Runaway Electron Control in FTU

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Abstract. Experimental results on the position and current control of disruption generated runaway electrons (RE) in FTU are presented. A scanning interferometer diagnostic has been used to analyze the time evolution of the RE beam radial position and its instabilities. Correspondence of the interferometer time traces, radial profile reconstructed via magnetic measurements and fission chamber signals are discussed. New RE control algorithms, which define in real-time updated plasma current and position references, have been tested in two experimental scenarios featuring disruption generated RE plateaus. Comparative studies among 52 discharges with disruption generated RE beam plateaus are presented in order to assess the effectiveness of the proposed control strategies as the RE beam interaction with the plasma facing components is reduced while the current is ramped-down.

Keywords: Runaway, plasma control

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1. Introduction

A crucial challenge towards a safe and efficient operation of ITER consists in the need of reducing the dangerous effects of runaway electrons (RE) during disruptions [1]. RE are considered to be potentially intolerable for ITER when exhibiting currents larger than 2MA. One of the most popular strategies to address this task is based mainly on RE suppression by means of Massive Gas Injection (MGI) of High-Z noble gas before the thermal quench (TQ), which possesses the additional advantage of reducing the localized heat load. However, MGI leads to long recovery time, requires effective disruption predictors, and may lead to hot tail RE generation [2] or high mechanical loads if the Current Quench (CQ) does not occur in a suitable time interval [1, 3, 4]. Nevertheless, in the circumstances in which such suppression strategy is not effective, for instance due to a delayed detection of the disruption and/or to a failure of the gas valves or of disruption avoidance techniques (e.g. ECRH) [5], an alternative strategy consisting of the RE beam energy and population dissipation by means of a RE active beam control may be pursued, as noted in [6, 7, 8]. Alternative mitigation techniques exploit magnetic (resonant) fluctuations/perturbations to displace RE; their effect on RE beam dissipation have been studied in [9, 10, 11]. Resonant magnetic perturbation techniques can be also used at the CQ to prevent large avalanche effects. However they require specific active coils that are not available at FTU.

The method proposed in this paper achieves stabilization of a disruption generated RE beam by minimizing its interaction with the plasma facing components (PFC). The RE energy dissipation is obtained by reducing the RE beam current via the central solenoid (inductive effects). Similar techniques have been investigated in DIII-D [6]. In particular, the focus here is on those RE that survive the CQ. When the RE beam position is stabilized, further techniques, not studied in the present paper, such as high-Z gas injection to increase RE beam radiative losses could be exploited.

In the last years, experiments on RE active control have been carried out in DIII-D, Tore Supra, FTU, JET, and initial studies have been carried out also at COMPASS [12]. In Tore Supra attempts of RE thermalization via MGI (He) have been investigated [13]. In DIII-D disruptions have been induced by injecting either Argon pellets or MGI while the ohmic coil current feedback has been left active to maintain constant current levels or to follow the desired current ramp-down [6]. DIII-D also studied the current beam dissipation rate by means of MGI with a final termination at approximatively 100kA [14]. Similar results on MGI mitigation of RE have been obtained at JET [15]. The present work goes along similar lines but RE beam dissipation is obtained only by inductive effects, i.e. via central solenoid as in [6], combined with a new dedicated tool of the Plasma Control System (PCS). This scheme yields a RE beam current ramp-down and position control. Effectiveness of the novel approach is measured in term of reduced interaction of highly energetic runaways with the PFC. Furthermore, as in [14], we
consider the RE beam radial position obtained by the CO$_2$/CO scanning interferometer, showing that is also in agreement with neutron diagnostics and the standard real-time algorithm based on magnetic measurements that estimate the plasma boundary.

A brief list of FTU diagnostics correlated with this work is given below. Further details are given in [16].

**Fission Chamber (FC):** a low sensitivity $^{235}\text{U}$ fission chamber manufactured by Centronic, with a coating of 30 $\mu$g/cm$^2$ of $^{235}\text{U}$ operated in pulse mode at 1 ms time resolution and calibrated with a 252Cf source. This diagnostic is essential in the analysis of the sequence of events occurring during the RE current plateau phase since the standard Hard X-ray (HXR) and neutron monitors are typically constantly saturated after the CQ. During the RE plateau phase this detector measures photoneutrons and photofissions induced by gamma rays with energy higher than 6 MeV (produced by bremsstrahlung of the RE interacting with the metallic plasma facing components).

**Soft-x (SXR):** the multichannel bolometer detects x rays emitted at the magnetic center of the toroidal camera (major radius equal to 0.96 m) in the range of 5eV to 10keV. Within this range also RE collisions with plasma impurities can be detected.

