Penetration of Resonant Magnetic Perturbations at the Tokamak Edge

A. Monnier[1], G. Fuhr[1], P. Beyer[1], S. Benkadda[1], X. Garbet[2]
[1] *PIIM, UMR 6633, CNRS-Université de Provence, Marseille*
[2] *CEA, IRFM,F-13108 St Paul lez Durance, France*

In tokamaks, improved confinement regimes allow to obtain temperatures in the plasma core that are sufficient to produce self-sustained nuclear fusion reactions. A key ingredient of these regimes is a so called transport barrier, i.e. a radially thin layer where turbulent transport of heat and matter is significantly reduced. Moreover, the pressure gradient is strongly increased in this layer. At the plasma boundary, the transport barrier typically is unstable and exhibits quasi-periodic relaxation oscillations associated with high energy flux peaks that eventually can damage the tokamak wall. These barrier relaxations are an essential characteristics of the so-called Edge Localize Modes (ELMs) [1]. The control of these modes is a critical issue for the next generation of experimental reactors such as ITER. Many studies on a variety of tokamaks such as DIII-D [2], JET [3] and TEXTOR [4] reveal a qualitative control of ELMs by imposing external Resonant Magnetic Perturbations (RMPs) at the plasma edge. These RMPs change the magnetic topology at the plasma edge.

The control of transport barrier relaxations by RMPs is generally due to a reduction in pressure gradient by a radial energy flux [5]. When increasing the RMP amplitude, the efficiency of ELMs control is enhanced. This property is generally attributed to the appearance of field line stochasticity, induced by overlapping of magnetic islands [5]. However, it is not clear to which extend the externally induced perturbation actually penetrates into the plasma. Indeed, in magnetohydrodynamical (MHD) modeling, an effective screening of the resonant magnetic perturbations by the rotating plasma has been observed [6, 7].

In previous works, barrier relaxations have been studied by three-dimensional edge turbulence simulations and the possible control of these relaxations by externally induced RMPs has been investigated [8, 9]. These works are based on an electrostatic turbulence model and the magnetic perturbation is imposed everywhere in the plasma. Here, we use a generalization of this model taking into account self-consistent electromagnetic fluctuations [10], and induce the RMP only at the plasma boundary. The goal is to study the penetration of these externally induced RMP into the plasma and to investigate their effect on transport barrier relaxations.

The model equations for the plasma pressure p, the electrostatic potential ϕ and the magnetic flux ψ are the following :

$$(\partial_t + \vec{\mathbf{u}}_E \cdot \nabla)\,\nabla_\perp^2 \phi = -\frac{1}{\alpha}\nabla_\parallel \nabla_\perp^2 \psi - \mathbf{G}p + \nu\nabla_\perp^4 \phi \ , \tag{1}$$

$$(\partial_t + \vec{\mathbf{u}}_E \cdot \nabla)\, p = \delta_c \mathbf{G}\phi + \chi_\parallel \nabla_\parallel^2 p + \nabla_\perp \cdot (\chi_\perp(x)\nabla_\perp p) + S(x) \ , \tag{2}$$

$$\partial_t \psi = -\nabla_\parallel \phi + \frac{1}{\alpha}\nabla_\perp^2 \psi + \lambda\,(x)\,(\psi_{RMP} - \psi) \ . \tag{3}$$

Equation (1) corresponds to vorticity equation, where $\nabla_\perp^2 \phi$ is the vorticity of the $\mathbf{E}\times\mathbf{B}$ flow, $\vec{\mathbf{u}}_E \cdot \nabla$ represents the advection by the $\mathbf{E}\times\mathbf{B}$ drift, $\nabla_\perp^2 \psi$ is the parallel current fluctuations, α is proportional to the plasma β, i.e. the ratio of kinetic to magnetic pressure. $\mathbf{G}$ is the magnetic curvature operator and ν the viscosity coefficient. Equation (2) corresponds to the energy conservation, where $\chi_\parallel$ and $\chi_\perp$ are the collisional heat diffusivities parallel and perpendicular to the magnetic field, δ_c is a curvature parameter, and $S(x)$ is an energy source modeling the constant heat-flux from the plasma core. Equation (3) corresponds to the Ohm's law. Simulations of this model are performed with the EMEDGE3D code [10]. Following the standard convention, x, y, z represent the normalised local radial, poloidal and toroidal coordinates, respectively. The parallel and perpendicular gradients (to the unperturbed magnetic field) are defined by $\nabla_\parallel = \partial_z + \frac{\kappa_z}{q(x)\kappa_y}\partial_y - \{\psi,\cdot\}$ where $\{\psi,\cdot\} = \partial_x\psi\partial_y\cdot - \partial_y\psi\partial_x\cdot$ and $\nabla_\perp^2 = \partial_x^2 + \partial_y^2$. Here, $q(x)$ is the safety factor and κ_y and κ_z are the minimal poloidal and toroidal wave numbers. The main computational domain corresponds to the volume delimited by the toroidal surfaces characterized by $q = 2.5$ and $q = 3.5$ (see Fig. 1c, shaded region). Additional buffer zones are added on both sides. The perpendicular heat diffusivity $\chi_\perp(x)$ is artificially increased in these regions (see Fig.1b) and the energy source $S(x)$ (see Fig.1a) is located in the inner buffer region.

