# Runaway electron experiments in FTU

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## Introduction

We present an overview of the FTU experimental results related to two important ITER physics issues concerning the mitigation of runaway electrons (RE): the measurement of the threshold electric field for RE generation and the position control and ramp-down of disruption-generated RE. A strong experimental program devoted to RE studies has been recently enabled in FTU by the integration of diagnostic, hardware and software tools in the real-time (RT) plasma control system. Several diagnostics are (being) upgraded to RT operation: the hard x-ray (HXR) radial profile monitor measuring in-plasma bremsstrahlung from RE, a set of Mirnov coils used for disruption prediction algorithms, the CO2 scanning interferometer for RE position control, a fission chamber monitoring the gamma-ray emission as a signature of RE interactions with the plasma facing components (PFC). In addition, a Cherenkov probe was installed to study the RE dynamics in presence of magnetic islands [1] and a RE imaging system (REIS) is being tested to detect visible/infrared synchrotron radiation emitted by RE.

## Measurement of threshold electric field for RE generation ($E_{thr}$)

The aim of these experiments is to measure $E_{thr}$ at the RE *onset* and RE *suppression* occurring in the plasma current ($I_p$) flattop phase of deuterium ohmic discharges. The RE *onset* (see an example in Fig.1(right)) is obtained through a decreasing electron density ($n_e$) in the $I_p$ flattop. The RE *suppression* is achieved by starting a discharge with low gas prefill thus creating a RE population subsequently suppressed by a feedback-controlled phase of constant or increasing $n_e$. Key diagnostics are the $BF_3$ neutron detectors and the NE213 neutron/gamma scintillator, which give overlapping signals in the absence of RE [2]. The results (shown in Fig.1(left); more details can be found in [3]) essentially confirm the findings reported in [2] but refer to a wider database (56 discharges with $B_t$=2-7.2 T, $I_p$=0.35-0.9 MA, $Z_{eff}$=1.5-10). The measured $E_{thr}$ (obtained as $V_{loop}(t_C)/2\pi R_0$, where $t_C$ is the time when NE213 and BF3 traces diverge/converge in the *onset*/*suppression* experiments) is ~2-5 times larger than predicted by the classical collisional theory [4] and consistent with the new threshold calculated including synchrotron radiation losses [5]. The local central density is used to calculate $E_R^{rad}$ since RE are initially generated in the core of the plasma ([2] and below Fig.3(left)).

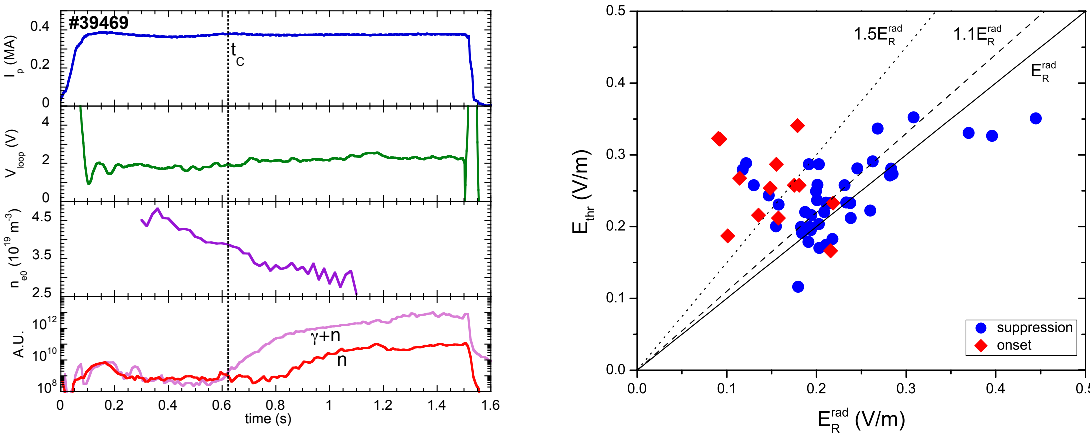


**Figure 1**. (left) *RE onset: time traces of $I_p$, loop voltage ($V_{loop}$), local central density, NE213 (γ+n) and $BF_3$ (n) signals*. (right) *Comparison of measured $E_{thr}$ with relativistic collisional+synchrotron radiation theory predictions ($E_R{}^{rad}$ [5]);*

