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Analysis of runaway beam suppression experiments in FTU

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Abstract:

Experimental results on RE suppression for post-disruption RE beams and plasma with large RE population are shown. The proposed suppression technique relies on a feedback system capable to detect RE events and to trigger a controlled current ramp-down modifying the central solenoid current while the RE beam position is stabilized. Experimental evidence of RE suppression is provided by different diagnostics and hysteresis of RE dynamics (Dricer) is shown. Latest results on MHD coupling with RE loss and toroidal loop voltage control is briefly introduced.

1 Introduction

The challenging task for a disruption mitigation system (DMS) is the implementation of reliable strategies in order to mitigate thermal, mechanical and electromagnetic loads at disruptions [1]. Furthermore, the DMS has to cope with control and suppression of runaway electron beams, which are possibly generated during major disruptions, in order to avoid localized high-energy deposition causing deep melting of the structures. Strategies for runaway electron (RE) suppression are Massive Gas Injection (MGI) or Shattered Pellet Injection (SPI) are discussed in [3,9,12] whereas an alternative (simultaneous) strategy based on RE current dissipation via the central solenoid (ohmic coil) has been proposed in [9,10]. On ITER a preemptive strategy to accommodate current quenches (CQ), yielding RE beam onset with current drop less than 5MA, has been proposed in [11]. In the case the position control of the RE beam is not lost during the CQ, the maximum RE beam current decay rate has to remain below 0.5MA/s, a limit that increases up to 1MA/s for initial RE current of 12 MA.

2 RE suppression via active control

Specific real-time control strategies have been studied at FTU in order to suppress the RE beam energy. The controllers have been developed to reduce the RE beam energy performing a current ramp-down, modifying the current in the coil of the central solenoid, meanwhile the beam position is controlled in order to avoid its collisions with the plasma facing components. The plasma position feedback system manages the currents flowing in three poloidal coils named V, F and H. The coils V and F are able to generate the vertical magnetic field for radial plasma control meanwhile the coil H generates an horizontal magnetic field to control the plasma vertical position. The current amplifier of the coil F is much faster than the one of the coil V and then F is used as the main coil to provide fast plasma radial stabilization. The F and V redundancy allows to adopt an allocation control scheme to avoid current saturations as described in [1] that are mandatory in RE suppression operations where large current drops have to be addressed. In this paper we briefly recall the actual RE beam controller, that is explained in [2], and first results of a new controller developed for toroidal voltage regulation are described.
The runaway suppression strategy implemented in the real-time MARTe control system at FTU provides a re-definition of the plasma current reference that substitutes the standard one whenever the hard-x signal stands above a threshold (0.2) for more than 10ms or a plasma current quench is detected by mean of dedicated algorithms [1, 2]. The slope of the new reference can be assigned at the beginning of the shot. During the ramp-down, the current allocation algorithm smoothly redefine the current I_F and I_V to avoid I_F saturation. A specific plasma current controller has been recently added in parallel to the standard PI controller in order to improve the tracking performances [3]. At the moment the current ramp-down sets in, also the reference of the plasma external radius is reduced in order to account for the outer shift of the RE beam barycenter. In fact, with respect to standard plasma configurations, the magnetic center of a RE beam is radially outward shifted [2, 4] and the external radius reference R_{ext} is reduced to avoid beam interactions with the low-field side wall. A further control tool has been provided in the last 2016 experimental campaign to modify in real-time the V_{loop} and study the MHD induced activity and consequently the RE loss as described in Sec. 4.
FTU has many useful detectors in studying runaway electrons [2]. High energy Bremsstrahlung emission of runaway electrons hitting the metallic wall are sensed by a low sensitivity ^{235}U Fission Chamber (FC). During the RE plateau phase this detector measures photoneutrons and photofissions induced by gamma rays with energy higher than 6 MeV. Soft-X (SXR) signals at the magnetic center of the toroidal camera (major radius equal to 0.96 m) are acquired by the multichannel bolometer detecting x rays in the range 5eV to 10keV. The Hard-X-rays are monitored by a NaI scintillator (energy higher than 200keV, HXR in the figures) and the NEU213 detector sensitive both to neutron and to gamma rays and cross calibrated with a BF3 neutron detector [5]. The ratio of these two signals allows to estimate the population/energy of RE. The REIS (Runaway Electron Imaging and Spectrometry) diagnostics provides simultaneously the image and the spectrum of RE synchrotron radiation to obtain information on the RE energy distribution function and the gamma camera (GC) provides radially resolved measurements of HXR emitted

