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Journal of Nuclear Materials 313–316 (2003) 1314–1320

journal of nuclear materials

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H-mode barrier control with external magnetic perturbations

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Received 27 May 2002; accepted 7 October 2002

Abstract

While present plasma scenarios rely on self generated plasma conditions, active control with ergodic divertor coils provide the means to operate in H-mode with divertor and SOL plasma conditions that are compatible with the technical constraints. The stochastisation of field lines in the vicinity of the separatrix, will produce a localized enhancement of electron heat transport. This will provide a control on the edge temperature (and thus pressure) barriers. Consequently, the local current profile, which is essentially bootstrap, will be modified. H-mode edge barriers can be controlled and type I Elms avoided in this way. Such controls are required for advanced regimes. The paper will discuss this in light of the theoretical and experimental advances of the last years: Tore Supra experiments gave evidence of the fine tuning capability of the perturbation on a well defined magnetic configuration while JFT-2M experiments showed that the edge stochastisation of the X point configuration has widened the operating windows of the type III ELM regime. The possible implementations of such control in a medium size tokamak (DIII-D) and eventually on ITER will also be described.

PACS: 52; 55
Keywords: Ergodic divertor; ELM control; ITER; Tore Supra; DIII-D; Edge pedestal

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1. Introduction

The control of the boundary plasma remains an open problem in extrapolation of 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 potentially lead to an excessive erosion rate affecting divertor plate lifetime [1], while the conjunction of the H-mode barrier with the ITB can lead to a termination of the ITB. In any case, the divertor heat exhaust capability might require some transport enhancement in the edge to broaden the heat load profile. In this respect, it is interesting to evaluate the merit of the ergodic divertor (ED) [2] in a shaped plasma, either working as a stand-alone divertor, as in Tore Supra, or in combination with an X-point as already investigated in JFT-2M [3]. This contribution will stress the edge pedestal pressure and current profile (and thus ELM) control expected from ergodized boundaries on the basis of JFT-2M and Tore Supra results but also on more configurational grounds which were given evidence by the combination of theoretical and experimental progress in the last 25 years [2,4]. Finally, a possible strategy to assess the use of the ED in present and future devices

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PII: S0022-3115(02)01509-X

will be presented. A priority programme would involve a test on an existing X point configuration (DIII-D typically) and an integration in the Next Step device (ITER typically). Possible implementations will be described in the two cases.

2. Experimental and theoretical basis for edge pedestal control

While the H-mode is the standard operation mode considered for ITER, the enhanced confinement regime yields type I ELMs for which the intense energy deposition leads to an intense erosion. Notwithstanding the uncertainty related to extrapolation from present results, the divertor plate lifetime would be much less than one 'burn-year', i.e. marginally acceptable for ITER and inconceivable for a reactor. Type II or type III ELMs are more acceptable but no real evidence of control of this ELM activity has been provided up to now, except for a delicate control of the magnetic configuration around the separatrix [5]. In the case of 'advanced tokamak' scenarios, the required control of pressure and current gradients may not be compatible with the self-organising edge barrier. A control of the edge pressure and current profiles may consequently be welcomed. Moreover, the understanding of the MHD modes involved in the stability of such regimes may open the way to the use of external magnetic perturbations such as the ones envisioned for ergodizing the plasma edge.

2.1. Experimental evidence in JFT-2M

On JFT-2M, the combination of both X point and ED configuration allowed the extension of the type III ELM regime, giving therefore evidence of some level of ELM control. The results are encouraging as they stressed the major expected phenomena [3] and especially: a control of the steepening of the edge pressure gradient with a fine tuning of the L- to H-mode transition, for a moderate edge perturbation and at the expense of a modest loss (10%) of energy confinement.

2.2. Experimental conclusions from the Tore Supra experiments

The stochastisation of field lines at the boundary at the very edge, as provided by the ED, produces a very localised enhancement of electron heat transport and may provide a control of 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 strong correlation between expected electron heat transport enhancement and effective electron temperature profile has been carefully verified [6,7]. The current density gradient was not measured directly. However, a modification of the current density gradient is expected from the decrease of T_e, this leads to an increase of the plasma resistivity and thus edge current control has been shown in the Tore Supra experiments, yielding favourable effects on MHD activity about the $q = 2$ flux surface [8].

