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GAS REFUELLING EFFICIENCY IN THE DIVERTOR CHAMBER

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ABSTRACT

In recent divertor experiments on DITE tokamak gas refuelling in the divertor chamber has been used with D_2 pressures of up to 30mTorr. At these high pressures the ionisation rate in the divertor plasma, calculated from the molecular flux across the plasma boundary using a 1-D simulation, is more than an order of magnitude higher than any ionisation source term consistent with the measured diverted plasma parameters. Similarly the predicted Dα emission is substantially greater than that measured. These inconsistencies are removed by introducing the requirement of a pressure balance at the plasma boundary between the influx of room temperature molecules, and the associated outflux of energetic (few eV) dissociated and charge exchange atoms. This considerably reduces the net molecular flow across the plasma boundary, and hence the ionisation rate and Dα emission.

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INTRODUCTION

The DITE tokamak, with the MkII bundle divertor and up to 2.0MW of neutral injection [1], has been operated with gas puffing into the divertor chamber. Refuelling the tokamak in this manner through the divertor gives line average densities of up to 7 x 10^{13} cm^{-3}, with neutral gas pressures in the divertor chamber of up to 30mTorr. However it is clear that at these high pressures the ionisation source term in the divertor plasma is considerably less than that expected from a simple molecular influx refuelling model.

If the divertor plasma is approximated by a plasma tube of total surface area A, volume V, immersed in a constant pressure of deuterium molecules, then the unhindered molecular flow across the boundary of the plasma would be given by $\Gamma = An\bar{c}/4$, where n is the molecular density and $\bar{c}$ the average molecular velocity. The plasma is sustained by power input at both ends through the divertor ducts. For D_2 at room temperature, and plasma dimensions equivalent to the divertor flux bundle, $A \sim 1.4.10^3$ cm^2, $V \sim 2.8.10^3$ cm^3 then $\Gamma \sim 1.9 \times 10^{21}$ mols/s/mTorr. A 1-D refuelling model of the divertor, described in the next section, indicates that approximately 1 electron is produced for each molecule incident on the plasma. Hence the ionisation source term in the divertor plasma would be ~ 2 x 10^{21} electrons/s/mTorr and this would lead either to a large increase in plasma density, which clearly does not occur, or to an increased convective particle flow from the four ends of the plasma tube (2 external faces in the ducts, 2 internal faces at the divertor plates). The maximum convected particle flow from the four ends of the plasma estimated from recent probe measurements [2] of parameters of the diverted plasma is ~ 1.5 x 10^{21} particles/s, which is to be compared with 6 x 10^{22} particles/s estimated from the molecular influx at 30mTorr. These simple calculations strongly suggest the presence of some mechanism which attenuates the molecular influx into the plasma at high neutral pressures. It is proposed that this mechanism is the momentum or pressure balance between the influx of room temperature molecules and the associated outflux of energetic (few eV) D atoms from dissociation and charge exchange.

1-D REFUELLING MODEL OF THE BUNDLE DIVERTOR PLASMA

In order to estimate the neutral atom outflux a 1-D divertor refuelling model has been considered, in which molecular and atomic rate equations are solved to evaluate particle densities and fluxes. The divertor plasma is simulated by a slab of width 2a = 7.5cm, with temperature and density variations of the form $T_e = T_{eo}(1 - x^2/a^2)^\alpha$, $n_e = n_{eo}(1 - x^2/a^2)^\beta$ respectively. A flux of molecules at room temperature is incident on one boundary. Three initial molecular processes are considered for the incident D_2 molecules:

$D_2 + e \rightarrow D + D + e$ dissociation

$D_2 + e \rightarrow D_2^+ + 2e$ molecular ionisation

$D_2 + e \rightarrow D^+ + D + 2e$ molecular dissociative ionisation

Dissociation dominates at $T_e < 15$eV, molecular ionisation at $T_e > 30$eV [3,4]. At all but the lowest densities and temperatures the mean free path of the molecules is much less than the plasma dimensions. Molecular ions, D_2^+, are broken up by reactions:

$D_2^+ + e \rightarrow D^+ + D + e$ ion dissociation

$D_2^+ + e \rightarrow 2D$ recombination

$D_2^+ + e \rightarrow 2D^+ + 2e$ ionisation

Ion dissocation dominates at all conditions of interest [3]. The six reactions outlined above result in a distributed ionisation source, together with a distributed source of energetic (energy 3-5eV [5]) D atoms, which may make further interactions with the plasma.

