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Ion heating and energy balance during magnetic reconnection events in the RFX-mod experiment

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Magnetic reconnection is a basic process involving a topological rearrangement of the magnetic field lines on a time scale faster than allowed by classical dissipation mechanisms; it is observed in almost all magnetized plasmas, including those relevant for controlled nuclear fusion experiments [1]. The magnetic energy released during reconnection events can be dissipated - thus contributing to thermal energy by direct heating - or converted into kinetic energy and particle acceleration. Reconnection usually develops suddenly, following a longer period in which the magnetic field is almost stationary or changes slowly. This occurs in astrophysical plasmas, such as the solar corona and the earth's magnetosphere, where impulsive reconnection interrupts a slower evolution of the field. A similar phenomenology is common also to tokamak and reversed field pinch (RFP) devices.

Aim of this contribution is to characterize the reconnection events in high current RFP plasmas associated to the partial or complete transition from a helical to an axisymmetric magnetic topology. The latter is typical of RFP configurations characterized by many resonating MHD Tearing Modes of similar amplitude (Multiple Helicity or MH regime); when one of these instabilities dominates the magnetic spectrum, leading to a helical deformation of the core flux surfaces, the plasma enters in the so-called quasi-single helicity state (QSH) [2].

The analyses here reported come from RFX-mod [3], which is at present the largest RFP experiment with major/minor radius of 2 m / 0.459 m, equipped with an advanced system of 192 feedback saddle coils for the control of MHD instabilities. The helical configurations in RFX-mod are usually characterized by a poloidal and toroidal wave number m=1 and n= -7 respectively (example in Fig. 1(a)), corresponding to the innermost resonant tearing mode (i.e. the dominant mode). Although QSH states can last even ten times longer than the typical energy confinement time (1-2ms), back-transitions from helical to MH states occur and are predicted by numerical simulations too: this intermittent behavior involves a reconnection process [4], as proved by the associated fast variation of the toroidal field. The duration of helical states and the amplitude of the dominant mode increase with the Hartmann number, which, in the RFX database, scales with the Lundquist number; conversely, the other magnetic perturbations (i.e. secondary modes) decrease thus reducing the level of stochasticity. During QSH phases in RFX-mod plasma electron transport barriers (eITB) can build up with maximum gradient between 2 and 6keV/m and core electron temperature up to $T_e = 1.5keV$ [5].

The QSH regimes in RFX-mod are interrupted both by major reconnection events (e.g. around 65ms in Fig.1(a)) where the dominant mode amplitude decreases by about 90% in few hundreds of ms (that means a full transition to a MH regime) and by minor drops (about 10%, e.g. at 60ms in Fig.1 (a)) which do not determine a total loss of the helical topology. Reconnection generally manifests itself as a burst of magnetic fluctuations with m=1, n< -7; only for complete QSH-MH transitions this is accompanied by a sudden increase of m=0 modes (Fig.1(a), dotted line).

A deeper understanding and a better characterization of these events is important since they play a significant role in the power balance, thus affecting the plasma confinement. To this end the variation of the magnetic energy ΔW_M associated with the equilibrium magnetic fields during a crash of the dominant mode has been computed (an example is shown in Fig.1(c)). The time average of such a quantity, i.e the dissipated power (P_{rec}) due to reconnections, is compared with the mean ohmic input power $P_{in} = V_{loop} I_p$, where I_p and V_{loop} are the plasma current and toroidal loop voltage, the latter computed also including the variation of the plasma inductance term [6]. In RFX-mod discharges with plasma current between 1.2 and 2MA and n/n_G in the range 0.1-0.5 (n and n_G are the electron and Greenwald density), P_{rec} amounts to a fraction between 30% and 60% of P_{in}. Moreover, back transitions from QSH to MH states are characterized by a fall of the electron thermal energy, as observed thanks to high time resolution electron temperature profile (T_e) measurements (Fig 1(b)). The decrease of T_e varies significantly from case to case and might affect the core and the mid/edge region of the plasma in different ways. Important changes of T_e (down to -40%) are observed also during minor reconnection events when the dominant mode decay is very small (≈ -10%) and this is related to the localized phase locking of increasing secondary modes which severely deteriorates the confinement [7]. This happens despite the magnetic topology keeps an almost global helical shape.

The fall of T_e profiles during partial and total MH back transitions shows that the magnetic energy dissipated by reconnections is not converted into electron thermal energy; moreover, also the radiative power (P_{rad}) generally does not vary significantly during these events and thus provides a limited contribution to the energy balance (5-10%) [7]. On the other side, there are several evidences that, especially in major MH back transitions, a fraction of the dissipated magnetic energy could be involved in ion heating and acceleration: this is indicated both by the Neutral Particle Analyzer (NPA) diagnostic [8] - which estimates the ion temperature from the distribution function of the neutral atoms - and DD neutron detection. Similar results have

been found also in other RFP devices, like the Madison Symmetric Torus, where the drop in magnetic energy during reconnection events is sufficient to explain the growth of the ion thermal energy [9], which is a rather interesting feature in a reactorial perspective. Thus, a further aim of this work is to verify if the dissipated energy during MH back transitions, once cleaned of the variation of known quantities (thermal and magnetic energy, outgoing energy by radiation or heat/particle diffusion and the flux of energy associated to the Poynting vector through the plasma surface), is compatible with the estimated change in the ion thermal energy. These items will be further investigated with dedicated experiments and new diagnostics in RFX-mod2, an upgrade of the present device currently under implementation [10], which will be characterized by modified boundary conditions likely influencing the helical states duration and the amount of energy losses associated to MH back-transitions.

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