RECENT THEORETICAL PROGRESS IN UNDERSTANDING RUNAWAY ELECTRON GENERATION AND DYNAMICS

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Presented at the Burning Plasma Organization webinar series,
October 6, 2016

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 Ec
  - The growth rate is (almost) a linear function of E/Ec-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

$$S = \frac{n_r}{4\pi \ln\Lambda}\delta(\xi - \xi_2)\frac{1}{p^2}\frac{\partial}{\partial p}\left(\frac{1}{1-\sqrt{1+p^2}}\right) \qquad \xi_2 = \frac{\sqrt{1+p^2}-1}{p}$$

  - 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
  - P. Aleynikov, B. Breizman, Phys. Rev. Lett., **114**, 155001 (2015).
- Columbia: Theoretical analyses of runaway dynamics
  - A. Boozer, Phys. Plasmas **22**, 032504 (2015).
- PPPL: Adjoint Fokker-Planck probability, nonlinear continuum seed and avalanche, Monte Carlo
  - C. Liu, D.P. Brennan, A. Bhattacharjee, and A.H. Boozer, Phys. Plasmas **23**, 010702 (2016).
- GA: MHD Simulations with relativistic tracer particles
  - V.A. Izzo, D.A. Humphreys, and M. Kornbluth, Plasma Phys. Control. Fusion 54, 095002 (2012).
- ORNL: Full-orbit effects in toroidal geometry, impurity transport, thermal anisotropy, Monte Carlo, UQ
  - D. del-Castillo-Negrete and L. Carbajal, 58th Annual Meeting of the APS Division of Plasma Physics GP10.00095 (2016); to be submitted to Physics of Plasmas.
  - L. Carbajal, D. del-Castillo-Negrete, D. Spong, S.Seal and L. Baylor. 58th Annual Meeting of the APS Division of Plasma Physics. GP10.00097 (2016).
  - G. Zhang, C. Webster, M. Gunzburger and J. Burkardt, *SIAM Review*, **58**, 517 (2016).
- LANL: Phase space structure and runaway transport processes, Vlasov Fokker-Planck
  - Z.Guo, C. Mcdevitt and X. Tang, Proceedings of the International Sherwood Fusion Theory Conference, Madison, Wisconsin, April 2016.
- European Groups: Complementary continuum solvers, Monte Carlo, and time dependent simulations
  - Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015).
  - Hirvijoki, Pusztai, Decker, Embréus, Stahl and Fülöp, **JPP** (2015).
  - E. Nilsson, J. Decker, Y. Peysson, R.S. Granetz, F. Saint-Laurent and M. Vlainic, Plasma Phys. Control. Fusion **57**, 095006 (2015).

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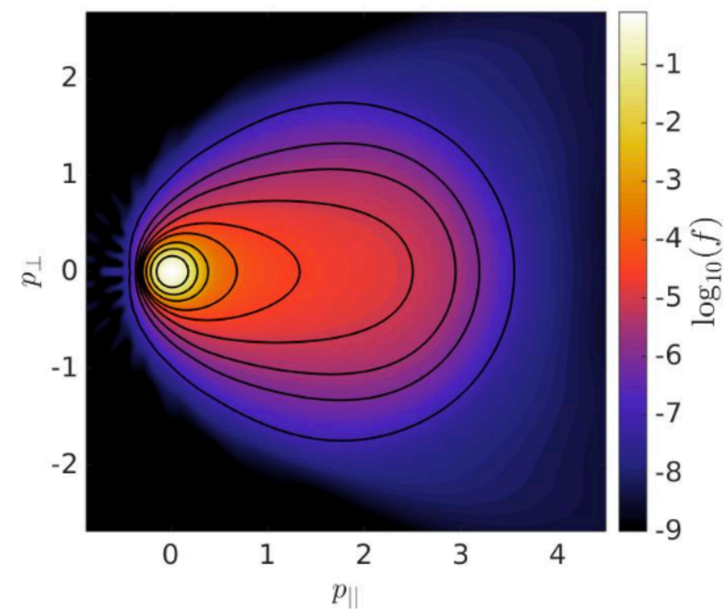
Continuum kinetic code approach has lead to rapid advance in understanding RE distributions

- 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

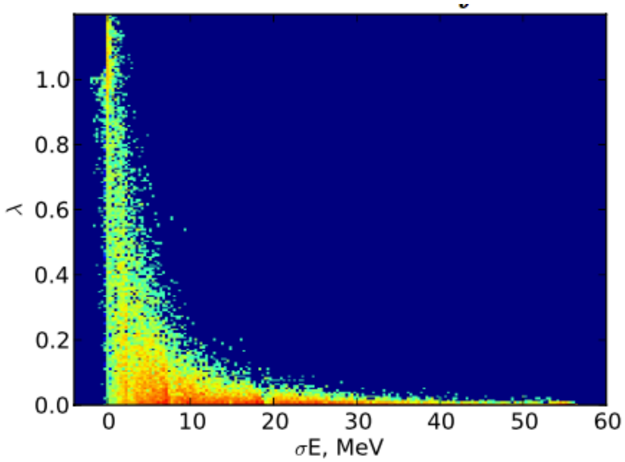
Peak in nonmonotonic distribution thoroughly studied by Chalmers group

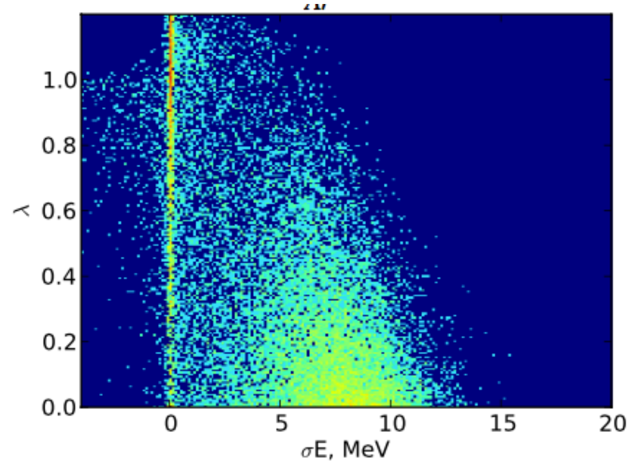


M. Landreman, A. Stahl, and T. Fülöp, Comp. Phys. Comm. **185**, 847 (2014).

Monte Carlo Simulation has facilitated inclusion of key physics

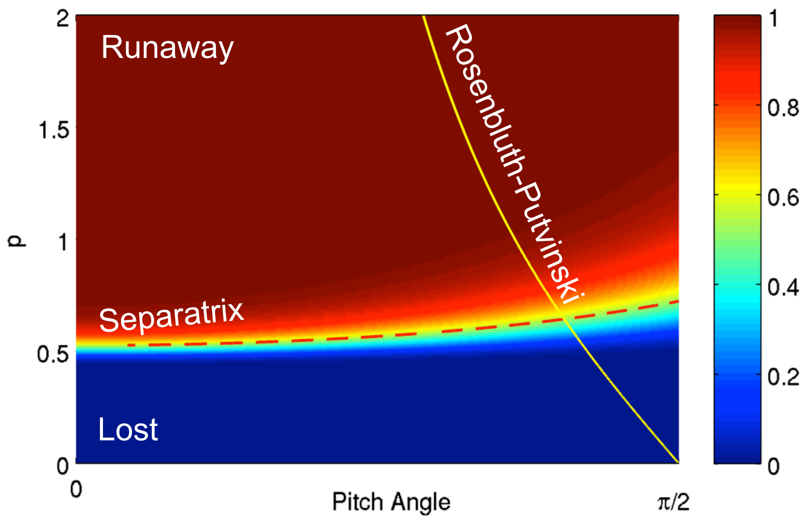
- Straight forward to implement / make rapid progress
- Easy to implement knock-on source term
  - Conserve energy and momentum
- Synchrotron and bremsstrahlung radiation forces included
- Advantageous to use to calculate transport of runaways

