EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(03)01-32

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**See Annex of J. Pamela et al., "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in Proceedings of the
EPS Conference on Controlled Fusion and Plasma Physics,
(St. Petersburg, Russia, 7-11 July 2003)

ABSTRACT

In helium (He) experiments in JET the power threshold for He was observed to be 50% higher than for deuterium (D) [1]. However, in experiments using H, D and T plasmas, the mass dependence of the L-H transition power threshold was observed to be $P_{thr} \propto A^1$ [2] implying a possible strong dependence of threshold power on charge number Z. The transition temperature scales only weakly as a function of mass number, i.e., $T_{thr} \propto A^{0.14\pm0.19}$ [3] but the Z dependence is not well known. In this paper, experimental electron temperature data for He discharges and corresponding data for D reference discharges are compared. ECE data at the top of the pedestal at the time of L-H transition indicates higher threshold temperature for He than D. In Ref. [4], E_r at plasma edge in a realistic ASDEX Upgrade geometry was solved from the neoclassical radial current balance using the 5D orbit following Monte Carlo code ASCOT [5]. For a given temperature profile, the $E_r \times B$ flow shear was found to be much lower for He than for D. If the critical $E \times B$ flow shear for strong turbulence suppression is the same for D and He, this is in qualitative agreement with the observation of a higher L-H transition threshold temperature for He. Here, this same simulation is repeated using JET geometry and background parameters and a similar result is found. Such effects as collisionality, ion orbit losses, radial mean free path between collisions and finite orbit width all depend on mass and charge number.

These all are consistently taken into account in ASCOT simulations.

1. EXPERIMENTAL RESULTS

In JET deuterium plasmas, an unconstrained fit for the L-H transition electron temperature at JET gave a scaling [3]

$$T_{e,\,top}(\mathrm{keV}) = 0.39[0.19,\ 0.81]n_{ea}^{0.64\pm0.15}\ B_t^{1.69\pm0.18}\ A_{eff}^{0.15\pm0.19}\ A_{eff}\,q_{95}^{0.86\pm0.57} \tag{1}$$

where A_{eff} is the effective mass [amu], q_{95} is the safety factor at ψ_{95}, Bt is toroidal magnetic field [T], $T_{e,\,top}$ is the electron temperature at time of L-H transition at the location where the top of the pedestal (measured with the heterodyne radiometer) in H-mode is located [2] and n_{ea} is the line-averaged density from the far-infrared (FIR) interferometer at the fixed point R = 3.75m expressed in 10^{19} m^3. However, in experiments with H, D and T plasmas, the mass dependence of the L-H transition power threshold was observed to be much stronger, $P_{thr} \propto A^1$ [2], than the mass dependence of the threshold temperature. This difference arises from $P_{thr} \propto T_{thr}\, n/\tau_E$ where the confinement time has dependencies $\tau_E \propto A^{0.2}\ P^{0.67}$ i.e. a strong power dependence is included.

In recent helium experiments the power threshold for helium has been observed to be 50% higher than for deuterium. The confinement time was observed to be 24% lower for helium than deuterium. Thus, $T_{thr}/P_{thr}\, \tau_E/n$ should be 14 % higher for helium than deuterium. In Figure 1(a), the electron temperature at the time of the L-H transition at pedestal is plotted for five different cases. ‘Helium’ in the figures means discharges with a significant fraction of helium (40% to 100%) and

‘Deuterium’ means discharges with less than 5% of helium. Five different cases are given in Table 1. In general the critical temperature for L-H transition here seems to be higher for helium than for deuterium. In Fig.1(b), T_{ped} is normalized to the scaling $T_{e;top}$ given in Eq. (1) which includes the weak mass number dependence but not the charge number dependence. With this normalization the trend is clearer. Relative differences when compared to unnormalized plot arise from the $T_{e;top} \propto n_{ea}^{0.64}$ dependence in the scaling. For some discharges nea data does not exist, which explains the smaller number of data points in this figure.

case	B_t	q_{95}	He discharges	D reference(s)
1	1.8	3.3	54128 - 54132	53260
2	2.4	2.9	54177	53718
3	2.6	3.3	53937 - 53940	53936, 53170
4	2.6	3.3	53942, 53944 - 53946, 53948	53171
5	3.2	3.3	54182	53261

Table 1: Helium discharges and corresponding deuterium reference discharges shown in figure 1.

