ION HEATING AND ENERGY BALANCE DURING MAGNETIC RECONNECTION EVENTS IN THE RFX-MOD EXPERIMENT

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Abstract

Reconnection events in high current reversed field pinch plasmas are often associated to the partial or total loss of the helical magnetic topology. The electron temperature collapse during these phenomena is investigated in RFX-mod thanks to high time resolution soft-x-ray diagnostics; these data are used together with magnetic energy reconstructions to characterize the energy balance associated to reconnection events. The modified boundary conditions in RFX-mod2, an upgrade of the present device starting its operations from 2022, are expected to increase the helical states duration and reduce the frequency of the back-transitions to chaotic regimes, thus positively affecting the performance of the device. The paper also shows that the energy released during reconnection events, similarly to astrophysical plasmas, might be involved in ion heating, the latter being estimated by the energy distribution function of neutral atoms, a rather interesting feature in a rectorial perspective.

1. INTRODUCTION

Magnetic reconnection is a basic process involving a topological rearrangement of the magnetic field lines on a faster time scale with respect to the 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 fusion plasmas as observed in tokamak and reversed field pinch (RFP) devices [2]. Reconnection events in high current RFP plasmas are often associated to the partial or complete transition from a helical magnetic topology to a configuration characterized by many resonant 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) [3]. The characterization of the magnetic energy variation and of electron temperature \( T_e \) evolution during the reconnection processes is important since they play a significant role in the power balance, thus affecting the plasma confinement. In addition, there are several evidences that a fraction of the dissipated magnetic energy might be involved in ion heating and particle acceleration. In the next section of the paper the total and partial QSH-MH back transitions in RFX-mod are characterized both from the point of view of the magnetic energy evolution and of the power dissipated. In section 3 the attention is focused on the electron temperature dynamic during the reconnections and these data will be used in Section 4 to estimate the energy amount which might be involved in ion heating; the latter quantity is compared with experimental measurements of ion temperature available for few cases. Finally the conclusions are drawn in Section 5.

2. MAGNETIC ENERGY VARIATION IN RFX-MOD RECONNECTION EVENTS

The analyses here reported come from RFX-mod [4], which is at present the largest RFP experiment with major/minor radius of 2m/0.459 m respectively, 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, corresponding to the innermost resonant tearing mode (i.e. the dominant mode). 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 resonant magnetic perturbations (i.e. the secondary modes) decrease thus reducing the level of stochasticity [5].
dominant mode crashes:

- variation of the dominant mode between major and minor reconnections has been performed; while the former are characterized by a relative state on the associated magnetic energy variation. To this end a selected database of hydrogen discharges plasma core (i.e. the \( m=1 \) for random phases)

\[ m=1 \]

instabilities between the radially distributed tearing reconnection process; then structure might act as a possible trigger of the events in high.

A recent study on major reconnection events in high current RFX-mod plasmas [7] points out that a tiny growth of the helical structure might act as a possible trigger of the reconnection process; then, the interaction between the radially distributed tearing instabilities determines a phase locking of the \( m=1 \) modes as quantified in panel (e) by the locking strength, a parameter which range from 1, when all the considered secondary modes are in phase, to 0 for random phases. Reconnection starts at the locking position and is followed by a fast growth of \( m=1.0 \), as reported in panel (d). The timing of the perturbations dynamic suggests that such a process involves first the plasma core (i.e. the \( m=1 \) modes) and then propagates toward the edge (i.e. the \( m=0 \)).

In the following the attention is focused on the role played by both large and small perturbations of the helical state on the associated magnetic energy variation. To this end a selected database of hydrogen discharges (about 20 shots, \( 0.8< I_p < 2\text{MA} \), \( n_e = 1.4 \times 10^{19} \text{m}^{-3} \)) with different plasma current is considered and a systematic distinction between major and minor reconnections has been performed; while the former are characterized by a relative variation of the dominant mode \( \Delta b_s / b_s \) between -60% and -80% during the crash, the latter range in the interval: -40% \( \leq \Delta b_s / b_s \leq -10\% \). Another relevant quantity for energy balance analysis is the frequency \( \nu_b \) of the dominant mode crashes: for total QSH-MH back transitions \( \nu_b \) increases from 20 to 60 events/second in discharges with \( I_p \) between 0.8MA and 1.2MA and then saturates to about 80/s up to 2MA. The frequency of minor reconnection events, on the contrary, is characterized by a large variation at each \( I_p \) value, between 20/second and 80/second with greater values more likely to occur only at \( I_p > 1.2\text{MA} \).

