Spatial Transport of Runaway Electrons in Axisymmetric Tokamak Plasmas

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Motivation: Spatial Evolution of Runaway Electrons

- The spatial profile of runaway electrons plays an important role in the evolution of a disruption:
  - Can shape the q-profile and thus influence MHD stability
  - Sets the inductance of the plasma ➔ affects current decay rate

- Present reduced models of the evolution of a runaway electron population assume electrons to be tightly localized to magnetic flux surfaces [Smith et al. 2006, Konovalov et al. 2014, Martin-Solis et al. 2017]:
  - Spatial transport neglected or treated in an ad-hoc manner
    - In the presence of a 3D magnetic field transport is known to strongly impact the lifetime (energy) of a runaway electron population [Papp et al. 2011]

- This work seeks to identify under what circumstances non-negligible levels of runaway transport is present in the presence of good magnetic flux surfaces

Outline

- Impact of Toroidicity on avalanche growth rate/threshold
- Spatial transport of runaway electrons in an axisymmetric plasma
  - Drastic enhancement in the presence of partially ionized impurities
  - Ware pinch ⇔ inward collapse of runaway electron population
- Implications for phase space distribution of runaway electrons
  - Runaway spatial eigenmode

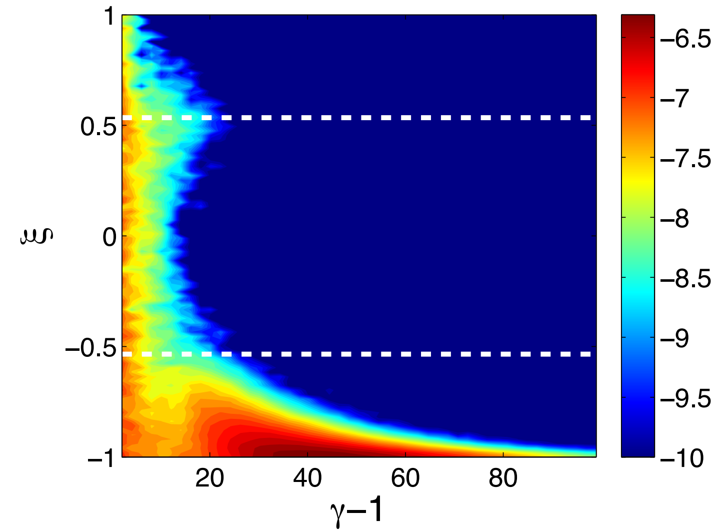
Description of Runaway Electrons

- Runaway electrons described by drift kinetic equation
- Allows 5D phase space to be evolved
  - Incorporates toroidal effects
  - Spatial transport
- Small-angle collisions treated by Monte Carlo collision operator [Boozer 1981]
  - Partial screening included [Hesslow et al. 2017]
- Synchrotron radiation damping incorporated
- Large-angle collisions (avalanche) described by Möller source
- Flux-surface averaged inductive electric field evolved via:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{j}, \quad E_{\|} = \eta \left(j_p - j_{RA} \right)$$

- Constant loop voltage ($V_{loop} = 2\pi R E_{\varphi} = \mathrm{const}$) assumed in this work

McDevitt et al. 2018



Avalanche Growth Rate in a Tokamak

- Avalanche mechanism sensitive to toroidal geometry [Rosenbluth 1997, Chiu et al. 1998, Eriksson et al. 2003, Nilsson et al. 2015,…]
  - Secondary electrons often born in trapped region ⇔ cannot be directly accelerated

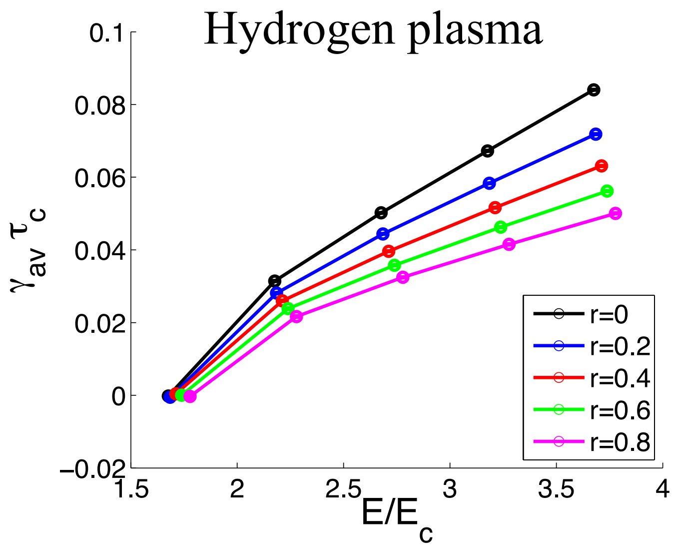
- Also useful to consider the number of exponentiations possible for a given change of plasma current [Rosenbluth 1997, Boozer 2018].

