Magnetic reconnection events in RFX-mod high current plasmas

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Introduction. Magnetic reconnection is a basic process involving a topological rearrangement of the magnetic topology observed in almost all magnetized plasmas, including those relevant for controlled nuclear fusion experiments. The magnetic energy released during reconnection events is converted into thermal or kinetic energy. Reconnection usually develops suddenly, following a longer period in which the magnetic field is almost stationary or changes slowly. This occurs commonly in astrophysical plasmas, where impulsive reconnection interrupts a slower evolution of the field, but a similar phenomenology is observed in fusion plasmas too [1]. For instance, anomalous ion heating during magnetic relaxation phenomena has been reported from spherical tokamaks like MAST [2], TST2 [3], CTX [4] SPHEX [5] and HIT-II [6]. Many results have been obtained also from reversed field pinch devices (RFP) [7] during the past years. Indeed, already in ZT-40M [8], an extra ion heating has been associated to fluctuations driven in the plasma under deep reversal of the main toroidal field; in REPUTE-1 [9] a strong heating of impurity ions has been observed at low electron density in correspondence of magnetic field fluctuations. More recently, the Madison Symmetric Torus experiments (MST) provided new details about discrete reconnection events and the corresponding decay of the stored magnetic energy and increase of ion temperature [10].

A further contribution comes from RFX-mod [11], the largest RFP in the world (major radius R_0=2m and minor radius a = 0.459m) and the one with the highest plasma current, up to 2 MA. Preliminary analyses on magnetic reconnection in RFX-mod have been reported in [12] and [13]; the latter in particular deals with those events associated to the partial or complete transition from a helical to an axisymmetric magnetic topology in hydrogen plasmas. These studies have been recently extended to a larger database and taking into consideration deuterium plasmas too.

Phenomenology of reconnection events. Helical configurations in RFX-mod are usually characterized by a poloidal and toroidal wave number m=1 and n=−7 respectively, corresponding to the innermost resonant tearing mode (i.e. the dominant mode). An example of its amplitude time evolution (toroidal component at r =a, b_7 here after) is reported in Fig.1(c)

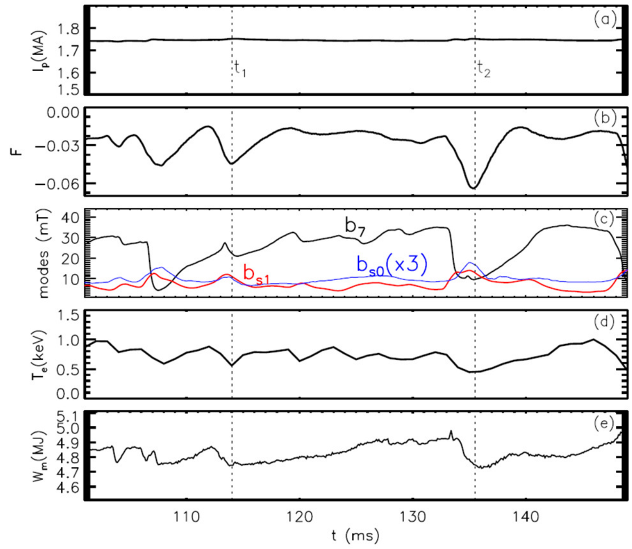

Figure 1. *From the top: plasma current (a), reversal parameter F (b), magnetic modes evolution (c), core electron temperature (d) and magnetic energy (e) during the flattop phase of a hydrogen RFX-mod discharge.*

during the flattop phase of a typical high current discharge (I_p = 1.75 MA, panel *a*). In the same panel the rms of the other m = 1, n= -8,-9… -24 and m = 0, n=1,2…12 modes is also shown (b_{s1} and b_{s0} respectively, the secondary modes). Reconnection events occur in correspondence of partial (e.g. at t_1=113ms in Fig.1) or total (e.g. at t_2=136ms) interruptions of those phases where $b_7 >> b_{s1}$. These are associated to a fast decrease of the reversal parameter F (panel *b*) i.e. the ratio between the toroidal field B_T at the edge and its average value inside the plasma volume, to a decreasing of the core electron temperature (panel *d*) and to a drop of the magnetic energy W_m (panel *e*) given by the formula:

