Runaway Generation in a Tokamak Plasma

Chris McDevitt

In collaboration with Xianzhu Tang

Los Alamos National Laboratory

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Outline

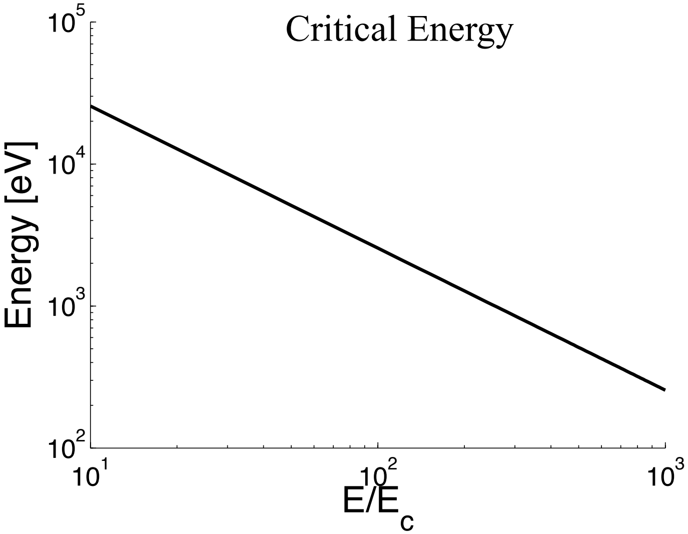
- Runaway generation processes in the presence of large inductive electric fields in axisymmetric geometry
  - Four dimensional reconstruction of the Runaway Probability Function (RPF)
- Two example cases:
  - Dreicer production
  - Avalanche amplification
- Self-Consistent runaway formation in an axisymmetric plasma
  - Runaway formation during the current quench

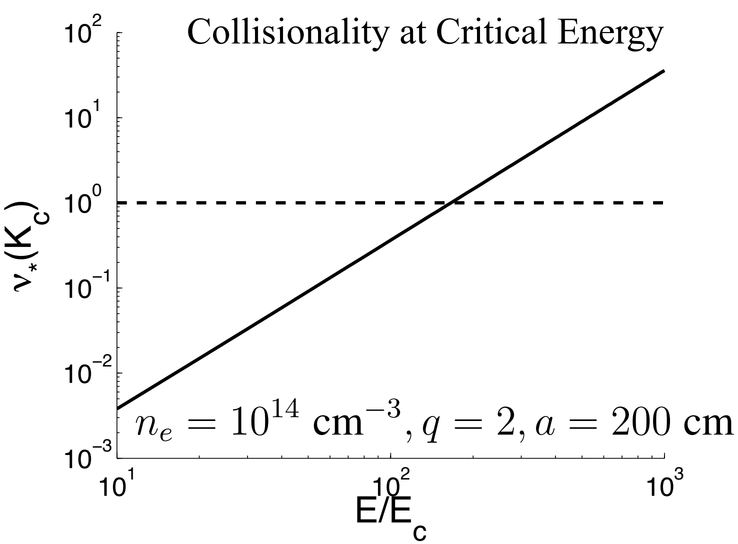
Motivation: Runaway Generation Processes in Tokamak Plasmas for Large Inductive Electric Fields

- Our intuition of how toroidal geometry impacts runaway generation is largely based on electron trapping
  - → Implies a reduction of runaway generation as the minor radius is increased [Rosenbluth-Putvinski 1997]
- The critical energy for an electron to run away in a hydrogen plasma can be approximated by:

$$\mathcal{K}_c \approx \left(\frac{m_e c^2}{2}\right)\left(\frac{E_c}{E}\right)$$

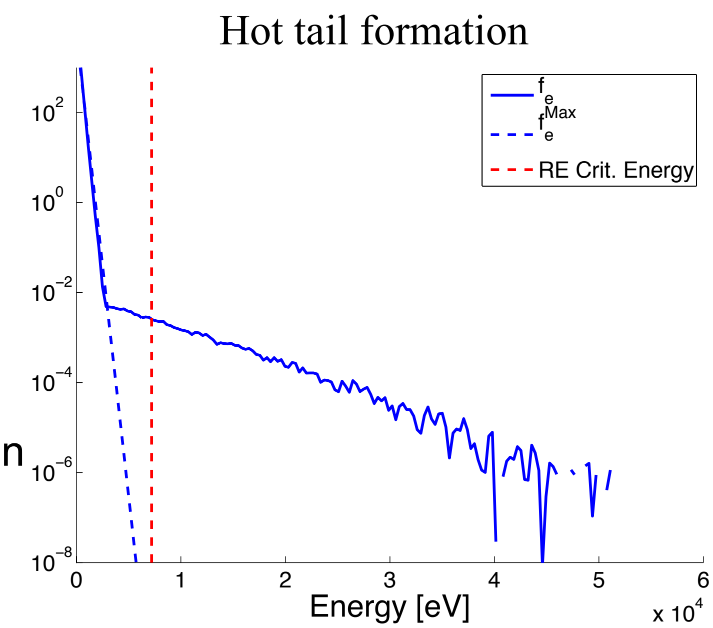
- For large electric fields this energy can be several hundred eV
  - Electrons at these modest energies are often characterized by $\nu_* \gg 1$





