

Analysis of Runaway Electron Dynamics in WEST based on Synchrotron Radiation Measurements

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Runaway electrons (RE) pose significant challenges to plasma-facing components in large tokamaks due to possible damages to materials and limitations in plasma operations. Therefore, understanding and controlling RE is a critical area of research, particularly for devices such as ITER, in which runaway events could have severe consequences. We present a study on the dynamics of RE in the WEST (Tungsten Environment in Steady State Tokamak) [1] tokamak, where up to 400 milliseconds RE beam have been achieved in post-disruption mode. The analysis includes discharges from experiments on the RE benign termination [2] as well as RE impact on the W-tiles of the inner bumper [3].

A method based on the comparison between experimental and simulated data has been adopted to infer the RE number, pitch angle, energy and radial profile [4]. The experimental data set consists of synchrotron spectra collected by the Runaway Electron Imaging and Spectroscopy System (REIS) in the range of 520-4600 nm, by means of three spectrometers (visible (VIS): 520-800 nm, Infra-Red (IR): 1020-2500 nm Medium-IR (MIR): 2500-4600 nm), as well as images captured using both VIS and IR cameras. The simulations are carried out by means of the synthetic synchrotron radiation diagnostic tool SOFT (Synchrotron-detecting Orbit Following Toolkit) [5]. The main improvements in the method with respect to [4] are the use of numerical magnetic fields in lieu of analytical fields, the implementation of a calibration of the three spectrometers, performed exclusively using a single blackbody with a temperature of 1300 °C, and the adoption of a novel image comparison algorithm, namely the Learned Perceptual Image Patch Similarity (LPIPS) using deep convolutional neural networks (CNNs) that have been pre-trained for image classification tasks to evaluate

similarity. Rather than relying on direct pixel-wise comparisons, LPIPS calculates the distance between the high-level, hierarchical feature representations extracted from the images [6].

In the approach used [4], the comparison between experimental and simulated data is performed, for each time interval, in two steps assuming a RE distribution function as:

$$f(r, p, \theta_p) = f(r)f(p)f(\theta_p) = f(r)\delta(p - p^*)e^{K\cos\theta_p}$$

where p is the momentum, θ_p is the pitch angle and K is a constant. In the first step, the best fits (least-squares minimization) of the experimental spectra are obtained (**Figure 1**) and the number of RE is determined (N_{RE}). In the second step, the best match between experimental and simulated images is found (**Figure 2**) using LPIPS and the parameters K and θ_p are determined. In this second step, the radial profile $f(r)$ is also determined (**Figure 3 (left)**) employing the Tikhonov regularization method [7] through minimization of the expression

$$\min_x (\|Af(r) - b\|_2^2 + \|\alpha\Gamma f(r)\|_2^2)$$

where A is the Green function multiplied by $f(\theta_p)$, b is the experimental image, Γ represents the discrete first-derivative operator and α is the regularization parameter. **Figure 3 (right)** shows the center of the RE radial profile (R_{RE}), its full-width half maximum, the plasma axis (R_{ax}) and the plasma outer radius (R_{out}): note that R_{RE} smoothly follows the variation of the plasma position and that the RE beam size is increasing from 20 cm before the disruption to about 30 cm after this event.

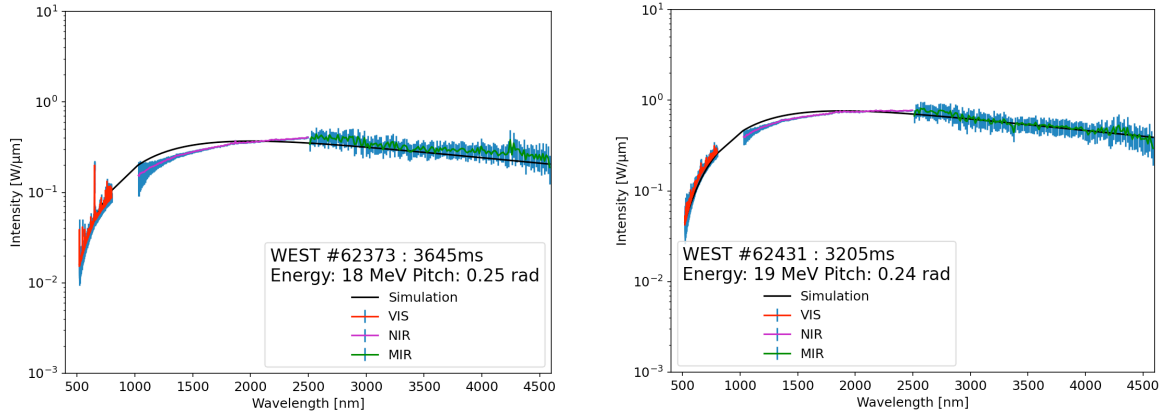


Figure 1: Experimental and best fit-simulated synchrotron radiation spectra; total uncertainties (statistical + calibration) shown in blue.