The magnetic energy \( W_m \) is computed in cylindrical geometry by the following equation:

\[
W_m = \frac{4\pi^2R_e}{2\mu_0} \int_0^a (B_r^2 + B_\theta^2) r \, dr
\]

where the toroidal \( B_t \) and poloidal \( B_\theta \) equilibrium magnetic fields radial profiles are calculated with a force free equilibrium \( \mu & p \) model [2]. The contribution to magnetic energy given by perturbations is neglected since it amounts to
less than 0.002% with respect to equilibrium fields. An example of $W_m$ time evolution is reported in Fig.1-(c): it slowly increases between two reconnections and rapidly drops at the crashes. The decay of $W_m$ might vary from case to case: for the major crash at $t=t_1$ $\Delta W_m = -0.2$ MJ while for the minor ones generally $|\Delta W_m| < 0.05$ MJ with higher values more common during the rising phase of the dominant mode (e.g. at $t=t_0$). The effect of a finite pressure has been tested for a subset of cases by using a modified μ&ρ model where also the experimental electron temperature $T_e$ measured by soft-x-ray double filter technique [8] - is included.

The corresponding magnetic energy $W_{m,TH}$ results systematically slightly lower than $W_m$, i.e. $\left(W_m/W_{m,TH}\right)W_m \approx 2.5\%$ so that $\Delta W_m \approx \Delta W_{m,TH}$ (dotted line Fig1- (c)); for this reason in the next sections of the paper all the results are referred to magnetic field profiles computed in force free approximation.

The results obtained for $\Delta W_m$ over the database here analyzed are displayed in Fig.2-(a) both for major (full dots) and minor (empty circles) reconnection events as function of $I_p$. While for major crashes a quasi linear decrease of $\Delta W_m$ with $I_p$ is found, from -0.1MJ at $I_p \approx 1$ MA to -0.25MJ at $I_p>1.6$ MA, on the contrary a clear dependence is not observed for the minor reconnection events which range between 0 and -0.1MJ at all $I_p$ values. The decay of magnetic energy at the crashes scales with the amplitude of secondary modes as reported in panels (b)-(c); nevertheless, the minor crashes with little to no change in magnetic energy ($|\Delta W_m| \leq 0.02$ MJ) are often characterized by a negligible variation of the $m=0$ amplitude too (i.e. they belong to the category of events like the one at $t=t_2$ in Fig.1).

The data on $\Delta W_m$ have been used to estimate the associated power dissipated $P_{diss}$ because of reconnection events in a single discharge by summing over each crash category (major and minor) the average magnetic energy variation $<\Delta W_m>$ multiplied by the corresponding average frequency $<\nu_{\delta}>$. The fraction of the total $P_{diss}$ with respect to the mean input power $P_m$ is between 25% and 50% and, as shown in Fig.3, increases with the plasma current. These results are very similar to those obtained in the reversed field pinch Madison Symmetric Torsor [9] for magnetic reconnections during sawtooth oscillations consisting of a fast crash phase followed by a slow recovery. Despite the different order of magnitude of the plasma current and magnetic field, also in MST the energy dissipated during these relaxation events is on average about one half of the input power.

The reduction of the secondary tearing modes amplitude expected with the upgrade of the boundary conditions in RFX-mod [10] should increase the helical states duration and make the back-transition events less frequent thus positively affecting the performances of the device.

