Kinetic modelling of runaway electron momentum distributions for the EU-DEMO tokamak

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DEMO is the demonstration power plant planned by EUROFusion, and the tokamak may be susceptible to runaway electron (RE) generation during disruptions due to its plasma parameters [1]. During the current quench (CQ), a significant portion of the initial ohmic plasma current may be converted into runaway electron current, and the formed RE beam can pose a threat to the plasma facing components of the device.

The plasma of DEMO is designed to contain argon as an intrinsic impurity to isotropically radiate power, thereby reducing localized heat loads on the plasma-facing components. However, the presence of argon also increases the likelihood of thermal instabilities, as its ionization energy of the 1s electron orbit is approximately 3.2 keV, while planned H-mode DEMO plasmas have average electron temperatures around 11 keV. The tokamak is currently planned to have so-called sacrificial limiters [2] to protect the other components of the first wall, primarily composed of tritium breeding blanket modules. These tungsten or tungsten-coated limiters must withstand both steady-state thermal loads and transients. They are designed to be more easily replaceable after damage compared to the blanket modules. Thermal loads during disruptions can melt the tungsten on these limiters to depths of several millimeters [3]. A comprehensive study of the damage induced by runaway electrons during a runaway impact event is currently underway. The aim of this project is to provide insights into momentum-space RE distributions in DEMO unmitigated disruptions for wall load and limiter load calculations.

In this work, disruption simulations were conducted using the DREAM code [4] for an unmitigated vertical displacement event (VDE) scenario [5] simulated in JOREK based on the 2021 H-mode baseline of EU-DEMO. We chose this simulation as an estimation of a realistic DEMO disruption scenario. DREAM is capable of self-consistent kinetic simulations using static magnetic geometries. The DREAM simulation was initialized at the moment in the VDE simulation when the q=2 surface reaches the wall of the tokamak. The plasma parameters and the magnetic geometry were taken from the VDE simulation and in our simulations, the plasma also contains argon with a uniform profile calculated from available Z_{eff} data resulting in a density of approximately 4×10^{17} m^{-3}. The stochastization of the magnetic field is emulated by prescribing large thermal and ion diffusion coefficients for the first 8 ms. To self-consistently model a somewhat realistic unmitigated disruption scenario, deuterium and tritium atoms are introduced in the outermost radial cell of the simulation. This material influx cools the plasma and enhances the line radiation of argon, leading to the thermal quench (TQ).

Our goal was to qualitatively describe the evolution of the runaway electron distribution function, identify the parameters governing runaway electron dynamics, and relate the numerical results to previously published analytical models [6-11]. The simulations of the runaway electron distribution functions were performed in three dimensions: 1D in real space and 2D in momentum space. Additionally, to verify our findings, different modes of thermal and hot electron population handling and various runaway generation models were examined. In DREAM, electrons can be treated as fluid populations (thermal and runaway) or with electron distribution functions, either 1D (p) or 2D (p, ξ_0) in momentum space. We chose to model the runaways in 2D momentum space in all simulations to be able to account for the slowing down caused by synchrotron radiation.

In isotropic mode, thermal electrons are treated as fluid, while hot electrons have a 1D distribution function in momentum. In superthermal mode, thermal electrons are fluid, and hot electrons have a 2D distribution in momentum space. In fully kinetic mode, both thermal and hot electrons are modeled with the same 2D distribution in momentum.

We performed initial simulations in isotropic mode, employing fluid generation models for tritium, Compton, and avalanche runaway generation methods. We focused on the first 150 ms post-disruption, as MHD events leading to runaway losses are expected within this timeframe. We observed that the thermal quench is initially incomplete due to ohmic heating counteracting radiation losses from argon. The TQ completes at around 75 ms, as shown in **Figure 1**, and significant runaway current begins to form at 65 ms, with full conversion of ohmic to runaway current occurring at 75 ms (see **Figure 1**). At this point, the electric field decreases to just above the critical electric field required for runaway generation. As we simulated nuclear operation, the Compton generation by gamma photons from the activated wall provided a seed population of runaways for secondary avalanche generation, that quickly took over as the most significant generation mechanism.

The runaway electron distribution function from these isotropic simulations monotonically decays towards higher momenta during the high electric field stage of the CQ (see **Figure 2**), and analytical models exist for this type of distribution [6,7]. During the