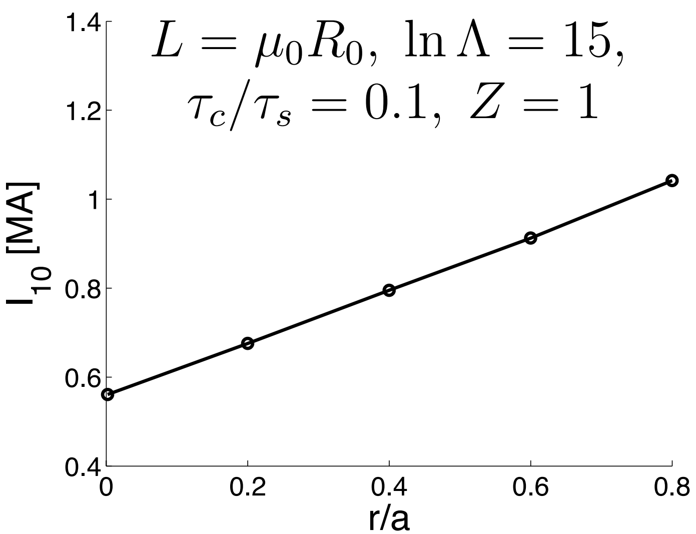
- Well above marginality:

$$\gamma_{av}\Delta t \approx \gamma_0 \frac{E}{E_c}\Delta t \sim -\frac{\gamma_0 \Delta t}{E_c}\frac{L}{2\pi R_0}\frac{\Delta I_p}{\Delta t} \sim \frac{\Delta I_p}{I_{exp}},$$

$$I_{exp} = \frac{2\pi R_0}{L}\frac{E_c}{\gamma_0}, \qquad I_{10} = \ln 10 I_{exp}$$

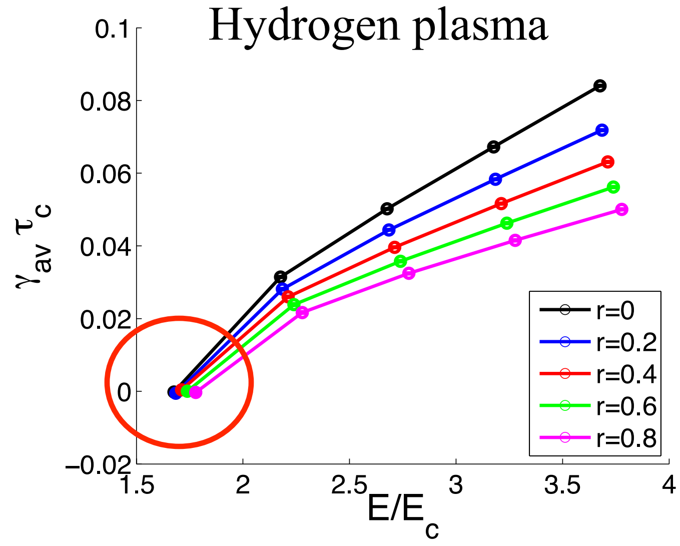
- Number of potential exponentiations scales linearly with plasma radius
  - The spatial profile of runaway electrons strongly impacts the efficiency of conversion of thermal current via the avalanche mechanism



