Response of a Neoclassical Four-Field Model to Electron Cyclotron Current Drive

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Abstract

The main objective of this work consists in the application of an appropriate set of Extended Magnetohydrodynamics (ExMHD) nonlinear equations for four continuum fields (poloidal magnetic flux ψ, electron pressure p_e, ion flow velocity v_i, and ion flow vorticity U) to study the response of the reconnecting modes in low collisionality regimes to specific inputs of localized external current. New information is gained on the time dependent effects of the external action on the magnetic islands, that is very important to formulate applicable control strategies, and also to help with the interpretation of experimental observations.

The design of means to counteract robustly the *classical and neoclassical* tearing modes in a tokamak by localized injection of an external control current to balance the destabilising field perturbations requires an ever growing understanding of the physical process, beyond the 0-dimensional models of the Rutherford type [1,2,3]. Here we consider a number of questions of principle that can be addressed operating in a simplified (slab) geometry, while retaining the essential physical ingredients. The formulation of reduced ExMHD equations by the scalar four-field model described in Ref. 4,5 is used to investigate the 2D effects in the response to specific inputs of the external current (generated by electron cyclotron waves) aligned with the magnetic island perturbation, and suitably modulated in time. A systematic inclusion of neoclassical effects comprises the bootstrap current density J_{bs} and same order contributions of pressure anisotropy $p_\Delta \equiv p_\parallel - p_\perp$ to the equations for parallel vorticity, parallel momentum and energy [6]. The model is given by the following equations [4,5]:

$$\frac{\partial \psi}{\partial t} + \frac{1}{B_0}\{\phi,\psi\} = \frac{1}{enB_0}\{p_e,\psi\} - \eta_{NC}\left(J_\parallel - J_{bs} - J_{EC}\right) + \mu_e \nabla^2 J_\parallel \tag{1}$$

$$\frac{\partial U}{\partial t} + \frac{1}{B_0}\{\phi,U\} = \frac{1}{m_i n}\{J_\parallel,\psi\} + \frac{\mu_0(1+\tau_T)}{m_i n B_0^2}\left(J_\parallel\{\psi,p_{e\Delta}\} + p_{e\Delta}\{\psi,J_\parallel\}\right) + \mu_\perp \nabla^2 U \tag{2}$$

$$\frac{\partial v_{i\parallel}}{\partial t} + \frac{1}{B_0}\{\phi,v_{i\parallel}\} = \frac{(1+\tau_T)}{m_i n B_0}\left(\{\psi,p_e\} + \frac{2}{3}\{\psi,p_{e\Delta}\}\right) + \mu_\parallel \nabla^2 v_{i\parallel} \tag{3}$$

$$\frac{\partial p_e}{\partial t}+\frac{1}{B_0}\{\phi,p_e\}=\frac{1}{B_0}\left(\frac{5}{3}p_e+\frac{4}{9}p_{e\Delta}\right)\{\psi,v_{i\|}-J_{\|}/en\} \tag{4}$$

where $\{f,g\}\equiv\hat{z}\cdot\vec{\nabla}f\times\vec{\nabla}g$ are the Poisson brackets, and the symbols ϕ, e, n, m, μ_0, τ_T, denote respectively the electrostatic potential, electron charge, particle number density, mass, free-space permeability and ion/electron temperature ratio. Furthermore, B_0 is the toroidal magnetic field on the magnetic axis, η_{NC} is the neoclassical resistivity [7], μ_e, $\mu_\perp$, $\mu_\|$ are small viscosity terms, $J_\|=\nabla^2\psi/\mu_0$, $U=\nabla^2\phi/B_0$, and J_{EC} represents the Electron Cyclotron Current Drive (ECCD) that can be modelled by time dependent amplitude with a Gaussian profile of width dictated by the absorption depth δ_{EC} [4,5]:

$$J_{EC}=j_{EC}(t)\exp\left(-\frac{(\psi-\psi_0)^2}{\delta_{EC}^2}\right) \tag{5}$$

