Runaway electron mitigation by resonant and non-resonant magnetic perturbations in RFX-mod tokamak discharges

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Introduction. Understanding the mechanisms behind Runaway Electron (RE) generation and the ways RE formation can be prevented is of paramount importance for future fusion reactors. In fact, RE with energies of several MeV generated during the sudden cooling involved in disruptions may cause severe damage to the plasma facing components and vacuum vessel wall. The injection of massive gas into the plasma is the main solution presently envisaged to avoid the RE avalanche. Also other strategies have been developed to enhance the RE de-correlation as the application of external magnetic perturbations (MP) [1].
The RFX-mod device [2] (major radius R_0=2m, minor radius a =0.459m, maximum toroidal field on axis B_0=0.6T) which can be run as a Tokamak, is equipped with an advanced system for the control of Magnetohydrodynamic modes based on 192 saddle coils independently fed and on a state of the art real-time hardware and software architecture [3]; for this reason, it is well suited to study the possible RE de-confinement in response of applied magnetic perturbations with different modal numbers and amplitude.
In this paper the conditions when a significant number of high energy electrons is generated during the flattop phase of tokamak RFX-mod plasmas are analyzed, both in terms of density and of loop voltage (V_{loop}), thus contributing to the scaling studies reported in [4]. Magnetic perturbations have been applied in order to enhance fast electron losses preventing their acceleration to higher energies; results are discussed and interpreted by numerical simulations with the Hamiltonian guiding center code ORBIT [5], recently updated to a relativistic version.

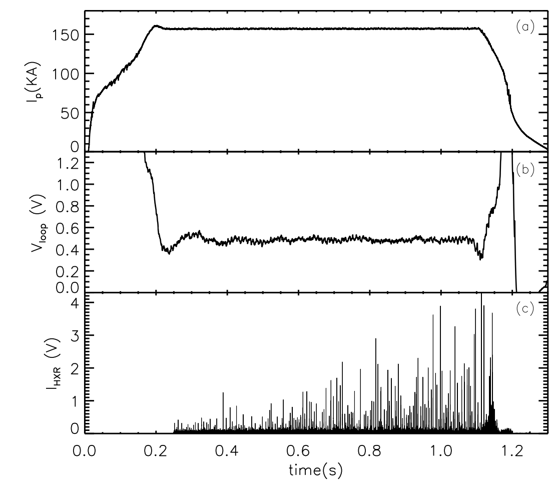

Figure 1. *Example of Tokamak discharge (#37936) in RFX-mod: (a) plasma current, (b) loop voltage and (c) signal from the scintillators detecting RE events.*

RE generation/suppression in RFX-mod. The high energy electrons dynamics in RFX-mod is investigated thanks to the soft-x-ray tomography and to 2 scintillators, which allow the detection of hard-x-rays produced when the electrons are lost from the plasma and impact on the first wall. The scintillators are placed at two different toroidal positions (ϕ_1=187.5°, ϕ_2=262.5°) on the equatorial plane. Fig.1-(a) shows the plasma current evolution in a typical RFX-mod tokamak discharge at low density (n_e<2•10^{18}m^{-3}, corresponding to n_e/n_G<0.1) with safety factor at the edge q(a) < 2; in (b) the corresponding V_{loop} is reported. The scintillator signal I_{HXR} is shown in panel (c) as a function of time: each event (spike) corresponds to hard-x-ray (HXR) emission from a lost electron hitting the first wall and the amplitude of the signal is proportional to the energy carried by the electron itself. As it is clear from panel (c), on average, the energy of the lost electrons increases with time as they are continuously accelerated by the toroidal electric field before drifting out of the plasma. A statistical study has been carried out over many discharges (~150, similar to the one reported in Fig. 1 but with different electron density), dividing the time scale into intervals of 5ms; for each of them the total number of RE events with an amplitude greater than the background noise (≈ 0.2 V) has been determined together with the averaged values of other quantities like density and V_{loop}. The results of this analysis are summarized in the contour plot shown in Fig.2 reporting the percentage fraction of RE events at a given n_e (x-axis) and accelerating toroidal electric field (i.e $E=V_{loop}/(2\pi R_0)$, y-axis). Most of the events occur at density lower than n_e<4•10^{18}m^{-3} with electric field in the range 0.03-0.1V/m. Nevertheless, few events can be observed at higher density (~10^{19} m^{-3}) too at greater amplitudes of the electric field.