As the ELMs drivers seem to be ballooning and kink modes [9], the edge stochastisation, by acting on both pressure and edge current gradients will be a very powerful tool. The localisation of the effect may be varied with the exact q profiles, the major toroidal (n) and poloidal (m) mode numbers, being resonant on surfaces $q = m/n$.

An interesting feature, which is still speculative, would stem from direct interactions between the static modes induced by the perturbation coils and the MHD instability mode. Precise toroidal mode numbers for the ELMs are not known. However, recent observations of ELM precursors indicate [10] medium n mode numbers in the range between $n = 3$ and 12. Ballooning modes with high-n mode numbers are expected to be most unstable at high-pressure gradient/low-current density. Low-n kink (peeling) modes are the most unstable modes at low-pressure gradient/high-edge current density. In the intermediate regime, a combination of ballooning and kink mode is most unstable with typical mode numbers of the order 12–15.

2.3. Theoretical basis of plasma edge ergodization

The ergodization of the edge field lines results from the combination of a high-safety factor shear ($r\mathrm{d}q/q\mathrm{d}r$) and of a perturbation poloidal spectrum wide enough to generate islands chains on various rational surfaces with the above quoted resonance conditions. Modular coils may be designed to provide the desired spectrum. It is important to note that the ergodization will be obtained only if successive island chains overlap. The overlap condition is commonly described by the Chirikov parameter, i.e. the ratio of radial island width to the distance between successive resonant surfaces [2]. The Tore Supra experiments showed that this parameter could be used to describe the perturbed area extent. For an X point configuration, it is important to note that the shear becomes very high in proximity to the separatrix, easing the overlapping of islands on very close surfaces. However, in this case, the use of a rather high-m value (>10) will insure a rapid decrease of the mode amplitude away from the coil as $(r/a)^m$. A corollary of this fact is that the coil cannot be installed too far from the plasma. A simple rule for the total perturbation current I_{ED} is $I_{\mathrm{ED}}/I_{\mathrm{p}} \propto (1 + \Delta/a)^{m-1}$ where I_{p} is the plasma current, Δ the distance between the coil and the plasma boundary and a the plasma minor radius.

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. One could infer values of the latter parameter larger by at least one order of magnitude than the usual turbulent diffusion with values of typically of $2\sqrt{T_{\mathrm{eV}}}$ m^2/s [4] where T_{eV} is the electron temperature in eV.

3. Extrapolation to next step devices

3.1. Conceptual design of a test experiment

Implementation of an ergodizing 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. To calculate it, we generalise the magnetic co-ordinate system used for an action–angle description of the magnetic equilibrium to the case of a shaped plasma [2]. 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. It is important to note that the Chirikov parameter scales as the square root of the perturbation current. Consequently, smaller Chirikov parameter requirements would translate into strong decrease of the current needs.

Fig. 1 shows a Tore Supra ED coil. It can be considered as a generic ED coil configuration. The coil is made of two layers of conductors. The layers are arranged in such a way that the currents add up in the bars along the 'toroidal' direction and cancel in the bars