$$W_m = \frac{4\pi^2 R_0}{2\mu_0}\int_0^a (B_T^2 + B_P^2) r dr \quad (1)$$

where the toroidal (B_T) and poloidal (B_p) equilibrium magnetic fields radial profiles are calculated with a force free equilibrium model [7]. The phenomenology is similar both in hydrogen and deuterium shots. In this paper a database of discharges with $0.8 < I_p < 2$ MA, and electron density n_e = 1–4 × 10^{19} m^{-3} is considered. Fig.2-(a) shows the variation of magnetic energy $|\Delta W_m|$ during reconnection events as function of plasma current for hydrogen and deuterium plasmas. In general $|\Delta W_m|$ ~ 5-200kJ with higher values more frequent at larger I_p. It is worth to note that in the range of plasma current available for both hydrogen and deuterium (between 1.25 and 1.4MA) the variation of $|\Delta W_m|$ is similar for the two isotopes. This is even more evident from panel (b) of the same figure reporting the corresponding distributions of $|\Delta W_m|$ (normalized to the respective number of events). The maximum in $|\Delta W_m|$ observed for hydrogen (70kJ) is very close to the one for deuterium (50-60kJ),

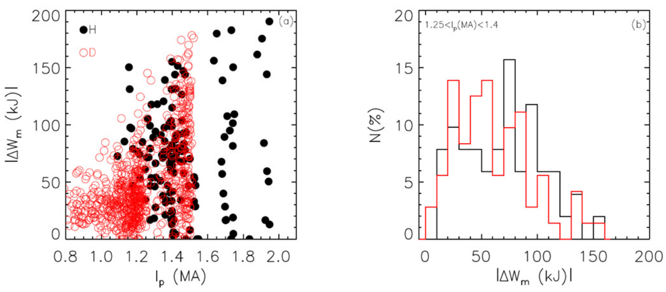

Figure 2. *(a) Magnetic energy variation as function of plasma current for hydrogen (black) and deuterium (red) RFX-mod discharges; (b) distribution of the magnetic energy variation for the two isotopes in the common range of I_p available (1.25-1.4MA).*

A similar analysis has been performed for the variation of the core electron temperature T_e and of the electron thermal energy $U_{TH,e}$ during reconnections. The overall behaviour of the electron temperature decay is similar in H and D plasmas, even in presence of significant variations of T_e from shot to shot. The same holds also for $\Delta U_{TH,e}$ which is between -5kJ and -20kJ for both gases.

Energy balance during reconnections. The data collected for $\Delta U_{TH,e}$ and ΔW_m, together with other quantities like the loop voltage V_T, the plasma current and the radiated power P_{rad}, have been used to estimate the amount of energy released during reconnection events which could be involved in ion heating and in other processes like particle acceleration. To this end the energy balance equation can be written as:

$$\frac{\partial U_s}{\partial t} + \frac{\partial U_{TH,e}}{\partial t} = \int (S_0 - \nabla \cdot Q_e - H_e)\, dV \qquad [2]$$

to be solved for the quantity U_s which takes into account of the ion thermal energy, of the terms involving ion heat diffusion/convection and of particle acceleration from suprathermal electrons and ions. The volume integral of S_0 includes the sources (ohmic heating and ΔW_m) and sinks (P_{rad}) of energy and Q_e and H_e are the electron heat diffusion and convection terms respectively. As discussed in [13] convection terms are quite small, of the order of few tens of Joule, so they are neglected in the following. The electron heat diffusion term is evaluated assuming that the electron thermal diffusivity scales with the amplitude of the secondary modes as $\propto b_s^{1.5}$; indeed, as shown in [14], due to the peculiar magnetic field structures typical of RFX-mod, the transport coefficients have been found not to follow a simple Rechester Rosenbluth dependence [15]. Fig.3 reports the results for U_s in both hydrogen and deuterium plasmas. In particular, panels (a) and (c) show that the radiated energy together with electron energy terms (mainly heat losses) roughly scale with the ohmic input during the reconnection time, both for hydrogen and deuterium. On the contrary, the term U_s - in panels (b) and (d)- scales well with ΔW_m, suggesting that the decay of magnetic energy is a source of energy possibly involved in ion heating (and ion heat losses) or particle acceleration. Again, no

