Runaway electron seed population dependence on temperature profile using continuous electric field evolution

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Motivation

During a thermal collapse in a tokamak plasma, the bulk of the electron population thermalizes 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 other large tokamaks. Understanding the precise conditions that initiate RE populations is essential in developing RE mitigation strategies. One of the least understood aspects of 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. In this poster we discuss our approach to studying this dependence using CODE (COllisional Distributions of Electrons) modified with continuous electric field evolution.

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.

CODE

CODE, written jointly by Adam Stahl and Matthew Landremann, 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, C is the electron collision operator, and S is a variable that represents any source terms [2]. The distribution f is defined terms of linear momentum and the cosine of the pitch angle (p, ξ). CODE uses a finite difference grid to resolve p, and Legendre mode decomposition to resolve momentum pitch angle. 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 $B = 2$ 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. This initialized distribution can be seen in Figure 1.

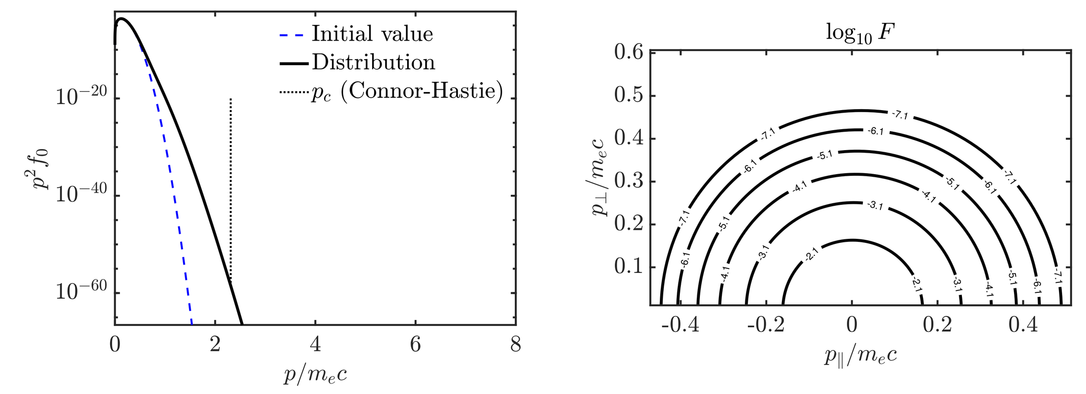

Fig. 1: Left: Normalized initial electron distribution in terms of $p/m_e c$. Right: Contour plot of $\log_{10}$ of the initial electron distribution in $p_\parallel/m_e c$ and $p_\perp/m_e c$, $T_0 = 4$ keV, $d = 1.5$.

Temperature profile grid

We used a tanh function to create a set of temperature drops over four initial temperatures (T_0) and six drop widths (d). We define the drop width d as the percent of total timesteps over which the temperature drop occurs. Our T_0 values were 1 keV, 4 keV, 7 keV, and 10 keV. Our d values were 10, 5, 2.5, 1.25, 0.4167, 0.1, and 0.0026. Figure 2 shows all temperature profile used in our investigation.

