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

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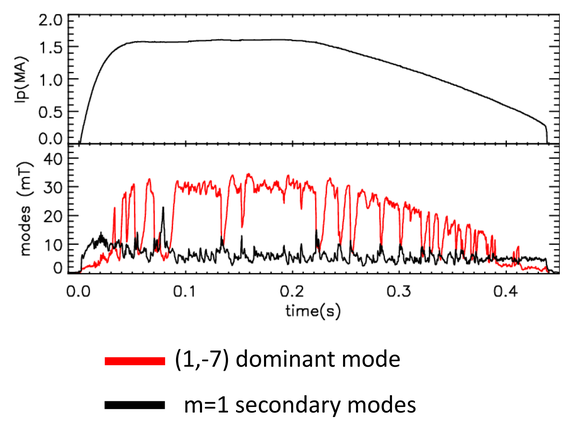
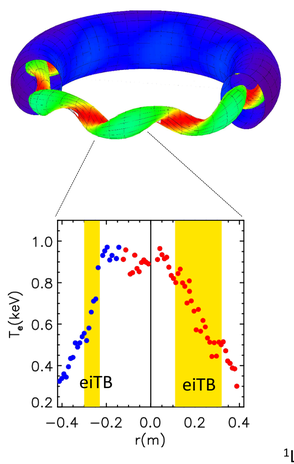
ABSTRACT

- Reconnection events in high current reversed field pinch plasmas are often associated to the partial or total transitions from a helical topology with conserved flux surfaces to a configuration characterized by a chaotic magnetic field.
- The electron temperature dynamic together with the magnetic energy reconstructions are used to evaluate the energy balance during these events and to quantify the associated dissipated power and released energy.
- A fraction of the energy released during reconnection events is involved in ion heating, as estimated by the energy distribution function of neutral atoms, a rather interesting feature in a reactorial perspective.

BACKGROUND

- The analyses reported are relative to RFX-mod[1] (R_0=2m, a=0.459m) with: I_p=1.2-2MA, n/n_G=0.1-0.2, reversal parameter $F=B_T(a)/\langle B_T\rangle$ in the range [-0.1,-0.01].
- Helical equilibrium at high current (QSH - Quasi Single Helicity): the innermost resonant mode (m=1,n=-7 with amplitude b_7) grows while the other harmonics (secondary modes with amplitude b_s) decrease[2].
- Electron Internal Transport Barriers (eITBs) build up during helical states.
- Partial/total interruptions of helical states and back transitions to chaotic regimes (MH-Multiple Helicity) are associated to reconnection events.



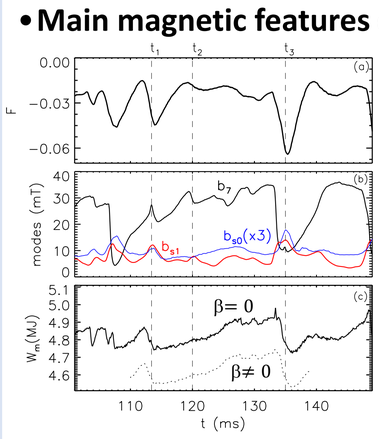


- helical core + weak residual magnetic chaos
- T_e up to 1keV
- eITB: ∇T_e> 2keV/m

[1]L.MARRELLI et al. Nucl.Fusion **61** (2021)
[2]S.CAPPELLO et al. this conference TH/P7-12

PHENOMENOLOGY OF RECONNECTION EVENTS

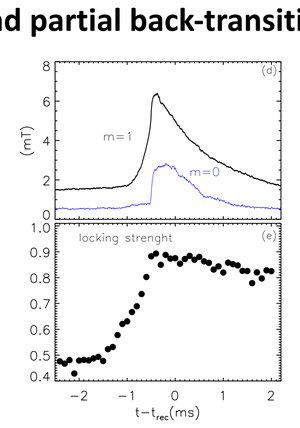
• Main magnetic features of QSH-MH total and partial back-transitions:



Fast decrease of F.

Loss of helical state (b_7); increase of m=1 (core) and m=0 (edge) modes.

Decay of magnetic energy: $W_m = \int \frac{B^2}{2\mu_0} dV$.

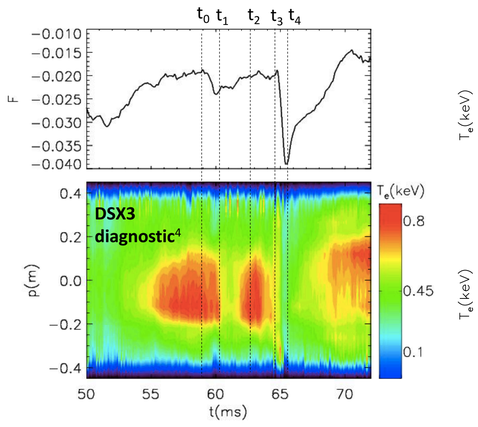


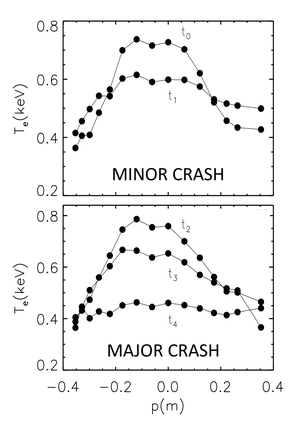
The phase locking of the m=1 modes is quantified by the *locking strength*, a parameter ranging from 1 (secondary modes in phase at some toroidal angle, to 0 (random phases).

