Current sheet fragmentation following magnetic reconnection in RFP plasmas

L. Cordaro[1], M. Zuin[1], B. Momo[1], E. Martines[1], M. Spolaore[1], F. Auriemma[1],
R. Cavazzana[1], G. De Masi[1], P. Scarin[1], S. Spagnolo[1], N. Vianello[1], D. Cester[2],
L. Stevanato[2], H. Isliker[3], L. Vlahos[3], W. Schneider[4].
[1] *Consorzio RFX, corso Stati Uniti 4, Padova, Italy*
[2] *Department of Physics and Astronomy, University of Padova, Italy*
[3] *Department of Physics, Aristotle University, 52124 Thessaloniki, Greece*
[4] *Max-Planck Institut für Plasmaphysik, EURATOM Association, Greifswald, Germany*

In Reversed Field Pinch (RFP) discharges, magnetic reconnection events are related to self-organization processes[1]. Along with the action of the continuous dynamo, discrete quasi-cyclic relaxation events, leading to rearrangement of magnetic field topology through magnetic reconnection phenomena, have been observed in RFP plasmas, with a dynamics resembling that of sawtooth in tokamak plasmas. This behavior can be observed looking at the intermittent quasi-periodic negative peaks that characterize the temporal evolution of the *reversal parameter* $F \equiv \frac{B_\Phi(a)}{<B_\Phi>}$ (Fig. 1), being $B_\Phi(a)$ the edge toroidal magnetic field and $<B_\Phi>$ the toroidal field averaged over the plasma cross-section. The value of the F parameter is negative because, in a RFP discharge, the toroidal magnetic field at the edge is reversed with respect to that on axis. In RFX-mod ($R = 2m, a = 0.459m$), it was shown that these relaxation events are associated with the rapid formation of localized magnetic perturbations characterized by a main m=0 periodicity [2], resonant on the reversal surface where the condition $q = 0$ is satisfied. Such perturbations correspond to the formation of poloidal current sheets. The m=0 activity starts in a localized region around a given toroidal position and then moves with plasma in the direction opposite to the toroidal current, as can be seen in Fig. 2, showing the amplitude of the m=0 magnetic field component as a function of time and toroidal angle, during a single relaxation event. While it moves with plasma, the perturbation appears to break into smaller structures until it vanishes in about one toroidal turn. In this paper, a characterization of such perturbations and particle dynamics associated with them is presented.

Diagnostic setting up and analysis tools

The data analysis here presented refers to the toroidal magnetic field measurements collected by the magnetic coils of the *Integrated System of Internal Sensors* (ISIS) [3], which are placed just behind the graphite tiles of the first-wall ($r = 1.03a$). They form two toroidal arrays of 48 B_Φ probes each at diametrically opposite positions ($\theta = 70°$, $\theta = 250°$, being θ the poloidal

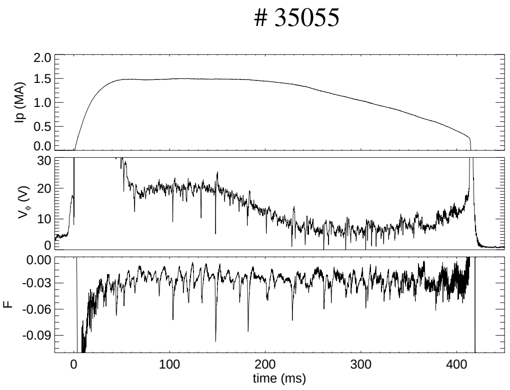

Figure 1: Time evolution of plasma parameters: plasma current (top), loop voltage (middle) and reversal parameter (bottom) for a typical RFX-mod discharge.

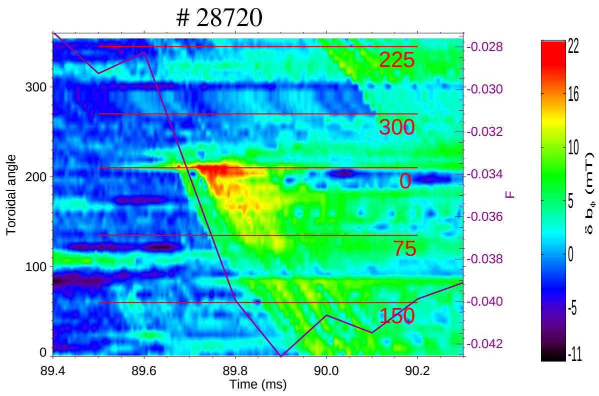

Figure 2: Contour plot of the m=0 magnetic field. F parameter is superimposed. Horizontal lines represent the new adopted reference system

angle, $\theta = 0°$ on the equatorial LFS plane).

