Extrapolation of the Ergodic Divertor to a Next Step tokamak

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1. Introduction

The control of the boundary plasma remains an open problem to extrapolate the high performance scenarios presently achieved to Next Step operation. 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 affecting divertor plate lifetime [1], 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 [2] in a shaped plasma, either working as a stand-alone divertor, as in Tore Supra, or in combination with an X-point as investigated in JFT-2M. Another paper at this conference [3] addresses the “effectiveness” ofergodic vs. axisymmetric divertors. This contribution will stress the ELM control expected from ergodised boundaries on the basis of JFT-2M results, before addressing a possible strategy to assess the ergodic divertor use in present and future devices. A priority programme would involve a trial on a large X point configuration (JET typically) and an implementation in the Next Step device (ITER-FEAT typically).This implies a capability to implement rather high poloidal and toroidal modes magnetic coils. Various concepts are investigated depending on the dominant constraint given in each device.

2. ELM control

If H mode is the standard operation mode considered for ITER FEAT, the better confinement regime yields type IELMs for which the intense energy deposition leads to an intense erosion. Notwithstanding the uncertainty related to an extrapolation from actual results, the divertor plate lifetime would be much less than one “burn-year”, i.e. marginally acceptable for ITER and forbidden in a reactor case. Type II or type III ELMs are more acceptable but no real control of this ELM activity is not really given evidence up to now. In the case of “advanced tokamak” scenarios, the rather strict control of pressure and current gradients may not be compatible with the self organising edge barrier. A control of the edge pressure may consequently be welcomed.

The stochastisation of field lines at the boundary at the very edge, as provided by the ergodic divertor, by producing a very localised enhancement of electron heat transport may provide an actuator on the edge barriers. In the case where the magnetic perturbation is produced by coils, the current modulation offers an opportunity for a fine tuning of the feedback mechanism. The control of the current density gradient is more questionable. However, such a control has been given evidence in the Tore Supra experiments [4].

On JFT-2M, the combination of the 2 divertors has opened the way to extend the type III ELM regime, and so some level of ELM control. The results are encouraging as they stress the major expected phenomena:

- the application of a magnetic perturbation which is resonant at the edge essentially (i.e. with a spectrum with rather high poloidal and toroidal mode number) allow the triggering of type III ELMs

- the effect is indeed a control of the steepening of the edge pressure gradient [5] likely just below a ballooning type limit
- a fine tuning of the L to H mode transition including the ELMy regime can be obtained depending of the magnetic perturbation amplitude
- the perturbation needed to produce such control appears to be moderate (less than 2% of the minor radius for the main mode)
- this can be done at the expense of a modest loss of energy confinement.

3. A possible implementation in an actual large tokamak

Implementation of an ergodising system in a large tokamak would be very important to assess its capabilities in an adequate size and configuration device. The aims would be to check that magnetic configuration of the perturbation similar to the one used in Tore Supra would apply in a D shaped X point configuration.

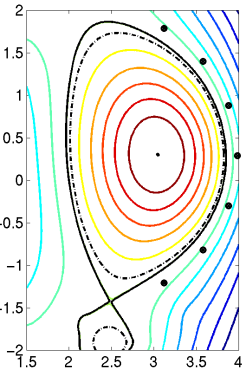

fig.1 Low field side implementation of a m=7 Ergodic Divertor. Six ED modules : poloidal extension 120°, toroidal extension 15°.

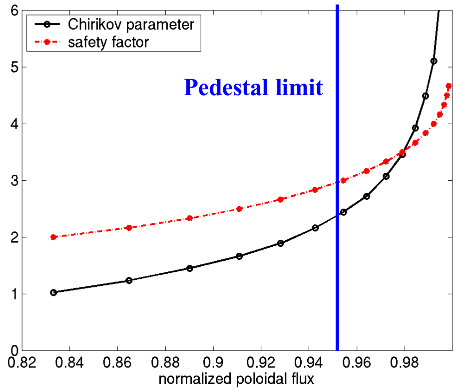

fig.2 Chirikov parameter and safety factor vs normalized poloidal flux for I_{ED} = 100kA. Shaded is the estimated pedestal region

A conceptual test is done by calculation applying the field created by 6 modules to a configuration of JET envisioned in the framework of the JET Extended Performance Project [6]. The modules would be installed inside the vessel with its front face located at 5 cm from the separatrix**.** The current inside the coil would amount to 100 kA.

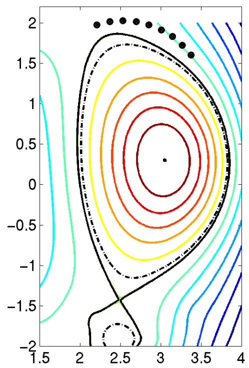

fig.3 Top implementation of a m=9 Ergodic Divertor. Six ED modules : poloidal extension 72°, toroidal extension 40°.

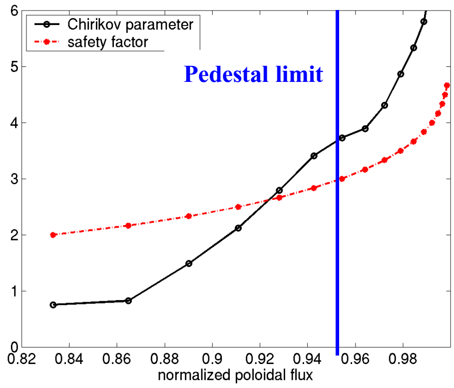

fig.4 Chirikov parameter and safety factor vs. normalized poloidal flux for I_{ED} = 100kA. Shaded is the estimated pedestal region

In this work, we generalise the magnetic coordinate system used for an action-angle description of the magnetic equilibrium to the case of a shaped plasma. This then allows one to determine analytically the location of the stochastic boundary and other figures of merit of the perturbation. Interestingly enough this method allows one to generalise this work to a stellarator boundary. Figure 1 and 3 display poloidal cuts of the coil sections. Note that the current direction is alternating from one bar to the other. The results are appreciated in terms of Chirikov parameters in fig. 2 and 4. Value higher than 2 lead to very large enhancements of heat transport. The location of the coil in the top region would be preferable as requiring less on the useful LFS in the chamber (antennas, etc…) but its sensitivity to plasma elongation and triangularity should be studied in more detail. In any case, the results presented here are preliminary. Note also that a smaller requirement in terms ofChirikov parameter (>2 in both cases in the whole estimated pedestal region) would decrease the current as its square value.