**Hard-x (HXR):** the X-rays are monitored by two systems:

a) NaI scintillator detector sensitive to hard-x rays with energy higher than 200keV mainly emitted by RE hitting the vessel (labeled as HXR in the figures).

b) The NEU213 detector sensitive both to neutron and to gamma rays and cross calibrated with a BF3 neutron detector in discharges with no RE [31]. This detector is used to monitor the formation of RE during the discharge, however at the disruption and during the RE plateau its signal is usually saturated and therefore the gamma monitoring is replaced by the fission chamber.

**Interferometer:** the CO$_2$/CO scanning interferometer can provide the number of electrons measured on several plasma vertical chords (lines of sight, LOS) intercepting the equatorial plane at different radii ranging from 0.8965 m to 1.2297 m with a sampling time of 62.5 $\mu$s. Detailed information related to mounting position and specific features are given in [33].

**MHD sensors:** the amplitude of the Mirnov coil signal [17] considered is directly related to helical deformations of the plasma resulting from MHD instabilities, having in most cases n=1 (m=2) toroidal (poloidal) periodicity.

## 2. Control strategies

Dedicated FTU plasma discharges have been performed to test two novel real-time (RT) RE control algorithms, named PCS-REf1 and PCS-REf2. Such algorithms have been implemented within the framework of the FTU plasma control system (PCS) for position and $I_p$ ramp-down control of disruption-generated RE. The active coils used to control the position and the current of the plasma are shown in Figure [1]. The PCS of FTU, extensively described in [18], exploits the current flowing within the T coil, called the
central solenoid, to impose the plasma current via inductive effect. The T coil current $I_T$ is regulated via a feedback control scheme based on a Proportional-Integral-Derivative (PID) regulator, which is driven by the plasma current error plus a preprogrammed signal. The horizontal position of the plasma is controlled by means of an additional PID regulator that is fed with the horizontal position error. The latter error is obtained by on-line processing of a series of pick-up coil signals to determine the plasma boundary (last closed magnetic surface) which is compared along the equatorial plane to the desired plasma internal $R_{\text{int}}$ and external $R_{\text{ext}}$ radii, see [19, 20, 21, 22] for further details. The current flowing in the F coil ($I_F$), by geometrical construction, allows us also to modify the plasma elongation $\hat{e}$. The current on the V coil ($I_V$), which allows us to produce a vertical field similar to F but with a slower rate of change, is modified by a specific controller named Current Allocator [23] in order to change at run-time $I_F$ and maintain unchanged the vertical field. In such a way, the plasma radial position is left unchanged and meanwhile it is possible to steer the value $I_F$ away from saturation levels. The current redistribution (reallocation) between $I_F$ and $I_V$ is performed by the Current Allocator at a slower-rate than the changes imposed on $I_F$ by the PID regulator (PID-F) for plasma horizontal stabilization (two time scale feedback system [24]).

The PCS safety rules impose that whenever the HXR signal takes value above a given safety threshold (0.2) for more than 10 ms, indication that harmful RE are present, the discharge has to be shut-down. In the previous shut-down policy the $I_p$ reference was exponentially decreased down to zero and the desired $R_{\text{int}}$ and $R_{\text{ext}}$ were left unchanged.

The new controller PCS-REf1 has been specifically designed for RE beam dissipation and comprises two different phases. In the first phase, specific algorithms described in [23] are employed to detect the CQ and the RE beam plateau by processing the $I_p$ and the HXR signal. At the same time, the Current Allocator steers the values of $I_F$ away from saturation limits, to ensure that a larger excursion is available for the control of the RE beam position.
In the second phase, once the RE beam event has been detected (CQ or HXR level), the $I_p$ reference is ramped-down in order to dissipate the RE beam energy by means of the central solenoid. In particular, a scan of the initial values and slope of the updated $I_p$ reference for RE suppression (current ramp-down), that substitutes the original $I_p$ reference when the RE beam is detected, have been performed. At the same time the desired (reference) external radius $R_{ext}$ is reduced linearly with different slopes down to predefined constant values. However, the updated $R_{ext}$ reference is such that, below 1.1 m, it is constrained to be not smaller than $R_{ext} - 0.03$ m to avoid large position errors that might induce harmful oscillations of the RE beam due to the action of the PID-F position controller. The $R_{ext}$ has been reduced in order to compensate for a large outward shift of the RE beam, hence to preserve the low field side vessel from RE beam impacts. The reduction of the external plasma radius reference can be considered the way of finding the RE beam radial position that provides minimal RE beam interaction with PFC, similar findings have been discussed in [6] and the RE beam position with minimal PFC interaction is called the “safe zone”. In all the experiments, the internal radius $R_{int}$ is not changed since we are operating in (internal) limiter configuration. Nevertheless, the control system has the objective to maintain the plasma within the desired horizontal and vertical radii, avoiding the plasma impact with the vessel (both side).

