Predicting the Behavior of Magnetic Reconnection Processes in Fusion Burning Plasma Experiments

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Abstract: Critical stability issues involving magnetic reconnection, which are likely to influence the successful operation of burning plasma experiments, are addressed. In particular, we discuss: 1) sawtooth oscillations; 2) nonlinear tearing mode stability, including neo-classical effects; 3) reconnection near the X-points of magnetic separatrices.

1. Introduction

Magnetic reconnection is a well known process in magnetically confined plasmas, both in space and in laboratory experiments. It is quite exciting that near-future burning plasma experiments, such as ITER-FEAT, will enter new regimes where a variety of kinetic effects on reconnection are expected to become important. These experiments will provide a test bed for existing theories and will most likely change our views of how reconnection works. At the same time, there are a number of crucial stability issues that involve reconnection, which are likely to influence the successful operation of burning plasma experiments. The issues that we address in the present paper are: 1) sawtooth oscillations; 2) nonlinear tearing mode stability, including neo-classical effects; 3) reconnection near the X-points of magnetic separatrices. The last issue is relatively new: we present a case for possible reconnection activity affecting the structure of the magnetic separatrix.

2. Sawtooth Oscillations

Sawteeth are plasma relaxation oscillations in the core, extending somewhat beyond the radius where the magnetic winding index, q, equals unity. With the exclusion of the so-called advanced tokamak scenarios, where q may be maintained above unity by intense current drive and the optimization of the bootstrap current, all standard scenarios, where burning plasma conditions are projected, call for large plasma currents, relatively low values of q at the plasma edge and as a consequence rather wide regions where $q(r)$ falls below unity, with the $q = 1$ radius approaching half of the plasma minor radius on the resistive diffusion time scale. Note that this is true for ITER-FEAT as well as for other burning plasma experiments under consideration, such as FIRE and IGNITOR. The implication for all these devices is that sawtooth activity under these conditions may seriously degrade the plasma confinement. Indeed, the amplitude of the sawtooth crash can become quite large, so that the coupling of the dominant $m = 1$ mode with higher poloidal harmonics becomes important. These harmonics, which extend all the way to the edge, may trigger neoclassical tearing modes and ELMs, resulting in a net loss of plasma energy and alpha particles at each relaxation event. In addition, if confinement relies on peaked profiles, a large sawtooth may quench the burning phase.

Two strategies are considered to avoid the deleterious effects of large sawteeth on plasma confinement. The first is to reach burning conditions before the first sawtooth crash. This is the strategy adopted in IGNITOR [1]. It may work in ITER-FEAT as well, as simulations based on the sawtooth trigger model developed in Ref. [2] indicate that, if a significant population of alpha particles are produced early on during the discharge, these particles will prevent the occurrence of sawtooth crashes for as long as the plasma current has not fully penetrated. The current penetration time in a hot plasma with the size and the density of ITER-FEAT is rather long. Thus, the first sawtooth crash may occur after perhaps 50 seconds from the start of the current flat top, i.e. after several expected confinement times, allowing for steady burn at least as far as the plasma thermal energy is concerned [2]. The problem remains if the objective in ITER-FEAT is to prolong the burning phase on the time scale of the current penetration. In this case, a better strategy may be to induce frequent sawtoothing, for instance by localized current drive resulting in an increase of the local magnetic shear near the $q = 1$ surface. In this way, one may prevent the $q = 1$ radius to grow large, so that the sawtooth amplitude will remain small. These conclusions are drawn on the basis of a model for the sawtooth crash and amplitude [2], which incorporates the present understanding on the linear stability of $m = 1$ modes in relevant plasma regimes. This model has also been applied to the simulation of sawteeth in various tokamaks, such as FTU [3], TCV [4] and JET [5], with satisfactory results.

In order to check the consistency of this model with the various aspects of the sawtooth activity, we have recently developed a code, called M1TEV [6], which is based on $m = 1$ magnetic reconnection. This model follows the evolution of the plasma temperature and density in the presence of particle and heat sources. The first applications of this model successfully reproduced the humpback relaxation behaviour observed in ECRH heated discharges in T-10 and in TCV [7, 8]; it also provided a possible interpretation for the multi-peaked temperature profiles (so called filaments) that were observed in RTP and in TEXT [6].

