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Journal of Nuclear Materials 337–339 (2005) 831–834

journal of nuclear materials

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High energy electron deposition within vertical ports, during lower hybrid current drive on Tore Supra

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Abstract

Unexpected hot spots were observed around the edges of vertical ports on Tore-Supra, caused by fast electrons, accelerated by the lower hybrid waves used to drive the current, and trapped in the local ripple wells. Trajectory calculations, with the magnetic fields alone, show that no electrons should reach such locations. However, electrostatic potentials, at a kilovolt level, can induce a toroidal pinch of the trajectories, allowing particle deposition in these normally shadowed areas. Their origin is attributed first to a strong increase of the sheath potential at the port entrance, due to the fast electron flux itself, and second to its reduction within the port, when the sheath width becomes larger than the port width, due to the too low value of the local density. An increase of the capability of the cooling panels within the port, to cope with these additional fluxes, has been implemented.

PACS: 52.40.Hf; 52.65.Cc; 52.50.Gj; 52.55.Fa

Keywords: Particle orbits; Electric field; Sheaths; Steady state; Tore Supra

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1. Introduction

The Tore Supra toroidal magnetic field exhibits a high ripple level, up to a few percent at the plasma edge, due to the closeness of its 18 magnetic coils to the plasma [1]. Even in the core of the plasma, the local magnetic wells are deep enough to trap fast particles. In particular, electrons accelerated up to 200 keV by lower hybrid waves (LH), used to drive the current, can undergo pitch angle scattering, and be trapped between two adjacent toroidal coils in the local magnetic well [2,3]. Curvature and gradient drifts, no longer cancelled, then push the electrons toward the top of the vessel, where they are lost on the first wall, as the collision rate for electrons above 50 keV are too low for de-trapping.

Up to 10% of the LH power (P_{LH}, up to 4 MW) can be lost through this channel, on very localised spots around and inside the vertical ports. High flux components have been designed to cope with these electron fluxes, up to 20 MW/m^2. The precise geometry of these components is tailored to intercept all the trajectories of the electrons within the magnetic topology. Dedicated studies of these fast trapped electron were carried out [4]. B_4C coated CuCrZr tubes are used on the leading edges of the vertical ports where the fluxes are the highest. There are also stainless steel panels, shadowed by these tubes, where fluxes stay below 0.5 MW/m^2

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doi:10.1016/j.jnucmat.2004.09.049

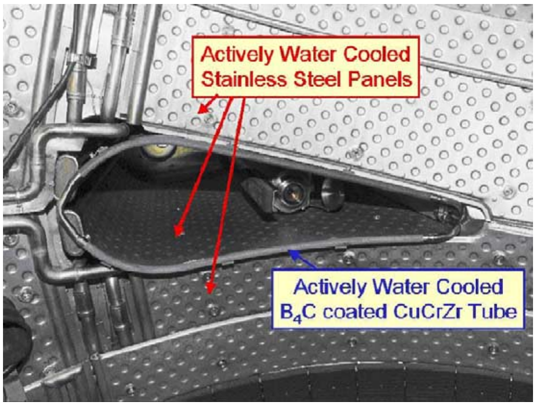

Fig. 1. View of the Tore Supra inner vessel around a vertical port. The B_4C coated CuCrZr tube and the stainless steel panels are identified.

(Fig. 1). Both components are actively cooled by pressurised water at 120 °C.

2. Experimental observations

During long pulse plasma operation, a high level of LH power is required to generate the major part of the plasma current. As the current drive efficiency decreases as $1/n_e$, the density n_e must be reduced for full current drive. Under these conditions, the ripple losses, which scale roughly as P^2_{LH}/n^2_e, are significant, and hot spots are observed on the stainless steel panel edges, with a visible CCD camera (Fig. 2). After a few tens of second, the iron impurity content of the plasma rises, and a blue halo is seen by the CCD camera, interpreted as iron vapour going into the plasma.

