NORSE Simulation of Runaway Electrons on Short Timescales in Tokamak Plasmas

David Abramovitch[1], Chang Liu[2], Dylan Brennan[2]

1. *Physics Department, University of California Berkeley*
2. *Princeton Plasma Physics Lab*

NORSE Simulation of Runaway Electrons on Short Timescales in Tokamak Plasmas

David Abramovitch[1], Chang Liu[2], Dylan Brennan[2]

1. *Physics Department, University of California Berkeley*
2. *Princeton Plasma Physics Lab*

Runaways in Tokamak Plasmas

Runaway Electrons (REs) are high energy electrons which can be produce during disruptions in tokamaks and can cause extreme damage

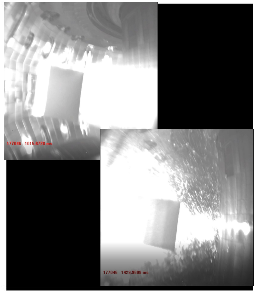
Higher energy electrons collide less, decreasing resistance

Rapid Cooling → Collisionality and Resistance Up → High Inductive Electric field → Electrons above threshold momentum accelerated

Short timescales: E field increases, High energy tail forms RE seed

Long timescales: Avalanche effect leads to exponential growth

REs (a) forming and (b) hitting the wall of the DIII-D tokamak



NORSE and Methodology

Nonlinear Relativistic Solver for Electrons

Solves kinetic equation in time:

$$\frac{\partial f}{\partial t} - \frac{e\boldsymbol{E}}{m_e c} \cdot \frac{\partial f}{\partial \boldsymbol{p}} + \frac{\partial}{\partial \boldsymbol{p}} \cdot (\boldsymbol{F}_s f) = C\{f\} + S$$

Here, $f(\boldsymbol{p} = (p, \xi = cos(\theta)))$ is the electron momentum distribution, $\boldsymbol{E}$ is the electric field, $\boldsymbol{F}_s$ is the synchrotron radiation, $C\{f\}$ is the collision operator between species in the plasma, and S is sources or sinks (for instance, a way to implement the avalanche effect).

Key Advantages over previous methods:

1. Calculates E field inductively, compared to constant current or constant E field methods
2. Implements full non-linear relativistic electron-electron collision operator

Relevant Scales:

Energy: a few eV (bulk) to 10s of MeV (REs)
Time: ~ 10^{-8} seconds (10 eV collisional time) to 10s of ms (slow cooling)

Thermal quench:

Focus on fast thermal quenches, cooling exponentially from 5 - 12 keV to 10 eV with a time constant TQ = 10 - 40 μs

Numerical Parameters:

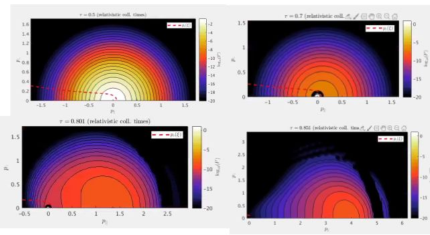
Grid and timesteps to converge: 500 x 75 grid, timestep = 0.0001 τ_0, pMax = 20 mc, nL = 15.

Electron Distributions in Thermal Quenches

Electron momentum distributions show cooling, separation of hot tail, and acceleration of REs

Populations:
Runaways: p > 1.8 mc
Maxwellian: contained within a thermal distribution at the bulk temperature
Low Energy Nonthermal: p < 1.8 mc with thermal Maxwellian subtracted

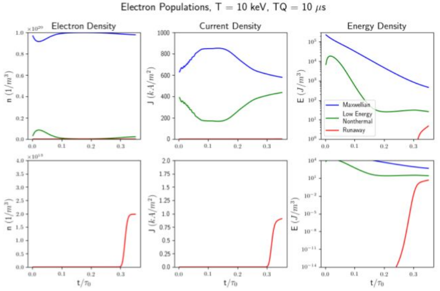
2D Momentum Distributions (10 keV, 10 μs quench rate)



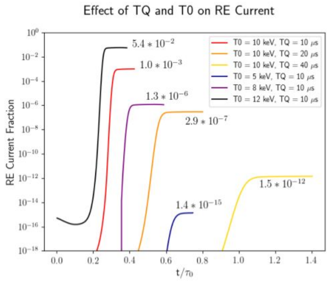
Current, Density, and Energy by Population

The RE population accounts for a small number and current fraction but a large energy fraction, while a large fraction of the electrons and current are low energy but non thermal. The remainder is Maxwellian.