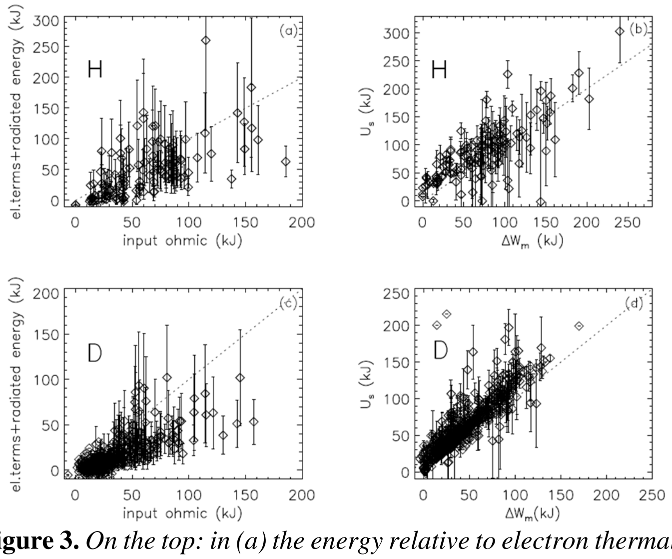

Figure 3. *On the top: in (a) the energy relative to electron thermal energy/heat losses and radiated power as function of the input ohmic during reconnection events in hydrogen discharges; in (b) the quantity U_s as function of the variation of magnetic energy during reconnections. In (c) and (d) similar plots for deuterium plasmas.*

substantial differences are found between H and D.

Ion temperature profile reconstruction. Experimental evidences of ion heating during reconnections come from the neutral particle analyzer (NPA) diagnostic [16] and from the DD neutron detection in deuterium plasmas. In particular, the NPA diagnostic resolves the energy distribution of the neutral particles produced by charge exchange (CX) processes and leaving the plasma. These data have been used as inputs to estimate the changes in the ion temperature profile during a reconnection event at low I_p (1.3MA), as explained in [13] for a hydrogen discharge. The results are shown in Fig.4 reporting a comparison between the resulting T_i profiles across the reconnection event together with the T_e measured by the diagnostic DSX3 (Diagnostic Soft-X-rays 3-arrays) using the double filter technique [17]. Before the crash $T_i \sim T_e$ whereas just after the crash (+ 0.5 ms) T_e decreases but T_i increases in $r/a < 0.6$ with $\delta T_i(0) = +250$ eV, showing that the ion heating mechanism is mainly concentrated in the core region. At t = +3 ms after the event the T_i profile decreases, a clear sign that the ion heating due to the reconnection event is not present anymore. The corresponding enhancement of ion thermal energy is in the range 0.5–0.7 kJ, much lower with respect to the decay of magnetic energy during the reconnection (about 10kJ in this case), thus suggesting that a fraction of the released energy might be involved in particle acceleration and ion heat loss mechanisms. Further analysis for deuterium are still in progress to determine if an isotopic effect is present in the ion heating process during the reconnection events in RFX-mod.

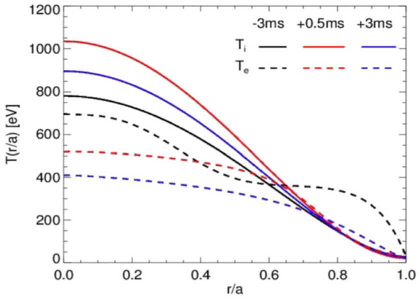

Figure 4. *Ion and electron temperature profiles before the crash, at the reconnection event and after 3 ms.*

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