3. ELECTRON TEMPERATURE DYNAMIC DURING RECONNECTION EVENTS

During QSH phases in RFX-mod plasmas, electron transport barriers (eITB) build up with maximum gradient between 2 and 6keV/m and core electron temperature up to $T_e=1.5$keV [8]. QSH-MH back transitions are accompanied by a strong decrease of the $T_e$ profile, as shown in the example of Fig.4 (right-hand side) reporting data from the high frequency soft-x-ray double filter diagnostic (DSX3); this happens not only at major reconnections (e.g. at $t=t_2-t_3$) but also at minor crashes of the dominant mode (e.g. at $t=t_0$ and $t_1$). In both cases, as the secondary modes start to increase, the eITB is rapidly lost as confirmed by the fast drop of the electron temperature gradient in panel (c). Nevertheless, during minor crashes, the fall of $T_e$ is generally below the 25-30%; on the contrary full QSH-MH back transitions are often characterized by a total flattening of the profile with the core $T_e$ reduced of more than 50%. This behaviour is statistically confirmed in the analyzed database as can be observed in Fig.5 reporting the relative change of the core $T_{e0}$ with respect to the pre-reconnection value $T_{e0}$ in panel (a) and also the corresponding variation of the thermal energy $\Delta U_{Th,e}$ in panel (b).
In particular, major reconnections are characterized by a relevant dispersion of $\Delta T_{ew}/T_{ew}$ with values which can decrease down to -80%; more limited is the relative temperature decay during minor crashes. The cases with a large decrease of $T_{ew}$ are more common at magnetic energy variation below -0.1MJ and so, as discussed in the previous section (Fig.2), correspond to a greater growth of the secondary $m=1.0$ modes amplitude i.e. to an enhanced level of magnetic stochasticity in the plasma. This is shown for a couple of examples in Fig.6 reporting the Poincarè plots at a fixed poloidal angle ($\psi_p$ is the poloidal flux coordinate while $\xi$ is the toroidal angle) obtained by the guiding center code ORBIT [11] at different times during a major (a) and minor reconnection event (b). At $t=78$ms a clear structure with periodicity $m=1$ and $n=7$ is visible in the inner core of the plasma, confirming the helical deformation of most the volume. Already at $t=78.3$ms, when the secondary modes have grown from $\approx 2$ to $\approx 5$mT, the conserved surfaces are partially destroyed due to secondary islands getting larger; finally, at $t=78.5$ms the plasma is dominated by magnetic chaos. This means a significant worsening of confinement properties with the vanishing of eITB and an increase of heat losses to the wall. During a minor crash of the dominant mode the dynamic is similar, however in this case a small region with conserved surfaces still survives (e.g. at $t_b=125.9$ms). The surviving of a small conserved structure might explain why in minor events the fall in $T_p$ is less dramatic than in full QSH-MH back-transitions. The results reported above (Fig.5-6 and also Fig.2-(b)-(c)) show that, because of the fast stochasticization of the field during QSH-MH back transitions, the electron thermal energy is rapidly lost from the plasma. Similar results are seen in the topological structure of edge $m=0$ islands during these events in RFX-mod, with a threshold for the stochasticization of the SOL approximately equal to $b_p/b_1,\gamma=0.3$ [12]. The decay in the magnetic energy during the reconnection thus is not feeding the electron thermal component; nevertheless, a possible conversion of $W_m$ into kinetic energy could be relevant for suprathermal electrons - which are not detected by the DSX3 diagnostic- or, more in general, for particle acceleration. Thanks to the availability of diagnostics dedicated to neutral atoms energy characterization is possible to extract -at least for a subset of cases- some information on the ion temperature variation during the reconnection events which can be compared with the amount of energy dissipated associated to these phenomena, as will be discussed in the next section.

4. ENERGY BALANCE AND ION HEATING

The data presented so far are here used to estimate the “surplus” amount of energy resulting during a reconnection event which could be involved in ion heating and in other non-thermal processes like particle acceleration. The total magnetic energy of the plasma must satisfy the following conservation equation:

$$-\frac{dW_m}{dt} = \int_{\Sigma} S \cdot \mathbf{v}_E d\Sigma + \int_{\Sigma} E \cdot \mathbf{B} dV = -l_{\phi} V_\phi + l_p V_p - P_{\text{diss}}$$

