The role of mode-locking in the fast termination of high density and high current RFX discharges

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Introduction

A previous work [1] presented the description of sudden discharge terminations that are likely to occur in high density, high current ($I_p \geq 0.9$ MA) RFX plasmas, all characterized by MHD modes locked at the wall. The first wall in RFX is made entirely of graphite tiles. In RFX, for a given current, at high density the radiated power dominates the energy balance and generally provokes a soft termination of the discharge, when I/N<1. 10^{-14} Am. The fact that the fast terminations in most of the cases occur for I/N ≤2.5 10^{-14} Am, that is well below this expected density limit, calls for an explanation peculiar to those discharges. The purpose of the present contribution is to analyze the role of wall-modes locking in the observed fast discharge terminations.

The fast termination shows up as a sudden drop of the central electron temperature followed, after several ms, by the loss of the magnetic field reversal at the edge, a necessary condition for a RFP to exist, and eventually by the fast current quench [see Fig.1]. The temperature drop is accompanied by the enhancement of the dynamo modes and by the broadening of the m=1 MHD spectrum towards higher n. The electron density behaves differently from case to case; however, a fast termination always occurs for value of the ratio I/N lower or equal to 2.5 10^{-14} Am, at high currents (I≥0.9 MA).

A number of observations suggest that the region where the MHD modes lock plays a role in the fast terminated discharges:

-The total shift of the plasma column at the wall-mode locking position (WMLP) results larger in the fast terminated discharge than in the non fast terminated discharges (4-5 cm against typical 2-3 cm)

-when, by external means, the modes are unlocked the density increase is stopped and the shot does not terminate.

-while the influxes far from the WMLP are insensitive to the central temperature drop, the influxes at the WMLP start to increase as the central temperature starts to drop.

-the electron density at locking increases coherently with the enhanced influxes.

A 0-dimensional model has been developed in which particle and energy behaviour at the toroidal position of locking and in the remainder of the plasma are considered. The energy densities in the two regions are assumed to be the same (pressure constant along the field lines) and the time evolution of the energy is calculated with the two regions linked through the power flux along the field lines (perpendicular to the magnetic perturbation at the WMLP). Particle contents however are separated and different hydrogen influxes in the two regions are considered, according to the experimental evidence. The ratio between particle confinement times at the WMLP and far from it is fixed assuming the same electron densities in the two regions (before the electron temperature drop) and taking into account that the hydrogen influxes observed at the WMLP are about one order of magnitude higher than those measured elsewhere[2]. Experimental observations indicate that electron density and influxes increase in the locking region during the electron temperature drop. The result of the model indicates that if the hydrogen influx at the WMLP is constant in time and not too high, only the region at locking cools down, while the rest of plasma is unaffected; instead, if the hydrogen influx at the WMLP increases in time (with a time scale similar to that of the electron temperature decrease during a fast termination) also the electron temperature of the remaining plasma drops.

Description of the model and results

A system of 6 equations is solved to describe the time evolution of particle density (neutrals and electrons) in the two toroidal regions and energies (which are the same in the 2 regions)

$$\frac{dn_B}{dt} = n_B n_{0B} S_B - n_B n_{0B} \alpha_B - \frac{n_B}{\tau_{p,B}}$$
$$\frac{dn_{0B}}{dt} = -n_B n_{0B} S_B + n_B n_{0B} \alpha_B + \Gamma_{H,B} \frac{2}{a}$$
$$\frac{dn_L}{dt} = n_L n_{0L} S_L - n_L n_{0L} \alpha_L - \frac{n_L}{\tau_{p,L}}$$
$$\frac{dn_{0L}}{dt} = -n_L n_{0L} S_L + n_L n_{0L} \alpha_L + \Gamma_{H,L} \frac{2}{a}$$
$$\frac{d(n_B T_B)}{dt} = P_{Ohm,\,B} - P_{rad} - P_{dis} - P_{//\,m,n} - \frac{n_B T_B}{\tau_B}$$
$$n_L T_L = n_B T_B$$