A second novel controller $PCS-REf2$ has been designed with the same objective of RE beam control and energy suppression. The main difference between this second controller and PCS-REf1 consists in an alternative profile for $R_{ext}$, when the latter is ramped-down. In this case the updated reference of $R_{ext}$ is ramped-down to a specific constant value, within the range $[1.11, 1.13]$ m, associated to low level of the FC signal during the experiments where PCS-REf1 was active, plus a small time-varying term. This small time-varying term constrained to belong to the set $[-0.04, 0.04]$ m, is computed in real-time by processing the measured $R_{ext}$ and FC signals according to the extremum seeking technique (similar to a gradient algorithm discussed in [29, 30]) in order to minimize the real-time FC signal. Furthermore, the $I_p$ ramp-down slope selected for PCS-REf2 is about three times smaller than PCS-REf1. Note that due to the current amplifiers limitations the control system is not expected to be effective in position and $I_p$ current ramp-down control within $25 - 30$ ms of the CQ detection.

3. Experimental results

3.1. Experimental scenarios

The new RE control architecture has been applied in low-density plasma discharges. In a first scenario a significant RE population is generated during the $I_p$ ramp-up/flat top at $360\text{kA}$ by selecting low gas prefill and (low) density reference of $1.5E - 19 \text{ m}^{-3}$, followed by an injection of Ne gas to induce a disruption. The sudden variation of the resistivity and the increased loop voltage at the disruption accelerate the pre-existing
RE population and lead, in some cases, to the formation of a RE current plateau which is the target scenario of these experiments. Note that this is not a method to create runaways but to turn an existing seed population of RE in a runaway plateau at the disruption. The discharge is run with an initial low gas prefill in such a way that early in the discharge ramp up a runaway population is established. The controller PCS-REf1 has been tested in the above scenario whereas the controller PCS-REf2 has been tested in a second scenario that differs with respect to the previous one in terms of an extremely low gas prefill that causes spontaneous disruption during the \( I_p \) ramp-up. This leads, in some cases, to a RE plateau. Note that since Ne gas is not injected to induce disruptions, the \( Z_{\text{eff}} \) is generally less than the first scenario.

\[ 0.75 \quad 0.76 \quad 0.77 \quad 0.78 \quad 0.79 \quad 0.8 \quad 0.81 \quad 0.82 \quad 0.83 \quad 0.84 \quad 0.85 \]

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \]

\[ \text{time [s]} \]

\[ \text{Ne tot.} \quad \text{IP} \quad \text{Vloop (scaled)} \quad \text{Ne tot. (scaled)} \]

\[ \text{P1} \quad \text{P2} \quad \text{P3} \quad \text{P4} \quad \text{P5} \]

\[ \text{SHOT #35965} \]

\[ N_e \text{tot.} \]

**Figure 2.** Pulse #35965: plasma/RE current (black), total number of electrons obtained by the scanning interferometer using the Gaussian interpolation profiles (red solid), loop voltage (dashed blue). Different pulse phases are highlighted from P1 to P5 and the time trace of the total number of electrons is magnified within the time window [0.80, 0.81] in the subplot (b).

3.2. RE beam analysis

The characterization of the different phases of a disruption with the generation of a RE plateau is given in Figure 2 for the discharge #35965, which may be considered a typical instance of the first scenario. After Ne gas injection, the plasma density slightly increases during the pre-disruptive phase P1 (grey box). The TQ (phase P2, orange box), lasting few milliseconds (1-2ms), in which the plasma confinement is lost and the thermal energy is released to the vessel combined with the high electrical field, produces a large increase of the electron density. The CQ phase P3 (green box) follows: it is characterized by a sudden drop of the plasma current and a high self-induced parallel

\[ \hat{v} \]

Formation of the RE plateau depends upon a number of factors at TQ and CQ that cannot be easily controlled.
electric field \((V_{\text{loop}})\) that further accelerates the preexisting RE and possibly increases their number. If the RE beam survives during the CQ to collisionality drag, loss of position control \(\S\) MHD induced expulsion (to mention only few RE loss phenomena), then the RE plateau phase (P4) is started. In this specific RE scenario, generally the latter phase P4 can be in turn divided into three sub-phases: during phase P4.1 the RE beam current exponentially replaces a large fraction of the ohmic \(I_p\) current (see [14], this process starts with the onset of the CQ); subsequently part of such current can be lost due to instabilities (P4.2), while the rest of the beam can survive (further plateau in phase P4.3) before the final loss (phase P5).

