Runaway electron modelling in the EU-IM framework

S. Olasz[1,2], M. Aradi[3], M. Hoppe[4], O. Embreus[4], G. Papp[5], T. Johnsson[6], J. Ferreira[7], D. Coster[5], P. Strand[4], D. Yadikin[4], I. Ivanova-Stanik[8], M. Poradziński[8], G. Pautasso[5], I. Voitsekhovitch[5], J. Decker[9], Y. Peysson[10], G.I. Pokol[1,2], EU-IM Team*, EUROfusion-MST1 Team**, ASDEX Upgrade Team***

[1] NTI, University of Technology and Economics, Budapest, Hungary

[2] Centre For Energy Research, Budapest, Hungary

[3] Barcelona Supercomputing Center (BSC), Barcelona, Spain

[4] Chalmers University of Technology, Göteborg, Sweden

[5] Max-Planck Institute for Plasma Physics, Garching, Germany

[6] KTH Royal Institute of Technology, Stockholm, Sweden

[7] IPFN, IST, Universidade de Lisboa, Lisboa, Portugal

[8] Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland

[9] EPFL, Swiss Plasma Center, Lausanne, Switzerland

[10] CEA, IRFM, Saint-Paul-lez-Durance, France

* *https://users.euro-fusion.org/eu-im*

** *See author list at Labit B. et al., Nucl. Fusion 59 086020 (2019)*

*** *See the author list of H. Meyer et al. Nucl. Fusion 59 112014 (2019)*

Introduction In tokamak discharges runaway electrons can be generated in the presence of large toroidal electric fields. In large devices, such as the upcoming ITER, they can form a strong beam of relativistic particles, carrying currents of megaamperes magnitude [1]. The beam can cause significant damage to the plasma facing components if it gets unconfined. Hence, the correct understanding and modelling of runaway electron generation is of crucial importance. The European Integrated Modelling Framework (EU-IM) [2] has been used to develop runaway electron modelling tools of different sophistication. The modelling framework consists of a standardized data structure and an access layer to the data structure. It allows for creation of graphical workflows, where different physical models can be coupled to create complex, self-consistent simulations. Two such workflows were developed to study runaway electron generation. The Runaway Electron Test Workflow (RETW) is a tool created to test the integration of different runaway electron models into the modelling framework and perform comparative studies. The European Transport Simulator (ETS) is a self-consistent, complex workflow which aims to simulate full tokamak discharges.

Table 1. The physical parameters used for the different simulated cases

	Start-up phase	Start of disruption	End of disruption	Low density discharge
Electron density [m^{-3}]	5×10^{17}	1×10^{20}	1×10^{20}	5×10^{17}
Temperature [eV]	300	10000	300	10000
Electric field [Vm^{-1}]	2.81×10^{-3}	2.96×10^{-2}	3.66×10^{0}	4.38×10^{-1}
Critical field [Vm^{-1}]	5.06×10^{-4}	4.16×10^{-4}	6.98×10^{-2}	8.77×10^{-2}
Normalized electric field [-]	5.55	71.00	52.50	5.00
Coulomb logarithm [-]	19.9	16.3	13.7	17.2
Critical collision time [s]	2.58×10^{-1}	6.84×10^{-3}	6.42×10^{-5}	1.74×10^{-3}

Runaway Electron Test Workflow The Runaway Electron Test Workflow contains three different runaway electron codes. The simplest code, Runaway Indicator, only gives warnings when simulation parameters make runaway electron generation possible [3]. Runaway Fluid calculates the runaway electron population using analytical formulae for Dreicer and avalanche generations [3]. The NORSE [4] kinetic solver has recently been added to the workflow. NORSE uses a non-linear collision operator to calculate the runaway electron distribution.