In the model the energetic neutral atoms, mass M, are assumed to have an energy E of 4eV, and are directed with equal probability inwards or outwards at a velocity of 1/2 $\sqrt{2E/m}$. The atoms can be ionised, suffer charge exchange or escape depending on their position when formed and the plasma parameters. Charge exchange atoms are produced with a temperature corresponding to the local value of T_i (assumed equal to T_e) and are treated similarly to 4eV atoms.

All rate coefficients are taken from Jones [3] and Freeman and Jones [4]. The code produces, for a given incident molecular flux, the ionisation source, the 4eV neutral atom outflux and the charge exchange atom outflux. Figure 1 shows the spatial distribution of the ionisation rate for the four components: D_2 and $D_2^+ \rightarrow D^+$, $D_2 \rightarrow D_2^+$, D(4eV) $\rightarrow D^+$ and D(C/X) $\rightarrow D^+$, at 1mTorr of D_2 and plasma profiles typical of the divertor: $n_{eo} = 1.5 \times 10^{13}$, cm^{-3} T_{eo} = 30eV, $\alpha = 0.6$, $\beta = 2$. The mean free path of the molecules is ~ 0.9cm, which defines the region of ionisation input from molecular ionisation. The ionisation source term from D atoms is fairly uniformly distributed across the plasma, weighted slightly towards the central high density regions.

From the D_2 and D fluxes in the plasma it is possible to compute the Dα emission rates. Part of the Dα emission is produced in dissociative excitation of D_2, when one of the dissociated atoms is produced in the $n > 3$ quantum state. De-excitation of the atom takes place immediately with a given probability of emission of Dα. Hα emission cross-sections are taken from Vroom and de Heer [6] in conjunction with the data of Karolis and Harding [7] for Hα and Dα cross-section ratios. Dα is also produced by electron impact excitation of D atoms. The excitation rates of Johnson and Hinnov [8] for H atoms have been assumed to be directly applicable to D. The spatial forms of the Dα emission computed by the code from dissociative excitation and from electron impact excitation closely follow the profiles of the D_2 and D ionisation source terms respectively. For the plasma profiles given above the code predicts ~ 60% of the total Dα is emitted by 4eV atoms, ~ 35% from molecular dissociative excitation and ~ 5% from charge exchange atoms.

Figures 2 and 3 present calculations of ionisation, particle escape and Dα emission for constant profile shapes $\alpha = 0.6$, $\beta = 2.0$ but different values of n_{eo}, T_{eo}. These curves indicate that for parameters typical of divertor plasmas, $T_{eo} > 20$eV, $n_{eo} > 1.10^{13}$ cm^{-3}, (i) approximately 1 electron is produced per incident molecule, independent of density (ii) one energetic D atom is emitted per incident molecule (iii) the number of Dα photons emitted per incident molecule is ~ 2-3 x 10^{-2}, weakly dependent on temperature.

Dα LINE PROFILE MEASUREMENTS

There is strong evidence for the presence of D atoms with energies ~ 4eV in the divertor plasma. Line profile measurements of Dα and Hα emission have been made with a high resolution monochromator fitted with an optical multichannel analyser. The system has a resolution of 0.4Å. Because of the high magnetic field in the divertor (> 3T) strong Zeeman splitting of Dα is observed. The viewing geometry was chosen to be perpendicular to the magnetic field lines and a polariser was used to select the unshifted π components.

Figure 4 shows such a line profile, integrated over a time of 65ms, for a discharge with ~ 1MW neutral injection. The Hα peak on the long wavelength side is due to the presence of hydrogen introduced by neutral injection.

Also shown in figure 4 is the result of a fit to the data, of three gaussians with fixed central wavelengths at Dα and Hα but variable width, convolved with the instrument function. The three components correspond to neutral atom Maxwellian mean energies of 0.47eV, 4.1eV and 40.0eV, with ratios .12, .64, .24 respectively. When analysed in this way, the two major components appear at about the energies expected for atomic dissociation and charge exchange. A gaussian line shape would not, a priori, be expected for Dα emission from the 4eV dissociated atoms, and without a model to take into account a finite energy spread of the atoms, accurate plasma profiles, plasma shape and viewing geometry, no significant comparison can be made between the ratios of the atom species derived from the measurements and those predicted by the modelling. It should however be pointed out that the presence of a cold component, energy ~ 0.4eV, is consistent with Dα radiation from molecular dissociative excitation [9].

