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Open problems of magnetic island control by electron cyclotron current drive

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This paper reviews key aspects of the problem of magnetic islands control by electron cyclotron current drive in fusion devices. On the basis of the ordering of the basic spatial and time scales of the magnetic reconnection physics, we present the established results, highlighting some of the open issues posed by the small-scale structures that typically accompany the nonlinear evolution of the magnetic islands and constrain the effect of the control action.

Key words: fusion plasma, plasma dynamics, plasma instabilities

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Magnetic reconnection is a fundamental process in magnetically confined plasmas, often responsible for sudden relaxation phenomena during which a significant amount of magnetic energy is converted into heat and ordered kinetic energy in a relatively short time. Where a local violation of the ideal 'frozen' magnetic flux condition is possible, the magnetic field lines can be torn and reconnected into a new topological configuration forming closed secondary structures called magnetic islands. In fusion experimental devices, they may have detrimental consequences for energy confinement and, in their nonlinear stage, are often precursors of disruptions of the confined plasma configuration (Waelbroeck 2009).

The ordering of the basic space scales $\rho_e < d_e < \rho_\tau < d_i < \delta_\eta$ (i.e. electron gyroradius, electron skin depth, sound Larmor radius, ion skin depth and resistive layer width) identifies the physical mechanisms associated with the reconnection process: electron pressure tensor and electron inertial effects, ion sound and ion inertial effects, viscosity and drift kinetic effects of deeply trapped particles and resistive diffusion of the perturbed magnetic field (Aydemir 1992; Ottaviani & Porcelli 1993; Cafaro *et al.* 1998; Fitzpatrick & Porcelli 2004; Lazzaro, Comisso & Valdettaro 2010; Liu, Hastie & Hender 2012; Comisso *et al.* 2013, 2016). The onset of magnetic reconnection in fusion devices depends on many factors such as the type of equilibrium current profile, the collisionality and viscosity regime, the β effects (bootstrap and polarization currents), the plasma non-uniform equilibrium rotation and external drives (error fields with helical component resonant with a $q = m/n$ rational magnetic surface, sudden

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radiative cooling, coupling effects with other magnetic perturbations). Moreover, in the neoclassical regime, the tearing modes (NTMs) (Callen *et al.* 1987; Smolyakov *et al.* 1995) present onset thresholds.

It is important to notice that the linear growth of the tearing instabilities depends on the different physical mechanisms driving the decoupling of the magnetic field motion from the plasma one: resistivity, electron inertia, agyrotropy of the electron pressure tensor. In particular, for the relevant case of reconnection processes in the low collisionality regime, the linear growth rate depends on the comparison between d_e and ρ_τ (Grasso *et al.* 2000). This regime may be characterized by a sudden increase in the time derivative of the reconnection rate (Grasso *et al.* 2000; Comisso *et al.* 2013) as nonlinearity takes over the linear phase. For a wide range of d_e values, the peak nonlinear growth is approximately twice the value of the linear one, but it can increase up to one order of magnitude more for very low d_e values (Comisso *et al.* 2013). Besides the cases in which the instability grows spontaneously, it is important to note that in fusion devices the conditions (like error fields or resonant magnetic perturbations) that lead to forced reconnection events may frequently occur. In these cases also the plasmoid instability may develop and its relevant fast time scales must be considered (Loureiro, Schekochihin & Cowley 2007; Comisso *et al.* 2016; Comisso & Grasso 2016). We recall that the relevance of the physical parameters in determining the growth rate of the reconnection process depends also on the magnetic energy available to the system. The smaller this energy the larger the reconnection time scale is. For the spontaneous reconnection process a measure of this energy is given by the so called Δ' parameter (Furth, Killeen & Rosenbluth 1963), while for driven reconnection it depends on the intensity of the forcing (Comisso, Grasso & Waelbroeck 2015).

The magnetic reconnection is then a multiscale phenomenon affecting the evolution of the continuum perturbed magnetic flux $\psi(\boldsymbol{r}, t)$, which can be described in its nonlinear stage with a coarse graining procedure. This procedure, first introduced by Rutherford (Rutherford 1973), consists in evaluating the dynamics of a moment of the (m, n) Fourier component of the field $\psi(\boldsymbol{r}, t)$, normally the island width $W(t)$ corresponding to the amplitude of the observable magnetic perturbation and its phase. Typically, coherent islands correspond to helical magnetic perturbations with low poloidal and toroidal mode numbers, such as classical and neoclassical tearing modes and $m = 1$ resistive kinks (Ara *et al.* 1978). The control of the dynamics of magnetic islands is a major challenge for present and future fusion devices, and its key issue is to prevent modes growth to dangerous amplitudes for the whole duration of a tokamak discharge. Starting from the 1980s, many efforts have been devoted to one of the most promising methods of controlling magnetic islands based on the attempt to drive a current directly into the magnetic island by absorption of radio-frequency (rf) waves at the lower hybrid frequency (Reiman 1983) or at the electron cyclotron frequency (ECCD) (Fisch & Boozer 1980), with a (m, n) helical component counteracting the destabilizing current perturbation. Successful ECCD experiments of NTM control, with different methods, have been carried out in ASDEX Upgrade (Gantenbein *et al.* 2000), JT60U (Isayama *et al.* 2000), FTU (Berrino *et al.* 2006), DIII-D (Petty *et al.* 2004) and EAST (Wang, Ma & Zhang 2016). The main task of a theoretical study of rf control of these tearing instabilities, in the observable nonlinear phase, is the estimate of the necessary driven current, e.g. the rf power necessary to reduce the 'state variable' $W(t)$ and to design real time strategies for the rf launching for an effective power deposition and possible tracking of the moving island. A basic question for the design of a control concept is the order of the fastest and slowest