The low energy non thermal population may be related to a Drecier tail and could form REs.



Effect of Quench Rate and Initial Temperature



Effect of Thermal Quench Rate:

Seed population diminishes quickly with slower thermal quench or lower temperature, though much of the current remains nonthermal.

Effect of Initial Temperature

Seed population decreases at lower temperature due to a lower initial high energy population.

Discussion and Conclusion

Runaway Electron Physics in NORSE

Most constant current, linear collision methods predict REs to assume almost all current

In our simulations, we see a majority of current carried by a low energy, largely nonthermal population. This could be due to non-linear small angle collisions.

We see only a small portion of the current get converted to REs during fast transfer.

There is some precedent for lower RE conversion in DIII-D experiments.

Scales and Challenges

Large range of momentum and time scales required make simulations numerically challenging

Theory is required to understand relation between seed and final RE population

Effects on longer timescales:

- E field will reach constant value
- Drecier tail can form and produce REs
- Avalanche effect

Runaways in Tokamak Plasmas

REs (a) forming and (b) hitting the wall of the DIII-D tokamak

Runaway Electrons (REs) are high energy electrons which can be produce during disruptions in tokamaks and can cause extreme damage

Higher energy electrons collide less, decreasing resistance

Rapid Cooling → Collisionality and Resistance Up → High Inductive Electric field → Electrons above threshold momentum accelerated

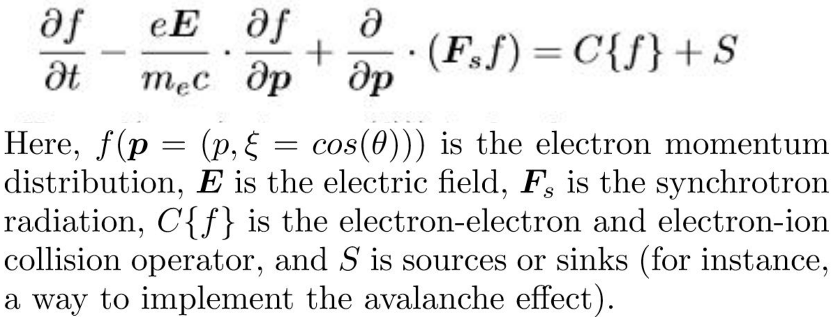
Short timescales: E field increases, High energy tail forms RE seed

Long timescales: Avalanche effect leads to exponential growth

NORSE and Methodology

Nonlinear Relativistic Solver for Electrons

Solves kinetic equation in time:



$$\frac{\partial f}{\partial t} - \frac{e\boldsymbol{E}}{m_e c} \cdot \frac{\partial f}{\partial \boldsymbol{p}} + \frac{\partial}{\partial \boldsymbol{p}} \cdot (\boldsymbol{F}_s f) = C\{f\} + S$$

Here, $f(\boldsymbol{p} = (p, \xi = cos(\theta)))$ is the electron momentum distribution, $\boldsymbol{E}$ is the electric field, $\boldsymbol{F}_s$ is the synchrotron radiation, $C\{f\}$ is the electron-electron and electron-ion collision operator, and S is sources or sinks (for instance, a way to implement the avalanche effect).