2. ASCOT SIMULATION OF ER STRUCTURE

In this section, the results of fully kinetic Monte Carlo orbit-following simulations with ASCOT [5] are shown. The kinetic calculation of the radial electric field in ASCOT is based on the neoclassical radial current balance including also the ion orbit losses. The ion ensemble corresponding to the main plasma ions is initially distributed according to the assumed background density and temperature profile with a Maxwellian energy distribution. Each ion is followed along its guiding-centre orbit determined by the $\vec{E}_r \times \vec{B}$, the gradient and curvature drifts, collisions, and the polarization and viscosity drifts. The radial electric field E_r is evaluated from the condition $\langle j_r \rangle = 0$ of the radial ion current density. Here, $\langle ... \rangle$ denotes the flux surface (and ensemble) average. The E_r dynamics arises through the polarization drift $v_{rp} = (1/\Omega B)\, \partial E_r / \partial t$ affecting each ion. Here $\Omega = ZeB/m_i$, Ze is the ion charge and m_i is the ion mass. The density profile is inherently kept unchanged. The simulation is continued until the steady-state is found.

Figure 2(a) shows the steady-state profiles of $d\Phi/d\rho$ for typical ASDEX Upgrade parameters in the region $0.97 < \rho < 1$ for plasmas consisting of various isotopes of hydrogen and helium. When changing the isotope, the electron density profile and other parameters are kept fixed. Differences in the hydrogen isotope curves can only be seen in about a one centimeter wide region inside the separatrix. Only a slight increase of shear can be observed when A increases. Further inside the results are almost identical. However, for helium, the shear is much lower. Assuming that the critical shear is not sensitive to A and Z, this implies that the threshold temperature for L-H transition is higher for helium than for deuterium, which is qualitatively consistent with the results of the previous section. In Fig.2(b), the same simulation is shown for JET data and the conclusions are the same. As discussed in Ref. [6], the width of the E_r structure is extended to $\min(r_p, L_r)$ from separatrix where $r_p = v_T m/ZeB_p \propto A^{1/2}/Z$ is the poloidal Larmor radius, $L_r = v_r/v_{ii}$ is the radial mean free path based on Coulomb collisions, v_r is the radial drift velocity of the ion and v_{ii} is the ion-ion collision frequency. Since $v_r \propto T/ZBR$ we obtain $L_r \propto T^{5/2}A^{1/2}/Z^5 nBR$ for the radial mean free path. For helium, L_r is smaller and a higher edge T is required to obtain the same shear in the $E_r \times \mathrm{B}$ flow in agreement with the present numerical results. Here, in the ASDEX Upgrade case, collisionality $v_* \approx 4$ and in the JET case $v_* = 0.6$ at the separatrix for deuterium cases. Since $v_* \propto \mathrm{Z}^4$, the helium cases both for ASDEX Upgrade and JET are clearly in the collisional regime. One should note also that the units in the figure are not E_r but $d\Phi/d\rho$. Thus, the electric field ($\propto \nabla\rho$) and especially its shear ($\propto |\nabla\rho|^2$) are much higher for ASDEX Upgrade than for JET in this example although $d\Phi/d\rho$ is almost same.

CONCLUSION.

In general, the critical temperature for L-H transition here seems to be higher for helium than deuterium, which is qualitatively consistent with the ASCOT simulations for $E \times B$ shear in which the main origin of the $E \times B$ shear is ion orbit losses. We do not claim that these are from strictly collisionless orbits. As written above, the essential parameters are the mean free path, enabling ions to proceed over the separatrix, and the processes which prevent the particles coming back. These non-standard extra losses increase E_r when compared to conventional neoclassical theory. One such non-standard process discussed in the literature is the so-called X-transport [7] which means non- ambipolar collisional convective loss of ions in the X-point region where B_p becomes vanishingly small and some ions with small parallel speed do not have enough poloidal rotation to move out of the region. This process is self-consistently included also in the present simulation, although its effect is not separately studied.