where $\mathbf{S}$ is the Poynting vector, $\mathbf{v}_E$ is the unit versor perpendicular to the plasma surface $\Sigma$ and $P_{\text{diss}}$ is the energy dissipated in the plasma for unit of time. $\mathbf{E}$ and $\mathbf{J}$ are the electric field and current density in the plasma, $I_{\phi}$, $I_p$ the poloidal-toroidal (plasma) current respectively and $V_\phi$ and $V_p$ the poloidal and toroidal voltage; the expression is solved in cylindrical geometry. Focusing on the time $\Delta t_{\text{rec}}$ during a reconnection event, and handling for sake of clarity with absolute values, the equation above can be written as:
so that $P_{\text{diss}} \Delta \tau_{\text{rec}}$ is the energy which can actively heat electrons, ions or being dissipated by radiation, conduction and convention mechanisms during the reconnection time. In the following the known processes in the energy transport are separated from those which have not been directly quantified or measured. The former are relative to terms involving electron thermal energy, the latter might concern ion thermal heating or particles acceleration (i.e. suprathermal ions/electrons generation). The volume integrated energy diffusion equation is then written as:

$$\frac{\partial U_s}{\partial t} + \frac{\partial U_{Th,e}}{\partial t} = \int_V \left( S_0 - \nabla \cdot Q_e - \Gamma_e \right) dV$$

with $U_{Th,e}$ the electron thermal energy, $S_0$ the source/sink of energy, $Q_e$ the electron heat diffusion term and $\Gamma_e = \nabla \cdot \left( \frac{1}{2} \frac{m_e}{2} \nabla T_e \right)$ the electron convection term. Sources correspond to the energy dissipated ($P_{\text{diss}}$) while the sinks are the losses because of radiation ($P_{\text{rad}}$). The unknown term $U_i$ takes into account the total energy density not included in the thermal electron one. By integrating over the volume and expressing the conduction and convection terms in cylindrical geometry this equation gives the explicit variation of $U_i$ in the time $\Delta \tau_{\text{rec}}$.

$$\Delta U_s = (I_T V_e - I_0 I_0) P_{\text{rad}} \Delta \tau_{\text{rec}} + \Delta W_m + \Delta U_{Th,e} - 4 \pi^2 a R_0 n_e(a) \left( \chi_e(a) \left| \frac{\partial T_e}{\partial r} \right| \right)_{r=a} + v_r(a) T_e(a) \Delta \tau_{\text{rec}}$$

where $\Delta U_{Th,e} = \Delta U_{Th,i}$ (since $T_e$ always decreases at partial/total QSH-MH back transitions). All these quantities are averages during the reconnection time. Most of the terms on the right-hand side have been directly measured or estimated by models, some of them like $\Delta W_m$ and $\Delta U_{Th,e}$ are those reported in the previous sections. The quantity $P_{\text{rad}}$ is determined by bolometric measurements and generally is in the range 2-6MW in RFX-mod high current discharges as shown in [12]. The estimate of diffusion and convection terms is more difficult given the great uncertainty in the quantity $v_r(a)$ and $\chi_e(a)$. The latter has been well evaluated during the QSH phases before reconnection and the results are reported in [13] ($\chi_{e,\text{QSH}}(a) \approx 80-100 \text{m}^2/\text{s}$). Since during back transitions both $m=1$ and $m=0$ modes increase, it is assumed for $\chi_e(a)$ a Rechester Rosenbluth [14] dependence i.e. a scaling with the mean square root of the secondary modes i.e. $\chi_e(a)/\chi_{e,\text{QSH}}(a) \propto \left( b_{k,\text{rec}}/b_{k,\text{QSH}} \right)^2$ where $b_{k,\text{rec}}$ is the rms of $m=0,1$ modes at the reconnection and $b_{k,\text{QSH}}$ the same quantity but evaluated just before the crash.

Measurements of electron density and temperature at the edge ($n_e(a), T_e(a)$) are provided by the thermal helium beam diagnostic [15] only in few shots and do not show relevant variations; the values assumed here for all the cases are: $n_e(a) = (0.8 \pm 0.5) \times 10^{19} \text{m}^{-3}$, $T_e(a) \approx 30 \text{eV}$ and $\left| \frac{\partial T_e}{\partial r} \right|_{r=a} = (2 \pm 0.5) \text{keV/m}$. Thus, the electron heat diffusion term varies between a minimum of 30MW and a maximum of 50MW with most of the contribute depending on $\chi_e(a)$ (i.e. on the secondary modes amplitude). Measurements for $v_r(a)$ in RFX-mod are reported in [16] and are generally below 5m/s during a stationary phase of the helical states; nevertheless, given the low electron temperature at the edge, the convection term is quite small in comparison to others (3-9kW) and can be neglected. Finally, the reconnection time $\Delta \tau_{\text{rec}}$ has been evaluated for each event of the database looking at the F crashes variation: they range between a minimum of 0.8ms for fast reconnections to 2ms for the slowest ones. For minor crashes this quantity is partially reduced: between 0.5 and 1.3ms.

