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Magnetic relaxation and discrete dynamo action in RFX

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I. INTRODUCTION

Magnetic relaxation is the mechanism by which the Reversed Field Pinch (RFP) configuration recovers a stable equilibrium that was previously lost by resistive diffusion. It is also recognised to be associated with the MHD dynamo mechanisms that sustain the magnetic configuration. At the same time the associated transient magnetic field fluctuations are responsible for part of the energy and particle transport in the RFP.

The crash of the reversal parameter, which often occur in RFP experiments, is referred to as discrete dynamo magnetic relaxation event, also called Dynamo Relaxation Event (DRE), and is the most visible result of the magnetic relaxation. It has been experimentally observed in all RFP experiments and its dynamics has been studied experimentally [1,2,3] and theoretically [4,5]. It is generally agreed that the DRE originates when the safety factor profile is destabilised by the resistive diffusion. Due to the resistive-kink/tearing instability, the m=1 modes grow and by non linear coupling generate the m=0,2, n>0 modes. The m=0 modes in particular act to distribute in a axis-symmetric way the magnetic flux generated initially by m=1 modes, which is helical symmetric.

In spite of the DREs have been studied in many RFP experiments, confirming in general the picture obtained in MHD studies, still many aspects are not completely understood. In this work we try to give an overview of the different observations available in our experiment concerning this process.

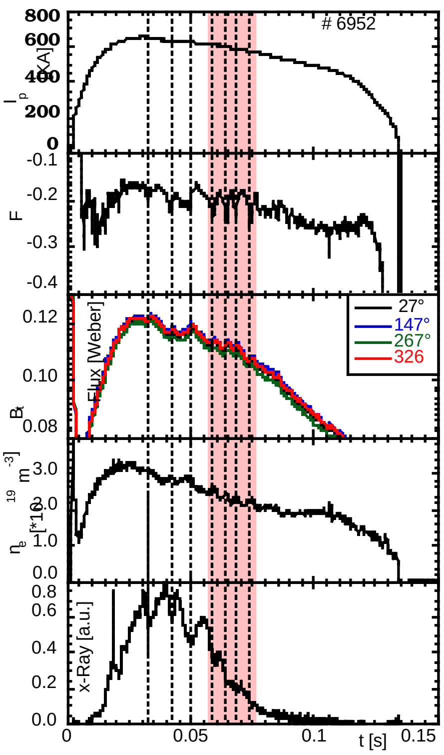

Fig. 1 Plasma current, reversal parameter F, internal toroidal magnetic flux, plasma electron density and soft x-Ray emission for a discharge with many DREs.

In RFX (a=0.46 m, R=2 m, I = 1 MA) large DREs are generally observed during the current ramping up phase, while during the current flat top phase only very small DREs are often present and a continuum magnetic field regeneration seems to act to sustain the field reversal configuration. Pellet injection or a rotating toroidal magnetic field perturbation can externally induce large DRE during the flat top. We will describe initially the features of the spontaneous DREs both on a single shot basis and then statistically. Finally we will analyse the externally induced DREs.

II. SPONTANEOUS DRE

In fig. 1 a discharge displaying many DREs is shown. DREs are present both in the current ramping up phase, during which they generate the internal magnetic flux, and in the current flat top phase, to counteract the natural resistive decay. In the same figure it is possible to see that for this discharge the DREs produce an effect on both the soft x-Ray emission and electron density. Those last phenomena

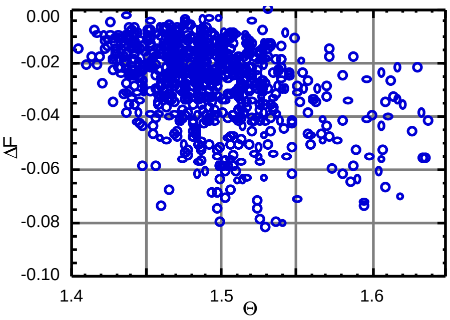

Fig. 2 Dependence from the pinch parameter of the reversal variation during a DRE.