Key Advantages over previous methods:

1. Calculates E field inductively, compared to constant current or constant E field methods
2. Implements full non-linear relativistic electron-electron collision operator

Relevant Scales:

Energy: a few eV (bulk) to 10s of MeV (REs)
Time: ~ 10^{-8} seconds (10 eV collisional time) to 10s of ms (slow cooling)

Thermal quench:

Focus on fast thermal quenches, cooling exponentially from 5 - 12 keV to 10 eV with a time constant TQ = 10 - 40 μs

Numerical Parameters:

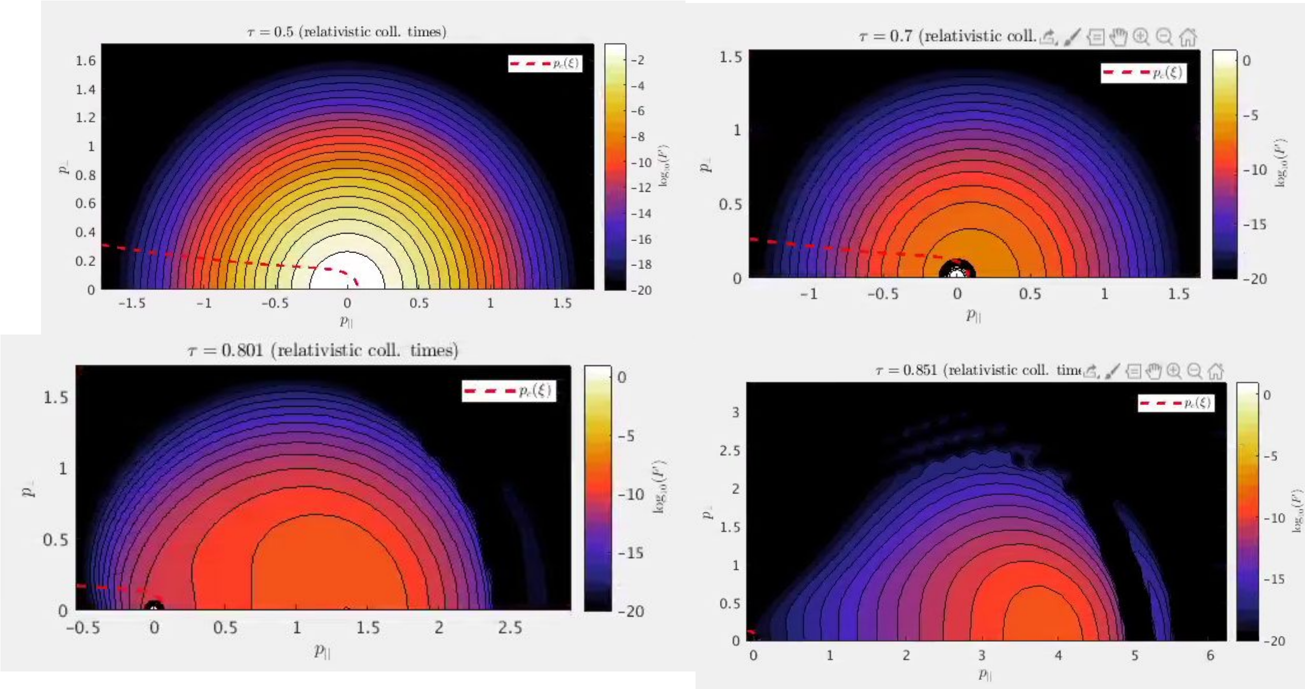
Grid and timesteps to converge: 500 x 75 grid, timestep = 0.0001 τ_0, pMax = 20 mc, nL = 15.

Electron Distributions in Thermal Quenches

Electron momentum distributions show cooling, separation of hot tail, and acceleration of REs

Populations:
Runaways: p > 1.8 mc
Maxwellian: contained within a thermal distribution at the bulk temperature
Low Energy Nonthermal: p < 1.8 mc with thermal Maxwellian subtracted

