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Controlled dynamics of neoclassical tearing modes in a sheared flow

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Introduction

The plasma energy confinement and maximum operational plasma β_p in tokamaks are strongly limited by the onset of Neoclassical Tearing Modes (NTMs). These modes, stable at low β_p, are excited by the reduction of the bootstrap current within the island as a result of a local pressure flattening. The problem of stabilization of magnetic islands has been largely investigated using schemes based on the Electron Cyclotron Current Drive (ECCD) [1]. On the other hand in realistic conditions of operation of high performance tokamaks, the plasma is rotating with a velocity profile that may influence both the equilibrium, through centrifugal force contributions, and the stability of MHD perturbations. Asymmetric deformation of the magnetic islands may arise due to the effect of the stress associated with the sheared viscous flow; the deformation is described by an amplitude correction term and a radially non uniform dephasing factor [2]. We reconsider the reconnection process in rotating plasma considering that the geometric deformations of the island flux contours, due to the sheared flow are equivalent to additional parallel current that affects the island dynamics. A new generalized Rutherford evolution equation is obtained that includes the modifications of the growth time scales and of the helical ECCD efficiency, both depending on the island deformation. The dynamics of the free and controlled system is discussed by an analysis of the region of metastability in the phase space (W, dW/dt). Important consequences are found for the estimate of the value of rf power needed for NTM quenching and for the definition of strategy of control.

Deformed magnetic island geometry

Sheared plasma velocity can deform the magnetic field lines reconnected in closed surfaces by the tearing resistive instabilities around helical current filaments on q=m/n rational surfaces, being m and n the poloidal and toroidal mode numbers. Viscous forces drive a parallel current prone to modify the island shape through an amplitude first order correction factor Δ'_c and a dephasing factor Δ'_s both depending on the plasma perpendicular viscosity ν [3]. The contour levels of a deformed island can be represented in a coordinate system (r, ϑ, φ) by:

$$\Psi(x,\xi) = -2\frac{x^2}{W^2} + \psi_s(1+\frac{1}{2}\Delta'_c x)\cos(\xi - \frac{1}{2}\Delta'_s x) \quad \text{with} \;\; x = \frac{W}{4\,Q}\Big[\big[A\big] \pm \sqrt{A^2 + 2Q\big[\Omega + \cos\xi\big]}\Big]$$

where W is the full island width, $\xi=m\vartheta-n\varphi$ is the helical angle with ϑ the poloidal angle and φ the toroidal one, $x=r_s-r$ the distance from the rational surface q=m/n, ψ_s the perturbed reconnected flux proportional to W^2, and $A=W\Delta'_c/8\cos\xi+ W\Delta'_s/8\sin\xi$, $Q=1+(W\Delta'_s/8)^2\cos\xi-W^2(\Delta'_c\Delta'_s/32)\sin\xi$, where $\Omega=\Psi/\psi_s$ is the normalized label of the isobaric flux tubes (Ω=-1 at the island elliptic O-point, Ω=1-symmetric fluxes- and Ω<1-asymmetric fluxes- at the iperbolic X-point). Since the perpendicular viscosity ν may have a wide range of values in the different collisionality regimes we choose to consider in this study Δ'_s and Δ'_s as free parameters assuming $0.5\Delta'_c x<1$ and $0.5\Delta'_s x<1$. In **Fig.1** we plot three separatrices for symmetric and deformed in amplitude and in phase islands. Note that the O-point for deformed islands not necessary lies on r_s. The time evolution of the perturbed flux over the full island region is computed by performing nonlinear averages and integrations in the plane (Ω,ξ) for any f function on any contour Ω according with the expressions:

$$\langle f\rangle = \frac{\oint d\xi\;\, f/(\partial\Omega/\partial x)/2\pi}{\oint d\xi/(\partial\Omega/\partial x)/2\pi} \quad \text{with} \quad \partial\Omega/\partial x = \sqrt{A^2 + 2Q\big[\Omega + \cos\xi\big]}$$ and then for all the fluxes projected along the parallel current direction:

$$r_s\frac{W}{4}\frac{\partial\psi_s}{\partial t}\left[\int d\Omega\left\langle(1+\frac{1}{2}\Delta'_c x)\cos(\xi-\frac{1}{2}\Delta'_s x)\right\rangle\cos\xi/\sqrt{A^2+2Q\big[\Omega+\cos\xi\big]}/2\pi\;\right] = r_s\frac{W}{4}\frac{\partial\psi_s}{\partial t}\big[g_1\big]$$

here g_1 is the inertial coefficient associated with the island geometry. For a symmetric island g_1=0.82 (traditional value) while g_1= $g_1(W)$ for asymmetric shapes.

