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# Tore Supra divertor screening efficiency during density regime experiments

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**Abstract**

The Tore Supra ergodic divertor (ED) screening efficiency has been investigated in density regime experiments. The ED screening efficiency is analysed by using the 'tightness' concept, which is the ratio of the density on the ED neutraliser plates to the volume averaged plasma density. Tightness is studied as a function of different plasma edge parameters, such as $T_{div}$, ED magnetic perturbation ($\Delta$), plasma composition, location of recycling source, and additional power. Tightness is shown to increase with $\Delta$, $P_{div}^{0.55}/(1-\mathrm{Fr})^{1.22}$, and $1/T_{div}^{0.5}$. These trends are well explained by a simple 0-D model, where the particle confinement time in the ergodized peripheral region is very small. Finally, tightness increases with the power conducted onto the ED plates. Since ED plasmas have low $P_{div}$, their tightness value remains low compared to that obtained with axisymmetric divertors for which $P_{div}$ is considerably larger. Increasing $P_{div}$ will result in an improved tightness and a better particle control. 

*Keywords:* Tore Supra; Screening; Ergodic divertor; Divertor

## 1. Introduction

In a fusion reactor, two plasma edge major goals have to be realised at the same time: a large conducted power (up to 10–20 MW per m$^2$) must be exhausted on target plates, and the recycling fluxes, proportional to the exhaust particle fluxes, must be controlled. In this perspective, divertor tokamaks are actually the best candidates, since they have proved to be able to sustain reactor relevant conducted power values. Moreover, due to the diverted plasma properties, the recycling surfaces are more distant from the last closed flux surface, compared to limiter plasmas; the plasma core is, therefore, more decoupled from recycling. Practically, the best divertor will be capable to decouple completely the core plasma from the edge. However, in these conditions, the gas core fueling will be non-existent, and neutral beam or pellet injection will be necessary to fuel the plasma.

Tore Supra is equipped with an ergodic divertor (ED); it is an open divertor, which has proved to be efficient to control particle recycling fluxes. Indeed, the gas fueling efficiency of ED plasmas is lower than 5%, whereas in limiter plasmas it is approximately 20% [1].

In order to characterise the ED edge-core plasma decoupling, we use the tightness value, which is the ratio of the edge density, measured on the ED neutraliser ($N_{div}$), to the volume averaged plasma density ($\langle n\rangle$).

In this paper, the ED tightness is studied during density regime experiments in which the central density is increased through gas injection. In Tore Supra, as in the other divertor devices, density regimes are studied through the $N_{div}$ evolution when $\langle n\rangle$ is increased. Three density regimes are found [2]: linear, high recycling, and detached regimes. The ED tightness is evaluated during these density regimes as a function of different plasma edge parameters, such as the ED intensity perturbation, the position of the recycling sources with respect to the ED neutralisers, the external pumping device, the intensity of ICRH heating, and the plasma particle composition.

However, before presenting all the experimental results, a simple screening model will be introduced,

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allowing to write the ED tightness as a function of the relevant plasma edge parameters.

## 2. Modelling the ED tightness

The following equations are expressed in the frame of a simple 0-D model, presented in [2], and are straightforward modifications of this initial presentation.

The ED target electron temperature is written as

$$T_{\mathrm{div}} \propto P_{\mathrm{div}}/\Gamma_{\mathrm{div}}, \tag{1}$$

where $P_{\mathrm{div}}$ and $\Gamma_{\mathrm{div}}$ are the impinging energy and particle fluxes on the ED target.

If $\langle n\rangle$ is the volume averaged plasma density, the particle core outflux is given by $\langle n\rangle V/\tau_{\mathrm{p}}$, where $V$ is the confined plasma volume and $\tau_{\mathrm{p}}$ the particle confinement time.