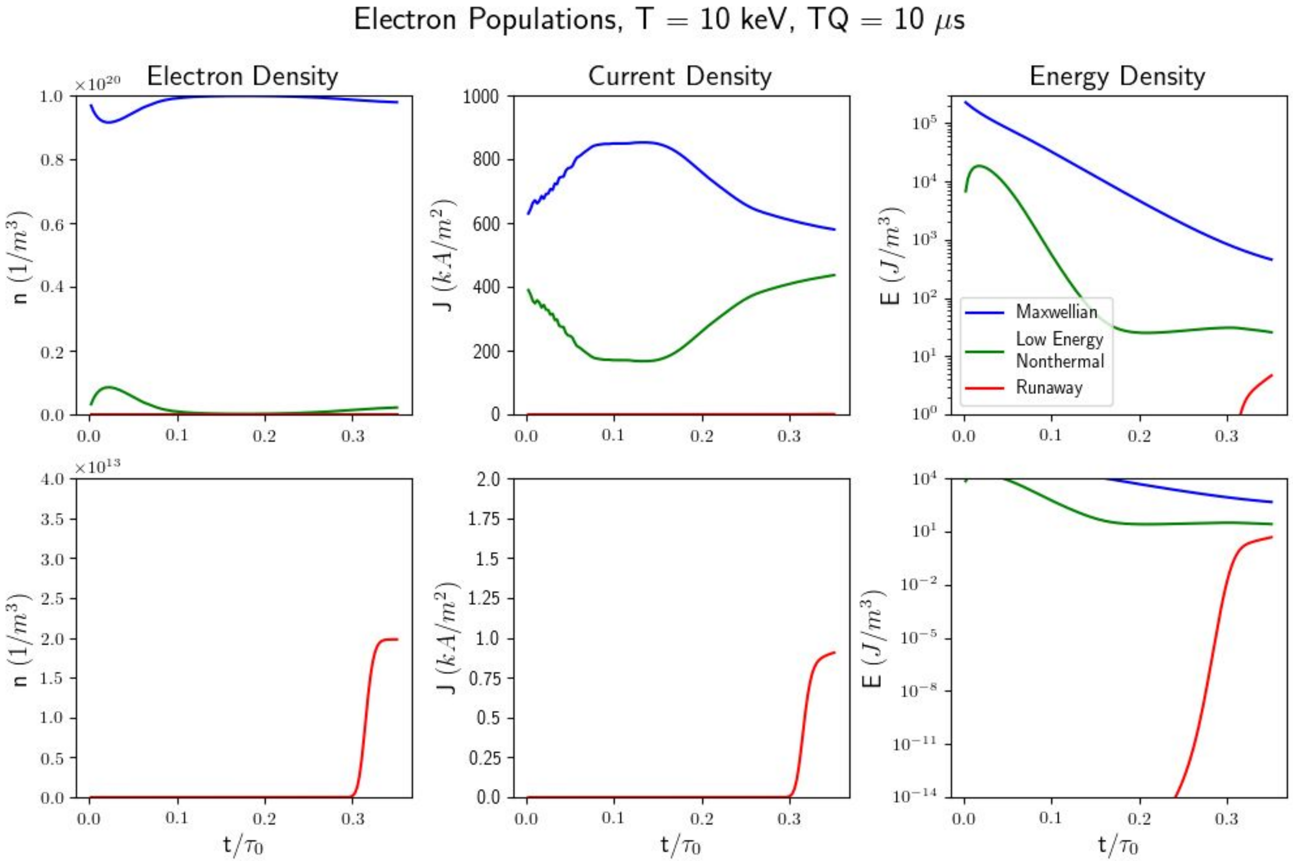
2D Momentum Distributions (10 keV, 10 μs quench rate)



