Progress and challenges in predictive modeling of runaway electron generation in ITER

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Outline

- Brief History and Motivation
- FEM treatment of electron f with background ions including impurities
- Runaway probability calculation used to calculate seed population
- Brief context: The SCREAM collaboration
- Concluding Remarks

Motivation: initial seed distribution study including nonlinear e,e and linear e,i collisions

Important question: how many seed electrons available for runaway and avalanche

High energy tail can be lost in two ways

- Collisional drag on cold electrons
- Lost to walls due to destroyed surfaces

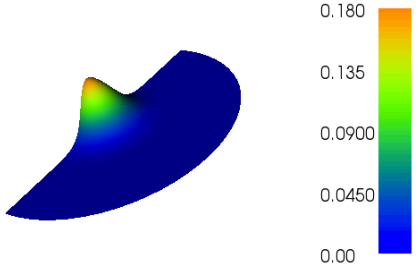
Leads to three possible outcomes

- Fast transfer : eneough seed electrons to immediately take up Ip
- Avalanche : some seed electrons, generate enough to take ~ Ip
- Sub-Critical : not enough seed electrons

Fokker-Planck solver with background Maxwellian ions and sources/sinks

Kinetic equation includes electric field E, e,e and e,i collisions, with L a source dependent on f (eg. for parallel loss) and s an independent source (eg. for cold e source)

$$\frac{\partial f_a}{\partial t} + \frac{e_a \boldsymbol{E}}{m_a} \cdot \frac{\partial f_a}{\partial \boldsymbol{v}} = C_{aa}[f_a, f_a] + C_{ab}[f_a, f_b] + L[f_a] + s,$$



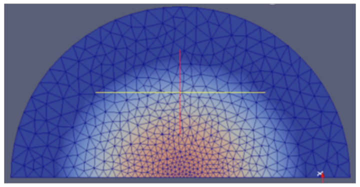
Both e and i distributions are represented in Rosenbluth potentials

$$\phi(\boldsymbol{v}) = -\frac{1}{4\pi} \int f(\boldsymbol{v}') \frac{1}{\mid \boldsymbol{v} - \boldsymbol{v}' \mid} d\boldsymbol{v}', \qquad \psi(\boldsymbol{v}) = -\frac{1}{8\pi} \int f(\boldsymbol{v}') \mid \boldsymbol{v} - \boldsymbol{v}' \mid d\boldsymbol{v}',$$

$$C_{ab}[f_a, f_b] = \left(\frac{e_a^2 e_b^2 \ln \Lambda_{ab}}{m_a^2 \varepsilon_0^2} \right) \frac{\partial}{\partial \boldsymbol{v}} \cdot \left(\frac{m_a}{m_b} \frac{\partial \phi_b}{\partial \boldsymbol{v}} f_a - \frac{\partial^2 \psi_b}{\partial \boldsymbol{v} \partial \boldsymbol{v}} \cdot \frac{\partial f_a}{\partial \boldsymbol{v}} \right).$$

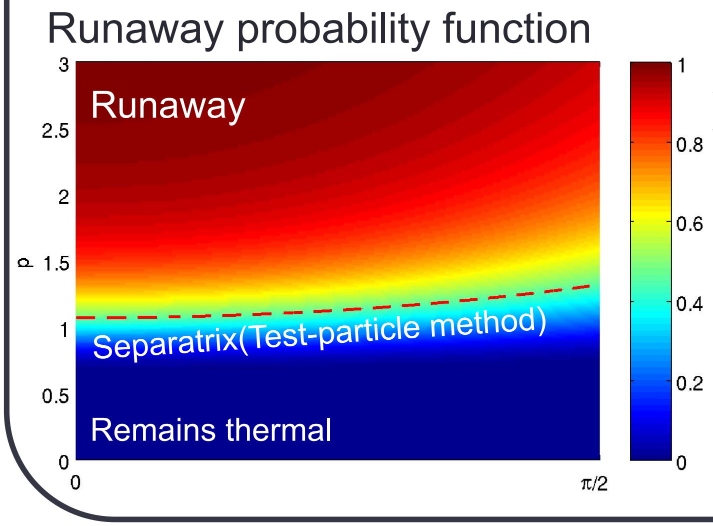
Can impose a current constraint $\boldsymbol{E} \cdot \int \boldsymbol{v} \frac{\partial f_a}{\partial t} d\boldsymbol{v} = 0,$

