Replies to Dr. Eva Tomesova

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Dear Dr. Eva Tomesova,

I would like to thank you for reviewing my PhD dissertation. Thank you very much for the endorsement, kind remarks and suggestions made in the review. With regard of the formatting and equation changes suggested, unfortunately the submitted thesis cannot be modified anymore, but I will make sure to fix them and attach them in an errata. In the integrated modeling parts I followed the convention of using the plotting routines provided by the developers of the data structures, this might have caused the inconsistencies between the figures of the ETS5 and ETS6 results. Another information worth noting with regards of the ETS runs is that the data I had on them were lost in the flooding of the Macroni cluster. Fortunately I had enough results to present my findings, but it affects the amount of details I can present. I will answer each of your questions in order below.

Answers to the questions:

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?*

    Hot-tail generation is a transient runaway electron generation typically happening when the plasma rapidly cools down, for example during a tokamak disruption. When this happens, the high energy tail of the distribution function will not have time to thermalize - as the collision time of particles decreases for energies larger than the thermal energy - before the critical momentum boundary of the runaway electron region becomes lower than the momentum of the hot tail of the distribution. This way the tail of the distribution will end up in the runaway region generating runaway electrons.

The Runaway Indicator calculates the critical field and the Dreicer generation rate based on background plasma parameters, and gives a warning if the electric field is larger than the critical field ($E > E_C$). Although an analytic formula is available to give an estimate on the hot-tail generation rate [1], it is not implemented in Runaway Indicator as it is not as generally applicable as the generation rate for Dreicer generation for example. Hence it was not implemented in a code, which might not be used within the necessary validity boundaries.

In scenarios where the hot-tail generation is dominant, an electric field is still required to be larger than the critical field in order to generate a runaway electron population. The slowly thermalizing fast electron population will end up being runaways if the velocity boundary for runaway electrons will be lower then some of the fast electrons. This boundary only exists if an electric field larger than the critical field is present, and hence it would be indicated by Runaway Indicator. The code would not give a warning for too large Dreicer generation if the scenario is dominated by hot-tail generation, it would have to be simulated by more sophisticated models to analyze this.

On the second part of your question, the study presented focused on Dreicer generation comparison between kinetic and fluid models. We deliberately created scenarios where other generation methods were not studied, the hot-tail generation was not present as the plasma parameters were kept constant, except for the electric field. You are right that the disruption scenarios discussed in this section are typically dominated by hot-tail generation, but the current implementation of the workflow does not allow for studying hot-tail generation. If one would want to modify the workflow to work for this runaway electron generation type, the Runaway fluid model would have to be modified to include a fluid generation rate for hot-tail generation. This would allow for a similar study as the one presented in the dissertation. If the comparison between modeling approach is is not the goal, the workflow can be used with only the NORSE model to study the hot-tail generation, or the DREAM code can be utilized standalone for such purposes.

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*)?*

   The choice of the simulation time length was deliberately chosen through the exponential decay rate of the plasma temperature. The goal of the simulations depicted in Figures 4.9 and 4.10 was to demonstrate the capabilities of DREAM to be run directly with experimental data. To ensure certain runaway electron generation in the predictive simulation with DREAM, I chose the exponential decay time to be short, so significant runaway generation can be expected. The results do not carry other physical meanings. It also poses significant challenge to accurately simulate runaway electron generation on TCV, as runaway electrons generated during the start-up phase can significantly affect the results. The development of the IMAS interface also helps with the study of this problem.

The filamentation causing the second peak seen on Figure 4.10 removed from the magnetic axis is caused by a thermal instability during the simulation, described in this masters thesis [2]. Most likely there was a local temperature maximum in the grid point corresponding to the peak in runaway electron current due to the heating power of the plasma current overcoming the radiative losses. This reduced the resistivity locally, further enhancing the current flow in this grid point and slowing the temperature drop. When the electric field induced by the current decay starts to generate runaway electrons, the Dreicer generation in this local point will be increased due to the sensitivity of Dreicer generation to temperature, which will generate the peak in runaway current over time through avalanche generation. I have seen these kind of filamentation in simulations during my PhD, so I assumed this was the case for this simulation as well. Unfortunately the data for this run was lost in the Macroni server collapse, so I cannot confirm this by more thorough investigation of this run.