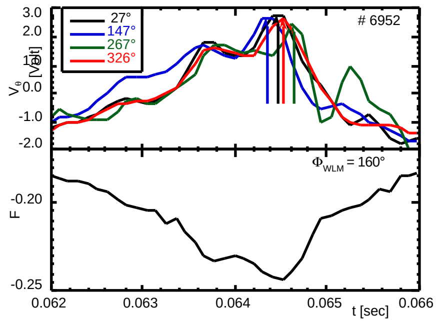

Fig. 3 Poloidal voltage measured on four toroidal sections (27°, 147°, 267°, 326°) and F during a DRE of fig.1.

are present only in a small fraction of the DREs and often not simultaneously. As common to other RFP experiments the soft x-Ray emission presents, during the crash, a large decrease in the core region while for r/a>0.6 the emission increases, showing a cooling of the plasma core and a large radial energy transport. When present, the density fluctuations are always in phase with the toroidal magnetic flux generation. The multi-chords interferometer shows that the fluctuations correspond to a density increase on the whole plasma section that is larger on the external region. This density increase is due to a larger plasma wall interaction, as confirmed from the increased hydrogen and carbon fraction deduced by spectroscopic measurements. This is different from what observed in the MST experiment [6] where, during the DRE crash, the density decreases in the core and increases in the edge region. This difference is probably due to a stronger plasma wall interaction in RFX than in MST and to the presence of graphite first wall in RFX that is able to produce a large influx. Statistically the usual dependence of the DRE amplitude from the pinch parameter, fig. 2, has been confirmed.

Analysing in more detail the magnetic field configuration one can see that the wall locked mode, WLM, which characterises all RFX discharges, affects most of the reconnection process. A clear effect is observed on the non axis-symmetric toroidal flux regeneration. The poloidal voltage (fig. 3) starts to increase and reaches the maximum value first on the measurement section closer to WLM position (for this discharge Φ_{WLM}=160°) then moves in direction opposite to the plasma current with an approximate toroidal speed of 30 km/sec. It is interesting to note that there is some indication that the flux starts to increase on a toroidal angle slightly smaller than the WLM position. Indeed when the poloidal voltage measurement is at the same position of the WLM a noisy signal it is often observed. This phenomenon is similar to what observed in T2 [3], it differs only in that in RFX the poloidal voltage keeps its shape as it propagates toroidally, while, in T2, it spreads out in time and angle. Since in the MST experiment, which has a size similar to RFX, no spread was observed [2] while it was observed on the smaller ZT-40M [7], probably, the way the flux symmetrises toroidally depends on the S values with no spread for large S values. This is partially confirmed by the RFX data: some spread out is found for DREs occurring during the plasma ramp down phase when the S value is smaller. The reason why the poloidal voltage increase is first observed on a section closer to WLM (but not at the same position) can be obtained from the analysis of the stationary m=0 perturbation associated to WLM [8]. The analysis shows the presence of non axis-symmetric poloidal currents that have a maximum about 10° toroidally before the WLM position. These WLM m=0 poloidal currents can be the source (for example by shrinking the plasma core) of the internal m=1 reconnection.

We can now analyse the time evolution of the toroidal magnetic field modes during a DRE (see fig. 4 for the shaded time interval on fig. 1). For this discharge during a DRE the

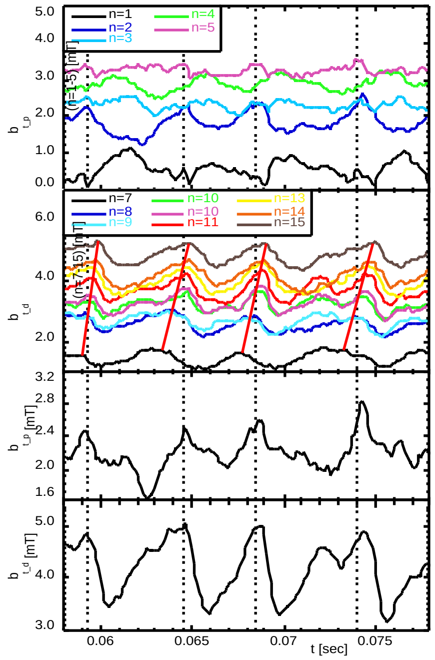

Fig. 4 Even (n=1-5), odd (7-15) toroidal magnetic field modes, and total even and odd toroidal magnetic field fluctuation.

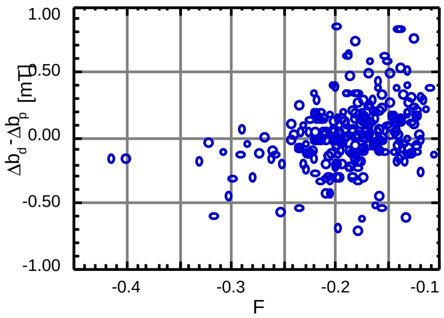

Fig. 5 Dependence of the difference between the amplitude variation, after and before the DRE, of the odd and even toroidal field fluctuation.