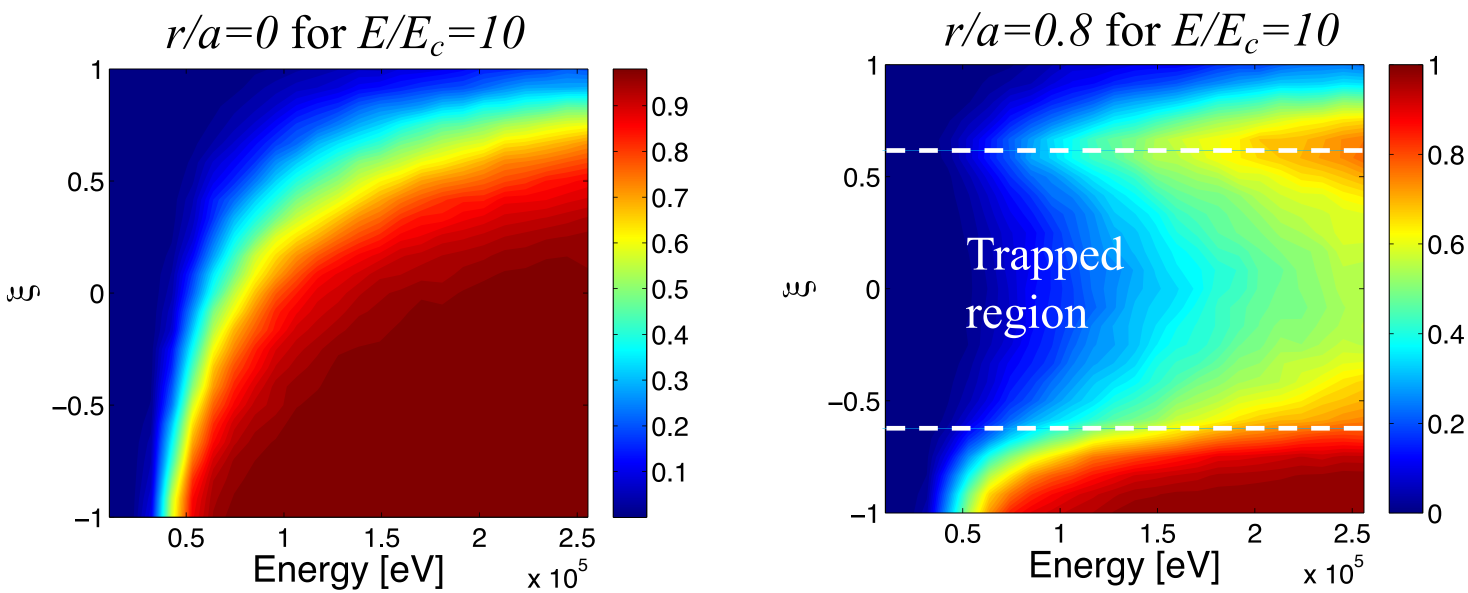
Drift Kinetic Description of Runaway Electrons

- Particle based guiding-center solver for 3D-2V runaway electron population [McDevitt et al. 2019] → does not require asymptotically small collisionality
  - Large-angle collisions described by a Möller source
  - Seed mechanisms (hot tail and Dreicer) incorporated via a variable weight scheme
  - Flux-surface averaged inductive electric field can be evolved self-consistently



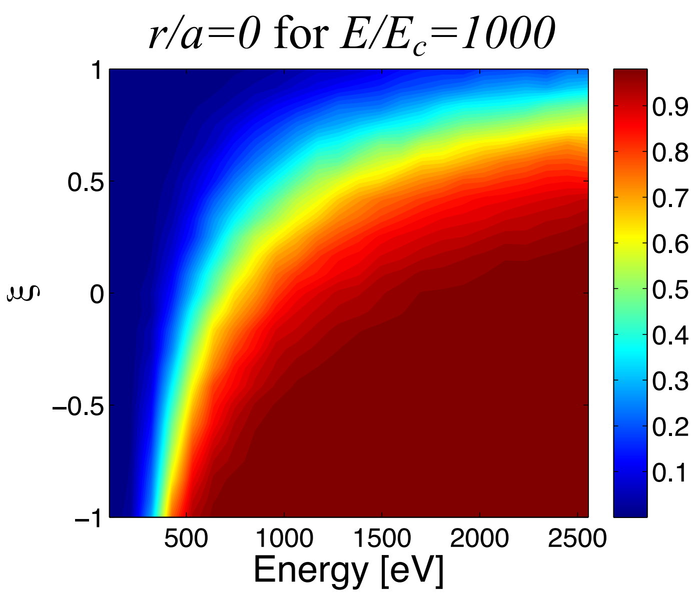
- Provides high physics fidelity description of:
  - Runaway seed formation
  - Avalanche amplification of initial seed population
  - Self-consistent evolution of flux-surface averaged inductive electric field