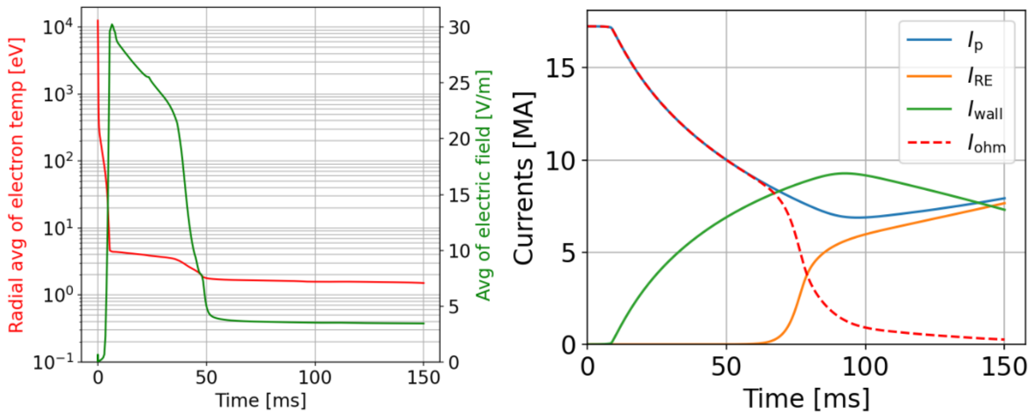

Figure 1 – The time evolution of the average electron temperature and toroidal electric field (left); and the time evolution of different currents (right) during the isotropic DREAM simulation of a DEMO disruption. The amount of total influxed deuterium and tritium atoms is 6×10^{23} in this scenario.

runaway plateau, after the conversion of ohmic current to runaway current, the toroidal electric field weakens to a marginally critical level. Consequently, higher momentum electrons experience reduced acceleration while simultaneously being slowed by Bremsstrahlung, synchrotron radiation, and collisions. This leads to the formation of a bump in the distribution (at 10-15 m_ec), which grows over time. The bump-on-tail distribution can also be described by analytical models [8-11]. Additionally, we noted that if the material influx is larger (right subfigure of **Figure 2**), the bump appears at slightly different momenta (20-25 m_ec) and is more pronounced on a similar timescale. However, due to limited data points, we can only infer that this results from higher collisionality and a greater rate of pitch angle scattering, causing the electrons to slow down more rapidly.

Following the initial isotropic simulations, a fully kinetic simulation was initiated to more accurately assess whether significant hot-tail or Dreicer generation can be expected during the TQ in our scenario. This simulation was computationally expensive and slow to execute, with the distribution solution exhibiting signs of numerical instability. As a result, only the first 6 ms of the disruption were simulated. During this period, the electron temperature in the

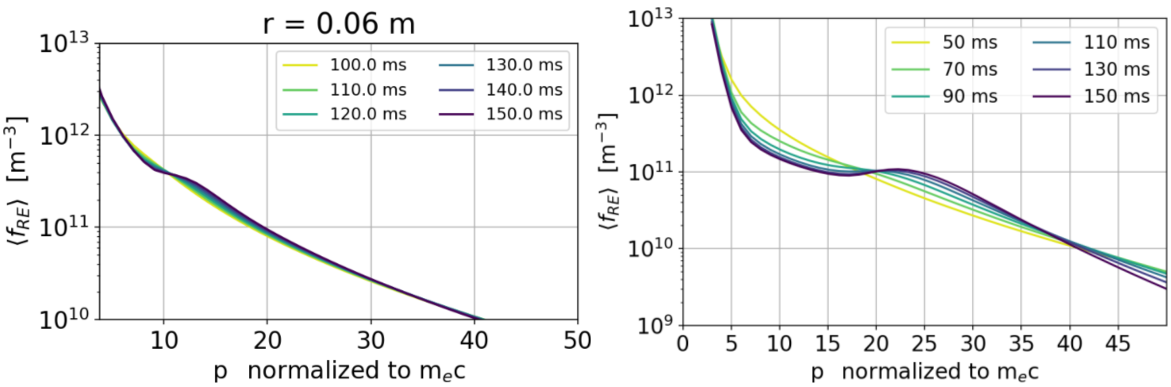

Figure 2 – The runaway electron momentum distribution function time evolution in two isotropic DREAM simulations, in the centermost radial cell. The amount of total influxed deuterium and tritium atoms is 6×10^{23} in the scenario corresponding to the left, and 6×10^{24} for the right subfigure.

plasma core dropped to approximately 100 eV, while at the plasma edge it reached 1 eV due to the D-T influx. No significant hot-tail or Dreicer generation was observed at any radial location during the simulated timeframe.

To avoid numerical instabilities and account for the validity of models used in DREAM, superthermal simulations were initialized from the initial isotropic simulation – with a total influx of 6×10^{23} D and T atoms – at the 50 ms mark. In these simulations, kinetic tritium and Compton generation models [12] were employed, along with the kinetic avalanche model. The resulting distribution function evolved similarly to that presented in the left subfigure of **Figure 2**, confirming our previous results using different physical models.

In conclusion, we performed EU-DEMO disruption simulations using DREAM in three modes, using different runaway electron generation models to determine possible RE distributions that are relevant for wall load calculations. We found that during the high electric field stage of the CQ the distribution monotonically decays towards higher momenta. As the electric field decreases to values marginally above the critical field during the runaway plateau, a bump forms on the distribution. This dynamic is found in all our simulations; however, the exact location, magnitude and time evolution of the bump are influenced by disruption parameters which warrants further study. Nevertheless, a robust estimation of a set of RE distributions has been forwarded for runaway beam wall impact calculations [13].

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