Searching for a flux-expansion divertor in TJ-II

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In this work, we explore the possibility of having a flux-expansion divertor in TJ-II. A 3D map of the particle flux has been obtained for two different plasma regimes using the code ISDEP, which follows the ion guiding-centre trajectories. In TJ-II, one must consider the particle trajectories rather than the field lines due to the fact that common ion orbits can separate from the field lines, and moreover the plasma electric field and the collisionality must be considered. We have chosen a configuration that presents flux expansion at given toroidal positions. We have estimated the heat and particle fluxes and checked that it is possible to reduce them strongly by intersecting the trajectories at a given zone of the space. Future studies, maybe including the creation of an ergodic zone, will determine the strategy for intercepting such trajectories.

Keywords: flux expansion, divertor, ion kinetic transport, Montecarlo code.

1 Introduction and motivation.

The quest for the stellarator reactor needs a robust divertor concept to guarantee low plasma-wall interaction and power exhaust [1]. A good divertor concept should reduce the particle and heat fluxes on its divertor. Additionally, the path of the recycled neutrals that will enter the plasma must be large in the real space, and the plasma profiles should ideally present a steep pressure gradient in the edge. These facts ensure that they cannot go beyond the plasma edge. The tokamak divertor, based on locating one or two X points inside the vacuum chamber, has been demonstrated as a good solution in such devices. It has been recently suggested that this kind of effects can also be reached in tokamaks locating the X point outside the vacuum chamber (see [2] and references therein). This transforms the divertor configuration into a limiter configuration with flux expansion.

The divertor programme in stellarators needs to consider a wider range of concepts due to the diverse possible configurations. To start with, LHD presents the helical divertor concept. It is based in a natural ergodic zone of its magnetic configuration that rotates with the same law as the helical coils of the device [3].

The island-based divertor is a promising concept, as has been demonstrated in W7-AS [4], where excellent results have been obtained. This concept is suitable for devices like W7-X, which has a fixed robust magnetic configuration. For this concept to work, it is necessary that the island positions and widths do not change substantially during plasma operation. The same can be said about the helical divertor: its topology must remain unchanged during plasma operation. This fact makes island and helical divertors not appropriated for devices that rely their configuration on the bootstrap current, like QPS or NCSX, or for devices that present high flexibility in their rotational transform values, like TJ-II. For these cases, the flux expansion concept [5] could be a good candidate for the divertor. This concept is based on intercepting the particle and energy fluxes with plates in an ergodic area of the plasma where the magnetic lines are well separated, so that the power flux onto the plates is small enough and the resulting neutrals and impurities can be pumped. The large flux expansion should also guarantee that the neutrals entering the plasma have to perform a large path, thus diminishing the probability that they go deep inside the device core.

TJ-II presents specific plasma-wall interaction issues. Due to its magnetic configuration, the groove is the preferred zone for the escaping particles to strike. Since the groove is physically close to the centre of the device, one should try to diminish such flux by intersecting the particle trajectories far from that position.

We have found several magnetic configurations that are suitable for such a divertor concept, since they have plasma zones where the density of magnetic surfaces is especially low. The point is to look for a position in which the efficiency of the divertor is maximum (i.e. intersects a large fraction of the flux) and to try to make compatible this requirement with a low enough heat flux on the plates.

No natural ergodic zones appear outside the last closed flux surface in TJ-II. Therefore, a second phase of this work may imply the creation of such ergodic zone by introducing extra coils that create a resonant magnetic field.

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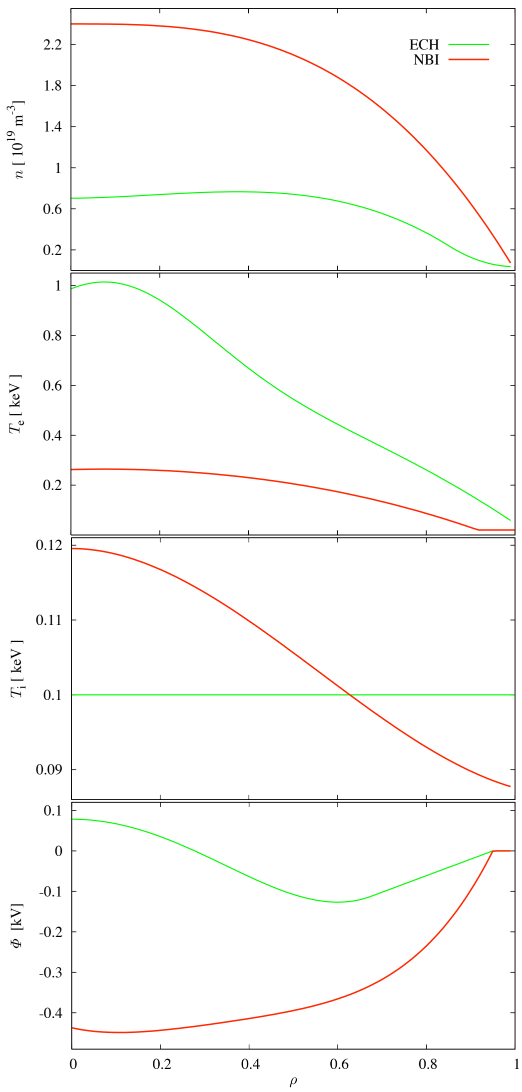

Fig. 1 Radial plasma profiles in the two regimes.