We now present an application of the M1TEV code, capable of reproducing aspects of sawtooth behaviour in FTU. Figure 1 displays peculiar soft X rays traces of a FTU discharge with pellet injection and Ohmic heating. Four sawtooth crashes can be clearly recognized. On the line integration chord passing at a distance $z = 5$ cm $\sim r_{inv}/2$ from the original magnetic axis, the oscillations survive through the sawtooth crash, indicating incomplete reconnection. A frequency doubling appears towards the end of the last two periods for $z = 11cm \approx r_{inv}$, while the oscillations disappear at $z = 12$.

These traces can be explained by a modification [6] of the sawtooth Kadomtsev model [9], implemented in the M1TEV code in order to account for incomplete reconnection. During one sawtooth period, the displacement ξ of the magnetic axis grows up to $\xi_{max} < r_{mix}$ ($r_{mix} =$ Kadomtsev mixing radius), and then goes back to a small value. Furthermore, the density, which was kept flat in [6], is now evolved as a consequence of particle diffusion and the mixing of helical flux surfaces, $\Psi_\star = const$, according to

$$n_e(A(\Psi_\star)) = \pi \left[n_e(r_{2sp}^2) dr_{2sp}^2/dA - n_e(r_{1sp}^2) dr_{1sp}^2/dA \right] . \qquad (1)$$

Here, A is the poloidal cross-sectional area of the helical magnetic contours, r_{1sp}, r_{2sp} are the radii of the $m = 1$ internal and external circles forming the island separatrix, respectively.

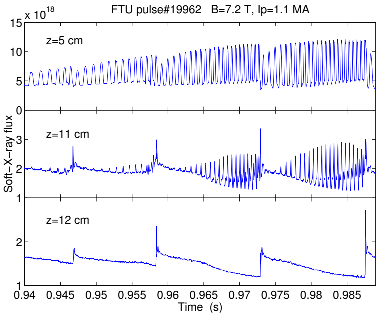

Fig.1 Soft X rays traces for different impact parameters z.

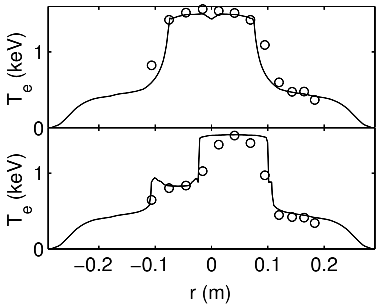

Fig.2 Calculated T_e profiles superimposed to the observed ones (circles) at $t = 0$ (i.e. just after pellet ablation) and 25 s.

During the simulations, starting from the experimental profiles and in particular an off-axis source of particles associated with the injected pellet near the initial $q = 1$ radius, we observe an inward flux of particles due to the reconnection of helical flux tubes, with the density becoming peaked within the island core. Note that impurities, which radiate strongly, are also expected to become trapped within the island core. The simulated soft X ray traces display the frequency doubling observed in Fig. 1, due to the successive passage of the island (dense and cold) and the core (hot but less dense). Incomplete reconnection is necessary to reproduce the experimental traces, otherwise the density profile would be flattened by the crash. Evidence of particle trapping within the core of the $m = 1$ island can also be found in the asymmetric experimental T_e profiles (Fig. 2), which can be interpreted as a reduced electron temperature inside the island following the density becoming peaked in that region [10].

The success of the M1TEV model in the interpretation of different sawtooth aspects lends confidence to sawtooth predictions based on the analysis of $m = 1$ reconnecting behaviour.

The sawtooth crash is another important scientific issue. Experiments in JET, FTU and other machines have revealed that the crash phase is shorter than the mean electron-ion collision time. Recent advances in collisionless reconnection indicate that the sawtooth crash may proceed on a time scale determined by a combination of the electron skin depth and the ion sound Larmor radius, which compares favorably with the experimental data (see, e.g., Ref. [11]). This theory also indicates that an explosive (i.e., super-exponential) phase occurs during the early nonlinear stage of the growth of an $m = 1$ magnetic island [12]. The nature of the collisionless reconnection process has also been clarified in a recent work, where it is shown that spatial phase mixing of conserved Lagrangian fields associated with the collisionless fluid dynamics replace dissipation in allowing for the irreversible growth and saturation of unstable magnetic islands [13].