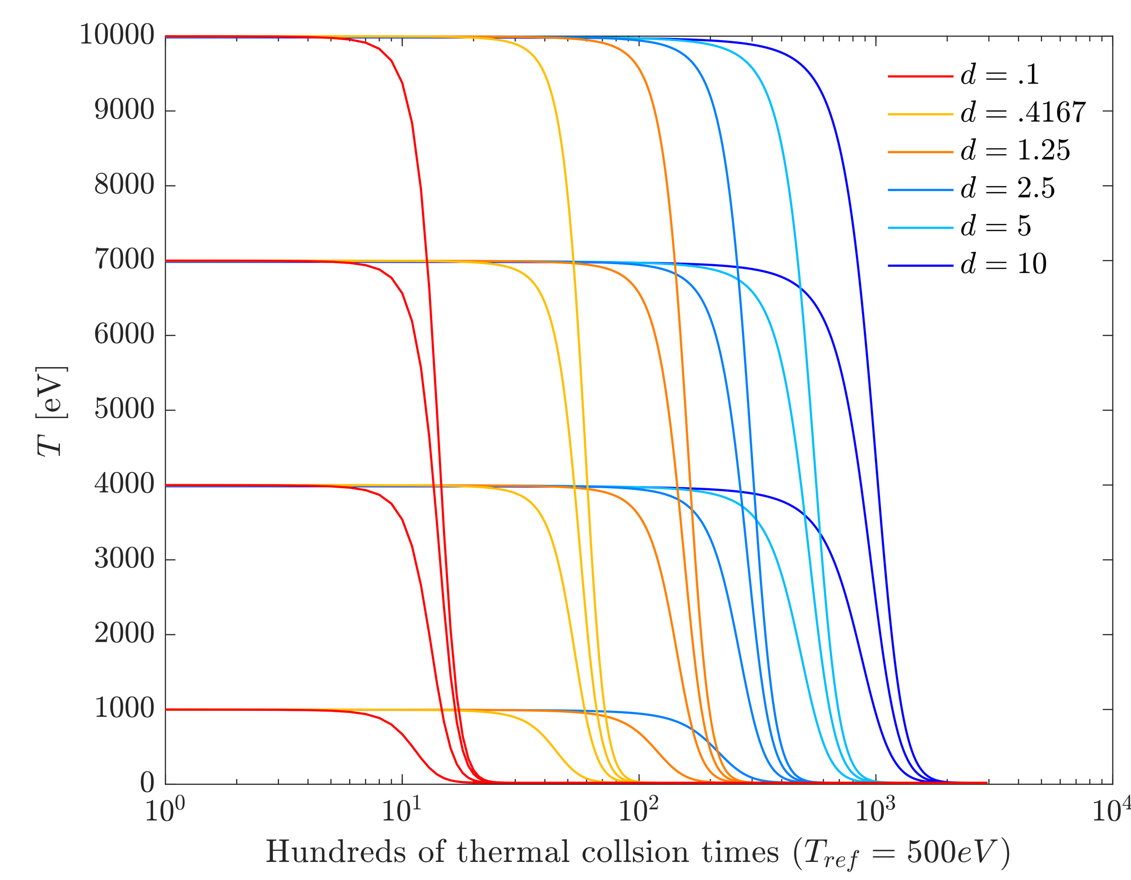

Fig. 2: Temperature profiles

Results

Looking at Figure 3, we see at thermal collapse timescales between $\log_{10} d = 0$ and $\log_{10} d = 1$ – translating to 8ms-80ms – there is a steep transition in the size of the seed population ranging 30 orders of magnitude. For very fast collapse times ($\log_{10} d < -1.5$), the size of the seed population is only a few orders of magnitude below n, suggesting the a fast transfer of thermal current to runaway current. For very slow collapse times, ($\log_{10} d > 0.25$), n_{re} the seed population is more than 45 orders of magnitude smaller that n, and such a seed population (if it physically exists) would carry only a negligible portion of the thermal current.

