RECENT THEORETICAL PROGRESS IN UNDERSTANDING RUNAWAY ELECTRON GENERATION AND DYNAMICS

Dylan Brennan
Plasma Physics Laboratory
Princeton University

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Outline

• Brief History
  • Recent developments address critical issues with seminal papers

• Three Methods to Address Runaway Physics
  • Continuum, Monte Carlo and Probability methods each contribute
  • Improvements to the kinetic model have been made

• Theory results have recently answered puzzles
  • Critical Electric Field
  • Hysteresis in Ramp Up vs Ramp Down
  • Redistribution of RE Distribution

• Clear Need for US Center on Runaway Electron Theory and Simulation
  • Important issues remain to be predictive
  • Advanced Computing necessary component

• The SCREAM Collaboration
  • Goals and Scope
  • Who, Where and What: Highlights

• Concluding Remarks
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Understanding of runaway electron kinetic physics started with seminal studies

• First analysis of runaway phenomena carried by [Dreicer 1958, 1959]
• Relativistic case studied by [Connor&Hastie 1975]
• First well-known and most-cited work on secondary runaway electron generation by [Rosenbluth & Putvinski 1997]

• Through large angle collision, high energy RE can transfer large fraction of energy and momentum to low energy electron and knock it into runaway regime ➔ avalanche
• Critical electric field for avalanche is Connor-Hastie $E_c$
• The growth rate is (almost) a linear function of $E/E_c - 1$

$$\frac{\partial f}{\partial t} + E\{f\} + C\{f\} + R\{f\} = S$$

- $E$: Electric field drive
- $C$: Collision operator
- $R$: Synchrotron radiation back-reaction force
- $S$: Secondary runaway electron generation
Limitations of Rosenbluth-Putvinski model prevent quantitative experimental analyses

- A simplified source term for the secondary generation
  \[ S = \frac{n_r}{4\pi \ln \Lambda} \delta(\xi - \xi_2) \frac{1}{p^2} \frac{\partial}{\partial p} \left( \frac{1}{1 - \sqrt{1 + p^2}} \right) \]
  \[ \xi_2 = \frac{\sqrt{1 + p^2} - 1}{p} \]
  - All RE assumed to have infinite momentum and zero pitch angle
  - Secondary RE can have larger momentum than the seed one! (unphysical)
  - Pitch angle distribution is singular
  - Change of momentum and pitch angle of seed electron after collision not considered – violate conservation law

- Missing kinetic effects
  - Radiation reaction force (synchrotron and bremsstrahlung) important for high energy electron
  - Other effects (magnetic perturbations, kinetic instabilities)
Recent progress has accelerated - quantitative understanding of experiments advancing

Multiple groups have accelerated effort in the last two years (2015-16 papers)

- IFS, IPP and ITER: Monte Carlo methods and rigorous marginal E analytics

- Columbia: Theoretical analyses of runaway dynamics

- PPPL: Adjoint Fokker-Planck probability, nonlinear continuum seed and avalanche, Monte Carlo

- GA: MHD Simulations with relativistic tracer particles

- ORNL: Full-orbit effects in toroidal geometry, impurity transport, thermal anisotropy, Monte Carlo, UQ

- LANL: Phase space structure and runaway transport processes, Vlasov Fokker-Planck

- European Groups: Complementary continuum solvers, Monte Carlo, and time dependent simulations
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Continuum kinetic code approach has lead to rapid advance in understanding RE distributions

- Directly solve electron distribution function
- 2D in momentum space, no spatial dependency (yet, under development, only LUKE does 2V +1X)
- Includes Primary and secondary runaway generation
- Lightweight
- Able to get steady-state solution very efficiently

Monte Carlo Simulation has facilitated inclusion of key physics

- Straight forward to implement / make rapid progress
- Easy to implement knock-on source term
  - Conserve energy and momentum
- Synchrotron and bremsstrahlung radiation forces included
- Advantageous to use to calculate transport of runaways

Adjoint Fokker–Planck equation: new method for runaway probability calculation

- A smooth probability function showing the transition from loss to runaway
- Overcomes caveats of test particle method (truncation & coordinates dependence).
- Agrees well with Monte-Carlo simulation. (Efficiency is better.)