3. Nonlinear Tearing Modes

It is well known that electron pressure gradient effects influence significantly the evolution of the tearing mode. In particular, in the so-called drift-tearing regime, the unstable mode acquires an oscillation frequency determined by the electron drift-wave frequency and the growth rate is significantly reduced [14, 15].

Recently, we have investigated the stability of these modes in the weakly-collisional regime, where the electron drift-wave frequency, ω_*, is larger than the electron-ion collision frequency, ν_{ei} [16]. We have found instability at values of the Δ' stability parameter above the threshold

$$\Delta'_{cr} \approx \alpha (L_s/L_n)^{1/2} \beta/\rho_s, \tag{2}$$

where $\alpha = 3$ in the semicollisional regime [17] and $\alpha = 1.5$ in the collisionless limit, L_s is the magnetic shear length, L_n is the scale length of the equilibrium density gradient, ρ_s is the ion sound Larmor radius and β is the plasma beta parameter, which in this model introduces the coupling of tearing modes with drift-acoustic waves. In present day tokamaks, the value of the product $\Delta'_{cr} r_s$, where r_s is the radius of the mode-rational surface, can be as large as 10^2.

A legitimate question is whether stability at $\Delta' < \Delta'_{cr}$ persists for finite amplitude perturbations. We investigate this question on the basis of full nonlinear simulations of the four field model [18]. We have performed a numerical campaign, keeping all parameter values (including Δ') fixed, but changing the value of β. The values of the relevant parameters are: $\eta = 1 \times 10^{-3}$, $\mu = 2 \times 10^{-4}$, $D = 5 \times 10^{-5}$, $\rho_* = 0.1$, $\omega_* = 0.094$, $\Delta' = 0.41$, $d_e = 0$. For a given Δ', linear theory predicts stable perturbations at β above $\beta_{cr} \approx 3.2 \times 10^{-3}$. Figures 3 and 4 summarize our main findings.

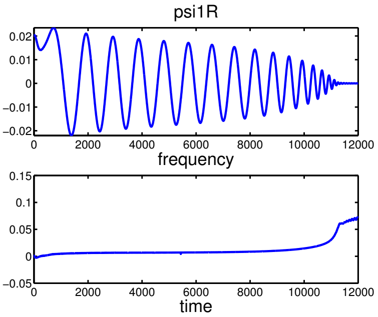

Fig.3 Simulations performed at $\beta = 5 \times 10^{-3}$, showing the suppression of the magnetic island: (a) Re(ψ); (b) oscillation frequency as functions of time.

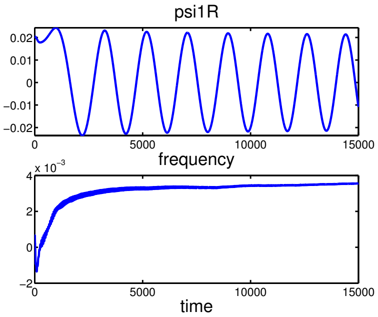

Fig.4 Simulations performed at $\beta = 2.5 \times 10^{-3}$. In this case the island is not suppressed: (a) Re(ψ); (b) oscillation frequency, both as a function of time.

The width of the initial magnetic island (a saturated equilibrium island at $\beta = 0$), normalized to the macroscopic scale length (the half-width of the integration domain), is $w_{initial} = 0.2$. Figure 3 illustrates the result of a simulation with $\beta = 5 \times 10^{-3}$, for which the linear analysis predicts stability; Fig. 3a shows the behavior in time of a magnetic signal, the real part of ψ. This figure clearly indicates that the island is suppressed in time; Fig. 3b illustrates the behavior of the mode frequency as a function of time. While the initial, saturated island is nearly locked to the plasma rest frame, the oscillation frequency increases as the island width decreases in time. A similar behavior is observed for larger values of β. The results of Fig. 3 are contrasted by those in Fig. 4, which represent a simulation at $\beta = 2.5 \times 10^{-3}$, i.e. a value of β at which the linear analysis predicts instability. Fig. 4a indicates that the amplitudes of the initial fields (only ψ is shown in the figure) decrease slightly in time, however the magnetic island is not suppressed in this case. After an initial transient, the rotation frequency as a function of time, shown in Fig. 4b, increases very little.

