Peculiar Transport Barriers Onset in Large Aspect Ratio Tokamaks

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Internal transport barriers can reduce magnetic field line escape to the tokamak vessel and contribute to the plasma confinement improvement. The shape of the safety factor profile is among the factors responsible to the onset of such barriers. In this work, we investigate the onset of magnetic field line transport barriers for two kinds of peculiar safety factor profiles. For these profiles, we perform numerical simulations in the symplectic Ullmann map [1, 2] that describes the MHD equilibrium in large aspect-ratio tokamaks perturbed by a chaotic limiter.

Initially we take into account evidences that the formation of barriers may be correlated with some local flattening of the otherwise monotonic safety factor [3]. In this case, a local safety factor profile modification creates a low-shear zone where transport barriers can emerge [4]. Here, we show, for the considered symplectic Ullmann map, that a local flattened profile modifies the field lines topology and reduces the magnetic field lines escape.

For a large aspect ratio tokamak with ergodic magnetic limiter, we obtain the magnetic field line mapping from the Ullmann map. For the equilibrium the map is given by [1]:

$$r_{n+1} = \frac{r_n}{1 - a_1 sen\Theta_n}$$

$$\Theta_{n+1} = \Theta_n + \frac{2\pi}{q_0(r_{n+1})} + a_1 cos\Theta_n$$

where a_1 is introduced to take into account a correction for the toroidal geometry. The perturbation due to the effect of the ergodic limiter on the equilibrium configuration is given by [1]:

$$r_{n+1} = r_n^* - bC\left(\frac{r_n^*}{b}\right)^{m-1} sen(m\Theta_n^*)$$

$$\Theta_n^* = \Theta_{n+1} - C\left(\frac{r_n^*}{b}\right)^{m-2} cos(m\Theta_n^*)$$

where the control parameters are $q_0(0)$, $q_0(a)$, the perturbation amplitude C and the number of the wires m.

The equilibrium safety factor is given by

$$q_0 = \frac{rB_z}{R_0 B_\Theta} \quad (1)$$

where B_θ and B_z are the poloidal and toroidal components, R_0 is the major radius (Fig. 1).

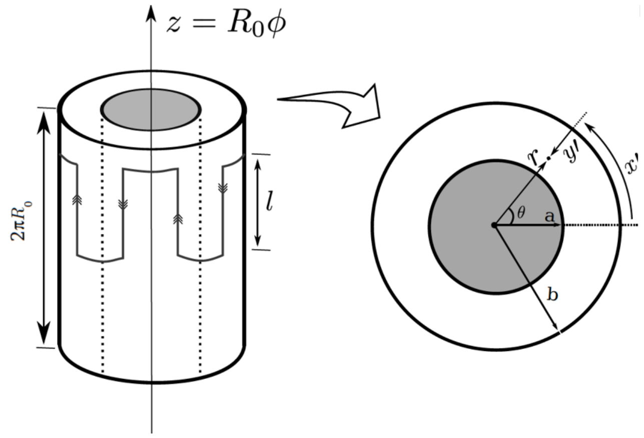

Figure 1: Coordinates x', y', major R_0 and minor a, b radii.

For each current density profile, we will have a poloidal magnetic field and a correspondent safety factor profile. The perturbed safety factor is numerically calculated as:

$$q \equiv \lim_{k\to\infty} \frac{2\pi k}{\sum_{j=0}^{k}(\theta_{j+1} - \theta_j)} \quad (2)$$

For a monotonic equilibrium safety factor profile with a local flatness point, shown in Fig. 2a, the perturbation map emerges from the effect of the ergodic limiter on the equilibrium configuration. Fig. 2b shows the map, for the considered q_0 profile, with an external invariant curve acting as a barrier in the low part of the map (small y) [5].

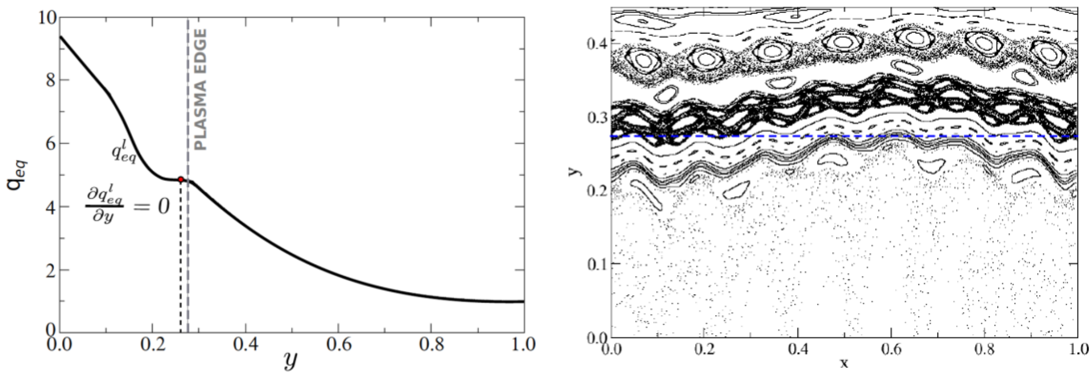

Figure 2: a) Safety factor profile. Red point indicates the local flatness. b) Phase space for the symplectic map monotonic profile with one flatness point ($q_0(0) = 0.83$, $q_0(a) = 5.0$, C=0.33).

