Runaway electron seed population dependence using continuous parameter evolution

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Motivation

During a thermal collapse in a magnetically confined plasma, the bulk of the electron population drops in energy and begins to equilibrate with the ions, which increases the bulk resistivity of the plasma. As the resistivity increases, a large electric field forms within the plasma to sustain the equilibrium current. This electric field can become very strong, and pulls a small number of electrons to relativistic speeds. These 'runaway electrons' (RE) are a serious risk to the operational stability of ITER and large tokamaks. Understanding the precise conditions that initiate RE populations is essential in developing RE mitigation strategies. One of the least understood aspects of the RE generation is the dependence of the initial number of accelerated electrons – the **seed population** – on the time history of the plasma temperature and electron density. Computational investigations with time-dependent parameters allows us to study this dependence. Codes for simulating the electron distribution with user-defined time-dependent parameters exist, and we work with the code CODE (COllisional Distributions of Electrons) to implement specific methods for continuous parameter evolution. In this poster, we outline this implementation within CODE and discuss our results.

The Code

We used CODE, written jointly by Adam Stahl and Matthew Landremann, to implement our parameter evolution scheme. CODE solves the kinetic equation for the electron distribution f:

$$\frac{\partial f}{\partial t} - eE\mathbf{b}\cdot\nabla\mathbf{p}f = C\left\{f\right\} + S,$$

where e is the electron charge, E is the component of the electric field along the magnetic field, $\mathbf{b}$ the magnetic field unit vector, $\nabla\mathbf{p}$ is the gradient of the relativistic momentum, and C is the electron collision operator[2]. The distribution f is defined terms of linear momentum and the cosine of the pitch angle (p, ξ). CODE requires five plasma parameters, T (bulk plasma temperature), n (electron density), Z (plasma effective charge), E (electric field), and B (magnetic field). CODE allows all but B to vary in time.

Parameter Evolution Scheme

We begin with Ohm's law for the electric field E

$$E = \eta J,$$

where η is the resistivity, and J is the current density in the plasma. The resistivity is governed by *Spitzer resistivity*, $\eta_{Spitz} \propto T^{-3/2}$ from the thermal electrons. The current carried by runaways does not contribute to the electric field, so we split J into the difference of the total current density, J_{tot}, and the RE current density, J_{RE}. Substituting these terms gives us our equation for the electric field used in our parameter evolution scheme:

$$E = \eta_{Spitz}\left(J_{tot} - J_{RE}\right).$$

Using this definition for the electric field is particularly useful as the current densities are calculated as moments of the distribution, which in turn depends on the electric field, so self consistent behavior is easy to implement.

The number of runaways, N_{RE}, is defined as

$$N_{RE} \equiv \int p^2 f\left(p, \xi\right) dp$$

Results

For our investigation, we used a nonuniform $p-$grid, with dense grid at the cusp of the thermalized electron peak in energy, and sparse grid at greater energies. We used a tanh function to create a set of temperature drops over four initial temperatures (T_0) and six drop widths (d). We used $B = 2$ T, $n = 1e20$ m^{-3}, and $Z = 1$. Before initiating thermal collapse we used our E-field evolution to draw out current to a steady state.