Effects of asymmetric island on the NTM evolution

The deformation of a symmetric island can produce new effects on the terms of the island evolution equation acting on the NTM stabilization. We propose a new form of the generalized Rutherford equation including the new inertial factor g_1 and a new expression for the non-inductive term Δ'_{EC}, associated with the injected electron cyclotron (EC) power, taking into account the deformation factors. This new nonlinear evolution equation reads as:

$$g_1\big(W\big)\frac{\tau_R}{r_s}\frac{dW}{dt} = \Delta'_0 r_s + \beta_p r_s\big[\Delta'_{BS} - \Delta'_{GGJ} - \Delta'_{pol}\big] - r_s\Delta'_w - r_s\Delta'_{EC}\, f\big(\Delta'_c,\Delta'_s\big)$$

where Δ'_0 is the usual stability parameter, Δ'_{BS} is associated to the bootstrap current, Δ'_{GGJ} is related to the equilibrium pressure gradient and curvature, Δ'_{pol} is related to the ion polarization current, Δ'_{wall} is due to the action of a resistive wall. Modifications of the growth rate of the NTM magnetic island are expected to occur when $g_1(W)$ changes from its value for symmetric shape. In **Fig.2** phase space diagrams (W, dW/dt) are sketched to show the effects of the deformation factors Δ'_c and Δ'_s on the island evolution for an ITER-like plasma. The region of positive island growth decreases for $g_1(W) > 0.82$ corresponding to $\Delta'_c \neq 0$: the effect is the increase of the resistive time, keeping the island width smaller for a longer time; for $\Delta'_s \neq 0$, $g_1(W)$ is slightly different from the value of symmetric island: the corresponding growth rates look similar. Reduction of the positive growth rate up to zero or negative values can also be obtained switching on an external heat source such as that from the EC waves injection. In such a way a non-inductive current parallel to the magnetic field lines can be driven as an additional contribution replacing the reduced bootstrap current and controlling the island growth. A conventional expression for the ECCD Δ'_{EC} term is:

$$\Delta'_{EC} = 8\frac{32}{\pi} r_s \frac{I_{EC}}{I_p(r_s)} \frac{L_q}{\delta^2{}_{EC}} \frac{1}{\left(\delta_{EC}/r_s + 2\sqrt{\pi}\right)} \eta(\overline{W}, \Delta'_c, \Delta'_s) \quad \text{with} \quad \eta = \int_{-1}^{\infty} d\Omega \int_{-\xi_{min}}^{+\xi_{max}} \frac{d\xi}{\partial\Omega/\partial x} \langle J_{EC}\rangle \cos\xi \,/ \int \frac{d\xi}{\partial\Omega/\partial x} \langle J_{EC}\rangle$$

where I_{EC} is the total EC current driven in the island region, $I_p(r_s)$ the plasma current at r_s location, δ_{EC} full radial width of the current channel, $\overline{W}=W/\delta_{EC}$ and $\eta(\overline{W}, \Delta'_c, \Delta'_s)$ is the helical current drive efficiency in the island region inside ξ_{min}, ξ_{max}. The J_{EC} current profile is modelled by: $J_{EC} = J_0 \exp(-((x - x_0)/\delta_{EC})^2 \Pi(\xi_0, \Delta\xi)$ where J_0 is the peak value, (x_0 ξ_0) are the coordinates of the applied EC wave beam peak in the island frame in a $\Delta\xi$ range: $\Pi(\xi)=1$ EC on, $\Pi(\xi)=0$ EC off. **Fig.3** shows the helical current drive efficiency for the symmetric and asymmetric island for continuous (CW) and modulated EC waves injection and **Fig.4** the corresponding phase space still obtained for an ITER-like plasma equilibrium. The phase space shows how the NTM control significantly depends on the island shape.

