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Edge localized modes control by resonant magnetic perturbations

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Abstract

A number of designs for external or in-vessel coils generating Resonant Magnetic Perturbations (RMPs) for type I ELMs control in ITER are analyzed. The RMPs generated by the I-coils in the successful DIII-D ELMs control experiments are taken as a reference. The three ITER characteristic scenarios (H-mode, hybrid and steady-state) are studied. In a second part of the paper, the first results of a self-consistent non-linear MHD modelling of the plasma response to the RMPs with the JOREK code, for a DIII-D case, are presented.

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Keywords: DIII-D; ELM; ITER

1. Introduction

The reduction of impulsive heat and particles loads on the plasma facing components due to type I Edge Localized Modes (ELMs) remains a significant research problem for ITER [1]. Resonant Magnetic Perturbations (RMPs) generated by so-called 'I-coils' in DIII-D have been able to suppress the type I ELMs reliably without degrading the plasma confinement [2]. The DIII-D results motivated the study, presented in Section 2, of the possibility to install similar coils in ITER in order to control the ELMs. One should keep in mind, however, that the mechanisms that led to the ELMs suppression in DIII-D are not completely understood yet, so that an effort to model the DIII-D results is still

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necessary. A part of this modelling work is presented in Section 3.

2. Coils design for ELMs control by RMPs in ITER

The precise features of the RMPs required for the ELMs suppression are not known yet. However, it seems clear that the RMPs should have a sufficient strength at the edge. On the other hand, core RMPs should be minimized in order to avoid destabilizing core MHD modes. These are the two main physics requirements considered for this design work. In terms of strength at the edge, we take as a reference the RMPs produced by the DIII-D I-coils in their so-called 'even parity' phasing, fed with 3 kA, in a standard H-mode with $q_{95} = 3.7$ (details can be found in [3]). As in [3], we make here the hypothesis that the magnetic field generated by the coils in the plasma is just as it would be in vacuum.

In the intrinsic equilibrium coordinates (s, θ^*, φ), where $s \equiv \sqrt{\psi_{\rm pol}} \Big/ \sqrt{\psi_{\rm pol}^{\rm sep}}$ ($\psi_{\rm pol}$ being the poloidal magnetic flux and $\psi_{\rm pol}^{\rm sep}$ its value at the separatrix), φ is the toroidal angle, and θ^* is such that the magnetic field lines are straight in the (θ^*, φ) planes at fixed s, we define $B^1 \equiv (\vec{B}, \vec{\nabla}s)$, which can be written as

$$B^1 = \sum_{m,n=-\infty}^{+\infty} B^1_{m,n}(s) \mathrm{e}^{i(m\theta^* + n\varphi)}.$$

Assuming that the dominant toroidal harmonic of the perturbations is n_0 (typically generated, in the designs we consider, by $2n_0$ identical coils [or sets of coils] centred at $\varphi_k = \frac{k\pi}{n_0}$ $[k = 1, \ldots, 2n_0]$ with alternate direction of current in adjacent coils; for instance in DIII-D, the 6 upper and 6 lower to the midplane I-coils produce mainly an $n_0 = 3$ perturbation), the main resonant parts of the perturbations are located on the $q = m/n_0$ surfaces, and can be estimated as

$$B^1_{\rm res} \approx \left| B^1_{m,-n_0} + B^{1*}_{-m,n_0} \right|$$

(the star designating the conjugate complex).

We define also the effective radial resonant perturbations normalized to the toroidal magnetic field on axis, B_0, as

$$b^{\rm r,eff}_{\rm res} \equiv \left| B^1_{\rm res} \right| / B_0 < \| \vec{\nabla} s \| >_{\theta^*}.$$

We estimate the half-widths of the magnetic islands generated by the RMPs on the resonant surfaces by adapting the analytical cylindrical expression:

$$\delta_{m,n_0} \approx \left(4R_0 a q^2 b^{\rm r,eff}_{\rm res} \Big/ m \frac{\mathrm{d}q}{\mathrm{d}s} \right)^{1/2},$$

where R_0 (resp. a) represents the major (resp. minor) radius.

