PhD Thesis Review

Candidate: Soma Olasz
Title: Simulation of Runaway Electron Dynamics in Tokamak Disruptions
Reviewer: Eva Tomesova, Institute of Plasma Physics of Czech Academy of Sciences

1. Subject and Significance of the Thesis

The thesis investigates Runaway Electrons (RE) generation, dynamics, and diagnostics under various plasma conditions, combining theoretical analysis with integrated simulations within the EU-IM and IMAS frameworks.

A major contribution is the integration of RE solvers—NORSE, DREAM, and the Runaway Fluid actor—into the ETS workflow. This required substantial programming effort and a strong understanding of both kinetic and fluid modeling, and an analytical approach. The candidate also developed a Python interface for DREAM within IMAS, enabling direct use of experimental data.

The simulation results demonstrate the versatility and practical value of the developed tools. The work advances fusion plasma modeling both methodologically and by offering insights into RE behavior in tokamaks.

2. Detailed Evaluation

Chapter 1

This chapter provides a concise introduction to fusion principles and magnetic confinement. It clearly presents the motivation and main challenges of fusion, such as high neutron fluxes.

Chapter 2

This chapter outlines the theoretical foundations of plasma and RE physics. The first part, based on Helander and Sigmar (2002), summarizes kinetic plasma theory and collision operators, including the relativistic case. A valuable addition appears in Section 2.1.3, which discusses how individual collision frequencies influence the evolution of the distribution function.

The second part reviews RE generation mechanisms, diagnostics, and mitigation methods. The candidate demonstrates strong knowledge, especially for a non-experimentalist, and discusses stellarator benefits and emerging mitigation strategies. A brief mention of RE position control and calorimetric diagnostics could further strengthen the chapter.

Chapter 3

Chapter 3 describes the modeling tools used in the thesis, including the ETS workflow in Kepler, integrated with EU-IM and IMAS frameworks and RE physics modules. The roles of the Runaway Indicator and Fluid actors are introduced.

The candidate successfully integrated the NORSE kinetic code into EU-IM, the RE solvers into ETS within IMAS, and the DREAM code, which supports fluid, kinetic, and hybrid modeling. The SOFT tool for synthetic synchrotron diagnostics is also briefly discussed. Including some remarks on numerical methods and stability would further strengthen this chapter.

Chapter 4

Chapter 4 presents modeling results in four parts: (1) Dreicer generation in dynamic plasmas, (2) kinetic modeling in the integrated modeling frameworks, (3) self-consistent ETS disruption simulations, and (4) RE radiation modeling in JT-60SA disruptions.

The first part, based on Olasz et al. (NF, 2021), uses the ETS RE Test Workflow with NORSE, RE Fluid, and Indicator actors. Complemented by DREAM and LUKE simulations, it identifies the electron–electron collision time at critical velocity as a criterion for kinetic modeling. This finding represents an important contribution to improving the efficiency and applicability of RE modeling. However, hot-tail and avalanche generation are not addressed, limiting interpretation where Dreicer generation is weak or absent.

The second part details the integration of DREAM with IMAS via a Python wrapper, enabling simulations based on experimental data and without the need for compilation. A TCV disruption-like test case in fluid mode models Dreicer generation using a neural network surrogate and treats avalanche generation analytically. The integration is technically mature and forward-looking. However, the simulation timescale of 10^{-5} s appears unrealistically short and would benefit from brief justification.

The third part covers ETS5 and ETS6 simulations of AUG discharge #33108, including pre-disruption modeling and self-consistent RE evolution following MGI. After adjustments ETS6 reproduces current quench dynamics in good agreement with experiments and ASTRA-STRAHL simulations. However, key ETS simulation details, such as active RE mechanisms, transport coefficients, modeling mode—are missing, and certain features (e.g., sharp density/temperature rises) remain unexplained.

The final part assesses EDICAM's potential for RE detection in JT-60SA disruption scenarios using synthetic diagnostics. DREAM simulations of RE dynamics provide input to SOFT, which generates synchrotron images for comparison with expected EDICAM observations. Based on the candidate's 2023 *Fusion Engineering and Design* paper, the results are visually convincing and demonstrate strong potential for future application.

3. Scientific Content

The thesis is supported by three peer-reviewed journal papers and several conference contributions. The candidate is first author on two core publications: [P2], a high-quality study on Dreicer generation in dynamic plasmas (*Nuclear Fusion*), and [P3], on the feasibility of RE detection using EDICAM in JT-60SA (*Fusion Engineering and Design*). These works form the core of the thesis and demonstrate the candidate's ability to conduct independent research. A co-authored paper, [P1], reflects the candidate's contributions to RE modeling in ETS.