\[
\frac{\partial f}{\partial t} = -\frac{\partial}{\partial x}[v(x)f] + \frac{\partial^2}{\partial x^2}[D(x)f]
\]

\[
v(x)\frac{dP(x)}{dx} + D(x)\frac{d^2P(x)}{dx^2} = 0
\]

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Improvements to the kinetic model have been made across the community

- Improved operators used for secondary generation
  - Take into account the seed RE momentum and pitch angle distribution
  - Secondary RE momentum constrained
  - Energy and momentum conservation
- Detailed forces in the kinetic equation
  - Synchrotron radiation
  - Cerenkov radiation
  - Bremsstrahlung radiation
- Trapping effects included in some studies
  - Radial dependence of trapping (not shown here)

\[
\frac{\partial f}{\partial t} + E\{f\} + C\{f\} + R\{f\} = S
\]

- \(E\): Electric field drive
- \(C\): Collision operator
- \(R\): Synchrotron radiation back-reaction force
- \(S\): Secondary runaway electron generation
Synchrotron radiation major loss mechanism for high energy electrons: affects critical E field

  - Synchrotron radiation reaction force can help RE form a bump-on-tail distribution.
  - Synchrotron radiation can increase the effective critical electric field, and can also change RE momentum space structure.
  - Synchrotron radiation reaction force and form a separatrix and an attractor in the momentum space. This can give two threshold electric field one for the avalanche to start and one for it to stop.
Recent focus on formation of seed runaway electron in thermal quench

In a thermal quench of a large tokamak like ITER, due to the sudden drop of temperature and high induced electric field, the hot electron Maxwellian tail is expected to be largely driven away and become seed electrons.

  - Introduce a new code NORSE, which implement a fully nonlinear kinetic equation. The electric field required for thermal electron to have a significant slide-away is smaller than previous prediction.
- P. Aleynikov and B.N. Breizman, in progress,
  - In a thermal quench triggered by impurity injection, a large fraction of runaway electron current can be directly converted from the Maxwellian tail. In this case the avalanche is not required.
- D. Brennan, E. Hirvijoki, C. Liu, in progress,
  - Study of the non-linear evolution of the electron Maxwellian distribution in a thermal quench, and use the runaway probability function from adjoint method to calculate the number of seed runaway electrons.
Kinetic instabilities of runaway electron beams key to understanding

Similar to bump-on-tail instabilities, runaway electron beam can trigger various kinds of kinetic instabilities in plasma. The free energy comes from the anisotropic distribution of runaway electron tail.


The local threshold of the instability depends on the runaway electron density, the magnetic field, and the collisionality (plasma temperature and ion charge $Z$).


The instability can cause isotropization of RE distribution function, and a subsequent formation of a plateau in the distribution.


The most unstable mode associated with RE is the high frequency extraordinary electron (EXEL) wave. Quasi-linear analysis of the wave-particle interaction confirms rapid pitch angle scattering from plasma waves.


Use a ray tracing code to study the collective amplification of plasma wave in the tokamak from runaway electron beam.

By introducing the spatial dependence, the instability criterion is modified and get a better agreement with the experiments.
Critical electric field increases with $Z$ and decreases with $\tau_{\text{rad}}$

- In presence of radiation and pitch angle scattering, the critical electric field (first and secondary) increases.
- New critical field depends on the $\tau_r$ (inverse proportional to $B^2$) and $Z$.
- Two method developed for finding critical electric field (Direct electron distribution analysis & Adjoint Fokker-Planck equation)

Critical electric field for $E/E_c$ ramping up (Dreicer) strongly affected by synchrotron

- Dreicer growth rates strongly $T_e$ dependent
- $E/E_d > 1\% - 2\%$ required for substantial growth
- Synchrotron radiation leads to reduction of growth rate for small $E/E_c$

Avalanche onset field $E_a$ is greater than the runaways sustainment field $E_0$ with synchrotron.

- The avalanche onset condition

$$\gamma_{\text{max}} + 1 \geq 2\gamma_{\text{min}}$$

$E_0$ determined by $\gamma_{\text{max}} = \gamma_{\text{min}}$

After collision, both original and Knocked electron have at least $\gamma_{\text{min}}$

$p_{\text{max}}$ is attractor point

Critical electric field for avalanche ramping up vs. ramping down shows hysteresis

- Ramping up threshold is at $E_a > E_0$
- Ramping down, RE population shifts from growing to sustained at $E_a$, and decaying at $E_0$

RE redistribution occurs during ramping down

- Experiments find the turning point of HXR signal corresponds to 3~5 $E_C$, much larger than $E_0$ estimation
- Current diagnostic for RE (HXR and SE) sensitive to the RE energy distribution
- Observed signal decay may not be RE current decay, but redistribution of RE in energy space
- In simulation, when the signal starts to decay, secondary generation is still occurring!

Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL 114, 115002 (2015)
Critical electric field will determine RE dynamics in ITER plateau

- In the post thermal collapse stage, RE current will grow exponentially and take up the plasma current, then enter the plateau phase.
- In the decaying phase, $E$ stays between $E_0$ and $E_a$, which is close to $E_0$.
- The current decay is linear and the decay rate is given by

$$\frac{d(I_{re} + I_\Omega)}{dt} \approx -\frac{2\pi R}{(L - L_{wall})} E_0$$

- The current decay time scale is determined by $E_0$
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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.
Recent Workshops and Exascale Review Highlighted Need for a Center

• Need for progress in runaway electron physics was clearly made in both the 2015 Integrated Simulations and Transients workshops, and simulation of disruptions has been a recent focus of the 2016 Exascale Requirements Review, all three involving partnerships between FES and ASCR.

• An eventual reliable design tool for runaway mitigation requires almost the full functionality of the whole device modeling (WDM) of a tokamak, the proposed physics studies will naturally lead to a runaway physics module for WDM.
Collaboration needed between theory, simulation and algorithmic development

Center assembles experts in runaway electron physics, tokamak disruptions, magnetohydrodynamics (MHD) simulations, and advanced computing.

**Theory:** Analytic plasma theory, or employing light weight code for analysis

**Simulation:** Production code development/improvement and large simulations

**Algorithms:** Designing, implementing and testing innovative algorithms and performance enhancements for runaways

Collaborative center needed to address 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.

**Center needed to address physics questions**
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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.

Collaborations underway between several groups

Principal Investigators:
- **FES:**
  - Dylan Brennan (Princeton)
  - Lead PI - Universities
  - Xianzhu Tang (LANL)
  - Lead PI - Labs
  - Arnitava Bhattacharjee (PPPL)
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Effort combines FES theory and modeling of runaway physics with numerical simulation facilitated by ASCR applied mathematics.
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.
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Current Spikes and Runaway Electrons

Allen Boozer

Sudden plasma cooling in experiments is associated with a spike in the plasma current.

This spike and the associated sudden change in the plasma inductance implies magnetic surfaces are broken on a 1ms time scale.

The implied rapid magnetic reconnection would
1. Prevent electron runaway if all magnetic field lines intercept the walls.
2. Catalyze the transfer of the current to relativistic electrons if any magnetic flux tubes remained confined to the plasma.

Simulations imply that central magnetic field lines remain confined.

N.F. 56, 026007 (2016)
The speed of surface breakup (magnetic reconnection) is set by Alfvénic not resistive physics; direct numerical simulation is challenging.

During the fast reconnection, a number of quantities are conserved, including a new form of magnetic helicity, which allow the determination of

1. post-thermal-quench plasma properties
2. the production of relativistic electrons on the 1ms time scale.

The pivotal question for runaways on ITER:

*Are all tubes of confined magnetic field lines that survive the thermal quench dissipated before any magnetic surfaces reform?*

If the answer is positive, *runaways should be of little danger to ITER.*

If the answer is negative, *a large fraction of the plasma current can be expected to be transferred to relativistic electrons that strike the walls in multiple short pulses along narrow flux tubes.*
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Collaborations underway between several groups
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)

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

Both $e$ and $i$ distributions are represented in Rosenbluth potentials

$$\phi(\mathbf{v}) = -\frac{1}{4\pi} \int f(\mathbf{v}') \frac{1}{|\mathbf{v} - \mathbf{v}'|} d\mathbf{v}', \quad \psi(\mathbf{v}) = -\frac{1}{8\pi} \int f(\mathbf{v}') |\mathbf{v} - \mathbf{v}'| d\mathbf{v'},$$

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

Can impose a current constraint

$$E \cdot \int \mathbf{v} \frac{\partial f_a}{\partial t} d\mathbf{v} = 0,$$
Runaway Probability Function applied to RE seed calculation

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

\(f(p, \theta, t)\) solved for various temperature collapse and impurity injection scenarios

- \(f\) and \(P\) used to estimate the number of seed RE in thermal quench \(n_{se} = \int d^3 \mathbf{v} \, f \cdot P\)
- Result: Fast transfer difficult to achieve, avalanche dominant

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Runaway seed formation during plasma cooling
(UT Austin & Max-Planck Greifswald)

Thermal quench scenario:

1. Hot electrons heat the “cold” bulk
2. The bulk overtakes a fraction of the current
3. Bulk conductivity drops due to radiative losses.