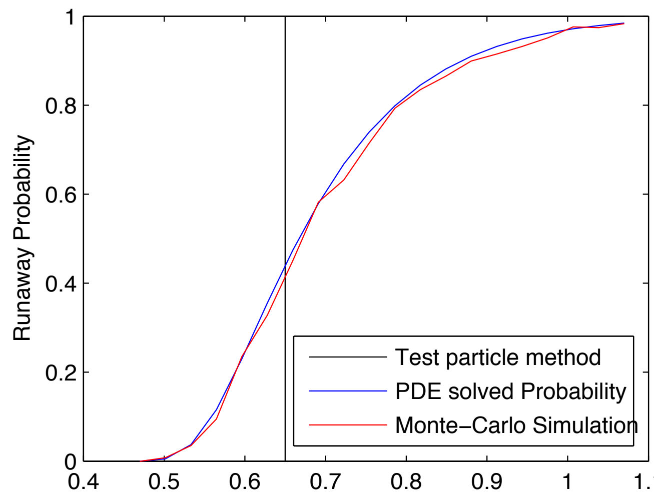




P. Aleynikov, K. Aleynikova, B. Breizman, G. Huijsmans, S. Konovalov, S. Putvinski, and V. Zhogolev, in Proceedings of the 25th IAEA FEC, St. Petersburg, Russian Federation, 2014, pp. TH/P3–38

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.)

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

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

C. Liu, D.P. Brennan, A. Bhattacharjee, and A.H. Boozer, Phys. Plasmas **23**, 010702 (2016).

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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)

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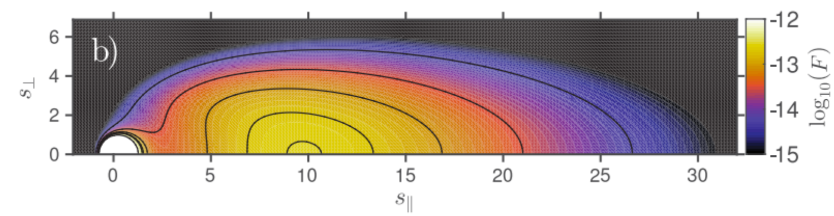
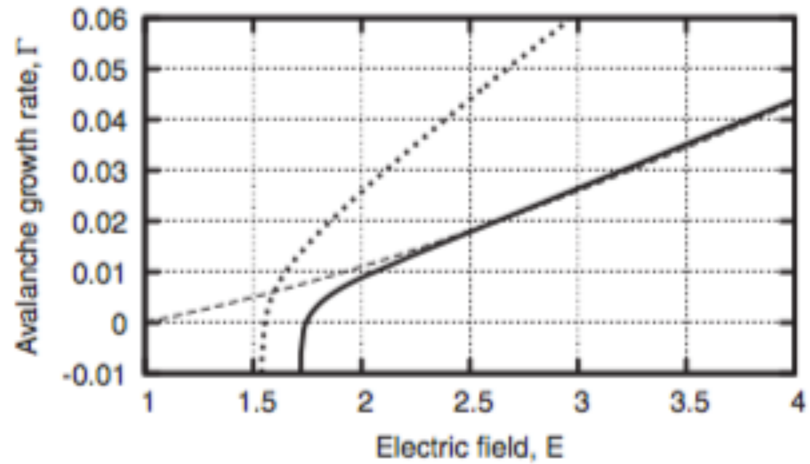
Synchrotron radiation major loss mechanism for high energy electrons: affects critical E field

- E. Hirvijoki, I. Pusztai, J. Decker, O. Embréus, A. Stahl, and T. Fülöp, J. Plasma Phys. **81**, 475810502 (2015).
  - Synchrotron radiation reaction force can help RE form a bump-on-tail distribution.
- A. Stahl, E. Hirvijoki, J. Decker, O. Embréus, and T. Fülöp, Phys. Rev. Lett. **114**, 115002 (2015).
  - Synchrotron radiation can increase the effective critical electric field, and can also change RE momentum space structure.
- P. Aleynikov and B.N. Breizman, Phys. Rev. Lett. **114**, 155001 (2015)
  - 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.

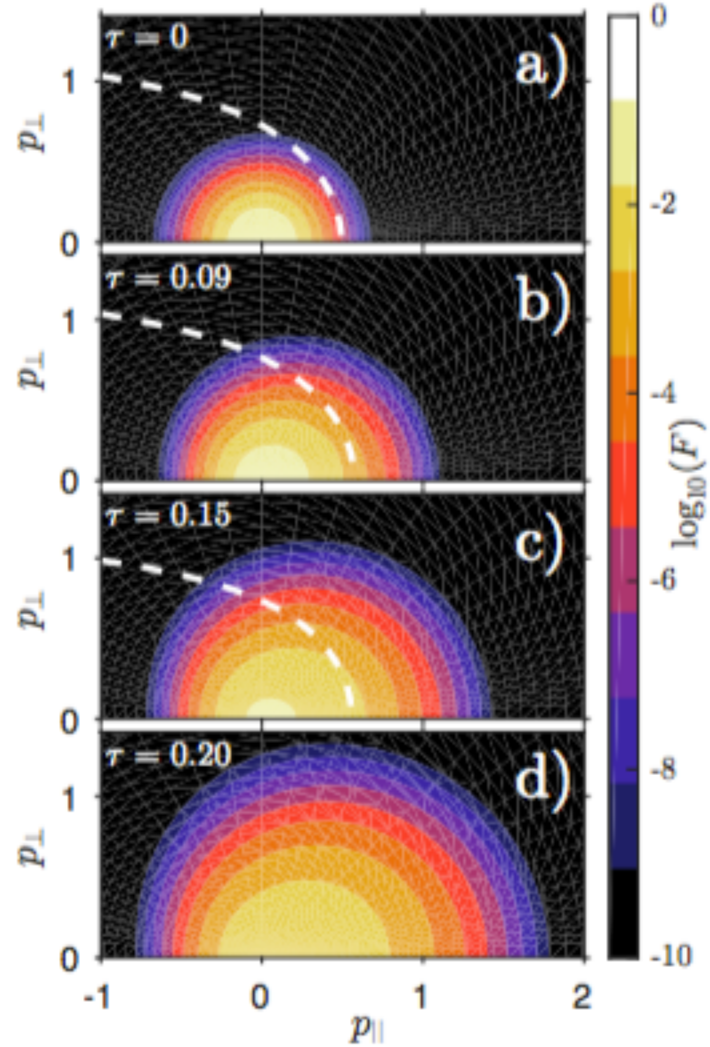




Recent focus on formation of seed runaway electron in thermal quench

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.