Three possibilities for placing RMPs coils in ITER are considered in the present paper (Fig. 1). We would like to point out that some freedom exists in the choice of the main toroidal mode number of the perturbations n_0, but that a comparison of similar designs with different n_0 (different numbers of coils) suggests that $n_0 = 3$ is the best compromise

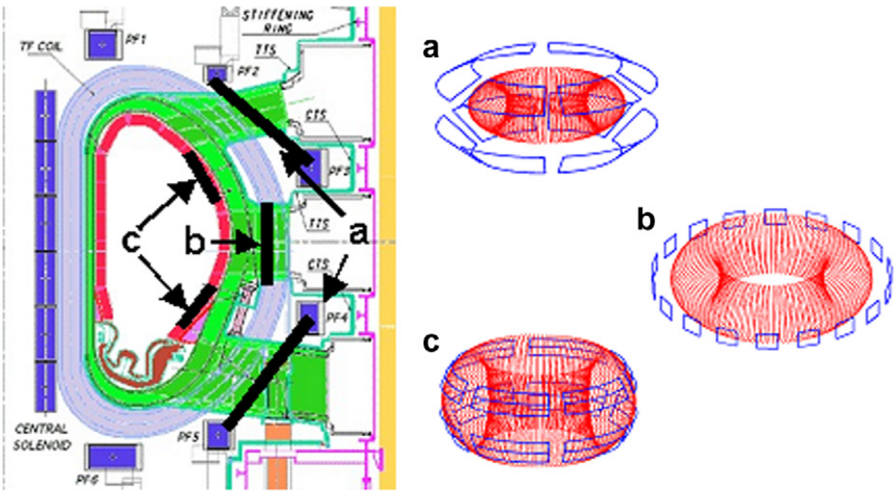

Fig. 1. Left: poloidal cut of ITER with the locations of the three possible designs studied here. Right: 3D view of these three designs together with the plasma (in red in the coloured version). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

between strong pedestal and weak core RMPs, while keeping a reasonable value of the required current in the coils. Thus, the designs considered here all have an $n_0 = 3$ symmetry. The first possibility is to fix the coils using the poloidal field coils as supports (design *a*). The second one is to wind them around the 18 midplane port plugs of the machine (design *b*). The third one is to wind them around selected blanket modules (design *c*), with the assumed possibility of changing, at will, the direction of the current in each coil independently from the others. The third design, with coils inside the vacuum vessel (VV), is technically more challenging than the first two, which are external to the VV, but engineering considerations are out of the scope of the present paper.

The values of $b_{\rm res}^{\rm r,eff}$ on the $q = m/n_0 = m/3$ surfaces for designs *a*, *b* and *c*, for an ITER H-mode reference scenario from [4], with $B_0 = 5.3T$ and $q_{95} = 3.4$, are shown on Fig. 2. One can see that the currents that are required in order to reach the DIII-D reference value in the pedestal $\left(b_{\rm res}^{\rm r,eff} \approx 2\times 10^{-4}\right)$ are about 480 kA for *a*, 240 kA for *b*, and only 20 kA for *c*. The estimated vacuum islands widths on the innermost resonant surface $q = 4/3$ are about 8.5 cm for *a* and *b*, and about 7 cm for *c*.

