Adaptive control design and energy distribution estimation via nonlinear observer for runaway electron in FTU

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[9] *Meyer et al., Nuclear Fusion FEC 2016 Special Issue (2017)*

The stabilization of post-disruptive runaway (RE) beams is of crucial importance to avoid major damages to the plasma facing components. RE beam dynamics are quite different from standard plasmas and deserve specific controllers to improve their confinement [1, 2, 3]. Mitigation techniques (MGI, shattered pellet injections) can be combined with RE beam stabilization and controlled current ramp-down strategies to provide a complete mitigation system. In this work we introduce an ad-hoc adaptive control technique, based on recent methodologies [11, 4, 5], tailored to improve the control scheme robustness necessary for machine portability. During the controlled RE beam ramp-down, data related to beam interaction with pellet/impurity injections have been collected as well as information related to expelled runaways hitting the Cherenkov probes [6] and RE beam instabilities. We also propose a methodology to estimate the energy distribution function and the plasma parameters exploiting spectral measurements provided by the new Runaway Electron Imaging and Spectrometry (REIS) system. The proposed methodology relies on optimization algorithms combined with estimation theory (dynamical observer) to retrieve the best plasma parameters that fit the REIS data. In particular, a simulation test has been prepared in order to validate the proposed methodology whereas experimental data are going to be used in the next future. The proposed algorithm iteratively searches for the best plasma parameters and/or RE energy distribution in order to minimize a cost functional

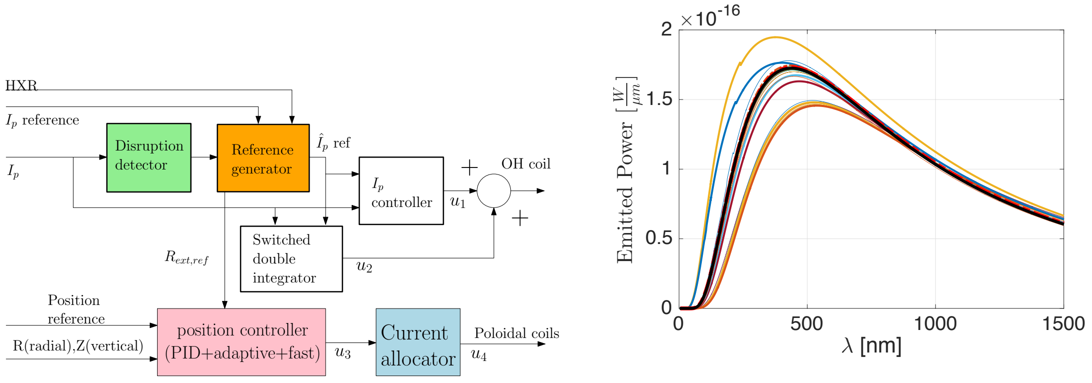

Figure 1: (Left) Runaway beam control system. (Right) Optimization procedure to retrieve the plasma parameters necessary to fit the (single) reference spectrum (black solid).

$J = \sum_i^n ||S_i(\lambda,\theta) - S_i(\lambda,\hat{\theta})||$, where $S_i(\lambda,\hat{\theta})$ is the spectra obtained by the SYRUP code [9] and $\hat{\theta}$ are the estimated parameters within a time window of n samples (spectra measurements). Note that if a single spectrum S_i is considered, the problem admits multiple solutions (consider for example the infinite solutions for RE pitch angle and momentum to fit a single spectrum). Furthermore, since spectra at different times have to be evaluated, the initial estimated distribution is evolved using CODE [10], although also [8, 7] can be considered. To solve the issue of local minima, a Monte-Carlo like approach has been adopted. The results of the estimation algorithm are shown in Fig. 1 (right) where the reference spectrum is shown as a solid black curve and the other ones, converging to the former spectrum, are obtained iteratively with the optimization procedure on the plasma parameters (Z_{eff}, T_e, V_{loop}).