Finally, the neoclassical closure used for this ExMHD model is the following [4,5]:

$$p_{e\Delta}=\frac{\nu_e m_e n\mu_{00}^e q}{\varepsilon}\frac{B_0}{\langle\{\psi,B\}\rangle}\left(\frac{\partial\phi}{\partial x}-\frac{1}{en}\frac{\partial p_e}{\partial x}+\frac{1}{3en}\frac{\partial p_{e\Delta}}{\partial x}\right) \tag{6}$$

where the operator $\langle\ \rangle$ denotes the flux-surface average, ν the Coulomb collision frequency, ε the tokamak inverse aspect ratio, μ_{00}^e the (0,0) element of the neoclassical viscous matrix [7], and q the safety factor in the large aspect ratio circular tokamak.

The dimensionless form of equations (1)-(4) was solved in a two-dimensional periodic box $L_x\times L_y$, using a Fourier pseudospectral method for the space variables and a second-order Adams-Bashforth method for the time variable. Production runs were carried out with a 200×200 points grid and time step $\Delta t=1\cdot10^{-3}$. The calculations presented here have been performed in a regime of classical resistive modes with typical parameters: $n=10^{20}\ \#/\mathrm{m}^3$, $T=10^4\mathrm{eV}$, $B=5\mathrm{T}$, $\tau_T=1$, $\beta=1\cdot10^{-3}$, $S=1\cdot10^3$; and small viscous coefficients: $\mu_e=1\cdot10^{-5}$, $\mu_\perp=1\cdot10^{-2}$, $\mu_\|=1\cdot10^{-4}$.

The final nonlinear phase evolution of the fields' rms spectral amplitude for the free system (i.e. in the absence of ECCD) is displayed in Fig. 1(a). At $t=1100\,\tau_A$ the isolines of ψ show that reconnection process has generated a magnetic island in the middle of the slab domain [Fig. 1(b)]. At $t=1180\,\tau_A$ the magnetic island appears considerably enlarged [Fig. 1(c)]. The narrow ECCD pulses (from $t=1100\,\tau_A$ and $30\,\tau_A$ duration) exactly focused on the

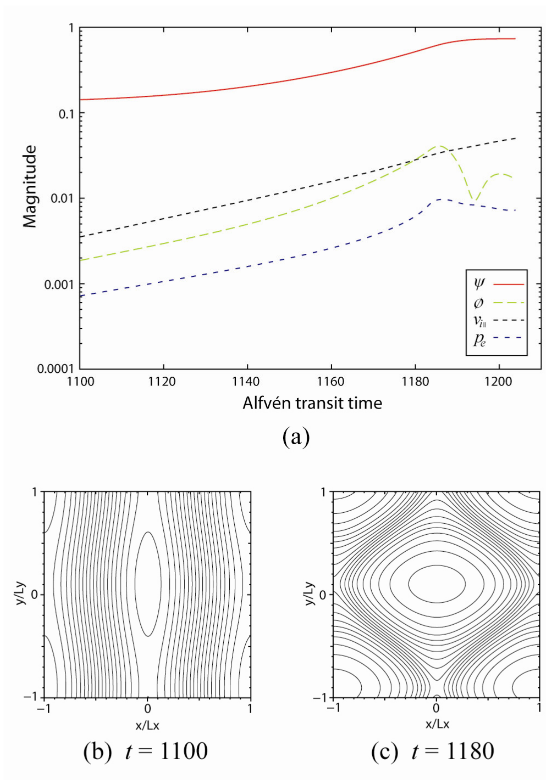

Fig. 1. Time evolution of fields' rms spectral amplitude in the final nonlinear phase for the free system evolution case (a), and isolines of poloidal magnetic flux function ψ (b)-(c)