At equilibrium, the plasma core outflux is related to the particle target flux through the following expression:

$$\langle n\rangle V/\tau_{\mathrm{p}} = \Gamma_{\mathrm{div}} S_{\mathrm{div}} \exp(-\Delta/\lambda_{\mathrm{i}}), \tag{2}$$

where $S_{\mathrm{div}}$ is the target surface, $\exp(-\Delta/\lambda_{\mathrm{i}})$ a flux attenuation factor, $\Delta$ the radial extent of the low confinement region due to the ED perturbation, and $\lambda_{\mathrm{i}}$ is the ionisation mean free path.

Since

$$N_{\mathrm{div}} T_{\mathrm{div}}^{1/2} \propto \Gamma_{\mathrm{div}}, \tag{3}$$

it follows that

$$N_{\mathrm{div}}/\langle n\rangle = V/S_{\mathrm{div}} 1/\tau_{\mathrm{p}} \exp(\Delta/\lambda_{\mathrm{i}}) 1/T_{\mathrm{div}}^{1/2}. \tag{4}$$

Tightness increases with the ED perturbation and when $T_{\mathrm{div}}$ decreases.

Using the *L*-mode Tore Supra scaling law and assuming that $\tau_p$ is proportional to $\tau_{\mathrm{E}}$, one has

$$\tau_{\mathrm{p}} \propto \langle n\rangle^{0.4} P^{-0.73},$$

where $P$ is the core plasma power. From (2)

$$N_{\mathrm{div}}/\langle n\rangle \propto \exp(\Delta/(0.6\lambda_{\mathrm{i}}))(N_{\mathrm{div}}^{0.6} T_{\mathrm{div}}/P_{\mathrm{div}})^{1/0.6} P^{1.22}. \tag{5}$$

Multiplying (5) by $N_{\mathrm{div}}$, since $N_{\mathrm{div}} \propto P_{\mathrm{div}}/T_{\mathrm{div}}^{3/2}$ and $P_{\mathrm{div}} = P(1-\mathrm{Fr})$, where Fr is the radiated fraction, we finally obtain

$$N_{\mathrm{div}}/\langle n\rangle \propto P_{\mathrm{div}}^{0.55}(1-\mathrm{Fr})^{-1.2} T_{\mathrm{div}}^{0.16}. \tag{6}$$

Tightness increases with $P_{\mathrm{div}}$, the conducted power onto the ED target.

## 3. ED tightness studies

In the following, the plasma edge measurements ($N_{\mathrm{div}}$, $T_{\mathrm{div}}$) come from domed Langmuir probes, located on the neutraliser of the ED [3]. During Tore Supra density regime studies, gas injection is feedback controlled on $T_{\mathrm{div}}$ to avoid plasma disruptions [4]. $T_{\mathrm{div}}$ is determined by taking the average value deduced from two separated domed probes, in order to attenuate the effects of temperature inhomogeneities (which are observed near the ED target). The usual plasma operating scenario is to decrease $T_{\mathrm{div}}$ by means of a large $D_2$ gas injection, leading to an $\langle n\rangle$ increase and a tightness modification presented in Fig. 1(a) (tightness is plotted versus $T_{\mathrm{div}}$, for a series plasmas, leaning on the ED, with maximum ED perturbation). Tightness varies from 0.1 at 60 eV to more than 0.4 at 10 eV, which is the limit of the attached regime with the open Tore Supra divertor. In Fig. 1(b), tightness is plotted versus $1/T_{\mathrm{div}}^{1/2}$. These data can be linearly fitted, in agreement with Eq. (4). This linear behaviour with $1/T_{\mathrm{div}}^{1/2}$ shows that $T_{\mathrm{div}}$ controls the tightness decrease, and that the factor $\exp(\Delta/\lambda_{\mathrm{i}})$ does not play a significant role (due to an almost constant and small $\lambda_{\mathrm{i}}$ compared to $\Delta$ in this range of temperature).

