Influence of the X-point position on structure formation by thermoelectric currents

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In high confinement mode (H-mode) plasmas of poloidal divertor tokamaks, stochastic magnetic boundaries are of growing importance for edge transport control. H-mode plasmas are characterized by steep edge pressure gradients and associated edge instabilities, causing a repetitive relaxation of over-critical edge pressure gradients - the so-called edge localized modes (ELMs). Understanding ELM dynamics beyond the initial linear phase is still in its infancy. Questions like scaling with plasma geometry and operating conditions as well as mitigation by resonant magnetic perturbations (RMPs) lack a good theoretical foundation. Experiments on DIII-D have shown that edge stochastization significantly influences ELM dynamics [1]. In DIII-D, RMPs have suppressed ELMs [2].

Based on a conceptual model [3, 4], which describes the dynamics of the edge plasma and the evolution of the pedestal magnetic topology following the linear growth phase of a peeling-ballooning instability, a two step numerical model was implemented [5]. The latter shows that the change in magnetic topology due to thermoelectric currents leads to a self-amplification as proposed by Ref. [6]. The model assumes that thermoelectric currents flow in short connection length flux tubes [7], initially established by error fields and other non-axisymmetric magnetic perturbations. Such flux tubes introduce a natural limitation of the currents due to position and size of the tubes.

At the onset of a peeling-ballooning instability [8], when the pedestal pressure gradient exceeds the stability limit, an initial pulse of heat and particles is triggered. As described in Ref. [3], the pulse arrives at the outer target plate well before it reaches the inner target plate. Thus, a thermoelectric current is driven between the targets. Magnetic perturbations resulting from the thereby created currents have to be incorporated into the magnetic topology. As shown in Ref. [5], an initial current of 300 A leads to the formation of new, large, one-poloidal-turn flux tubes. Thereby the formation is based on a connection to the upper targets. Such a connection is highly sensitive to the position of the upper X-point. For various discharges the distance Δs of the upper X-point to the main separatrix was calculated in the unperturbed reference case. Then the necessary current I_n to create the first, large, one-poloidal-turn flux tube was determined numerically. The necessary current increases exponentially with the distance Δs; we have

$$I_n = I_0 e^{\Delta s / s_0} \tag{1}$$

with the parameters $I_0 = 46.75$ A and $s_0 = 9.356$ cm. Note that Eq. (1) is numerically verified for values of Δs between 10 cm and 35 cm only.

In the discharge 133908, see Ref. [5], the upper X-point is very close to the main separatrix, about 10.5 cm, so that the connection to the upper targets is established easily. Only about 150 A initial current is necessary to form the first large tube [4]. For other discharges the necessary current can be much larger, resulting in a different scenario of flux tube formation. In the following we will analyze discharge 132741, with a distance of $\Delta s = 33.1$ cm, in more detail.

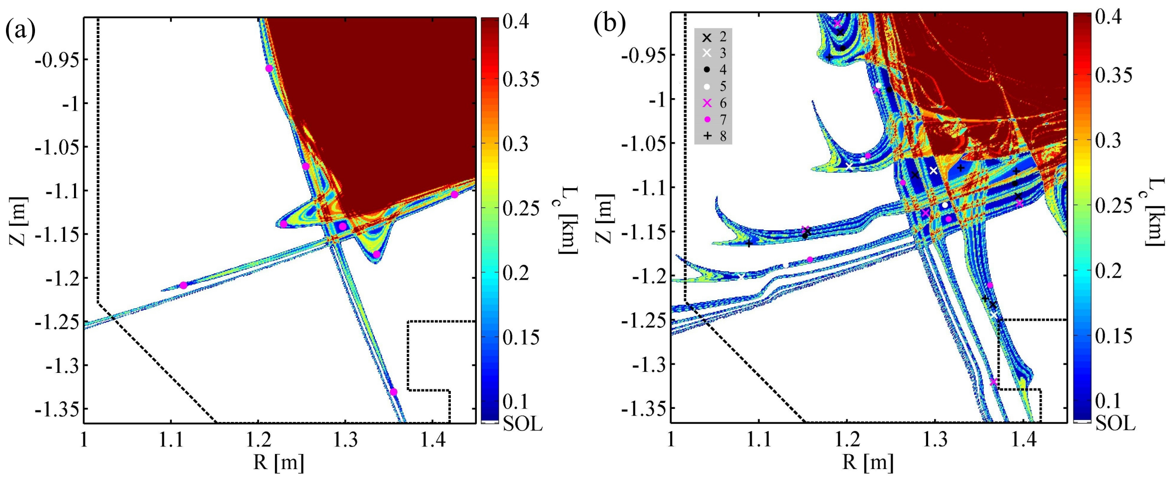

Figure 1: (a) Connection length plot of the lower target area in DIII-D of shot# 132741 at 3000 ms. The red circles indicate the intersection points of the initial current filament with the poloidal cross-section. The blue area around the circles is referred to as flux tube 1 in the following. The white areas represent the scrape-off-layer (SOL). (b) Same as (a), but with the perturbation of a 300 A current filament in flux tube 1 included. Each of the various markings specifies intersections of a different current filament used in the second step of the model.