FIG. 7 (a) Statistical distribution of surplus energy for the major reconnection events analyzed in this paper; (b) surplus vs magnetic energy variation both for major (black dots) and minor (red dots) crashes.
The results for $\Delta U_i$ are reported for full QSH-MH back transitions in Fig.7: their statistical distribution has a maximum around 50kJ but the few data on the far right, up to 150-200 kJ, show that there are events where a small increase of the magnetic modes amplitude (i.e. low $X_r(a)$) combined with a strong variation of $\Delta W_m$ might result in a significant amount of energy not related with thermal electrons or radiation emission. In panel (b) $\Delta U_i$ is reported as a function of the corresponding decay of magnetic energy $\Delta W_m$ and the evaluation has been performed also for a subset of minor reconnection events (red empty circles) considering only the cases with a variation of $b_\parallel$ and $\Delta W_m$ significantly different from zero. This computation shows that there are a relevant fraction of magnetic energy lost during reconnection which might be available for other heating/acceleration processes. It is worth to note that the presence of plasma-wall interaction could lead to very localized increase of radiation and of thermal load not taken into account in the computation since the diagnostics might be in the wrong position to detect these phenomena. Nevertheless even if only a fraction of $\Delta U_i$ were going to heat ions, assuming a Maxwellian distribution with $\Delta T_i > V \Delta U_i$, the in-average ion temperature could be of $\Delta T_i \approx 200eV$ for $\Delta U_i = 10kJ$, thus well measurable.