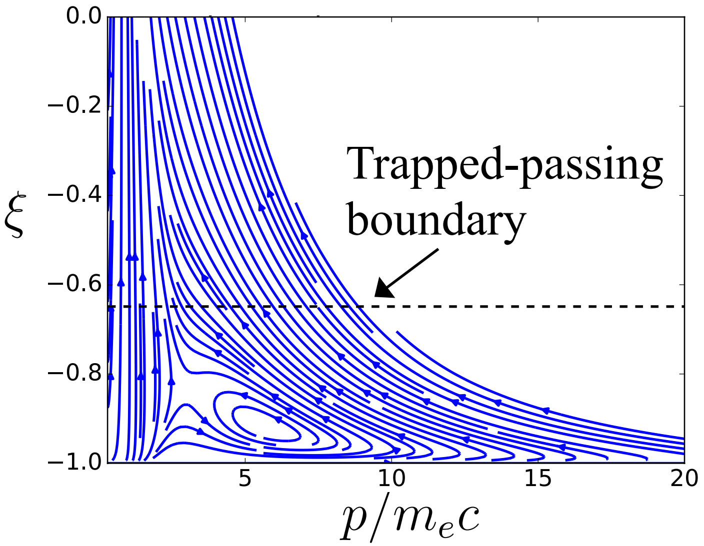


Impact of Toroidicity on Avalanche Threshold

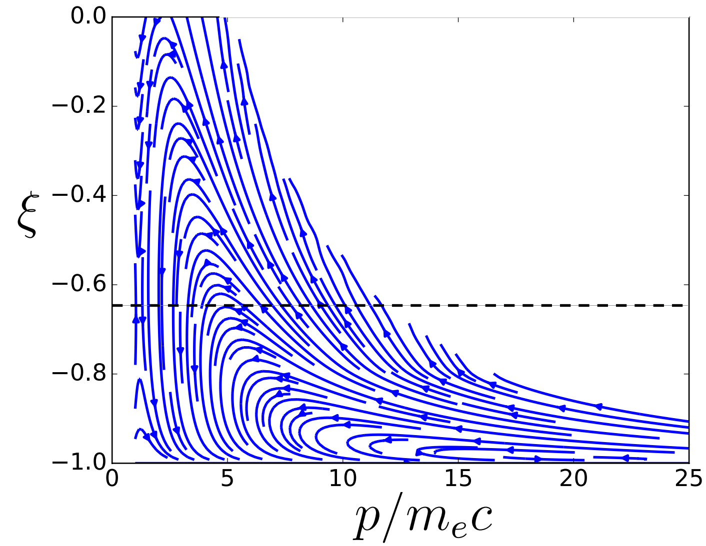
- Avalanche threshold only weakly impacted by toroidicity
- Well above threshold, runaway vortex strongly affected by trapped-passing boundary
  - Near threshold O and X points far from the trapped-passing boundary ⇔ toroidicity only weakly affects avalanche threshold
  - Above threshold, runaway vortex occupies a larger region of phase space ⇔ avalanche growth rate strongly impacted



