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Alfvénic Reconnection in FTU Plasma and Sawtooth Trigger Analysis

P. Buratti and E.Giovannozzi

EURATOM-ENEA Association, C.R. Frascati, CP 65, 00044 Frascati, Italy

1. Introduction

Fast magnetic reconnection is a long-debated problem both in tokamak and in space plasma physics, the main questions being the time scale and the trigger mechanism. In the following a sawtooth trigger mechanism will be proposed. Challenges raised by the observed spatial structure and fast reconnection rate will be pointed out. The relevance of this analysis to other tokamak experiments will be discussed.

2. Spatial structure and time scales

Sawtooth collapses without precursor oscillations have been analyzed in order to have clear-cut data on the trigger mechanism. Fig. 1 shows a profile evolution example: the hot core moves towards the high field side, leaving a flattened region. Comparison between collapses with displacement along different poloidal angles shows that the flattened region is crescent-shaped. Comparison between ECE and soft-x-ray views at different toroidal angles shows that the core displacement has q=1 helicity. The spatial structure is then consistent with the classical Kadomtsev reconnection model [1].

The constancy of temperature inside the displaced hot core (see fig. 1) allows inferring the displacement evolution from temperature contours. A similar principle was used in rotation imaging reconstruction of temperature oscillations [2]. Rotation imaging gives accurate 2D information with moderate time resolution; in our case 2D information is indirect but time resolution is better.

Fig. 2 shows (R, t) temperature contours. Having selected a collapse with displacement along the ECE diagnostic line of sight, the displacement can be

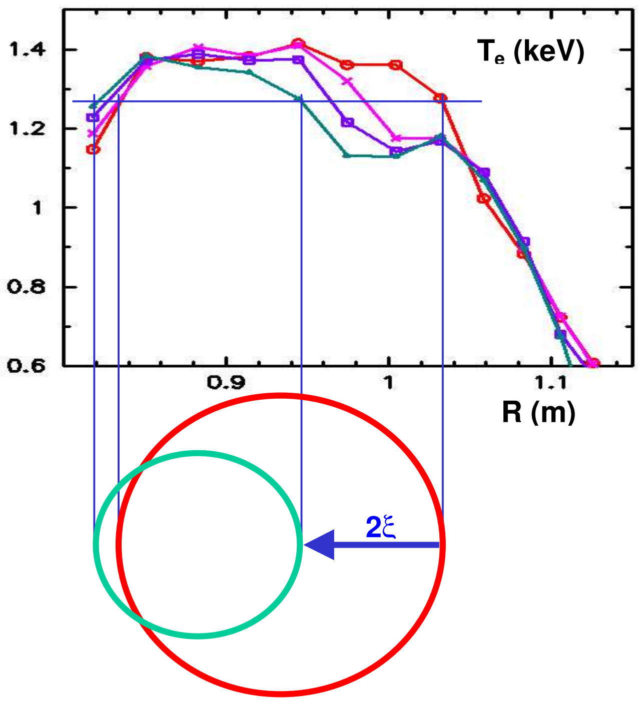

Fig. 1. ECE temperature profiles during a sawtooth collapse. The circles sketch hot core evolution in the poloidal section. Time lag between extreme profiles is 165 μs.

directly inferred from contours, for example the sawtooth inversion radius can be readily recognized from contours divergence at t≈0.8039. The displacement evolution clearly shows two different time scales, characterizing the initial relatively slow displacement (t<0.80389) and the following dramatic acceleration phase respectively. Both scales (100 µs and 10 µs respectively) are much shorter than the Kadomtsev time (≈1 ms).

The reliability of temperature contours as fluid displacement markers could be compromised by heating due to magnetic field dissipation or by secondary instabilities. Both effects however can be excluded as long as the hot core keeps a well-defined boundary. This is enough to determine the time-scales, whereas, due to the lack of adequate space resolution, no conclusion can be drawn on the occurrence of full reconnection in the very last part of the collapse.

