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# First experimental results of runaway beam control in TCV

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**Abstract**. The first attempts of suppression of runaway electron (RE) beams in TCV are presented. Disruption-generated RE are obtained through small injections of high-Z impurities (Ar and Ne) in low-density inner limiter circular plasmas ($B_t$=1.43 T, $I_p$=200 kA). The gas injection is performed by means of the disruption mitigation valve system. A dedicated controller for RE suppression is implemented in the digital plasma control system. The current quench (CQ) and the RE plateau onset are detected by feeding $I_p$ to an approximate derivative linear filter with specific logic. Once the RE plateau onset is detected, a new $I_p$ reference, ramping-down to zero with a pre-selectable rate, replaces the standard reference. To improve the ramp-down tracking performance, a further logic block, implementing a novel double integrator scheme, is paired with the standard plasma current controller to select the appropriate voltage for the amplifiers powering the ohmic coils. The RE beam has slow radial outward shift during the plateau phase of the order of 0.15 m, but the position control system is able to avoid RE interactions with the vessel before the RE final loss.

## 1. Introduction

Runaway mitigation is one of the main concerns for safe ITER operation. The disruption mitigation system (DMS), still under development for ITER [1], will be designed to inject the correct amount of high-Z impurities in order to dissipate thermal and magnetic energy by radiation within the mechanical limits of the structure. During the disruption phase in ITER and specifically during the Current Quench (CQ), significant production of high-energy runaway electrons (RE) is foreseen due to primary and secondary generation mechanisms. Current strategies to limit post-disruption runaway formation and suppression are based on Massive Gas Injection (MGI) and shattered pellet injection (SPI) [2,3]. The main drawback of such approaches is a conflict with the admissible time window of 50-150 ms for the CQ duration in order to meet ITER mechanical constraints. Within this time, it seems unlikely that in ITER the theoretical amount of high-Z (Ne or Ar) would be assimilated quickly enough without reducing the CQ duration below the limit of 50 ms [1]. A further issue for appropriate tuning of the MGI on ITER is the current dissipation rate of the formed RE beam, which should stay below 1 MA/s while the CQ drop should not exceed 5 MA in order to meet the position control system constraints [4]. Nevertheless, promising results using MGI have been obtained in various tokamaks [2,5]. A different approach, more likely to be used simultaneously to MGI, exploits the ohmic coils to obtain a RE beam current ramp-down while its position is stabilized [3,6,7]. This paper describes the first experimental attempts, carried out in 2015, of position and current (ramp-down) control of disruption-generated RE beams in TCV. The prerequisites for the experiment were the establishment of a reliable scenario for the generation of RE in the post-disruption phase (*runaway plateau*), since no major prior experience on RE was available in TCV, and the implementation of RE control policies in the TCV control system.

## 2. Disruption-generated RE scenario

A reliable scenario for the generation of a *runaway plateau* in post-disruption phase has been achieved in TCV by using the Disruption Mitigation Valve (DMV) [**ref DMV**] with either Ar or Ne during the flattop phase in very low-density deuterium plasmas. Small injections of high-Z impurities (Ar and Ne) have been performed in inner limiter circular plasmas (electron density, $n_e$=1-5×$10^{18}$ $m^{-3}$, toroidal magnetic field, $B_t$= 1.43 T and plasma current, $I_p$= 200 kA). Feedforward deuterium injection is kept to an absolute minimum during the discharge, resulting in a decreasing electron density after the end of the $I_p$ ramp-up. A RE population sets up when the density drops below ~2.6×$10^{18}$ $m^{-3}$. The DMV impurity is injected at t=0.4 s, when the $V_{loop}$ is still high (after the $I_p$ ramp-up phase) and $n_e$~2×$10^{18}$ $m^{-3}$. The high $V_{loop}$ at the CQ increases the runaway population and energy leading, in some cases, to the RE current plateau. A total of 25 discharges have been performed. The first attempts to produce RE plateau in disruptions during the $I_p$ ramp-up (without DMV) failed, resulting in just ~3 ms long RE plateaus. The use of DMV lead to the generation of much longer RE plateaus whose durations range from 30 ms to 100 ms (see **Figure 1**): 2 *plateaus* were obtained with Ar (out of 13 attempts) and 3 *plateaus* with Ne (out of 8 attempts). A slight larger current decay appears to be correlated to the use of Ar.