RE seed calculation using the runaway probability function

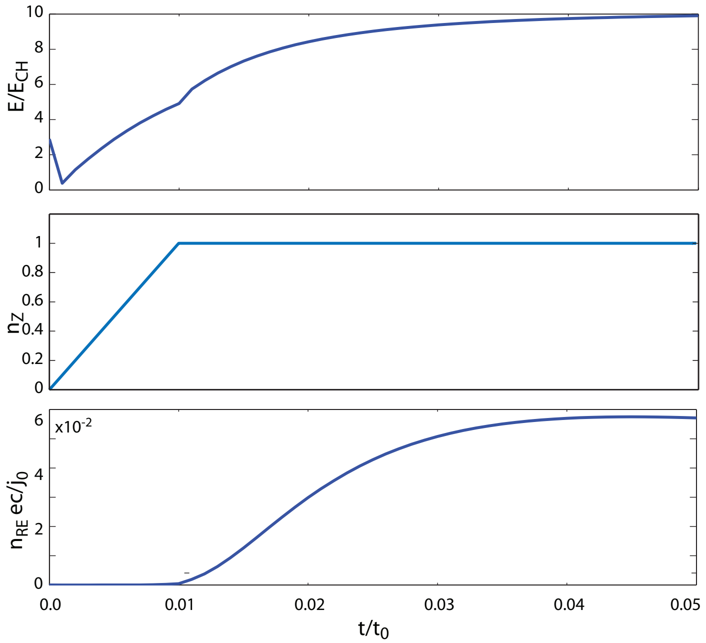


$$\frac{\partial f_a}{\partial t} + \frac{e_a \boldsymbol{E}}{m_a} \cdot \frac{\partial f_a}{\partial \boldsymbol{v}} = C_{aa}[f_a, f_a] + C_{ab}[f_a, f_b] + L[f_a] + s,$$

$$a(p)\frac{dP(p)}{dx} + D(p)\frac{d^2P(p)}{dp^2} = 0 \quad P\big|_{p_1} = 0 \quad P\big|_{p_2} = 1$$


Runaway probability function

E/E_c=6
Z=18
τ_r/τ=100 B=3T,
n_e=10^{21}m^3



- *f and P* used to estimate the number of seed RE in thermal quench $n_{se} = \int d^3v\, f \cdot P$

C. Liu, D.P. Brennan, A. Bhattacharjee, and A.H. Boozer, Phys. Plasmas **23**, 010702 (2016).
D.P. Brennan, E. Hirvijoki, C. Liu, A.H. Boozer and A. Bhattacharjee, Proceedings IAEA FEC, TH/P1-35, Kyoto 2016

