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MAGNETIC FIELD LINE ESCAPE: COMPARISON WITH MEAN FREE PATH

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1. INTRODUCTION

Plasma-wall interaction is one of the critical issues for development of an energy source based on nuclear fusion. Reversed magnetic shear in tokamaks improves the plasma confinement due to the formation of internal transport barriers as pointed in Ref.[1]. In this work, the length connection from a reversed field line is estimated and compared with the electron-ion collision mean free path. Magnetic surfaces are destroyed by resonant perturbations caused by an ergodic magnetic limiter. Recent work has shown that the connection length is comparable to the mean free path for tokamaks with divertors [2].

2. EQUILIBRIUM MODEL AND THE LIMITER FIELDS

The field line geometry is described in non-orthogonal polar-toroidal coordinates (rt, θt, φt) [3], which has been introduced to evidence toroidal effects in the equilibrium field geometry. In the large aspect-ratio limit, these coordinates reduce to the local polar coordinates (r, θ, φ). Magnetic surfaces are characterized by nested surfaces of r_t = constant, for which the non-monotonic safety factor reads [4]

$$q_c(r_t) = q_c(a)\frac{r_t^2}{a^2}\left[1-(1+\beta'\frac{r_t^2}{a^2})(1-\frac{r_t^2}{a^2})^{\gamma+1}\right]^{-1} \quad (1)$$

with $q_c(a) = (I_p a^2/)(I_e R_0'^2)$. Ip is the total plasma current, Ie is the total current of the toroidal magnetic system, a is the plasma radius, R_0' is the position of the magnetic axis and the parameters γ=0.78 and β=3.0, with β'=β(γ+1)/(β+γ+2), describe the plasma current profile [3]. We choose q ≅ 5 at the plasma edge (rt = a). We also choose a/R0'=0,28, which is typical for tokamak discharges.

To create resonant perturbation we use an ergodic magnetic limiter, which consists of Nr current rings of length l located symmetrically along the toroidal direction of the tokamak. These current rings are located at rt=b (where b is the minor radius) and conduct a current Ih with opposite sense for adjacent conductors. The role of these rings is to induce a resonant perturbation in the tokamak [4]. We use a winding law that emulates the actual magnetic field lines, given by $u_t = m_0[\theta t + \lambda\sin(\theta t)] - n_0\varphi t$, where λ is a tunable parameter and (m_0, n_0) are the poloidal and toroidal mode numbers respectively and they are constant along a field line [4].

3. COMPARISON BETWEEN MEAN FREE PATH AND CONNECTION LENGHTS

Since the equilibrium field has an axial symmetry, we define the azimuthal angle φt=t, as a time-like variable, which together with the action-angle (J,η) introduced in [4], allows us to describe the field line equations in a Hamiltonian form. Thus the total Hamiltonian can be written as an equilibrium Hamiltonian plus a perturbed Hamiltonian [1,4]. Figure 1 shows the distribution of the connection lengths, NcL(J,η), which is the number of toroidal turns described by the field line to reach the tokamak wall. The field line is considered lost when it reaches the radial position J=0.055, which corresponds to rt=b. We consider the perturbation parameter Ih/Ip=0.11, and perturbation mode number (4,1). In Figure 1 the complex mixing of initial conditions with different colors indicates that field lines with large and small connection lengths are densely mixed [1]. Field lines with connection lengths higher than a given limit (NcL=4000), can be considered trapped. Hence, the region with large connection lengths in the toroidal section represents an effective transport barrier. The total quantity of magnetic field lines we consider is 2.0x105 as the total of magnetic field lines.

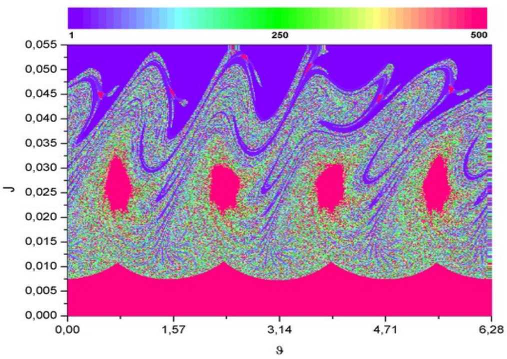

Figure 1 : Distribution of connection lengths in the range [1,500] for mode number (4, 1) and perturbation parameter I_h/i_p=0.11.