2 ISDEP code and the chosen plasma conditions.

Previous calculations performed to explore the flux expansion concept divertor in NCSX [5] followed magnetic field line trajectories, including a diffusion coefficient of about $1\,\mathrm{ms}^{-2}$, of the order of the one experimentally measured. This approach happens to be valid for devices where the particle trajectories do not separate very much from the field lines. This is not fulfilled in TJ-II [6], and the particle trajectories must be followed to estimate the fluxes.

ISDEP (Integrator of Stochastic Differential Equations in Plasmas) [7], is a Montecarlo code that follows ion guiding-centre trajectories considering a given electrostatic potential profile and ion-ion as well as ion-electron Coulomb collisions [8]. This code has been used in the present work to study the ion collisional flux properties in the chosen magnetic configuration and various plasma regimes. The plasma parameters used in our simulations are taken from experimental measurements: the density and electron temperature are obtained from Thomson-Scattering measurements [9], the ion temperature from the CX-NPA diagnostic [10], and the electrostatic potential comes from HIBP measurements [11].

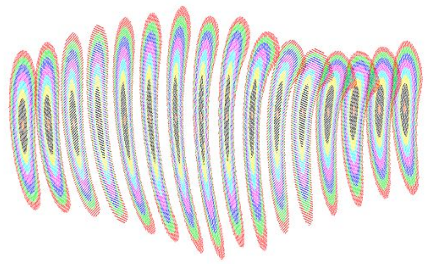

Fig. 2 Plasma toroidal sections. The surfaces in the ends lay in $\phi=0$ (left) and $\phi=\frac{\pi}{2}$ (right).

Obviously, the quantitative results will depend on plasma characteristics, namely the collisionality and the electrostatic potential. Nevertheless, we expect our results on the divertor effect to hold in a range of plasma parameters. In order to check this, two characteristic (and very different) plasma regimes have been chosen in this work. The plasma parameters are shown in Fig. 1 as a function of the effective radius ρ: a low density, low collisionality ECRH plasma, which presents a positive electric field in the core, according to the electron root [12], and an NBI plasma, with high density and low electron temperature. The electrostatic potential is negative in this case, which will have strong consequences on the ion confinement.

3 The chosen configuration.

One of the main properties of TJ-II heliac is its flexibility. By changing the currents that circulate by the two coils of the central conductor, it is possible to change the plasma size and shape as well as the rotational transform (TJ-II is an almost shearless device).

After studying several magnetic configurations, we have chosen the 100_68_91 (the numbers stand for the currents that circulate by the coils), which presents a large flux expansion in given toroidal positions. The average minor radius is $a=0.2$ m and the rotational transform in the edge is 1.825. In this magnetic configuration, similarly to the majority of TJ-II ones, a large fraction of the particle fluxes strike the groove, as will be shown in Section 4. Therefore, the neutrals coming from the wall appear very close to the plasma bulk. Hence, the main goal of this divertor should be to diminish as much as possible the fluxes that are directed to the groove. Fig. 2 shows several Poincaré maps of the field lines of the chosen configuration (the sections have been rotated for a better comparison). It is possible to appreciate that the maximum flux expansion happens for a toroidal angle around $\phi = \frac{\pi}{4}$ (and of course also around

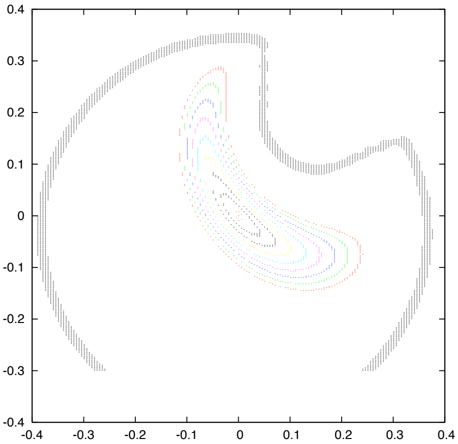

Fig. 3 Plasma coronas at $\phi \approx \frac{\pi}{6}$ and sketch of the wall of the vacuum chamber.