It was found that the optimum time for the optimum DMV aperture time is Δt=10 ms, as larger Δt values (≥ 15 ms) cause abrupt disruption without RE plateau while lower Δt values (≈ 5 ms) are not enough for the disruption to occur. In some discharges, a later timing of the impurity injection (t=0.6 s and t=1.2 s) was also tried without any RE plateau formation, probably due to the lower $V_{loop}$ at such later times. Finally, injection of ECRH (used in AUG to obtain disruption-generated RE [**ref AUG**]) was used in one discharge, but did not prove to be useful since it led to density increase, probably not beneficial for RE generation.

The PMTX is a good diagnostic to monitor the RE plateau phase and quantify the RE beam emission (bremsstrahlung radiation). The system, placed outside the torus in the hall of the machine, is composed by a scintillator coupled to a photomultiplier tube enabling the Hard-X Ray (HXR) RE emission to be measured. The two other HXR diagnostics (the HXR tomographic spectrometer with measured HXR energy, $E_{HXR}$≤300 keV and the duplex multiwire proportional x-ray counter with $E_{HXR}$≤20 keV) saturate during the RE plateau phase due to the large and energetic production of HXRs.

The sharp decrease of the electron temperature measured by Thomson Scattering diagnostic from t=0.4s onwards supports the presence of cold plasma and the existence in the discharge of a RE beam carrying the largest fraction of current.

## 3. Runaway Control Implementation

A dedicated controller for RE suppression has been implemented in the SCD (Système de Contrôle Distribué), the digital plasma control system of TCV. As first, the CQ and the RE plateau onset are detected when $I_p$ is fed to an approximate derivative linear filter with specific logic. After the RE plateau onset, a new current reference smoothly replaces (via an exponential decay) the standard reference. The new current reference, starting from the value $I_p(t_{cq})$, is ramped-down toward zero with a pre-selectable rate. To improve the ramp-down tracking performance, a further logic block is paired with the standard plasma current controller to select the appropriate voltage for the amplifiers powering the ohmic coils. This block implements a novel double integrator scheme [8], necessary to have null steady-state plasma current error during ramps: it is switched on at 0.3 s to guarantee its action in case a disruption occurs afterwards.

## 4. Runaway Control Experimental Results

**Figure 1** summarizes the results of the experiments by comparing 2 discharges with RE control ON (#50980 - Ar injection and #50990 - Ne injection) with 1 discharge with RE OFF (#50991). The HXRS signal (saturated in the later RE plateau phase) indicates that RE form approximately at t~0.23 s. After the impurity injection, the HXR emission increases strongly (see PMTX panel) and within 200 ms a CQ occurs leading to a RE plateau (see details in **Figure 2**). In discharge #50991 the standard control system drives a larger electric field attempting to restore the reference 200 kA $I_p$: the result is a final disruption almost at the flattop $I_p$ value. On the contrary, in the two discharges with RE control ON the $I_p$ is gradually reduced (according to the newly defined $I_p$ references, see **Figure 3**) and the final RE loss occurs at a lower $I_p$.