perpendicularly to the magnetic field and produced by RE through bremsstrahlung in the plasma [6, 7]. The amplitude of the considered Mirnov coil signal [8] is directly related to helical deformations of the plasma resulting from MHD instabilities, having in most cases n=1 (m=2) toroidal (poloidal) periodicity.
The plasma scenario developed in order to obtain runaway plateaus consists in very low deuterium prefill at plasma ignition and density below 2.5E19 m^{-3} during the discharge. Neon gas injection is performed by standard gas valve to induce disruptions that, in some case, accelerates and increases the pre-existent RE population leading to RE plateau. Also spontaneous disruptions of low density plasmas leading to RE plateaus have been observed.
In the following we discuss some experimental results of RE suppression event triggered in case of disruption-generated RE beam or when the HXR signal exceed safety threshold indicating that an armful RE population is in the plasma (soft-stop).

2.1 Controlled shut-down for plasmas with RE

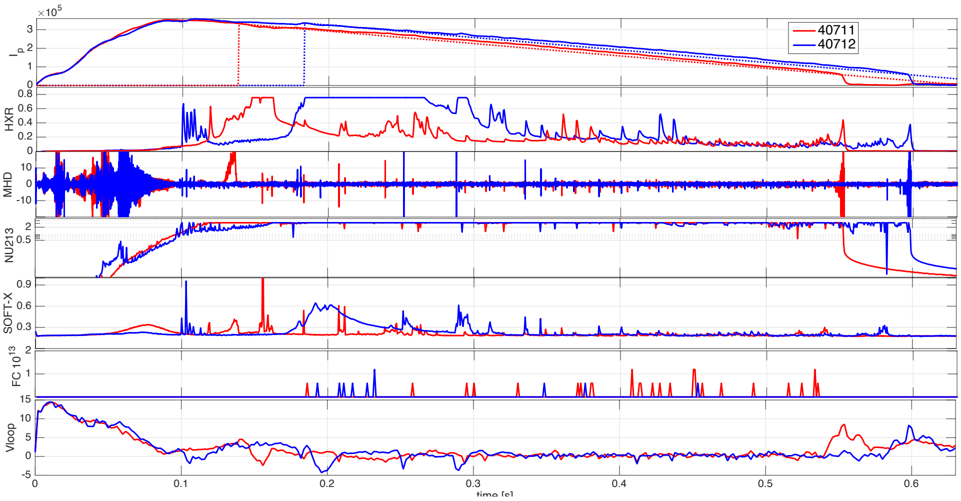

FIG. 1: Safety shut-down (soft-stop) triggered in case of plasmas with high HXR level produced by runaways.

We show in this section the experimental results related to RE suppression events triggered by high levels of HXR, such events are called "soft-stop". In Fig. 1, for readability, we illustrate only two of many soft-stops achieved in FTU during the campaigns of the last three years. In the first panel are shown the plasma currents (solid) and the new I_p references (dotted) that set in when the HXR overpass the safety threshold (0.2 A.U.) for more than 10 ms. Closely to the sets in of the new I_p reference, the HXR signal saturates as a result of RE interactions with the vessel and the signal NEU213, that is used to reveal the presence of RE in flat-top plasmas, increases up to the saturation level (this measure is much more sensitive and usually gets saturated all the time during RE beam plateaus). However, note that HXR indicates that RE population decreases along the ramp-down in number/energy and MHD induced RE loss are clearly visible and strongly correlated also to Soft-X spikes shown in the fifth panel whereas a weak correlation is noted with the fission chamber (FC) signal in panel six. The FC signal is quite low in these case since it is sensible only to high energy RE (more than 6MeV) which are usually produced during a current quench by the high loop voltage. The claim that RE energy suppression is achieved, note that in these discharges we do not refer to (post-disruption) RE beams but RE population within a plasma, is supported by the decreasing levels of HXR, Soft-X, and even NEU213 (small drops below the saturation level) and very small residual currents. The result shown in Sec. 2.3 corroborates this claim.

