Towards an experimental investigation of stochastic magnetic fields to control edge transport barriers in Next Step Tokamaks

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Abstract Active control of poloidally diverted tokamaks with ergodic divertor (ED) coils provides means to operate in conditions that are compatible with technical constraints. Control of type I ELM activity in H-mode scenarios or control of the transition to H-mode during Internal Transport Barrier scenarios is sought. We present a very simple ED configuration for ITER comprising only six conductors located behind the blanket. For a given ergodized width the current needed in the ED conductors is smaller for this simple ED configuration as compared to more complex configurations; moreover the size of the magnetic islands created in the core plasma is comparable. For a current of 200kA in the ED coils up to 12cm can be ergodized inside the separatrix on the low field side of ITER. The concept can be tested in DIII-D; for a similar geometry with conductors in the vacuum vessel, a current of 20kA in the ED coils is needed to ergodize 7cm inside the separatrix.

1. Introduction

While present plasma scenarios rely on self generated situations, active control with ergodic divertor (ED) coils provide means to operate the H mode in conditions that are compatible with technical constraints. Well known issues are the control of type I ELM activity in H-mode scenarios or the transition to H-mode during Internal Transport Barrier scenarios. Type I ELMs could lead to an excessive erosion rate significantly reducing divertor plate lifetime, while the conjunction of the H-mode barrier with the ITB may lead to a termination of the ITB. In this respect, it is interesting to evaluate the merit of the ergodic divertor in a D shaped plasma. This contribution will only stress the ELM control expected from ergodised boundaries before addressing a possible strategy to assess the ergodic divertor use in present and future devices. A possible programme would involve a trial on a present X point configuration and an implementation in ITER. DIII-D appears more appropriate to test the concept. Such an experiment could give evidence that rather small perturbations are needed to provide edge gradients control. Compared to previous proposals [1] the characteristics of the X point configuration are used to reduce the number of conductors.

2. ELM control

The stochastisation of field lines in the vicinity of the separatrix, as provided by the perturbation coils, will produce a localised enhancement of electron heat transport [2]. This may provide an actuator on the edge temperature (and thus pressure) barriers. The control of the current density gradient is more questionable but may stem from the pressure gradient control if as foreseen bootstrap current dominates at the plasma edge. On JFT-2M, the combination of two divertors has widened the operating window of the type III ELM regime, and has provided some level of ELM control [3].

The ergodisation of the edge field lines results from the combination of a high safety factor shear (rdq/qdr) and of a perturbation poloidal spectrum wide enough to generate islands chains on various resonant rational surfaces. Modular coils may be designed to provide the desired spectrum. It is important to note that the ergodisation will be obtained only if successive island chains overlap. The overlapping condition is commonly described by the Chirikov parameter, i.e. the ratio of radial island width to the distance between successive resonant surfaces. The Tore Supra experiments showed that this parameter could be used to describe the perturbed area extension. For an X point configuration, it is important to note that the shear becomes very high close to the separatrix, easing the overlapping of islands on very close surfaces. For values of the Chirikov much larger than 1, the effective field line diffusion (as they travel around the torus) will result in an effective electron heat radial diffusion.

3. A simple ED for ITER

In a DT burning tokamak an ED cannot be located in the first wall since it would be exposed to a high neutron fluence. Moreover it would reduce the Tritium breeding ratio and it could hardly be fit into the modular structure of the blanket. Unrealistic value of the perturbation current would be needed if the ED is located outside the vacuum vessel. Copper conductors located just behind the blanket appear to be a good compromise. The distance between the ED and the plasma is therefore of the order of 1m. In order to be able to ergodize with tractable perturbation currents the plasma over a depth of the order the width of the pressure pedestal (resp. of atomic physics lengths), the ‘poloidal’ distance between the conductors of the ED has to be large compared to this distance. The optimal poloidal location of the conductors of an ED for a ‘single null’ plasma corresponds to the equatorial plane of the machine.