Loss of helical state can be total (major crash-t_3) or only partial (minor crash-t_1,t_2); in the latter cases the W_m decay is minor (t_1) or absent (t_2) and the same for m=0 variation.

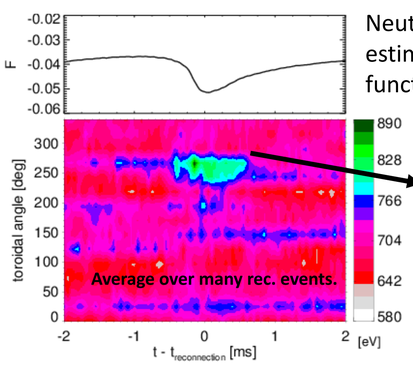
Reconnection starts at the locking position and is followed by a fast growth of m=1 (core region) and then of m=0 (edge region) modes[3].

• Electron temperature evolution and NPA data during reconnection events:



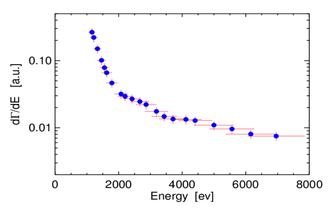


- Flattening of T_e profiles during both minor ($\Delta T_e/T_e$∼-30%) and major F crash ($\Delta T_e/T_e$∼ -60%) .
- The decrease of the electron temperature often begins ∼ 1ms before the minimum of F.
- Different dynamic of T_e during the reconnection event: complete profile flattening or increase in the edge region.



Neutral Particle Analyzer (NPA): estimates T_i from the distribution function of neutral atoms.

a clear increase of T_i when the reconnection occurs in the region observed by the NPA diagnostic, between ϕ=250° and ϕ=300° .

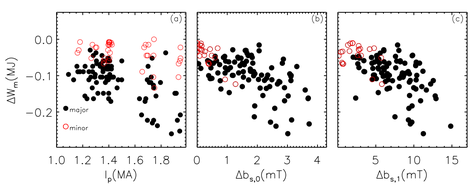


the energy distribution of the neutrals from NPA is characterized by a maxwellian bulk population (up 2 keV) plus a high energy tail (3-8keV)

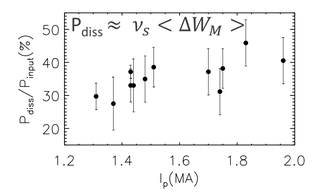
[3]B.MOMO et al. Nucl.Fusion **60** (2020) [4]P.FRANZ et al. Nucl.Fusion **53** (2013)

ENERGY BALANCE DURING RECONNECTION EVENTS

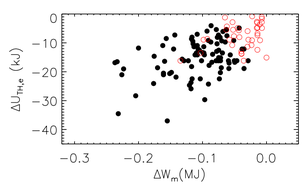
ν_s: frequency of reconnection events.



Variation of magnetic energy with plasma current and secondary modes.



Fraction of input power dissipated during reconnections.



Electron thermal energy variation.

MAG.ENERGY VARIATION + **ENERGY DIFFUSION EQUATION**

$$P_{diss} = \left|\frac{\Delta W_M}{\Delta t_{rec}}\right| + \left(I_p V_T - |V_\theta I_\theta|\right) \qquad \frac{\partial U_s}{\partial t} + \frac{\partial U_{TH,e}}{\partial t} = \int_V^0 (S_0 - \nabla \cdot Q_e - \Gamma_e)\, dV$$

POYNTING

Unknown '**surplus energy**' available for ion heating or particle acceleration.

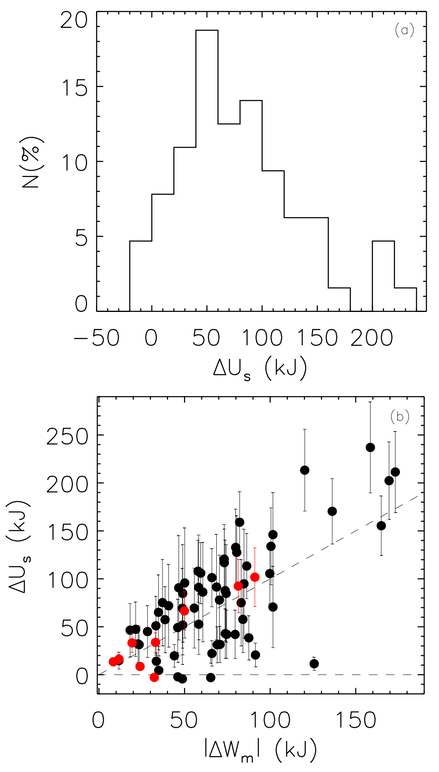
Sources (P_{diss}) and sinks (P_{rad}) of energy