It is however important to notice that computations for the H-mode alone are not sufficient, since the spectrum of the RMPs can depend strongly on the equilibrium. In particular, the spectrum is very sensitive to the *q* profile, through the pitch angle of the field lines as they pass in front of the coils. We present here results obtained by keeping the (s, θ^*, φ) coordinates from the H-mode and modifying only the *q* profile so as to make it hybrid-like ($q_{95} \sim 4$) or steady-state-like ($q_{95} \sim 5$). It turns out that the steady-state case is very unfavourable for design *a* (Fig. 3, left) and quite unfavourable for *b* in terms of strength of the RMPs at the edge, i.e. in terms of required current. In contrast, design *c* can be adapted by changing the phase of current between the different coils: in Fig. 3 (right), one can see that the so-called '+−−+' configuration (for which a poloidal cut of $b_{n=3}^R \equiv (\delta\vec{B}\cdot\vec{\nabla}R/B_0)_{n=3}$ is represented on Fig. 4), where the four signs

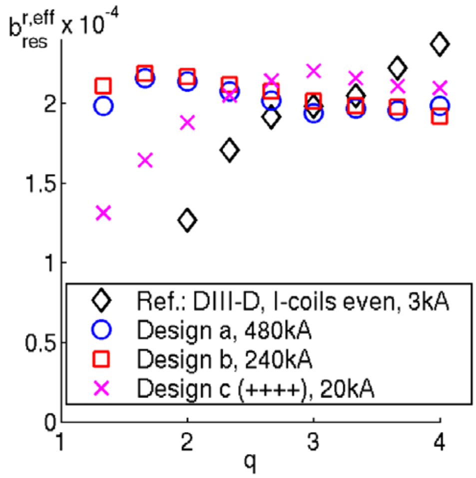

Fig. 2. Values of the effective resonant radial (normalized) magnetic perturbations $b_{\rm res}^{\rm r,eff}$ on the resonant ($q = m/3$) surfaces, for DIII-D's I-coils (see [3] for details) and for the three designs considered for ITER for the H-mode from [4].

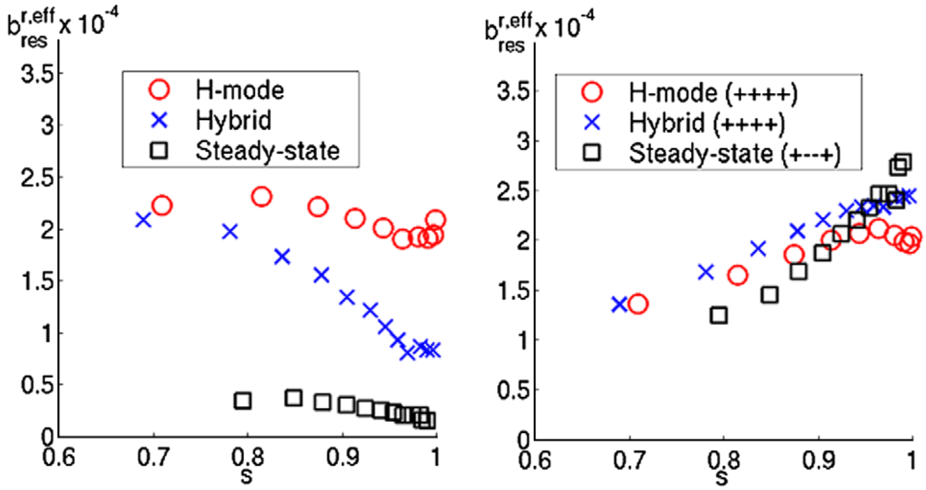

Fig. 3. Values of the effective resonant radial (normalized) magnetic perturbations $b_{\rm res}^{\rm r,eff}$ on the resonant ($q = m/3$) surfaces, calculated with the intrinsic (s, θ^*, φ) coordinates of the H-mode from [4], for three different *q* profiles: an H-mode-like ($q_{95} \sim 3.4$), an hybrid-like ($q_{95} \sim 3.4$), and a steady-state-like ($q_{95} \sim 5$). Left: design *a*. Right: design *c*.