DISCUSSION

The results of the refuelling model together with simple molecular flux calculations suggest an ionisation source term in the plasma inconsistent with the measured values of n_e and T_e, as has been referred to earlier. Figure 5 shows the experimentally measured rate of Dα emission from the divertor plasma as a function of divertor chamber pressure for a series of discharges with neutral injection and variable gas puff rate. A measurement was taken at the end of the neutral injection pulse for each discharge. From Fig. 5 it can be seen that the measured Dα rate for pressures above a few mTorr is well below that estimated from the model.

The refuelling code indicates that the neutral outflux from the plasma is approximately equal to the molecular influx, Figs. 2,3. However the incident molecules are at room temperature, whereas the outflux of atoms is at energies of ~ few eV. Hence there is a considerable net outflow of momentum. Cross-sections for elastic scattering of H atoms in D_2 [10] at atom energies of a few eV have been measured to be ~ 4 x 10^{-15} cm^{-2}. From this, the mean free path for elastic scattering of D in 1mTorr of D_2 is estimated to be ~ 8cm at 4eV. The momentum in the outflux of D atoms from the divertor plasma is dissipated within a few mean free paths of the plasma edge, providing a high impedance to the incident molecular flux. At the highest pressures used (~ 30mtorr), this distance will be a few mms.

The attenuation of the molecular influx, f, is determined by the momentum balance equation

$$M_{D_2} \bar{c}_{D_2} = \bar{c}_D \; f \; g(n_e,T_e) \; M_D$$

where M and $\bar{c}$ are masses and average velocities and the subscripts D_2 and D refer to molecules and atoms respectively. $g(n_e,T_e)$ is the parameter shown in Figs. 2,3, the number of atoms escaping per incident molecule. Hence

$$f = \frac{2\bar{c}_{D_2}}{\bar{c}_D \; g(n_e,T_e)}$$

The model gives $\frac{\bar{c}_{D_2}}{c_D} \sim 1/20$, $g \sim 1$ and hence $f \sim 0.1$. The molecular influx at the plasma boundary and hence the ionisation source and Dα emission are reduced by a factor of ~ 10, which is much more consistent with the measurements.

Attenuation by a factor of 10 suggests a scale length of interaction, L ~ 2.5 mean free paths. If L is greater than the distance between the plasma and the divertor chamber walls then the molecular influx will be less strongly attenuated. The geometry of the DITE divertor chamber is complex but typical distances are ~ 10cm. Hence for pressures > 3mTorr strong attenaution is expected. There is experimental evidence for this in Fig. 5, where the dashed curve corresponds to the predicted Dα emission, ignoring pressure balance effects. The full line represents the predicted line emission when pressure balance is taken into account. In the computation of both lines it has been assumed that the plasma parameters remain constant as the divertor chamber pressure is varied.

CONCLUSIONS

It has been shown that at the high neutral gas pressures achieved by gas puffing into the DITE bundle divertor chamber, the ionisation source term and Dα emission rate from the plasma, predicted by simple molecular flux calculations in conjunction with a 1-D refuelling model, are much greater than the experimentally determined quantities. Calculations have shown that the neutral atom efflux from the plasma, associated with dissociation or charge exchange, is approximately equal to the molecular influx. These atoms have energies of several eV, as is confirmed by Dα line profile analysis, and the momentum balance between the incoming molecules and the escaping atoms considerably reduces the net molecular influx. Within the accuracy limitations of the model this removes the inconsistency between the computed refuelling rates and Dα emission and the experimental data.

When the target chamber pressure is raised to the level where the neutral gas pressure becomes comparable with the plasma pressure the divertor plasma is expected to collapse. There is some evidence for this on DITE for discharges with high neutral pressure in the divertor and low neutral injection input power where the Dα emission decreases sharply near the end of the injection pulse. Work is in progress to identify the role of the pressure imbalance in this process as distinct from the more commonly assumed energy imbalance.