There are two possible outcomes:

1. Prompt conversion regime: blue
   Low energy REs carry the total current at low electric field.
2. Seed for avalanche regime: green
   Ohmic current requires high electric field -> high energy seed REs + avalanche.

RE seed current is determined by competition between bulk plasma cooling and hot electron cooling
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What is in NIMROD now?

Drift orbits for test-particle REs are calculated as the MHD fields evolve.

Initial locations, energies, and pitch angle are chosen as inputs.

Single energy equation includes terms for slowing due to collisions, synchrotron radiation and bremsstrahlung.

\[
\frac{dR}{dt} = \frac{v_\parallel B_R}{B} + \frac{1}{B^2} [\vec{E} \times \vec{B}]_R, \\
\frac{dZ}{dt} = \frac{v_\parallel B_Z}{B} + \frac{1}{R} \frac{\gamma m_e v_\perp^2}{2eB} + \frac{1}{R} \frac{\gamma m_e v_\parallel^2}{eB} + \frac{1}{B^2} [\vec{E} \times \vec{B}]_Z, \\
\frac{d\phi}{dt} = \frac{v_\parallel B_\phi}{RB} + \frac{1}{RB^2} [\vec{E} \times \vec{B}]_\phi.
\]

V.A. Izzo, et al, NF 51, 063032 (2011)
Model has been used to predict RE “prompt loss” in DIII-D experiments

Variation in RE current for DIII-D discharges correlated with predicted losses of seed REs during the thermal quench.

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Runaway saturation in a tokamak governed by complex phase space dynamics

LAPS-RFP (LANL) is a continuum, relativistic Fokker-Planck code including radiation forces for tokamak runaways.

Trapping region squeezes the RE vortex to the passing zone → significant reduction of RE population

FIG. 1. TOP: $f(p, \xi)$ and phase-space flow in slab geometry with $E = 2.25E_c, \alpha = 0.2, Z = 1$; BOTTOM: $f(p, \xi, \theta = 0)$ and phase-space flow in tokamak geometry with $E = 2.25, \alpha = 0.2, Z = 1, r/R_0 = 0.2$
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Summary and Conclusions

Multiple groups now in quantitative consensus of Synchrotron effects on runaway dynamics

Two physics points stand out as highlights

- Threshold field/hysteresis/ramp up ramp down
- Bump on tail/ Redistribution and HXR/other signals

Important Issues Remain and are Being Investigated

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

The DMS for ITER has a deadline of 2017!!

- Requirements for mitigation of halo current and forces (under study in NSTX-U) need to be balanced with mitigation requirements for REs (on DIII-D).
Concluding Remarks about SCREAM

**SCREAM will serve** as a US counterpart to the CEA efforts (Y. Peysson) 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.
QRE experiments important to ITER because they are in the same dimensionless regime

- For synchrotron radiation, the critical dimensionless parameter is the ratio of radiation versus collision timescale

\[
\hat{\tau}_{rad} \equiv \frac{\tau_{rad}}{\tau} = \frac{2}{3} \left( \frac{m_e \ln \Lambda}{\epsilon_0} \right) \frac{n_{eff}}{B^2} = 278 \frac{n_{eff} [10^{20}]}{(B[T])^2}
\]

- DIII-D plateau: \( n_{eff} [10^{20}] \approx 10, B[T] \approx 2 \quad \hat{\tau}_{rad} \approx 700 \)

- DIII-D QRE: \( n_{eff} [10^{20}] \approx 0.1, B[T] \approx 1.5 \quad \hat{\tau}_{rad} = 20 \)

- ITER plateau: \( n_{eff} [10^{20}] \approx 10, B[T] \approx 6 \quad \hat{\tau}_{rad} \approx 70 \)

- DIII-D QRE experiments are in ITER plateau regime