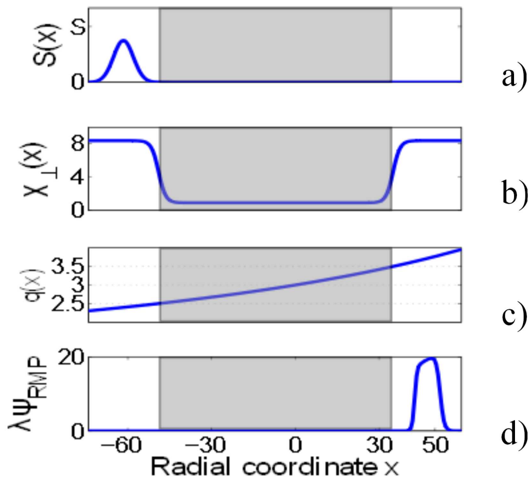

Figure 1: Radial profiles of the energy source $S(x)$ (a), the perpendicular diffusion $\chi_\perp$ (b), the safety factor (c)and the magnetic perturbation forcing $\lambda(x)\psi_{m_0}(x)$ (d) as a function of the normalized coordinate x. The shaded region indicates the main computational domain between $q = 2.5$ and $q = 3.5$.

As a first step towards the simulation with the EMEDGE3D code of the plasma response to an external magnetic perturbation, we define here the numerical technique to impose this perturbation at the plasma boundary, study its penetration into a vacuum, and compare the result with the analytical solution. In previous studies in an electrostatic model [8, 9], the following magnetic flux perturbation was imposed in the plasma, motivated by the perturbation from the DED in the TEXTOR tokamak [11],

$$\psi_{RMP}^{single} = \psi_{m_0}(x)\cos(m_0\kappa_y y - n_0\kappa_z z) \qquad \text{with} \qquad \psi_{m_0}(x) = \hat{\psi}\exp\left(\frac{m_0\xi_{bal}}{\beta_1 r_c}x\right)\times F(x).$$

Here, $(m_0, n_0) = (12, 4)$ is the main harmonic of the perturbation which is resonant at $q = q_0 = 3$, ξ_{bal} is the perpendicular normalisation length, β_1 and r_c are geometrical parameters of the RMP coils. The function $F(x)$ is equal to 1 in the main region, and decreases to 0 in the buffer regions such that $\psi_{m_0} = 0$ at the boundaries. In the present study, we impose the same magnetic perturbation at the plasma boundary only, by choosing the forcing coefficient $\lambda(x)$ to be non-zero only in the external buffer region $x > x_{q=3.5}$,

$$\lambda(x) = \lambda_0 \left\{ \frac{1}{2} \tanh\left[\sigma\left(x - x_{q=3.5} - \Delta\right)\right] + \frac{1}{2} \right\} . \tag{4}$$

The coefficients λ_0, σ and Δ are chosen conveniently and the profile of $\lambda(x)\,\psi_{m_0}(x)$ is shown in Fig.1d) . In the main computational domain, $\lambda(x) = 0$ and the magnetic perturbation evolves self-consistently following equations (1-3). As a test case, we calculate here the penetration of the magnetic perturbation in vacuum, i.e. for $\nabla_{\|}\phi = 0$ in Ohm's law (3). Furthermore we study the effect this magnetic perturbation on the equilibrium pressure field. The subset of equations (1-3) used for this study is :

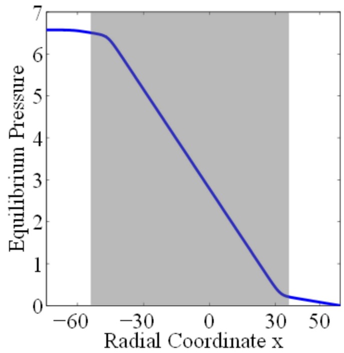

Figure 2: Equilibrium pressure profile.

$$\partial_t p = \chi_{\|}\nabla_{\|}^2 p + \nabla_{\perp}\cdot\left(\chi_{\perp}(x)\nabla_{\perp} p\right) + S(x) , \tag{5}$$

$$\partial_t \psi = \frac{1}{\alpha}\nabla_{\perp}^2\psi + \lambda(x)\left(\psi_{RMP} - \psi\right) . \tag{6}$$