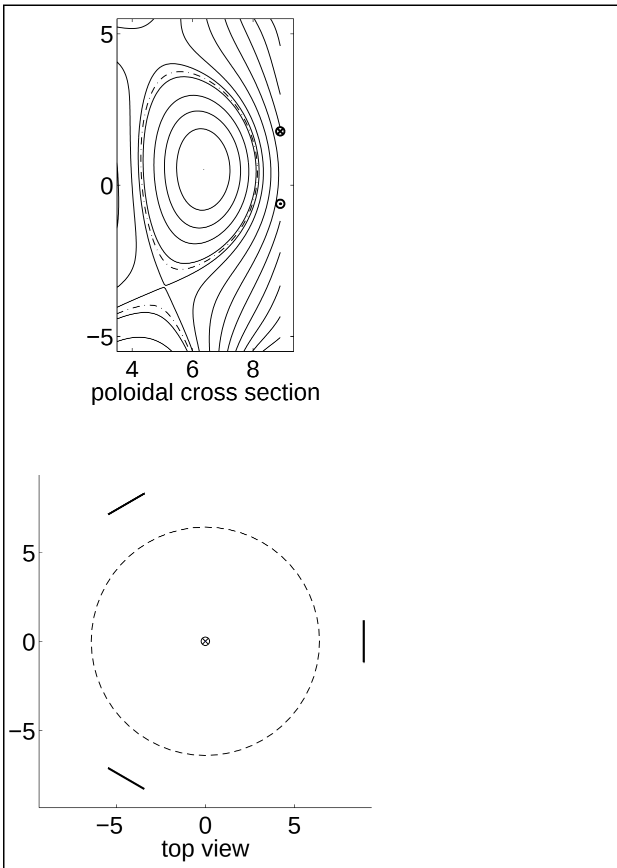

Fig.1 ITER : implementation of a m=2 Ergodic Divertor **behind the blanket**. Three modules: toroidal extension: 15° each module.

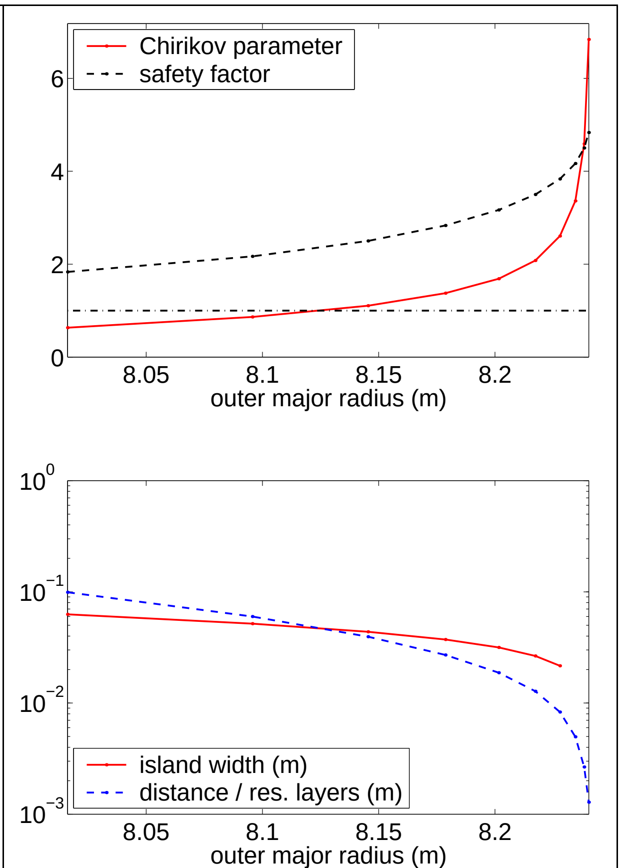

Fig.2 ITER: ED of fig.1 with $\mathbf{I_{ED}}$**=200kA**. Top: Chirikov parameter and safety factor. Bottom: island width and distance between resonant layers. Both vs. major radius at outboard midplane

The farther the distance from the equatorial plane the smaller the shear and the larger the distance between the conductors (located on the vacuum vessel) and the plasma. At locations far form the equatorial plane the smaller shear in the top and bottom parts of the plasma increase the distance between the resonant flux surfaces and the larger distance between the conductors and the plasma reduces the magnitude of the perturbation thus the width of the magnetic islands. Both effects contribute to the reduction of the Chirikov parameter and thus the ergodization efficiency.