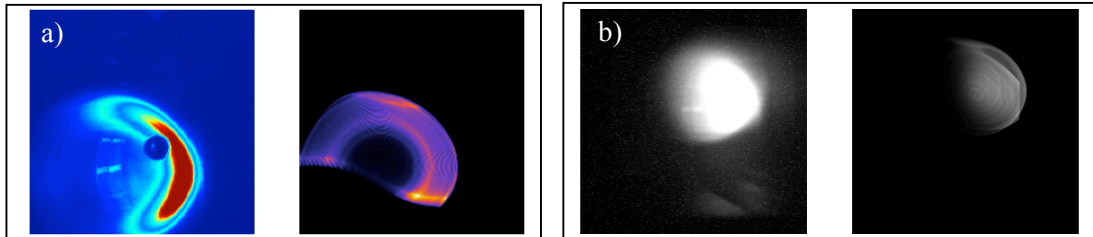


Figure 2: Experimental (left) and best-fit simulated images (right): (a) discharge #62373 (infrared camera image) at $t=705$ ms ($\theta_p = 0.15$ rad, $E = 19.5$ MeV); (b) discharge #62431 (visible camera image) at $t=2805$ ms ($\theta_p = 0.25$ rad $E = 19.5$ MeV).

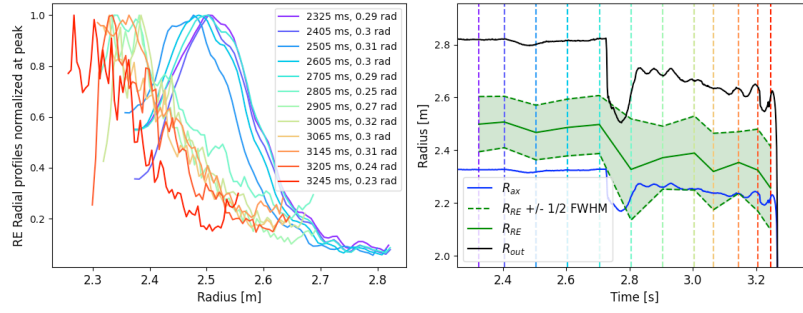


Figure 3: Discharge #62431: (left) RE radial profiles; (right) position of the RE beam and RE beam FWHM together with the plasma axis and outer plasma radii.

The panels in **Figure 4** show for a discharge with RE benign termination (#62373 (top)) and a discharge in which RE have impacted on the W-tiles (#62431 (bottom)), from top to bottom: the loop voltage (V_{loop}), the plasma current (I_p), the neutron rate together with the Ar and D₂ injected gas, the central line-integrated electron density (n_e) together with the radiated power (P_{rad}), the integral of the camera images, the integral of the three spectrometers (black points representing data above background noise) and the RE parameters as determined above (energy, θ_p and N_{RE}). The error bars on energy, θ_p and N_{RE} are estimated by taking their extremes in the region where the LPIPS score is differing $\leq 2\%$ from its minimum value.

