Replies to Dr. Attila Bencze

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Dear Dr. Attila Bencze,

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. Your recommended modifications cannot be added to the submitted thesis at this point as it cannot be modified. But I would like to take the opportunity to react to some of the suggestions you have raised.

Figure 3.1 and 3.2 are added to the dissertation to demonstrate the structure of actors in the Kepler framework, and while I agree with the observation that some of the text can be difficult to read, it is unfortunately impossible to increase the text sizes without leaving parts of the structure out of the images. These images are taken directly from the Kepler canvas and personalization the texts cannot be done.

The physics behind Runaway Fluid and Runaway Indicator is extensively discussed in Chapter 2, both of them are simple models working with the analytical formulas introduced either in Chapter 2 or in the appropriate parts in Chapter 3, but some technical details might still not be available in the thesis. For these, I refer to the Pokol NF [1] publication, which I am co-author of.

I will now answer each of your questions in order below.

Answers to the questions:

1. *Can the Candidate elaborate on the specific uncertainties and sensitivities of the kinetic modeling methods, especially concerning different collision operator treatments?*

   Kinetic modeling methods all treat the electron population through the evolution of the electron distribution function by solving the kinetic equation (2.27), in one form or the other. The different kinetic approaches in DREAM, the fully kinetic, the suprathermal and the isotropic, are all solving the same equation with the same collisional operator [2]. The difference between the three modes lies in the different description of the electron population. DREAM separates the electron population to three different regions in momentum space: the cold electron population, which is the thermal part of the Maxwellian distribution, the hot electron population, which is the high energy tail of the distribution, and the runaway electron part (see Figure 3.3 in the dissertation). The three different methods define how is the electron population is resolved up until p_{re}.

In the *fully kinetic mode* both the cold and the hot part of the momentum space is resolved kinetically in 2-D momentum space (normalized momentum and pitch angle) by solving the kinetic equation with a linearized test-particle Fokker-Planck operator. The collision operator is pushing the distribution to a Maxwell-Jüttner equilibrium distribution. The runaway electron part of the momentum space is resolved kinetically in 2-D momentum space as well. The fully kinetic approach is the most physically accurate though it has high computational costs.

The *superthermal mode* is used when the thermal part of the electron distribution is considered so slow that its temperature approaches zero $T_{cold} \to 0$. This typically happens in the later stages of plasma disruptions. In this case only the hot part of the momentum space is resolved on a 2-D momentum gird and the cold electron part is described by $\langle \mathrm{n}_{\mathrm{cold}} \rangle$ density. The $\mathrm{p}_{\mathrm{hot}}$ lower boundary of the hot electron region is $\mathrm{p}_{\mathrm{hot}} = 0$, meaning that all electrons below this boundary are lost and are given to the cold electron density. The kinetic equation will not equilibrate to a Maxwell distribution as it will have a particle sink at the lower momentum boundary. The runaway electron region can once again be modeled either kinetically or in fluid mode.

If the hot electron part of the momentum space can be considered isotropic the *isotropic mode* can be used. This resolves the momentum space in the same way as the superthermal mode, except it pitch angle averages the kinetic equation to solve it in only one momentum space coordinate, further reducing the computational costs. This mode is ideal for describing processes where pitch angle scattering is dominant, hence isotropic distribution function can be expected. Such process can be resonant scattering on electromagnetic waves and typically applies to superthermal but not yet runaway electrons.

In each of these cases DREAM solves the kinetic equation using a linearized test-particle Fokker-Planck collision operator, which is linearized around the Maxwellian distribution, and considers the hot and runaway electron parts as deviation from the thermal part. The test particle operator describes the affect of collisions with the background plasma species on the distribution of the test particle species.

When a significant part of the collisions is happening between relativistic particles, the linearized operator cannot accurately predict the evolution of the distribution function as it assumes that the relativistic part of the population is negligible compared to the Maxwellian distribution. In such cases the non-linear collision operator is required to describe the collision between relativistic particles. Such collision operator is used in NORSE [3], which includes full description of collisions between relativistic particles, although it is not limited to cases where the background plasma is also relativistic. This approach is required when an electric field is significantly large compared to the Dreicer field resulting a slide-away scenario, where a significant part of the distribution reaches relativistic energies. In such cases, models with linearized collision operator, such as DREAM cannot accurately predict the evolution of the electron population. This effect can be seen in the results presented in Section 4.1.