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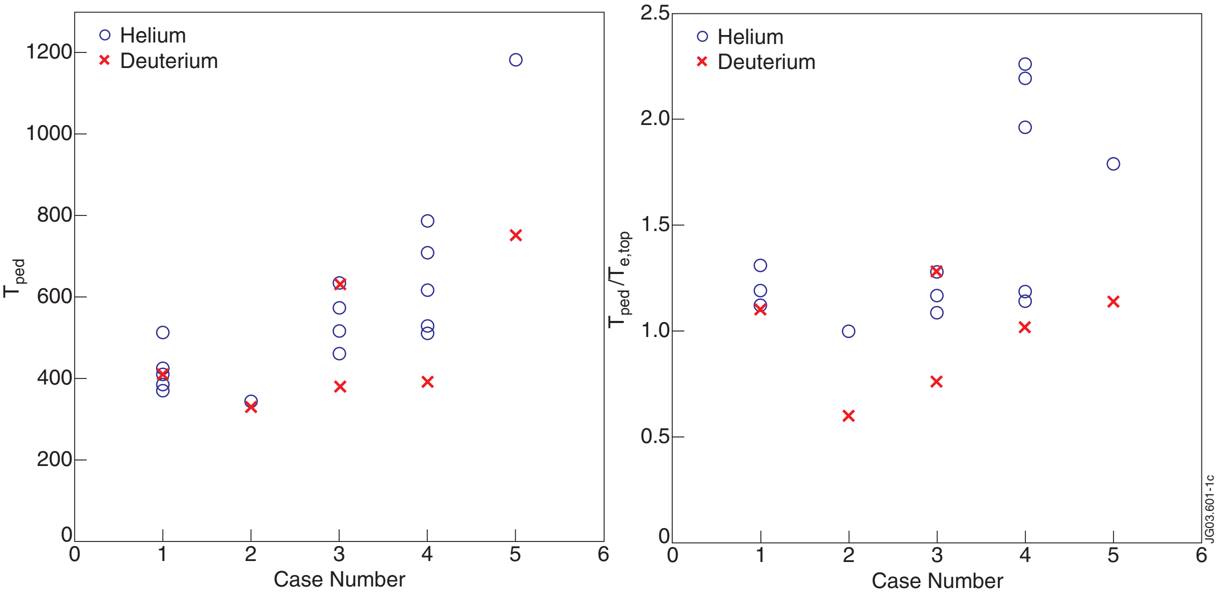

Figure 1: (a) ECE data for electron temperature shows a higher L-H transition threshold temperature for helium than deuterium (see Table 1 for parameters). b) Same as (a) but normalized to scaling $T_{e;top}$ given in Eq. (1).

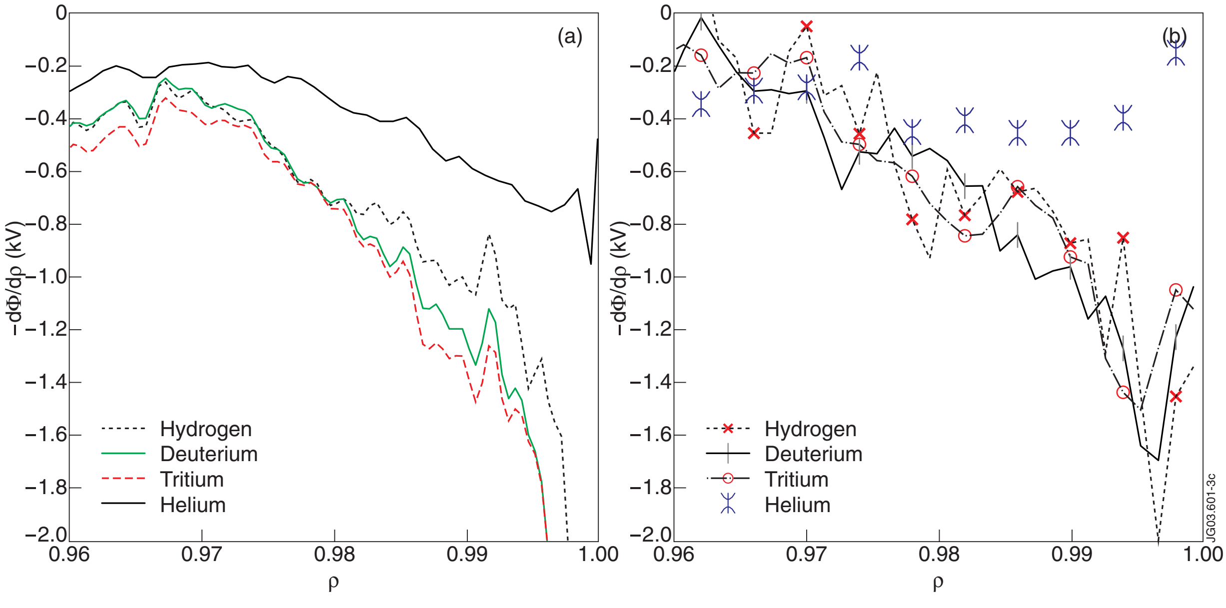

Figure 2: $\omega_{E\times B}$ for various isotopes of hydrogen and helium for a) ASDEX Upgrade and b) JET.