The index B indicates the region far form the WMLP , L indicates the locking region. S and α are the ionization and recombination rates, respectively; n and T are the density and temperature of electrons (or H ions) (all the parameters have to be considered representative of radial averages in the 2 regions). The energy and particle confinement times (τ and τ_p) are calculated from the previous equations in stationary conditions preceeding the fast termination and then kept constant. The Ohmic power P_{Ohm} chosen at the beginning of the calculation according to the experimental values is re-evaluated at each time step taking into account the temperature variations. The radiated power is calculated assuming concentrations of C and O which are typical for RFX (during the fast terminated discharge the effective charge does not increase) and using the Summers-Mc Whirter model; P_{dis} is the power dissipated to excite and ionize neutrals coming from the wall [3,4]; $P_{//,m,,n}$ is the energy exchange between the two regions, it represents the flux along the magnetic field lines, calculated perpendicularly to the perturbation with mode numbers m,n.
The single mode (m,n) perturbation calculated at the shell is represented by the unity vector

$$b = \left(0, \frac{m}{\sqrt{m^2 + n^2 \varepsilon^2}}, \frac{n\varepsilon}{\sqrt{m^2 + n^2\varepsilon^2}}\right);$$

The expression of $P_{//,m,,\,n}$ is obtained by projecting the parallel thermal flux onto the perpendicular to b :

$$P_{//\,m,n} = K_{//} \frac{T_B - T_L}{\pi a/2} \frac{1}{\sqrt{(2/\varepsilon)^2 + (1/q)^2}} [1 - \frac{1}{\sqrt{1 + (q/\varepsilon)^2}} \frac{1}{\sqrt{m^2 + (n\varepsilon)^2}} (m + nq)] 2S$$

where q is the safety factor , ε = a/R, S = surface in radial direction of the locked region: S = (R Δ $\Delta\phi$) , where Δ , $\Delta\phi$ are the radial and toroidal extensions of the perturbation respectively.
To simplify the calculations, only 1 mode with m=1,n=8 has been considered, since it has demonstrated to be one of the most prominent in RFX.

The results of the calculation indicate that, when the hydrogen influx at the WMLP is 10^{23} m^{-2} s^{-1} as experimentally observed in high current discharges, the densities and the averaged temperatures at the WMLP and far from it are the same; the system is able to maintain the temperature against the losses at the wall. As already said, the influxes at the WLMP start to increase when the electron temperature drops; the time scale of this increase is not known since the experimental signals rapidly became saturated. The results of the model, with an influx at locking increasing in about 2 ms (which is the experimentally observed time scale of Te drop), are shown in Fig.2 : the electron temperature decreases both in the locking region (L) and in the rest of the plasma (B region), the density increases at the WMLP while remaining constant far from it (as experimentally seen). The time evolution of the temperature and its final value are inversely related to the density increase in the locking region.
In this way the destiny of a high current, high density discharge is correlated to its density behaviour, and therefore to the influx from the wall: if the influx is very high (this condition is verified in the locking region) and increases with time there is the concrete risk of a temperature collapse.
In a RFP the field configuration is maintained against the resistive diffusion by the dynamo processes which, through the reconnection of the magnetic field lines induced by the MHD modes, sustain the toroidal flux. The time scale of the resistive diffusion in RFX is about 100-200 ms at Te=100eV. In absence of the field sustaining dynamo the RFP configuration would be lost in about 1/30 of the diffusion time [5], that is in about 3-6 ms. Experimentally it is seen that the MHD activity during the terminations is increasing so that the dynamo process has to be more effective to counteract the resistive diffusion. The decrease of the electron temperature accelerates the resistive diffusion and then the loss of the configuration is possible in a nonlinear way, leading to the fast termination phenomena experimentally observed.

Conclusions

A simple 0-dimensional model describing the time behaviour of particles and energy in the locking region and far from it supports the idea that the influx from the region of the wall affected by mode locking may be crucial in driving the discharge to a sudden premature termination. The model shows that if such localized influx increases to values of the order of 10^{24} m^{-2} s^{-1} on a time scale of 1-2 ms the electron temperature of the entire plasma may decrease on the same time scale. When the electron temperature drops rapidly, a non linear evolution of the RFP field configuration governed by the two competing processes, resistive diffusion and dynamo, may lead to the loss of the magnetic field reversal and the termination of the discharge.