Finally, pressure balance effects are undoubtedly important in controlling refuelling rates in conventional gas puffing into tokamaks, and probably affect limiter recycling. As far as the authors are aware this effect has not been considered experimentally or in any of the more sophisticated refuelling codes.

ACKNOWLEDGEMENTS

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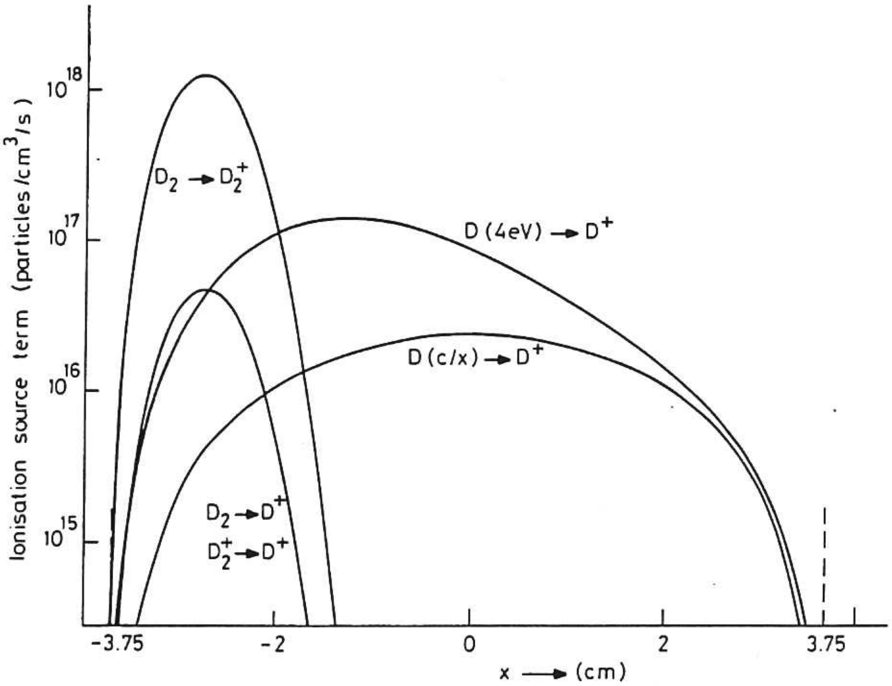

Fig. 1 Ionisation source terms for the processes $D_2 \rightarrow D_2^+$, D_2 and $D_2^+ \rightarrow D^+$, $D(4\,eV) \rightarrow D^+$, $D(C/X) \rightarrow D^+$ computed from the 1-D model.

Initial D_2 influx $(X = -3.75) = 1.5 \times 10^{18}$ mols/cm²/s
Plasma parameters $T_e(x) = 30(1 - x^2/a^2)^{0.6}$ (eV)
$n_e(x) = 1.5 \times 10^{13}(1 - x^2/a^2)^2 (cm^{-3})$
$a = 3.75$ cm.

