Ion fluxes in the ergodic divertor of Tore Supra

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In this contribution we examine the coupling between the ergodic divertor and global recycling patterns in Tore Supra. Experience has shown that activation of the ergodic divertor reduces the fueling efficiency of the gas injection; more gas flow is required to maintain a fixed core density with the divertor on than with the divertor off [1]. Simple reasoning suggests that this could be due to geometrical effects. The volume of the laminar zone, that region whose connected magnetic flux tubes define the presheath of the divertor structure, increases with the divertor current I_{ED}. Test particle modeling shows that particles ionized inside the laminar zone are more likely to return to the targets during one poloidal transit than they are to diffuse into the confined region [2]. Therefore the total ionization rate must be increased in order to maintain constant core density.

A series of density ramps with deuterium gas injection and plasma current $I_p = 1.5\text{MA}$ was performed at different values of divertor current. Here we examine Tore Supra discharges TS28287, TS28293, and TS28269 having divertor currents I_{ED}=15, 30 and 45 kA respectively and all other parameters identical. The outboard pump limiter was withdrawn behind the divertor and therefore plays no role in the particle balance. As we will see below, the divertor affects the global performance of the plasma, modifying the relationship between edge and core, and changing the density limit. Therefore, in order to avoid radiative limit disruptions during the density ramps, an alarm triggered by an increase of the degree of detachment (DoD), as measured in real time by the target probes, was used to cut off the gas flow at the critical moment [3]. Assuming that the typical length of a laminar flux tube is one half of a poloidal turn, then the volume of the laminar zone can be characterized by the parallel projection of the divertor's wetted surface area A_{ED}. This quantity is taken be characteristic of the strength of the effective particle sink; it has been estimated by the field-line-tracing code MASTOC to vary roughly as $A_{ED} \propto I_{ED}^{0.5}$. The poloidal component of A_{ED} is defined by the mechanical structure of the divertor, and the radial component by the strength of the divertor perturbation relative to the total magnetic field. We suppose that in steady state all the ionized deuterium flows onto the targets so that we can define the global ionization rate as

$$\nu_I = \int_{plasma} S_I dV = \int_{targets} \Gamma_{//} dA = \langle J_{SAT} / e \rangle A_{ED} \quad (1)$$

where $\langle J_{SAT} / e \rangle$ is the parallel ion flux density estimated by averaging over all fourteen divertor target probes. Recombination does not occur in Tore Supra due to the high edge temperature and low edge density [4]. The possible contribution of ionized impurities to the measured current is ignored. It has been previously shown that this measurement agrees with a similar calculation derived from CCD imaging of one target plate in D_α light [2].

We consider separately the high recycling regime and the detached regime. The division between the two regimes is signalled by the rollover of the total source rate (Fig. 1), the saturation of the edge electron temperature (Fig. 2), a minimum of Z_{EFF} (Fig. 3), a runaway of the total radiated power accompanied by a MARFE-like phenomenon [5] (Fig. 4), and a minimum of the dynamic gas fueling efficiency (Fig. 5). In the high-recycling regime, for a fixed value of core density, the global ionization rate increases approximately linearly with divertor current, and therefore as the square of the thickness of the laminar layer $\nu_I \propto A_{ED}{}^2$. It is difficult to evaluate the significance of this behaviour : this quantity includes the ionization that feeds the core directly (neutral penetration) [6], indirectly (diffusion from the laminar layer), plus the local recycling at the targets. The source rate increase coincides with a proportional decrease of the edge electron temperature. (The reader will notice that the

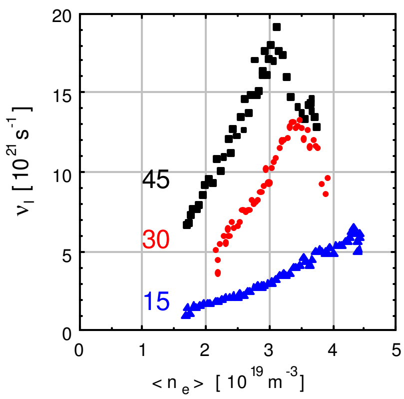

Fig. 1. Total source rate vs. volume-averaged core density for three values of divertor current.

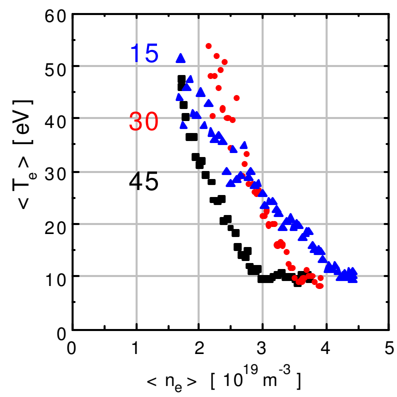

Fig. 2. Average electron temperature on targets.