In order to characterize particle dynamics associated with magnetic reconnection phenomena, a neutron diagnostic is also used. Such a diagnostic system makes use of a 51 mm diameter, 51 mm thick EJ-301 liquid scintillator cell and of a calibrated crystal NaI(Tl) larger scintillator coupled to H8500 flat-panel photomultipliers[4]. The liquid scintillator is sensitive to neutron and gamma radiation, signals being classified on the basis of a pulse shape discrimination (PSD) process.

Moreover, thanks to a Neutral Particle Analyzer (NPA) diagnostics, the time evolution of the distribution function of the neutral atoms produced by charge-exchange processes can be followed. The NPA has 11 energy channels, being the energy and mass dispersion produced by a combination of electrostatic and magnetic fields.

In order to recognize the intermittent structures that characterize the magnetic field perturbations and study their dynamics, a method based on the wavelet transform [5] was used. Such algorithm selects, for each scale factor, those signal structures that exceed a certain threshold of the *local intermittency measure* (LIM), a factor characterizing the signal activity for every s and τ[5]. It is defined as follow:

$$l(\tau,s) = \frac{C(\tau,s)^2}{\langle C(\tau,s)^2 \rangle} \tag{1}$$

where $C(\tau,s)$ represents the wavelet coefficients, s is the scale factor, τ is the time shift, $\langle\rangle$ symbol denotes time average. A not intermittent signal has $l = 1$ for every τ and s, instead $l > 1$ corresponds to fluctuations greater than the average value at the s scale. For each recognized intermittent structure, the amplitude is evaluated as the variation of the signal itself in a time interval equal to the s scale factor.

Experimental analysis

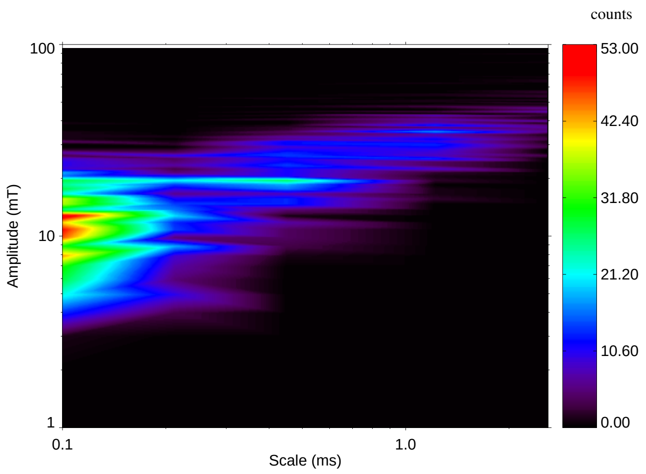

Figure 3: Contour plot showing the number of recognized events as a function of scale (abscissa) and amplitude (ordinate) with respect to a fixed angle Φ'.

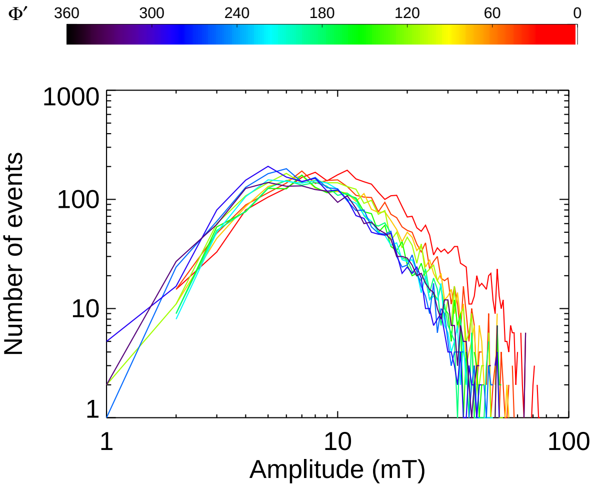

Figure 4: Structures distribution of m=0 magnetic field component as a function of amplitude. The color bar on the top shows the color-angle correspondence: the red curve refers to the angle $\Phi' = 0$ where the major perturbation occurs.