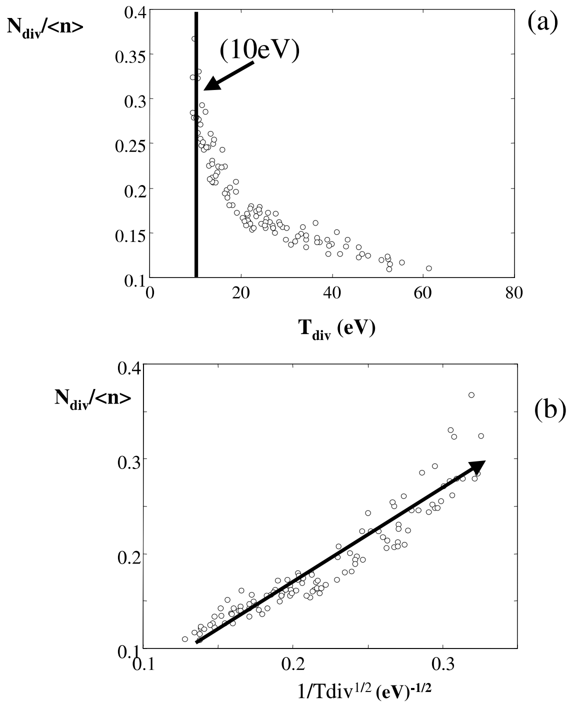


Fig. 1. (a) Tightness as a function of $T_{\mathrm{div}}$ for a series of plasma shots. Maximum ED perturbation and plasma in contact with the ED modules; (b) tightness as a function of $1/T_{\mathrm{div}}^{1/2}$ for the same cases than (a).

### 3.1. With the ED perturbation intensity

In Fig. 2, tightness is presented versus the intensity of the ED current ($I_{\mathrm{ed}}$) for two divertor temperatures,

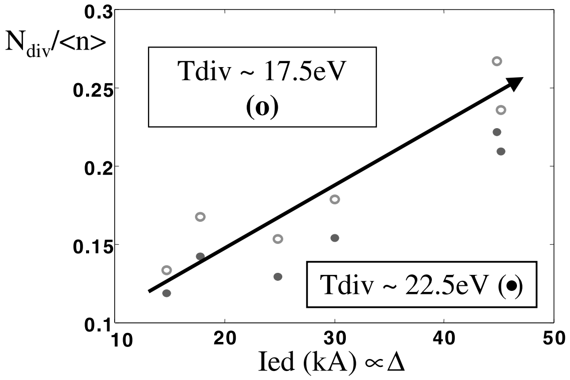


Fig. 2. Tightness versus ED current for two ED electron temperatures. The ED current varies from 15 to 45 kA (maximum possible value).

17.5 eV (open circles) and 22.5 eV (filled dots). The radial extent of the ED perturbation ($\Delta$) is proportional to the intensity of the ED current. As shown in Eq. (4), tightness increases with $\Delta$, e.g., when the plasma edge volume perturbed by the ED increases. For the same value of $\Delta$ ($\propto I_{ed}$), tightness increases by a factor of 2 when $T_{div}$ decreases, as shown in Fig. 1(a) and predicted by Eq. (4).

When $I_{ed}(\Delta)$ varies at constant $T_{div}$, tightness changes, because $\langle n \rangle$ decreases more rapidly than $N_{div}$ when the ED perturbation increases (see Fig. 3). $\langle n \rangle$ decreases by 50% when $I_{ed}$ varies from 25 to 45 kA for the same plasma edge temperature; it becomes more difficult to increase the plasma core density at large ED perturbations. This is confirmed by the much lower fueling efficiency value during ED shots (<5% without active pumping) than during limiter shots (~20% without active pumping). Therefore, a 'good' ED leads to a high core-edge plasma decoupling and pellet (or neutral beam) injection should be used to compensate for the observed low fueling efficiency.

