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

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Introduction

Problem

- **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.*

Case study

- *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]**.

Objective

- *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]**.

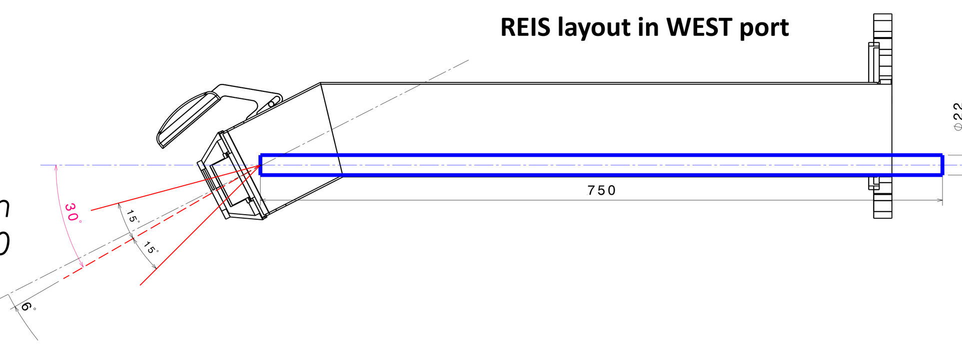
Experimental setup

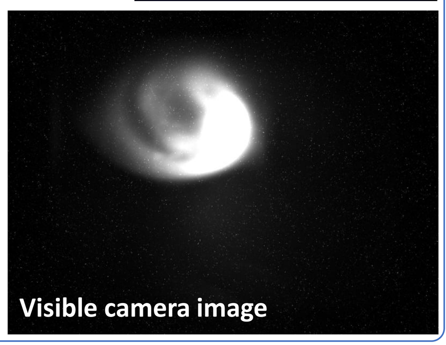
Diagnostics

- **Synchrotron spectra** *collected by the* **Runaway Electron Imaging and Spectroscopy System** *(REIS), port Q4Bm :*
  - **Visible** *spectrometer* (**VIS**)*: 520-800 nm*
  - **Near Infra-Red** *spectrometer* (**NIR**)*: 1020-2500 nm*
  - **Medium Infra-Red** *spectrometer* (**MIR**)*: 2500-4600 nm*
- **Synchrotron images** *recorded by:*
  - **WEST fast Visible Camera** *(Phantom), port Q5B*
  - **WEST fast Infrared Camera** *(Telops MS3F), port Q5B*

Selected WEST discharges

- **RE benign termination**, #62373, B_t=3.75 T, *Injection of Ar and D2*
- **RE impact on the W-tiles of the inner bumper**, #62431, B_t=3.75 T, *Ar puff followed by I_p ramp-up*





Analysis

Simulation method

- *Carried out by means of the synthetic synchrotron radiation diagnostic tool* **SOFT** *(Synchrotron detecting Orbit Following Toolkit)* **[5]**.

$$I=\int_A\int_{\Omega_n}\int_\lambda \frac{d^3P_0(\mathbf{x},\mathbf{n},\lambda,t)}{dA\,d\Omega_n\,d\lambda}\,dA\,d\Omega_n\,d\lambda$$

I is the synchrotron radiation power reaching the detector at time t

- *Same method as used in* **[4]** *with some improvements:*
  - *use of* **numerical magnetic fields** *in lieu of analytical fields*
  - *implementation of a calibration performed exclusively using a single* **blackbody** *with a temperature of 1300°C*
  - *adoption of a novel image comparison algorithm, namely the* **Learned Perceptual Image Patch Similarity** *(LPIPS)* **[6]**.

