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Fast dynamics of relaxation event in RFX-mod

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Relaxation events in reversed field pinch (RFP) plasmas are sign of self-organization processes, well known to occur in almost all current-carrying fusion plasmas (they play a key role in sawteeth activity in tokamak discharges) as well as in many astrophysical phenomena such as the evolution of solar flares and the formation and accretion of stars and galaxies. In RFP devices, a spontaneous, almost cyclic, rearrangement of the magnetic topology occurs, which is considered to be due to reconnection of magnetic field lines[1]. The effect of relaxation events on plasma magnetic and electrostatic dynamics is the object of this study. The measurements described herein have been performed on the RFX-mod device[2], equipped with a large set of electrostatic and magnetic probes located inside the vacuum vessel, which constitute the ISIS (Integrated System of Internal Sensors) system, mainly aimed at the investigation of the edge plasma[3].

In particular, we report here the results concerning magnetic fluctuations, obtained by means of pick-up coils measuring the time derivative of the toroidal component of the magnetic field. The probes, placed behind the graphite tiles, which cover the first wall of the machine, are evenly distributed in the toroidal direction, on two arrays located in two opposite poloidal positions (top-bottom). Each array consists of 48 coils. The sampling frequency is 2 MHz, while the estimated bandwidth of the measurement is up to 300-400 kHz. In a set of experiments performed at low toroidal plasma current ($\leq$ 400 kA), a probe consisting of two Boron Nitride cases, 5 cm toroidally spaced, could be radially inserted from the vacuum chamber up to $r/a \approx 0.9$, where a is the plasma minor radius, without significant perturbation to the plasma. Each case contains 40 electrostatic pins, combined in eight 5-pins balanced triple probes, 6 mm radially spaced. Together with electrostatic pins a radial array of 7 three-axial magnetic coils is located in each case in order to measure the time derivative of the three components of the magnetic field. All magnetic signals have been numerically integrated.

In Fig. 1 an example is shown of the toroidal spectrum of magnetic fluctuations during a single relaxation event, which is recognized as a rapid variation of the magnetic flux (and of the reversal parameter $F=B_{\Phi}(a)/\langle B_{\varphi}\rangle$). An increased activity of internally resonating $m=1$ modes (dynamo modes) is at first observed, with an energy cascade from $n=-7$ towards higher $|n|$ modes (negative n values correspond to perturbation resonating internally with respect to the reversal surface). This corresponds, in real space, to a toroidally localised magnetic perturbation becoming narrower. The presence of a localised perturbation in the RFX-mod device is due to the non-linear coupling of the dynamo modes, which have a natural tendency to lock in phase, and to form the so dubbed locked mode (LM), at one toroidal position ϕ_{lock}[4], where many $m=1$ modes have their maxima.

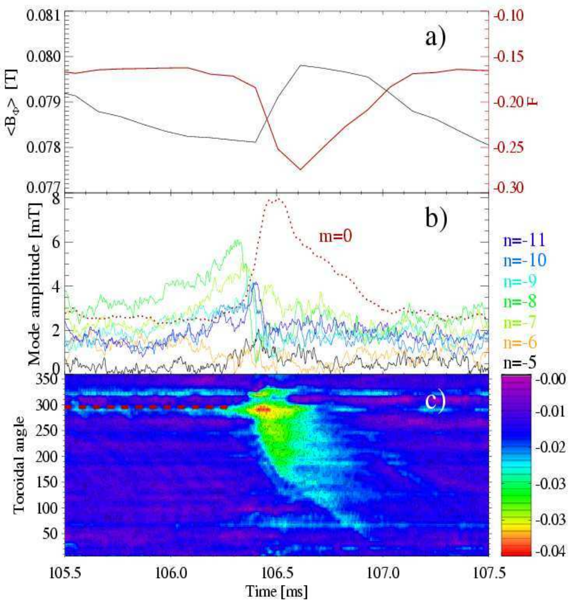

Fig. 1: Time behavior of: a) Average of toroidal field and reversal parameter F; b) $m=1$ dynamo modes and total $m=0$ energy; c) contour plot of $m=0$ components of magnetic signals (dashed line indicates the toroidal position of the LM).

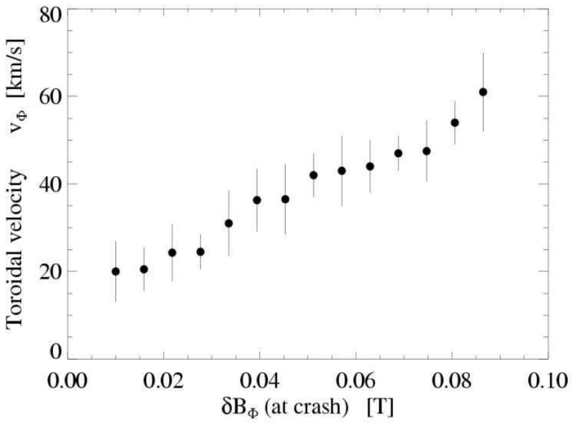

Fig. 2: Toroidal velocity of $m=0$ perturbation as a function of its maximum amplitude.

The growth of the $m=1$ modes is rapidly followed by an abrupt decrease (crash) of their amplitude, with a large part of the magnetic energy transferred to an $m=0$ perturbation. This $m=0$ activity is always observed to initially occur at ϕ_{lock} (toroidally extending for about 90°), and then to move mainly in counter toroidal plasma current direction (towards decreasing toroidal angle, ϕ). During this propagation, the amplitude of the $m=0$ perturbation decreases, and it is never observed to last for more than a single toroidal turn. The initial velocity is in the same direction of, but larger than, plasma flow velocity at the edge, which is known in RFX-mod to be about 20 km/s[5]. In particular, the starting velocity of the $m=0$ perturbation is observed to depend on its maximum amplitude (Fig. 2) and is comparable to plasma velocity at the edge (20 km/s) for almost vanishing magnetic perturbation.