Momentum Flux Slab: Near Threshold



Momentum Flux Slab: Above Threshold



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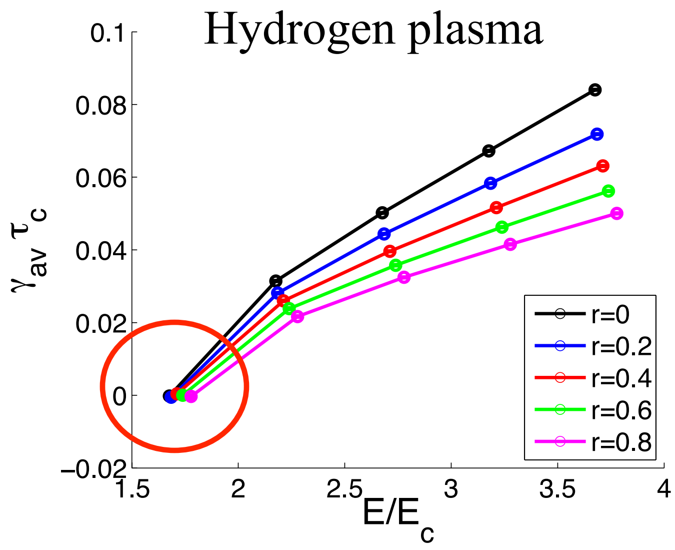
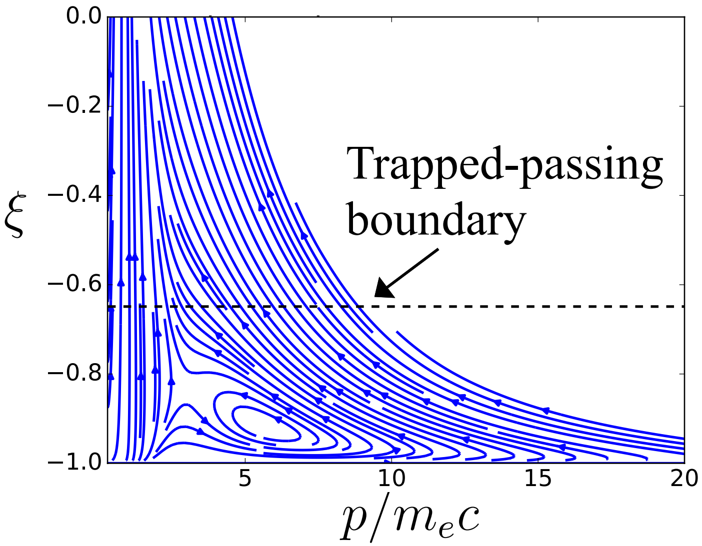
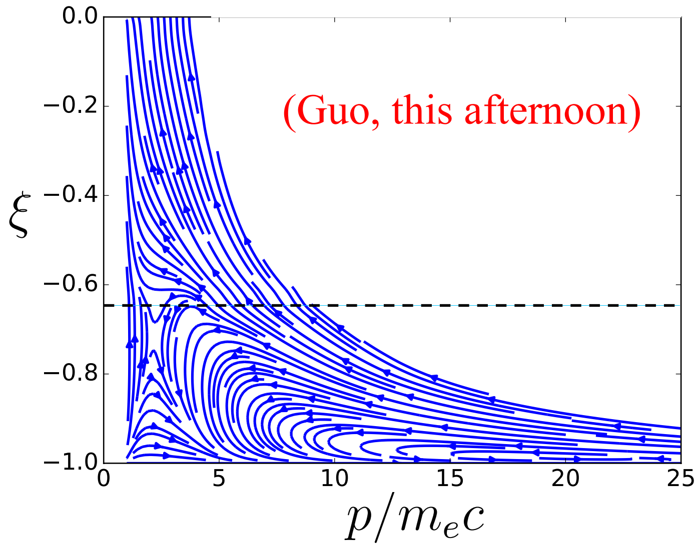