Assumed RE distribution function

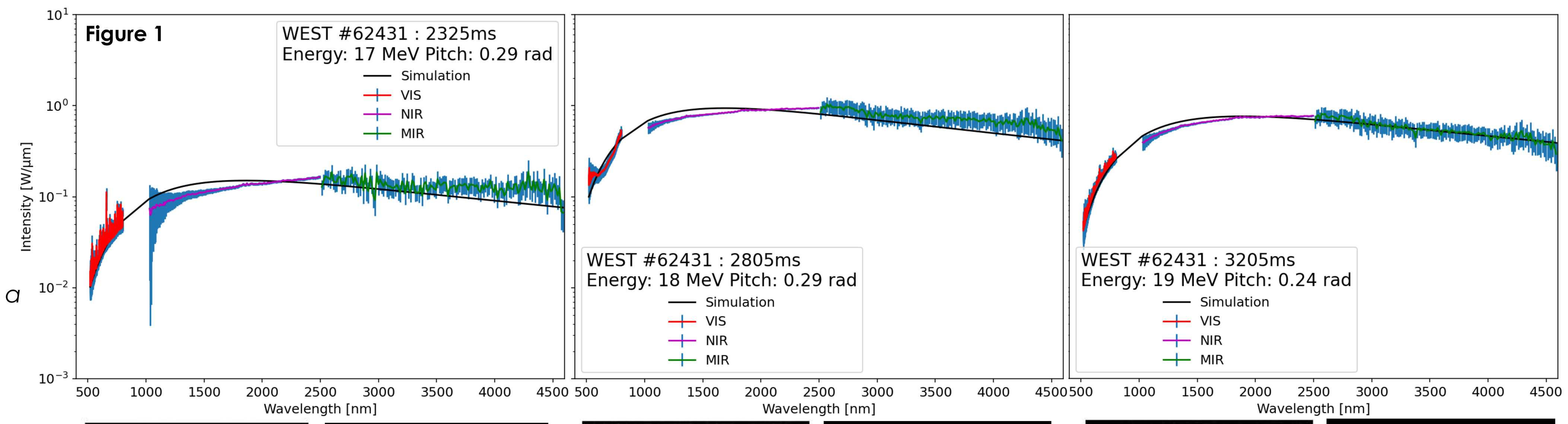
- *Comparison between experimental and simulated data performed, for each time interval, in* **two steps** *assuming:*

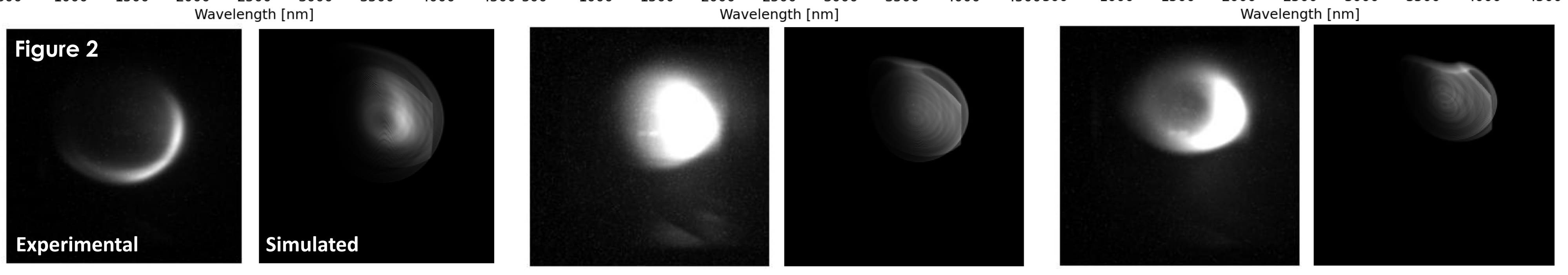
$$f(r,p,\theta_p)=f(r)f(p)f(\theta_p)=f(r)\delta(p-p^*)e^{K\cos\theta_p}$$