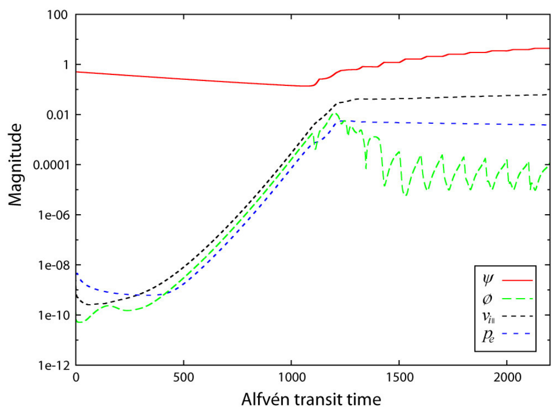

Fig. 2. Time evolution of fields' rms spectral amplitude for the case of narrow ECCD pulses

island elliptic point affects significantly the time evolution of the fields' rms spectral amplitude, as shown in Fig. 2. The contour plots in Figs. 3(a) and 3(b) show the cancellation and the subsequent reappearance of elliptic and hyperbolic points. The 2D description shows that nonlinear reconnection can be limited in evolution by ECCD but not restored reversibly to its initial condition. After a certain time there is not cancellation of the singular points, that are increased by the appearance of a secondary island as displayed in Fig. 3(c), but there is a

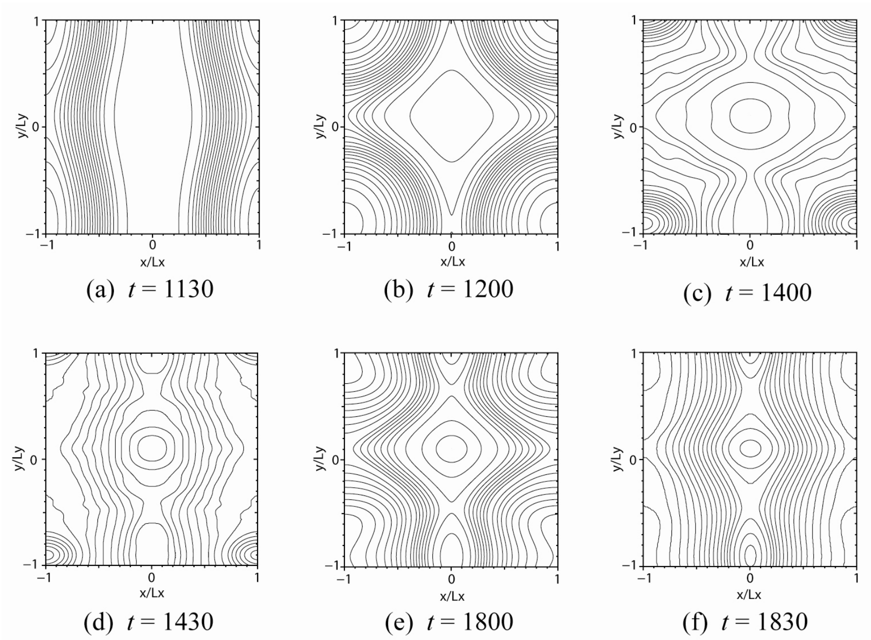

Fig. 3. Isolines of poloidal magnetic flux function ψ showing the magnetic island evolution of the system with narrow ECCD pulses exactly centered on the island elliptic point

reduction of the magnetic islands [Fig. 3(d)] and a stable time behavior are achieved. This process continues [Figs. 3(e) and 3(f)] stretching the life of the system.

In conclusion, the irreversibility of the nonlinear 2D process makes the choice of the control strategy more difficult than suggested by 0-dimensional models [8,9]. In particular a *narrow* current deposition increases the topological complexity with appearance of multiple axis and current sheets, therefore the customary concept of phase matching becomes less robust for effective control of the instability in the nonlinear stage. Instead a more suitable strategy could be based on both an accurate radial focusing and on an intermittent pulsed application of rf power associated with assigned threshold of a relevant state variable.

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