Momentum Flux Slab: Near Threshold

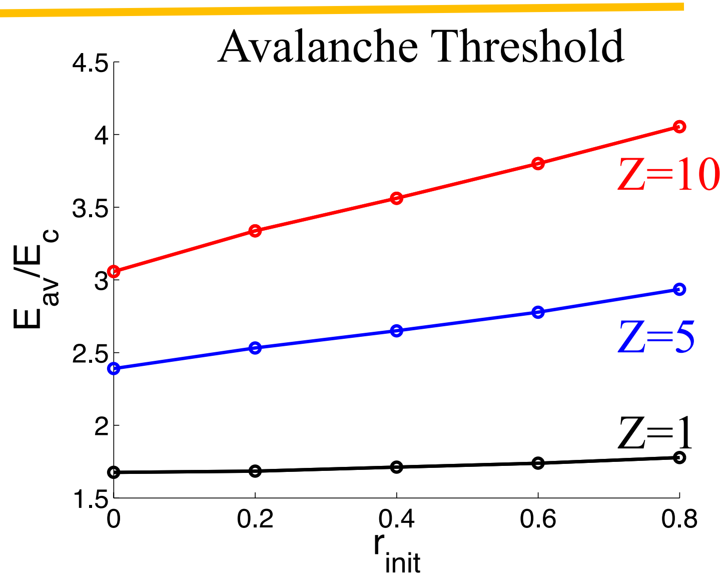


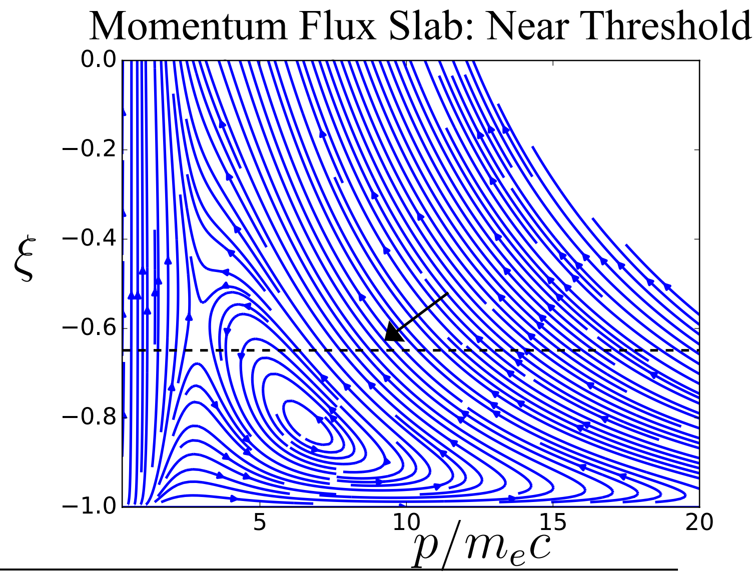
Momentum Flux Torus: Above Threshold



Impact of Toroidicity on Avalanche Threshold (cont'd)

- Threshold more strongly affected for high-Z_{eff} plasmas
- Presence of high-Z_{eff} ions enhances pitch-angle scattering
  - Broadens runaway distribution in pitch
  - Runaways more strongly affected by trapped passing boundary
- Trend not captured in early studies due to the neglect of synchrotron radiation





Collisional Transport of Runaway Electrons

- Collisional transport of runaway electrons is often assumed to be negligible
- The collisional transport of runaway electrons can be estimated as:

$$\frac{\tau_c D_{RA}}{a^2} \approx f_t^{RA} \frac{\Delta r^2}{2a^2} \tau_c \nu_D \approx \frac{f_t^{RA}}{2} \left(\frac{c}{a\omega_{c\theta}} \right)^2 (Z_{eff} + 1)$$

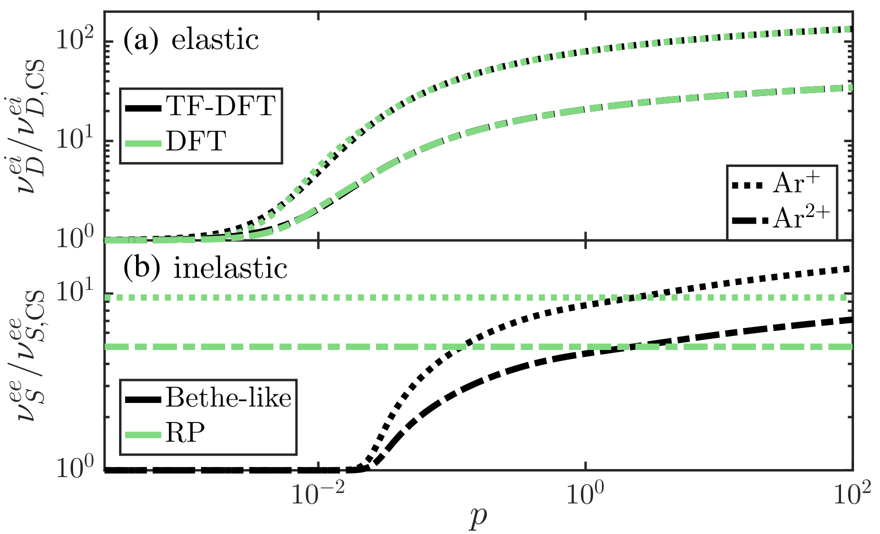
- where $\Delta r \sim c\gamma/\omega_{c\theta}$ (banana width of runaway), $\tau_c \nu_D \sim (Z_{eff} + 1)/p^2$, and f_t^{RA} is the fraction of trapped runaway electrons
- Comparing with thermal electrons yields (banana regime)

$$\frac{D_{RA}}{D_{Te}} \sim \frac{f_t^{RA}}{f_t} \frac{v_{Te}}{c} \ll 1$$

- Implies negligible transport of runaway electrons due to collisions

Impact of Plasma Impurities/Partial Screening

Hesslow et al. 2017



- Impurities often injected as a means of mitigating the heat load during the thermal quench
  - Radiate a significant fraction of thermal energy
- Resulting plasma composed of:
  - A low temperature bulk plasma containing weakly ionized impurities
  - Relativistic electrons
- Relativistic electrons able to probe internal structure of partially ionized impurity
  - Runaway electrons able to probe unshielded nuclei ➔ enhanced pitch-angle scattering by a factor related to Z^2
  - Runaway electrons able to slow down against bound electrons ➔ enhances drag by a factor of order Z