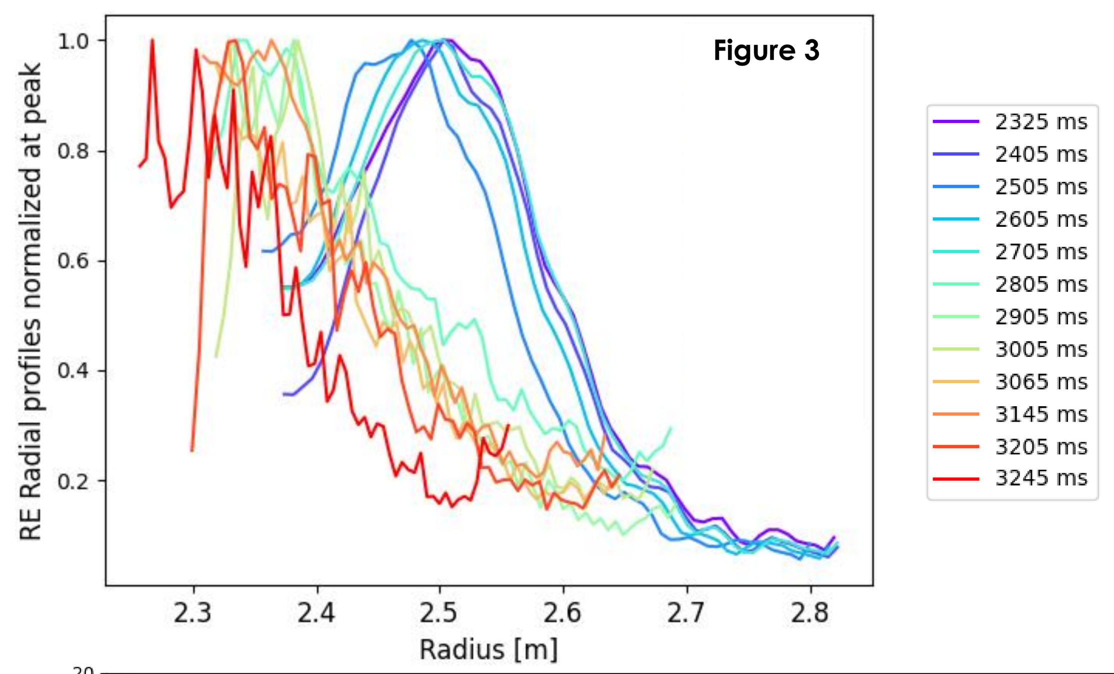
where p is the **momentum**, *θ_p is the* **pitch angle** *and K is a* **constant**.