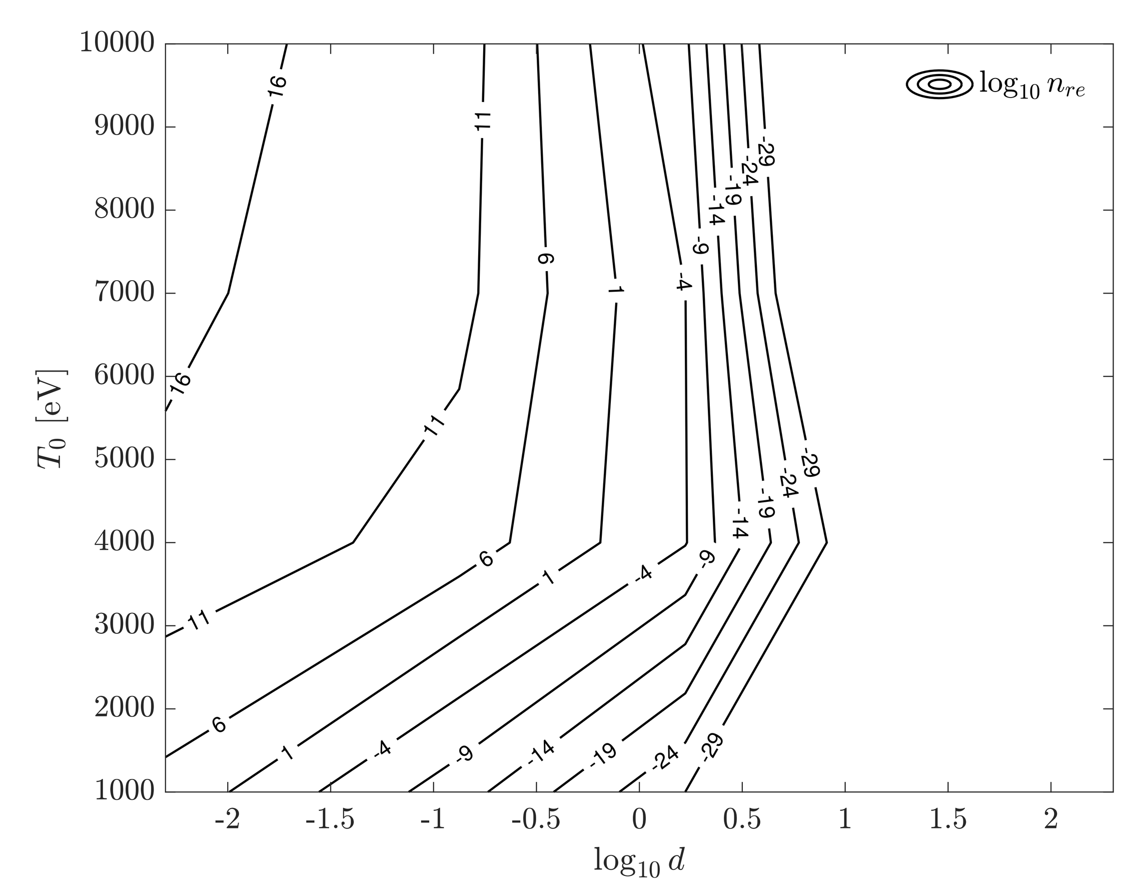

Fig. 3: Contour plot of $\log_{10} n_{re}$ of the seed population in T_0 and $\log_{10} d$

Figure 4 shows the evolution of electron distribution during the formation of the seed population. At $t = 211$ we see the first part of the seed population form around $p_\parallel/m_e c = 1.8$. Over the next 5 timesteps, the seed population grows in energy but remains relatively constant in size.

Past $t = 216$ we start to lose information about the seed population as those electrons leave the momentum grid to higher energies and are highly sensitive to changes in pitch angle. Fully resolving this behavior will require higher resolution in ξ as well as adding more points to the linear momentum grid.