In Figure 2, beside the time traces of the plasma/RE beam current (solid black) and loop voltage (dashed blue), the time trace of the total number of electrons estimated by fitting the scanning interferometer data with a Gaussian function (solid red) are shown. Note that the vertical lines of sight of the CO\(_2\) interferometer are placed only in the central and lower field side of the torus (from 0.8965 m to 1.2297 m). We

\(\S\) The loss of the RE beam during the CQ typically occurs toward the inner wall since the vertical field, produced by the active coils, is not quickly reduced to match the fast variation of the CQ.
have fitted the LOS electrons radial profile with Gaussian functions, whose parameters have been obtained exploiting least square algorithms, in order to estimate also the electron density for major radius belonging to the range $[0.63, 0.89]$ m (the LOS at 0.8965 m is affected by large measurement noise and has been neglected). Example of fitted Gaussian functions on experimental data are given in Figure 3(e). The total number of electrons have been estimated integrating, with respect to the toroidal angle, the number of electrons (evaluated by the Gaussian density radial profile) falling into poloidal plane vertical strips of 0.5 cm radial width (numerical discretization), and summing up all the contributions from $R = 0.63$ (low-field limiter) up to $R = 1.23$ (high-field limiter).

In order to obtain an estimate of the number of RE we consider a time interval in which the loop voltage $V_{\text{loop}}$ induced by the central solenoid is larger than 5 V. In fact in this case a decrease in the plasma current $I_p$ cannot be associated to the suppression induced by central solenoid but it is essentially due to the RE confinement loss. Furthermore, we restrict the analysis to the time interval where the interferometer signal indicates a shift of the electrons toward the (low field-side) poloidal limiter, i.e. toward the portion of the torus where the interferometer LOS are present. Under such conditions, which are met within the time interval $[0.8, 0.81]$ s in discharge №35965 shown in Figure 2, it is possible to infer that most likely the $I_p$ reduction is directly related to the loss of RE (that carry most of the current) in the low field-side of the vacuum chamber. Moreover, the FC detector reveals that (a percentage of) RE have energy higher than about 6 MeV. In the time interval $[0.8, 0.81]$ s, letting $v_{||,\text{RE}} \approx \cos(\bar{\theta}) v_{\text{tot,RE}}$ where $\bar{\theta}$ is the RE beam mean pitch-angle, $v_{\text{tot,RE}} \approx c$ for 6 MeV RE, then by using current drop $\Delta I_p = 50 kA$, major radius of the RE beam centroid (Gaussian barycenter) $R_{re} \approx 1.07$ m, drop of electron density $\Delta N_e = 5.6 E^{18}$ it is possible to obtain a rough estimate of the ratio between RE and cold lost electrons by means of

$$\frac{n_{\text{lost}}^{\text{re}}}{n_{\text{tot}}^{\text{lost}}} \approx \frac{\Delta N_{re}}{\Delta N_{\text{tot}}} \approx \frac{\Delta I_p 2\pi R_{re}}{e^{-v_{||,\text{re}}\Delta N_e}}, \quad (1)$$

belonging to the range $[1.3, 2.5]E^{-3}$, assuming $\bar{\theta} \in [20^\circ, 60^\circ]$ as reported in [31]. The percentage of the RE with respect to background plasma estimated using the total number of electrons $N_e$ within the same time interval by using

$$\frac{n_{re}}{n_{\text{tot}}} \approx \frac{I_p 2\pi R_{re}}{e^{-v_{||,\text{re}}N_e}}, \quad (2)$$

belongs to the range $[2.6, 5.2]E^{-3}$, assuming $\bar{\theta} \in [20^\circ, 60^\circ]$. Similar ratios have been found in DIII-D [14] and Tore-Supra [13]. It is interesting to note the similar ratios between lost and beam runaway electrons. Moreover since the cold plasma closely moves together with the RE beam, the RE should be subject to a further mechanism of energy loss due to its magnetic interaction with the cold plasma that, as the synchrotron radiation [32] effect, would drain/limit energy of the RE beam.