Deposition shows small seed population: difficult to get fast transfer

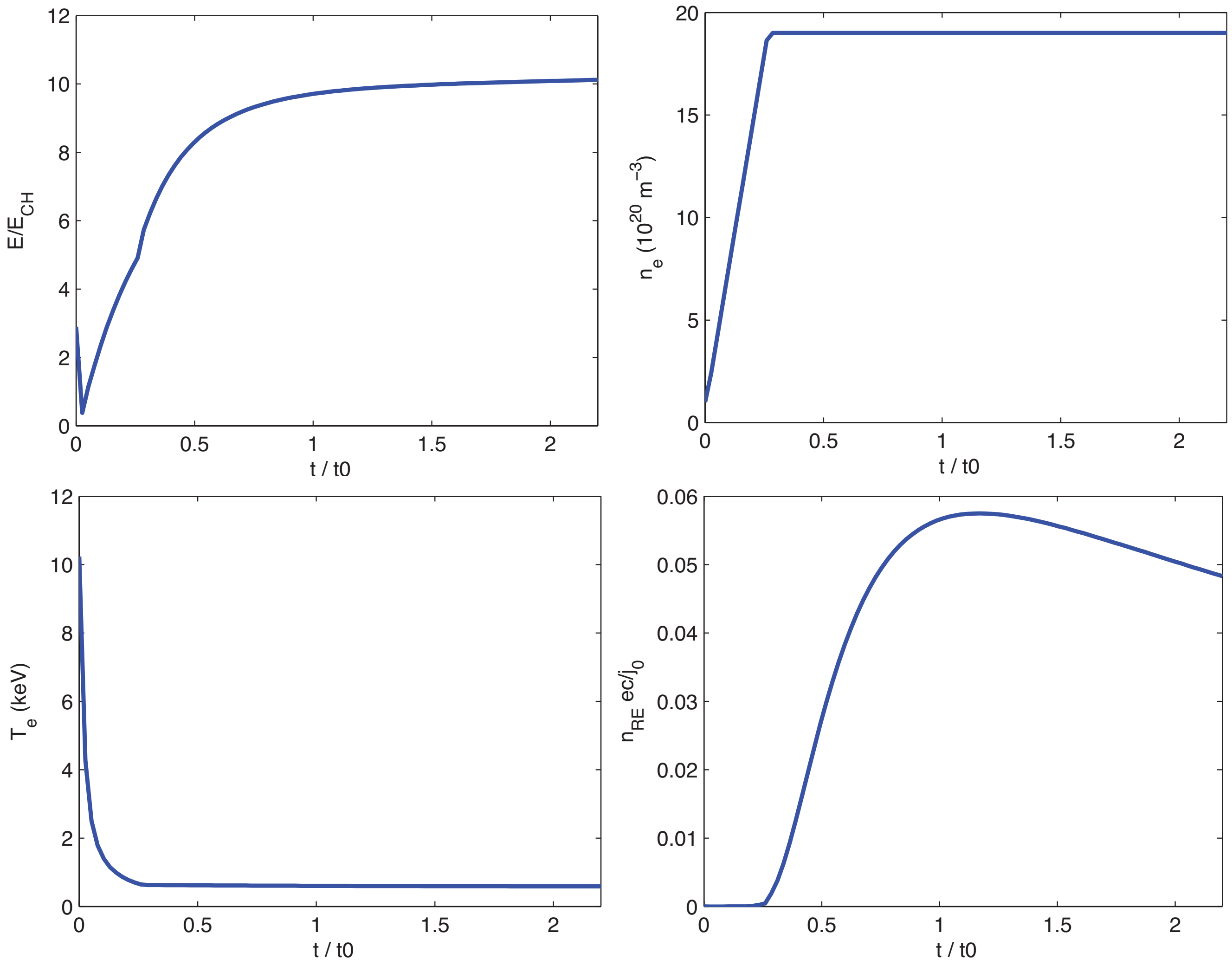
Deposition ~100us

Initial E=3E_{ch}

Initial transient before collisional diffusion

Electric field rises as electrons cool

Enough electrons for avalanche, but weak



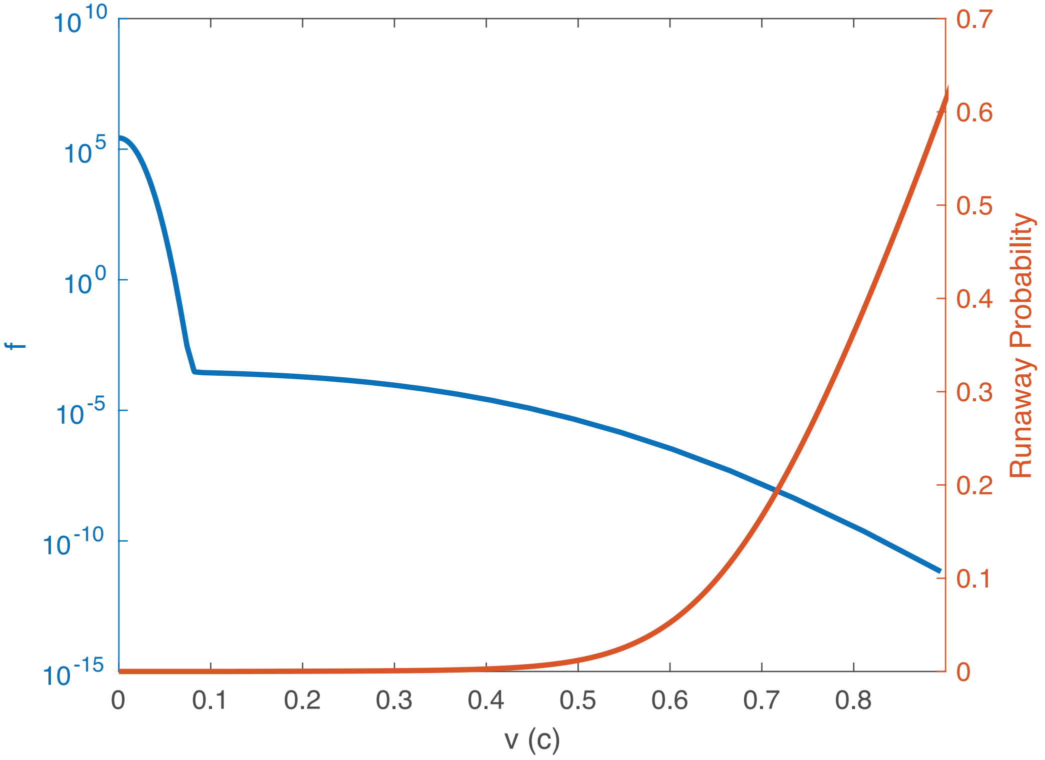
Cold electrons cool fast population but electric field does not increase fast enough for REs