The FTU runaway control tool has four main blocks (scheme of Fig. 1): current quench detector, ramp-down reference generator, RE beam position controller and current allocator. The current ramp-down, with the new current and position references, is triggered once the current quench and then the onset of the plateau is detected or the HXR signal rises above security thresholds. Different slopes of the current ramp-down and waveforms of external radius reference can be selected. The feedback loop of the beam position is constituted by an adaptive algorithm that identifies the "slow" dynamics at run-time during the ramp-down: a fast numerical procedure is conceived in order to retrieve the coefficients of a linear plant (described by stationary ODEs) modeling the beam movements based on real-time estimation of the I_p and active poloidal coils trends. The model parameters are continuously identified within a sliding time window. The output of the adaptive controller are ramp-like signals with reduced slope (slow control action). We designed also a fast controller in order to reduce the risk of fast RE beam loss: a ramp input with self-tuning slope rises if the position, its first and second derivative, lie within predefined bounds (switching controller). Then, the output u_3 is the sum of the fast, adaptive and PID controllers. The radial component of u_3, related to radial stabilization,

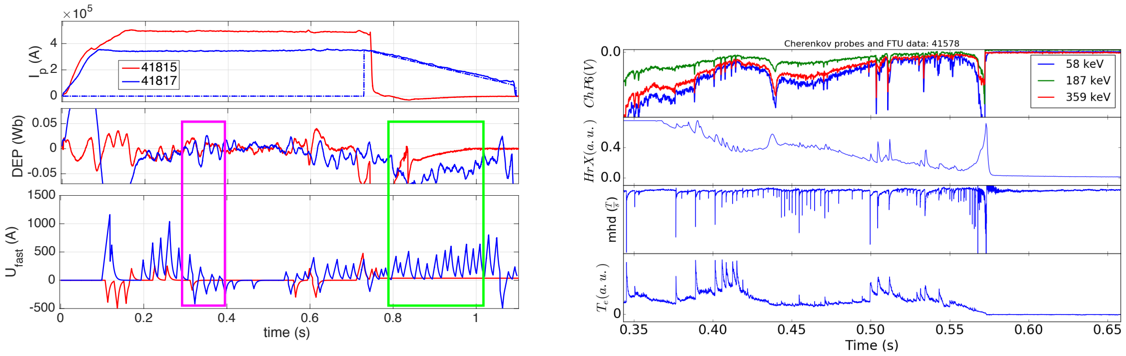

Figure 2: (Left) Fast controller for radial stabilization: (top) I_p current, (middle) radial displacement in therms of flux error, (bottom) fast controller output. (Right) Cherenkov signals during a runaway beam ramp-down: note the synchronization between the magnetic activity (mhd) and the electron cyclotron emission.

is processed by the input allocator that reassigns the current in the two coils V and F, that both generate the vertical field, in order to maintain the current flowing in the coils as far as possible from the saturation levels without perturbing the plasma position. This is extremely important during current ramp-down and its use is fundamental to avoid RE beam loss due to coil current saturation. To improve the I_p tracking performances during the ramp-down a switched double integrator (see [11]) is introduced. The fast controller output, shown at the bottom plot of Fig. 2, is characterized by ramps with a time-varying slope that rise when the amplitude and the time derivative of the radial flux error signal (DEP), i.e. the radial plasma displacement, overpasses selected thresholds (switching regions). The ramp is then exponentially decreased down to zero if the sign of the DEP second derivative is opposite to the sign of the DEP first derivative. This allows to promptly decrease the control action and avoid oscillations induced by the phase lag introduced by the plant such as coil self/mutual inductances, amplifiers dynamics, etc. In the left plot of Fig. 2 the experimental results of the fast controller applied to radial stabilization is shown for the standard discharge #41815, and the low-density shot #41817 having high level of flat-top runaways, which is shut-down around 0.75s (soft-stop): the new current reference, shown in dashed line in the top plot, is defined by the control system when a controlled shut-down is triggered by high level of HXR. Note how in the discharge #41815 the fast controller acts in order to recover the fast plasma oscillations. In the discharge #41817 the control parameters have been modified in order to increase the action of the fast controller and shows the adaptive mechanism: if oscillations of opposite signs are induced, then the slope of the ramp is decreased (magenta time window) whereas it is increased if oscillations in the same directions are detected (green time window).

The right plot of Fig. 2 shows the signal of the three Cherenkov probes, placed at the equatorial plane in the low-field side of the camber and within 2.5cm from the poloidal limiter. The three probes detect REs leaving the plasma with energy higher than 58, 189 and 359 keV, respectively, as shown by different colors. Subsequent analyses revealed that peaks in the signal of the Cherenkov probes are synchronous with magnetic activity, and spikes of electron cyclotron emission, revealing a beam instability of the anomalous Doppler type. During the RE beam ramp-down we performed experiments in which deuterium pellets have been injected in order to investigate their interaction with the RE beam. The signals of the CO2 scanning interferometer, H-alpha, Soft/Hard-X and Mirnov coil reveal that the pellet is completely ablated by the RE beam but the deuterium ionization is small fraction with respect to the case of a hot plasma (or hot plasma with REs). This could be explained by the very low temperature of the beam and of the collisional rate of highly energetic REs even on a solid D pellet.

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