References

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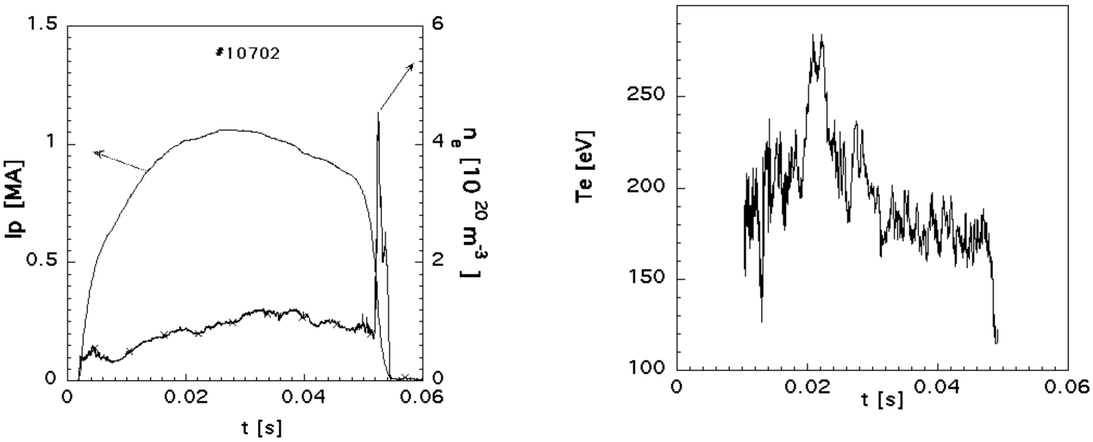

Fig.1 Time waveforms of I_p,n_e,T_e, during a RFX high current, fast terminated discharge

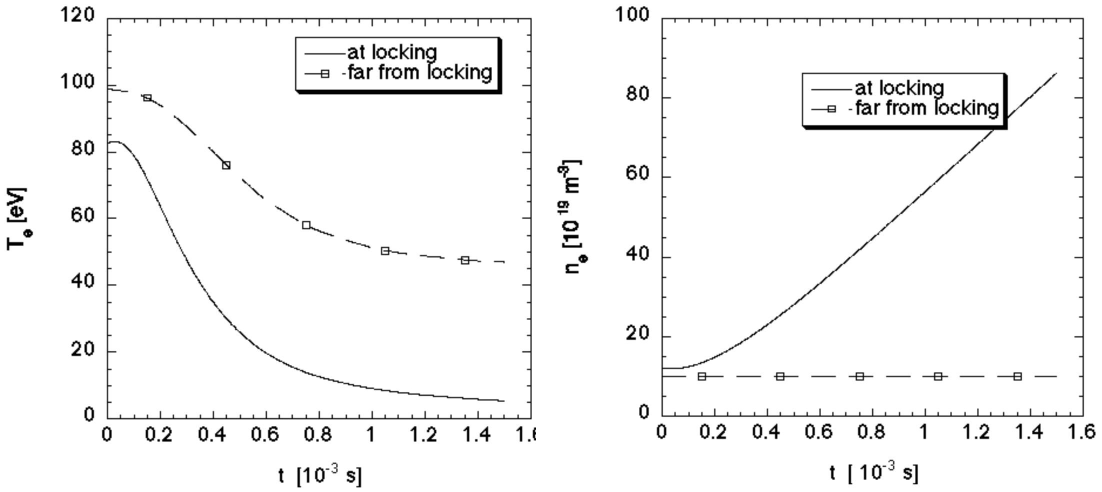

Fig.2 Time evolution of electron temperatures and densities in the region at locking and in the remaining plasma with the hydrogen influx at locking increasing in time $\Gamma=10^{23}$ —10^{24} m^{-2} s^{-1}