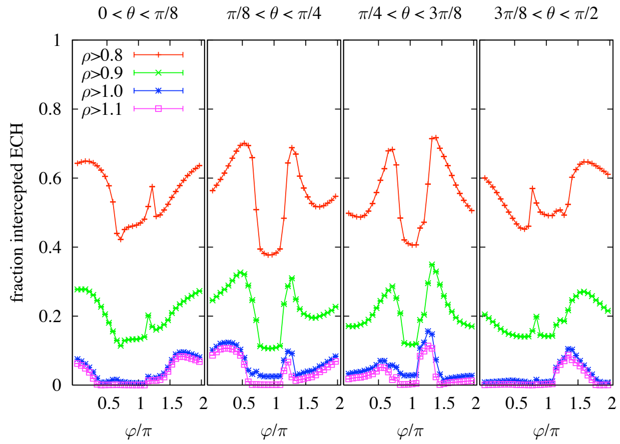

Fig. 4 Proportion of ions intersected as a function of the angular position of the plate for the ECH plasma.

$\phi = \frac{3\pi}{4}$, $5\pi/4$ and $\frac{7\pi}{4}$). Fortunately, the zone with large flux expansion lays on a wide range around these angles. This gives us quite a lot freedom in our optimizing task. Fig. 3 shows a particular toroidal section, together with a sketch of the wall of the vacuum chamber. The distance from the magnetic axis to the groove is about 12 cm, and only a thin sheet separates the edge and the plasma bulk. If the plasma-wall interaction can be concentrated at the zone where the flux expansion is maximum, the particle flux onto the groove will be strongly reduced. The amount of neutrals that enter the plasma bulk will also decrease.

4 Design and results.

In order to search for the optimal position of the plates, we have performed a map of the ion flux on several magnetic surfaces and at different toroidal and poloidal angles. Since TJ-II is a four-field-period device, we will center our discussion in one of the periods, but will consider all of them in calculation. We have accomplished this task defining our plates as the locus of points such that:

$$\rho > \rho_0,\ \frac{2\pi}{N_\phi} i < \phi < \frac{2\pi}{N_\phi}(i+1),\ \frac{2\pi}{N_\theta} j < \theta < \frac{2\pi}{N_\theta}(j+1). \quad (1)$$

By setting $N_\phi = 4$ (four ϕ intervals in each period) and $N_\theta = 32$, we have 128 plates defined. An sketch of one ensemble of them will be shown in Fig. 6. We follow a number of trajectories and study the individual effect of each plate on the particle flux. More precisely, in Fig. 4 we show, for the ECH plasma, the fraction of the trajectories that would be intercepted by each plate in the case where this plate were the only one in our device. Note that the contributions of two plates cannot be directly added, since they may partly shadow each other. The structures in Fig. 4 suggest the positions where a plate can be more effective. We will be interested in plates in the outer region of the plasma, where $\rho > 1.0$, for an acceptable interaction with the hot plasma. In such radial positions, $\theta \approx \frac{3\pi}{2}$ for $\frac{\pi}{4} < \phi < \frac{3\pi}{8}$ and $\frac{3\pi}{8} < \phi < \frac{\pi}{2}$ looks promising, since 10% of particles would be intercepted by each of them. Considering the mirror images of these plates in the other three periods (altough, as we know, their contributions do not simply add up), one could expect to concentrate a great proportion of the plasma-wall interaction in these plates. Note that our choice is not the optimal intercepting particles, but it is the best that makes it far from the groove.

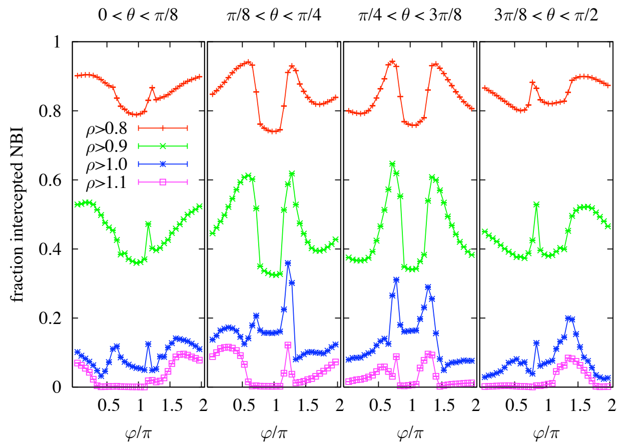

Fig. 5 Same as Fig. 4 for the NBI plasma.

Fig. 5 shows the same quantity for the case of the NBI plasma. Here, the radial electric field clearly improves the confinement. One of the consequences is that each ion has more probability of being intercepted by each plate, since it performs more toroidal turns around TJ-II. Our former proposal of divertor configuration still seems one of the best possible. These are good news, since one would desire a divertor design valid for a wide range of plasma parameters. Looking at both figures, our first tentative design will be plates located at $\rho > 1.0$, $\frac{11\pi}{8} < \theta < \frac{23\pi}{16}$ along all the toroidal angle. This configuration is sketched in Fig. 6.