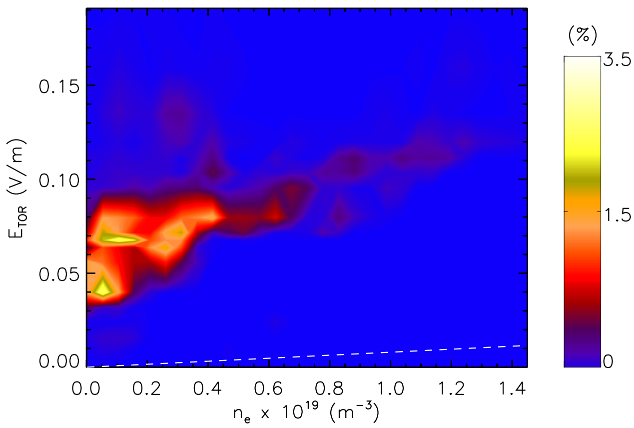

Figure 2. *Percentage fraction of RE events as a function of the electron density and toroidal electric field in RFX-mod Tokamak discharges.*

As reported in [4] for several devices, also in RFX-mod the critical toroidal electric field, required to observe RE events at a given density, exceeds the theoretical one predicted taking into account only of the friction effect due to collisionality (dotted white line in the plot). This confirms, also for RFX-mod, that other yet unknown loss mechanisms might play a role in the RE generation/suppression mechanisms.

Effect of magnetic perturbations on RE losses. The presence of small radial magnetic fields can prevent the electrons to reach high energy before being lost. In fact, when magnetic perturbations are applied, depending on their amplitude and on the equilibrium configuration, partially chaotic regions may develop. Due to fast radial diffusion within these domains, electrons are lost in a shorter time and with lower energy with respect to an unperturbed configuration. Hence, the energy of the lost electrons is expected to be a decreasing function of the applied perturbation amplitude.

To investigate this issue, MPs have been applied during the flattop phase of low density Tokamak discharges similar to those described in the previous section. An example of MP evolution is shown in Fig. 3-(a) where a 10Hz rotating (2,1) mode is applied to a plasma with q(a) < 2. The amplitude of the MP increases linearly to a maximum value and then decreases to zero. The corresponding signal from the scintillator is reported in panel (b). It is worth to note that the maximum of RE energy is observed to occur about 0.15-0.2s after the beginning of the MP. Similarly there is a delay of 0.1-0.15s between the maximum of the MP and the minimum of the scintillator signal. Such a behavior can be explained by considering that during the MP application, the toroidal electric field is still accelerating the electrons and a finite time is required for electrons to diffuse till the edge of the plasma. This phenomenology can be roughly described by assuming that the variation of energy dU for electrons in a partially chaotic domain during a time interval dt is given by:

$$dU = Evdt - \alpha[b_r(t)]^2 dt \qquad (1)$$

where the first term takes into account of the electric field (E) acceleration and the second one represents an "effective" friction force due to stochastic diffusion, here assumed to be proportional (by a costant α) to the square of the amplitude b_r of the mode. Collisional effects are neglected. By solving this differential equation (writing the velocity v as a function of U: $v=(U/2m)^{1/2}$) the energy time evolution $U(t)$ is obtained as reported in panel (b) with a continuous red line and shows the same delay (hereafter called Δ) observed experimentally between the scintillator signal and the MP. This simple model has been used to interpret also