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time scales of the processes to be controlled (fast reconnection, slow nonlinear growth and saturation, island rotation period), and the associated space scales suggesting how sharp the focusing, radial and/or angular, should be. Moreover, in addition to all the physical scale lengths mentioned above, one has to consider also that the rf-driven current 'forces' another typical scale length, the absorption depth d_{CD}. This length depends only on the wave beam launching and propagation conditions and plasma equilibrium quantities, such as density and temperature.

A generalized equation for the evolution of the island width $W = 4\sqrt{\psi_s L_s / B}$, which includes the effect of the ECCD, can be obtained from the rate of flux reconnection with surface averaging of the Faraday equation and currently goes under the name of generalized Rutherford equations (GRE) (see, e.g. Lazzaro & Ramponi 1996; Giruzzi *et al.* 1999):

$$g_1 \frac{\tau_R}{r_s} \frac{\mathrm{d}W}{\mathrm{d}t} = r_s \left[\Delta'_0 + \frac{(\Delta'_{bs0} - \Delta'_{GGJ0})W}{W^2 + W_c^2} + \frac{\Delta'_{pol0}(\omega - \omega_E)(\omega - \omega_E - \omega_{*i})}{\omega_{*e}^2} \frac{\rho_{\theta i}^2}{W^3} - \frac{I_{CD}}{I_p} \frac{L_q}{d_{cd}^2} \eta_{CD} \left(\frac{W}{d_{cd}} \right) \right]. \tag{0.1}$$

Here, $\eta_{CD} = (\int \mathrm{d}\Omega \int \mathrm{d}\alpha J_{CD} \cos(m\alpha) / \int \mathrm{d}\Omega \int \mathrm{d}\alpha J_{CD})$ is the expression of the ECCD efficiency of the (m, n) helical current (Hegna & Callen 1997; Lazzaro & Ramponi 1996; Giruzzi *et al.* 1999), with $\alpha = \theta - (n/m)\phi$ and J_{CD} indicating the driven current density. This efficiency can be asymptotically estimated to give its dependence on (W/d_{CD}) (Sauter 2004). The quantity W_c in the second (bootstrap current) term represents a lower limit of the island width related to the finite ratio of heat conductivity along and across the B field $(\chi_\parallel/\chi_\perp)$, and governing the incomplete flattening of the temperature profile within the island separatrix (Fitzpatrick & Hender 1994; Fitzpatrick 1995). It is important to recall that the Rutherford equation is derived under the assumption that the linear condition of tearing modes growing slowly with respect to the diffusion time is valid also nonlinerly. For this reason, the Rutherford equation looses its validity as soon as highly nonlinear effects, such as mode–mode coupling, intervene in the evolution of the reconnection process.

In the neoclassical collisional regime, at low β_p, a NTM is linearly and nonlinearly stable. At higher β_p, in the phase plane $(\mathrm{d}W/\mathrm{d}t, W)$ there is an unstable region with $\mathrm{d}W/\mathrm{d}t > 0$. The plasma is metastable without an island, until a 'seed' perturbation (presumably of the same helicity) triggers the growth, proportional to β_p (Callen *et al.* 1987; La Haye 2006). Often the seed island for NTM onset is associated with a sawtooth fast reconnection, providing appropriate resonant harmonics. The third term represents the polarization current due to the inertial ions effect. It depends on the mode rotation frequency and therefore can be stabilizing or destabilizing (Mikhailovskii 2003; Wilson *et al.* 1996). Finally, the last term is the ECCD coercive term, that should make negative or null the whole right-hand side of the GRE, leading to a chosen equilibrium value of W, possibly, but not necessarily, zero.