In the following we discuss the RE beam dynamics in the phase P4.1-P4.3 looking at the signals of Fig. 3. The reader can also refer to the density LOS profile versus time
shown in the left graph of Fig. 5.
The trends of the LOS in the time interval between the RE plateau onset (about 0.775 s) and 0.82 s, depicted in Figure 3(e), show that the cold plasma column is moving toward the low-field side: correspondingly the FC signal increases due to the increased RE loss on the outer limiter (low-field side, phase P4.1).
In Figure 3(e) a large outer shift and an extremely peaked profile of the cold plasma column can be seen at approximatively 0.81 s. Such large shift towards the low-field side is caused by the control system that handles \( I_F \) and \( I_V \) to obtain a centered RE beam (0.96 m) as shown by an analysis on the equilibrium conditions obtained by a simple formula given in [34], also confirmed by the more sophisticated CREATE NL tool [35]. Anyway the presence of a large outward shift of the RE beam orbits is indeed a well known feature of the RE beam [6]. Furthermore, the vertical magnetic field produced by the active coils (F and V) cannot be responsible for the high peaked profile (same analysis as above). Therefore, the RE beam that magnetically confines the cold electrons is responsible for the peaked LOS profiles having a large radial shift. This fact is in agreement with [14] where it is shown that the RE beam is enveloped by the cold plasma and this supports the use of the interferometer data to estimate the barycenter of the RE beam.

In Figure 3(b) we have reported the time traces of \( R_{\text{int}} \) and \( R_{\text{ext}} \), that are the internal and external plasma radii evaluated via magnetic measurements of the pick-up coils (see [18]). In the same subplot, we have depicted the interferometer barycenter, i.e. the major radius corresponding to the highest peak of the interferometer density profile, and the Gaussian barycenter that is the major radius corresponding to the highest peak of the Gaussian functions that are very similar to the magnetic axes depicted in green solid line with circle marks obtained by using the ODIN algorithm, an equilibrium code that uses magnetic measurements [18]. For the considered discharge #35965 of Fig. 3 the ODIN algorithm converges up to 0.795 s.
These signals allow to estimate the centroid of the RE beam and it can be seen that if the plasma is not highly peaked (before 0.805 s as shown in the subplot (e)) and it is not in the high-field side where \( CO_2 \) LOS are not present (after 0.823 s), trends of magnetically reconstructed plasma external radii and the interferometer barycenter are very similar (this fact generally holds for RE beam plateau at FTU). The corresponding increment of the FC signal amplitude is the mark that a greater number of RE, displaced from the RE beam by the MHD activity, hit the vessel. At 0.821 s a particularly intense MHD activity, registered as a sudden spike in the subplot 3(d), associated also to highly peaked LOS profile in the subplot (e), displaces a large fraction of the RE beam towards the toroidal (inner wall) limiter as shown by the inward movement of the cold plasma in the subplot 3(e) (phase P4.2). Consequently, there is a large spike also in the FC at 0.822 s. The displacement of RE towards the toroidal limiter induces a drop of the loop voltage, shown in Figure 2. This voltage drop, measured by the coil placed within the inner limiter, is induced by flux increment produced by the inward displacement of the RE beam. A detailed study of the loop voltage sudden drop at time 0.821 s, not...
reported here, has been carried out confirming the RE beam shift towards the inner wall. Detailed studies on this phenomenon have been carried out in [28].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{First scenario: Comparison between experimental results with the old RE shut-down policy (#35965, #35964) in the left column, and the PCS-REf1 controller (#36569, #36574, #36634) in the right column.}
\end{figure}

3.3. RE position and current control performances

Experimental results of the first and second scenario are shown in the Figures 4 and 5, respectively. In the left column subplots of the two figures the results of the previous control policy are reported. The plasma current $I_p$ reference at flat top is 360kA, except for the shots #20532, #23448, #18723 that is equal to 500 kA. In the new policies the old plasma current reference (exponentially decreased down to zero whenever the HXR signal is above 0.2 for more than 10 ms) is substituted by a linear ramp-down as shown by the dashed lines in the subplots (a). Before the new reference (dashed lines) sets in, the previous one is used. In the experiments where the new controller PCS-REf1 has been activated, the switching time of the plasma current ramp-down has been changed by modifying specific parameters of the CQ detector among different pulses, whereas the different slopes have been set directly modifying the controller configuration file. The alternative plasma current reference allows to define an updated plasma current error that is fed to the PID-T controller (the PID regulator used for current control in the T coil). Then, the PID-T acts on a current amplifier in order to change the current flowing within the central solenoid, $I_T$, yielding the RE beam current suppression by induction.