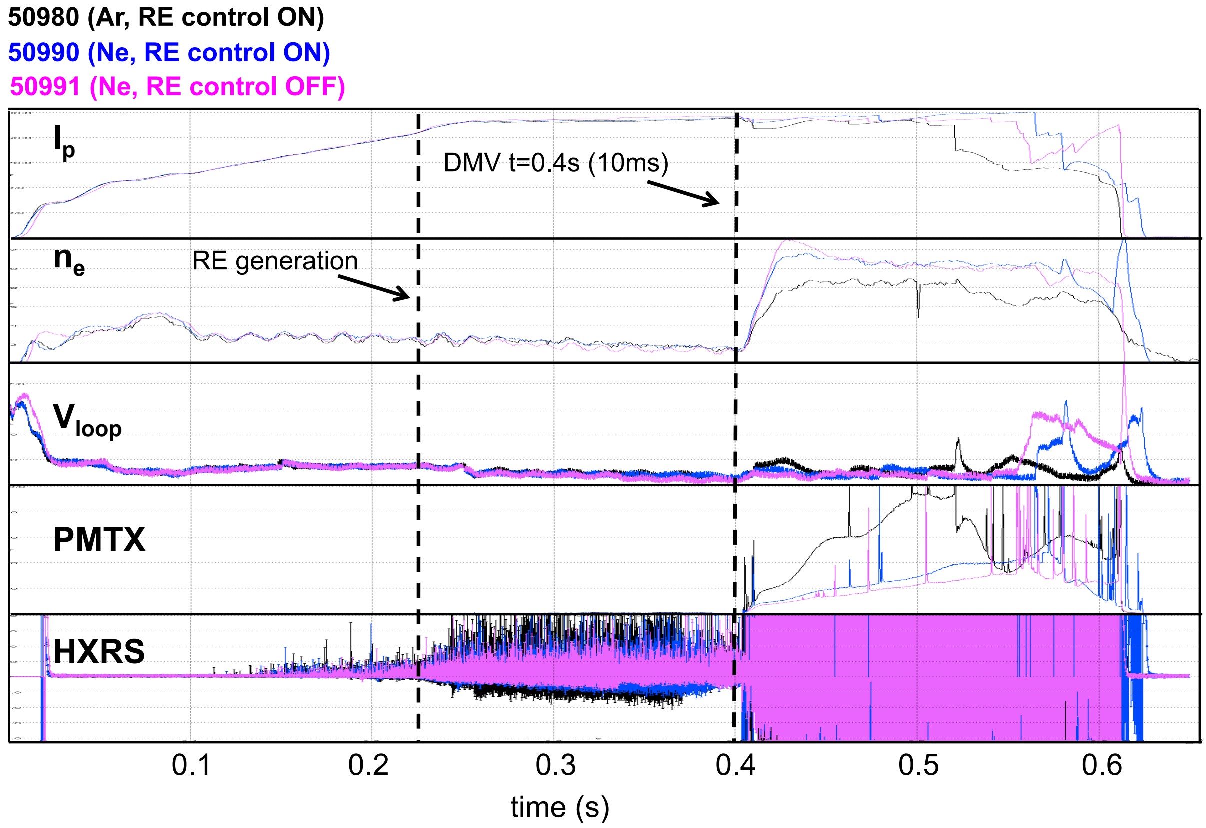

*Figure 1: Post-disruption generated RE beams. The beams, starting at the disruption, between t=0.5 s and 0.6 s, last for ~90 ms in #50980 and for ~45 ms in #50990.*

Note that the higher level of PMTX for #50980 is most likely caused by the use in this discharge of Ar instead of Ne. All $I_p$ drops, also after the RE plateau onset phase, are clearly correlated with MHD mode activity. After the CQ, the PMTX level is mainly given by RE Coulomb collisions with Ne/Ar, whereas spikes are caused by sudden expulsions of RE from the main beam and are triggered by MHD instabilities, as shown by the MHD signal amplitudes (bottom panel of **Figure 2**). The control system appears to be able to maintain the position of the RE beam before the final loss with moderate interactions with the plasma facing components: this is suggested by two facts: a) the PMTX signal does not increase significantly during the controlled RE beam phase; b) the RE beam has a just slow radial outward shift of the order of 0.1 m during the plateau (**Figure 4**).