4. Technical extrapolation to a Next Step Device

A key problem is the exponential decrease of the magnetic perturbation and thus the impact of the neutron shielding on the magnitude of the perturbation at the plasma boundary. It was shown in a previous paper [7] that a solution based on standard superconductors is within reasonable engineering constraints for a reactor grade device, R~ 9 m with 1 m neutron shield, ergodic divertor currents in the range of 650 kA are needed. With 50 MA m^{-2} current density and the mechanical structure to balance the forces, the cross section of the coil would then reach 0.04 m^2. The coil would be located on the low field side both, where space is available and where the exponential decay of the perturbation is minimised.

The aspect ratio is less favourable in a Next Step device such as ITER FEAT where the minor radius is 2 m instead of 3 m for a reactor, as the perturbation current needed increases by a factor about 3 in the former case due to the strong exponential attenuation. Moreover, in ITER-FEAT, the implementation of a superconducting coil within the vacuum vessel does not meet reasonable requirements. Consequently, in the case of a test of an ergodic divertor in this device, one has to envision solutions where the coils would either become a part of the blanket itself or be located just behind it. In the former case, the coils could be installed 10 to 15 cm below the blanket surface, i.e. about 30 cm from the separatrix while they would 80 cm away in the latter. The coil current could be limited to 160kA in the first case while reaching about 650 kA in the latter for similar module geometry. This value could be decreased by increasing the effective areas of the coil, which is necessary to keep the coil radial width (0.15m) and the Joule power (10 MW) at a reasonable level, thus limiting the current at 100 kA. The radiation levels at the coil location (< 10^{12} rads and <10^{19} n/cm²) should not affect substantially the copper electrical conductivity nor the insulation capacity of mineral insulators.

In fact we investigated also in a first approach a coil structure (2 m toroidal extension, 8 poloidal bars supplying each 160 kA) located in the stainless steel front part, behind the Beryllium/Copper first wall of the ITER blanket module assembly in spite of the major problems to be encountered to install the conductors inside the blanket. In the case of copper coils, the interconnection of the electrical isolated and water-cooled conductor windings between individual blanket models are difficult to design especially if remote handling considerations are to be met.

Another interesting option is to consider a liquid lithium coil. Then, the major engineering constraints are the possible conductor temperature range due to Joule losses and nuclear heating, plus the pressure drop for the involved circulating liquids (especially estimation of MHD pressure losses due to ExB effects). Flowing liquid metal such as lithium (200-400°C), in insulated wall channels, as an electrical conductor and cooling fluid [8] could be envisioned as satisfying the above mentioned constraints. Even though simple engineering calculations does not rule out this solution, it seems that the liquid metal solution may be considered only if the whole blanket is lithium cooled, as the coexistence of water and lithium within the vessel cannot be considered from a safety point of view.

Another mean to provide the magnetic perturbation could be considered : the use of permanent magnets alternatively oriented N/S and S/N. To create a perturbation equivalent to the one of an ED with a set of m conductors each carrying a current I_{DE} the Magnet Ergodic Divertor (MED) has to include N_m magnets with N_m = m-1, of radial thickness μ_0 I_{DE}/Br (where Br is the residual induction), i.e. of the same order as coils width. If this solution exhibits important pros such as no need for power supplies and reduced cooling power, or simple manufacturing process, while possibly contributing to ripple reduction, a series of cons will have to be reversed especially the coercive field which should be of the order of the toroidal field, the magnetic properties degradation with temperature and the sensitivity to neutrons and gamma rays. Development of new materials should be surveyed such as Sm-Fe-N or Nd-Fe-B magnets. A test of such implementation could be done in present tokamak such as Tore Supra if its life time is prolonged enough.

5. Conclusions

The ergodic divertor may act as an integral open divertor, but offers also the capability to complement X point configurations as far as ELM control is concerned. This is based on the assessment done in the 10 years experiments in Tore Supra but also on results obtained in JFT2 – M, which give confidence in this peculiar effect. However, experiments in an actual device needed. The Dynamic Ergodic Divertor of TEXTOR [9] is the only designed installation to go soon into operation. Of interest for a reactor will be the experience with a different set-up of the perturbation coils as continuous windings at the The DED is designed to distribute the power to a large wall section, and at the highest frequencies to induce a torque to the plasma edge which may lead to a differential rotation resulting possibly in a confinement enhancement and an unlocking of modes. Edge diagnostics will complete the general knowledge on ergodised zones. Looking to the future, application to D shape tokamak has been studied from a magnetic configuration point of view and preliminary results are encouraging. An optimisation should lead to a sound proposal for a tokamak like JET. Extrapolation to a reactor appears achievable. Superconducting coils may be implemented behind a shield for a 3m minor radius device. Yet, more difficulty is expected in ITER FEAT, where an option with water cooled copper coils could be still considered if the control of the erosion due to the ELMs require an effective and tuneable scheme. One should keep an eye on development on permanent magnets and an implementation on Tore Supra could be envisioned if steady state aspects (including compatibility with scenarios) are to be assessed.

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