Subplots (b, f) of Figures 4 and 5 show the estimated (solid) $R_{ext}$ via magnetic measurements and the new $R_{ext}$ desired value (dashed). In the old policy $R_{ext}$ was kept
constant and equal to 1.23 m, whereas in the new PCS-REf1 it is changed dynamically at run-time as discussed in Section 2. The loop voltages are depicted in the subplots (c, g) of Figure 4 whereas the time traces of the NEU213 x-ray monitor are provided in Figure 5. In the subplots (d, h) the FC (solid) and HXR (dashed) signals (the latter, scaled by a factor 2E14, saturates at 1.5 \times 2E14) are shown.

The new $I_p$ ramp-down induces a lower $V_{loop}$ in comparison to old shots (see Figure 4(c, g)), due to the action of the control system that modifies the rate of the current in the central solenoid coil, hence reducing the energy transferred by the central solenoid to the RE and consequently reducing also the radial shift. On the contrary, in the old policy, the effort of the PCS to recover the flat-top $I_p$ value induced large voltages that increased the RE energy and consequently also their outward shift. At the same time, the smaller $R_{ext}$ of the new reference contributes to the reduction of the RE beam interaction with the low-field side wall. Since the discharges of the first scenario (pre-disruption level of RE and the FC signal during the CQ) are almost comparable, the improvements in terms of reduced FC signal compared to discharge #35965 and #35964 without PCS-REf1 are quite evident. It is interesting to note the large improvement for the shots #36574 and #36634, also with respect to the #36569, when the external radius is reduced of more than 10%.

Data obtained in the first scenario have been processed to determine a suitable constant $R_{ext}$ reference associated to minimal FC signal values. The values found are in the range
$R_{\text{ext}} \in [1.11, 1.13] \, \text{m}$ against the standard 1.23 m. This reduction is in agreement with the RE beam outward shift $\Delta R_{RE}$ given by the approximated formula [6]

$$\Delta R_{RE} \approx \frac{qW_{RE}}{ecB},$$

where $q$ is the averaged safety factor $q \in [2, 17]$, $W_{RE} \in [6, 20] \, \text{MeV}$ is the RE energy, $B = 6T$ is the toroidal field yielding $\Delta R_{RE} \in [2, 12.5] \, \text{cm}$. This new constant values have been used for the controller PCS-REf2, tested in a second scenario, whose results are shown in Figure 5. In the latter case also the real-time FC signal is exploited in order to slightly modify $R_{\text{ext}}$ and minimize the FC signal: see the dashed lines in Figure 5(f) that suddenly ramp down to 1.11 m and 1.13 m for #38519 and #38513, respectively, and then slightly changes in time. Although the number of the available discharges in the second scenario was not sufficient to optimally tune the gains of the extremum seeking policy, the results are encouraging.

Discharges of the second scenario characterized by a sudden increase of the FC signal at CQ have been found on the FTU database and some of them have been reported in the left column of Fig. 5. The discharges with active RE beam control #38513 and #38519 show a reduction of the FC signal down to zero while the $I_p$ is slowly ramped-down and the reference of $R_{\text{ext}}$ is reduced. On the contrary the discharges #20532, #23448, #18723, without the active control, show a substantial increase of the FC signal slightly before and during the final loss. In the discharges #38513 and #38519 the two hard x-rays monitors NEU213 and HXR shown in the figure 5(c,g) are saturated from the CQ throughout the $I_p$ ramp-down indicating that energetic RE are present. In the discharge #38519 at the end of the current ramp-down, about 30 ms before the final loss, the NEU213 have small drops below the saturation value. In the left column of Fig. 5 it is shown the shot #36912 that is an example of shot where only a ramp-down current is performed and where the current allocator is not active. It can been seen that after the CQ there is the usual compression against the inner wall but then, due to the control system that try to reestablish the desired $R_{\text{ext}} = 1.23 \, \text{m}$, the beam moves outward and the discharges terminate due to the collision of the beam with the outer limiter.

It has to be noted that in the second scenario the new controller is activated not by the detection of the CQ or current plateau onset, as for the first scenario, but because the HXR signal is above 0.2 for more than 10 ms. This safety condition triggers the new current ramp-down and $R_{\text{ext}}$ references in the shots #38519 and #38513. The decreasing of $R_{\text{ext}}$ reference before the plateau onset, although not clearly visible, might be associated with a larger initial loss of the runway electrons in the high-field side of the vessel and this will be take into consideration for future controller design. Furthermore, in order to further reduce RE beam interaction with the inner vessel, we could even consider the DIII-D approach activating a saturated control to decrease as fast as possible the vertical magnetic field produced by the active coils (F and V) whenever the CQ is detected. The selection of the saturated control time duration would require detailed analysis on FTU. The PCS-REf1/2 results seem to suggest the importance of
reducing the external radius reference to minimize the RE interaction with the vessel, confirming similar results discussed in [6]. As additional evidence observe the rise of the FC signal in correspondence of the increase of $R_{\text{ext}}$ in the discharges run with the old controller of Figure 5 (left column).