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?*

   As you mentioned in your question, ETS5 has a significant runaway electron portion in current density at the final time step on the magnetic axis. The runaway electron current contribution to the total plasma current however is less significant, as on the outer radii, the total current density is carried by Ohmic current, so the integration of the current density would result in a much larger contribution from Ohmic current than from runaway electrons current. I expect a similar contribution as seen on Figure 4.16 for ETS6. The total current conversion could not be simulated with either ETS version due to numerical instabilities.

Unfortunately I cannot produce a total current plot for ETS5 similar to Figure 4.16 due to data loss in the Macroni server collapse.

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?*

   Unfortunately I cannot answer this question as I do not have the data on the total current evolution for the ETS5 simulation as it was lost in the Macroni server collapse. However, the simulation dynamics resembled behaviour seen in experiments in both of the ETS 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?*

   The clarifications for the ETS settings are as follows:

   - The runaway electron population was modeled by Runaway Fluid in both ETS versions. Runaway Fluid considers the Dreicer and the avalanche generation of runaway electrons, both of which are calculated using analytical formulas. Both of these were used in the simulations.
   - Fluid mode was used as Runaway Fluid can only have analyitcal formulas for generation rates.

- The additional transport coefficients of impurity ions were set as 100 m^2/s for diffusion and -200 m/s for convection, exponentially dropping in time to avoid instabilities in the plasma centre.
- The numerical issue arises at the end of the simulation, while it can be seen on the other time steps in the bottom row that the q profile relaxes to a more physical form, so this is most likely not the cause for the instabilities. I was also concerned by the initial shape of the q-profile, but after cross checking I concluded that the shape comes from the experimental data.
- The difference most likely comes form the different origins of the data loaded into the ETS simulation. In the ETS5 case, the data was loaded from raw experimental data available, while in the ETS6 cases it most likely comes from IDA (Integrated Data Analysis) data. It is possible that the algorithms collecting the experimental data from the AUG database collected the data from different sources for the CPO and IDS versions.
- The first time step in ETS6 already contains the impurities injected at the edge as shown by the green line and the ionization of these impurities cause the increase in the electron density as well. The plot shown as $t = 0$ ms actually shows data after ETS6 stepped once in time, due to how the data is handled in ETS.
- This is again due to the impurity content of the plasma, and the ionization that releases the addition electrons in the plasma. ETS6 handles the electron density through quasi-neutrality, it calculates the ionization states of the main ion plasma and the impurities and calculates the electrons density to maintain a total neutrality. The shape of the electron density profile is coming from the shape of the impurity profile as well.

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?*

   This is caused by how SOFT considers the the tokamak shape and the plasma shape itself. Both the plasma and the tokamak chamber is considered circular in SOFT, so the sharp line is the shadow of the central solenoid according to the SOFT geometry. This cannot be resolved with finer resolution, only with using realistic tokamak geometry, which cannot be done in SOFT.

7. *Do you have suggestions for extracting RE parameters from EDICAM*

data during postprocessing, especially when reflections and background radiation are present?

Yes, this is something I am working on at the moment. The energy distribution of the runaway electron distribution function cannot be extracted from the EDICAM images, as it requires spectral data, which is not available in the EDICAM images [3]. But, since the synchrotron radiation is highly directional, the shape of the synchrotron radiation spot might be used to gain information of the magnetic structure of the plasma. For this purpose we have started the development of a convolutional neural network, to gain information from EDICAM experimental images. I have presented the first preliminary results at this year's Runaway Electron Modeling meeting, but the neural network is not yet in a state to be directly applicable.

Bibliography

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[3] T. Wijkamp, A. Perek, J. Decker, B. Duval, M. Hoppe, G. Papp, U. Sheikh, I. Classen, R. Jaspers, the TCV Team, and the EUROfusion MST1 Team, "Tomographic reconstruction of the runaway distribution function in tcv using multispectral synchrotron images," *Nuclear Fusion*, vol. 61, p. 046044, mar 2021.