2.2 Post-disruption RE beam suppression

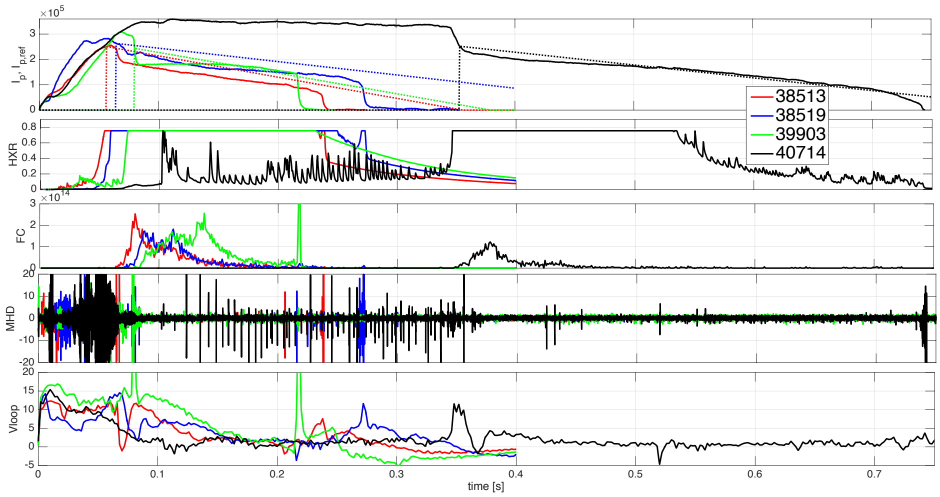

FIG. 2: Post disruption RE beam suppression with the central solenoid and the new control system.

In Figure 2 the results of current ramp-down of post-disruption generated RE beam is shown. In all discharges the disruption has been spontaneous although it happened during a series of shots where Ne injection has been performed (at 0.9s) polluting the camera and then highly increasing Z-eff. In the first plot of the Figure 2 the measured plasma current is depicted in solid lines whereas in dot lines are shown the new current references that substitute the standard one (360kA) when the current quench is detected. It is possible to appreciate the improved tracking performances during the ramp-down of the shot #40714 where the double integrator has been switched on. In the second and third plots the time traces of the HXR and FC signals reveal an important information: A large and energetic population is created/increased at CQ, a fraction of which is lost in the initial part of the plateau (interactions with the vessel, high-Z nuclei scattering and MHD loss) causing the saturation of the HXR and high levels of FC, however the remaining RE beam current decreases and, apart the pulse #39903, the FC signal does not show the usual peak observed in a number of previous discharges without the RE controller in correspondence of the final loss, especially for #38513 and #38519 with larger final current drops. The missing FC peak at final loss reveals that energetic RE are no more present at the end. In the shot #39903 the V_{loop} is higher than others in the initial phase of the plateau since the current reference is higher than the measured one and the control system try to restore it increasing the RE beam current via the central solenoid [9]. Successively, the RE beam #39903 is prematurely lost at 0.22 s since the current allocator was not active (this was not a dedicate RE control shot although the ramp-down policy is now available for any shot) causing a saturation of the current I_F and its loss against the inner wall: the FC signal exhibits a final peak since highly energetic RE have not been thermalized as in the other discharges and are lost against the vessel at the final termination. In fact, the ramp-down in the other discharges lasted long enough with low values of V_{loop} leading to RE energy suppression by primary mechanism. Noticeable is the shot #40714 with a plateau lasting about 400ms and that shows also an interesting RE expulsion along all the discharge induced by the MHD mode activity depicted at the fourth plot. A key variable to achieve suppression, meanwhile the RE beam is stabilized, is the V_{loop} that during the ramp-down has to be controlled to low values by acting on the current I_T flowing in the central solenoid.

2.3 RE energy by REIS camera

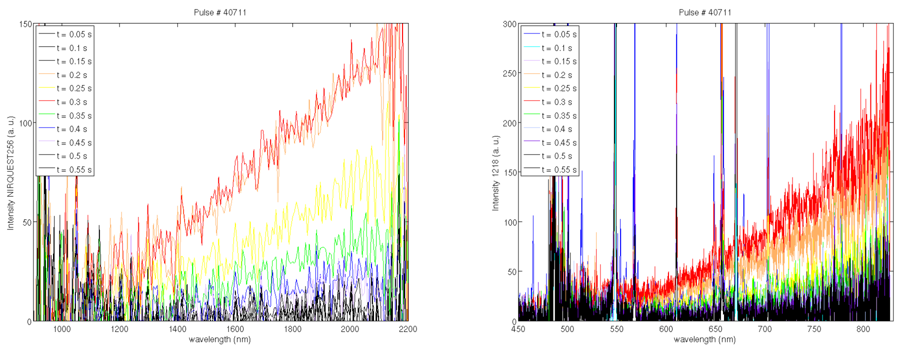

FIG. 3: Energy of Near Infrared (NIR - left) and Visible (right) spectra during the current ramp-down of the shot #40711.

