Effects of pellets and impurity injection on runaway control experiments on FTU

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Introduction

FTU is conducting an extensive program aimed at controlling and mitigating purposely generated runaway electron (RE) beams in natural and induced disruptions [1, 2]. During the latest experimental campaign different mitigation techniques have been tested, which involved injection of Laser Blow Off (LBO) metal impurities and of multiple Deuterium pellets ($1\div2\times10^{20}$ atoms). A large number of discharges has been analysed correlating various plasma signals to REs behaviour. The injections have been performed both during the plasma current flat top, with seed REs embedded in a hot plasma, and also after current quench (CQ), with current mainly carried by REs, in order to extrapolate information for ITER predictions. The main RE measurements used in this work were the following diagnostic systems: BF3 chambers, only sensitive to neutrons; NEU213 organic liquid scintillator, sensitive both to neutrons and hard X-rays (HXR); Gamma camera to measure HXR produced by the REs through bremsstrahlung in the plasma; Cherenkov probes to detect REs escaping the plasma [2,3].

Impurity injection results

As far as the LBO is concerned, different impurities have been injected, such as Tungsten, Molybdenum, Iron and Zirconium; in this work only results with Fe injection are discussed, as this element provides the most extensive information. Injections during the plasma current flat-top in RE discharges show up in the spectroscopic diagnostics, bolometry and Soft X-ray tomography (SXR). The signal time correlations are related to the amount of REs in the plasma, qualitatively estimated from the γ counts. In particular, Fig. 1 shows three discharges with different levels of REs, respectively low, high and intermediate. Mitigation of REs is evident in shot #42106, where an intense ionization of Fe injected impurity is detected by the X-VUV spectrometer Schwob [4], as shown by the evolution of Fe XXIII (135.80 Å) line brightness normalized to the electron density. The LBO injection induces a spike in loop voltage, and an important MHD activity that leads to REs ejection. This effect is more important in shot #42106 relative to #42109, where a stronger REs population is estimated by the detected gamma emissions, as shown in Fig. 2. In this case, the injected impurity is only partially ionized, due to the lower plasma temperature, and consequently a less intense MHD activity is produced. In shot #42108, with higher level of REs, there is a poor spectroscopic evidence of the Fe ionization; presumably, the even colder plasma, due to the larger REs population, does not allow ionization of the impurity (Fig.1).

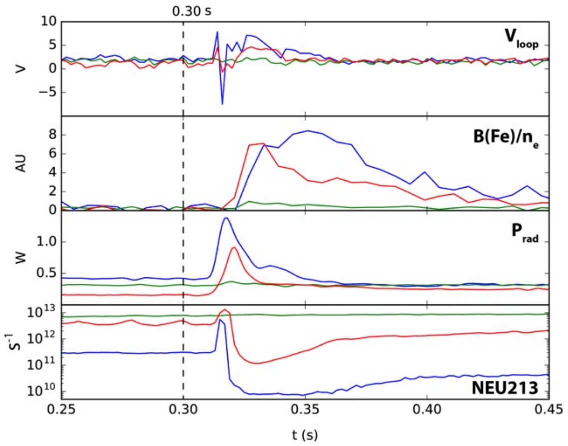

Fig.1 Pulses #42106 (blue), #42108 (green), #42109 (red): Fe injection at 0.3 s.

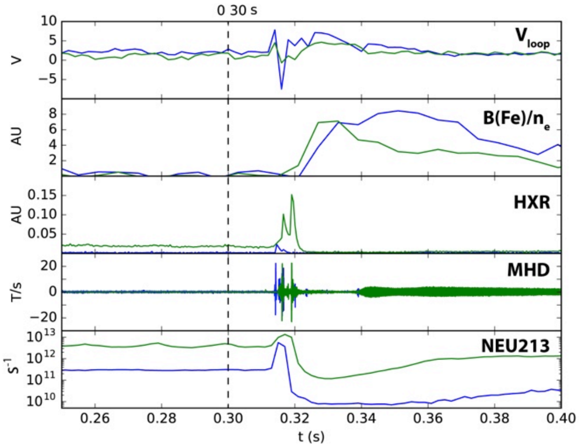

Fig.2 Pulses #42106 (green) e #42109 (blue): Fe injection at 0.3s.

LBO injections of Fe have been carried out also during current ramp-up and ramp-down in discharges with weak REs population. In these cases, different ionization effects on SXR and spectroscopic measurements are observed, depending on the different background plasma electron temperatures; anyhow, there is no evidence of injection effects on plasma signals such as loop voltage, and mitigation effects on REs do not appear.