Why?

High energy tail cools before E increases large enough.

Cooling of low energy electrons from radiation is necessary to get high electric field.

Reduced modeling (Aleynikov/Breizmann) shows this to be key effect.

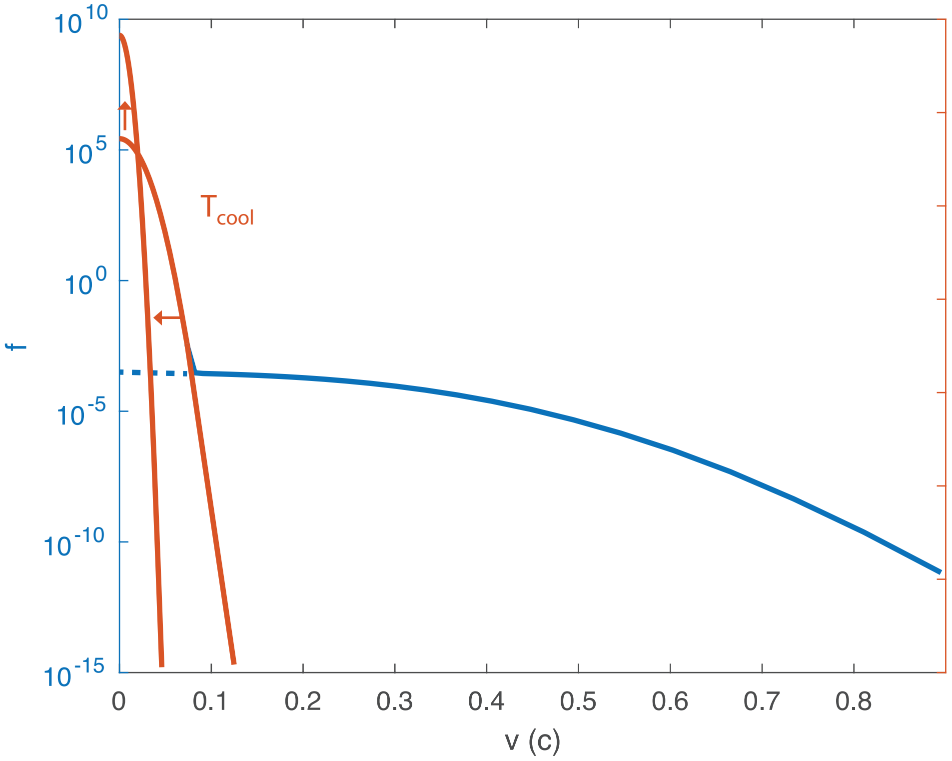


B. Breizmann and P. Aleynikov, Proceedings of the International Sherwood Fusion Theory Conference, Madison WI, April 2016
H.P. Summers, W.J. Dickson, M.G. O'Mullane et al. Plasma Phys. Control. Fusion **48**, 263 (2006).

Line radiation model needed in electron kinetic equation

Next step: Include cooling of low energy electrons due to line radiation within numerical distribution.