Electron heat diffusion and convection terms.

$$\Delta U_s \cong \left(I_p V_T - |V_\theta I_\theta|\right) - P_{rad}\Delta t_{rec} + \Delta W_M + \Delta U_{TH,e} - 4\pi^2 a R_0 n_e(a)\left(\chi_e(a)\left|\frac{\partial T_e}{\partial r}\right|_{r=a} + v_r(a) T_e(a)\right)\Delta t_{rec}$$

- P_{rad} from bolometry[5]: 2-6MW;
- $\chi_e(a) \propto (b_s/Bo)^2 \cong$ 80-100m²/s during reconnections, from Rechester-Rosenbluth dependence on secondary modes (heat diffusion term amounts to 30-50MW);
- $v_r(a) \cong$5km/s→ heat convection term ≅ 3-9KW;
- From thermal helium beam[6]: $n_e(a)$ =(0.8 ±0.5) 10^{19}m^{-3}, $T_e(a) \approx$ 30eV ; $\left|\frac{\partial T_e}{\partial r}\right|_{r=a}$ = (2 ±0.5)keV/m
- $\Delta t_{rec} \cong$ 0.8-2 ms

- The statistical distribution of ΔU_s has a maximum at 50kJ but with few cases up to 150-200kJ that might result in a significant amount of energy not related with thermal electrons or radiation emission.
- ΔU_s is of the order of ΔW_M both in major and minor reconnection events.
- The presence of plasma-wall interaction could lead to a 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.
- If ΔU_s =3/2 n $\langle\Delta T_i\rangle$ V→ $\langle\Delta T_i\rangle \cong$ 1keV for ΔU_s =10kJ (assuming only a conversion into thermal energy).

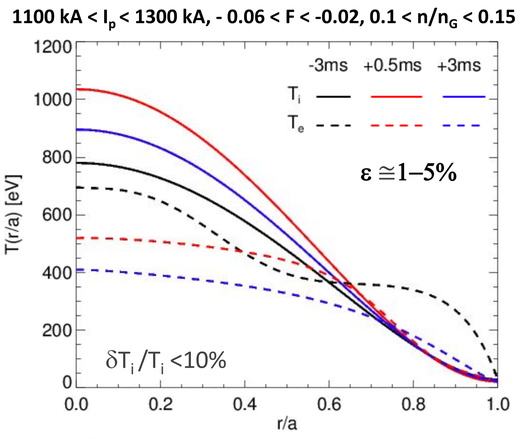


[5]P.SCARIN et al. Nucl.Fusion **59** (2019)
[6]M.AGOSTINI et al. Rev. Sci. Instrum. **81** (2010)

ION TEMPERATURE PROFILE DYNAMICS FROM NPA DATA

- The numerical neutral thermal outflux Γ_{num} is computed by the code NENE[7] using the experimental T_e, n_e, wall particle influx, Z_{eff} ; the associated $T_i(r)$ profile is adjusted in order to minimize ε, the relative difference with the thermal region of the NPA spectrum Γ_{exp}: $\varepsilon = \Sigma|\Gamma_{num} - \Gamma_{exp}|/(N\Gamma_{exp})$, being the sum over the *N* NPA channels.
- Before the crash $T_i \sim T_e$ whereas just after the crash (+0.5ms) T_e decreases; on the contrary T_i increases in r/a<0.6 with $\Delta T_i(0)$=+250eV (ion heating mechanism in the core region). At t=+3ms after the event the T_i profile decreases.
- $\Delta U_{th,i}$=0.5KJ < ΔU_s =5-10KJ in these I_p and n/n_G ranges→ a large fraction of released energy probably related to the suprathermal ion component and electrons acceleration.

1100 kA < I_p < 1300 kA, - 0.06 < F < -0.02, 0.1 < n/n_G < 0.15



[7]R.Lorenzini et al. Plasma Phys. Control. Fusion **13** (2006)

CONCLUSIONS

- A large fraction of the input power (30-50%) is dissipated during reconnections in RFX-mod; in parallel the electron thermal energy is reduced significantly (-30%).
- By a power balance technique the quantity of energy possibly involved in particle acceleration/ion heating has been estimated in the range 10-200kJ, of the order of the magnetic energy decay during a reconnection event.
- Experimental measurements from the NPA diagnostic show an increase of $\Delta T_i \approx$250eV in the core region; the corresponding ion thermal energy variation (∼ 0.5kJ) is much lower than the magnetic energy released thus suggesting that suprathermal ion heating and electron acceleration mechanisms are dominant.
- Strong relevance of ion heating in a reactorial perspective, new campaigns planned in the modified RFX-mod experiment[8], in operation from the mid of 2022.

[8]L.Marrelli et al. Nucl. Fusion. **59** (2019)

ACKNOWLEDGEMENTS

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