A control problem could envisage either a prompt intervention to suppress the island of width W as soon as the instability is detected, or a continuous control of a finite island within chosen bounds (Zohm *et al.* 1999; Pletzer & Perkins 1999; Gantenbein *et al.* 2000), or alternatively a time optimal control policy to suppress an island with the maximum power as the mode reaches a target amplitude (LaSalle 1959). Finally, a variant of the latter concept is provided by the strategy of sweeping the ECCD across the q-rational surface (Fevrier *et al.* 2016) to mitigate the consequences of misalignment, which may lead to driven instability. Here we stress again that

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the instability time and space scales mentioned earlier constrain the choice of the best strategy. It is important to have in mind that the injection of a helical electron cyclotron current is accompanied both by a local intense (electron) heating and an axisymmetric current component, which may contribute to the evolution/control of the instability through the modification of the local magnetic shear and of the parameter Δ'_0 (Bertelli & Westerhof 2009). However, it has long been known (DeLuca, Jacchia & Lazzaro 1986) that the direct effect of EC heating and electron cyclotron (EC) current drive on tearing modes is destabilizing if the rf heating is applied on the inner (high field) side of the q-rational surface. Therefore, the radial focusing (relative to the mode elliptic point) of the rf deposition is a control issue (Comisso & Lazzaro 2010; Lazzaro *et al.* 2010). In the following of this paper, we will highlight some of the open physics problems which come from the evolution of the magnetic field topology and require special consideration in view of the realization of working control schemes.

The first aspect that must be underlined is that the equation obtained for $W(t)$ (and the related equation for the island phase (Smolyakov *et al.* 1995; Lazzaro & Ramponi 1996)) necessarily masks several effects on the scales smaller than the island separatrix width. The injected EC current may form a new magnetic topology structure which is not completely symmetric (Comisso & Lazzaro 2010; Lazzaro *et al.* 2010; Sun, Dong & Duan 2015). The optimal localization and the duration of the ECCD pulse depend on the space scale and growth rates of both the fastest reconnection process and the strong nonlinear effect at the later phase. The amplitude of the total required ECCD is expected to be just of the order of the local current perturbation (e.g. $\sim$1.2 times the local bootstrap current density for NTMs (Prater *et al.* 2003)), but the local current density is distributed on the flux tubes intercepted by the beam 'spot' and therefore follows the island nonlinear shape and size evolution. A number of studies (Borgogno *et al.* 2014; Sun *et al.* 2015; Wang *et al.* 2016) have established that the stabilizing effect is inversely proportional to the depostion width, d_{CD}, for the same total driven current.

A second aspect that must be considered is related to new instabilities that may develop during the control itself. These can be for instance generated by an intense driven current, when its deposition depth d_{CD} is narrower than the magnetic island separarix (like triple tearing modes (Wang *et al.* 2016)), while wider d_{CD} leads to improved stabilization, albeit at the cost of reduced rf efficiency. Moreover, the appearance of secondary structures (plasmoids) destroys the concept of 'island phase' to be used in tracking an evolving island in a standard real time feedback control scheme (Volpe *et al.* 2009; van den Brand *et al.* 2012). Recently, simulations carried out for National Spherical Torus Experiment (NSTX) together with analysis of camera data directly from the experiment have proved the formation for plasmoids also in presence of a large guide field (Ebrahimi & Raman 2015). Other studies in this direction (Ishii, Azumi & Smolyakov 2007) have shown that the rapid growth of the magnetic island is associated with its deformation that leads to the secondary magnetic island formation around the original X-points.

Furthermore, the control efficiency of the ECCD well focused on the island O-point may be significantly reduced due to a magnetic topology transition occurring when the primary island is squeezed below the relevant scale of the reconnection layer. Under these circumstances, an unstable ideal MagnetoHydroDynamic (MHD) state is restored in which the X- and O-points have switched their positions and the field lines do reconnect, in a bifurcated configuration equivalent to a phase flip of π on an inertial time scale (Borgogno *et al.* 2014; Fevrier *et al.* 2016), with total loss of control.

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Also the injection of a current drive into a nonlinear island can be compromised by topological modifications. Indeed, the island nonlinear response to the ECCD leads to thin, bar-shaped velocity layers distributed along the axes, where the higher-order harmonics drive secondary Kelvin–Helmholtz instability, which affects the strong sheared plasma flows that form at the initial stages of the control process (Borgogno *et al.* 2014).

Finally, we highlight another aspect, related to the second term in (0.1), that would require a deeper insight. Indeed, in the low collisionality regime, neoclassical viscosity affects the stability of magnetic islands by providing an additional source of the transverse electric current contributing to the net longitudinal current in the magnetic island. It has been shown (Smolyakov & Lazzaro 2004) that the additional current is associated with variations of plasma pressure (temperature) within the perturbed magnetic surfaces. These effects may provide a significant stabilizing influence that is comparable to the ion polarization current and finite $\chi_{\parallel}/\chi_{\perp}$ effects considered previously. Such variations can be expected from the ion polarization drift across the magnetic surface and by the finite parallel heat conductivity.

In conclusion, the description of the magnetic islands evolution by a GRE or a set of coupled GREs is a robust tool for the design of control algorithms, but the choice of control strategies requires consideration of finer, but strong, nonlinear effects related to the fragile topology of the reconnection layer. Further development of basic theory appears crucial in providing guidance toward a reliable system.

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