$, associated with these processes is determined mainly by the time at which the first collision takes place ($t_Z^{\parallel} \simeq t_Z^c$).

- Diffusion across the field, described here by anomalous transport with diffusion coefficient equal to the deuterium diffusion coefficient $D_\perp$ (determined from Langmuir probe measurements). Hence the characteristic radial diffusion time, from the ionization point to the limiter is given by

$$t_{diff} = \frac{x_{ion}^2}{2D_\perp} \ , \tag{3}$$

where $D_\perp$ is the diffusion coefficient.

The radiation of the atom during the ionization time, and of the various charged ions during t_{diff} (or $t_Z^{\parallel}$ if smaller), is studied with the transient ionization code and we take as representative plasma conditions for this calculation those at the ionization point.

3. Neutral Hydrogen model

To calculate the neutral hydrogen density near the limiter and the hydrogen recycling losses a recycling coefficient $R \simeq 1$ is assumed. We consider an average normal speed for the incoming neutrals

$$v_0 = \sqrt{\frac{2kT_0}{m_D}} \ ; \ T_0 = 2.5eV, \tag{4}$$

in agreement with Monte-Carlo simulations for ohmic discharges in JET [8]. The neutral density is

$$n_0 = \frac{\Gamma(a)}{v_0} \sin \phi, \tag{5}$$

where $\Gamma(a)$ is the particle flux along $\vec{B}$, measured by the Langmuir probes, and ϕ is the average angle between the field line and the limiter surface ($\phi \simeq 1°$, from magnetic equilibrium and the experimentally determined geometry of the SOL).

The value for the recycling losses per hydrogen atom is taken from the literature and in the range of density and temperature studied is about 30 eV per recycled atom.

4. Results

In Fig.1 the typical separatrix values for temperature and density (deduced from Langmuir probes assuming $T_e = T_i$) are shown for a 3MA ohmic limiter discharge in JET. These values are used as reference in our calculations.

Fig.2 shows $\bar{E}_{Be}$ versus $T_e(a)$. The points are from spectroscopic measurements of Doppler broadening for BeI(440.7 nm) [9]. The lines are predictions of $\bar{E}_{Be}$ with three different assumed T_i/T_e. Although $T_i/T_e \leq 5$ appears consistent with the data, values up to about 10 cannot be excluded when systematic errors are considered.

The total recycling power loss for beryllium is given by

$$P_{Be}^{rec} = \Gamma_T Y(Be) \xi(Be), \tag{6}$$

where $\xi(Be)$ is the recycling loss per impurity atom , obtained from the transient ionization code; Γ_T is the total particle flux and Y(Be) is the sputtering yield.

It is found that, for these experimental conditions, the influence of charge exchange between the impurity ions and the neutral hydrogen is small due to the short time spent by these ions in the neutral cloud ($\sim 10^{-4}s$).

For hydrogen recycling the expression is similar but in this case $\xi(H) \simeq 30eV$ and the recycling coefficient is $R \simeq 1$.

Fig. 3 shows various power losses versus $T_e(a)$, for $T_i = T_e$. The spread in beryllium recycling losses is due to the various interpolations used for n_e, T_e profiles. In spite of this spread, the qualitative trend of these recycling losses is consistent with experimental observations of BeII(436.1nm). If the recycling losses for hydrogen and beryllium are added, they are typically $\sim$ 50% of the power going to the limiter measured by the Langmuir probes (assuming $T_i = T_e$). Absolute agreement with P_{INPUT}^{EDGE} is not obtained because of the systematic errors mentioned and is not relevant to the aims of this paper.

Fig. 4 shows the power losses versus $T_e(a)$, for $T_i = 5T_e$. Here linear profiles n_e, T_e inside the separatrix are used and sputtered impurities assumed. The recycling losses are $\sim$ 50% of the power arriving at the limiter deduced from Langmuir probes with $T_i = 5T_e$. For higher values of T_i/T_e, the ratio of the recycling power losses to power arriving at the limiter decreases to $\sim$ 30%.

5. Conclusions

The magnitude of the recycling power losses has been shown to be a substantial fraction of the power arriving at the limiter and it has been found that they are not observed bolometrically in JET. These losses are mainly due to radiation from hydrogen and impurities in low charged states (Be^0, Be^+, Be^{2+}) emitted close to the limiters, but not significantly enhanced due to charge exchange in this experiment.

Improvements of the model, experimental measurements of the profiles of n_e, T_e at the edge region and determination of the power deposition asymmetries eg [10], are needed and will be developed to make a complete study of the edge plasma power balance.

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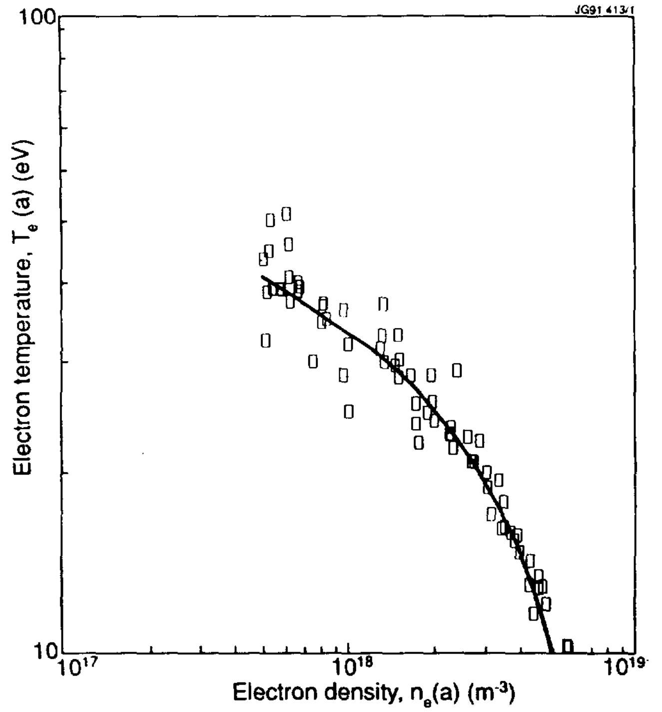

Fig.1. $T_e(a)$ versus $n_e(a)$ for typical ohmic limiter discharge I=3MA.