2. *How significantly would the presence of partially ionized high-Z impurities alter the presented simulation results, especially in disruption scenarios?*

   The presence of partially ionized high-Z impurities in tokamak plasmas is relevant for one of the proposed runaway electron mitigation methods, the massive material injection. These method was proposed because it as shown that the presence of these high-Z atoms can significantly increase the electric field required for runaway electron generation [4]. This method seemed suitable to prevent runaway electron generation due to the increase in the required electric field from effects of partial screening and radiation losses, and also increases the free electron density, hence increasing the drag force on the electron population. It was later shown however, that the avalanche rate is significantly increased in the presence of high-Z impurities and large electric fields [5, 6] as the increase of targets for relativistic electrons would result in increased avalanche generation, overcoming the positive results from the increased critical electric field. Because of the increased effective critical field it was shown that a reduced Dreicer generation can be expected in such cases. A neural network was trained on kinetic simulations to calculate the steady state Dreicer generation in the presence of partially ionized ions [7].

   The Dreicer generation study had no partially ionized impurities included, but in the case it had, it would only change the value of the steady state generation rate, not the overall transient properties of the models. DREAM has the effects of partially ionized ions included in the calculations, whereas the other three models do not, so I would expect differences between DREAM and the other two kinetic codes.

In the ETS simulations however I would expect to have significant differences in calculating the runaway electron generation in the presence of partially ionized impurities. The runaway electron evolution was calculated in those scenarios by the Runaway Fluid model, which does not take these effects into account. As shown in [7] the Dreicer generation is expected to be lower in scenarios with massive material injection, such as the ETS simulation, but the losses in Dreicer generation are possibly balanced by the avalanche generation. Unfortunately the runaway electron dominated parts of the disruption simulations with ETS were prevented by numerical instabilities due to the high gradients in the plasma centre, so a comparison is not possible at the moment.

In the simulations for the synchrotron radiation on JT-60SA, DREAM was used to calculate the runaway electron distribution function. DREAM has the effects of partially ionized impurities included in its kinetic and fluid modes as well.

3. *What are the primary numerical or physical limitations constraining further improvements in the integrated modeling approach?*

   The biggest limitations of the integrated modeling approach is the difficulty of ensuring the physical consistency between the different models simulating certain parts of the total tokamak disruptions. Certain models might work under certain assumptions which are inconsistent with other modules in the framework. This necessitates thorough consideration when setting up the physical model in ETS. Despite this difficulty the integrated modeling framework can be used to predict and simulate tokamak shots in the flat-top region [8].

   In the simulations I have preformed with ETS, the main difficulty lied in the fact that ETS was developed for standard tokamak discharges during the flat-top plasma operation and not for disruption simulations. Due to this it was difficult to set up a proper physical model which would describe a disruption self-consistently along with runaway electron evolution in a numerically stable way. This problem was solved by collaboration with the developers of the ETS workflow, hence I am confident that the ETS simulations gave physically relevant results. Despite our best efforts, the numerical instability of running ETS at the edge of its validity range prevented from reaching full disruption simulations with this model.

4. *How could the Candidate's modeling of runaway electron radiation in JT-60SA be directly employed to enhance experimental diagnostics or inform practical operational strategies?*

   This is a project we are currently working on by development of an artificial neural network to recognize and gain information from synchrotron radiation images. It was previously shown that the reconstruction of the electron energy distribution function requires data on the radiation spectrum [9]. Since the synchrotron radiation is a highly directional radiation, it is possible that information on the magnetic geometry can be obtained from the shape of the synchrotron radiation shape and possibly gain some information on the distribution function as well.

   For this purpose we started the development of a convolutional neural network, to recognize synchrotron radiation on experimental camera images. The first repliminary results of the neural network was presented on this years Runaway Electron Modeling meeting in the first week of June. It was trained on synthetic images generated by combining synchrotron radiation images form SOFT and the background plasma radiation by Cherab. A 5-D phase space was scanned to generate the necessary images, in electric field, effective plasma charge are two parameters of the electron distribution function, radius, q-profile (to include the effects of the magnetic geometry) and the radiation intensity. Currently it gives prediction on whether runaway electron radiation can be seen or not, and whether the q-profile is linear or quadratic. We are planning to extend this capability to give quantitative prediction on the q-profile shape.

   In the long run it might be possible to give real time information to the control system of a tokamak to modify the discharge program if runaway electron radiation is detected by the neural network.

5. *Considering the findings, what practical mitigation strategies does the Candidate foresee for effectively preventing or limiting runaway electron generation in largescale tokamaks?*

   Currently multiple different strategies are considered for preventing runaway electron generation and the mitigation of runaway electron damage. In the dissertation I listed multiple promising methods, the shattered pellet injection (SPI), the resonant magnetic perturbation (RMP) and the benign termination. All of these methods show promise, but are required to achieve full elimination of the runaway electron seed, or full neutralization of the companion plasma in case of the benign termination.

Based on the current state of scientific understanding I believe each of these methods have the potential for runaway electron prevention and mitigation, but I believe that if SPI proves to be successful during the ITER operation, it will be the major mitigation method in future devices in Europe.

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