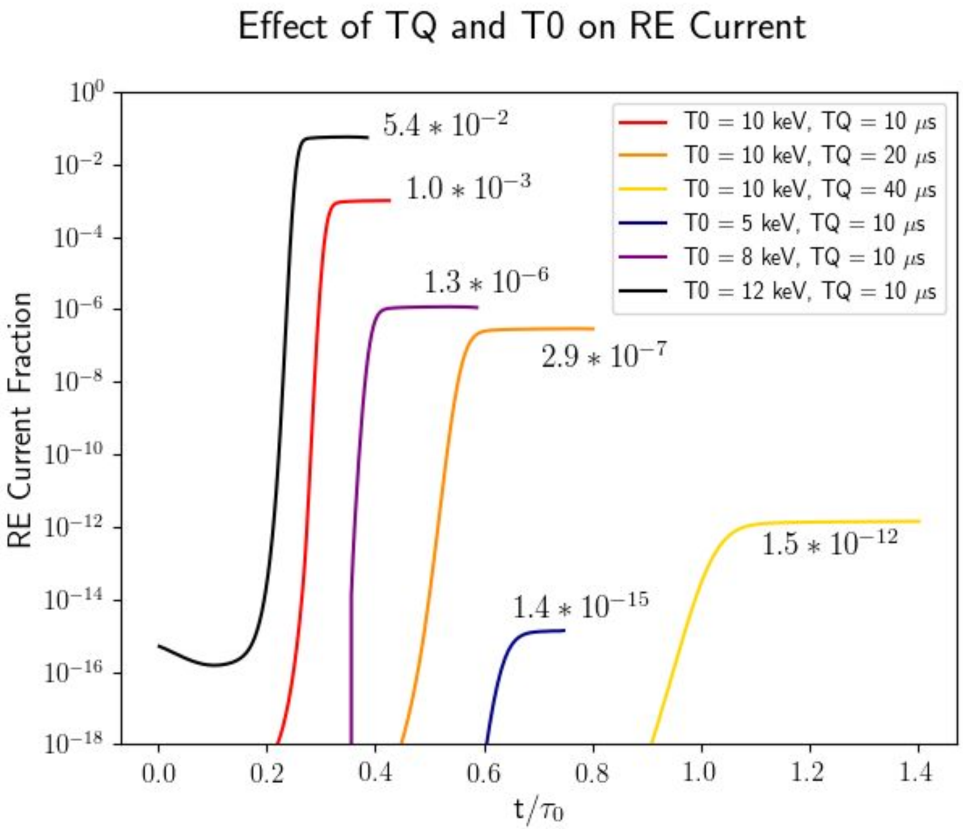
Current, Density, and Energy by Population

The RE population accounts for a small number and current fraction but a large energy fraction, while a large fraction of the electrons and current are low energy but non thermal. The remainder is Maxwellian.

The low energy non thermal population may be related to a Drecier tail and could form REs.



Effect of Quench Rate and Initial Temperature



Effect of Thermal Quench Rate:

Seed population diminishes quickly with slower thermal quench or lower temperature, though much of the current remains nonthermal.

Effect of Initial Temperature

Seed population decreases at lower temperature due to a lower initial high energy population.

Discussion and Conclusion

Runaway Electron Physics in NORSE

Most constant current, linear collision methods predict REs to assume almost all current

In our simulations, we see a majority of current carried by a low energy, largely nonthermal population. This could be due to non-linear small angle collisions.

We see only a small portion of the current get converted to REs during fast transfer.

There is some precedent for lower RE conversion in DIII-D experiments.

Scales and Challenges

Large range of momentum and time scales required make simulations numerically challenging

Theory is required to understand relation between seed and final RE population

Effects on longer timescales:

- E field will reach constant value
- Drecier tail can form and produce REs
- Avalanche effect

Acknowledgements

I would like to thank Dylan Brennan and Chang Liu for their mentoring on this project, as well as the PPPL Science Education Staff

This work was made possible by funding from the Department of Energy for the Summer Undergraduate Laboratory Internship (SULI) program. This work is supported by the US DOE Contract No. DE-AC02-09CH11466.

References

1. A. H. Boozer, Theory of runaway electrons in iter:Equations, important parameters, and implications for mitigation, Physics of Plasmas 22, 032504 (2015),https://doi.org/10.1063/1.4913582.
2. P. Aleynikov and B. N. Breizman, Generation of runaway electrons during the thermal quench in tokamaks, Nuclear Fusion 57, 046009 (2017).
3. C. Liu, D. P. Brennan, A. Bhattacharjee, and A. H.Boozer, Adjoint fokker-planck equation and runaway electron dynamics, Physics of Plasmas 23, 010702 (2016),https://doi.org/10.1063/1.4938510.
4. C. Paz-Soldan, P. Aleynikov, E. Hollmann, A. Lvovskiy,I. Bykov, X. Du, N. Eidietis, and D. Shiraki, Runaway electron seed formation at reactor-relevant temperature,Nuclear Fusion 60, 056020 (2020).
5. A. Stahl, M. Landreman, O. Embr´eus, and T. F¨ul¨op,Norse: A solver for the relativistic non-linear fokker-planck equation for electrons in a homogeneous plasma,Computer Physics Communications 212 (2016).