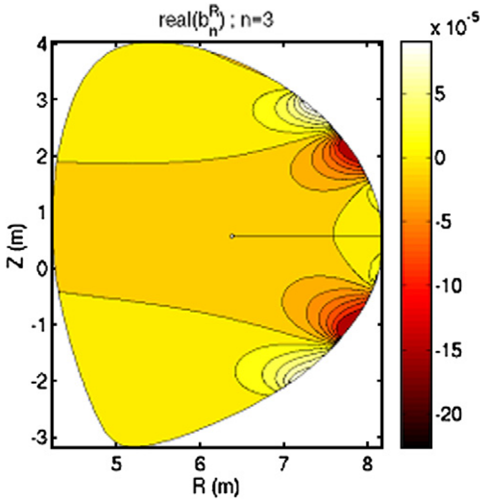

Fig. 4. Poloidal cut of $b^R_{n=3} \equiv (\delta\vec{B} \cdot \vec{\nabla}R/B_0)_{n=3}$ calculated for design c in the '+−−+' configuration.

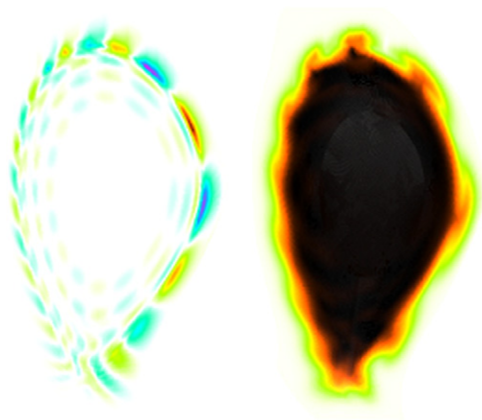

Fig. 5. Colour plots of the $n = 3$ harmonic of the electric potential (left) and plasma density (right) after 800 τ_A (τ_A being the Alfvén time). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

'+−−+' represent the directions of current in the four coils that are centred on $\varphi = 0$, from top to bottom, appears to be adapted to the steady-state scenario, while the '++++' configuration, which has already been shown to be adapted to the H-mode (Fig. 2), is also good for the hybrid scenario.

A possible compromise to avoid in-vessel coils but still keep flexibility in the RMPs spectrum would be to fix the RMPs coils on the toroidal field coils, behind the vacuum vessel. Our estimations lead to currents in the coils of about 100–150 kA. However, the details of this design are out of the scope of the present paper.

3. Self-consistent MHD reaction of the plasma to the RMPs

In the work described above, the hypothesis of vacuum field perturbation is made. The JOREK [5] 3D non-linear MHD code (able to include the X-point) allows to check this hypothesis. Simulations are done for a DIII-D-like plasma, and the presence of the I-coils is taken into account by fixing the $n = 3$ harmonic of the poloidal magnetic flux to its vacuum value at the boundaries of the computational domain.

In a simulation with 4 kA in the I-coils (in their even parity configuration) and zero toroidal plasma rotation, the Poincaré plots show no significant modifications of the vacuum magnetic perturbations by the plasma: the hypothesis done above therefore seems correct in that case. On the other hand, similarly to what is observed in [6] for a TEXTOR modelling, structures appear on the $n = 3$ harmonic of the electric potential which produce $\vec{E} \times \vec{B}$ convective cells (Fig. 5). This phenomenon could play a role in the experimentally observed and up to now puzzling density pump-out caused by the I-coils in the low-collisionality experiments [2].

4. Conclusions

Preliminary design studies for ELMs-controlling RMPs systems for ITER show that the two external designs considered here require a significant amount of current: ~240 and 480 kA in H-mode, and much more in hybrid and steady-state discharges, while the in-vessel design only requires ~20 kA, whatever the equilibrium. The question of core perturbations should be considered carefully, the estimated 4/3 islands widths being typically about 8 cm. An MHD self-consistent modelling for the plasma reaction to the RMPs has been started. The first simulations show no significant screening or enhancement of the RMPs by the plasma, but an $\vec{E} \times \vec{B}$ convection of density is observed which could explain the up to now puzzling density pump-out caused by the I-coils in DIII-D's low-collisionality experiments.

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