The need for a large distance between the conductors, the poor efficiency of the conductors located far from the equatorial plane and the attractiveness of a simple implementation leads to an ED design with a small number of conductors. The ED shown on figure 1 is comprised of three modules spanning 15° toroidally. Each module is comprised of two conductors. For this geometry the ergodized width on the low field side is 5cm for Ied~80kA and 10cm for Ied~160kA. In this current range the ergodized width scales linearly with the ED current. For higher values of Ied the scaling saturates and at Ied~300kA the ergodized width scales as the square root of Ied. Such trend is related to the shear profile: the further the distance from the separatrix the larger the distance between the resonant flux surfaces and the harder overlapping of the magnetic islands.

For a given ergodized width the size of the magnetic islands created at the q=2 flux surface is almost independent of the number of conductors of the ED. Since the smaller the poloidal number of conductors of the ED the smaller the currents needed to ergodize a given width, the simple configuration proposed appears to be quite attractive. The width of the magnetic islands at the q ~ 2 flux surface is of the order of 4 cm (resp. 5 cm) for ergodized width of 5 cm (resp. 10 cm).

Typical cross section diameter of the copper conductors for Ied= 80 and 160 kA are 13 and 18 cm respectively. Such conductors can be integrated in the backplate of the blanket. Another solution for the implementation of a ED in ITER is the location of the conductors in a void space between the blanket and the vacuum vessel at the bottom of the machine. Although this location is far from optimal, implementation of the conductors in this void space would have less impact on the design of ITER than the optimal location. The intensity of the current needed to ergodize 5 cm (resp. 10 cm) on the low field side is 300 kA (resp. 650 kA). The corresponding diameters of the cross sections of the conductors are 25 and 36 cm respectively. Since the total area occupied by the DE is small it is also possible to use permanent magnets instead of copper conductors. The thickness of the magnet needed to ergodize a given depth is μ_0.Ide/Br where Ide is the current in the equivalent ED and Br is the residual induction of the magnet material. For rare earth magnets Br~ 1T and the magnet thickness capable to ergodize 5 cm (resp. 10 cm) is 37 cm (resp. 82 cm). One of the main advantages of the permanent magnet solution is to avoid the implementation of current leads.

4. Test of the concept in DIII-D

DIII-D appears to be a good candidate to test the control of ELMs with an ergodic divertor in a poloidally diverted tokamak. Type I, II and III ELMs have been observed in high confinement regimes. An ED geometry for DIII-D similar to the one proposed for ITER is shown on figure 3. The poloidal distance between the ED conductors is such that the modules can be fit between the ports. For this geometry the ergodized width on the low field side is 5cm for Ied~12kA and 10cm for Ied~35kA.

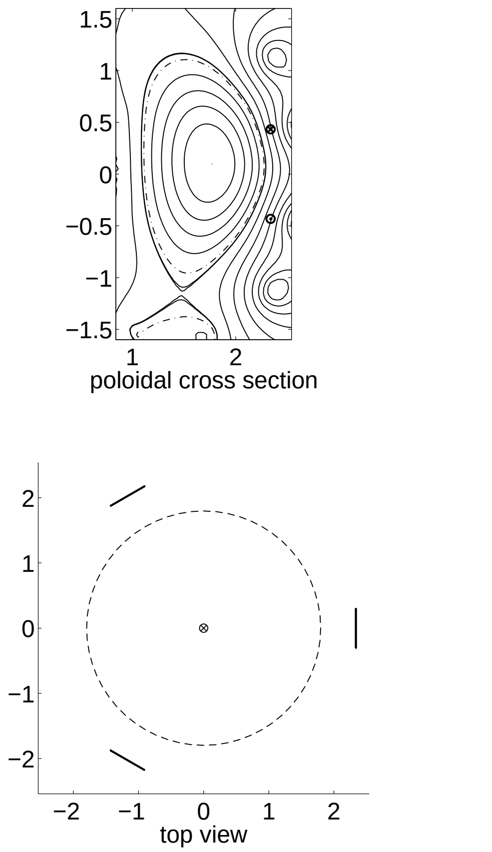

Fig.3 DIII-D : implementation of a m=2 Ergodic Divertor **inside the VV**. Three modules: toroidal extension: 15° each module.