- A. Stahl, M. Landreman, O. Embréus, and T. Fülöp, arXiv:1608.02742 (2016).
  - 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 direcly coverted 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 calcualte 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.

T. Fülöp, G. Pokol, P. Helander, and M. Lisak, Phys. Plasmas 13, 62506 (2006).

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

V.V. Parail and O.P. Pogutse, Nucl. Fusion **18**, 303 (1978).

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

G.I. Pokol, A. Kómár, A. Budai, A. Stahl, and T. Fülöp, Phys. Plasmas **21**, 102503 (2014).

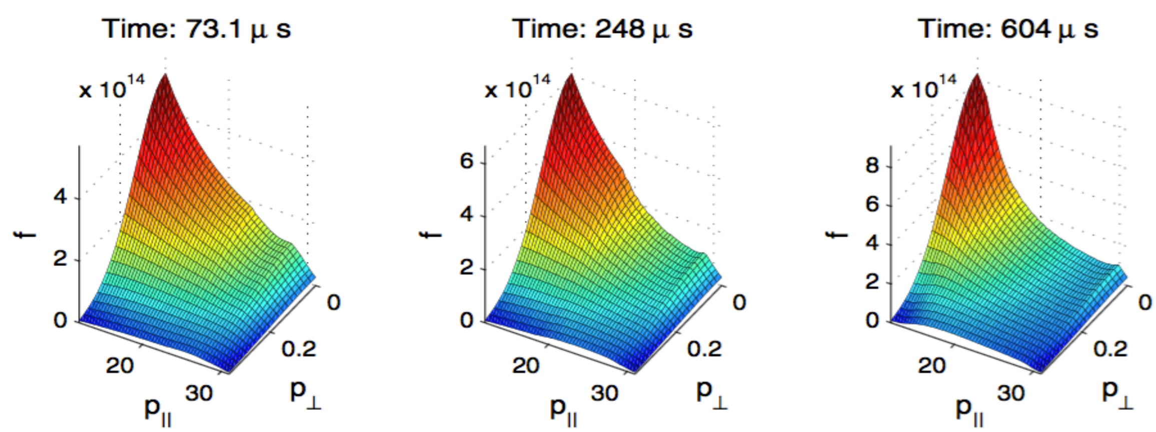
The most unstable mode associated with RE is the high frequency extraordinary electron (EXEL) wave.

Quasi-linear analysis of the wave-particle interaction confirms rapid pitch angle scattering from plasma waves.

P. Aleynikov and B. Breizman, Nucl. Fusion **55**, 43014 (2015).

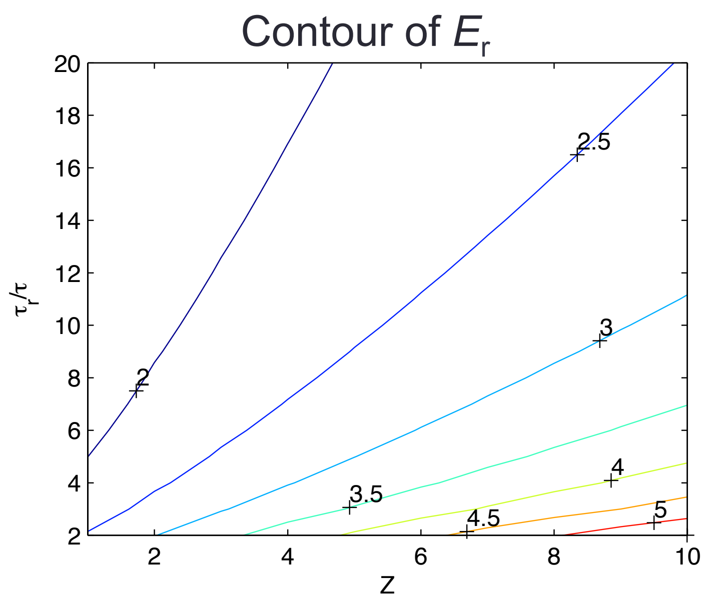
Use a ray tracing code to study the collective amplification of plasma wave in the tokamak from runaway electron beam.

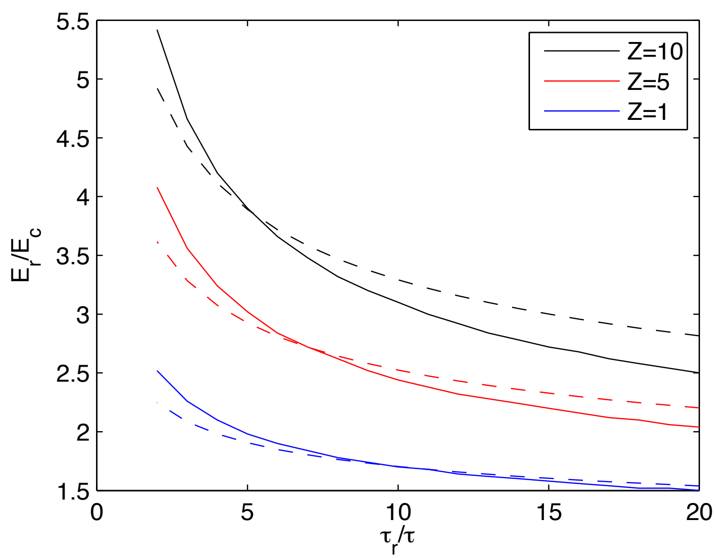
By introducing the spatial dependence, the instability criterion is modified and get a better agreement with the experiments.