amplitudes of the odd and even magnetic field fluctuations increase simultaneously with a larger variation for the odd modes. Analysing in detail the various modes, it is possible to see a cascading mechanism for the odd modes: first the n=7 mode starts to increase and then, with a delay of about 0.1÷0.2 ms between each mode, the larger n modes increase too. The even modes, on the contrary, do not show any regular sequence in their temporal evolution. Such behaviour is frequent on discharges with F≥-0.2. For deeper reversal the situation is typically different: the odd and even modes increase simultaneously and the total amplitude variation is larger for the even part of the magnetic field. The previous behaviour may be interpreted in the following way. Indeed at shallow reversal (or for low pinch parameter value) the reconnection process may start with the first resonant mode, n=7 in our case, which is very close to the axis. Then it proceeds with higher n modes resonanting closer to the edge. At deeper reversal the n=7 mode is not any more resonant (as indicated by the μ&p model profile reconstruction), in such cases the first resonant mode is far from the center and much closer to the others, which would facilitate their contemporary action. The dependence of the magnetic dynamics from the magnetic configuration has been confirmed from the statistical analysis of the spontaneous DREs. Although the data are affected by the presence of some non standard DRE, in fig. 5 it is possible to see that for values of reversal parameter higher than -0.15 the variation of the odd part of the toroidal field magnetic fluctuation is on the average larger then that of the even part, while for F<-0.2 the even part becomes dominant. This result is in agreement with the nonlinear MHD simulations that show an increasing importance of the m=0 modes at deeper reversal [9].

III. EXTERNALLY INDUCED DRE

Up to now we have described the characteristics of the spontaneous DRE. It is also interesting to show the dynamo events that are externally induced. One of the most interesting cases is the DRE induced by a fast rotating modulated external toroidal magnetic field. This rotating field, obtained by varying the current in the external toroidal field coils, is produced to rotate the position of the WLM [10]. Due to the time constant of the RFX vessel, which reduces the amplitude of the time modulated external perturbations, the higher rotating frequencies are unable to rotate the WLM position. In those cases the plasma responds to the rotating external m=0 perturbation producing a DRE when the rotating modulation increases the absolute amplitude of the external toroidal field. When the WLM is

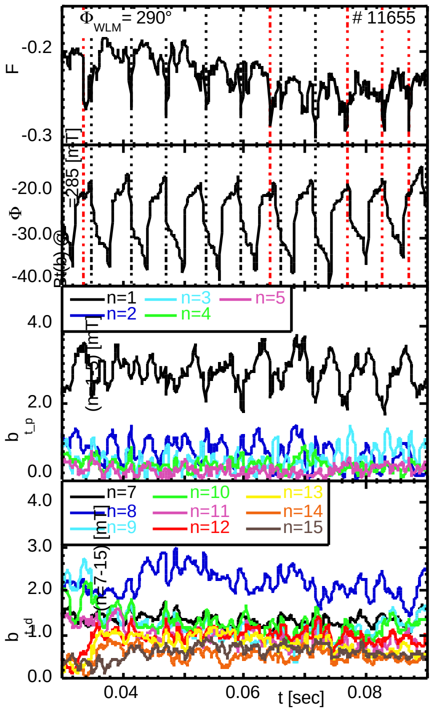

Fig. 6 Reversal parameter F, toroidal magnetic field on WLM position, even (n=1-5) and odd (7-15) toroidal magnetic field modes. The black dashed lines show DREs produced by the external perturbation while the red dashed-dotted lines shown the spontaneous DREs.

positioned at one of the two poloidal shell gaps, nearly every time the external perturbation reaches the WLM position a DRE is induced (fig. 6). When the WLM is out of the gaps the correspondence is partially lost. The reason why the external perturbation produce a DRE can be understood in the same framework previously used to explain the toroidal reconnection starting point. In fact the external modulated toroidal field compresses the plasma, when the compression act on the shrinking position produced by the WLM m=0 mode the reconnection is induced.

Another way to induce a DRE in RFX is by injecting a pellet [11]: usually when the pellet reaches the plasma core a DRE is induced, degrading the confinement. The mode analysis shows that the dynamic is similar to what described for the spontaneous DREs. This seems to indicate that the only effect of the pellet is to speed-up the current peaking process that is the origin of the instability that drives the mode growth.

IV. CONCLUSIONS

In RFX dynamo reconnection events are observed in many conditions showing features similar to what previously observed in other RFP experiments. Indeed we may find a large variety of behaviours which are sometimes difficult to explain in terms of the available models, many discharges exist that do not show any DRE although they are very similar to discharges that show clear DREs. In any case it is seen that the RFX magnetic configuration can be sustained by a quasi continuum reconnection process (characterised by very low amplitude DRE) or by the sharper discrete dynamics associated with the helical deformation.

A new kind of externally induced DREs as been found in RFX, their presence and effect on plasma confinement have to be considered when controlling the plasma by external means.

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