Starting from noise, the pressure and magnetic flux evolve to a steady state, where the axisymetric pressure profile (see Fig.2) is the determined by the source $S(x)$ and the $\chi_{\perp}(x)$ coefficient. The magnetic flux in the main computational domain is determined by the vacuum relation $\nabla_{\perp}^2\psi = 0$. Using the boundary conditions $\psi_0 = \psi\left(x = x_{q=3.75}\right)$ and $\psi(x = x_{min}) = 0$, the magnetic flux can be compared to the analytical solution (see Fig.3a) :

$$\psi(x) = \psi_0 \frac{\sinh\left(m_0\kappa_y\left(x - x_{min}\right)\right)}{\sinh\left(m_0\kappa_y\left(x_{q=3.75} - x_{min}\right)\right)} . \tag{7}$$

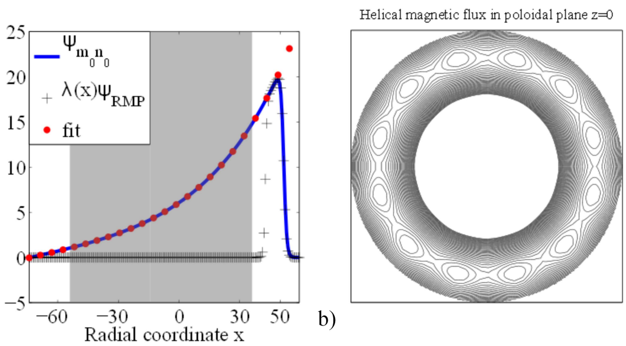

Figure 3: a) Radial profiles of $\psi_{m_0 n_0}$ in the steady state (in blue), $\lambda(x)\,\psi_{m_0}(x)$ (crosses) and the analytical solution (red points). b) Helical magnetic flux in the poloidal plane z=0.

Due to the parallel heat conductivity in equation (5), the magnetic perturbation induces helical variation of the equilibrium pressure. The profile of the (m_0, n_0) component of the equilibrium pressure is show in Fig.4a) . Comparing the pressure perturbation in the poloidal plane (see

Fig.4b) with the contours of the helical flux (see Fig.3b), it becomes evident that the equilibrium pressure gradient is flattened on the O-points and steepened on the X-points of the magnetic islands [12].

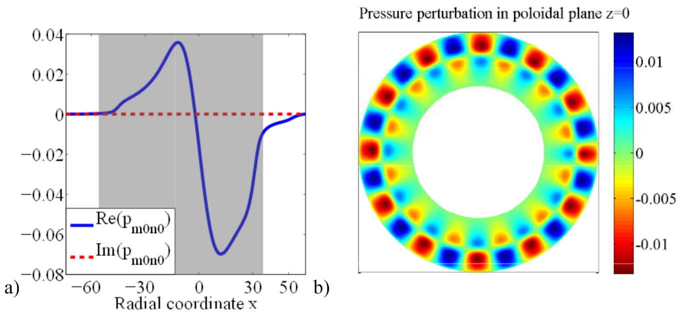

Figure 4: Radial profile (a) and representation in a poloidal plane (b) of the helical variation of equilibrium pressure.

To conclude, we have calculated with the EMEDGE3D code the penetration of an external RMP in the vacuum case and the pressure response to this magnetic perturbation. The result is in agreement with the analytical solution for the vacuum magnetic flux. The variation of the equilibrium pressure reproduces the well known flattening of the pressure gradient on the O-points of magnetic islands. This work represents a first step for the study of the penetration of externally induced RMPs into the plasma and the investigation of the effect on transport barrier relaxations. The aim is to complete previous studies performed in electrostatic approximation of the model reproducing the control of barrier relaxations by RMPs[8, 9].

References

[1] Connor J W 1998 *Plasma Phys. Control. Fusion* **40** 531

[2] Evans T E *et al* 2004 *Phys. Rev. Lett.* **92** 235003

[3] Liang Y *et al* 2007 *Phys. Rev. Lett* **98** 265004

[4] Finken K H *et al* 2007 *Nucl. Fusion* **47** 522

[5] Bécoulet M *et al* 2005 *Nucl. Fusion* **45** 1284

[6] Nardon E, Bécoulet M, Huysmans G and Czarny O 2007 *Phys. Plasmas* **14** 092501

[7] Reiser D and Chandra D 2009 *Phys. Plasmas* **16** 042317

[8] Leconte M, Beyer P, Garbet X and Benkadda S 2009 *Phys. Rev. Letters* **102** 045006

[9] Beyer P, De Solminihac F, *et al* 2011 *Plasma Phys. Controlled Fusion* **53** 054003

[10] Fuhr G, Beyer P, Benkadda S and Garbet X 2008 *Phys. Rev. Lett.* **101** 195001

[11] Abdullaev S S, Finken K H, *et al* 2003 *Nucl. Fusion* **43** 299

[12] Fitzpatrick R 1994 *Phys. Plasmas* **2** 825