The results are original, well-documented, and align with the thesis objectives. The candidate demonstrates advanced programming and modeling skills, particularly in integrating numerical tools within EU-IM and IMAS, along with a solid understanding of plasma and RE physics. Publication requirements are fully met, and the candidate has engaged actively with the fusion research community through multiple conference presentations. The scientific content is of high standard.

4. Structure, Presentation and Language

The thesis is generally well-written and logically organized. Explanations are concise and scientifically grounded, with relevant literature appropriately cited. However, some typographical and formatting issues reduce clarity:

- Figure 2.1: The angle α is referenced in the text but not labeled in the figure.
- Equation (2.17): missing tilde and LaTeX formatting error.
- Equation (2.32): $\partial v_l \partial v_l$ should be $\partial v_l \partial v_k$.
- Equation (2.43): use $e^{-(v/v_{tb})^2}$ instead of $e^{-(v/v_{tb})}$.

- Equation (2.72): $(\frac{E}{E_c - 1})$ should be $(\frac{E}{E_c} - 1)$.
- Equation (3.2): should be $(E_D/E)^{2/3}$, not $(E_D/E)^2$.
- Figure 4.11: The excessively long x-axis range reduces the readability of the plot.
- Figures 4.12–4.17: Inconsistent time steps, color schemes, and radial axes hinder comparison between ETS5 and ETS6 simulations. Using normalized radius and unified time steps would improve readability and facilitate easier comparison.
- Figure 4.15: Axis labels are too small, especially the order of magnitude on the density axis. The ion and impurity profiles should be scaled appropriately to improve clarity.

While most sections are clearly presented, Section 4.3 would benefit from more careful editing, improved figure formatting, and clearer explanations of simulation assumptions and outputs. The candidate's English is excellent, with high clarity and precision throughout.

5. Overall Assessment

The thesis meets the formal and scientific standards for a PhD dissertation. Despite some weaker points in Section 4.3, the overall quality is high. I recommend the thesis for public defense and look forward to the candidate's responses and the opportunity for further scientific discussion during the defense.

6. Questions for the Candidate

1. Could the candidate elaborate on hot-tail generation:

    - Would a scenario dominated by hot-tail and negligible Dreicer generation and with $E < E_c$ be detected by the current implementation of the RE Indicator? Do you plan to adapt it accordingly?
    - Two scenarios in Section 4.1 appear favorable for hot-tail generation. Since its timescale is also linked to τ_{ee}, how should this be handled in your workflow?

2. In Figures 4.9 and 4.10, the simulation uses a very short time scale. Does this reflect a modeling limitation or a deliberate choice based on initial conditions? Also, what mechanisms cause the second peak in runaway current density ($t > 0.7 \times 10^{-5}$ s and $r = 0.075$—0.1 m)?

3. Could you comment on the RE contribution to total plasma current in your ETS simulations? Figures 4.12 and 4.13 suggest a significant RE fraction in the ETS5 run but a much smaller one (Figure 4.16) in ETS6. Could you comment on this difference?

4. Did you achieve the same plasma current decay in ETS5 as shown in Figures 4.16–4.18, which represent the outcome of the ETS6 simulations?

5. Could you clarify the simulation setup for the ETS5 and ETS6 runs of AUG discharge #33108? Specifically:

   - Which RE generation mechanisms were active?
   - Were the runs performed in fluid mode, kinetic mode, or another configuration?
   - What radial transport coefficients were used?
   - In Figure 4.12 ($t = 0$ ms, bottom row), the q profile shows a sharp gradient at the edge. Could this cause numerical issues? Is such a high q value (e.g., $q > 120$ near $r = 0.6$ m) physically meaningful—e.g., indicating a stochastic region?
   - Why do the T_e and T_i profiles at $t = 0$ ms differ between the ETS5 (Fig. 4.12) and ETS6 (Fig. 4.14) runs?
   - What causes the sharp electron density peak at the plasma edge in Fig. 4.15 at $t = 0$ ms?
   - Which mechanisms are responsible for the relatively high electron density values and the shape of the profile in Fig. 4.15 at $t = 2.3$ ms?

6. What causes the abrupt intensity change in the upper part of the crescent shape in Figure 4.27? Could this be mitigated by using finer resolution in the radial or pitch-angle grids?

7. Do you have suggestions for extracting RE parameters from EDICAM data during postprocessing, especially when reflections and background radiation are present?