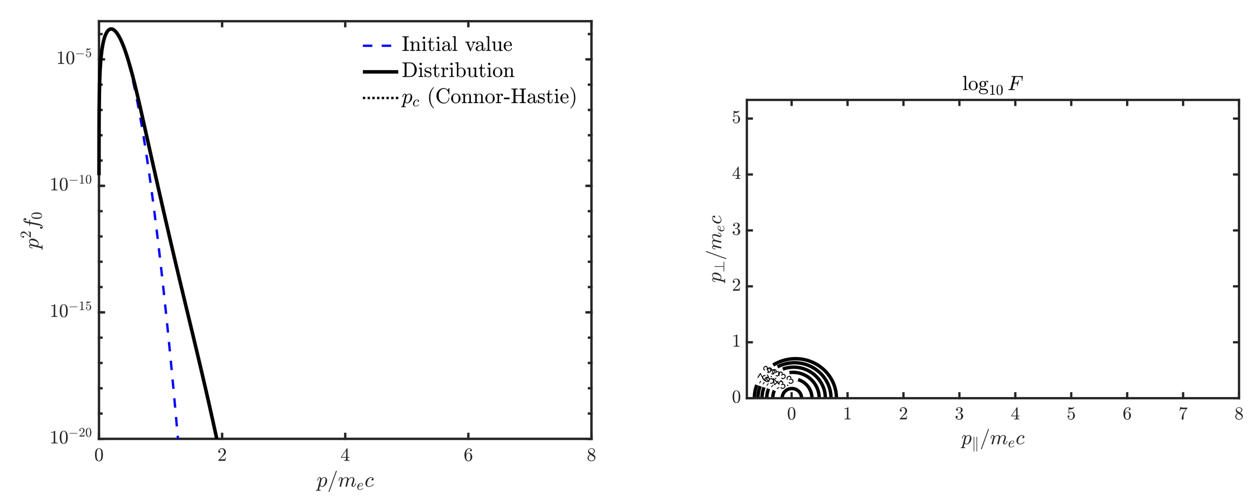

Fig. 1: Pre-thermal collapse distribution for $T = 10keV$, $n = 1e20m^{-3}$, $Z = 1$, $E_0 = 0.1V/m$, $B = 2T$.