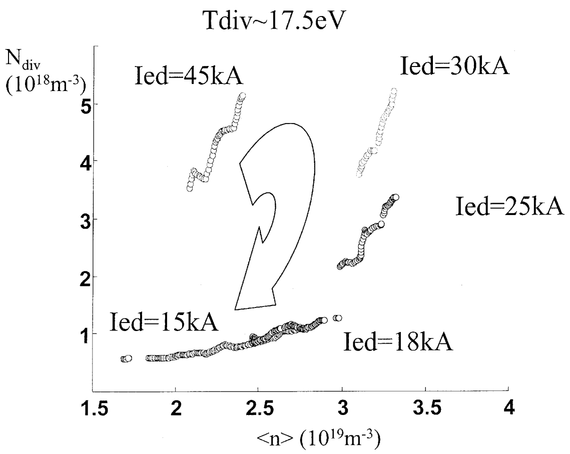


Fig. 3. Divertor density as a function of volume averaged plasma density for different ED currents. $N_{div}$ and $\langle n \rangle$ are plotted for a constant ED temperature.

### 3.2. With recycling and impurity injection

In Fig. 4, tightness is plotted versus $T_{div}$ for $D_2$ shots (same case as in Fig. 1(a)) and for pure He shots. Helium is a recycling particle, and $N_{div}$ is lower during helium shots than in the deuterium case for the same central density; tightness is much smaller in the He case. The sharp increase observed at 10 eV for the $D_2$ case is not observed in the He shots, and detachment is not observed in He [2,6].

In the case of neon injection (Fig. 5), tightness is also lower than for a pure deuterium case. At low temperature, tightness is three times higher without neon injection than with impurity injection. For the same $T_{div}$ and $N_{div}$ values, $\lambda_i$ for neon is much larger than for deuterium [5] and, according to Eq. (4), screening will be lower.

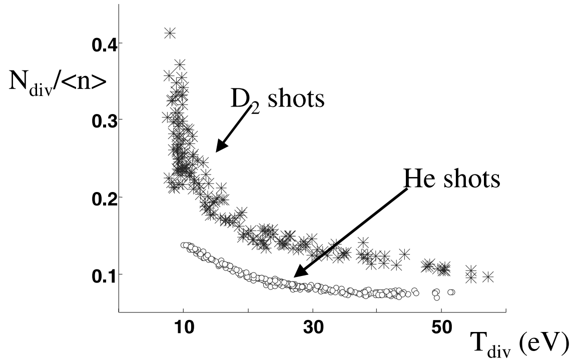


Fig. 4. Tightness versus $T_{div}$ for helium and deuterium plasmas.

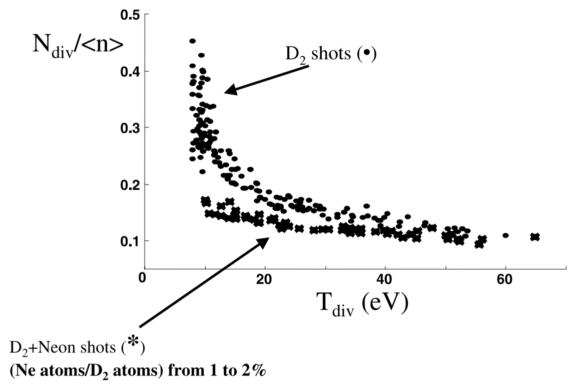


Fig. 5. Tightness as a function of $T_{div}$ for deuterium and deuterium + neon plasmas.

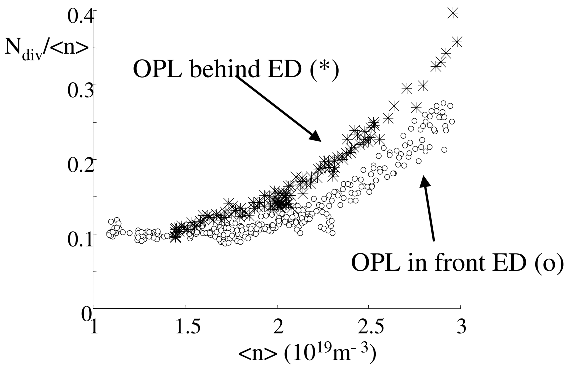


Fig. 6. Tightness versus $\langle n \rangle$ for two plasma series, with the OPL inserted in the ergodized volume (○), and with the OPL placed behind the ED modules (∗).