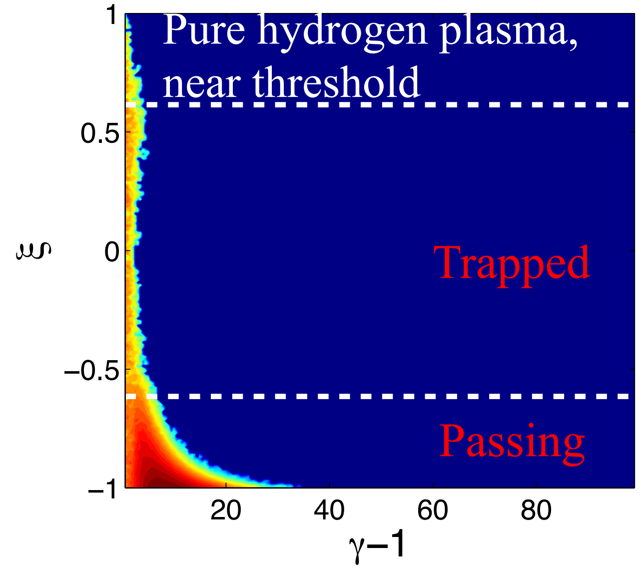
Consequences for Runaway Electron Distribution/Tranpsort

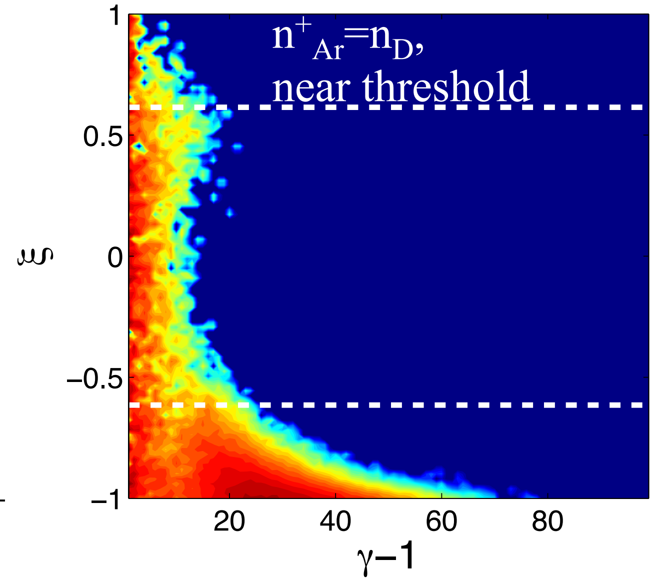
- Enhanced collisional scattering due to partial screening leads to broader distribution in pitch of runaway electron distribution

- Collisional transport drastically enhanced:

$$\frac{\tau_c D_{RA}}{a^2} \approx f_t^{RA} \frac{\Delta r^2}{2a^2} \tau_c \nu_D$$

  - Pitch-angle scattering enhanced by roughly two orders of magnitude
  - Finite trapped particle fraction at high energies





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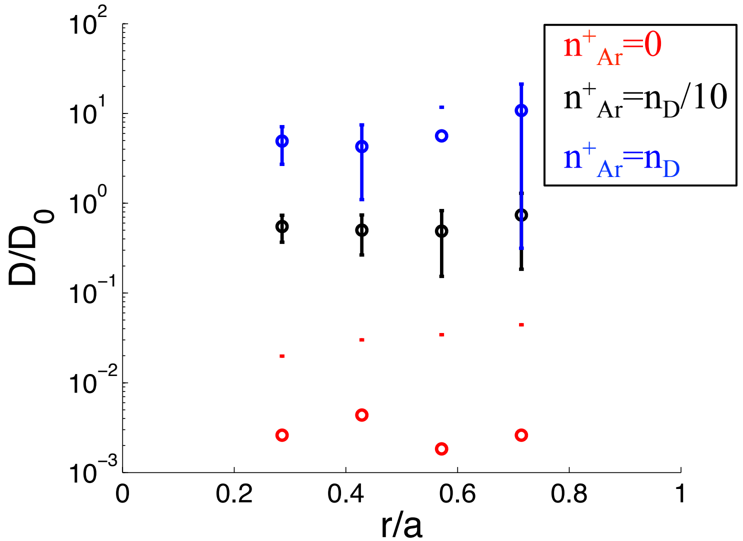
Spatial Transport of Runaway Electrons: Diffusion

