27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** *(2000) 1380 -1383*

Analysis of the high density limits in the RFX high current regimes

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Introduction

In the reversed field pinch (RFP) experiment RFX an upper density limit exists which is well described by the empirical Greenwald limit found in Tokamak ($n_e < 10^{14}\kappa < J >$ [MKSA], where κ is the plasma elongation). When expressed in terms of the plasma current divided by the area integrated density, the ratio I/N of common use in RFP literature, this limit corresponds to I/N>10 $^{-14}$ Am

The plasma behaviour observed in RFX when the discharge reaches this limit is however different depending on the plasma current. This contribution concentrates on the phenomena that have been observed accessing to the high-density limit when operating at high currents (I > 0.9 MA). Contrary to the low current case, where usually a soft decay of the plasma current occurs at the density limit, in high current discharges there are conditions where the plasma experiences a fast termination not due to a failure of the external circuits. The fast termination shows up as a sudden electron temperature drop 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. Electron density behaves differently from case to case; however a fast termination always occurs at a value of the ratio I/N lower or equal to 2.5 10 $^{-14}$ Am.

The detailed mechanism that leads to the fast loss of confinement is still unclear. In particular, uncertainties concern the importance of the local phenomena occurring at the wall mode-locking region, where severe power loads are dissipated. Edge radiation emission processes occurring far from the wall-mode locking location seem not to have a direct role. Indeed injection of radiative impurities in RFX has never resulted in a fast termination. Large amplitude of the plasma deformation at the mode-wall-locking region and especially a situation of high hydrogen influx from the wall seem to be conditions which favour fast termination. In hot wall experiments, for instance, the probability to have sudden density build up and to access the critical low I/N region is considerably higher.

Experimental observations and discussion

An example of a fast termination in high current discharges is shown in Fig.1.

The fast termination is characterised by a drop of the on axis electron temperature over time scales that vary from less than one ms to several ms, with a corresponding increase of the loop voltage. The mode energy and the plasma shift at the locking position increase as the temperature decreases. After about one or several ms reversal is lost and all the accumulated energy is dissipated on to the wall: density increases dramatically and the current quenches in few ms. The plasma current time derivative observed in the fast terminated discharges reaches a maximum value of 0.8 10^9A/s, well below the RFX project limit of 20 10^9A/s. Although fast termination at high density have been a frequent event in recent high current experimental campaigns, this behaviour is not entirely new to RFX: an analysis of old shots, obtained when wall conditioning with Glow Discharge Cleaning was not applied and field errors were more

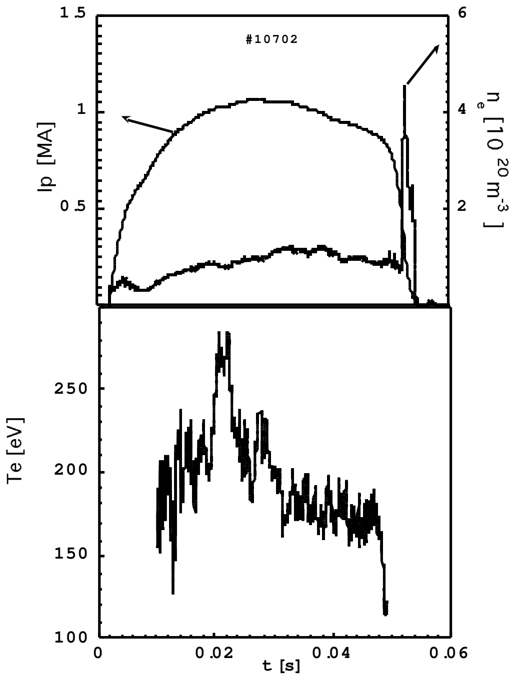

Fig.1 Time waveforms of I_p,n_e and T_e for a high current discharge with fast termination

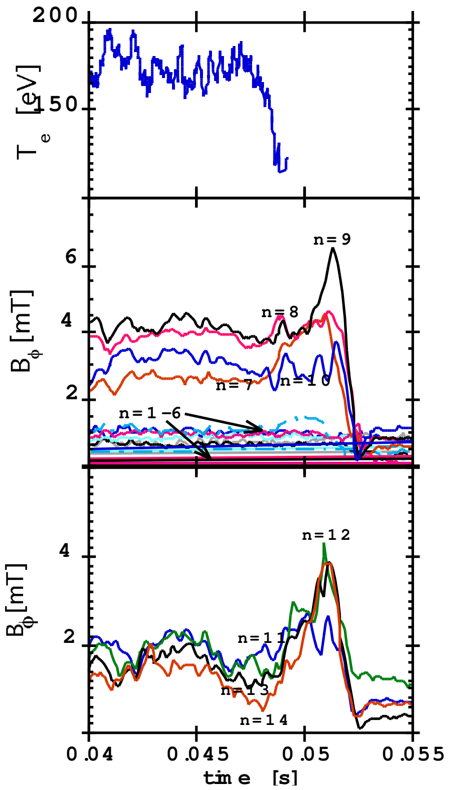

Fig 2 Temporal behaviours of T_e and toroidal field odd m harmonics for the shot in Fig.1