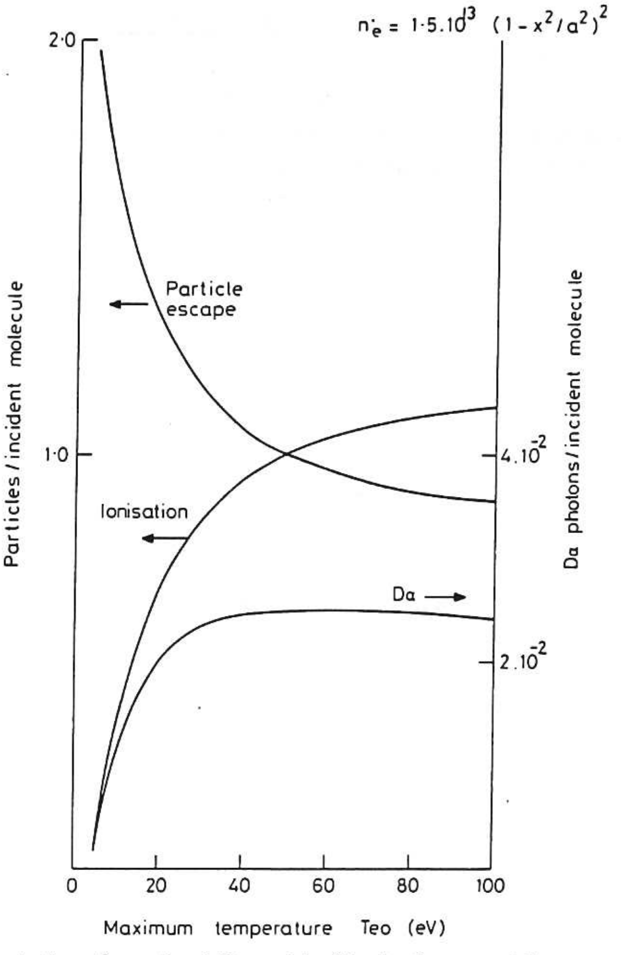

Fig. 2 Computations from the 1-D model of ionisation, particle escape and Dα emission probabilities per incident molecule as a function of plasma temperature $T_e = T_{eo}(1 - x^2/a^2)^{0.6}$, $n_e = 1.5.10^{13}(1 - x^2/a^2)^2$.

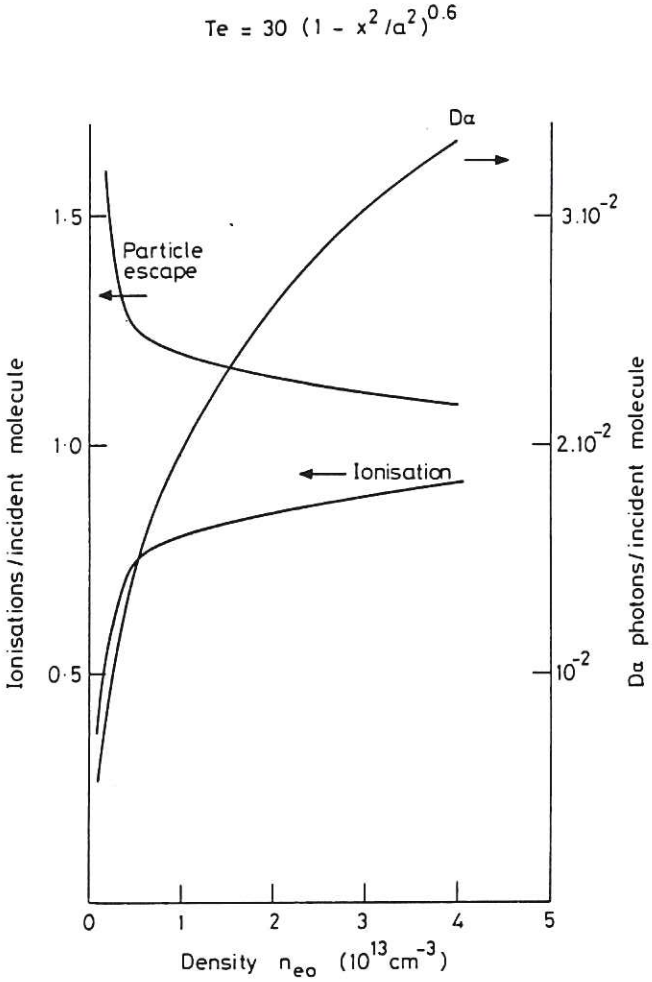

Fig. 3 Computations from the 1-D model of ionisation, particle escape and Dα emission probabilities per incident molecule as a function of plasma density $n_e = n_{eo}\,(1 - x^2/a^2)^2$, $T_e = 30(1 - x^2/a^2)^{0.6}$.