A further interesting feature is that despite the RE beam final current loss in the PCS-REf2 (right column of Figure 5) is larger, the corresponding final FC peaks are noticeably smaller if compared with the final peaks obtained in Figures 4 and 5. It is interesting to note also that in the shot #38519 (slightly in the #38513) the HXR signal drops below the saturation threshold before the final loss unlike all the other discharges at FTU: since the current drop at final loss is about 100 kA, this might suggest that a considerable RE beam energy has been dissipated during the ramp-down. These facts are signs that certain degree of RE energy dissipation has been obtained reducing the slope of the $I_p$ ramp-down and the $R_{\text{ext}}$ reference.

We proceed now to the analysis of the time evolution of the interferometer radial profiles. Figure 6 shows the time interval between the RE plateau onset and the final loss ($I_p \geq 20kA$), for discharges #35965 and #35964 obtained with the old controller in the first experimental scenario. Unfortunately we do not have the scanning interferometer data for the second scenario experiments with the old controller. Figure 7 shows two experiments with the new controllers: a) PCS-REf1 (discharge #36574, first plasma scenario) b) PCS-REf2 (discharge #38519, second plasma scenario. Fig. 6 indicates
that the RE plateau termination is triggered by MHD instabilities that suddenly move the background plasma/RE beam inward. Further studies are necessary in order to better understand the instability type, able to induce such RE beam displacements, shown in Fig. 6 for discharges #35964 and #35965. By looking at the Fig. 7 it is evident that the new control system is able to avoid the large outer oscillation shown in Fig. 6 as well as in the left columns of Fig. 5 and 4.

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**Figure 7.** Time evolution the interferometer LOS for RE beam controlled discharges #36574 (left) and #38519 (right). The solid red and green time traces at major radii 1.25m (duplicated at 0.85m) are the MHD and $V_{loop}$ signals, respectively, scaled by 1E18.

Finally, in Figures 8 and 9 we show a comparison of 52 disruption generated RE beam plateaus, retrieved by ad-hoc algorithm on the FTU database among 35000 discharges, subdivided as follow: 2 shots with PCS-REf2 in the second scenario (blue cross), 5 shots with PCS-REf1 in the first scenario (blue circle), 5 shots with only a linear current ramp-down without $R_{ext}$ redefinition nor the current allocator active in the second scenario (blue square) and with the old controller 16 shots in the first scenario (red circle) and 24 shots in the second scenario (red cross). A black diamond is superimposed to the shots where the $I_F$ reached the saturation threshold.

The definition $\Delta T_{\text{plateau}} = t_{\text{FCspike}} - t_{\text{CQ}}$ is considered, where the $t_{\text{CQ}}$ is the onset of the current drop and $t_{\text{loss}}$ it is assumed to be the time corresponding to the last FC spike before $|I_p|$ drops below 40 kA, and generally individuates the knee of the $I_p$ time traces at final loss. The FC integral is evaluated as the sum of all counts from the beginning of the CQ up to the end of the shot.

In the top plot of the Figure 8 the FC final peak values are shown with respect to the RE beam plateau duration. The values obtained by PCS-REf2 are the smallest (blue
Figure 8. A comparison of different disruption generated RE beams. In red circles and crosses the first and second scenarios RE beam plateaus with old control policy, respectively. In blue circles and blue crosses the RE beams controlled by the PCS-REf1 (first scenario) and PCS-REf2 (second scenarios), whereas in blue squares are the shots with only a current ramp-down without a redefinition of $R_{ext}$ reference nor the use of the current allocator. An example of the latter type of shot is shown in Fig. 5 (#36912). A black diamond is superimposed to the shots where the $I_F$ reached the saturation threshold. Low levels are also obtained by PCS-REf2 (blue circles), whereas the only current ramp-down without the $R_{ext}$ redefinition and current allocator (blue square) are slightly above the former. For the shots in which the current of the coil $I_F$ reaches the saturation, leading to plasma radial loss of confinement, a black diamond is superimposed. The saturation of the coil F is not observed in the shots where the current allocator, that modifies the current $I_V$ in order to maintain $I_F$ far from saturation thresholds, is used (PCS-REf1,PCS-REf2). The reduction of the external radius goes along the same direction of reducing $I_F$ excursions. It is interesting to note that the final FC peaks of shots with only a current ramp-down (blue square) are higher than PCS-REf1 and PCS-REf2: a possible motivation of this difference, as well as the plateau duration, is the redefinition of the $R_{ext}$ reference and the use of the Curren Allocator.