These results indicate that the prediction of linear theory, i.e. the existence of a stability threshold for drift-tearing modes, remains valid also when starting from nonlinear equilibria with fully developed islands, in the sense that these islands are suppressed when the value of β is raised above the critical value predicted by linear theory, as shown in Fig. 3. The physical effect associated with finite β, in the model we are using is the coupling with the parallel ion motion, or equivalently the coupling with drift-acoustic perturbations.

In addition to island suppression at finite β, we have also found a phenomenon of so called bistability, i.e., the coexistence of two stable equilibria with magnetic islands for the same set of parameters, which appears to be associated with the coupling between tearing modes and electromagnetic drift waves [19].

The nonlinear stability of magnetic islands in a tokamak [20] is also affected by ion inertial effects, which are responsible for a polarization return current. Such a current may in fact be destabilising, leading to a thresholdless instability [21]. Recently, it has been argued that island deformation effects [22], induced by equilibrium shear flows moderated through viscosity, can justify the existence of a threshold, since the stabilising effect of the island deformation overcomes the destabilising effect of the polarisation current. Here, we show that forced reconnection driven by static external magnetic fields in plasmas with differential toroidal rotation leads to deformed islands, which therefore should be accounted for in theoretical stability analyses.

In a tearing-stable ($\Delta' < 0$) cylindrical configuration, neglecting viscosity, the reconnected flux at the mode-rational surface, $r = r_s$, reaches a steady state given by [23]

$$\tilde{\Psi}(r = r_s, t \gg \tau_A) \propto I_{ext}/[\exp 5i\pi/8(-nv_0/R_0)^{5/4} + |\Delta'|] \tag{3}$$

where τ_A is the Alfvén time, n is the toroidal mode number, R_0 is the major radius of the tokamak and I_{ext} is the magnitude of the current sheet driving the reconnection.

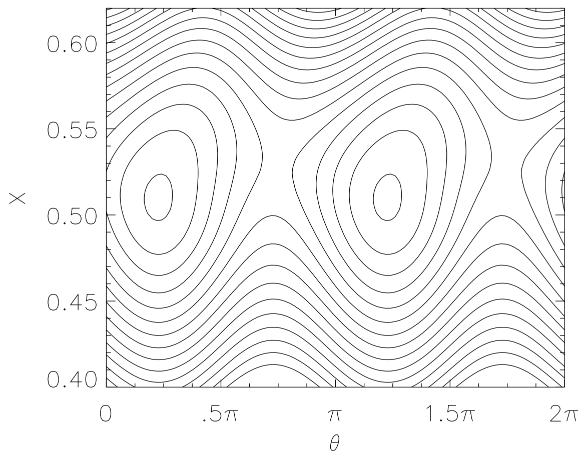

Fig. 5 Total flux contours evidencing a deformed island in the nonlinear regime obtained from a reduced MHD simulation.

The plasma is considered to be rotating rigidly in the toroidal direction with velocity v_0. From the complex-valued Eq. 3, one infers that the reconnected island will have a phase shift relative to the driving magnetic field, independent of the magnitude of the driving external current. In addition, it is clear that the static external field will have a direct effect only on the profile of the real part of ψ. The difference that results in the spatial profiles of the real and imaginary parts of the perturbed flux is at the origin of the non constant phase. More specifically, adopting the notation $\tilde{\Psi}(x,t) \equiv |\Psi| \exp i\phi$, one finds $\phi' \propto |\Psi|^{-2}$. Consequently, the larger the differential rotation, the smaller the reconnected flux and the narrower will be the layer where the phase is varying.