The statistical analysis of current sheets was done using the following approach: first, magnetic reconnection events, corresponding to large F parameter crashes, are identified; for each event, all the intermittent structures of the m=0 magnetic field component are recognized; then a toroidal angle (probe location) associated to the current-sheet formation, that is where the field perturbation is maximum, is identified. Such angle Φ_{max} is considered as the origin ($\Phi' = 0$) of a new reference system, as represented in Fig. 2. This process is repeated for each reconnection event and for all the considered shots. For each new angle (belonging to the new reference system), a distribution function is determined just evaluating the total number of events as a function of their amplitude. It is interesting to observe that, for each scale, the largest number of events is found for an amplitude which increases with the scale itself. This can be seen in the contour plot of Fig. 3 which represents the number of recognized structures as a function of wavelet scale and amplitude, taking into account a certain reference angle Φ'. The result of the analysis is shown in Fig. 4: the red curve corresponds to the number of structures revealed at the toroidal position where the major event occurs; the other colors towards blue correspond to increasing angles, according to the legend on the top. It is possible to note that at the greatest amplitudes (>20 mT), which correspond to the largest scales, the number of events decreases when Φ' increases. This tendency is inverted in correspondence of the lowest amplitudes $(< 10mT)$ which are related to the shortest scales. This feature suggests that the current sheet structures are subject to a fragmentation process and there is an energy transfer from the largest to the

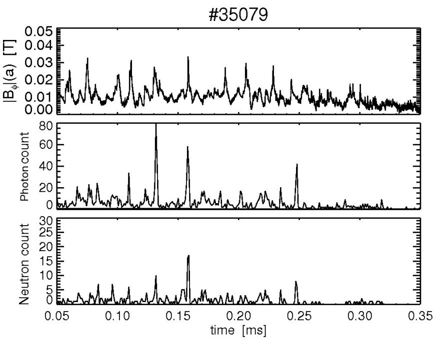

Figure 5: Time evolution of toroidal edge magnetic field perturbation (top), gamma photon count (middle) and neutron count (bottom)

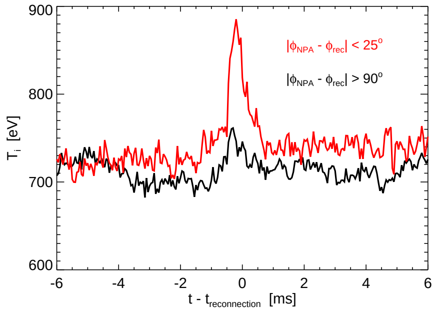

Figure 6: Ion temperature time evolution as deduced from the NPA diagnostics. Red and black traces refer to cases with magnetic reconnection processes occurring toroidally close (red) and far (black) from the diagnostics, respectively

smallest scales. This result is in agreement with what predicted by simulations presented in the literature, which highlight two important aspects: a current sheet could be naturally subject to fragmentation [6] and a fragmented current sheet represents a more efficient particle accelerator with respect to a monolithic one, by offering multiple particle acceleration sites [7]. Indeed, bursty generation of D-D fusion neutrons and gamma rays are observed, which appear to be time correlated with the reconnection dynamics, as can be seen in Fig. 5, which shows the time evolution of the toroidal field measured by ISIS magnetic probes and the count of gamma rays and neutrons. The correspondence among the signals' spikes seems to suggest the coupling among particle acceleration and magnetic reconnection phenomena. This is further confirmed by the analysis of the ion temperature dynamics, deduced from the exponential slope of the neutral particle fluxes from the NPA in the 1-3 keV energy range in maxwellian approximation. As shown in Fig. 6, a significant dynamic enhancement of the ion temperature is measured when the relaxation process occurs. Such a effect is particularly evident in those cases characterized by a generation of the $m = 0$ structure in close proximity to the NPA diagnostics. This result seems to indicate that the acceleration particle process is also strongly localized.

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