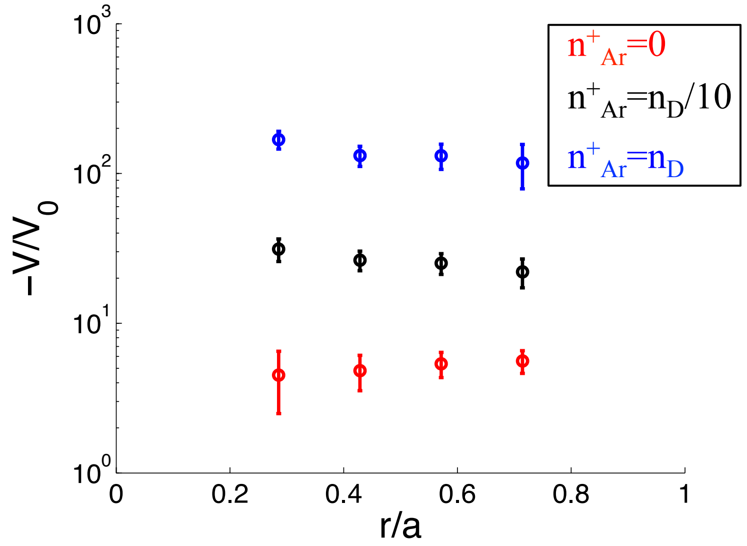
- Collisional diffusion of runaway electrons dramatically enhanced by partially ionized impurities
  - A small amount of argon impurities enhances transport by more than an order of magnitude
  - Collisional diffusivity increases with the amount of argon fraction

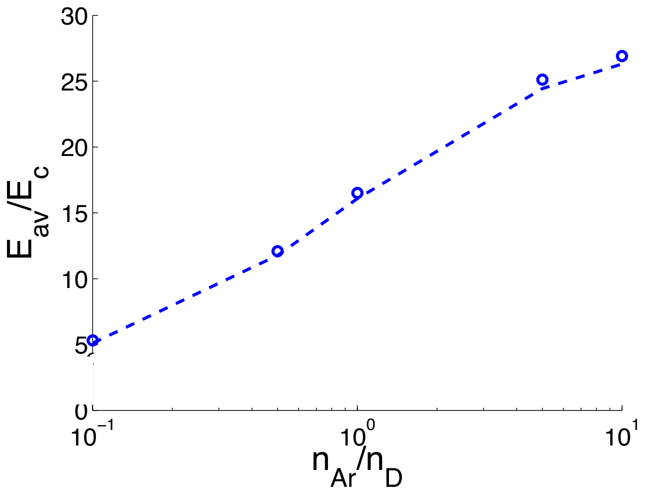


Spatial Transport of Runaway Electrons: Convection

- Convection velocity similarly enhanced
- Convective transport enhanced via two mechanisms:
  - The presence of a significant impurity population increases the magnitude of the inductive electric field necessary to sustain a runaway electron population
  - The increase of pitch-angle scattering results in a larger population of energetic trapped electrons ⇔ allows significant contribution from the Ware pinch