Critical electric field increases with Z and decreases with τ_{rad}

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



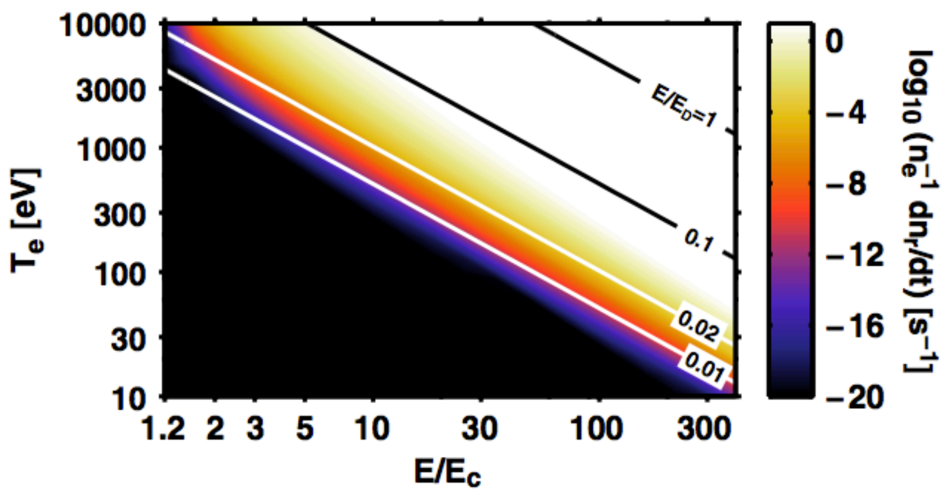


C. Liu, D.P. Brennan, A. Bhattacharjee, and A.H. Boozer, Phys. Plasmas **23**, 010702 (2016).

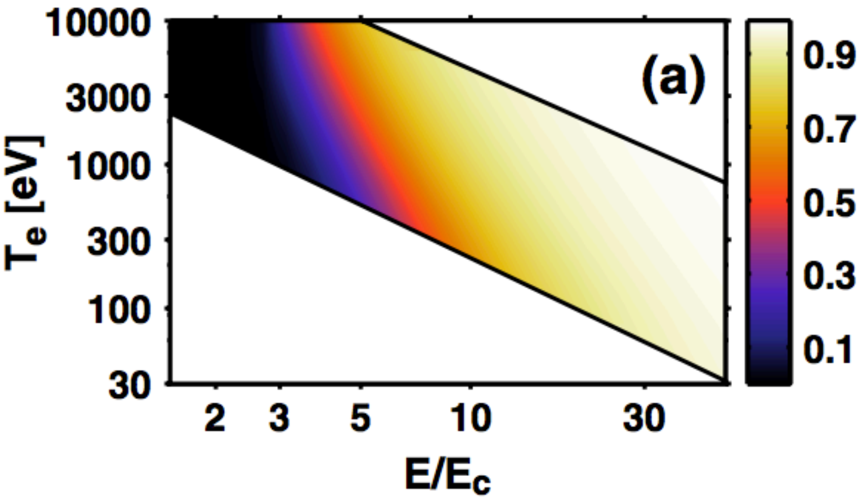
Critical electric field for E/E_c ramping up (Dreicer) strongly affected by synchrotron

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

Dreicer Growth no radiation



Ratio with to without radiation



Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)

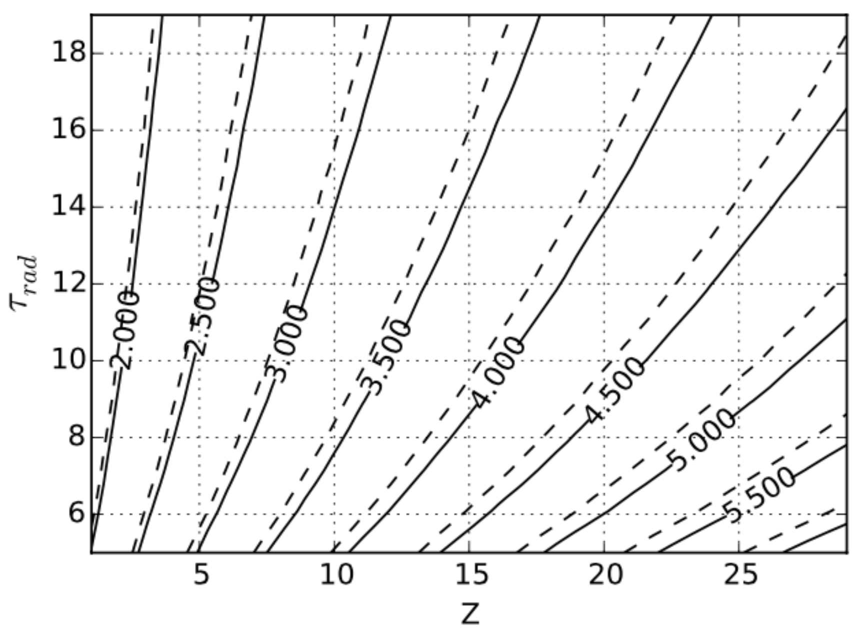
Avalanche onset field E_a is greater than the runaways sustainment field E_0 with synchrotron

- The avalanche onset condition

$$\gamma = \sqrt{1+p^2}$$

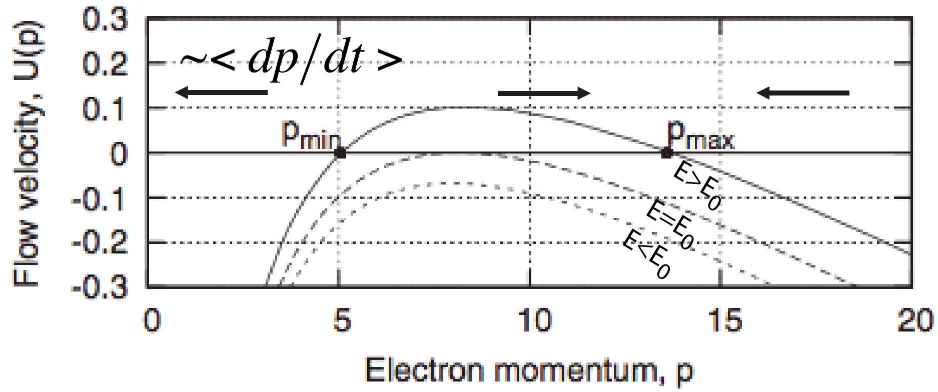
$$\gamma_{max} + 1 \geq 2\gamma_{min}$$

Contours of the avalanche onset field (dashed)



E_0 determined by $\gamma_{max} = \gamma_{min}$
After collision, both original and Knocked electron have at least γ_{min}