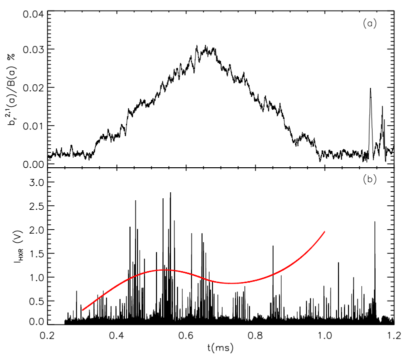

Figure 3. *(a) (2,1) rotating magnetic perturbation applied with varying amplitude (#37938);(b) scintillator signal in black ; in red the theoretical prediction.*

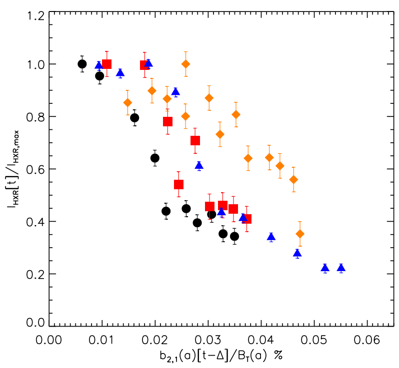

Figure 4. *Scintillator signal as a function of MP amplitude at the time t-Δ. Each color is a different shot.*

similar discharges: it is found that Δ mainly depends on the slope of the MP ramp and on the applied electric field magnitude. Fig.4 shows that the scintillator signal at the time *t* has a decreasing trend when plotted vs the amplitude of the MP evaluated at *t-Δ*.

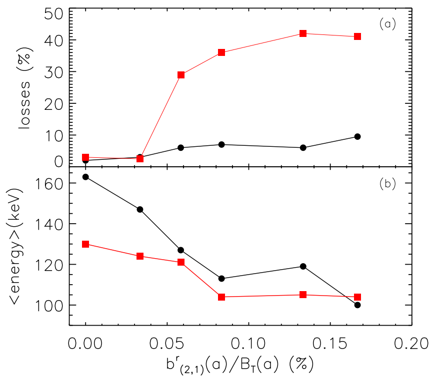

Figure 5. *Percentage fraction of RE lost from the plasma (a) and of their average final energy (b) from ORBIT numerical simulation. In black: q(a)=1.8; in red: q(a)=2.3*

Numerical simulations. The decreasing of the energy of the lost fast electrons at higher values of MP has been also observed in numerical studies performed with the code ORBIT. In these simulations electrons have an initial energy of 100keV; at t=0 a constant perturbation (2,1) is applied; the effect of the toroidal electric field (*E=0.05V/m*) is implemented as well as slowing down collisions (assuming $n_e=2\bullet 10^{18}m^{-3}$). Fig.5 (a) shows the number of lost electrons vs the MP amplitude after 8ms while their average energy is reported in Fig.5(b). Two RFX-mod equilibria have been considered, one with q(a)=1.8 (black line) and another one with q(a)=2.3 (red line). In the latter case a small amplitude of the perturbation is enough to increase the fraction of lost electrons to about 30-40% of the initial population; on the contrary, in the simulation with a q(a)<2 equilibrium, the fraction of lost electrons still depends on $b^r_{21}(a)/B_T(a)$ but remains under 10%. These results can be explained by the higher level of stochasticity developing in the scenario where the mode is resonant. In both cases the final energy of lost electrons decreases at higher MP with respect to an unperturbed equilibrium.

Conclusions. Dedicated experiments to study the RE dynamic in low density tokamak discharges have been recently performed for the first time in the RFX-mod device. Both experiments and simulations show that the application of MPs partially increases the losses of RE before they reach high energies. Further studies are currently in progress in order to understand which kind of MPs should be applied in order to de-correlate also the remaining confined electrons which still continue to be accelerated, especially in the core of the plasma.

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