Coronal model can simplify the calculation. Need to affect T_{cool} dominantly with a conservative cooling operator. Perhaps the simplest is of the form



$$\frac{\partial f}{\partial t} = \ldots + \nabla \cdot (\mathrm{K} f)$$

giving

$$\frac{\partial E}{\partial t} = \frac{m}{2} \int v^2 \frac{\partial f}{\partial t} d^3 v = \ldots + \frac{m}{2} \int v^2 \nabla \cdot (\mathrm{K} f) d^3 v = -\frac{m}{2} \int v \cdot K f d^3 v \qquad K = \frac{\vec{v}}{\tau v^2}$$

Important issues with RE dynamics remain to be addressed to be predictive about the DMS

- RE interaction with High-Z impurities
- Seed distribution (hot tail) effects in thermal quench events
- Spatial / configuration space dependence
- Kinetic instability
  - Whistler wave scattering
  - Bump on tail
- Magnetic fluctuations
- MHD instability coupling
- RE termination (magnetic energy conversion), RE-wall interaction

Open questions remain as to the best technical methods for coupling the runaway electron, impurity transport, and MHD simulation codes, managing and visualizing the large volumes of data, and determining its uncertainty, both in experiment and in simulation.

SCREAM is a FES/ASCR Collaboration between 12 Principal Investigators at 9 Institutions

Team Includes 9 Institutions with 12 PI's
8 Associated with FES
4 Associated with ASCR
$4.9M / 2yrs

Mission: combine theoretical models with advanced simulation and analysis facilitated by direct participation of ASCR SciDAC institutes to focus on the runaway risk for ITER and tokamaks in general.

Principal Investigators:

- FES:
  - Dylan Brennan (Princeton)
    - Lead PI - Universities
  - Xianzhu Tang (LANL)
    - Lead PI - Labs
  - Amitava Bhattacharjee (PPPL)
  - Allen Boozer (Columbia)
  - Boris Breizman (UT, Austin)
  - Diego Del-Castillo-Negrete (ORNL)
  - Valerie Izzo (UCSD)
  - Lang Lao (GA)
- ASCR
  - Mark Adams (LBNL)
  - Luis Chacon (LANL)
  - Irene Gamba (UT, Austin)
  - Guannan Zhang (ORNL)

Collaborations underway between several groups

Collaboration aims to advance understanding and quantitative prediction of runaway physics

Overall Goals

- Establish the physical basis for generation and evolution
- Explore scenarios for avoidance
- Investigate the leading candidates for mitigation

Initial Scope

- Theoretical investigation of runaway physics and mitigation
- Scoping studies of runaway electron generation with reduced modeling
- Relativistic Vlasov-Fokker-Planck simulations of runaway electrons using phase-space discretization
- Modeling of Disruptions and Runaway Electrons with NIMROD
- Simulating of Runaway Seed Current Generation with XGC1
- Monte Carlo simulations of runaway electrons including full-orbit, spatial/configuration space with KORC

Computational Methods

- Relativistic Fokker-Planck solvers using grid discretization in phase space
- Self-consistent particle-in-cell
- Particle-based Monte-Carlo
- MHD-particle hybrid

Cross-check between these different methods will provide an additional means for verification and will further bolster the fidelity of physics predictions.

Concluding Remarks

- Motivation: Include fully nonlinear collisonality in kinetic modeling of runaway seed generation

- New code with FEM treatment of electron f with background ions including impurities
  - Nonlinear e-e collisions, linear e-i collisions, f dependent and independent sourcing
  - Backward Euler implicit timestepping
  - Initial electric field drives current to steady state – triggers impurity injection
  - Electric field found from current density constraint after impurities injected

- Interface to runaway probability calculation used to calculate seed population
  - Fast and robust
  - Avalanche growth, and slowing down time also available
  - Because of large electric field, synchrotron unimportant

- Initial results indicate the fast transfer difficult to achieve under realistic timescales
  - Initial electric field and current must be large to get Avalanche regime
  - Need to model radiative cooling of low temperature electron and increase Ohmic electric field in early response

Concluding Remarks about SCREAM

SCREAM will serve as a US collaborative effort on simulation and theory of runaway electrons and directly contribute to ITPA.

Collaborations between groups forming : Multiple groups now in quantitative consensus on several radiative effects on runaway dynamics. Much progress in fundamental theory over past few years. Formulations of advanced algorithms for RE modeling coupled to background plasma advance currently under development.

Advanced Computing Needed : Theory community addressing physics and validation against experiment, but open questions remain, some best addressed through development in advanced computing.

SCREAM will help community address questions accessible through combining theory developments with advanced computing, such as interaction with magnetic fluctuations, to be quantitatively predictive on avoidance and mitigation.