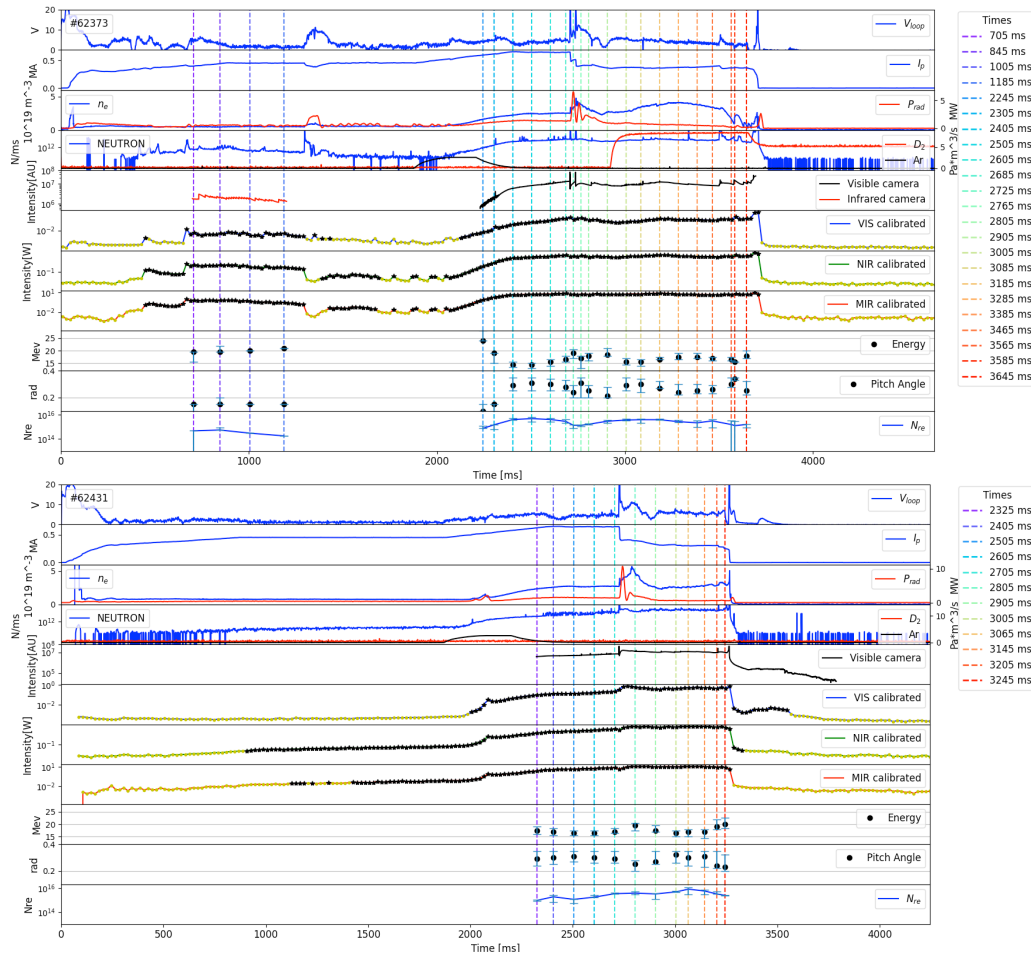


Figure 4: Overview of RE discharges #62373 (top) and #62431 (bottom).

The inferred maximum RE energy and θ_p as determined above have been compared (**Figure 5**) with the results of simulations based on a RE test particle model [8]: since the Z_{eff} is not known in these discharges, in the simulations Z_{eff} values have been chosen in order to have a match with the experimental points. The RE energy and θ_p range is estimated by carrying out the simulations for different values of the inductance L_{int} , which determines the electric field seen by the electrons during the I_p ramp-up and depends on the plasma current profile shape. In the pictures the four curves for each color correspond to simulations made assuming different initial energies for the runaways (0,1, 0.2, 0.5 and 1 MeV): apart from the initial phase they all converge towards single values. It is found that the energy values are well fitted assuming $Z_{eff}=18$ after the Ar injection ($t=2$ s), while for θ_p the simulated values are lower than the experimental ones, possibly because of an underestimation of the error bars.

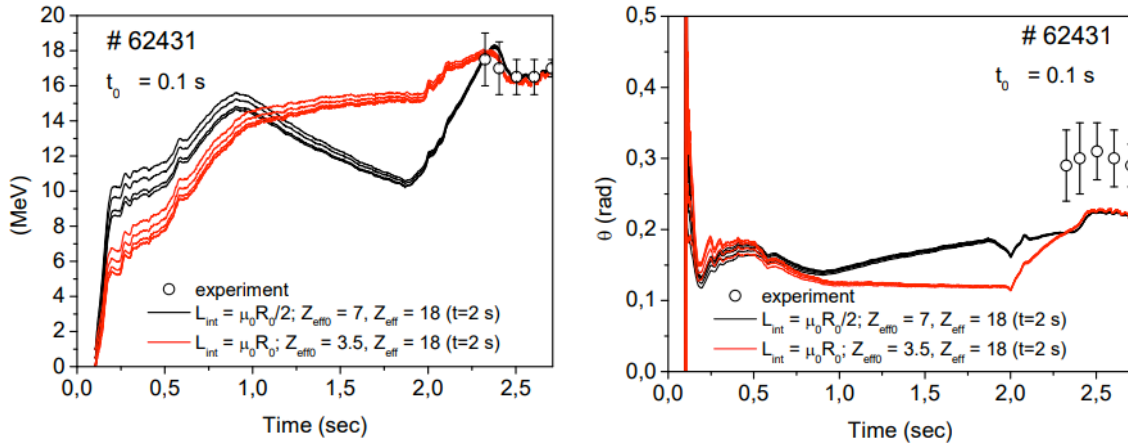


Figure 5: RE test particle model simulations for discharge #62431. Black and red curves refer to simulations with different values of the internal inductance (μ_0 is the vacuum permeability and R_0 the geometric axis of the device) and Z_{eff} (see pictures' inserts for details).

References

- [1] J. Bucalossi et al., Fusion Engineering and Design, **89** (2014) 907.
- [2] C. Reux et al., this conference.
- [3] Y. Corre, et al., accepted for publication in Nuclear Fusion (2026), DOI 10.1088/1741-4326/ae6d13
- [4] G. Ghillardi et al., Plasma Phys. Controlled Fusion **67** (2025) 055029.
- [5] M. Hoppe et al., Nucl. Fusion **58** (2018) 026032.
- [6] R. Zhang et al., Proc. of the IEEE Conference on Computer Vision and Pattern Recognition, (2018) 586.
- [7] A. N. Tikhonov, Soviet Mathematics Doklady **4** (1963) 1035.
- [8] J.R. Martin-Solis et al., Phys. Plasmas **5** (1998) 2370.