In the non-linear regime, i.e. when the island width becomes of the order of the tearing layer width, Eq. 3 breaks down. Nonetheless, for a slow I_{ext} ramp, one may consider Eq. 3 as an initial value condition for the non-linear evolution. Since the mode phase at the rational surface does not depend on I_{ext}, we may expect that the phase develops its characteristic profile before non-linear effects play a role. Once in this regime, the island grows in size and the deformation starts to be noticeable (see Fig. 5). The non-linear effects tend to reduce the deformation of the flux contours. As the island grows, the localised $\vec{J} \times \vec{B}$ forces will also increase in amplitude, leading to a gradual reduction (around the rational surface) of the equilibrium plasma flow and consequently of the phase of the mode. The deformation will be negligible only if the external driving current overcomes the threshold for mode amplification [24, 25].

The role of island deformation on the mode stability should be assessed both theoretically and experimentally, in order to provide a more complete description of the non-linear stability and evolution of neo-classical tearing modes in tokamaks.

4. Reconnection near magnetic X-points

X-points are special points of a two-dimensional field, where a component of the magnetic field vanishes. Near the X-point, the field structure is hyperbolic in nature. The magnetic surface that goes through the X-point forms the separatrix. If no current goes through the X-points, then the angles at the separatrix are 90^0 angles.

The X-point is a weak spot in the magnetic field structure, in the sense that converging flows can cause the field near such a point to collapse into a current sheet whose amplitude and width are limited by resistive diffusion or by electron inertia. Such process in the resistive version has been studied extensively, especially in the context of astrophysical plasmas [26]. When such a current sheet forms, the resulting magnetic structure is such that the X-point splits into two Y-points. If this process happened in a tokamak divertor field, the consequence would be that the strike points of the magnetic separatrix on the divertor target plates would not be as prescribed by equilibrium considerations.

The instability of the X-point structure in tokamak discharges may result from axisymmetric vertical displacements, which are normally suppressed by the feedback stabilization system in elongated tokamak configurations, but which may reappear in the form of relatively fast, non-rigid displacements localized in the peripheral plasma region near the magnetic X-point. Indeed, the vertical displacement has a spatial structure with toroidal mode number $n = 0$ and low poloidal mode numbers. The parallel wave vector, $\mathbf{k} \cdot \mathbf{B} = nB_\phi/R + mB_\theta/r$, vanishes at the X-point for $n = 0$. Thus, an axysimmetric perturbation is resonant and the plasma flow tends to become singular at the X-point. The singularity is resolved by relaxing the ideal-MHD frozen-in law, giving rise to reconnection. In Ref. [27], it was speculated that this process may be at the basis of ELMs, however a satisfactory theoretical model is still under construction. In the following, we discuss briefly some of the theoretical steps accomplished so far.

A first investigation of reconnection near magnetic X-points may be carried out in simplified, cylindrical geometry. The equilibrium configuration proposed by Gajewski [28] is a good starting point. In this configuration, the equilibrium current density is constant within an elliptical plasma column, with two magnetic X-point located symmetrically outside of the elliptical cross-section and the magnetic separatrix extending to infinity. This equilibrium can be expected to be ideal-MHD unstable, therefore it requires either a conducting wall or controlled currents in external coils to be stabilized. The latter case has been considered in a recent theoretical work [29] on the basis of the ideal MHD energy principle, extended to include the effect of external currents. The stabilized elliptical plasma column actually oscillates around the equilibrium position, the energy for such oscillation being provided by the generator producing the external currents. The question is whether this energy can be tapped in the presence of finite resistivity or electron inertia, giving rise to a current sheet centered on the location of the X-points at equilibrium.

We have considered an equivalent question in the context of the VTF magnetic reconnection experiment at MIT [30]. In the VTF device, a toroidal plasma is confined in an externally created magnetic field that has a quadrupole poloidal cusp component and a toroidal or guide component. Reconnection of the poloidal magnetic field is driven by plasma flows towards and away from the poloidal null or X-line, through $\mathbf{E} \times \mathbf{B}$ drifts generated by an externally induced toroidal electric field. A quadrupole magnetic configuration with some features similar to VTF was also investigated in the TS devices at the General Physics Institute of the Russian Academy of Sciences [31, 32]. Here, we discuss the strong guide field limit, where qualitative agreement between the theory (summarized below) and VTF experimental results can be claimed [33].