severe [1], has shown that some episodes had already occurred also at currents as low as 600 kA.

In Fig.2 it is shown that the on axis temperature drop is coupled to an increased energy in the magnetic field of dynamo modes and to a broadening of their spectrum towards the higher n (n=11-14); in many cases the first modes to increase are the most internal ones n=7-9, which in RFX have the highest amplitudes [2].

During the temperature drop the electron density profile typically tends to peak; in particular it results that the edge density remains quite constant while the central one increases. The time behaviour of line averaged Z_{eff} varies from case to case but it is not very much influenced by the Te decrease. Impurity and main species influxes far from the locking region are unaffected by the temperature decrease and do not change in time until the current quench. Moreover P_{rad} increases only after the decrease of T_e and only then also the plasma centre begins to irradiate. The soft X-ray emission profile tends to peak, consistently with the peaking of density, decreasing of T_e and constancy of Z_{eff}.These findings seem to exclude that processes such as radiative effects at the edge far from the locking region may play a role. In addition, highly radiative plasmas obtained at 800 kA with neon injection have never ended in a fast termination. As already said a fast termination occurs only at I/N values lower or equal to 2.5 $10^{-14}$$Am^{-1}$ and, although there are fast terminated discharges at medium current, the frequency of these events is a strong function of the plasma current.

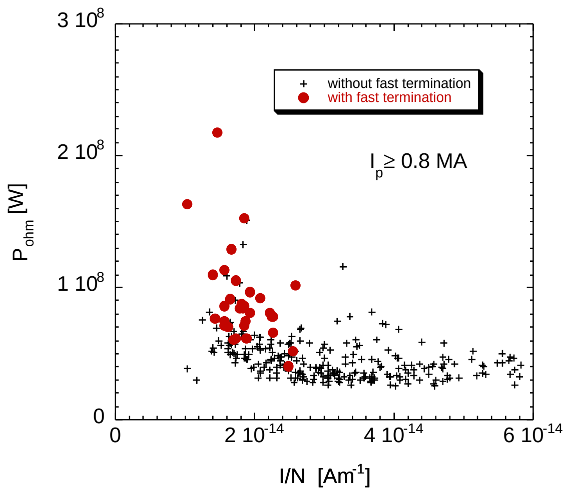

Fig.3 Pohm versus I/N in RFX

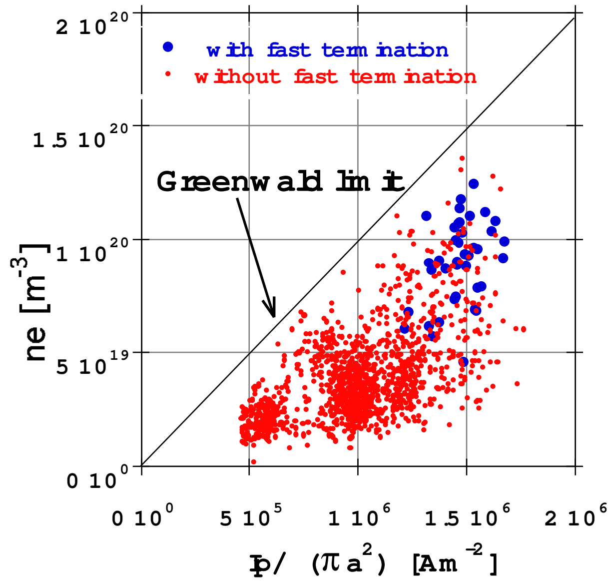

Fig.4 Electron density vs. the average toroidal current density. The equivalent of the Greenwald limit for Tokamaks is also shown.

In Fig. 3 it is shown that P_{ohm} is higher in the fast terminated discharges and it is important to notice that a lower limit in I/N might also be seen as an upper power threshold.