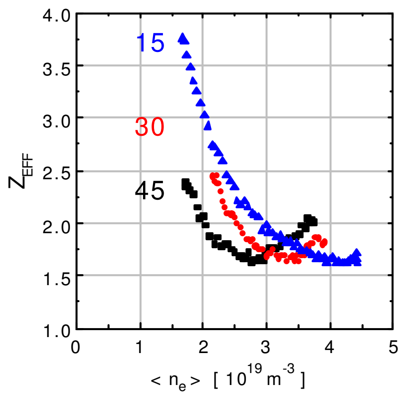

Fig. 3. Effective ion charge.

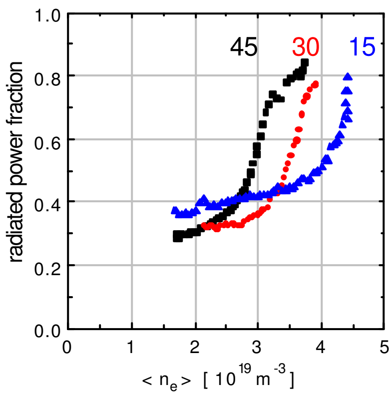

Fig. 4. Total radiated power measured by bolometry.

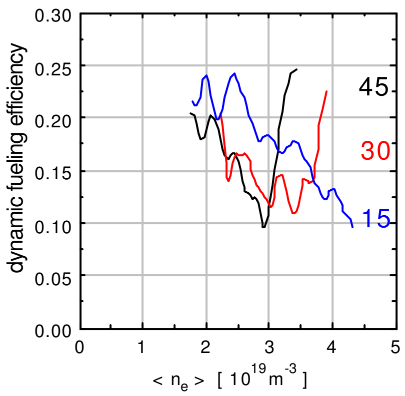

Fig. 5. Fueling efficiency defined as rate of change of core density divided by gas injection rate.

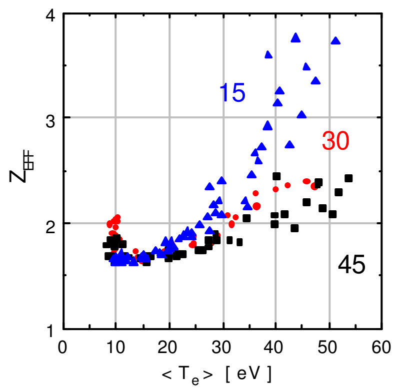

Fig. 6. Effective charge vs. target electron temperature.

probe data for the lowest value of divertor current do not quite follow the trend. This is because some of the probes are shadowed by neighbouring divertor modules and thus should not be included in the average. The same field line calculation that gives A_{ED} can be used to calculate this shadowing.) Even though the conducted power $P_{OHMIC} - P_{RAD}$ is roughly constant, the effective charge Z_{EFF} is dramatically reduced, implying improved radiation efficiency of intrinsic impurities [7].

The primary mechanism for the improved impurity screening could be the deuterium flow to the targets [2]. Test particle simulations reveal the existence of a thick blanket of large parallel flow that completely envelopes the confined plasma. The structure of the flow field was confirmed by Gundestrup probe measurements of the radial profile of parallel flow on top of the torus in various magnetic geometries. More rigourous predictive fluid modeling of TEXTOR's dynamic ergodic divertor shows similar effects [8]. Impurities that are ionized in this zone (we equate the flowing blanket with the laminar layer) are strongly coupled to the deuterium flow via the friction force, and can be swept rapidly to the targets before having a chance to diffuse to the core. In general the screening is efficient if the typical time for diffusion across the laminar layer is longer than a poloidal transit time. Obviously, the main parameters that come into play are (1) the ionization length of the incoming neutral impurity, (2) the impurity diffusion coefficient, (3) the thickness of the laminar layer, and (4) the deuterium flow speed. The screening effect is lost at high density, or more correctly, at low edge temperature when the flow speed drops. Furthermore, edge turbulence is observed to increase at detachment [9]. The primary control parameter of the discharge, especially into the detached regime, is in fact the electron temperature, independent of the magnetic geometry. When the critical value of roughly 10 eV is attained, bad things happen : neutral penetration increases, leading to runaway radiative losses and ultimately a disruption [4]. One notes that Z_{EFF} always has the same minimum value at the detachment threshold. The transition from high-recycling to detachment, and the evolution of the favourable screening properties of the flowing laminar layer, are well illustrated by plotting Z_{EFF} against the edge electron temperature (Fig. 6). At high temperature we clearly see the effect of the divertor perturbation, while at low temperature, it is completely swamped, presumably by the aforementioned atomic physics.

In summary, it seems that the simple notion of an edge deconfinement time, typically a poloidal transit time inside a zone defined strictly by the magnetic shadow of the divertor structure, is sufficient to explain the main features of ergodic divertor operation in the high-recycling regime. In the detached regime, atomic physics dominates, cancelling the beneficial effects of the divertor. Edge flows, and the ability to manipulate them (for example by ergodization or target plate biasing), should be considered as a plasma engineering tool in fusion devices.

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