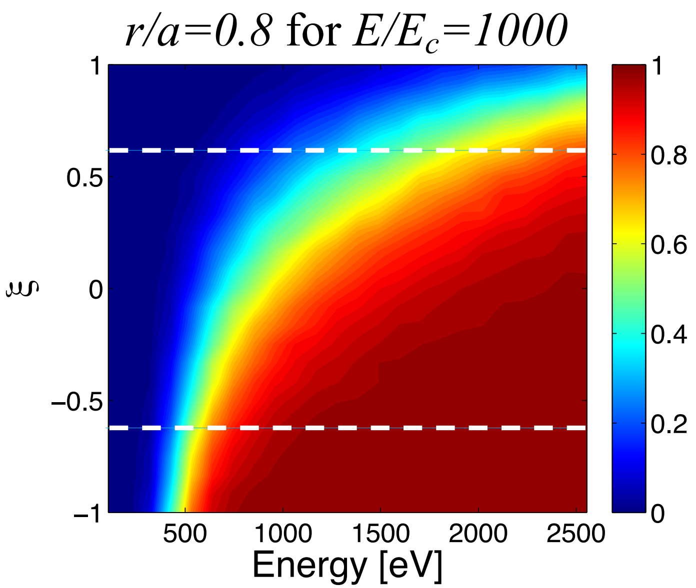
Runaway Probability Function in Toroidal Geometry: Weak Inductive Electric Field



- Interesting to contrast the runaway probability function (RPF) [Liu et al. 2016, Zhang et al. 2017] for *r/a=0* and *r/a=0.8*
  - Radiation neglected here → electrons accelerated to arbitrarily high energy are deemed runaways
  - Electrons that reach the thermal energy are deemed to not run away
- The RPF exhibits a strong local minimum at $\xi = 0$ for the off-axis case
  - Significantly reduces the efficiency of runaway generation at large minor radius

Runaway Probability Function in Toroidal Geometry: Strong Inductive Electric Field



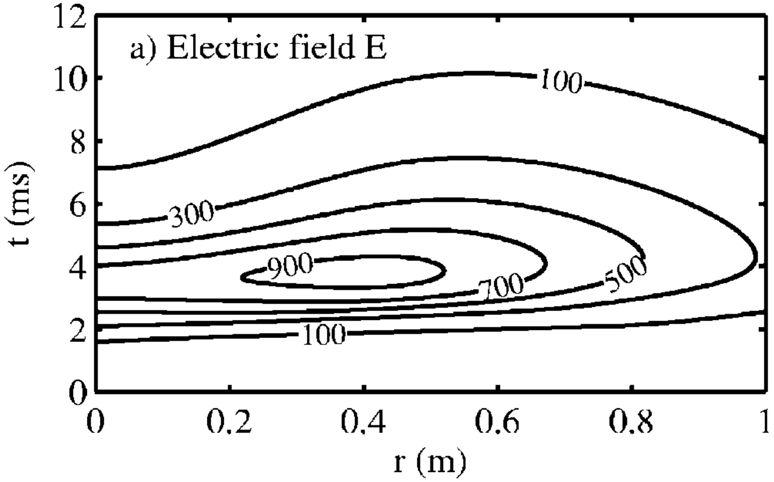


- For strong inductive electric fields, off-axis RPF no longer strongly reduced in “trapped” region
  - The large collisionality near the critical energy to run away prevents electrons from completing a bounce orbit
  - Impact of electron trapping is largely negated

Inductive Electric Field During a Tokamak Disruption

- The characteristic strength of the inductive electric field can be estimated based on the available poloidal flux [Boozer 2018]
- An ITER-like case with $75\ \mathrm{V \cdot s}$ of poloidal flux and a $100\ \mathrm{ms}$ current decay implies an average loop voltage of $750\ \mathrm{V}$
  - This implies $E/E_c \approx 380$ for $n_e=10^{14}$ cm^{-3}, $T_e=10$ eV, and $\ln \Lambda = 10$
- Maximum inductive electric field generally much larger

JET-like case
[Smith et al. 2006]