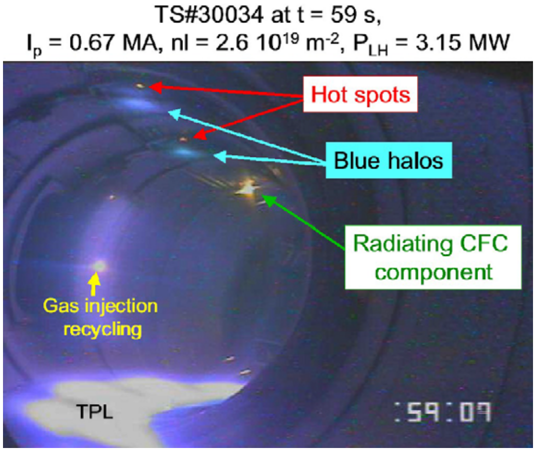

Fig. 2. Tangential view of a plasma after 1 min discharge duration (visible CCD camera). Hot spots located at the vertical port entrance are clearly visible as well as blue halos (see text). Also identified are the H_α recycling close to the main toroidal pumped limitor (TPL) and gas injection, and light from a radiating CFC component located between two toroidal coils where there is no vertical port.

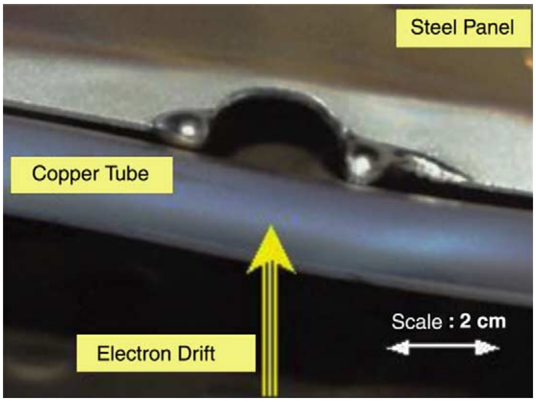

Fig. 3. Detailed view of the vertical panel melting zone located behind the shadowed copper tube zone.

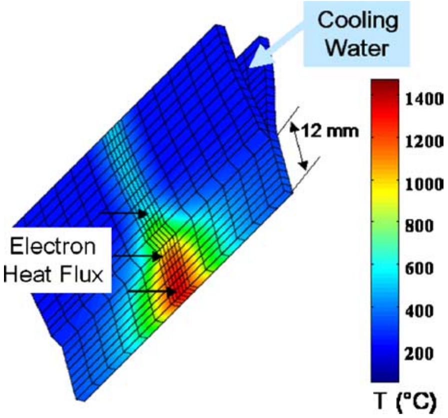

Fig. 4. 3D simulation of temperature distribution for 2.5 MW/m^2 incident heat flux, 6 mm wide, deposited on the panel border.

At the following shutdown, during access in the vessel, localised melting was observed on one side of each of the vertical ports, at the edge of the steel panels, just above the copper tubes (Fig. 3). Absolutely no power fluxes are expected at this location, as all trajectory calculations of the fast electrons trapped in the magnetic field indicate a total shadowing of the steel panel by the copper tubes. A 3D thermal simulation indicates that the power required to reach the melting at the panel border is of the order of 2.5 MW/m^2, this edge being at 12 mm from the cooling water. Under such flux, the local temperature reaches 1440 °C after typically 25 s (Fig. 4).

3. Fast electron trajectory

Particles locally trapped in the local well between toroidal coils are characterised by a parallel energy to transverse energy ratio ($E_{\parallel}/E_{\perp}$) smaller than the ripple well relative depth. As in a magnetic mirror, the particles oscillate inside the well. The closer to the well depth the $E_{\parallel}/E_{\perp}$ ratio, the larger the toroidal extension of the oscillation is. The trapped particles undergo a further vertical drift associated with the toroidal curvature of the main magnetic field. Calculation of energetic trapped electron trajectories ($E_{\parallel}/E_{\perp} = 0.02$ at the plane in the middle of the well) using the exact magnetic field topology shows that no electrons should reach the edge of the vertical steel panel. For electron energies within the expected range (50–200 keV), the vertical drift step between successive bounces remains in the sub-millimetre range (Fig. 5), insuring a total interception of the trajectory by the copper tubes. And, as the electron drifts higher and higher inside the vertical port, the toroidal width of the bounce decreases, as the magnetic well gets deeper. Under these conditions the electron trajectory can never reach the panel border. The knowledge of the magnetic topology, dominated by the 2.5 MA-turns carried by each toroidal field coil, and the 1 MA plasma current, is almost perfect. One cannot imagine any parasitic or locally induced current strong enough to modify this magnetic field topology.