The REIS facility allows to establish the energy spectrum of the runaways. Since the REIS camera has been recently installed and minor technical issues still arise during some shots, we can provide the REIS data for recent RE soft-stop events (? and one disruption generated RE beam that has been detected by the RE control system and partially suppress during a RE current ramp-down?). In Fig. 3 the energy spectrum of the shot #40711 (cfr. Se. 2.2) is drawn at different times. The current ramp-down sets in at 0.14 s and terminates at 0.6 s. The maximum energy sensed by the REIS in this shot is between 0.2 s and 0.3 s and then decreases. This is coherent with the discussion of Sec. 2.2 and the trend of the signals HXR, FC, NEU213 and Soft-X shown in Fig. 1 concluding that RE energy has been suppressed.

2.4 FTU database: RE beam comparison

In FTU a large database (650 pulses) of highly energetic RE beams, produced spontaneously or with high-Z gas injection, have been analyzed. Among these pulses, only a subset of 224 shots have been analyzed up to now and the most 58 energetic (saturation of HXR and high level of FC during the CQ phase) among them have been considered. In the major left plot of Fig. 4 we show the integral of the FC signal over the RE beam current (scaled by 1E12) during the last final loss phase ($t_{|I_p|<20kA} - t_{\text{onset final loss}}$) as a measure of the residual RE beam current ratio versus the mean slope of the current ramp-down ($I_{\text{onset plateau}}/\Delta T_{\text{plateau}}$). The markers are colored from black to red as a function of $\int_\Delta V_{loop}/\Delta$ where $\Delta = [t_{\text{onset plateau}} + T, t_{\text{onset final loss}}]$ and T is one third of the plateau duration: this coloring allows to discriminate between plateaus in which (mainly) the control system induced high (red) or low (black) V_{loop}. Supporting the results in [2, 4], slow current ramp-down, with low loop voltages values, achieve among safest RE suppressions. The discharges #38513, #38519 and #40714 presented in Sec. 2.2 are marked as stars. Other symbols represent pulses performed with different (or without) RE controllers.

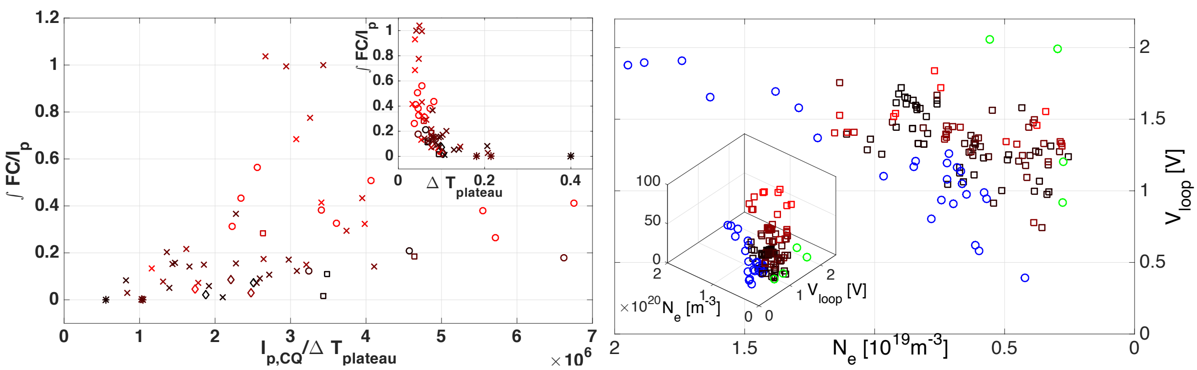

FIG. 4: (Left) Comparison among highly energetic RE beam plateaus. (Right) Hysteresis affecting the RE dynamics in homic steady-state plasmas.

3 Hysteresis in runaways population

A further issue that could even worsen the runaway suppression scenario adopting MGI is the hysteretic behavior of the runaway dynamics (primary generation) highlighted experimentally by the present study. The hysteresis that affects runaway dynamics [5, 10, 9] leads to increased density thresholds for runaway suppression once they have been previously formed. In Fig. 4 it is possible to appreciate the separation among runaway generation (green circles) and suppression (blue circles). In the between there are discharges with different number/energy of runaways represented by squares colored from black (no RE) to red (high RE), depending on the past history of the discharges. It is interesting to note how the separation between generation and suppression widens with increasing loop voltage. The generation and suppression values have been obtained as explained in [2] whereas the squares represent values of shots in stationary plasma conditions in which the density, I_p current, V_{loop} and NEU213 signals have almost zero slope and small standard deviations within a time window of 120 ms.