By means of the insertable probe, and applying Ampere's law, it has been possible to associate to the $m=0$ rotating perturbation a current density in the poloidal direction J_θ, as can be seen in Fig. 3. This current perturbation can be identified as the current sheet associated with the spontaneous magnetic reconnection, which is recognized to occur at the LM position, where the radial fields necessary to connect field lines at different radius are actually present. The almost linear dependence of the starting velocity on the amplitude of the perturbation (and therefore on current density) could thus be interpreted as the effect of a $J_\theta \times B_r$ (Lorentz) force acting at the LM position. In its motion along the torus, the current sheet is observed to induce a strong local perturbation to the edge plasma.

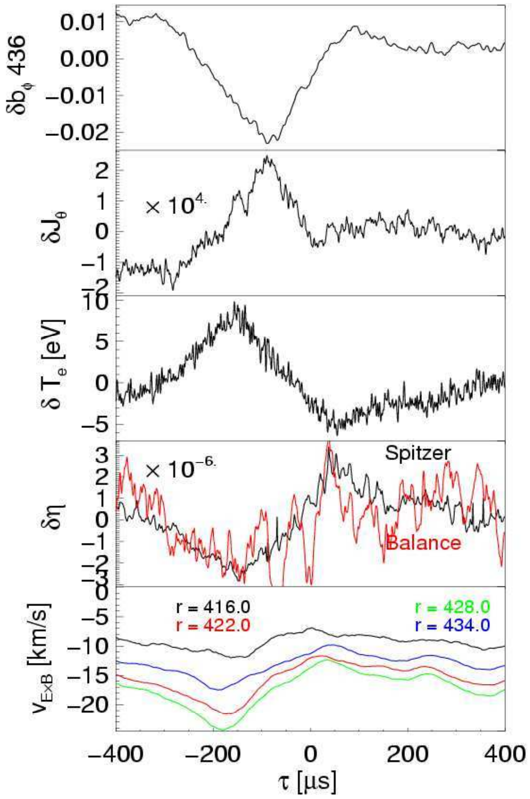

Fig. 3: Time behavior of (from the top): toroidal magnetic field at the edge; poloidal current density; electron temperature; plasma resistivity evaluated with Spitzer's formula and Ohm's law; ExB velocity at different radii.

In Fig. 3 the transit of the current structure at the position of the insertable probe is identified by the rapid variation of the toroidal magnetic field measured by the ISIS probe located in the same toroidal position (a conditional average over several events is performed). An increase of the electron temperature is observed, along with a flattening of the radial profile of the radial electric field. In particular, a robust decrease of the ExB shear flow is induced at the edge. In Fig. 3 the time behavior of the local plasma resistivity η evaluated by means of the measured electron temperature in the Spitzer's formula is compared to that deduced by the balancing of the poloidal Ohm's law, in the form

$E_\theta + \langle \tilde{v} \times \tilde{B} \rangle = \eta(\bar{J}_\theta + \tilde{J}_\theta)$. Good correlation between the two independent estimates is found, both showing a decreased plasma resistivity of the edge plasma.

By moving in the rest frame of the current sheet an exponential time decay of the amplitude of the m=0 perturbation is observed, as shown in Fig. 4, with a decay time constant τ_R of about 400 μs. The induction equation, $\frac{\partial \mathbf{B}}{\partial \mathbf{t}} = \nabla \times (\mathbf{u} \times \mathbf{B}) + (\eta / \mu_0)\nabla^2 \mathbf{B}$, which describes the time evolution of magnetic fields, by considering the velocity of the current sheet as representative of the local plasma velocity (and so the **u**×**B** term as negligible), becomes a diffusion equation: $\frac{\partial \mathbf{B}}{\partial t} \cong (\eta / \mu_0)\nabla^2 \mathbf{B}$. With an order of magnitude consideration for the toroidal component, and using $\tau_R = (\mu_0/\eta)L^2$, it is thus possible to estimate a minimum characteristic length L of the current sheet, corresponding, in our case, to its radial extent, of about 6 cm.

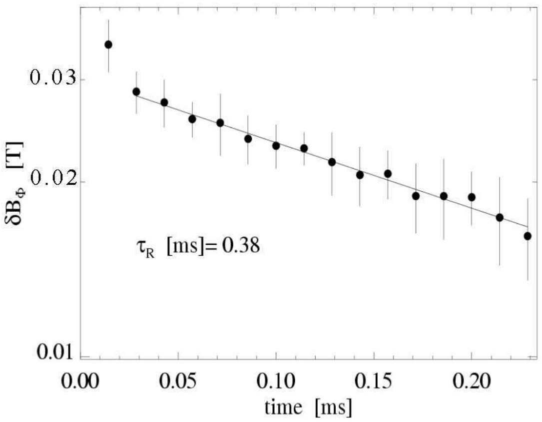

Fig. 4. Time Amplitude of the m=0 perturbation vs. time.

To summarize, the relaxation events in RFX-mod are interpreted as magnetic reconnection processes, due to an increased distortion of magnetic surfaces localised at the position of the locked mode. The poloidal current sheet associated to the reconnection event is observed to be generated in the same toroidal position and then to move in counter plasma current direction, strongly perturbing plasma properties at the edge. An analysis of the (resistive) decay time of the current structure gives an estimation of its radial width of few centimeters.

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