The only way to modify the trajectories is by considering electric potentials. A few 100's of volts are enough to change the very small parallel energy of the electrons, a few percent of their total energy. The toroidal extension of the trajectories can thus be strongly modified, indicating the huge sensitivity of the oscillation amplitude to the parallel energy (bouncing points are characterised by a null $E_{\parallel}$). A change in potential of -1 kV along the vertical drift induces a toroidal pinch of the bounce about 2 cm (Fig. 6). This pinch is caused by the decrease of the total electron energy, with the conservation of the first adiabatic invariant: the bounce occurs at a lower field value, closer to the bottom of the magnetic well.

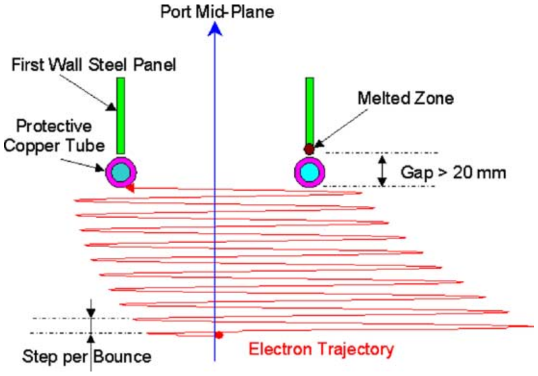

Fig. 5. Fast trapped electron trajectory and geometry of the vertical port in the Z–ϕ plane. For clarity, the step per bounce of the electron trajectory has been greatly enlarged.

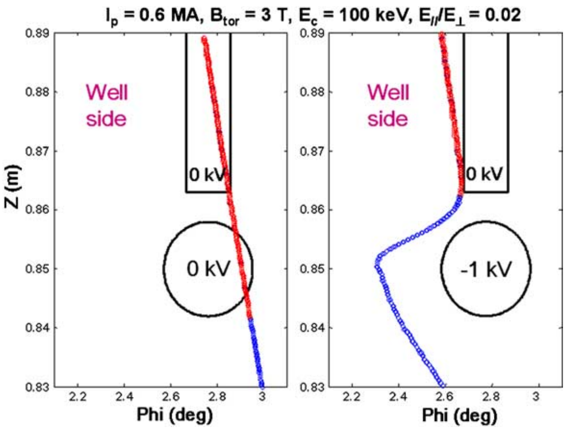

Fig. 6. Z–ϕ view of the bounce trajectory without (left) and with (right) a voltage on the copper tube. Calculations are performed for electrons with 100 keV total kinetic energy and a parallel to perpendicular energy ratio ($E_{\parallel}/E_{\perp}$) equal to 0.02. For clarity only the mirror point locations are drawn, using blue colour before any intersection with a material surface, and using red colour after such an intersection would occur.

However, to reach the vertical steel panel, the potential must be effective at the level of the copper tube, and furthermore must disappear at the level of the vertical panel to recover the initial toroidal extension of the oscillating trajectory (Fig. 6). Several hypotheses were studied for the origin of such a potential profile. It was suspected initially that the B_4C coating of the tubes, as an insulator, was being charged to generate such potential. However, the B_4C resistivity is too low, and the removal of the coating on some of the tubes does not suppress the hot spots. Our favoured explanation relies on a strong enhancement of the sheath potential at the port entrance, from the few volts expected in the cold edge plasma – more than 10 cm from the main plasma – up to kilovolt values. This explanation leaves the vertical panel and the copper tube potentials (which are electrically connected) at values close to ground and introduces a large floating potential inside the plasma.