The workflow with these models has been utilized to study the Dreicer generation rate in dynamic scenarios. The simulations were complemented with results from the DREAM code [5], a kinetic model with a linearized collision operator and LUKE [6] a bounced averaged kinetic solver with a linearized collision operator. The aim of the study was to find a robust parameter which can be used to determine when kinetic modelling is required in self-consistent simulations. The Dreicer generation was studied for four different density and temperature pairs, spanning the relevant tokamak operation space (Table 1). The behaviour of the runaway generation was studied in response to a jump in the electric field, while the other simulation parameters were kept constant. The change in the electric field caused a peak in the generation rate calculated by the kinetic models in every case, as shown in Figure 1. The effect is caused by the initial shift of the distribution function into the runaway region. The height of the peak depends on the definition of the runaway boundary in the different models. In two cases the steady state generation reached by the kinetic codes converges to the analytical value, while in two cases significant differences can be seen. In the later cases (Figure 1 (a) and (d)), the final runaway population reached about 10% of the total electron density, which causes significant interaction of runaway electrons with the bulk electron population, which is only handled in NORSE. It was found that the duration of the peak in the runaway electron generation can be related to the electron – electron collision time at the critical velocity for runaway electron generation (critical collision time), indicated with a yellow dashed line in Figure 1. This parameter can be used to determine the need for kinetic modelling in integrated modelling scenarios. If the parameters vary faster than the critical collision time, kinetic modelling is strongly advised.

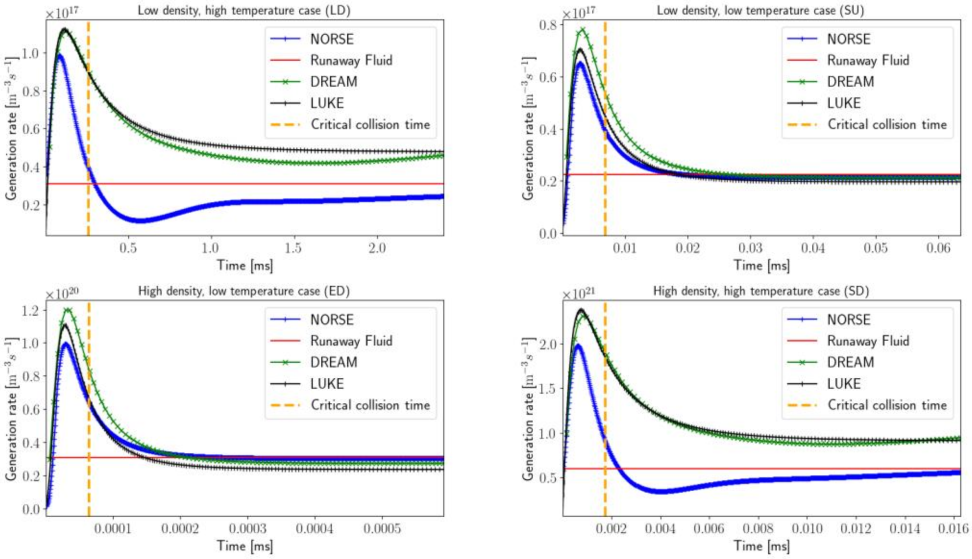

Figure 1. The Dreicer generation rate calculated by Runaway Fluid, NORSE, LUKE, and DREAM. A peak in the generation rate appears in every kinetic model on a timescale relatable to the electron-electron collision time at the critical velocity for runaway electron generation (yellow dashed lines).

ETS The European Transport Simulator [7] is a Kepler workflow in the EU-IM framework [2] which aims to simulate tokamak discharges in a self-consistent way. It contains Runaway Fluid to model the runaway electron generation, and this feature was benchmarked against the GO code for prescribed cooling scenarios earlier [3]. Here we report the use of ETS version 5 to simulate a massive material injection (MMI) induced thermal quench based on ASDEX Upgrade shot #33108. Pre-disruption shot data was imported to ETS by semi-automated tools. A peaked temperature profile was achieved with intense electron cyclotron resonance heating before the injection of the argon gas. This phase was simulated by running ETS in an interpretative mode to provide self-consistent initial conditions for the consecutive predictive run. In the next phase, a self-consistent predictive simulation was performed to model the effect of a large amount of argon gas injected from the edge of the plasma. The MHD mixing was simulated with enhanced diffusion coefficients for the impurity species, while inward convection was increased to ensure the penetration of the gas. The initial peaked temperature profiles flatten from the edge as the injected argon moves towards the magnetic axis as shown on the top row of Figure 2. The ionization of the argon increases the electron density as the impurity moves inwards (second row). The increased resistance of the cold plasma pushes the electric field and a current spike towards the centre as it is shown on the third row of Figure 2. This results in a runaway electron current which peaks near the centre.