A two-dimensional equilibrium is assumed, characterized by constant density, n_0, a guide field, $B_{z0}\mathbf{e}_z$, and a perpendicular magnetic flux $\psi_0(x, y) = B'_{c0}xy$ modeling the quadrupole cusp. The magnitude of the equilibrium guide field relative to the cusp field is given by the constant with dimensions of length $l_0 \equiv B_{z0}/B'_{c0}$. It can be shown that, starting from the full set of two-fluid equations, the Hall current does not play a role if $\beta << 1$ and $d_i << l_0$, with d_i the ion skin depth. The external drive is imposed through the boundary condition that, far away from the separatrices $(x, y \rightarrow \pm\infty)$, the z-component of the electric field, $E_z = \partial\psi/\partial t$, approaches E_∞, corresponding to a constant, externally applied electric field $E_\infty \mathbf{e}_z$. This external drive is assumed to be sufficiently weak to warrant the linearization of the relevant set of reduced fluid equations.

The long term asymptotic behavior of the current density at the X-line can be derived analytically. The result is

$$j(0,0,t \rightarrow \infty) \simeq E_\infty \tau_A \rho_s / 2\delta^2 d_e (1 + \pi t/\tau_e)^{1/2} \tag{4}$$

where $\delta \sim d_e$ is the width of the initial current sheet and τ_e is the electron collision time, much longer than the Alfvèn time, τ_A, in VTF. Details of the analytic derivation and the complete numerical solution of the initial value problem are presented in Ref. [33]. On the basis of these results, the evolution of the current density and perturbed flux can be described as follows. After an approximately linear rise, the X-line current density approaches a constant in the absence of collisions ($\tau_e \rightarrow \infty$), otherwise it decays in time as $(t/\tau_e)^{-1/2}$. The spatial profile of the current sheet develops a complex structure with an inner sublayer that shrinks without limit, similar to the findings of Ref. [12]. The long time rate of this current layer shrinking depends on the collisionality, being exponential in the collisionless case and power-like at finite resistivity. The reconnected flux is derived from the current density upon integration. We observe an initial phase during which reconnection proceeds linearly in time with a characteristic rate of the order of the inverse Alfvén time, independent of the resistivity. Subsequently, in the strictly collisionless case $(\tau_A/\tau_e = 0)$, reconnection practically ends after several Alfvén times and the total amount of reconnected flux is finite, $\psi_{rec}(t \rightarrow \infty) = E_\infty \tau_A d_e \rho_s / \delta^2$. Taking collisions into account, for $t > \tau_e$ the system transitions to a slower reconnection phase with $\psi_{rec}(t)$ proportional to $(t/\tau_e)^{1/2}$. The validity of the linear approximation eventually breaks down due to the narrowing of the current profile, and this narrowing is not expected to be prevented by non-linear effects [12, 13], although it is slowed down by the resistivity when $t > \tau_e$. Before that happens, however, 3D effects are likely to become dominant as the steep current gradient would drive secondary instabilities.

4. Conclusions

The following conclusions can be drawn: 1) A model for the sawtooth amplitude and period has been developed in the past few years. This model has been validated against experimental data. Theoretical developments indicate that the sawtooth crash time and the variety of sawtooth shapes that are observed during additional heating and pellet injection can be interpreted on the basis of the nonlinear evolution of $m = 1$ internal modes with relevant kinetic effects, although the conditions for the occurrence of incomplete sawtooth reconnection remain largely not understood. The irreversible nature of island growth and saturation in the absence of dissipation has been demonstrated; 2) The coupling of drift tearing modes with drift-acoustic waves introduces a rather significant threshold for the linear stability of these modes. We have shown that the stabilization mechanism is present also nonlinearly, i.e. for perturbations representing magnetic islands of finite width. An interesting phenomenon of bistability for nonlinear tearing modes has been hinted to. Furthermore, magnetic islands driven by static external fields are deformed. This may affect the nonlinear threshold for neoclassical tearing modes; 3) The X-point structure of a divertor magnetic configuration may become unstable to axisymmetric plasma displacements. This process has features in common with those of the VTF experiment at MIT. A first theoretical attempt aimed at the understanding of VTF observations has been discussed.

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