Experimental evidences of ion heating during reconnections come both from the Neutral Particle Analyzer (NPA) diagnostic [17] - which estimates the ion temperature from the distribution function of the neutral atoms - and from the DD neutron detection in deuterium plasmas. Fig.8-9 show the typical phenomenology during a reconnection event in RFX-mod: the energy distribution of the neutrals (produced by charge-exchange processes and exiting the plasma) measured by NPA is characterized by a Maxwellian bulk population, up to energies of the order of 2 keV plus a high energy tail extending from about 3keV to 8keV. In Fig.9 (bottom panel) the time evolution of the ion temperature (estimated from the slope of the Maxwellian component), as a function of the toroidal angle $\phi$ is reported as a color-coded contour plot. Such figure has been obtained by means of a conditional averaging procedure around a large number of reconnection events in high plasma current discharges, comparable in terms of electron density ($n_e/n_{eq} < 0.15$) and chosen equilibrium (F$_{II}$ = 0.3). For each reconnection process the toroidal angle refers to the location at which the maximum $m=0$ perturbation occurs, as estimated from the arrays of in-vessel coils measuring the toroidal magnetic field fluctuations along the toroidal angles, capable of discriminating the $m=0$ and $m=1$ spectrum components. The figure highlights a clear increase of $T_i$ when the reconnection and the associated localized $m=0$ current sheet occurs in the region observed by the NPA diagnostic, between $\phi=250^\circ$ and $\phi=300^\circ$. Similar results have been found also in other RFP devices, like the Madison Symmetric Torus (MST), where the drop in magnetic energy during reconnection events is sufficient to explain the growth of the ion thermal energy [18]. Moreover, in RFX-mod deuterium plasmas a time-correlation between the magnetic perturbation associated to the reconnection process and the increase of neutron and gamma fluxes is also found as shown in Fig.10. Neutron and gamma fluxes are measured and discriminated by means of a diagnostic system made of 2 scintillators (EJ-301 liquid and NaI(Tl)) coupled to flat-panel photomultipliers, which can be operated under magnetic fields [19]. The spikes in the time traces of DD neutron and gamma rays are clear indication of ion heating and acceleration occurring during the reconnection process in the RFP as also reported by the MST group, which highlighted in this respect the role played by the non-Maxwellian high energy tail [20].
To estimate more accurately the part of magnetic energy that contributes to bulk ion heating in RFX-mod hydrogen plasmas, the ion temperature radial profiles $T_i(r)$ have been reconstructed. To this aim, the numerical neutral thermal outflux from the plasma $\Gamma_{num}$ is computed with the NENE montecarlo code [21]. The plasma parameters ($T_e$, $n_e$, wall particle influx, $Z_{eff}$) are taken from the experiment and the $T_i(r)$ profile is adjusted in order to minimize $\varepsilon$, the relative difference with the thermal region of the NPA spectrum $\Gamma_{exp}$ (channels 1-7): $\varepsilon = \sum |\Gamma_{num} - \Gamma_{exp}| / (N\Gamma_{exp})$, being the sum over the number $N$ of NPA channels. The $T_i$ profile that minimizes $\varepsilon$ is considered as the best estimate of the bulk ion temperature [22]. For the present analysis, the plasma parameters and the experimental spectrum $\Gamma_{exp}(t)$ have been computed as conditional averages on a subset of plasma reconnection events in similar plasma condition. The plasma conditions are $1.1 \ MA < I_p < 1.3 \ MA$, $-0.06 < F < -0.02$, $0.1 < n/n_0 < 0.15$. The resulting value of $\varepsilon$ ranges between 1% and 5%, confirming the quality of the $T_i$ reconstruction. Thanks to the low plasma density $<n_e>$ and the high electron temperature concentrated in the plasma core, the neutrals attenuation factor [22] is sufficiently low to allow a good statistic also from the plasma core and a consequent relative error on $T_i$ lower than 10% on the whole plasma radius. Figure 11 shows the comparison of the resulting $T_i$ profiles across the reconnection event. Before the crash $T_i=T_e$, whereas just after the crash (+0.5ms) $T_i$ decreases, but $T_i$ increases in $r/a<0.6$ with $\Delta T_i(0)=+250eV$, showing that the ion heating mechanism is mainly concentrated in the core region. At $t=+3ms$ after the event the $T_i$ profile decreases, clear sign that the ion heating due to the reconnection event is not present anymore. Considering the whole temperature profile the corresponding enhancement of ion thermal energy is about 0.5kJ, much lower with respect to the decay of magnetic energy during the reconnection and of the previous estimate of $\Delta U_i$ (of the order of few kJ in this range of plasma current and density). This suggests that a large fraction of the released energy might be involved in particle acceleration (both ions and electrons), an important topic to investigate with the new diagnostics that will be available in the upgraded version of RFX-mod, in operation from next year.

5. CONCLUSIONS

The reconnection events correlated to the partial and total back transitions from helical to multiple helicity plasmas in RFX-mod have been analyzed with a dedicated attention to the associated thermal and magnetic energy variations. A large fraction of the input power, up to 50% at high plasma current, is dissipated during these phenomena; in parallel also the electron temperature profiles become flatter and the corresponding electron thermal energy is reduced significantly (about -30%). The decrease of both the electron temperature and the magnetic energy scales, in absolute value, with the rising of the secondary modes $m=1$, $m=0$ amplitude, in particular during complete QSH-MH back transitions. By a power balance technique, considering the main known different input (ohmic power) and output (radiation, heat conduction and convection) energy contributions during a reconnection event, it has been possible to estimate that the quantity of energy possibly involved in particle acceleration and ion heating is in the range 10-200kJ. Experimental measurements from Neutral Particle Analyzer diagnostic have been used to estimate the changes in the ion temperature profile during a reconnection event and show an increase of 250eV in the core region. The corresponding energy variation computed from the whole $T_i$ radial profile is much lower than the magnetic energy released during a reconnection event, thus suggesting that suprathermal ion heating and electron acceleration might be dominant and require to be quantified more in detail by new experiments and diagnostics. Given the relevance of ion heating during the reconnection events in a reactorial perspective, such a topic will be further investigated in the experimental campaigns following the upgrade of RFX-mod, starting its operation from the mid of 2022.
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