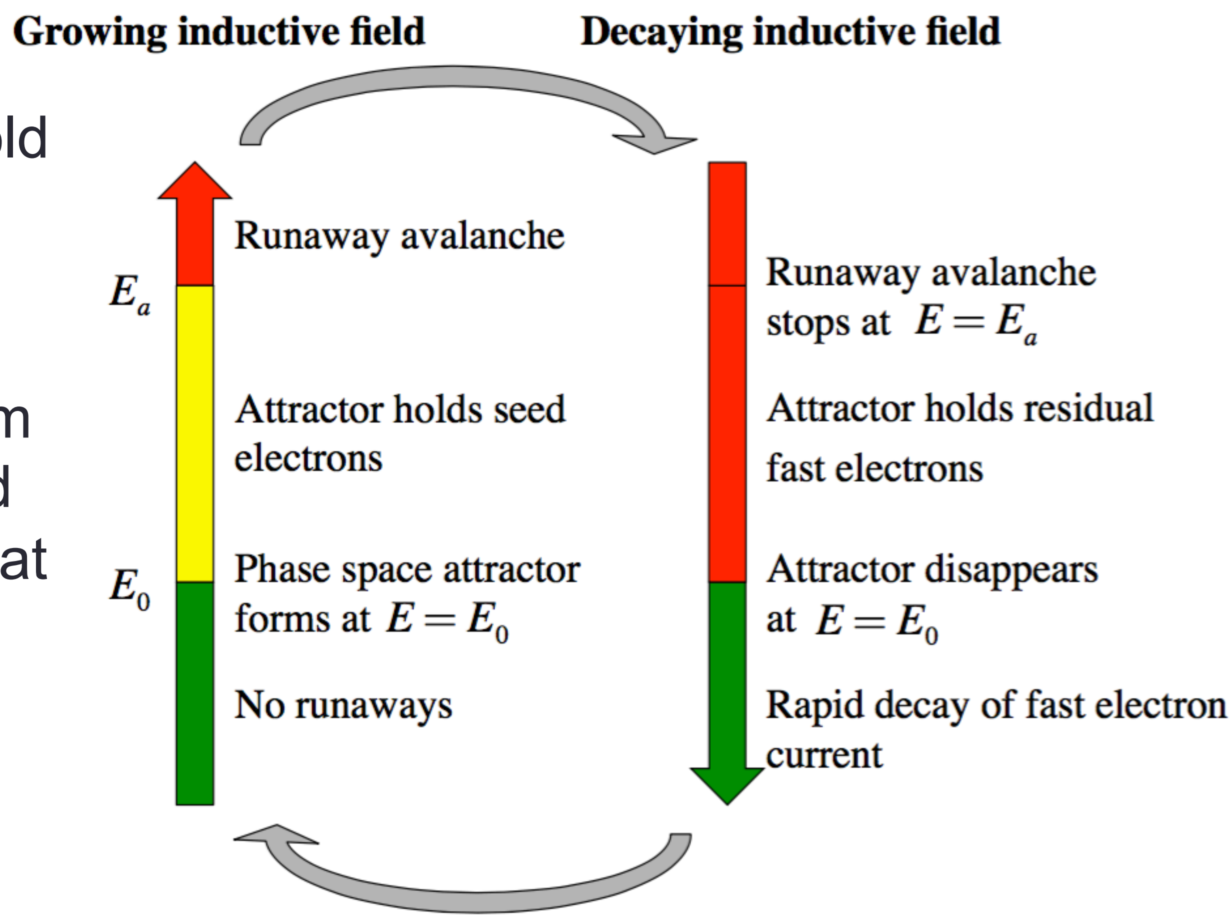
p_{max} is attractor point



P. Aleynikov, B. Breizman, Phys. Rev. Lett., **114**, 155001 (2015)

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

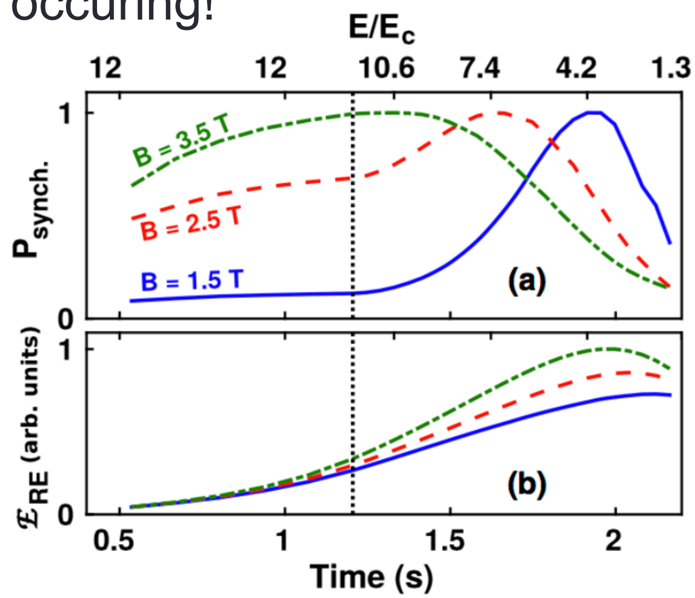
- Ramping up threshold is at $E_a > E_0$
- Ramping down, RE population shifts from growing to sustained at E_a, and decaying at E_0

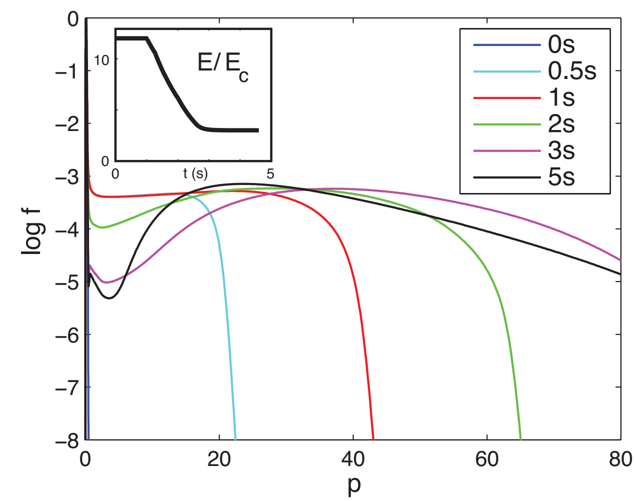


P. Aleynikov, B. Breizman, Phys. Rev. Lett., **114**, 155001 (2015)

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 occuring!





Stahl, Hirvijoki, Decker, Embréus and Fülöp, PRL **114**, 115002 (2015)
C.Liu, D.P. Brennan, A.H. Boozer and A. Bhattacharjee, to be submitted Phys. Plasmas (2016)

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.
  - C. Greenfield and R. Nazikian. Report on scientific challenges and research opportunities in transient research, 2015.
  - P. Bonoli and L.C. McInnes. Report of the workshop on integrated simulations for magnetic fusion energy sciences, 2015.

- 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.

Principal Investigators:

- FES:
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    - Lead PI - Labs
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  - Boris Breizman (UT, Austin)
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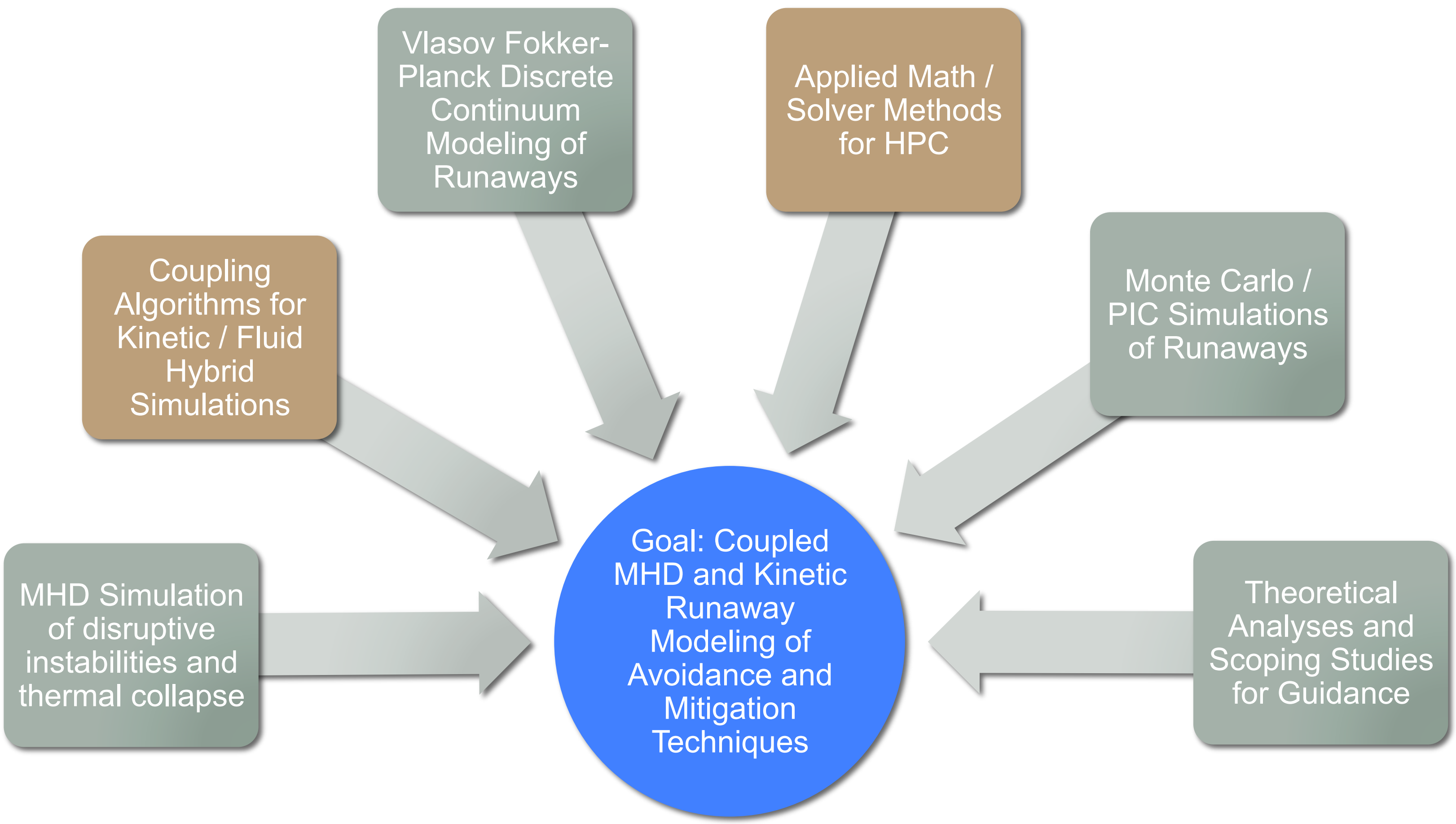
  - Valerie Izzo (UCSD)
  - Lang Lao (GA)
- ASCR
  - Mark Adams (LBNL)
  - Luis Chacon (LANL)
  - Irene Gamba (UT, Austin)
  - Guannan Zhang (ORNL)