### 3.3. With active pumping and localisation of recycling source

The outer Tore Supra pump limiter (OPL) can be inserted in the plasma edge radially ahead of the ED modules. The OPL ducts are therefore in the ergodized volume. However, the tightness evolution with $T_{div}$ does not seem to depend on the activation of the OPL turbomolecular pumps: active pumping does not affect tightness [6].

Fig. 6 shows the influence of the OPL position on the density regimes (circles correspond to the OPL placed ahead of the ED and stars to the OPL placed behind the ED). In both cases, pumping is not active. Tightness is higher for the removed OPL case, for which better core-edge plasma decoupling is obtained. This is a consequence of the fact that the recycling sources are closer to the separatrix when the OPL is in the ergodised zone, and, at the same time, $\Delta$ is lower. Detachment is obtained at lower $\langle n \rangle$ values if the OPL is far from the separatrix, due to higher $N_{div}$ and lower $T_{div}$.

### 3.4. During ion cyclotron resonance heating

Tightness is also studied when additional heating is applied to the discharge. In Fig. 7, tightness is plotted versus $P_{div}^{0.55}/(1-\mathrm{Fr})^{1.22}$ for a constant divertor temperature (18 eV); the behaviour predicted by Eq. (6) is found. Tightness increases with the divertor conducted power and with the additional coupled power to the discharge. The ED tightness is low compared to that of axisymmetric divertors [7] due to lower $P_{div}$ values. Increasing $P_{div}$ will lead to a better particle control with the ED.

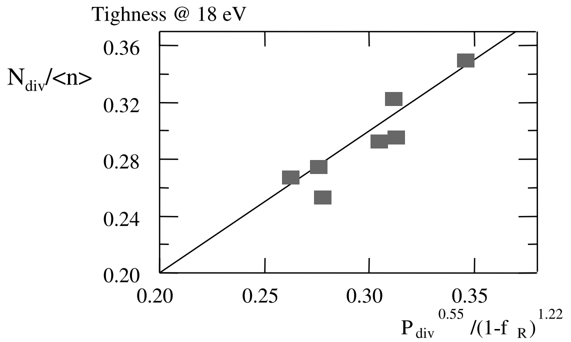


Fig. 7. Tightness as a function of $P_{div}^{0.55}/(1-\mathrm{Fr})^{1.22}$, for $T_{div} \sim 18$ eV.

## 4. Conclusions

In this paper, tightness, representing the ED ability to control recirculating particles, is studied as a function of different plasma edge parameters, such as $T_{div}$, ED magnetic perturbation ($\Delta$), plasma composition ($D_2$, He, and $D_2$ + Ne shots), position of recycling source in the plasma edge and additional power.

Tightness increases with increasing $\Delta$, $P_{div}^{0.55}/(1-\mathrm{Fr})^{1.22}$ and $1/T_{div}^{0.5}$. These trends are well explained by a simple 0-D model, in which the particle confinement time in the ergodized plasma edge is very small (zero in the model).

The best divertor is the one capable to decouple completely the core plasma from the edge. However, this leads to a decrease of $\langle n \rangle$ when the intensity of the ED perturbation increases. This is indeed observed in Tore Supra ED plasmas, and is correlated to a low fueling efficiency during ED experiments; increase of the core $\langle n \rangle$ will require the use of pellet (or/and neutral beam) injection.

Finally, tightness increases with the power conducted onto the ED plates. In the ED configuration, $P_{div}$ is low and tightness remains at a low level compared to axisymmetric divertors, where $P_{div}$ is considerably larger. Larger $P_{div}$ values will result in an improved tightness and a better particle control.

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