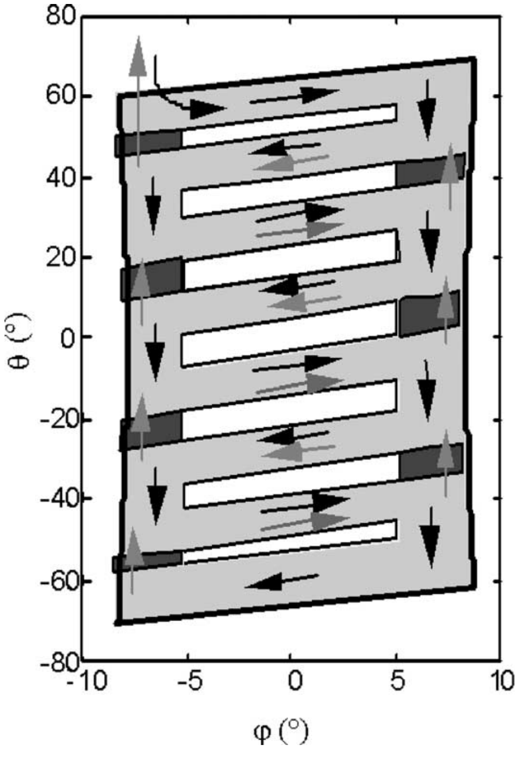

Fig. 1. Set up of an ED coil. φ corresponds to the toroidal direction, and θ to the poloidal direction. Light gray area and dark arrows correspond to top layer of conductors. Dark gray areas and light gray arrows correspond to second layer of conductors (when apparent). The arrows indicate the current flow. The layers are arranged in such a way that the currents add up in the bars along the toroidal direction and cancel in the bars along the poloidal direction. Note that the toroidal bars can have a pitch with respect to the toroidal direction.

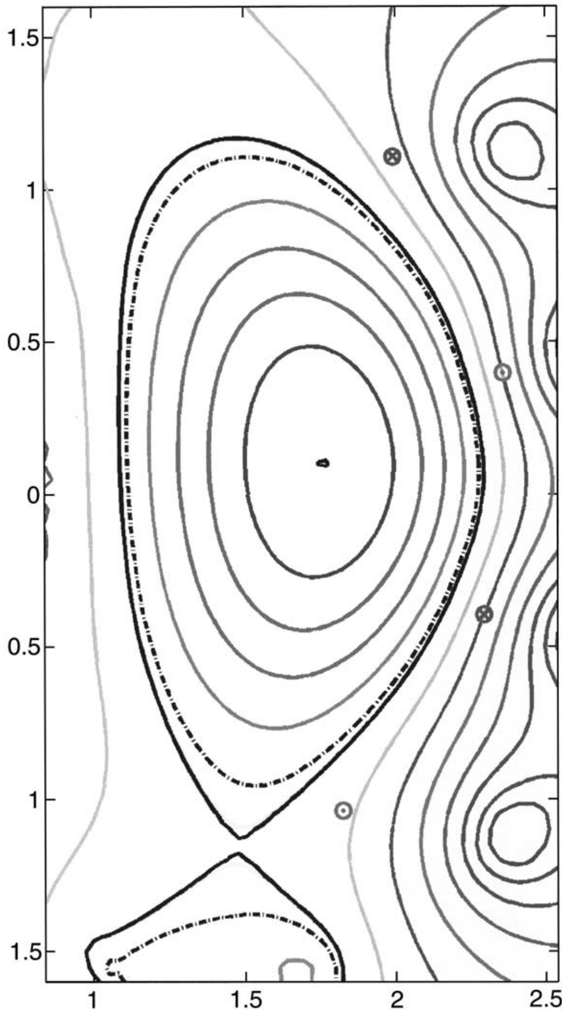

Fig. 2. Implementation of an $n = 6$, $M = 4$ ED inside the vacuum vessel of DIII-D. The ED comprises six coils evenly spaced toroidally. Each coil has a poloidal extension of 95°, and a toroidal extension of 15°. Crosses and dots show the directions of the currents in the toroidal conductors located on the first wall. The locations of the DIII-D PF coils correspond to the closed flux surfaces at the right.

along the 'poloidal' direction. In first approximation the coil can be modelled as a set of M toroidal conductors with a pitch. An ED comprises n coils of this type evenly spaced toroidally.

3.2. Implementation of an ED in DIII-D

DIII-D appears to be a very suitable candidate to test the control of ELMs with ED coils. Type I, II and III ELMs have been observed in high-confinement regimes. The toroidal number of coils of a ED has to be a divisor of 24, the number of TF coils of DIII-D. Shown in Fig. 2 is the poloidal cross-section of an $n = 6$, $M = 4$ ED located in the vacuum vessel. The Chirikov parameter on the low-field side of the plasma for a 10 kA current in one ED coil layer is shown in Fig. 3 (for 10 kA in one layer the current is 20 kA in the central bars and 10 kA in the extreme bars). It should be noted that the perturbation which is produced by such coils, has a sufficiently large spectrum around $m = 8$ and with a large extension allowing a wide perturbation in target zone. The field lines are ergodized 8 cm inside the separatrix on the low-field side and up to 12 cm on the high-field side i.e. up to the 0.77 normalized flux surface. If the ED is located outside the vacuum vessel, at the PF coils location ~100 kA are needed to ergodize the same region.