**RE control**

The aim of these experiments is the RT control of the horizontal position and current ramp-down of disruption-generated RE plateaus [6]. Two scenarios are adopted: a) a significant RE population is generated during the $I_p$ ramp-up/flattop by starting the discharge with low gas prefill and pre-programming a low $n_e$ reference (~$1.5x10^{19}$ m$^{-3}$), followed by Ne injection to induce the disruption. b) a spontaneous disruption is induced during the $I_p$ ramp-up by setting extremely low gas prefill. A limited database is available as these scenarios do not produce RE plateaus routinely in all discharges, but only in a fraction of the attempts. The plasma parameters are $I_p$=0.36 MA, $B_t$=6 T. Key RT diagnostics for RE control are the fission chambers, the Mirnov coils and the CO2 scanning interferometer. The active coils used to control the position of the plasma and $I_p$ are T (transformer) to control $I_p$, V (vertical) and F (feedback) to control the plasma radial movements and elongation and H (horizontal) to control the plasma vertical position. The current of the V coil, which produces a vertical field similar to F but with a slower rate of change, is varied by the Current Allocator controller [7] in order to modify at run-time the F current and maintain the vertical field unchanged. An example of the results is shown in Fig.2: 1) the standard $I_p$ reference is substituted by a ramp-down that produces a lower $V_{loop}$ (see panel g), hence reducing the energy transferred by the central solenoid to the RE and, consequently, also the radial Shafranov shift. 2) the plasma outer radius ($R_{ext}$) is reduced dynamically at run-time (panel f) and this contributes to the reduction of the RE beam interaction with the PFC as indicated by the lower fission chamber signal (panel h). The RE control strategy is being upgraded by means of a control-oriented dynamical model for RE position and energy [8].

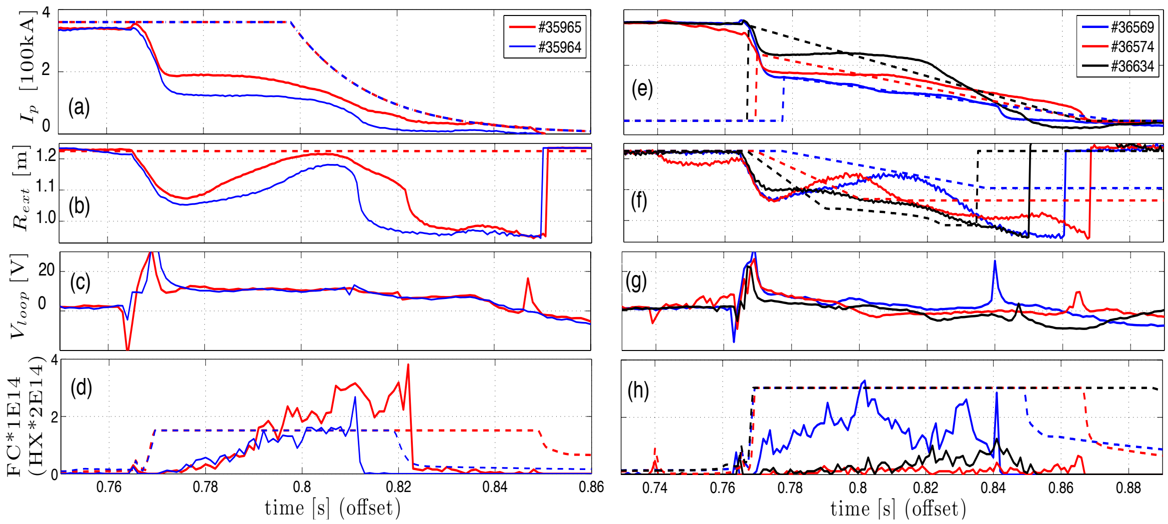


**Figure 2**. Position control and current ramp-down of RE plateau: (left) control OFF; (right) control ON. Dashed lines in panels (a), (b), (e) and (f) refer to reference traces, solid lines to actual measurements.

## RE diagnostics

Some results from two RE diagnostics recently implemented in FTU are presented below. Features of the HXR emitted perpendicularly to the magnetic field and produced by RE through bremsstrahlung in the plasma [9] are shown in Fig.3(left) (an increase of the RE energy is observed after the initial phase (0.6-1.0 s)) and Fig.3(right) (the RE beam originates in the plasma center and moves off-axis soon after). Fig.4(top) shows the (uncalibrated) spectra in the visible range obtained from the REIS: a wide-angle optical system collects the radiation from two plasma cross sections (corresponding respectively to the RE backward and forward view, see Fig.4(bottom left)) and transmits it to two visible spectrometers through an incoherent bundle of fibers. Optionally, an infrared spectrometer has been used in the forward view (Fig.4(bottom right)). These preliminary measurements (both discharges with $B_t$=4.1 T and $I_p$=0.5 MA) clearly indicate that the range of RE emission in FTU may extend from 500 nm to 2000 nm.