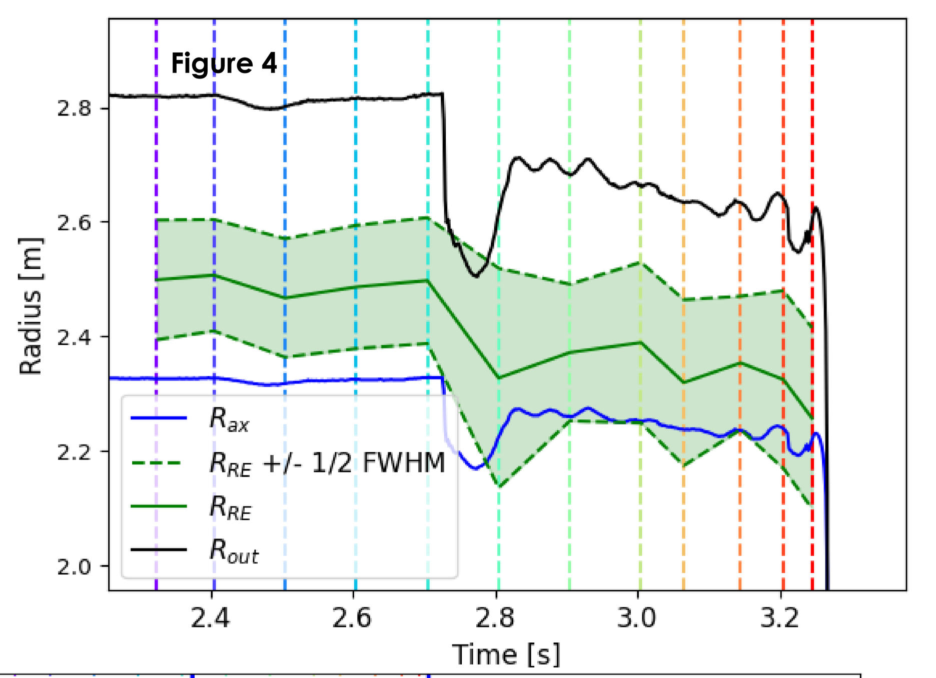
First simulation step

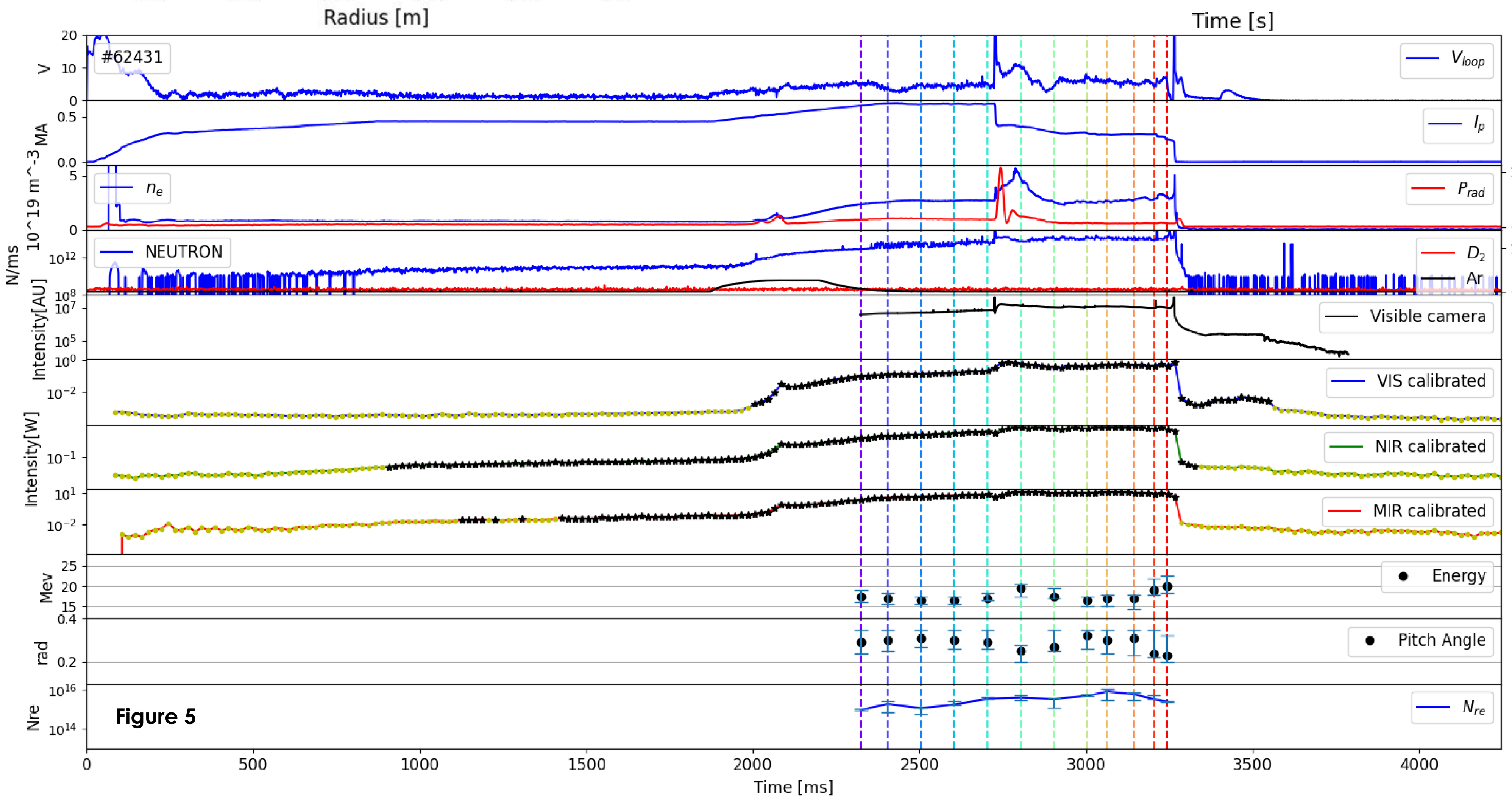
- *Best fits (least-squares minimization) of the experimental spectra are obtained* **(Figure 1)** *and the* **number of RE** *is determined (N_{RE}).*











Second simulation step

- *Best match between experimental and simulated images is found* **(Figure 2)** *using LPIPS and the parameters K and θ_p are determined.*
- *The* **radial profile** *$f(r)$ is also determined* **(Figure 3)** *employing the* **Tikhonov regularization method [7]** *through minimization of the expression:*

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

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**.