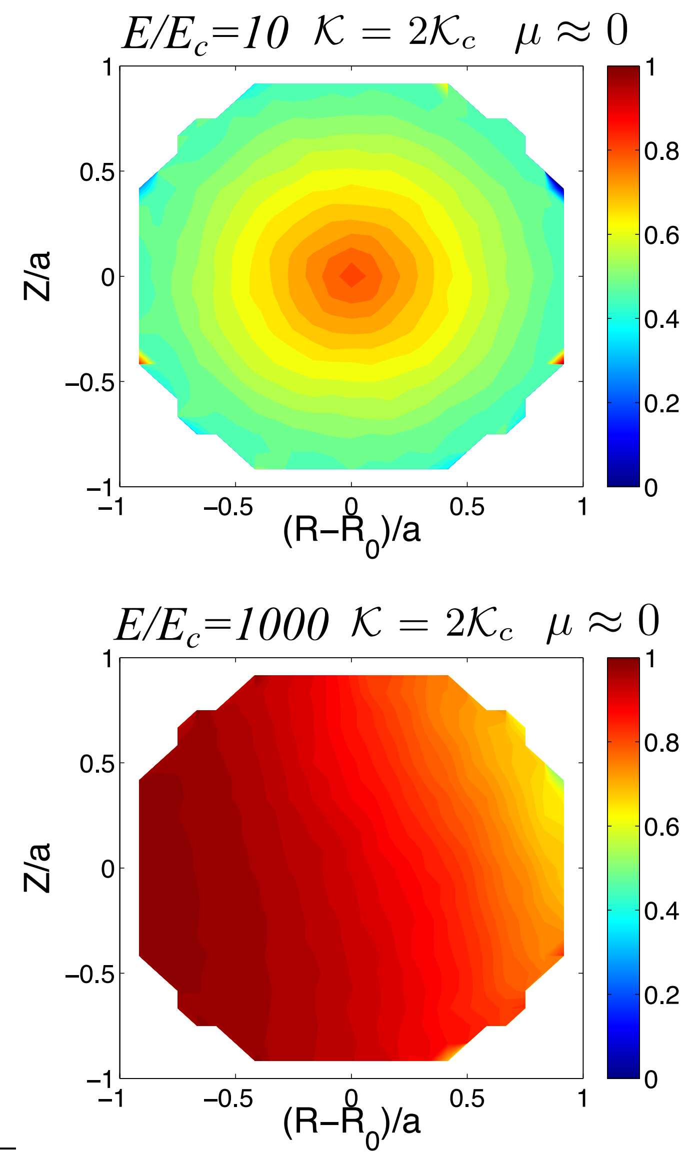


Runaway Electron Generation is Strongly Localized for Large Electric Fields

- For a large inductive electric field electrons can gain a significant amount of energy in a single toroidal transit
- Specifically, for an ITER-like case with an average loop voltage of $750\ \mathrm{V}$
  - An electron can gain up to $750\ \mathrm{eV}$ during a single toroidal transit
  - The critical energy at this electric field is $670\ \mathrm{eV}$
  - Electrons can more than double their energy in a single toroidal transit
  - For $q \gtrsim 1$, electrons can be accelerated before sampling the entire flux surface
- The inductive electric field in tokamak geometry scales as $1/R$
  - Implies strong poloidal localization of runaway generation for large inductive electric fields

Runaway Probability Function in Configuration Space

- In the low collisionality limit and a modest inductive electric field $f_e = f_e(\gamma, \mu, \psi)$
- For large inductive electric fields the RPF is no longer a flux surface function $\Leftrightarrow (\gamma, \mu, R, Z)$
  - The strong in-out asymmetry results from $E_\varphi \propto 1/R$
  - A weaker up-down asymmetry results from helicity of magnetic field line
- RPF substantially increased across poloidal cross section for large inductive electric field
  - Significant increase in efficiency of all runaway generation processes



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Parallel Electric Field in Axisymmetric Tokamak Geometry

- Incompressibility $\nabla \cdot \mathbf{j} = 0$, but $\nabla \cdot \mathbf{j}_\perp \neq 0$ implies [Helander-Sigmar]

$$j_\parallel = -\frac{I(\psi)}{B}\frac{dp}{d\psi} + K(\psi) B$$

- For a low-beta poloidal plasma, $j_\parallel / B \approx K(\psi) \Leftarrow$ Flux surface function

- From Ohm's law

$$E_\parallel = \eta j_\parallel = \eta B \left(\frac{j_\parallel}{B}\right) \approx \eta B K(\psi)$$

- In simplest limit $\eta = \eta(Z_{eff}, T_e) = \eta(\psi)$, $E_\parallel \propto B \propto 1/R$

- More complex cases possible for poloidally and toroidally localized impurity deposition ⬄ treat in future work

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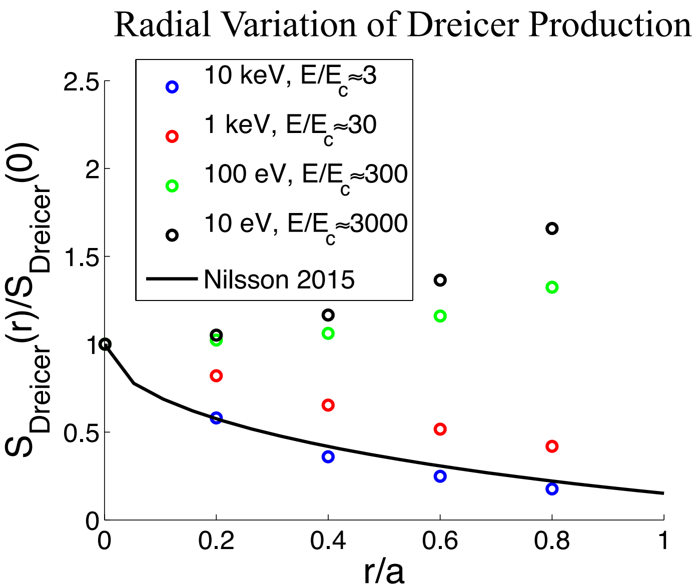
Dreicer Production in Tokamak Geometry

- Considering Dreicer production as a function of electric field strength
  - E/E_D held constant while the temperature is scanned
  - Noting $E/E_c = \left(m_e c^2/T_e\right)\left(E/E_D\right) \Leftrightarrow$ results in the strength of electric field being varied
- For modest values of the inductive electric field (high temperature) the results from Nilsson et al. 2015 are reproduced