The second considered safety profile is related to unperturbed plasma equilibrium with a radial hollow current profile (Fig. 3a).

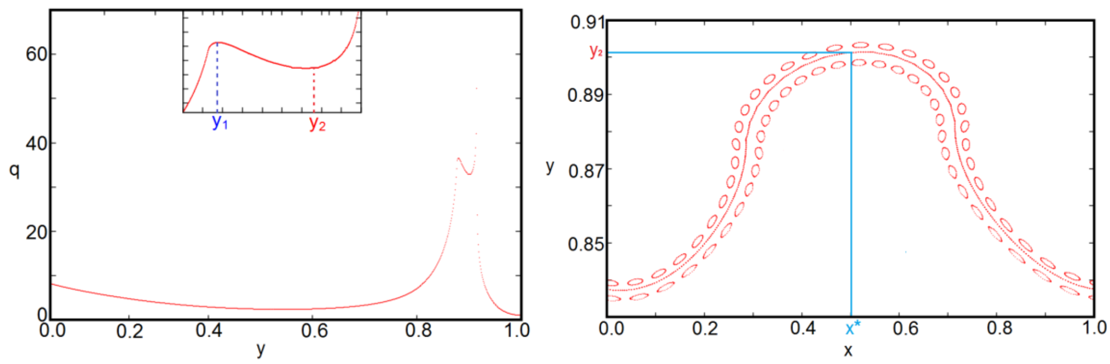

Figure 3: a) Numerical safety profile. In the inset, highlights of the maximum and minimum points. b) Shearless line and island chains ($q_0(0) = 0.83$, $q_0(a) = 5.0$, C=0.0).

Plasmas are confined in tokamaks by magnetic field lines on nested axisymmetric toroidal magnetic surfaces. However, some advanced confinement regimes with non inductive currents develop a radial hollow current profile, with a central hole where the current density is almost zero or even negative [6]. Solutions of the Grad-Shafranov equation describing magnetohydrodynamic equilibria with non nested magnetic surfaces have been proposed [7-10]. Here, we show that applying the Ullmann map for an equilibrium safety factor obtained from a central hollow electric current with negative density, gives rise to non-nested magnetic surfaces and two shearless invariant curves due to the current inversion (Fig. 3b). Furthermore, the considered equilibrium modified by the toroidal correction has a series of resonances with the corresponding islands and isolated chaotic regions (Fig. 4).

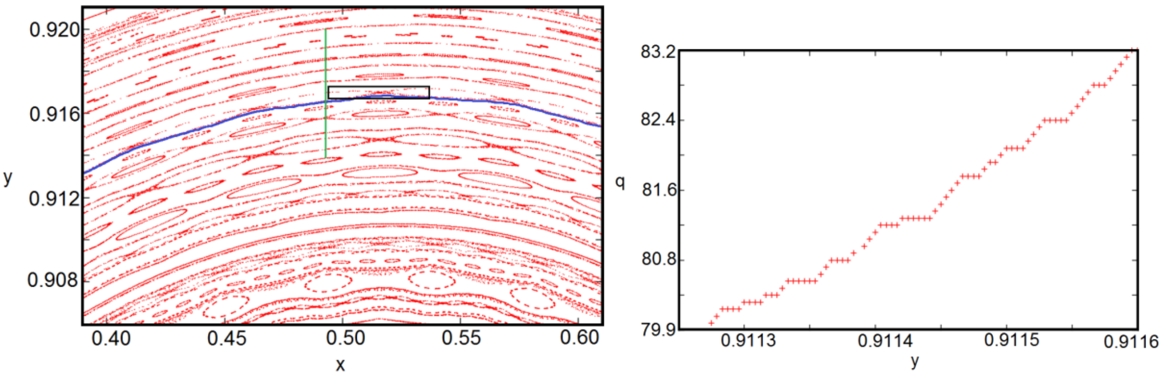

Figure 4: a) Poincaré section close to the divergence with many small island. b) Zoom of the numerical safety factor profile. Devil's stair indicates the presence of the islands. Same parameters of Fig. 3.

The described barriers are created by peculiar safety factor profiles. The first considered equilibrium has a local flat current profile at the plasma edge modifying the field lines topology and reducing the global field lines escape pattern [3]. The second equilibrium with non-nested magnetic surfaces presents two shearless invariant curves created by the current inversion reducing the field lines transport.

Acknowledgments

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