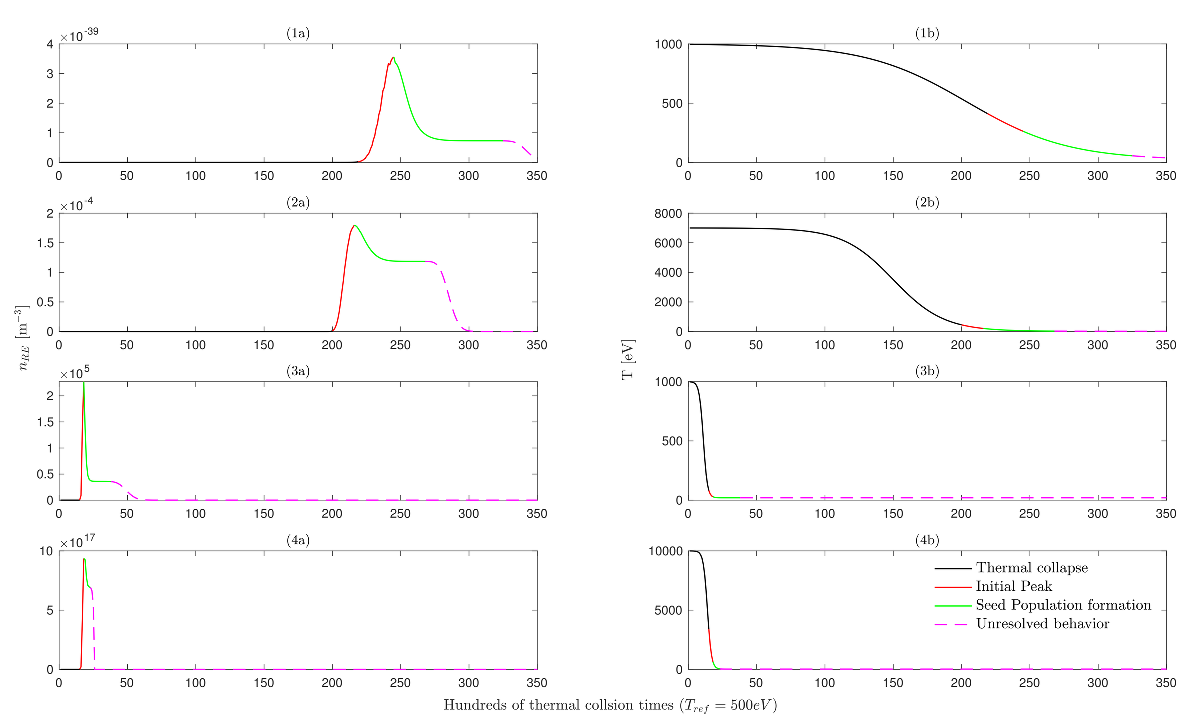

Fig. 2: (1) Initial peak and seed population formation, (2) Temperature profiles

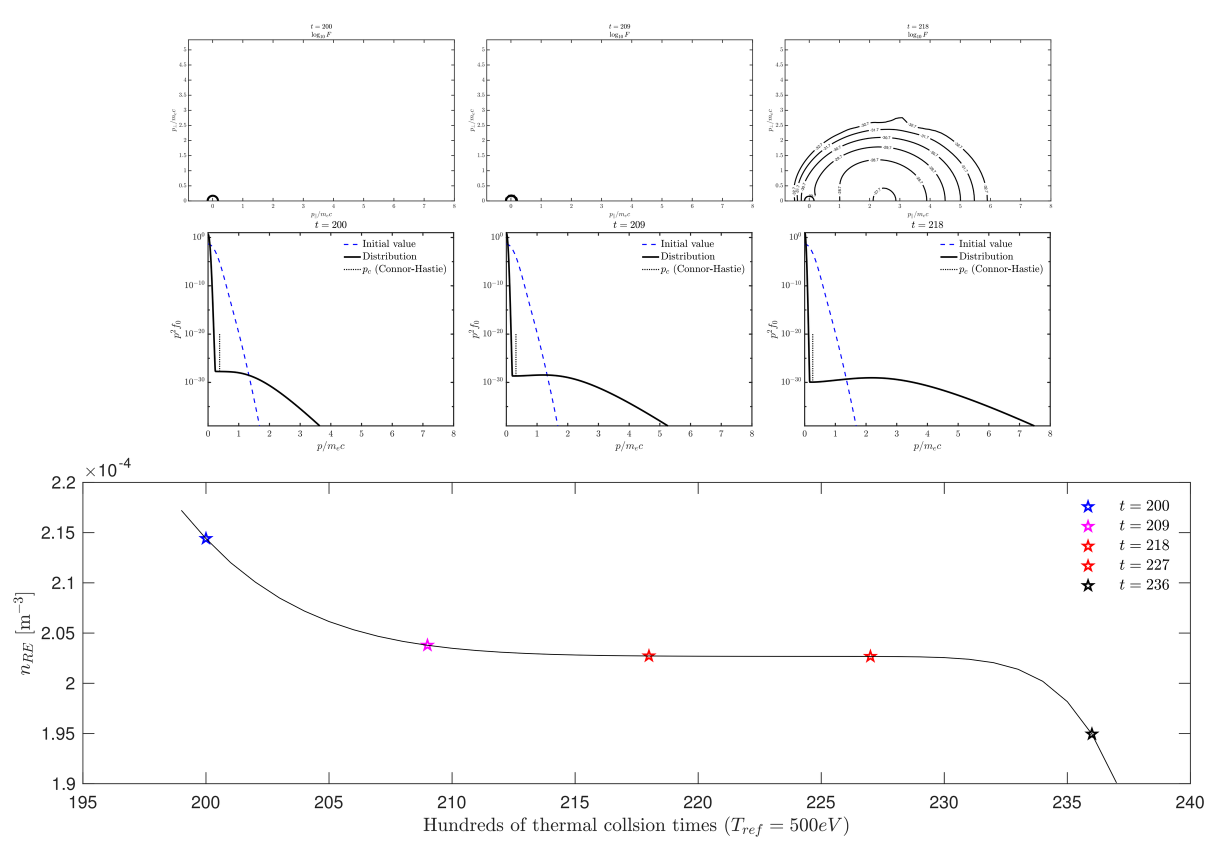

Fig. 3: Distribution evolution in time for $T_0 = 4$ keV, $d = 1.5$

Conclusion and Trajectories

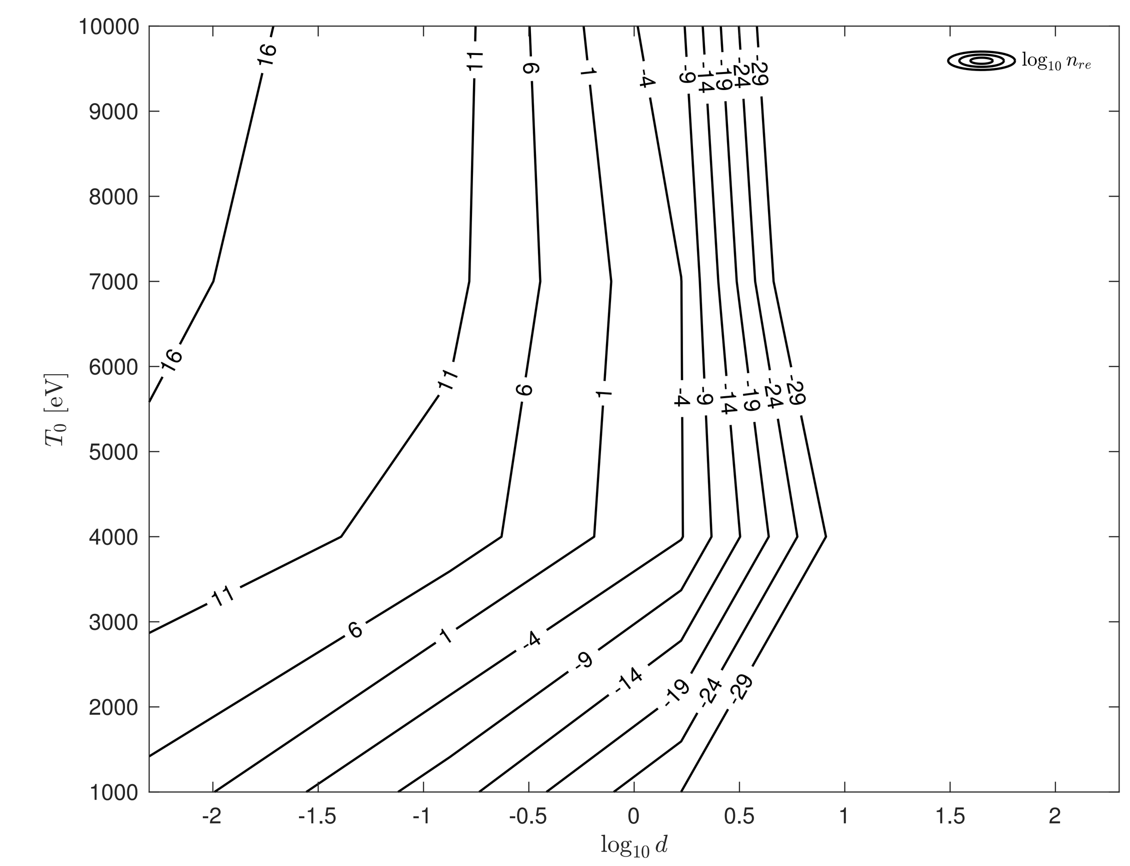

Fig. 4: Contour lines of n_{RE} over the (T_0, d) grid.

Looking at Fig. 4, the key initial result is that at thermal collapse timescales between $\log_{10} d = 0$ and $\log_{10} d = 1$ – translating to 8ms-80ms – there is a steep collapse of the driven seed electron population. This effect occurs in even shorter times for lower initial temperatures. For very fast collapse times, fast transfer of the thermal current to runaway current occurs, and for slow collapse, little to no runaway seed is driven. Between a sharp decline in the seed population is found between 8-80 ms for the thermal collapse. We see the generation of the runaway population in Figure 3. We lose electrons as they leave the momentum grid to higher energies. Fully resolving this behavior will require higher resolution in ξ as well as adding more points to the linear momentum grid. We see the formation of an initial peak of electrons pulled out from the bulk and the seed population as a relatively constant population being accelerated in Figure 2. We observe a trend of higher seed population at higher d and T_0 in Figure 4, which agrees with theoretical prediction. Short term work will incorporate the non-linear terms of the collision operator via use of the NORSE code that account for electron-electron collisions. In the medium term we will add proper treatments of the secondary runaway avalanche, the synchrotron and Bremsstrahlung radiation radiation reactions, and continuous evolution of Z while incorporating charge screening, in essence completing the work as proposed in [1]. Long term future work will implement self-consistent parameter evolution for the density and move to three-dimensional momentum space to account for the real geometry of a tokamak.

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