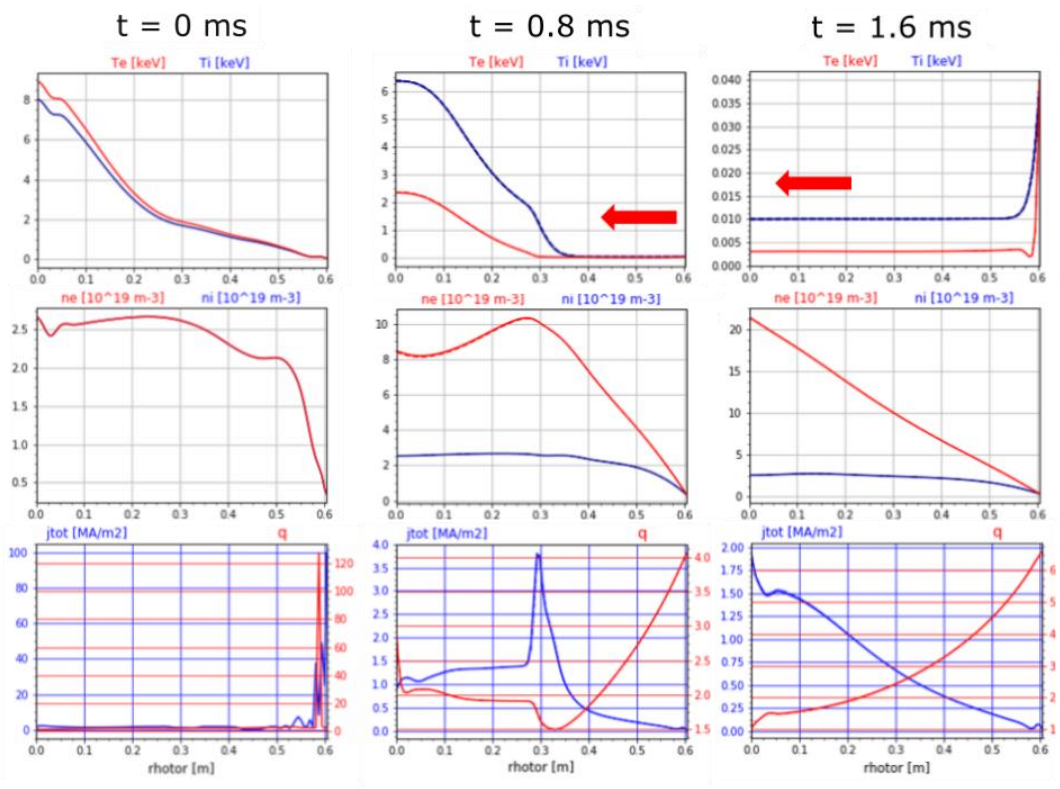

Figure 2. The evolution of the plasma profiles throughout the thermal quench simulation with ETS. The top row shows the evolution of the electron temperature in red and the ion temperature in blue. The first plot shows the initial profile, the second shows the profile halfway through the simulation, while the last plot shows final the result. The red arrow indicates the direction of the injected argon gas. The second row shows the evolution of the electron density in red and the ion density in blue for the same times. The q profile in red and the current density in blue is plotted in the bottom row.

Summary The Runaway Electron Test Workflow was used to study the behaviour of the Dreicer generation of runaway electrons in dynamic scenarios to find a parameter which can be used to determine the need of kinetic modelling in more complex simulations. It was found that for processes which vary faster than the collision time at the critical velocity for runaway electron generation, kinetic modelling is advised to capture potential kinetic effects. A more complex tool, the ETS have been used to simulate a self-consistent thermal quench induced by massive material injection with promising initial results. Development of ETS capabilities continues with introduction of kinetic modelling and moving onto the new ETS6 versions.

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