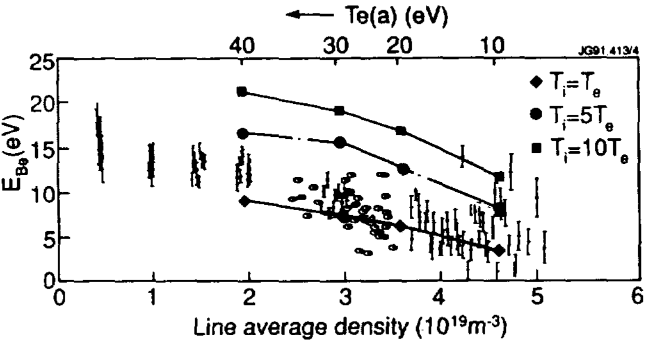

Fig.2. The energy of beryllium ions, $\bar{E}_{Be}$ plotted versus line average density (or $T_e(a)$). Points represent measurements from Doppler broadening . Lines represent model values calculated for several T_i/T_e.

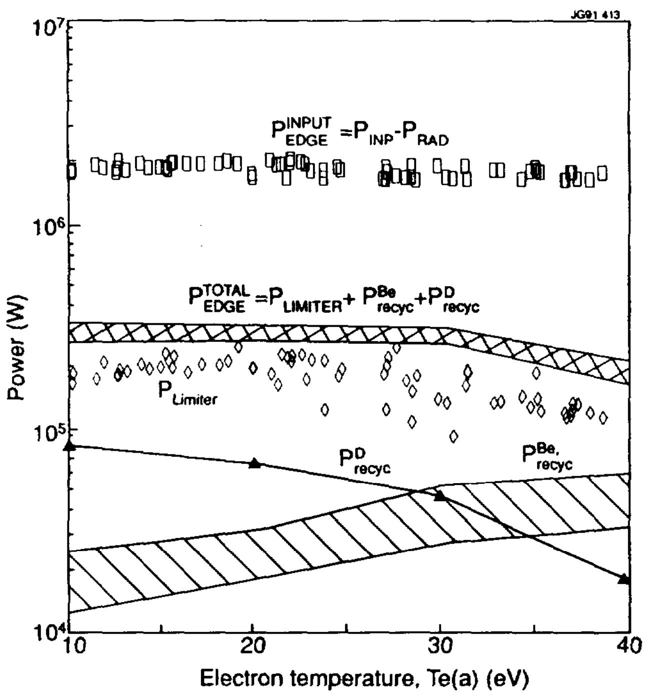

Fig.3. Limiter and recycling power losses versus $T_e(a)$, for $T_i = T_e$ and various assumptions of the n_e, T_e profiles. The power that reaches the plasma edge according to main plasma measurements ($P_{INP} - P_{RAD}$) is shown for comparison.

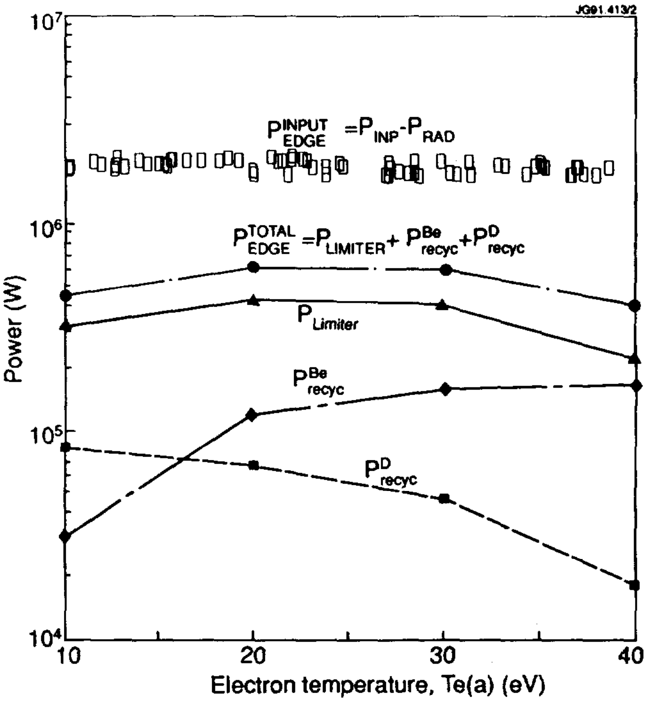

Fig.4. Limiter and recycling power losses versus $T_e(a)$, for $T_i = 5T_e$. Linear n_e, T_e profiles are used. The power ($P_{INP} - P_{RAD}$) is shown as in Fig.3, for comparison.

APPENDIX 1.

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