Collaborations underway between several groups

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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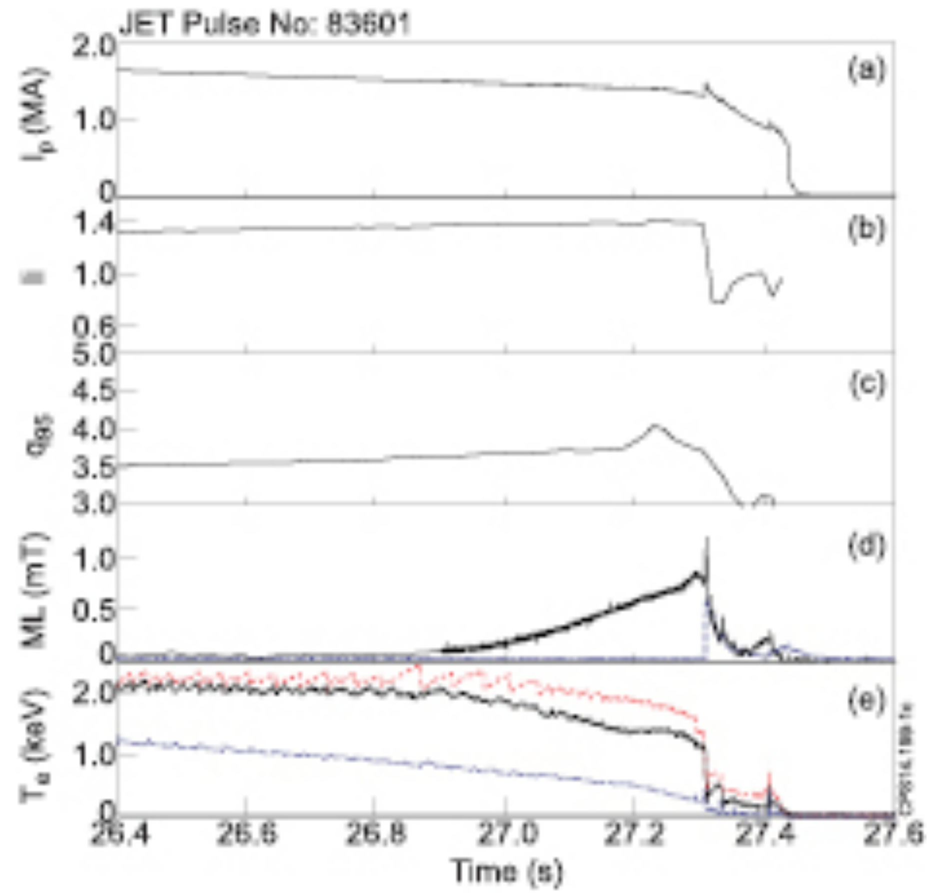
Current Spikes and Runaway Electrons

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.



N.F. 56, 026007 (2016)

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.

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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8 Associated with FES
4 Associated with ASCR
$4.9M / 2yrs

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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

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

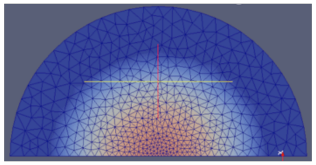
$$C_{ab}[f_a, f_b] = \left(\frac{e_a^2 e_b^2 \ln \Lambda_{ab}}{m_a^2 \varepsilon_0^2} \right) \frac{\partial}{\partial \boldsymbol{v}} \cdot \left(\frac{m_a}{m_b} \frac{\partial \phi_b}{\partial \boldsymbol{v}} f_a - \frac{\partial^2 \psi_b}{\partial \boldsymbol{v} \partial \boldsymbol{v}} \cdot \frac{\partial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

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

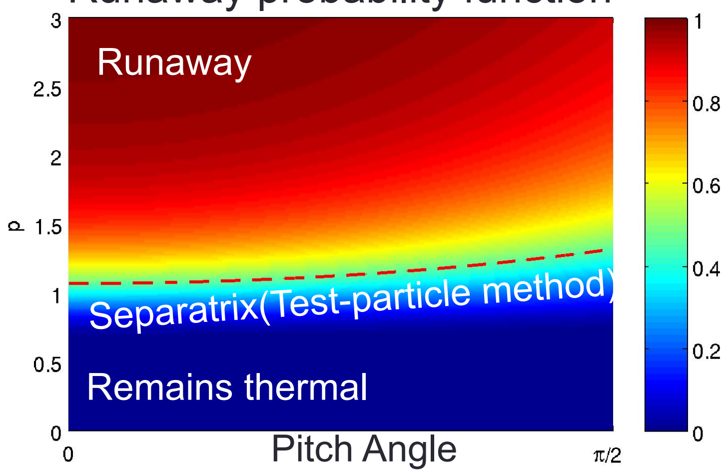
Runaway Probability Function applied to RE seed calculation