Results (inferred experimental RE parameters)

- *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})* **(Figure 4)**.
- **Energy**, θ_p *and* N_{RE}, *with error bars estimated by taking the extremes in the region where the LPIPS score is* **differing ≤2%** *from its minimum value* **(Figure 5)**.

Test Particle Model (simulated RE parameters)

- **Maximum RE energy** *and* θ_p *as determined above compared* **(Figure 6)** *with the results of simulations based on a* **RE Test Particle Model [8]**.
- *The four curves for each color represent different initial energies for the runaways:*
  - **0.1 MeV**
  - **0.2 MeV**
  - **0.5 MeV**
  - **1 MeV**
- **Energy** *values well fitted assuming* Z_{eff} *=18 after the* **Ar injection** *(t=2 s)*
- *For* θ_p *the simulated values are lower than the experimental ones, possibly because of an* **underestimation of the error bars**.

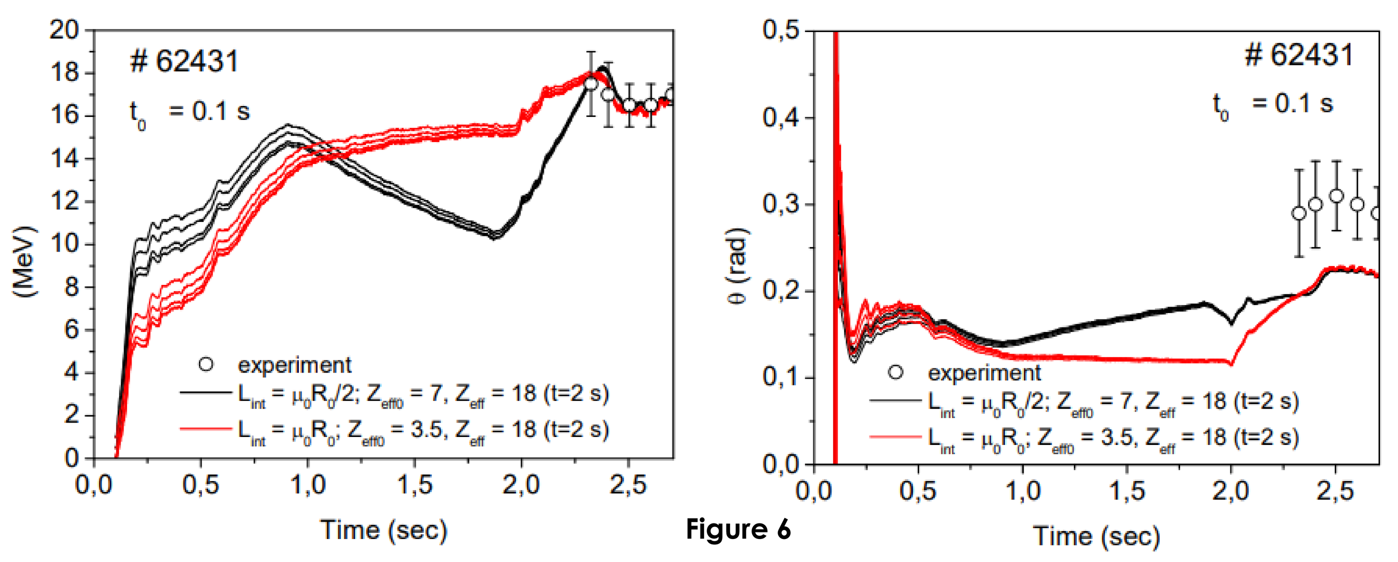


Figure 6

Conclusions

- **SOFT** *simulation best match of experimental data indicate (assuming monoenergetic RE distribution) that in post-disruption phase of WEST RE discharges:*
  - *RE Energy is in the range* **15-20 MeV**
  - *RE Pitch Angle is in the range* **0.20-0.35 rad**
- *Good match between experimental inferred and* **Test Particle Model** *simulation predicted RE energy and pitch angle, by assuming high* Z_{eff} *values.*

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