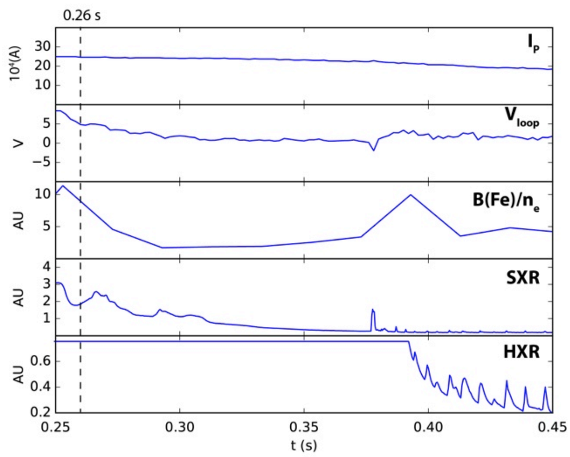

Fig.3 Pulse #41899: Fe LBO injection at 0.26 on REs plateau after the CQ.

Fig. 3 shows an example of Fe injection on REs plateau, formed after the CQ following a disruption. Again, no spectroscopic evidence of the injection is measured, due to the cold plasma background where the plasma current is mainly driven by REs. The same results are observed when impurity injection have been performed on fully formed RE beams, far from the CQ.

Pellet injection results

Deuterium pellets have been injected into steady-state flat-top discharges with REs and on post-disruption RE beams, in order to study the dynamics of particle interaction with the RE beam. A comparison between two discharges #42115 and #42116, with and without pellet injection respectively, is reported in Fig.4. In discharge #42115 pellets are injected during the current flat top: the plasma density is observed to increase after the pellet injection, with a consequence fast variation of loop voltage and a recurring MHD activity. In some discharges like this one, a loss of RE from the plasma, in correspondence with MHD bursts, is directly detected by diagnostics and the RE population decreases until full mitigation. In other discharges where MHD bursts have not been induced, the RE population grows up to γ flux

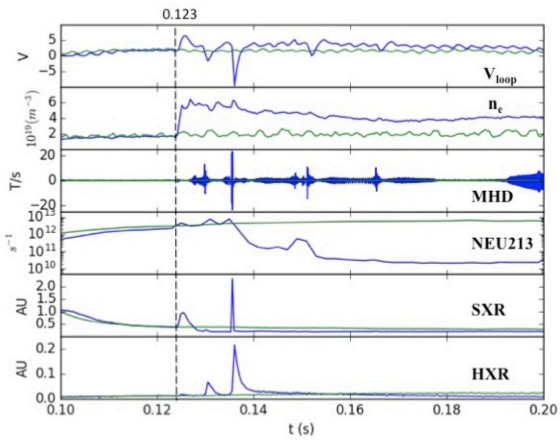

Fig.4 Pulses #42115 (blue), #42116 (green): with/without pellet injection on current flat top.

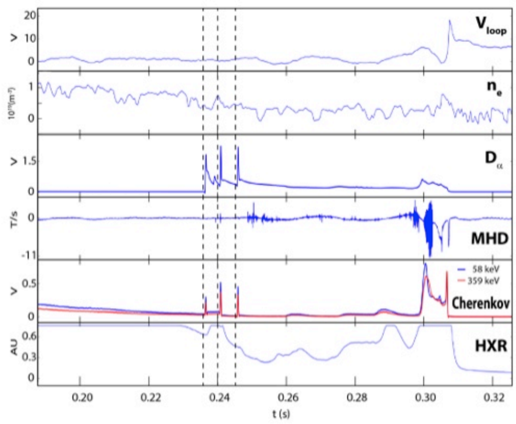

Fig.5 Pulse #42060: three pellets after the CQ on REs beam.

saturation (not discussed in this work). Deuterium pellets injected into a post-disruption phase display complex behaviours. In Fig. 5, pulse #42060 is an example of injection on RE beam after a CQ where the plasma current is carried by REs. Three pellets are injected and their ablation is detected by the D_α injector monitor and not by the other main plasma signals. Presumably this is because the background plasma is too cold, while an indication of REs expulsion is detected by correlated spikes on Cherenkov detectors and MHD probes.