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

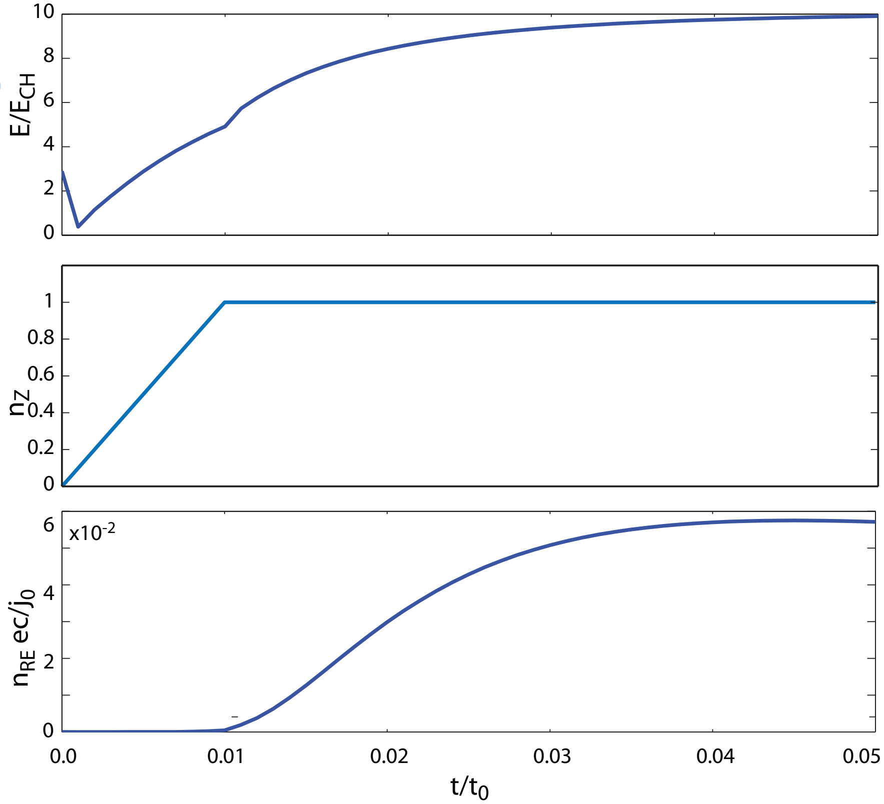
f(p,θ,t) solved for various temperature collapse and impurity injection scenarios



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 $n_{se} = \int d^3v\, f \cdot P$
- Result: Fast transfer difficult to achieve, avalanche dominant

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

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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:

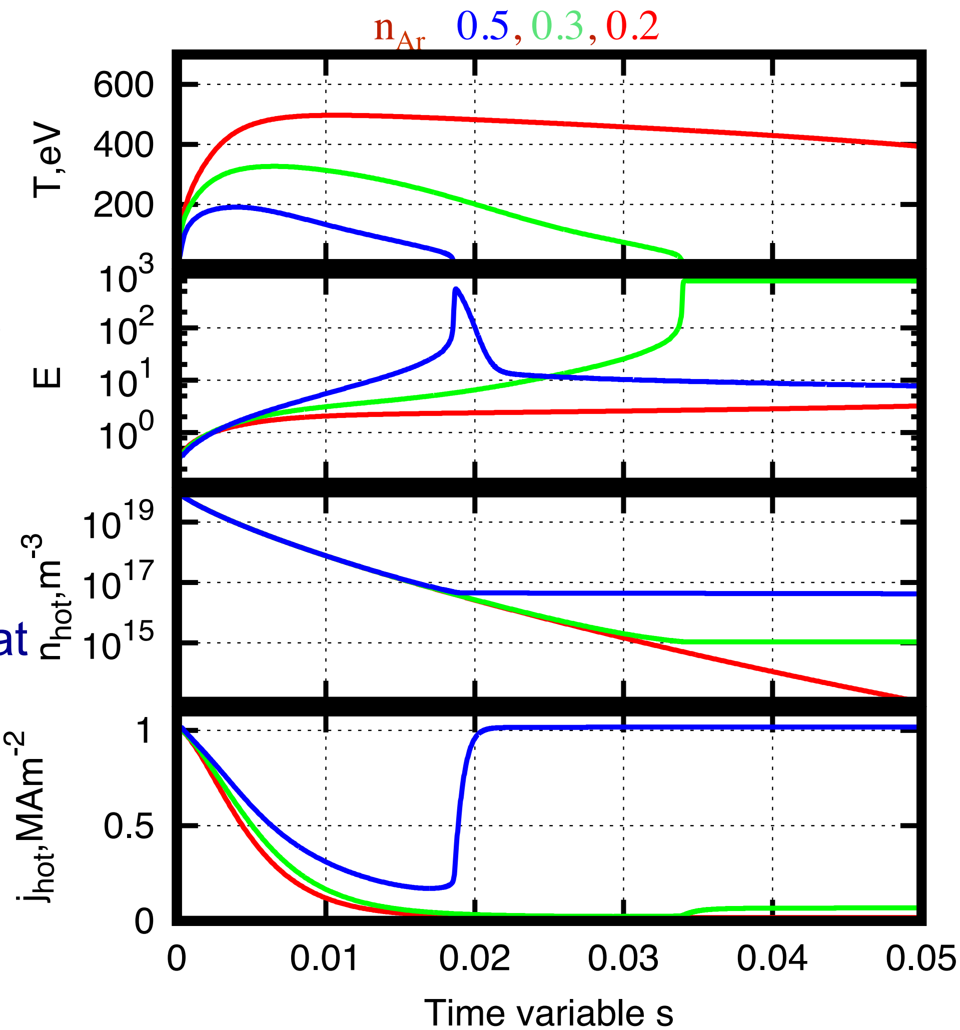
1. Prompt conversion regime: blue

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?

$$\mathrm{d}R = \frac{v_\parallel B_R}{B}\mathrm{d}t + \frac{1}{B^2}[\vec{E}\times\vec{B}]_R\,\mathrm{d}t,$$

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

$$\mathrm{d}Z = \frac{v_\parallel B_Z}{B}\mathrm{d}t + \frac{1}{R}\frac{\gamma m_e v_\perp^2}{2eB}\mathrm{d}t + \frac{1}{R}\frac{\gamma m_e v_\parallel^2}{eB}\mathrm{d}t + \frac{1}{B^2}[\vec{E}\times\vec{B}]_Z\,\mathrm{d}t,$$

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

$$\mathrm{d}\phi = \frac{v_\parallel B_\phi}{RB}\mathrm{d}t + \frac{1}{RB^2}[\vec{E}\times\vec{B}]_\phi\,\mathrm{d}t.$$

$$\mathrm{d}v_\parallel = -\frac{eE_\parallel}{\gamma^3 m_e}\mathrm{d}t + \frac{v_\perp^2}{\gamma^2}\frac{B_R}{2BR}\mathrm{d}t - \frac{1}{\gamma^4}\frac{v_\parallel}{|v_\parallel|^3}\frac{e^4\ln\Lambda}{4\pi\varepsilon_0^2 m_e^2}n_e(Z_{\mathrm{eff}}+1+\gamma)\,\mathrm{d}t - \gamma v_\parallel^3\frac{e^2}{6\pi\varepsilon_0 m_e c^3}\left(\frac{1}{R_0^2}+\frac{e^2B^2v_\perp^2}{\gamma^2 m_e^2 v_\parallel^4}\right)\mathrm{d}t - \frac{1}{\gamma^2}\frac{e^4(Z_{\mathrm{eff}}+1)}{548\pi^2\varepsilon_0^2 m_e^2 c^2}n_e\left(\ln(2\gamma)-\frac{1}{3}\right)\frac{v_\parallel}{|v_\parallel|}\mathrm{d}t.$$

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

V.A. Izzo, et al, NF 51, 063032 (2011)