$E/E_D = 0.06, n_e = 2 \times 10^{14}\ \mathrm{cm}^{-3}, Z_{eff} = 1$

- For large inductive electric fields (low temperature) the present results deviate qualitatively from previous predictions
  - Dreicer production more efficient at larger minor radii

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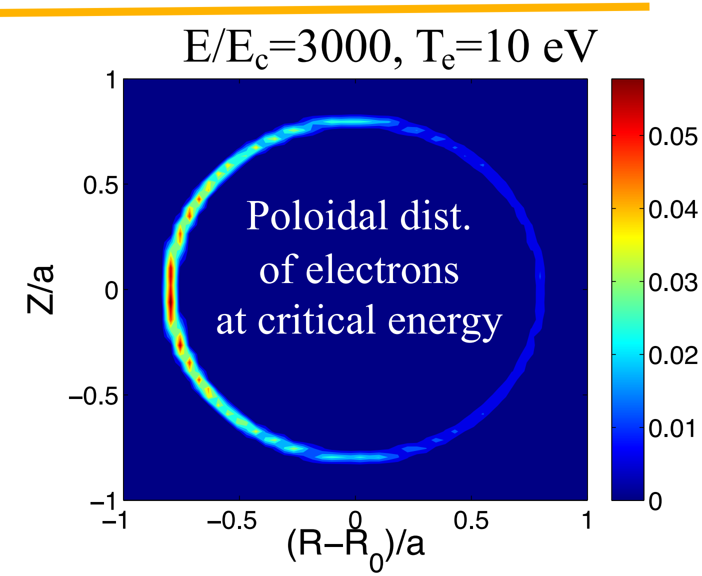
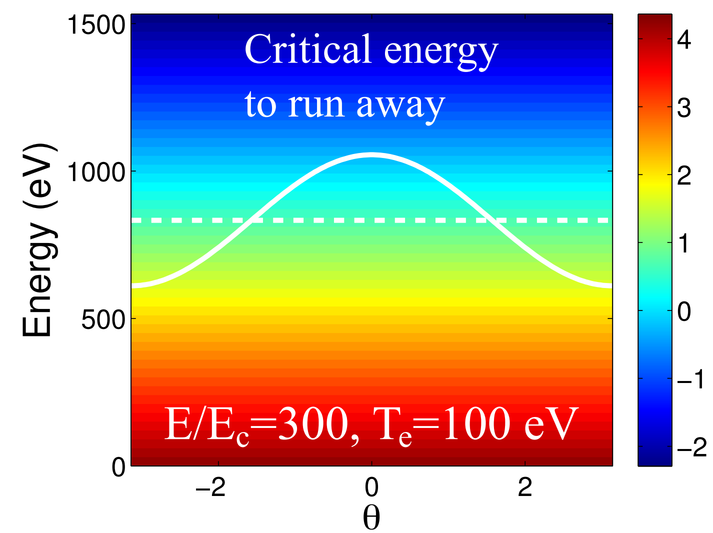
Runaway Distribution near Threshold Energy Strongly Asymmetric

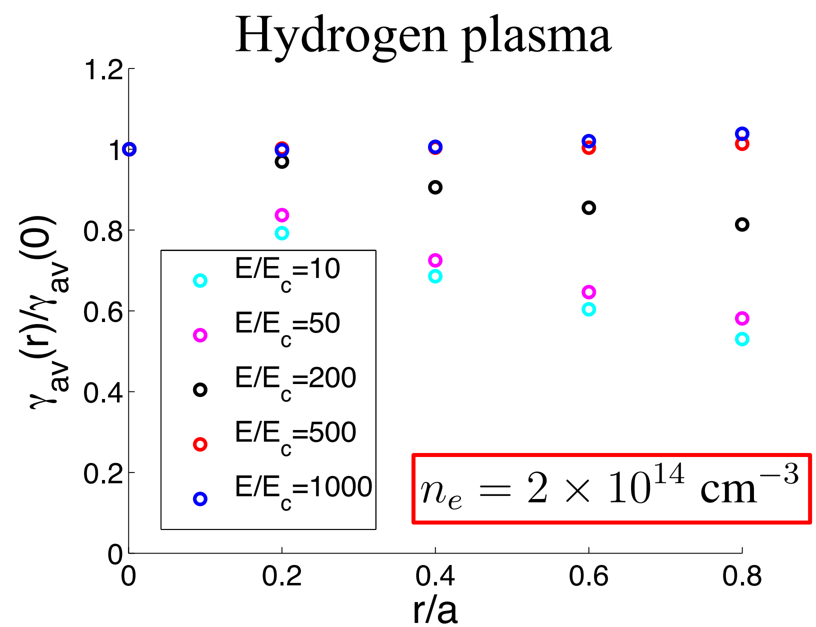
- Noting the modulation of inductive electric field $E_\varphi \propto 1/R$
  - Runaway electrons more efficiently accelerated on inboard side
  - Less efficiently on outboard side
- Poloidal modulation does not cancel:
  - Dreicer production depends non-linearly on the electric field strength