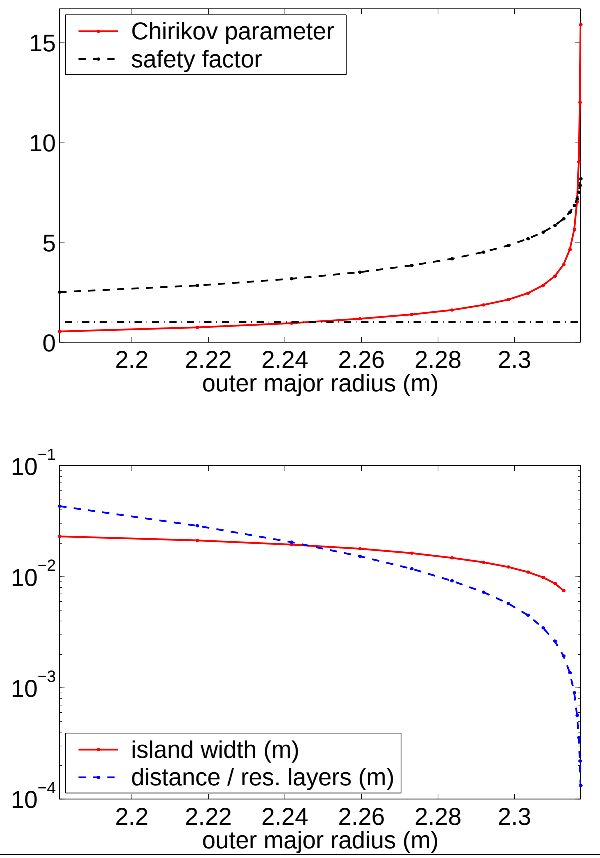

Fig.4 DIII-D: ED of fig.3 with $\mathbf{I_{ED}}$**=20kA**. Top: Chirikov parameter and safety factor. Bottom: island width and distance between resonant layers. Both vs. major radius at outboard midplane.

In this range of current the ergodized width scales as the square root of the ED current. For higher values of Ied the scaling saturates and at Ied~100kA the ergodized width scales as the cubic root of Ied. The faster saturation as compared to ITER is due to the steeper shear profile of DIII-D Typical diameter of the cross section of the copper conductor for Ied = 12 and 35 kA are 5 and 8 cm respectively; they can fit into the vacuum vessel. The width of the magnetic islands at the q ~ 2 flux surface is of the order of 2 cm (resp. 3 cm) for ergodized width of 5 cm (resp. 10 cm).

5. Conclusion

A simple ED configuration for ITER comprising only six conductors located behind the blanket is presented. For a given ergodized width the current needed in the ED conductors is smaller for this simple ED configuration as compared to more complex configurations which were considered previously; moreover the size of the magnetic islands created in the core plasma is comparable. For a current of 200kA in the ED coils, the plasma can be ergodized up to 12cm inside the separatrix on the low field side. It might provide a control on the pressure barriers in the pedestal zone and eventually type I ELMs will be avoided. The concept can be tested in DIII-D for a similar geometry with conductors inside the vacuum vessel.

[1] A. Grosman et al. to be published in J. Nuc. Mat.
[2] Ph. Ghendrih, A. Grosman and H. Capes, Plasma Phys. and Cont. Fus. 38(1996)1653.
[3] T. Shoji et al., 17th EPS Conf., ECA, 14B, p. 1452 (1990).