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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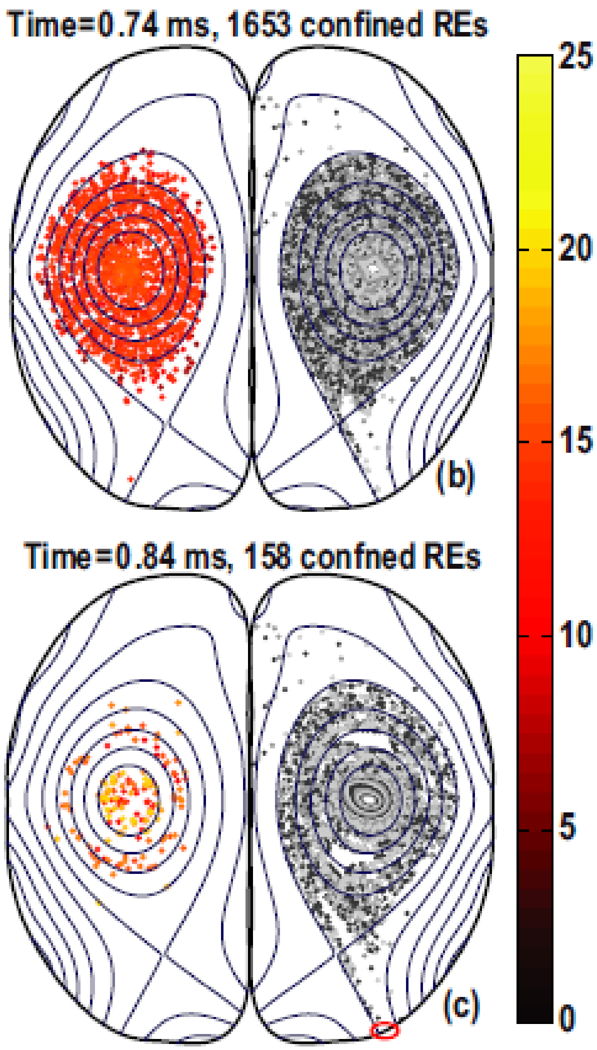
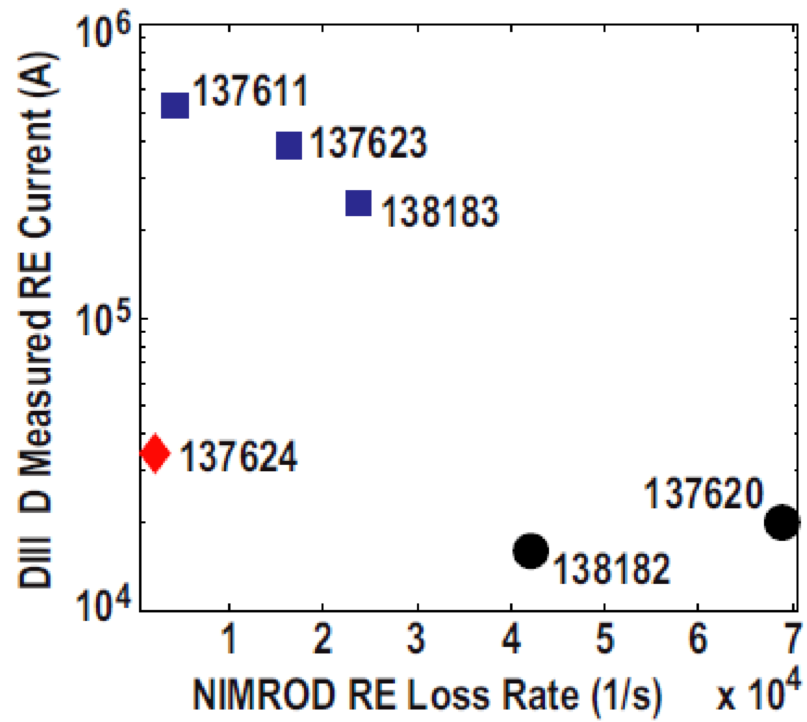
Model has been used to predict RE "prompt loss" in DIII-D experiments





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

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

V.A. Izzo, et al, PPCF 54, 095002 (2012)

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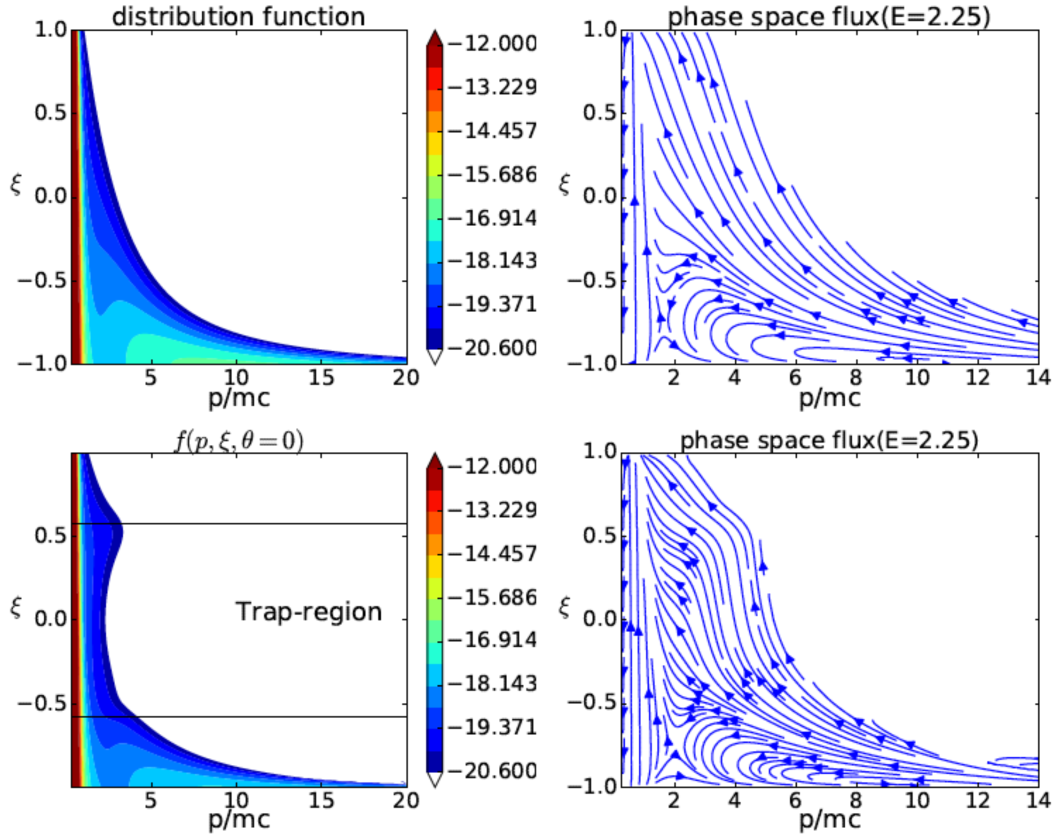
Collaborations underway between several groups

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 $E = 2.25, \alpha = 0.2, Z = 1, r/R_0 = 0.2$

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

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

$$\tau_{rad} = \frac{6\pi\varepsilon_0 m_e^3 c^3}{e^4 B^2}$$

$$\hat{\tau}_{rad} \equiv \frac{\tau_{rad}}{\tau} = \frac{2}{3}\left(\frac{m_e \ln\Lambda}{\varepsilon_0}\right)\frac{n_{eff}}{B^2} = 278\frac{n_{eff}[10^{20}]}{(B[T])^2}$$

$$\tau = \frac{4\pi\varepsilon_0^2 m_e^2 c^3}{e^4 n_e \ln\Lambda}$$

- 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