It has to be noted that the $q = 2$ flux surface is far enough from the separatrix so that the (2,1) mode cannot be destabilised by the ED if the width of the ergodized zone is less than 10 cm on the low-field side.

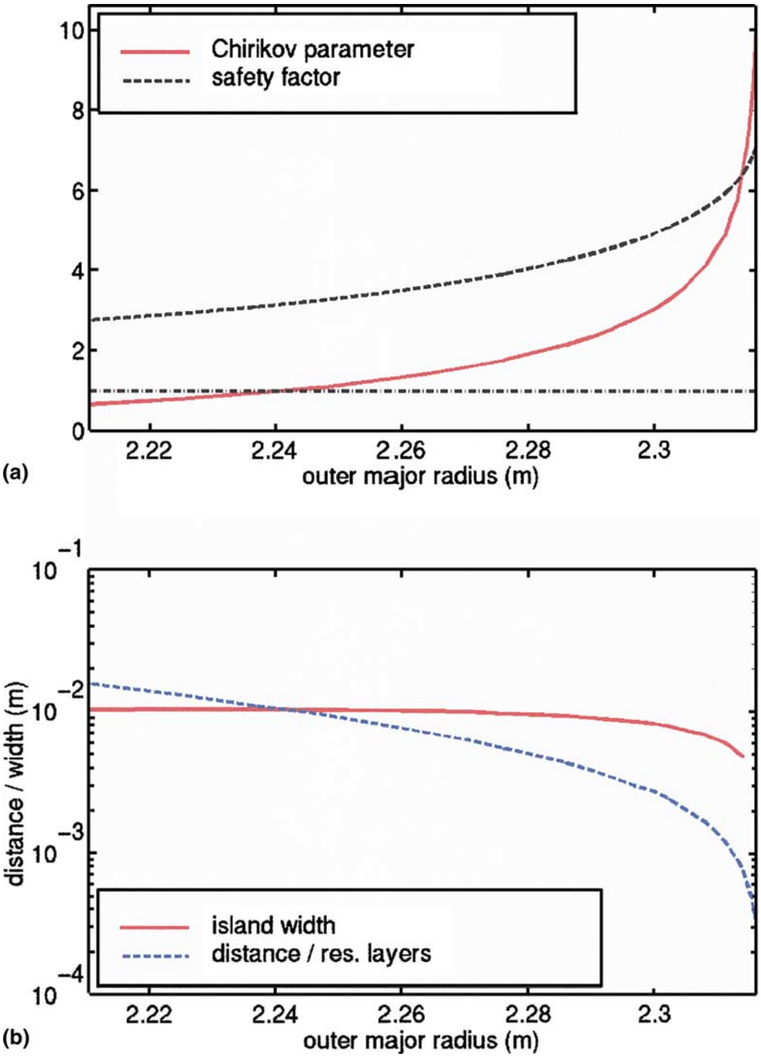

Fig. 3. DIII-D: Effect of the $n = 6$, $M = 4$ ED described in Fig. 2. Currents in the central bars: 20 kA. Currents in the upper and lower bars: 10 kA. Top (a): Chirikov parameter and safety factor vs. outer major radius. Bottom (b): radial width of the magnetic islands and distance between the resonant flux surfaces vs. outer major radius.

3.3. Extrapolation to ITER

Implementation of ED coils system in ITER could provide a feedback tool to control the ELMs regime. However from a technological point of view, the implementation is difficult. A key problem is the exponential decrease of the magnetic perturbation with the distance from the plasma edge and thus the impact of the neutron shielding large width on the magnitude of the perturbation at the plasma boundary. The coils would be located on the low-field side outside the vacuum vessel or behind the shielding, where space is available and where the exponential decay of the perturbation is not too large. Note that they could hardly be located in the modular blanket since large poloidal and/or toroidal extension of the ergodizing coils is needed. The interconnection of windings between individual blanket modules would be difficult to design especially if remote handling considerations are to be met.