Figure 1a shows the connection length plot of the lower X-point region for the reference case of the discharge. Only error fields and the $n = 1$ C-coil perturbation, used for error field correction, are considered. The lower X-point region is slightly perturbed, resulting in the formation of a small flux tube. The latter is assumed to carry the initial current filament as part of the first step of the model. Using the same current scaling as proposed in Ref. [5], a current of 300 A is justified. According to the current-distance scaling presented in Eq. (1), only a current larger than 1.6 kA would cause the formation of large one-poloidal-turn flux tubes. Such a high current in this small flux tube is definitely non-physical. A different process of self-amplification from the one described in Ref. [5], occurs in discharges where the upper X-point is far away from the main separatrix.

The modified magnetic topology, which includes the 300 A current filament perturbation, is shown in Fig. 1b. Two of the effects, described in Ref. [5], can be observed in the present case as well. Although a connection to the upper targets is not established at this current level, several new flux tubes are created leading to a similar self-amplification as in discharge 133908. In contrast to the latter, in this discharge the 300 A initial current causes the formation of many medium sized, two-poloidal-turn flux tubes (tube 2 to tube 7). The area scaling suggests currents between 670 A and 170 A running through these new tubes in the second step of the model. Additionally a three-poloidal-turn flux tube, tube 8, occurs. The formation of higher order flux tubes is a definite sign of bifurcation.

In the second step we run a total current of 3.155 kA distributed along all flux tubes according the their individual areas in the poloidal cross-section. A connection length simulation, which includes all perturbations, of the upper X-point region is shown in Fig. 2. The upper X-point is located outside the vacuum vessel. The formation of a heteroclinic structure is basically impossible in this configuration. Nevertheless, several large fingers reach out towards the upper target plates. A very large area is cut out of the SOL by the intersecting fingers. The area is transformed into a very large one-poloidal-turn flux tube. The large flux tube is split into two parts by another finger, which is created by the $n = 3$ perturbation of tube 8.

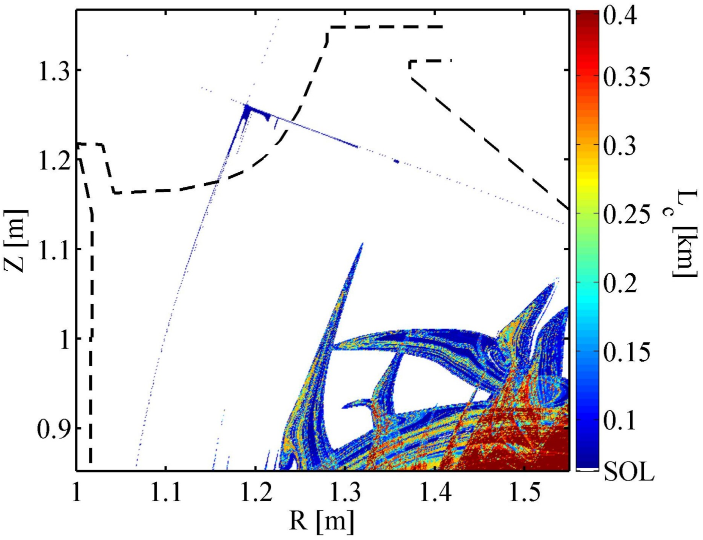

Figure 2: Connection length plot of the upper X-point region including the perturbations of all current filaments of the second step in the model.

The formation of such very large one-poloidal-turn flux tubes is again a clear sign of the self-amplifying nature of the ELM model. But, a further self-amplification by running current through the newly created one-poloidal-turn tubes is unlikely. The current leading to their formation is sustained by the ongoing heat transfer to the target plates. During an ELM the plasma edge pedestal collapses. So, heat in the pedestal is emitted to the wall by the ELM. This heat is the source to drive the thermoelectric currents. Once the heat source is depleted, the currents collapse and the magnetic topology returns to its initial structure of the reference case.

In this paper we showed that the self-amplification process of thermoelectric currents running through short connection length flux tubes is highly sensitive to the position of the upper X-point in poloidally diverted tokamaks. At small distances of the upper X-point to the main separatrix, a small initial current is sufficient to create large one-poloidal-turn flux tubes which take over the current conduction. This process finally leads to ELM-like structures on the vessel wall [5]. But the necessary current for a formation of large one-poloidal-turn flux tubes scales exponentially with the distance of the upper X-point to the main separatrix. At a large distance the process of self-amplification is different. In the case we showed in this paper, a large number of two-poloidal-turn and higher order flux tubes are created by the initial current. These flux tubes are then used for current conduction. Again the structure is perturbed in such a way that a further self-amplification would be possible. But, a further self-amplification is not considered in the model due to the lack of additional current sustaining heat. Nevertheless, the perturbed topology after the second step of the model shows similar footprint structures on the shelf as in discharge 133908.

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