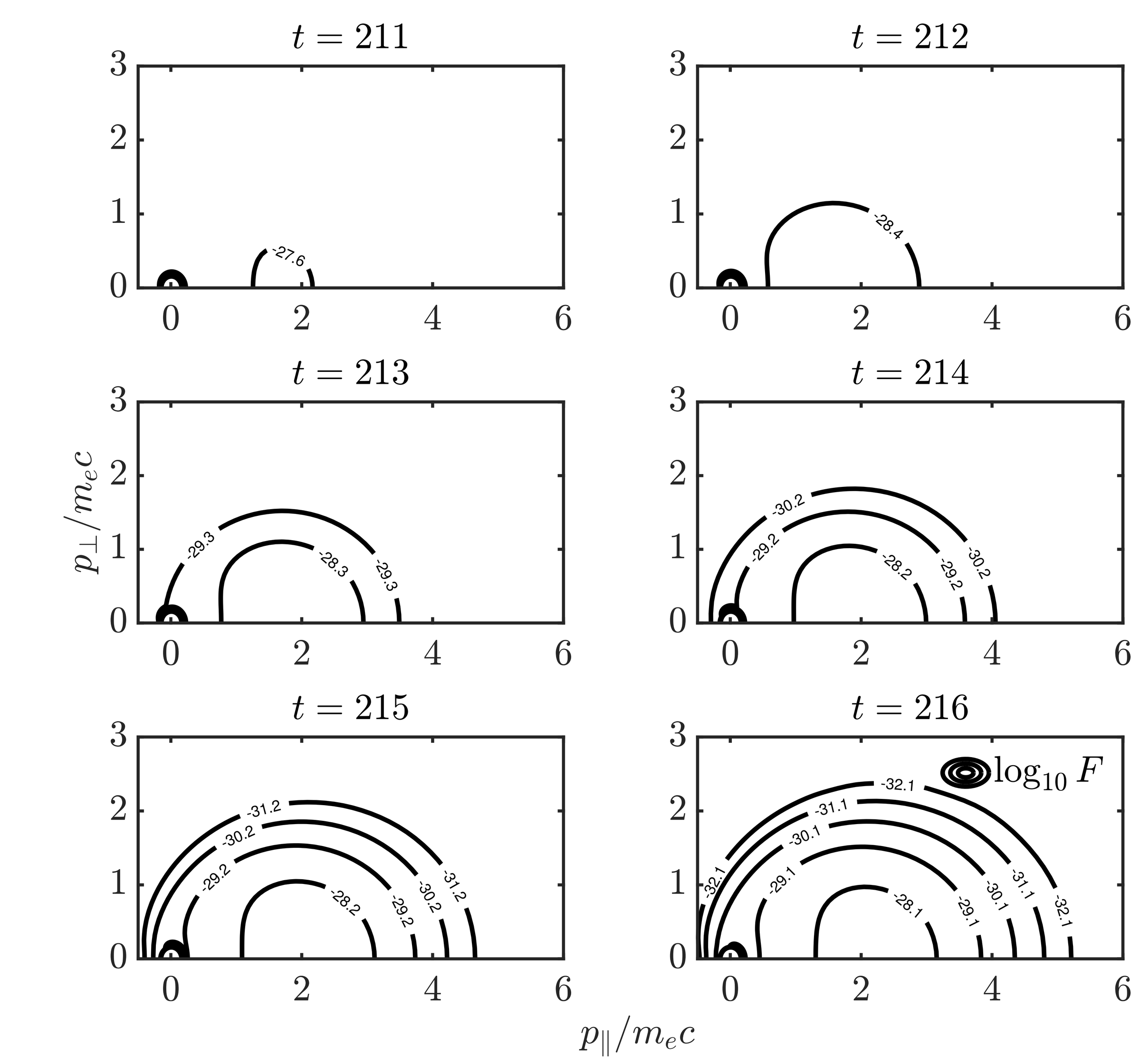

Fig. 4: Evolution of $\log_{10} F$ in in $p_\parallel/m_e c$ and $p_\perp/m_e c$, $T_0 = 4$ keV, $d = 1.5$.

Conclusion and Trajectories

We observe a trend of higher seed population at higher steepness and initial temperature in Figure 3, 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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References

[1] D. P. Brennan et al. "Collisional generation of runaway electron seed distributions leading to sub-criticality, avalanche, or fast transfer". In: *Proc. 26th IAEA Fusion Energy Conference (Kyoto, Japan), number TH/P1-35* (2016).

[2] M. Landreman, A. Stahl, and T. Fülöp. "Numerical calculation of the runaway electron distribution function and associated synchrotron emission". In: *Computer Physics Communications* 185 (Mar. 2014), pp. 847–855.