There are 18 toroidal field coils in ITER; we propose to implement an $n = 3$, $M = 4$ ED system behind the blanket, i.e. about 80 cm from the separatrix. The ED coils have a poloidal (respectively toroidal) extension of 80° (respectively 15°) (Fig. 4). In this configuration the pedestal zone is ergodized up to the 0.95 normalized flux surface if the current in the ED bars is of the order of 100 kA (Fig. 5). If ED coils are located just outside the vacuum vessel, i.e. about 160 cm from the separatrix, 200 kA are needed to ergodize up to the 0.95 normalized flux surface.

For the implementation behind the vacuum vessel the natural solution would be NbTi superconducting ED coils since the ED coils are located in the TF/PF coils cryostat. For such a conductor the allowed overall current density, (including ~50% structural material) is of the order of 20 A/mm^2. 200 kA would require a conductor cross-section of 10×10 cm^2. For the implementation behind the blanket, inside the vacuum vessel, a classical copper technology could be used. For copper coils the allowed overall current density, including ~50% structural material, is of the order of 5 A/mm^2. 100 kA would require a conductor cross-section of 15×15 cm^2. The radiation levels at the coil location ($<10^{11}$ rads and $<10^{19}$ n/cm^2) should not affect substantially the copper electrical conductivity nor the insulation capacity of fibre glass/epoxy or mineral insulators.

3.4. Other assets of the ED configuration

The paper is focussed on the use of ergodization to control H-mode edge pedestal. However, a ED could provide many other beneficial effects [11]. One would be to even prohibit the access to the H-mode: this could be an asset if advanced scenarios, which provide internal transport barriers, would be either more accessible or more controllable without an edge barrier. The ED may also allow heat exhaust control. The ergodization about the separatrix may provide an increase of the radial transport in the region connected to the divertor plates, with the aim of decreasing the peak heat flux onto them. As an extension of Tore Supra results, an effective increase of the edge volume with low-confinement may give access to more edge radiated power, without a too strong contamination of the plasma bulk. A more internal intrinsic transport barrier may also be sustained [12]. The amplitude of magnetic perturbation may however, differ from the one envisioned for pedestal control.

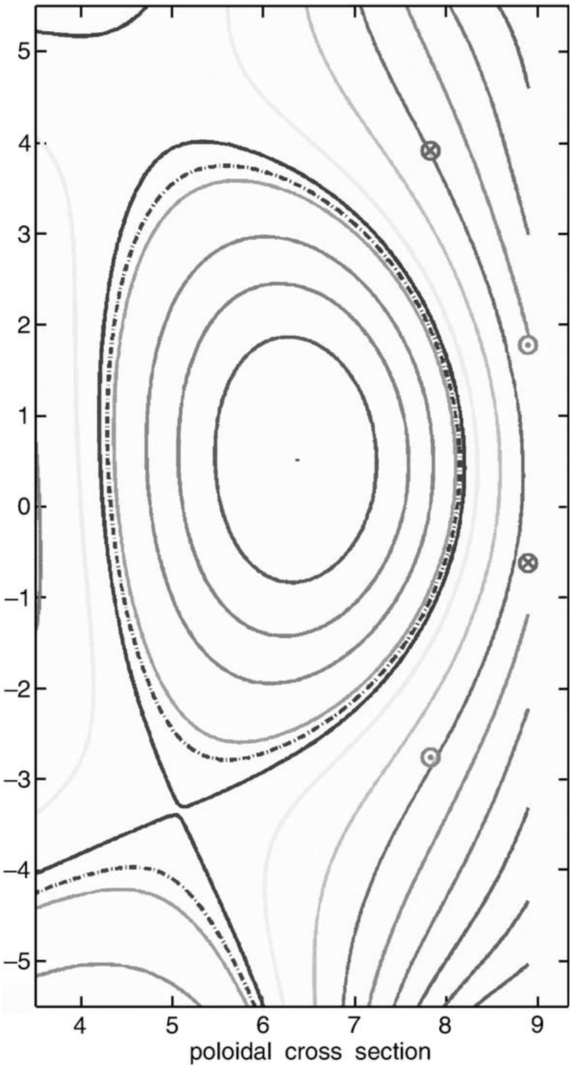

Fig. 4. Implementation of an $n = 3$, $M = 4$ ED behind the blanket of ITER. The ED comprises three coils evenly spaced toroidally. Each coil has a poloidal extension of 80°, and a toroidal extension of 15°. Crosses and dots show the directions of the currents in the toroidal conductors.