4 Expulsion triggered by V_{loop} control

The control system has been recently endowed with a new algorithm to control the electrical field V_{loop} during the discharge. Also in this case the output of this regulator is a term that modifies the plasma current reference to indirectly act on the central solenoid and modify the V_{loop}. The regulator output is provided by a saturated PID feed with V_{loop} tracking error and in these discharges it is switched on at 0.4 s and can be operated in flat-top as well as RE current ramp-down events. In these first experiments dedicated

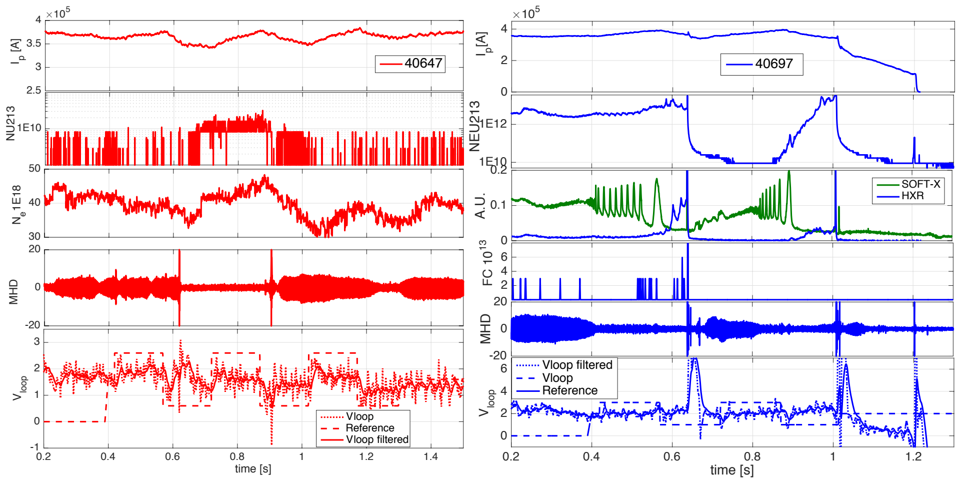

FIG. 5: Runaways expulsion triggered by MHD mode activity during the use of the V_{loop} controller.

to the new controller we have saturated the rate and amplitude of the changes in the plasma current reference and this did not allow to reach the desired V_{loop} voltage reference shown as a dashed line of the last panel of Fig. 5. As a matter of fact, only small changes of I_p have been induced. In particular, in the discharge #40647 the V_{loop} tracking error is sensibly smaller than in #40697 and this should be caused by the presence of RE current that increases the plasma self-inductance. In particular, when the V_{loop} reference drops, in the discharge #40697 the measured V_{loop} has a bounce that we refer to be effect of the higher self-inductance. In the shot #40647 it is interesting to note the sudden disappearing of MHD activity between 0.6 s and 0.9 s. In the discharge #40697 there are large RE losses corresponding to the drop in the signal NEU213, increment of HXR and Soft-X, due to MHD activity that most probably should be correlated with the V_{loop} changes. Note that the most energetic RE have been lost in the first MHD spike around 0.63 s as suggested by the FC signal. The Soft-X signal for the shot #40697 has a specific oscillation (observed also in other similar discharges with the V_{loop} controller) before the onset of the RE loss whose correlation with MHD mode activity is the subject of current studies. In the discharge #40647 a minimal number of RE is sensed exactly when the MHD activity disappears between 0.6 s and 0.9 s. Other discharges, not reported here for space constraint, suggest that MHD activity and RE loss of smaller magnitude than the one in #40697 can be obtained decreasing the steps amplitude of the V_{loop} reference signal and increasing its frequency. In the next FTU campaign experimental evidence of these correlations are expected.

5 Conclusions

To safely achieve RE beam suppression, a controlled current ramp-down has to be performed with the opportune slope to cope with coils position control amplitude and rate saturations. We have shortly discussed the experimental results on successful RE energy suppression either in case of post-disruption beam and plasma with large RE population. Comparison analysis with past RE beam discharges confirm that small V_{loop} and current ramp-down rates are associated to large runaways energy dissipation. Hysteresis of the RE dynamics have been found experimentally and initial results on V_{loop} controller and RE expulsions triggered by MHD mode activities have been reported.

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