4. Sheath potential interpretation

A sheath potential appears between a plasma and a wall, on the scale of the Debye length ($\lambda_{\text{Debye}} = (\frac{\varepsilon_0 kT_e}{n_e e^2})^{1/2}$ that is a few 100's of μm in typical edge plasmas), to repel the electrons, faster than the ions, thus insuring equality of ion and electron fluxes at the wall. In a thermal plasma, this potential is of the order of

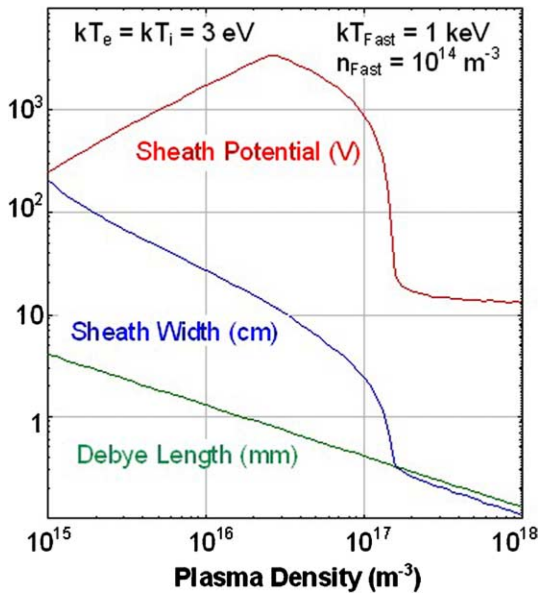

Fig. 7. Sheath analysis results for a fast electron distribution associated to a background plasma. Evolution of the sheath potential and the sheath width (compared to the Debye length) as a function of the surrounding plasma density.

3 times the electron temperature. Both fluxes impinging the wall are equal to the product of the ion density and the ion thermal velocity, called the Bohm flux or ion saturation current (ISC). In the presence of a supra-thermal electron flux, the sheath potential will increase higher than $3T_e$, to reduce the thermal electron flux even lower, and/or to stop the fast electron themselves. A large increase (from few volts to few kilovolts) occurs when the fast electron flux becomes higher than the Bohm flux. This increase in the sheath potential is correlated with a spatial enlargement of the sheath, as shown on Fig. 7. In this model, a constant 1 keV fast electron density of 10^{14} m^{-3} is assumed (estimated from the 2.5 MW/m^2 power flux), within a background plasma of 3 eV, with a density between 10^{15} and 10^{18} m^{-3}. Above 2×10^{17} m^{-3}, a standard sheath of 3–4 kT$_e$ is observed, with a width of typically 6–8 Debye lengths (1–2 mm). Below 2×10^{17} m^{-3}, this potential rises up to 3 kV, and the width rises up to one meter. However, when the sheath width is larger than half of the port width (12 cm), the potential cannot develop itself anymore, and the screening of the fast electrons is less and less effective. This effect occurs below 3×10^{16} m^{-3}.

The background plasma density at the port entrance is estimated to be 10^{17} m^{-3} from Langmuir probe and reflectometry measurements in the scrape-off layers. A characteristic length of $\lambda_n \approx 5$ mm is assumed in the port ($\lambda_n \approx 5$ cm has been measured in the scrape-off, close to the plasma, and a scaling as the square root of the connection length is used). The plasma density decays down to 10^{15} m^{-3} 20 mm inside the port, that is at the level of the steel panel border. Sheath potential models [5,6] have also been used to simulate the screening effect of a fast electron distribution in presence of a background edge plasma. All these models assume free ion and electron trajectories and Maxwell distributions, and the effects of magnetic field are never included. Results of the PIC model (Plasma in Cell [6]) show that an equilibrium is obtained, with a plasma density around few 10^{16} m^{-3} and a sheath potential around 400 V at the port entrance, allowing the deposition of the fast electrons (2.5 MW/m$^2 \cong 25$ A/m^2), both on the copper tube and the steel panel. The edge of the panel, due to its poor water cooling, melts under such flux.

5. Conclusion

This simplified sheath model gives a qualitative and quantitative explanation for the change in electron trajectories, necessary for their impact in the shadow of the copper tubes. The accuracy of the simulation is mainly limited by the lack of precise knowledge of the plasma parameters within the port (in absence of diagnostics, basic physics and scaling laws have been used). However, an increase of the capability of the protective cooling panels within the port, to cope with these additional fluxes, has been implemented. In addition, a thin foil of CFC, placed in front of the steel, dilutes the localised power, and avoids any melting.

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