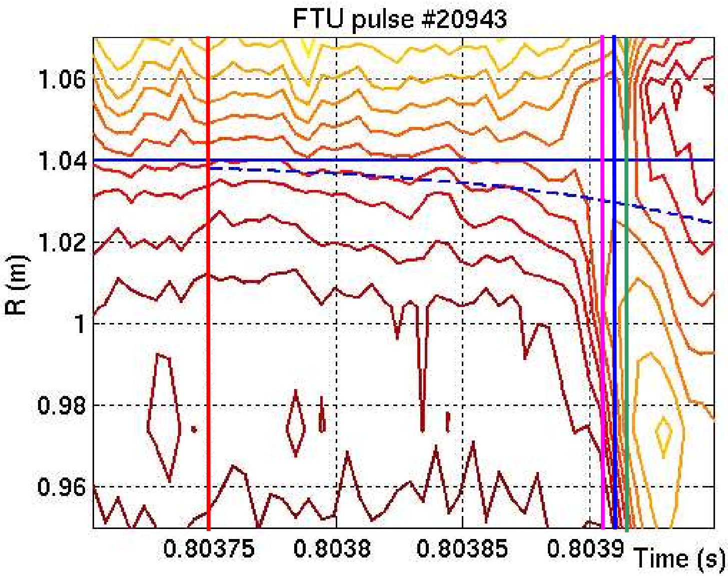

Fig. 2. Temperature contours near the inversion radius. Vertical lines correspond to profiles shown in fig. 1. The dashed line represents an exponentially growing displacement with an e-folding time of 97 µs. The time scale dramatically changes around t=0.8039. The horizontal line marks the previous average position of the fitted contour.

3. Time scales analysis and trigger mechanism

The first, longer time-scale is consistent with linear growth rate of a m=1 tearing mode in the semicollisional regime $\gamma_\rho = (2/\pi)^{2/7} (\rho_s / r_1)^{4/7} (\delta_\eta / r_1)^{3/7} \omega_A$, where ρ_s, δ_η, r_1 and ω_A are the ion sound Larmor radius, the resistive layer width, the q=1 radius and the shear-Alfvén frequency respectively. Fig. 2 shows that an exponential with γ_ρ growth rate reproduces very well the first evolution phase. During this phase, the hot core displacement ξ is in the early non-linear regime $\rho_s < \xi << r_1$ (smaller displacements being buried in noise); continued exponential growth at the linear rate is expected in this regime due to electron pressure effects [3]. We may then identify the first exponential growth as a purely growing precursor. Rotating precursors also grow exponentially, but their growth rate is typically smaller by an order of magnitude [4].

The linear semicollisional regime is characterized by the ordering $\rho_s>\delta_\eta>d_e$, where d_e is the collisionless skin depth and $\delta_\eta=r_1(sS)^{-1/3}$, S and s being the Lundquist number and magnetic shear at r_1 respectively. As long as velocity increases, the resistive layer shrinks as $\delta_\eta\approx\eta/(\mu_0 d\xi/dt)$, η being resistivity. In consequence, during the precursor phase the δ_η/d_e ratio drops from 4 to 0.6; this leads us to conjecture that the fast collapse trigger is a non-linear transition from the semicollisional regime to the collisionless one, where super-exponential growth is expected [5, 6].

Density (m^{-3})	Temp. (keV)	B_T (T)	Lundquist number	ρ_s (mm)	δ_η (mm)	d_e (mm)	r_1 (mm)	R (m)
2×10^{20}	1.2	5.6	3.8×10^6	1.8	1.4	0.37	100	0.95

Table 1. The main plasma parameters for FTU pulse #20943.

4. Fast collapse analysis

During the fast collapse phase, velocity dramatically increases and then it saturates at about 8×10^3 m/s, which is a significant fraction (20%) of the shear-Alfvén velocity. The effective growth rate dln(ξ)/dt increases by an order of magnitude with respect to the early non-linear phase , while the reconnection rate reaches values close to the limits found in numerical simulations. Here the reconnection rate is defined as the ratio between the velocity of mass flow into the reconnection layer and the upstream shear-Alfvén velocity [7]. In the early non-linear stage, the shear-Alfvén velocity can be evaluated as r_1/ω_A, with $\omega_A = R/sV_A$; exponential growth at the linear rate follows assuming that the reconnection rate $f = \gamma_\rho/\omega_A$. According to [8] $f \approx \rho_s/r_1$ should be used, but with our parameters (table 1) this makes nearly no difference.