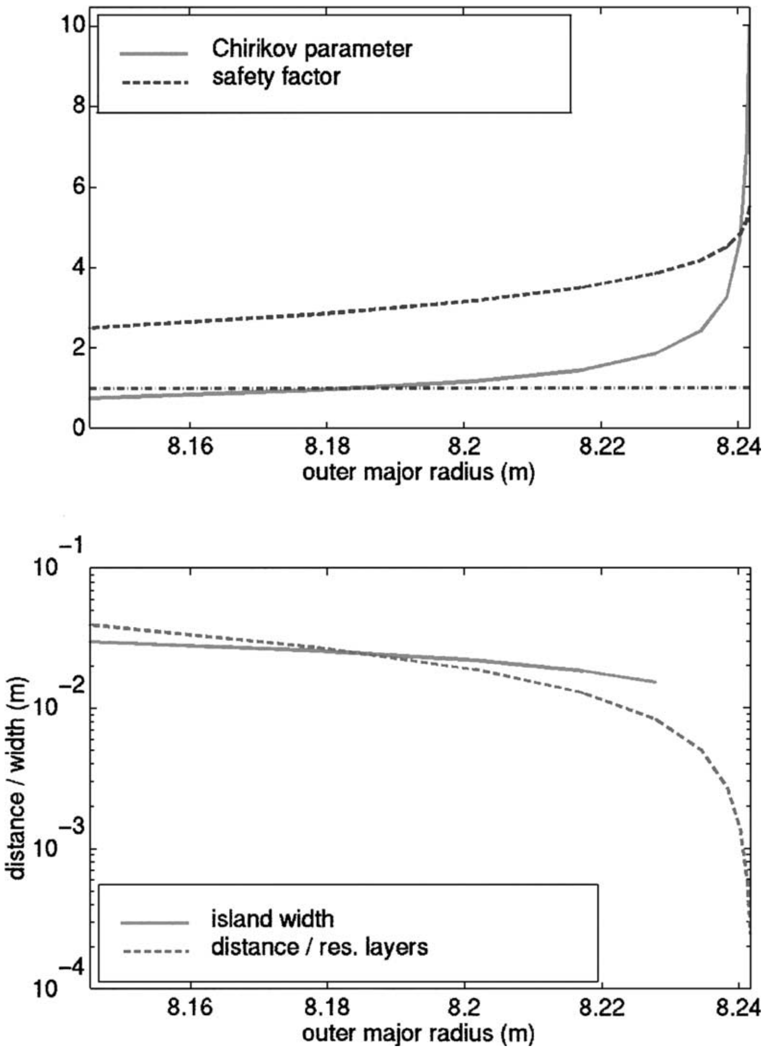

Fig. 5. ITER: effect of the $n = 3$, $m = 4$ ED described in Fig. 4. Currents in the central bars: 100 kA. Currents in the upper and lower bars: 50 kA. Top: Chirikov parameter and safety factor vs. outer major radius. Bottom: radial width of the magnetic islands and distance between the resonant flux surfaces vs. outer major radius.

4. Conclusion

The ED may act as an integral open divertor, but offers also the capability to complement X point configurations as far as edge pedestal (and thus ELM) control is concerned. This is based on the assessment done in the 10 years of experiments in Tore Supra but also on results obtained in JFT2-M, which give confidence in this effect. However, experiments in an actual device are needed. The dynamic ED of TEXTOR [13] is the only designed installation to go into operation soon. The application to D-shaped tokamak has been studied from a magnetic configuration point of view and preliminary results are encouraging as they involve modular coils with currents amounting to 10 s of kA, provided they can be implemented close to the plasma, i.e. for ITER within the vacuum vessel but behind the neutron shielding. The concept optimisation requires experiments in an actual tokamak: DIII-D would be well suited for this.

Acknowledgements

The authors acknowledge the communication of all references and additional elements by Dr Tamai, concerning the JFT-2M experiments.

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