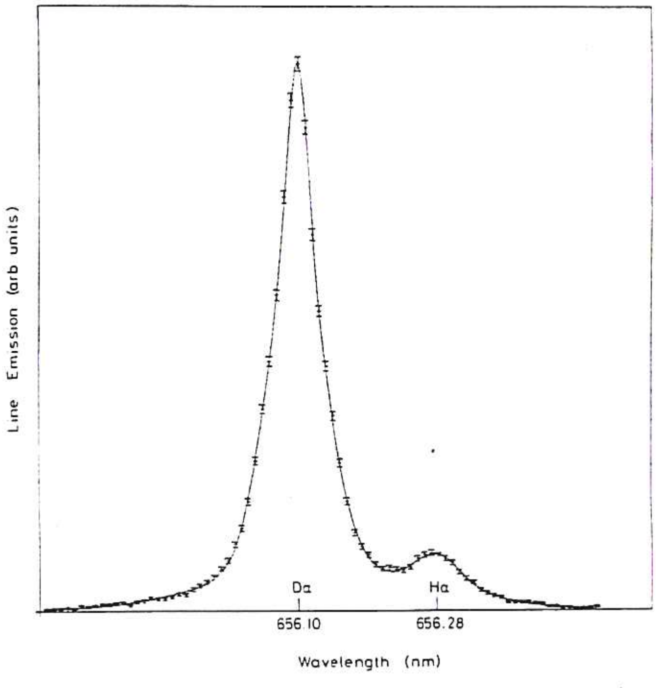

Fig. 4 Line emission profile measurements of Dα from the divertor chamber plasma. The fitted line is for three Guassians, centred at Dα, with widths corresponding to Maxwellian average energies of 0.46 eV, 4.1 eV and 40.0 eV and ratios 0.12, 0.64, 0.24 respectively, convolved with the instrument function.

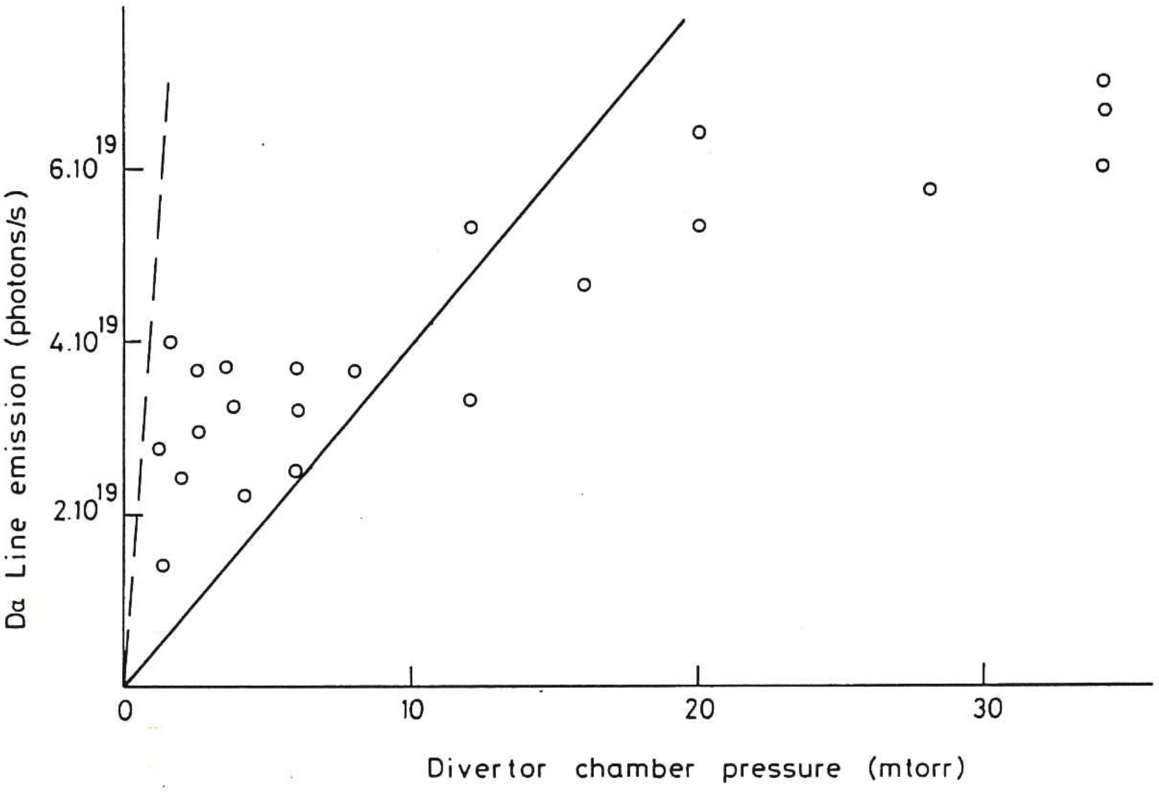

Fig.5 Dα line emission from the divertor chamber plasma for a series of discharges with varied gas feed rate. The dashed line corresponds to the Dα emission expected from the molecular influx at the divertor chamber neutral gas pressure, making use of the 1-D code but neglecting pressure balance effects. The full line is the predicted Dα behaviour when pressure balance is taken into account.