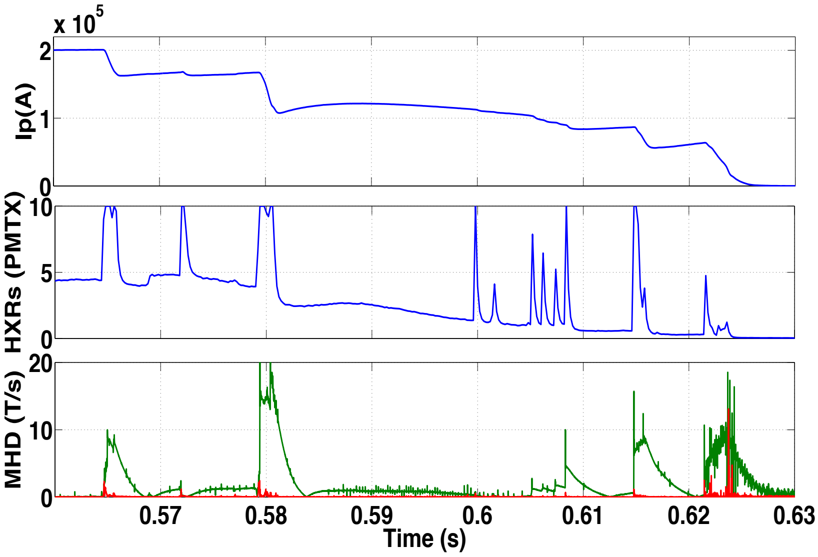

***Figure 2****: RE plateau (discharge #50990): correlation between the growth of the MHD modes and the HXR spikes.*

An interesting event occurred in discharge #51029, in which an atypical action of the standard control system (RE control OFF) led to an almost zero $V_{loop}$ and the RE current experienced a slow and almost MHD unperturbed decay (**Figure 5**). This experiment highlights the importance of the $V_{loop}$ in triggering harmful MHD instabilities leading to premature termination as occurred in the other discharges, especially #50991. Since for ITER it is mandatory to have final RE loss with $I_p$<2 MA, this observation suggests that future RE beam current controllers and current references should be designed to obtain a current suppression while maintaining a limited electric field.

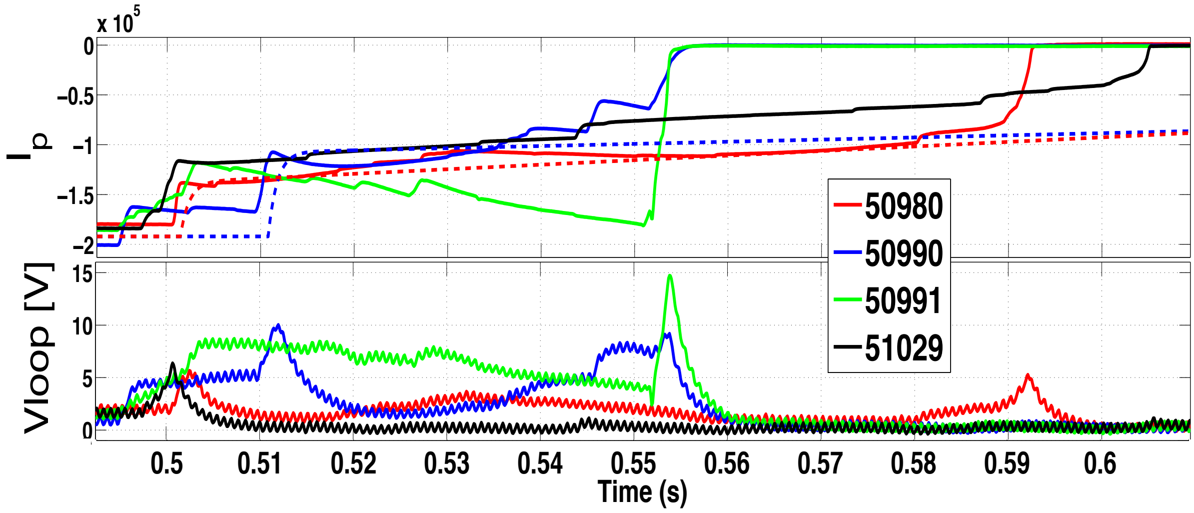

***Figure 3****: Measured $I_p$ (top) and $V_{loop}$ (bottom) during post-disruption generated RE beams: the dashed lines are the new $I_p$ references set by the RE control algorithm (discharges #50980 and #50990).*