In order to model the fast collapse, we evaluate the shear-Alfvén velocity as $V_A^*(r) = V_A \cdot (1/q(r) - 1) r/R$ and the inflow velocity as dξ/dt (the reconnection layer velocity should be subtracted, but this is a small effect, as shown by fig. 1). The equation for displacement evolution is then $d\xi/dt = f \cdot V_A^*(r_1 - \xi)$. This was solved analytically for the model profile $1/q(r) = 1 + 0.13(1 - r/r_1)$. Fig. 3 shows that good agreement with experimental contours turns

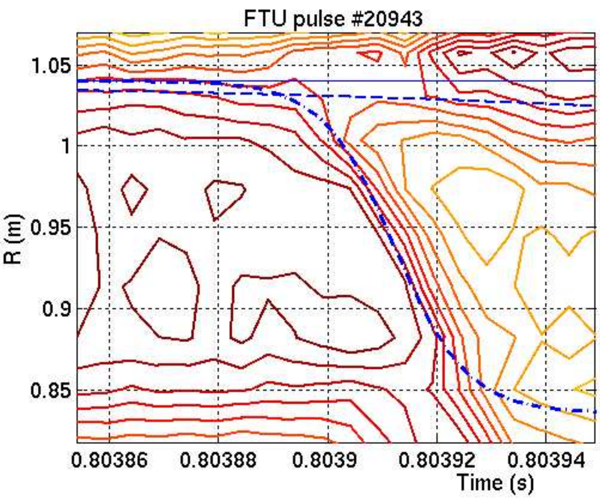

Fig. 3. Blow-up of the fast collapse phase. Dot-dashed line is the model equation solution; other lines as in fig. 2.

out assuming $f = 0.18$. Summing the two curves shown in fig. 3 gives a tight reproduction of experimental contours during both precursor and the collapse phases. The effective growth rate computed for this curve is constant during the precursor phase and then increases by an order of magnitude within half a growth time (fig. 4). A similar evolution was found in four-field numerical simulations of the sawtooth collapse [9].

The maximum reconnection rate is $f = 0.18 = \ln(r_1/d_e)$; such a logarithmic dependence on the microscopic scale has been found in numerical simulations with artificially localized resistivity, [7], but its general validity is an open question [3].

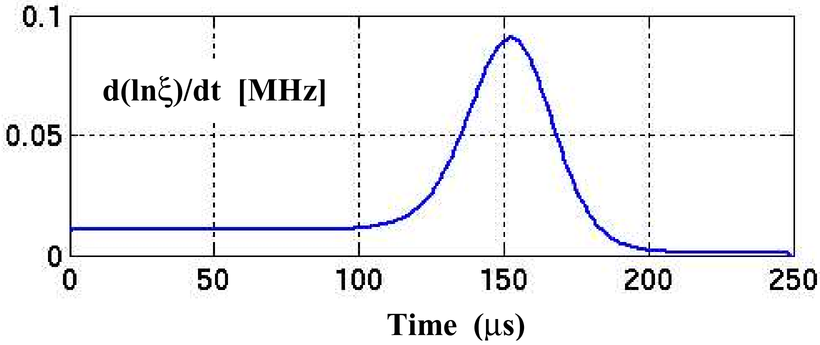

Fig. 4. Experimental growth rate as obtained from a data fit. At t=0 the displacement emerges from noise. The first exponential stage lasts 100 µs, i.e. one growth time. In the second stage the growth rate increases by an order of magnitude in half a linear time.

5. Concluding remarks

Apparently precursorless sawtooth collapses have indeed a purely growing precursor that can be identified as the early non-linear stage of the m=1 tearing instability. During the precursor, the reconnection regime non-linearly switches from semicollisional to collisionless; this seems to be the trigger for the subsequent fast collapse. This analysis was performed for high-density FTU discharges. Precursor duration should be shorter in plasmas that have $\delta_\eta < d_e$ already in the linear regime.

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