Control strategy and conclusions

The helical ECCD efficiency has been found higher than its value for symmetric island when a dephasing or a dephasing and amplitude corrections, applied together, are considered. The EC power needed to full stabilize an asymmetric island in CW regime is about 10-15% less than the power stabilizing a symmetric one. Much more relevant results are obtained in the case with 50% modulated EC injection: the required power to control the deformed islands is less than 55-60% with respect the CW case for symmetric configurations and for symmetric islands about 35-40% less then the same reference case. On the other hand, the deformation due to the sole Δ'_c decreases the efficiency even if the unstable phase region is reduced.

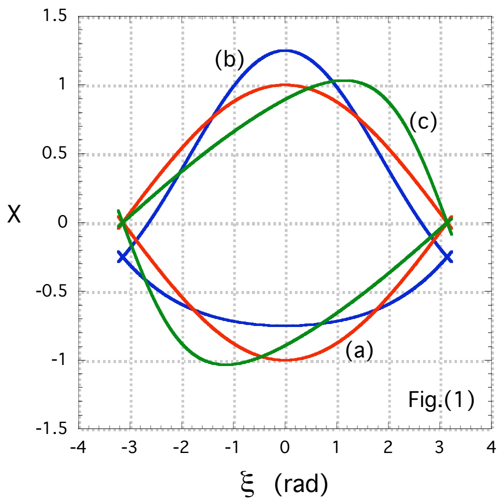

Fig.1: Separatrices for symmetric (a) and asymmetric islands with $\Delta'_c=2$, $\Delta'_s=0$ (b), $\Delta'_c=0$, $\Delta'_s=2$ (c),

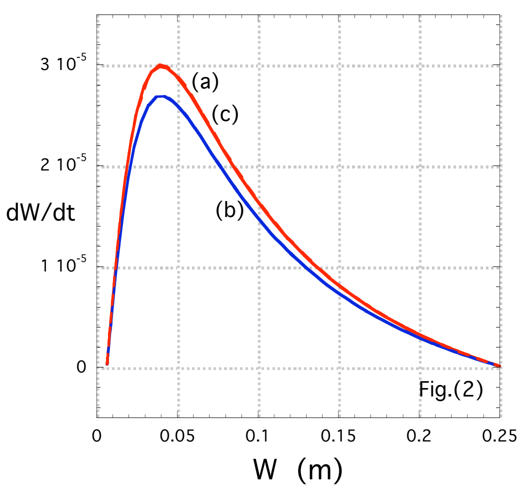

Fig.2:growth rate of islands as in Fig.1. Similar reduction of unstable region is shown for (a) and (c) labelled as before.

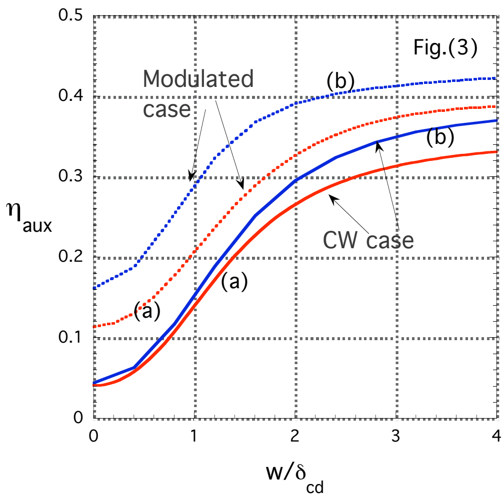

Fig.3:helical efficiency for CW (solid) and modulated case (dots) for (a)symm. and (b) asymmetric, $\Delta'_c\neq0$,$\Delta'_s\neq0$ islands

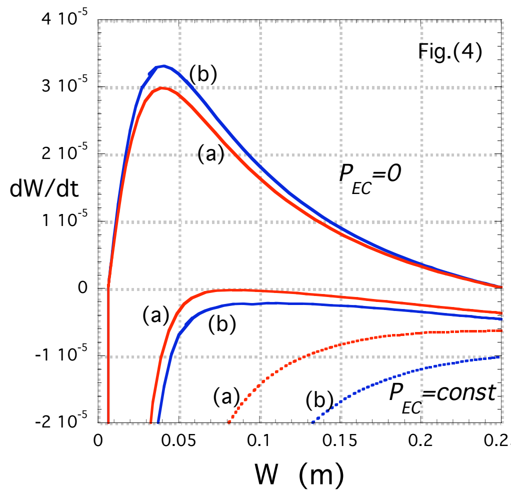

Fig.4:phase space for islands as in Fig.3 and the CW and modulated EC injection. Significant power reduction up to 60% is found for asymm. islands

References

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