Active control for current dissipation of runaway electrons in TCV

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The Disruption Mitigation System (DMS) for ITER, previously based on the Massive Gas Injection (MGI) technique, is now based on Shattered Pellet Injection (SPI) in order to provide heat loads mitigation at disruptions and possibly prevent the RE beam formation and dissipation. However, SPI scalability to ITER and high temperature plasma interaction is still an open question and species and pellet compositions need to be studied, furthermore it is still to be proved that SPI can be promptly injected in order to simultaneously satisfy mechanical and thermal loads achieving also RE suppression. In order to provide further studies on fully-formed RE beams surviving the Current Quench (CQ) phase, dedicated control algorithms, as the one implemented for FTU [1, 2], has been developed and tested in TCV to possibly analyze, on a confined RE beam, further techniques such as wave-particle interactions, triggering natural beam instabilities, deuterium (see [3]) pellet injection with high-Z material, etc. In TCV, initial experiments [4] revealed the possibility of confining the RE beam and ramping down its current using the central solenoid, although sudden current losses, leading to premature termination of RE beams, have been observed. In this work we present a new version of the Runaway Electrons Control System (RECS), dedicated to RE beam suppression and confinement, and the related experimental results. The RECS, schematically shown in Fig. 1, is divided into three main blocks: Disruption detector, current reference generator, position and current controllers. The *disruption detector* allows to identify the CQ and the onset of the plateau phases processing the plasma/beam current I_p and evaluating its derivatives. The peculiar sudden losses of small fractions of RE beam current, also seen in COMPASS but in other tokamaks, required to develop a code to identify multiple current quenches and plateaus. The *current reference generator* provides current and position references patched in real-time to induce a current ramp-down.
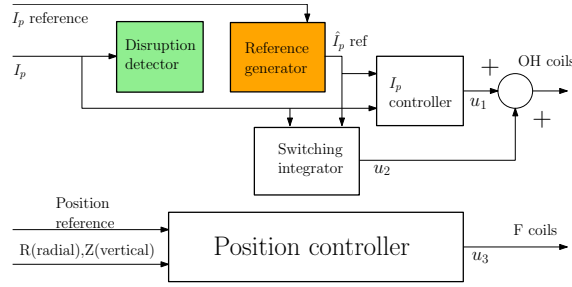
Figure 1: RECS: Runaway Electrons Control System.

The main strategy consists in ramping down the RE beam current to dissipate its energy through the central solenoid. The slope of the ramp can be preselected adjusting dedicated parameters in the configuration file. The last block provides the voltage request to the current amplifiers of the poloidal field coils (F coils) and the central solenoid (OH coils). To implement a first RE beam *position controller*, the coils used by the standard control system (F8, F7, F4,F3) when the plasma is in the upper part of the large TCV vacuum chamber (please refer to [5] for further details) have been considered. The position of the beam is assumed to be the position of the plasma barycenter reconstructed in real-time by the magnetic measurements as in the standard case. Studies on different machines, FTU, DIII-D and Tore Supra have confirmed the plausibility of such an assumption. The Switched Integrator block in Fig. 1 is described by the following switching system

$$\dot{u}_2 = \begin{cases} e_{ip} & \text{if } (|e_{I_p}| < e_0 \wedge |\dot{e}_{I_p}| < e_1) \\ 0 & \text{if } \left((|e_{I_p}| \geq e_0 \vee |\dot{e}_{I_p}| \geq e_1) \wedge u_1 u_2 \geq 0\right), \text{ where } e_{ip} = \hat{I}_{p,ref} - I_p, \\ -\alpha e_{ip}, & \text{otherwise.} \end{cases} \quad (1)$$