The fraction of magnetic field lines that are lost from the plasma to the wall are compared to an electron-ion collisional mean free path, which can be estimated from

$$\lambda_{mfp} = 2.5 \cdot 10^{17} \frac{T_e^2}{n_e \ln(\Lambda)} \qquad (2)$$

T_e is the electron temperature, n_e is the electron density and $\ln(\Lambda)=15.2-0.5\ln(n_e/10^{20})+\ln(T_e/1000)$ with T_e in eV and n_e in m^{-3}. We consider Te in an interval of 20 eV to 100 eV and n_e= $5.0\times10^{18} m^{-3}$. Figure 2 shows the field line loss fraction as a function of the action variable J. We can see that for J around 0.025 there is a depression which corresponds to an island chain in Figure 1.

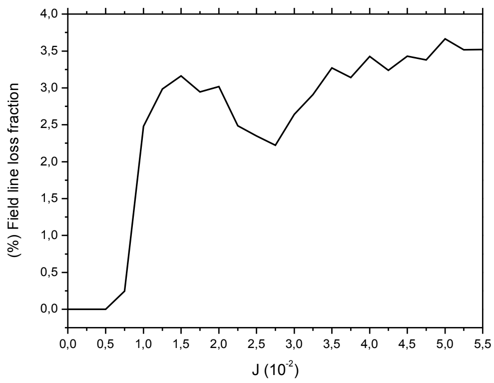

Figure 2: Percentage of field line loss fraction for the connection lengths of Figure 1.

In Figure 2 we considered the ratio between the total number of magnetic field lines in phase space and the number of lines that escape to the tokamak wall. As we can see in figures 1 and 2 the field lines escape increases near the tokamak edge.

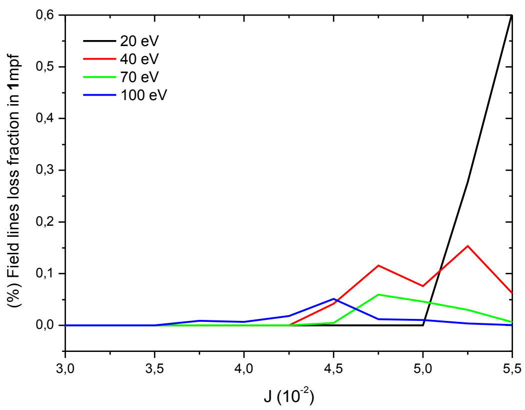

Figure 3: Percentage of field line loss fraction in one mean free path for different values of the electron temperature.

Figure 3 shows the field lines that are lost to the wall during a displacement equal to one collisional mean free path as a function of the action variable J, for electron temperature of 20, 40, 70, and 100eV. As we are interested in the peripheral region of the plasma, we choose the range J = [0,030; 0,055], in figure 3, which corresponds to the plasma edge. As we can see, close to the edge the field line escape increases. The reason for this behavior is the dimerized magnetic islands showed in Figure 1 (pink circles and colorful structures). These dimerized islands create a chaotic region that traps the magnetic field lines increasing the number of toroidal turns described by the lines until reach the wall. Near the wall there are regions in purple (Figure 1) which correspond to field lines with low connection lengths comparable to the mean free paths. This is the reason why the number of field lines that escape in one mean free path increases for large values of J. The mean free path increases with the temperature and therefore the fraction of lost field lines in such displacement decreases with temperature.

Figure 3 shows the fractions of lost field lines, to the wall, for one mean free path. This corresponds to 0,6% of the whole of magnetic field lines in the phase space for Te=20eV. The dimerized islands formed by the resonant perturbation plays the role of a chaotic barrier, increasing the toroidal turn number before the magnetic field lines reach the wall [3].

4. CONCLUSION

Transport barriers arise for a non-monotonic safety factor profile. These barriers influence the fraction of field lines that are lost toward the walls. We show that most of the magnetic field lines located inside the chaotic region describe long distances, much higher than the electron-ion collision mean free path, before reaching the wall.

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