In the ECH case, our plates intercept about half the particles in the plasma. This includes ions that end their trajectories in the groove of and ions that do not. The original

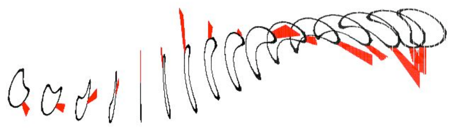

Fig. 6 Tentative design of plates. The $0.9 < \rho < 1.0$ surfaces are plotted in black, and the plates in red.

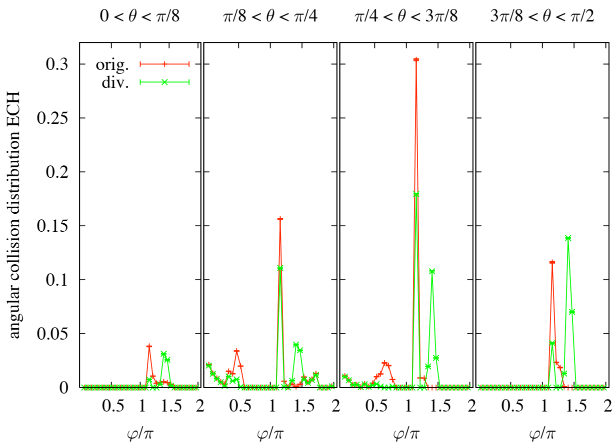

Fig. 7 Angular distribution of the collisions with the vacuum chamber and the plates for the ECH plasma with and without divertor.

and the modified angular distribution of trajectory ends are shown in Fig. 7. The high original peaks correspond to collisions with the groove, which in usual operation represent around 60% of the collisions with the vaccum chamber. The effect of our plates is to diminish this quantity to be around 35%, about half the proportion existing before. New peaks appear, corresponding to the location of our plates. This means that we have concentrated a great part of the plasma-wall interaction on the divertor plates. In the case of the NBI plasma, see Fig. 8, the same effect still exists, although a bit weaker. The proportion of the total trajectories that are intercepted is about 63%. Nevertheless, from about 50% of ions colliding with the groove, one reduces it to about 35%.

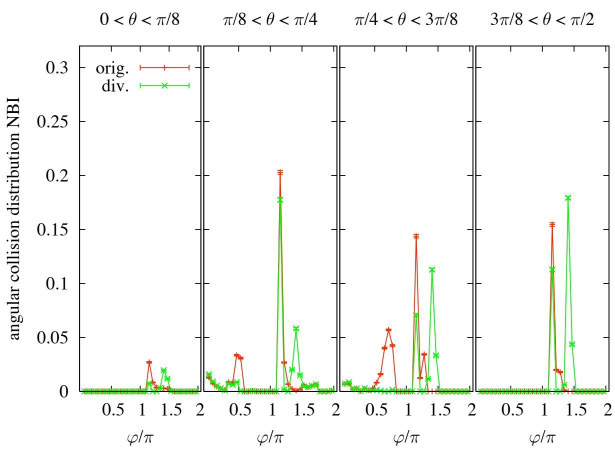

Fig. 8 Same as Fig. 7 for the NBI plasma.

5 Conclusions and future work.

We have found a promising configuration for having a flux expansion divertor, since the particle collisional flux maps are characterised by presenting strong poloidal asymmetries, showing a high value in the poloidal position corresponding to one of the extremes of the ”bean”.
This magnetic configuration has the property that the flux expansion is maximum in a region where the main part of the particle flux that goes onto the groove passes through. Therefore, one may minimize at the same time the flux onto the groove and onto the plates. Due to the TJ-II configuration characteristics, this effect is especially beneficial because we move the main plasma wall interaction to a zone much farther from the plasma bulk.
The beneficial effect of the divertor is larger in the NBI regime despite of the fact that this case presents a smaller mean free path, because the structure of electrostatic potential ensure that a large fraction of particles is intercepted.
The next step of this work is to optimize the design of the divertor plates in order that the interrupted particle flux on the groove is maximum. It may be also necessary to create an ergodic zone in order to minimize the particle and heat flux on the plates. Before assessing the feasibility of this construction, new flux calculations with the ergodic zone are mandatory. For this last phase of calculation, the effect of turbulence on particle trajectories must be included in order to have more refined calculations, especially in high-beta plasmas. Once the flux on the divertor plate is estimated, including the field ergodization effect, and before starting the engineering assessment of the coils and the divertor plates, it will be necessary to calculate the outgasing coming from the plate. A 2D neutral transport code is available and will be applied to this case. Experiments are also foreseen in TJ-II to benchmark all these theoretical results.

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