## Conclusions

The threshold electric field for RE generation was measured in the flattop of ohmic discharges and found to be larger by a factor ~2-5 than expected according to the purely collisional theory and very close to a new threshold that includes synchrotron radiation losses. This might imply a lower threshold density value to be achieved by means of massive gas injection (MGI) for RE suppression in ITER. The dissipation of the disruption–generated RE energy and population through RE horizontal position control was performed through feedback on the poloidal coils by exploiting a RT boundary reconstruction algorithm evaluated on magnetic moments. The RE beam was slowly ramped down within ≈100 ms with reduced interaction with the PFC. RE control can be therefore an alternative/complementary technique to MGI.

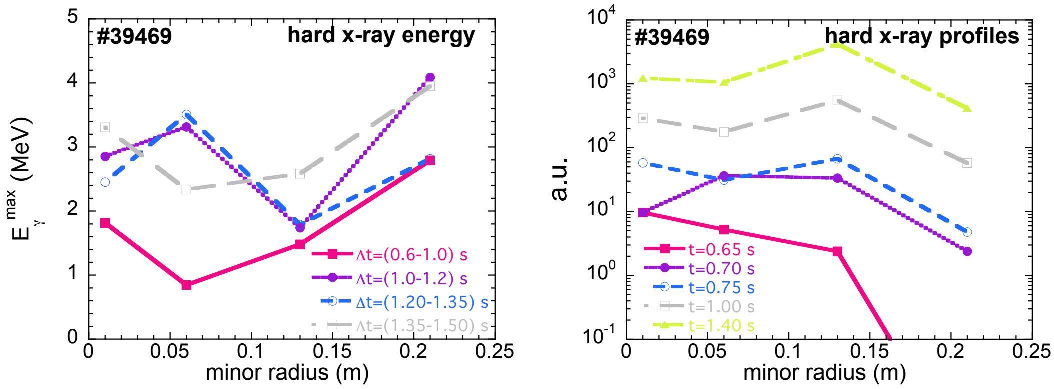


**Figure 3**. Discharge #39469: time evolution of radial profiles of HXR maximum energy (left) and line integrated HXR emission (right).

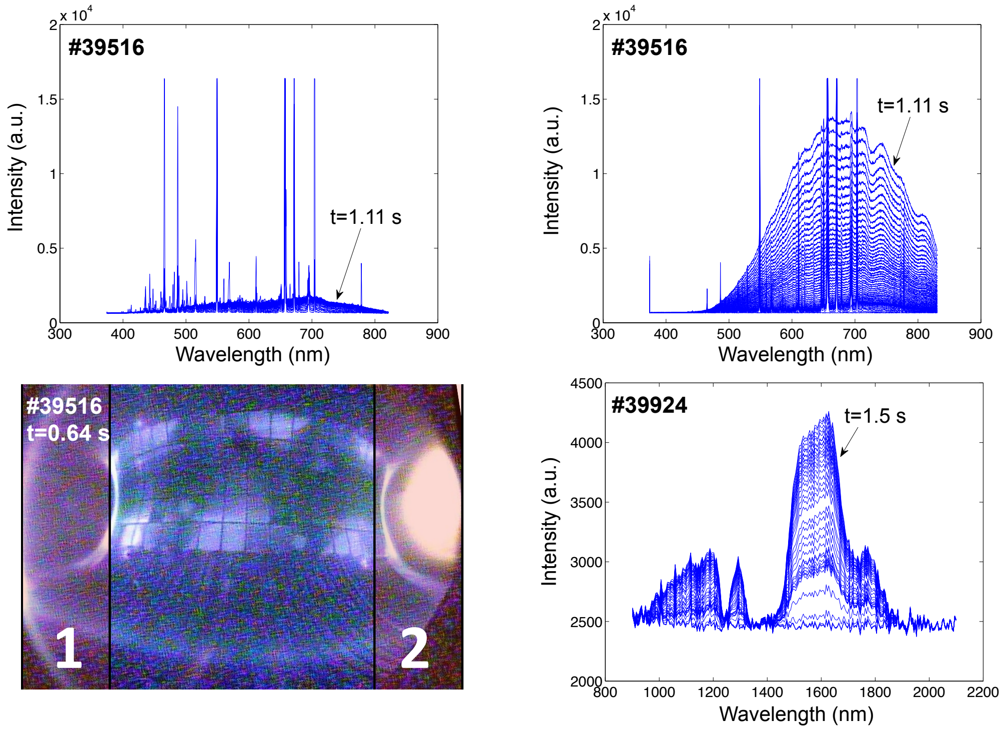


**Figure 4**. (top left) Backward and (top right) forward RE visible spectra (#39516); (bottom left) viewing layout of REIS: RE backward (1) and forward (2) view; (bottom right) forward RE infrared spectra (#39924): note the two OH-IR absorption bands (centered around 1.25 and 1.4 μm) due to the fiber bundle presence. Each spectral curve corresponds to a time slice: the last time (indicated by the arrow) is before the disruption.

## References


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