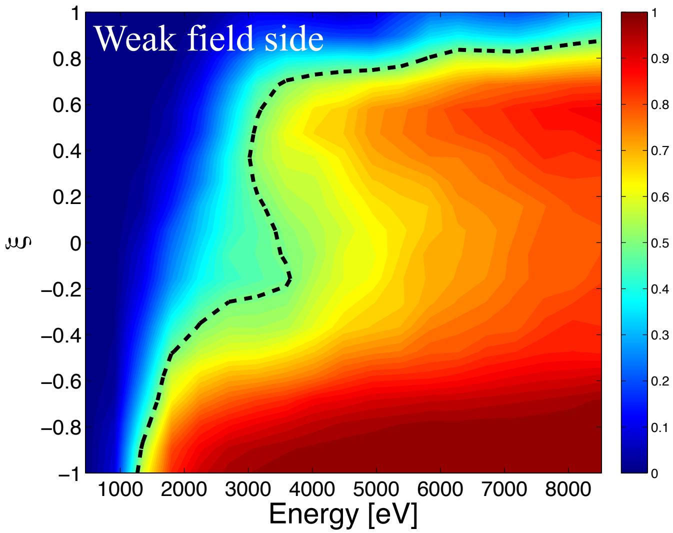
Avalanche Amplification for Large Electric Fields

- Related physics impacts avalanche amplification
- High collisionality at critical energy negates "neoclassical" reduction factor
- However, the avalanche growth rate is (approximately) linear with respect to the electric field:
  - $1/R$ modulation of inductive electric field will (nearly) cancel
  - Little to no increase expected at large minor radii for asymptotically large electric fields

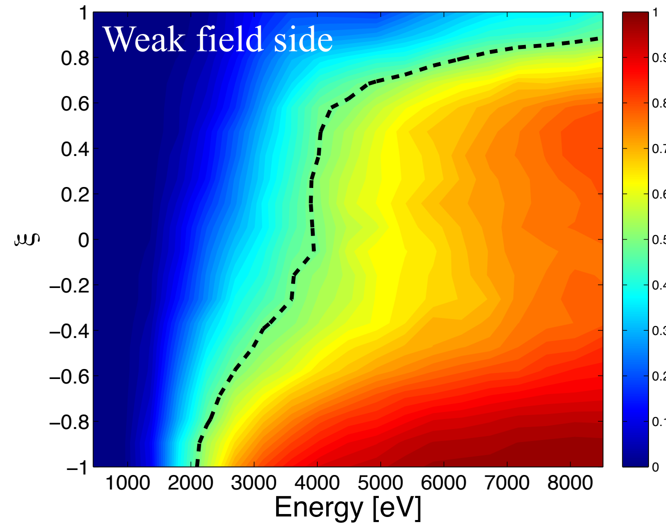


Impact of Impurities on Runaway Probability Function

r/a=0.8, E/E$_c$=300, Z$_{eff}$=1



r/a=0.8, E/E$_c$=300, Z$_{eff}$=5



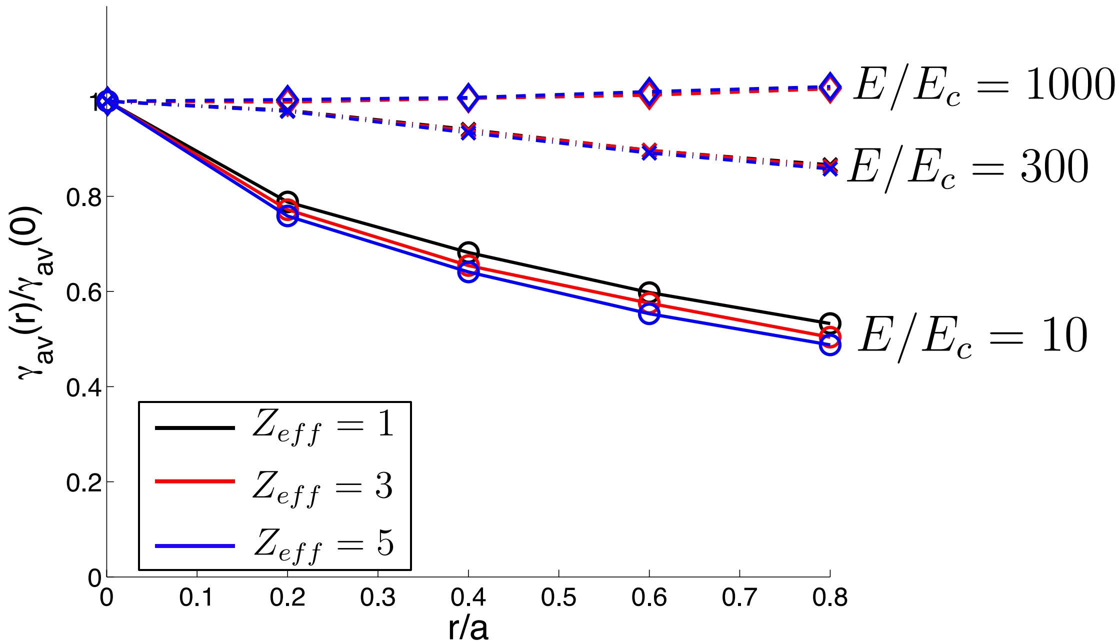
- Presence of impurities modifies the collisionality via two partially compensating trends

$$\nu_* \equiv \frac{\tau_{bounce}}{\tau_{detrap}} \propto n_e \left(Z_{eff} + 1\right) \left(\frac{c}{v}\right)^4$$