The integrator in the current control loop allows to have (asymptotically) null error at steady state for ramp current reference. Note that the hybrid integrator (1) acts as a standard integrator if the absolute value of the error $e_{I_p} = I_p - I_{p,ref}$ and its derivative are smaller than selected parameters (e_0, e_1), u_2 is kept constant if the inequalities are not verified but u_2 goes in the same direction of u_1 ($u_1 u_2 > 0$), otherwise u_2 is discharged to zero. An adaptive controller for slow radial and vertical drifts, usually associated to the ramp-down phase, is implemented by the position controller in order to provide slow rate changes in the control variable exploiting the approximation that within a given interval of time, retrieving the plasma/beam current derivatives along the ramp-down, an optimal rate of changes of the PF coils would approximately maintain the beam in the correct position. Then, an adaptation scheme has been implemented and initial results have been tested although a better controller tuning is foreseen in the upcoming MST1-T8 2017 campaign where a different usage of the PF coils should allow an extensive controller validation. A combination of the scenarios developed earlier in [4, 6] with Bt=1.45 T, inner
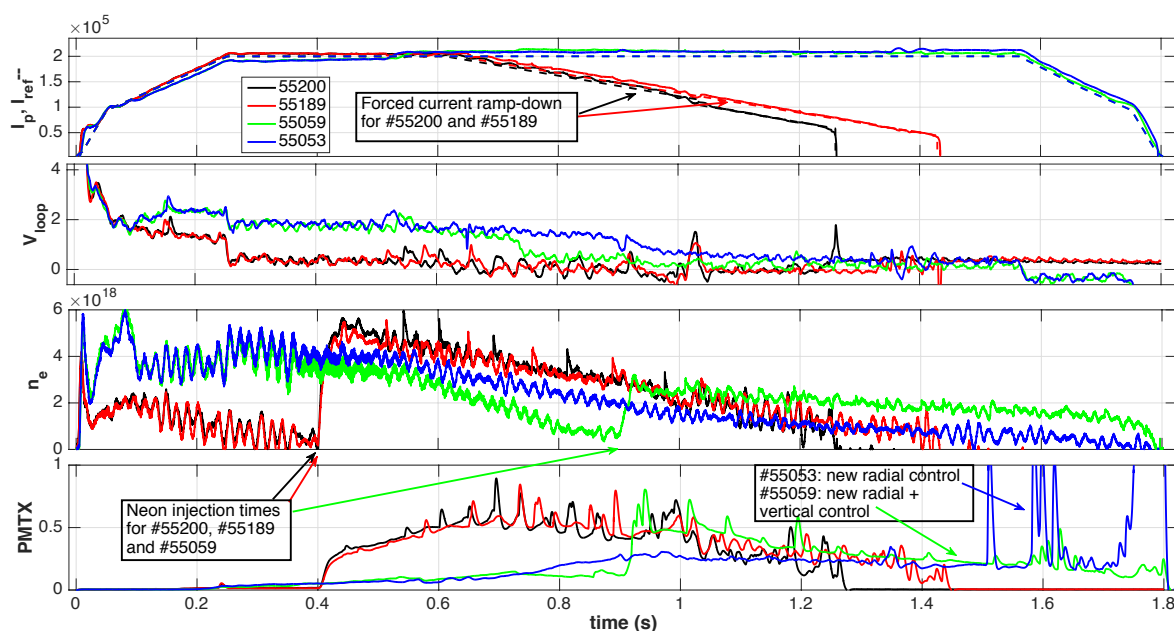
Figure 2: *Discharges with flat-top (#55053) and MGI induced runaways (#55059, #55189, #55200).*
Top: I_p (solid) and its reference. Bottom: the Photo Multiplier Tube X-ray (PMTX) measuring HXR.

wall limited circular plasmas, extremely low gas prefill and density target below 2E18 m^3 with Ne and Ar massive gas injection, at different pressure and valve opening times, allows further acceleration of the RE seeding population to form RE beams whose current is then ramped-down to zero. A sample of the discharges obtained in the 2016 campaign is shown in Fig. 2.

The discharge #55053 shows high level of runaways even without the injection of the Ne due to the high level of the electrical field (V_{loop}) induced by the central solenoid compared to the low density ($E > E_{critical}$) and then runaways start growing in a flat-top discharge which is eventually ramped-down by the standard procedure. In the

Figure 3: *(left): Plateau duration Vs final loss current; (right)*
RE beam flux surfaces reconstruction by Liuqe.

discharge #55059 a Ne injection at 0.9 s (7.5 bar) for 5 ms yields zero temperature and the full current conversion into a RE beam. The higher level of PMTX at 0.9 s is given by the RE interactions with the high-Z injected particles whereas the PMTX spikes are triggered by RE losses against the vessel most probably induced by MHD activity, as denoted by MHD amplitude signal synchronous spikes. The reduced values of the PMTX signal during the ramp-down of #55053 and #55059 are due to different position references: in the latter one the radial refer-
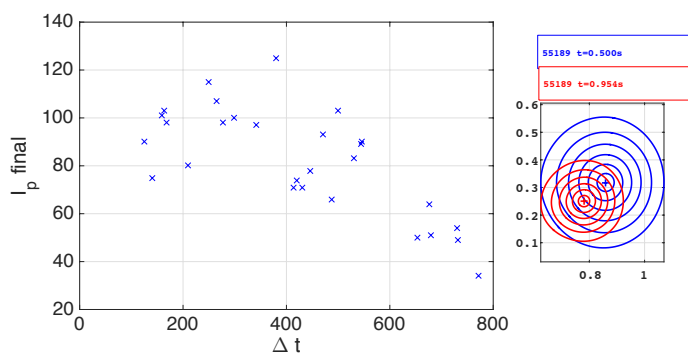
ence is 6 cm outward (toward low-field side) than the former one, improving the RE confinement during the current ramp-down where naturally the beam moves inside (toward high-field side). Note that the RE beam is maintained with constant current for about 700 ms. Ne injection at 0.4 s for 10 ms at 10 and 20 bar is then performed for the shots #55189 and #55200, respectively. Although the RECS is able to detect automatically current quenches, a ramp-down at 0.6 s is forced and the new current references shown by dashed lines in the top-plot of Fig. 2 lead to the beam current dissipation. The beam confinement is achieved exploiting the new controller and reduced final current losses have been reached. An important characteristics of the actual controller is that the current reference is defined in order to maintain the loop voltage within a desired value (1.75 V) during the ramp-down: this allows to minimize disruptive events triggered by amplified MHD modes. Two discharges have been performed adding a square wave signal of 20 ms period and 10 kA amplitude during the ramp-down in order to analyse possible RE expulsion as observed on FTU and COMPASS but with negative results. Large deuterium injections have been performed on the RE beams without noting any sensible change. In Fig. 3 it is shown the dependence of the final loss current amplitude versus the ramp-down time duration (different time intervals Δt have been tested): this is consistent with the FTU database [2] since slow ramp-down improve beam controllability. In the right plot of Fig. 3 are shown the equilibria reconstructions of a RE beam at different times: the last available time where the algorithm converges is at 0.954 s with about 140 kA.

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