In any case an upper limit appears to exist similar to the equivalent of the Greenwald limit for Tokamaks (I/N= 1 10^{-14} Am), see Fig. 4. As shown in Fig. 4 at high current fast termination may occur also at density al low as a factor two below the limit.

In RFX the lower limit on I/N could correspond to a limit on the radiated power only if radiation coming from the region of locking is taken into account since it can be as high as about one third of the total radiated power [3]. If the radiated power from locking is not considered, in RFX $\gamma=P_{rad}/P_{ohm}$ is always less than 0.5. In Tokamaks near the Greenwald limit the particle transport at the edge appears to increase non linearly, leading to an edge cooling by convection and recycling [4] so that limits on global parameters like <J> and $\bar{n}$ are related to localised phenomenon; in RFX, as already said, the edge parameters far from the locking region seem to be unaffected by the central temperature decrease but some uncertainties still concern the role of the wall mode-locking. In effect it is possible that this may have an important role since:

- the total shift of the plasma column at the locking position results to be larger in the fast terminated discharges [Fig 5] but this could be the consequence of the increased dynamo mode amplitude
- when the mode rotation is applied to displace the locking the density increase is stopped and the shot does not terminate as expected due to the improved density control.
- while the influxes far from the locking are insensitive to the temperature drop, the H, C and O influxes in the locking region start to increase as soon as the temperature starts to drop but once again this could be the consequence of the increased dynamo mode amplitude.
- the electron density at locking (when the measure is available) seems to increase, coherently with the enhanced influxes and to remain hollow.

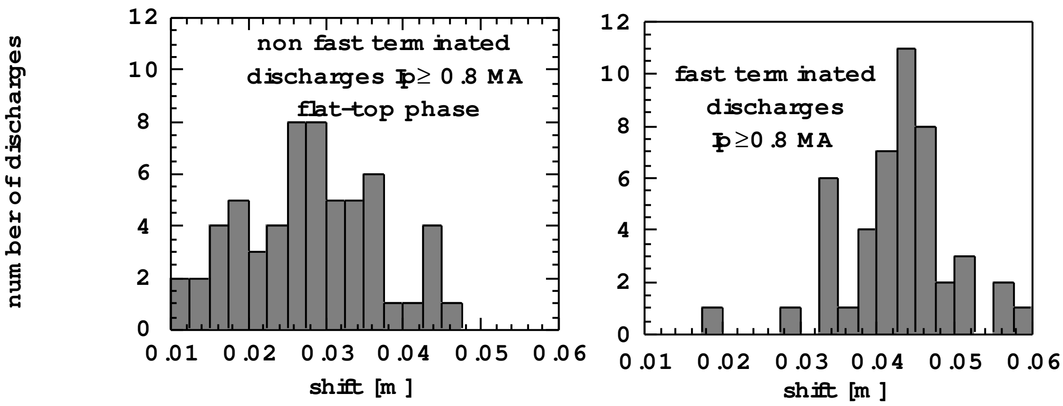

Fig.5 Number of shots versus plasma column shift at the locking position for non fast terminated discharges and fast terminated discharges (shift is averaged on 5 ms before the current quench).

Some specific conditions seem to be favourable to the fast termination: fast-terminated discharges occur especially in cases of high hydrogen recycling, such as for instance in the hot wall experiments. In the latter type of discharges the density control is much more difficult that in ordinary conditions; the probability to have sudden density build-up is higher and therefore also the probability to access the dangerous low I/N region is also higher. Discharges after a boronisation seem instead to be immune from fast termination and they allow to overcome the lower I/N limit. However, these discharges are characterised by a lower $\gamma=P_{rad}/P_{ohm}$ but also by the presence of a mixture of He and H.
The fact that none of the impurity seeded discharges at 850 KA [5],[6] shows fast termination, suggests that radiative instabilities are not causes of these phenomena.
The understanding of the mechanism underlying the fast terminations is only at the beginning; unfortunately, the fast time scale of the temperature drop and the fact that the analyzed electromagnetic signals are filtered by the liner is a complication for the interpretation of such fast phenomena.

Summary and conclusions
Despite the differences in the confinement schemes RFPÕs display a lower I/N limit similar to the Greenwald limit for Tokamaks. In RFX operating at very high density and current (I>0.9 MA) it may happens that the plasma current decays quickly following a sudden electron temperature drop.
The detailed mechanism underlying the fast termination is not clear and it is possible that the wall locking region, where severe power loads are dissipated, plays a crucial role while edge radiative processes far from the locking seem not to have responsibility in such events.

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