- Critical energy to runaway increased

- Pitch-angle scattering more efficient at a given energy

Impact of Impurities on Avalanche Amplification



- Presence of impurities only modestly impact radial modulation of avalanche amplification factor
  - Amplification factor reduced as radius is increased for small E/E_c
  - Amplification factor approximately constant for large E/E_c

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Runaway Electron Formation: Axisymmetric Plasma

- Interested in identifying the impact of the above physics on RE formation in an axisymmetric tokamak plasma
- Seek testbed for exploring coupling of RE to field evolution
- Incorporate accurate description of RE dynamics:
  - RE generation processes in toroidal geometry for arbitrary collisionality regimes
  - Spatial transport of RE for plasmas with large impurity content [McDevitt et al. 2019]
  - Finite orbit width effects
  - …
- Allows for spatial profile of RE current to be determined
  - MHD stability of RE current carrying plasma

RE Generation during Current Quench

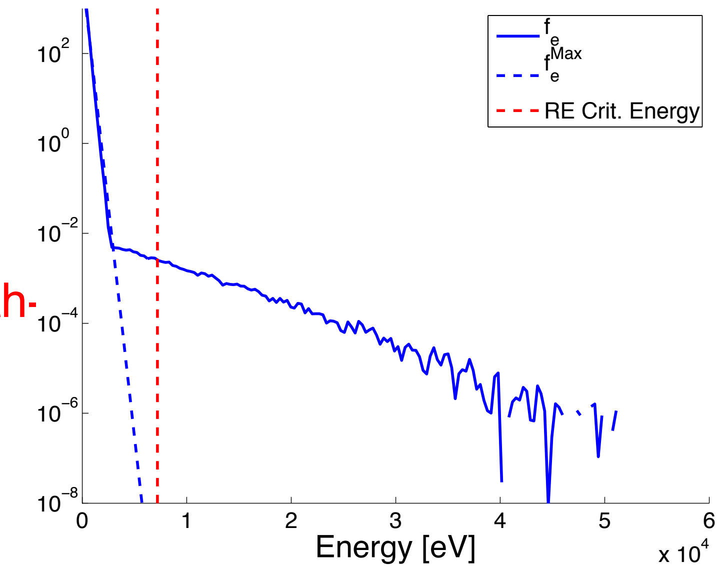
- Will evolve flux surface averaged induction equation

$$\nabla^2 \mathbf{E} = \mu_0 \frac{\partial \mathbf{j}}{\partial t}$$

- Along with a modified Ohm's law [Rosenbluth-Putvinski 1997]:

$$E_{\|} = \eta \left(j_{\|} - j_{RA} \right)$$

Hot tail formation



- j_{RA} evaluated from kinetic solution
  - Density and temperature profiles prescribed
- Incorporating seed mechanisms requires resolving both the tail and bulk plasma non-perturbatively
  - Variable weight scheme employed to improve resolution of tail population: marker particles split as they are accelerated
  - Only tail electrons fed back into field solve ⇔ j_{RA}

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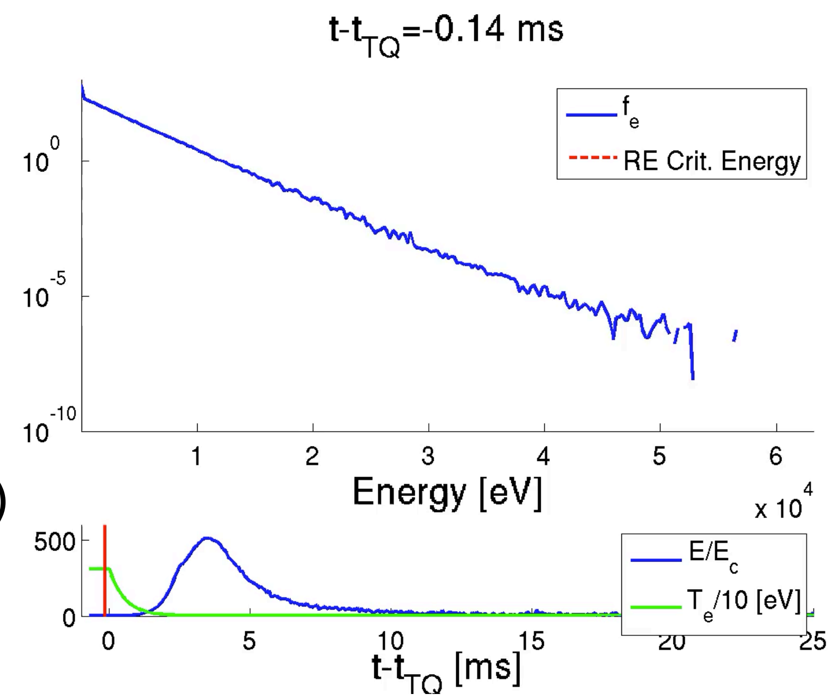
Current Transfer