In the bottom plot of the Figure 8 the FC integral is shown with respect to the RE beam plateau duration. In this case, the mean value of blue circles is slightly below the mean value of the FC integral evaluated with respect to the uncontrolled shots (red cross and circles) meanwhile the blue crosses have approximatively the same value. It is the worth of mentioning that the integral of the FC x-ray monitor is proportional to the total energy absorbed by the vessel during the shot, whereas the FC values are proportional to the power released by the RE beam onto the vessel. Since we are not
able to reconstruct the RE beam impact surfaces, we can not evaluate the actual power deposition.

![Graph showing FC final loss integral vs $I_p(t_{loss})$ and FC final peak vs $I_p$ decaying rate]

Figure 9. Comparative studies of the FC tail integral vs $I_p$ at the onset of the final current loss (top) and the FC final peak vs $I_p$ decaying rate (bottom).

Given that the FC integral mean values of blue circles and crosses are about the same of red ones, whereas the final FC peaks are much smaller for the newly controlled RE beam, we could infer that slow current ramp-down and $R_{ext}$ redefinition allow to decrease the RE beam energy and possibly reduce its interaction with the PFC.

In the top plot of the Figure 9, the FC final loss integral, evaluated summing up all the counts of the FC camera from $t_{loss}$ to the end of the shot versus the $|I_p(t_{loss})|$ is shown. The onset of the $I_p$ final loss defined is estimated as $t_{loss} = t_{FC spike} - 5$. This figure has been provided since the ratio between the FC tail integral and $|I_p(t_{loss})|$ should be related to percentage of the current (energy and number) still carried by the runaways before the final loss onset.

In the bottom plot of the same figure, the FC final peak value is shown with respect to the decaying rate of $I_p$, evaluated as the ration between $\Delta I_p = |I_p(t_{plateau}) - I_p(t_{loss})|$ and $\Delta T_{plateau}$, where $t_{plateau}$ is the onset of the RE beam plateau. It has to be noted that from this 2D picture it is not possible to see the value of $|I_p(t_{loss})|$ and the shots with high FC final peaks that seem to have a small current decaying rate are indeed shots with premature loss of confinement, leading to small $\Delta I_p$ and than a small decaying rate. To better show this dependence we add in the Figure 10 the dependence by $|I_p(t_{loss})|$. From these last two pictures it seems clear that to have small $|I_p(t_{loss})|$ and FC peaks the current decaying rate is below 2MA/s.
4. Conclusions

Two algorithms for the control of disruption generated RE have been implemented at FTU. The two algorithms redefine in real-time the $R_{\text{ext}}$ and $I_p$ ramp-down references, exploiting the magnetic and gamma-rays signals. The $I_p$ ramp-down is performed via the central solenoid and the current in the poloidal coils is changed to control the position of the RE beam as determined by the magnetic measurements. We have found that the external plasma radius $R_{\text{ext}}$ evaluated by magnetic moments at FTU can be used to estimate the RE beam radial position when the current profiles are not heavily peaked as shown by the interferometer data. It has been shown that modifying the plasma current reference (ramp-down) and reducing the $R_{\text{ext}}$ the gamma signal, provided by the FC chamber, decreases as an indication of RE beam energy suppression and reduced interactions with the vessel (especially the low-field side). A (slow) current decay rate of about 0.5 MA/s has been found to provide a better RE beam confinement and consequently a controlled energy dissipation. To further and quantitatively corroborate this fact, we have analyzed a considerable amount of post-disruption RE beam discharges at FTU showing that FC peaks at final loss decrease when slowly ramped-down. This is in accord with experimental findings in [6], where slow (1MA/s) current ramp-down have seen to provide better RE beam confinement. Although further experiments are necessary to better refine the optimal external radius reference during the RE beam current ramp-down, possibly defined as a function of $I_p$ and RE beam energy in future work, a constant value of approximatively 1.12 m seems to significantly help in reducing the RE impacts with the PFC. This corresponds to an
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external major radius reduction of approximatively 10% of the flat-top value (1.23 m) and a 40% reduction of to the plasma minor radius that is equal to 0.305 m in FTU. The interferometer signal analysis has shown that strong MHD induced instabilities, which displace a large percentage of the RE beam, arise when the (cold) electron profiles are highly peaked as in [27]. Now that we have found suitable plasma/RE beam current and position references, the current and position controllers PID-T and PID-F will be re-designed to further improve their performances specifically in the RE control phase. The novel controllers will be based on a RE beam dynamical model identification that is under development.

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