When the pellets are injected at a later time, after the CQ, into a warmer background plasma (energy is transferred to the background plasma by REs during the ramp-down) and a less

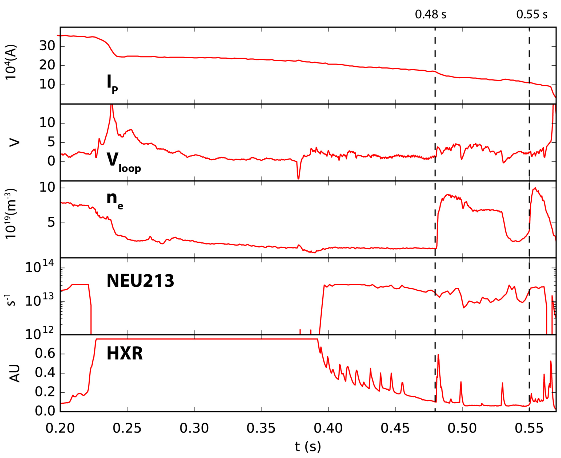

Fig.6 Pulse #41899: two pellets at 0.48 s and 0.55 s, at later time after the CQ. Electron density increases in correspondence of pellets for a long time.

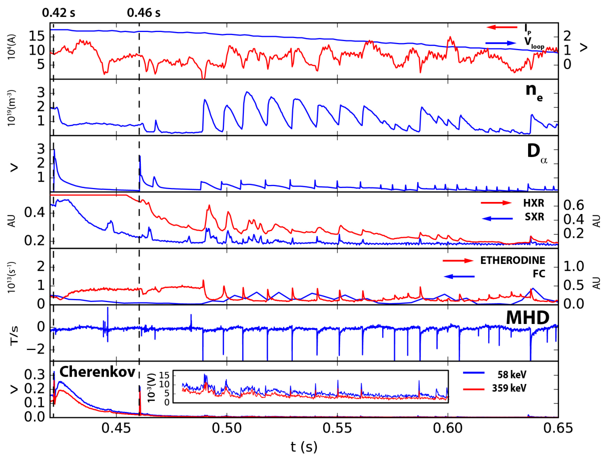

Fig.7 Pulse #41902: two pellets at 0.42 s and 0.46 s, sooner (with respect to #41899) after the CQ on a RE beam.

energetic RE beam, the ionization increases the electron density, as shown in Fig.6 (#41899). A good confinement of injected particles is observed after the first pellet, while no loss of REs is evident. Finally, in discharges like #41902, pellets have been injected and ablated shortly after the CQ, in the presence of a more energetic RE beam and a colder background plasma. In this case, the electron density diminishes sensibly: a possible explanation is that pellets further decrease the temperature of the background plasma below the point where recombination takes place (D_α emission increases). After two pellet injections, the repetitive spikes on electron density and D_α are synchronous with MHD and ECE spikes revealing a "fan instability" expelling REs and inducing recycling of the large amount of neutral gas filling the vacuum chamber. Fig. 7 shows the phase correlation between the drop in electron density, SXR, loop voltage, and neutron signals with a modulation of the MHD activity, associated with local RE losses.

Conclusions

The experimental results point to a complex picture where MHD effects, impurity transport and radiation, temperature and density variation all play different roles. REs mitigation appears correlated to the effects on the background plasma induced by the applied technique and they depend mostly on the target plasma condition. Mitigation effects, mainly correlated to induced MHD activity, have been observed. When injection either with LBO or pellet is performed on highly energetic RE beams, carrying a large fraction of the plasma current, feeble evidence of the aimed effects is observed and ionization is weakly detected. Pellets injected after the CQ can generate a drop on electron density; in this case a MHD activity is induced and its modulation is observed in the main plasma signals with consequent REs expulsion. The density increment, due to pellets injected later on RE beam, can be attributed to partial thermalization of the RE beam and/or warming up of the background surrounding plasma. This analysis points to an apparent lack of direct interaction between injected pellet or impurity with the REs beam. An evaluation of fast electron collision times for electron energies in the range 1-10 MeV shows that is respectively of the order of 0.1-1 s for a plasma temperature of 800 eV and electron density of 1×10^{20} m^{-3}. The collision time grows longer with RE energy than the diffusion time of injected impurity and pellet with increasing RE energy. The energy required for ablation of pellets in thermal plasmas is much smaller than the energy deposited by the REs in solid Deuterium, which have an estimated path length of few mm for 1-10 MeV energy. Experimental evidence is that, although the pellet is ablated, it does not produce measurable effects on the REs beam when this is highly energetic and the background plasma is cold. This work indicates for future studies on FTU the possibility of inducing a direct destabilization of the RE seeds by acting directly on the driving electric field.

Acknowledgments

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