Field Line Escape Pattern in a Poloidally Diverted Tokamak

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ABSTRACT

In order to simulate magnetic configuration in tokamaks like ITER, we use a model consisting of electric currents in five parallel infinite wires to obtain double-null magnetic surfaces with specific choices of magnetic axis position, triangularity, and elongation. This model reproduces quite well the ITER configuration and it can delineate dynamical properties of open and closed field lines near the separatrix. Comparing to numerical equilibria reconstructions to simulate plasma in the presence of poloidal divertors, which are time-consuming, this model is faster and versatile, reproducing ITER like magnetic topology. Due to the flexibility of the wires model, we can consider different effects of perturbing magnetic field lines near the separatrix. One of them is to include a perturbing error field, due to asymmetries on the external coils. Moreover, we include magnetic perturbations caused by external coils, similar to correction coils installed at the tokamak DIII-D and those that will be installed at ITER. We integrate numerically the field line differential equations to obtain the deposition patterns of magnetic field line in the divertor plate.

1 – INTRODUCTION

Several works have used non-axisymmetric magnetic perturbations in tokamaks to create a layer of chaotic magnetic field lines, which have an important role on the field line escape [1,2,3,4,6]. In this work, an equilibrium model described by five parallel infinite wires is analyzed [2] to simulate the magnetic configurations of tokamaks like ITER. We include magnetic perturbations created by error fields due to the asymmetries on the external coils [1,2], and perturbations caused by pairs of loop coils (C-coils) carrying opposite flowing currents, according to references [3,5,6]. The deposition patterns near the X point is analyzed under influence of error fields and C-coils.
2 – EQUILIBRIUM AND PERTURBATION CAUSED BY ERROR FILEDS AND C-COILS

We consider five wire loops carrying electric currents, with the position proposed in [2], to simulate the magnetic surfaces of the tokamak ITER. Reference [2] shows the wires positions and current values. One wire represents the plasma current, two wires create the lower (divertor position) and upper X points, respectively. Other two wires compress the left and right sides of the magnetic surfaces, producing the desired elongation of the plasma column.

At first, following reference [1], we add perturbations caused only by error fields due to asymmetries on external coils. We integrated the perturbed equations as described in [2]. Figure 1(a) shows the equilibrium surfaces with two X points as already mentioned. Figure 1(b) shows the magnetic lines perturbed by error fields with perturbation parameter $\varepsilon = 1 \times 10^{-4}$. A chaotic layer is observed around the lower hyperbolic point (X-point). They are no longer closed and they finish their trajectories at the divertor plate, located at $Z = -3.7$ m. It is possible to observe magnetic islands immersed in the chaotic layer.

![Fig 1. – (a) Equilibrium magnetic surfaces showing the upper and lower X points. (b) Magnetic surfaces perturbed by error fields.](image_url)

Next, we consider a non-axisymmetric perturbation generated by ten pairs of loop coils carrying opposite currents, $I_c = 70$ kA, according to references [3,5,6]. The perturbation created by these coils is similar to the C-coils installed at the DIII-D tokamak [3]. As the perturbed vector potential is known [5] we can integrate the magnetic field lines in order to obtain the perturbed mapping. Figures 2(a) and 2(b) show a chaotic layer around the lower hyperbolic point.
Fig. 2 – (a) Magnetic surfaces perturbed by N=10 pairs of loop coils with $I_c = 70$ kA. (b) Zoom in (a) showing islands immersed in the chaotic sea.

To investigate the escape of magnetic field lines to the divertor plate, placed horizontally at coordinate $Z = -3.7$ m, we consider perturbations caused by error fields and C-coils. We calculated the connection length, which is the number of toroidal turns, $m$, performed by a field line until it reaches the plate. The magnetic field line is integrated along the toroidal direction, for initial conditions with $4.6 \text{ m} \leq R_0 \leq 6.0 \text{ m}$ and $-3.7 \text{ m} \leq Z_0 \leq -2.7 \text{ m}$, until it reaches the divertor plate. Figure 3(a) shows the chaotic layer near the lower X point due to an error field with $\epsilon = 1 \times 10^{-4}$ and perturbation current, $I_c = 70$ kA, due to C-coils. Compared to Figures 1 and 2, we can see the effect of these two perturbations, with magnetic islands immersed in a thick chaotic layer around the X point. Figure 3(b) shows the connection lengths calculated using the same perturbation parameters of Figure 3(a), which indicates that field lines initially located around the lower X points reach the divertor plate with fewer toroidal turns than the ones located near the broken separatrix. Comparing Figures 2(b) to 3(a), the error field, superposed on the C-coils perturbation, amplifies the destruction of magnetic surfaces near the X point, resulting in field lines escaping with few toroidal turns, as observed in Figure 3(b).
Fig. 3 – (a) Magnetic surfaces perturbed by C-coils with \( I_e = 70 \) kA and error fields with perturbation parameter \( \varepsilon = 1 \times 10^{-4} \). (b) Connection lengths where the number of toroidal turns, \( m \), is represented by the color scale.

3 – RESULTS AND CONCLUSIONS

In conclusion, this work presented the effect of perturbations composed by error fields and correction coils on magnetic surfaces in tokamaks like ITER. Five parallel infinite wires were used to simulate the equilibrium magnetic surfaces with two X points. When error fields and C-coils perturbate the plasma simultaneously, a thick chaotic layer is observed around the lower X point. The distribution of connection lengths, calculated as the number of toroidal turns performed by a magnetic field line from a given initial condition until it reaches the divertor plate, showed that field lines escape with few toroidal turns in the chaotic region. On the other hand, larger connection lengths were observed near the broken separatrix. The presented approach allowed us to investigate the influence of resonant external perturbations and the error fields on the magnetic field line escape in tokamaks.

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REFERENCES