- Runaway generation occurs in three distinct phases

1. Hot tail generation: $t\text{-}t_{TQ}$=(1ms-2.3ms)
   - Strongly non-Maxwellian solution due to rapid thermal quench
2. Dreicer generation: $t\text{-}t_{TQ}$=(2.3ms-3ms)
   - Electric field directly accelerates electrons from thermal bulk
3. Avalanche amplification: $t\text{-}t_{TQ}$=(3ms-15ms)
   - Seed population amplified until RE's overtake plasma current



- Assume JET like shot with a thermal quench of τ_{TQ}=0.5 ms
  - Hydrogen plasma assumed

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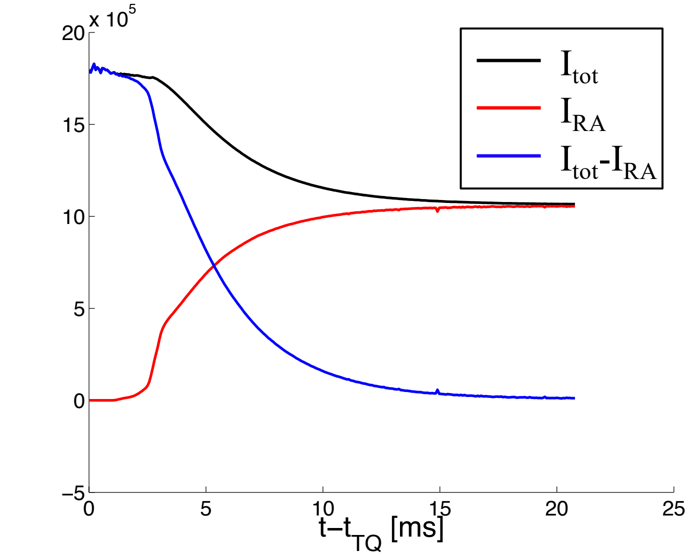
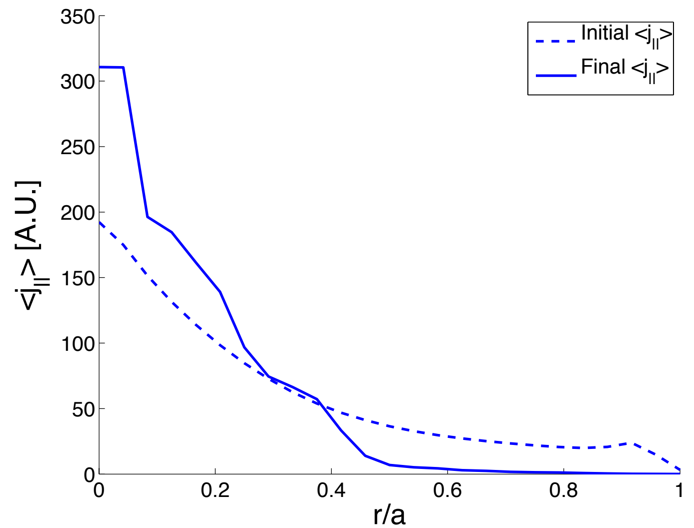
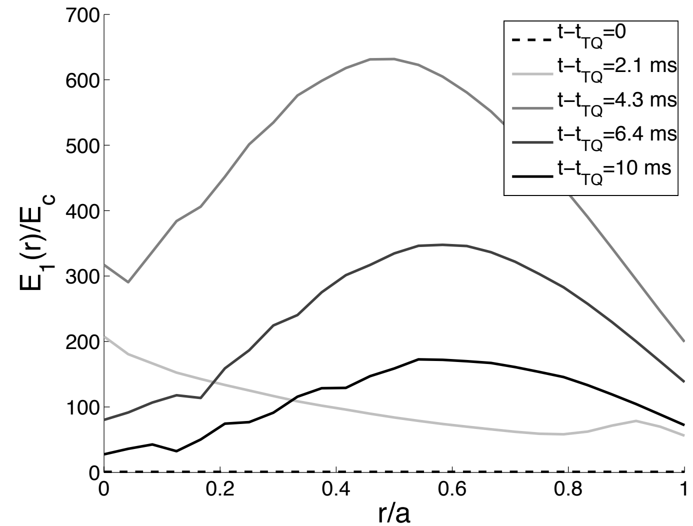
Profile Evolution during Current Quench

- Current plateau forms on a timescale of 15 ms
- Once the runaway beam forms, electric field drops
  - Hollow E-field profile forms due to peaked RE current profile







Summary

- Runaway probability function found to have a non-trivial structure in the 4-D phase space (γ, μ, R, Z)
  - Runaway distribution function is not well approximated as a flux surface function near critical energy to run away
- The efficiency of runaway generation processes found to be strongly modified in the limit of large inductive electric fields
  - Dreicer production rate is found to be enhanced at finite minor radii
  - Avalanche amplification found to be approximately constant in radius
- Runaway generation coupled to a self-consistently evolving inductive electric field in tokamak geometry
  - Provides high physics fidelity description of 2D-2V runaway electron phase space evolution
  - Future work aimed at incorporating a self-consistent collisional radiative model