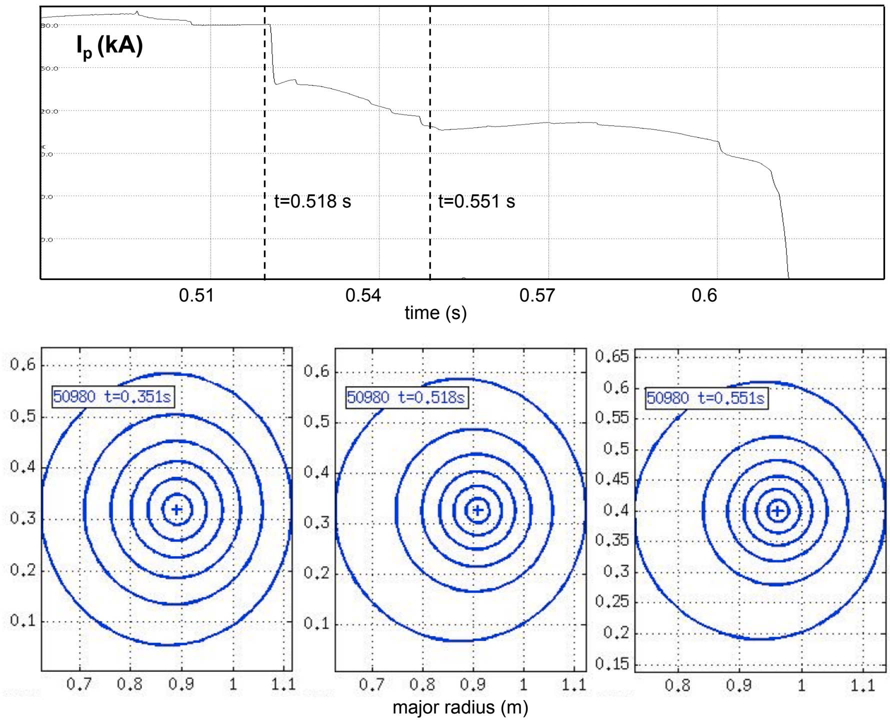

***Figure 4***: *Discharge #50980: (top) RE plateau phase; (bottom) LIUQUE [ref LIUQUE] equilibrium reconstructions showing slight outward shift of plasma column.*

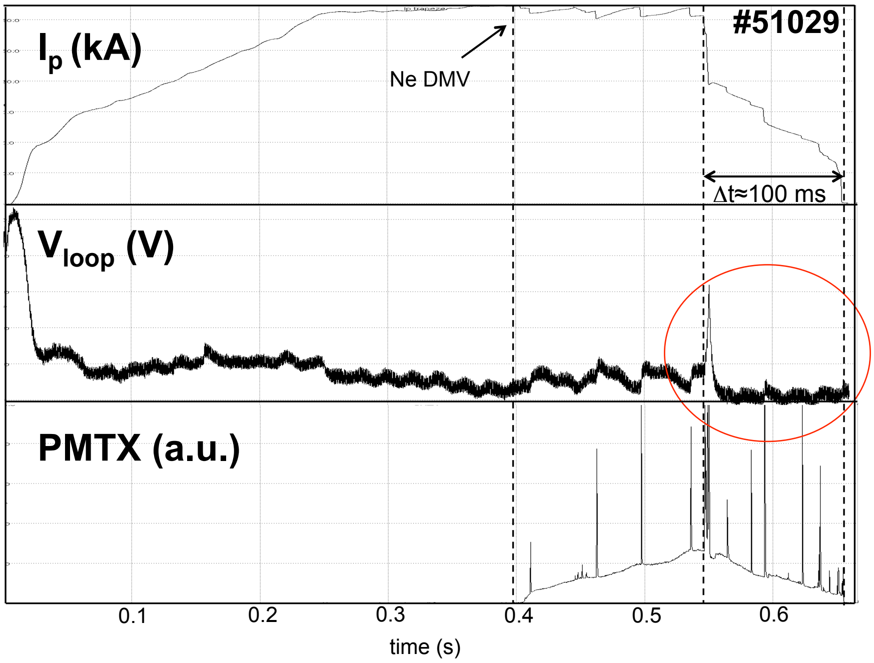

***Figure 5***: *RE plateau generation with RE control OFF: the standard control system leads to an almost zero $V_{loop}$ with the result that the RE current experiences a slow and almost MHD unperturbed decay.*

## 5. Conclusions and future prospects

RE control tools have been implemented in the digital plasma control system of TCV and tested in a disruption-generated RE plasma scenario specifically developed. After the detection of the CQ and RE plateau, the control sets a decreasing new reference for $I_p$ leading to a reduction of the RE current. This result, together with the finding that the TCV standard control system is inherently able to maintain the position of the RE beam with moderate interactions with the plasma facing components, lays down good prospects for further RE studies in TCV, in particular to analyze RE decorrelation via applied magnetic perturbations and current ramp-down policies in order to provide possible recipes complementary to MGI.

Future plans also include the development of additional RE Control Tools: voltage controller during RE beam ramp-down, closed-loop DMV trigger in real-time during RE beam ramp-down, position/shape control of RE beams (pre- and post-disruption) and multiple current quench detector for the $I_p$ reference.

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[9] Ref DMV
[10] Ref AUG
[11] Ref LIUQUE