$$\Gamma_r^{Ware} \sim -f_t^{RA} \frac{E_\varphi}{B_\theta}$$





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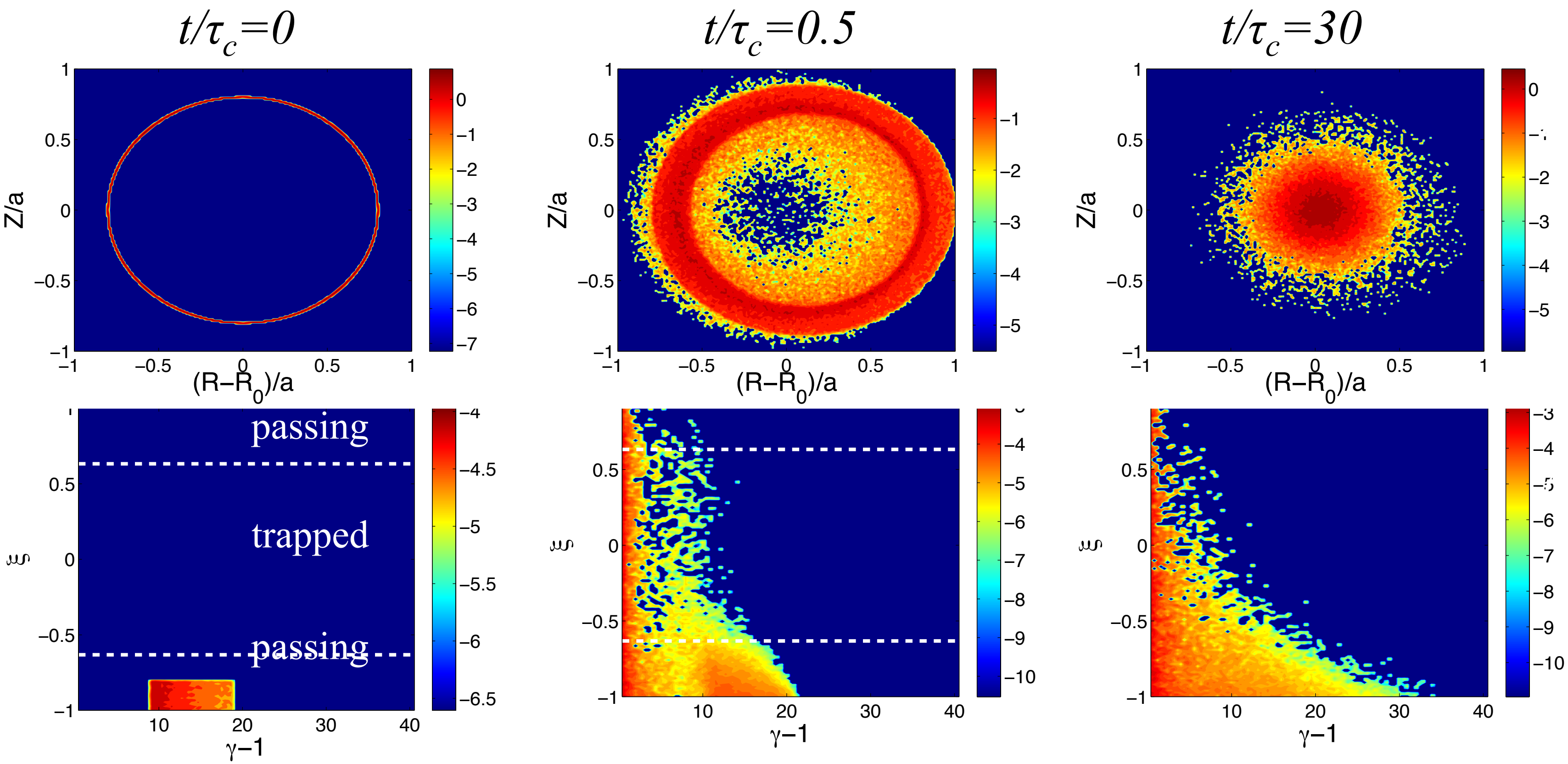
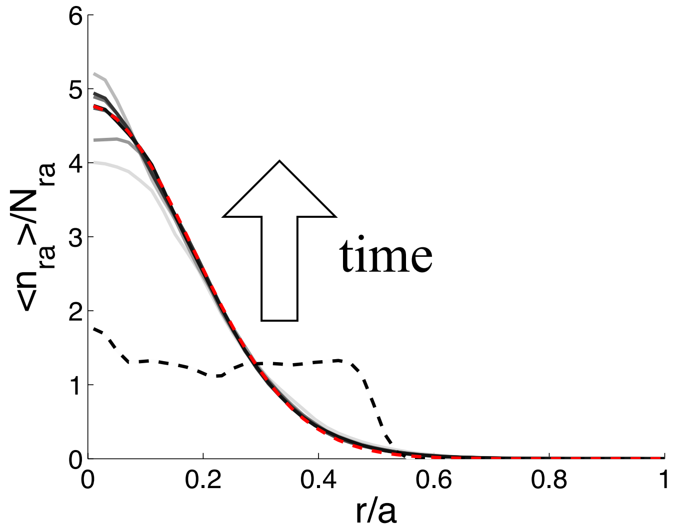
Spatial Transport: Role of Ware Pinch

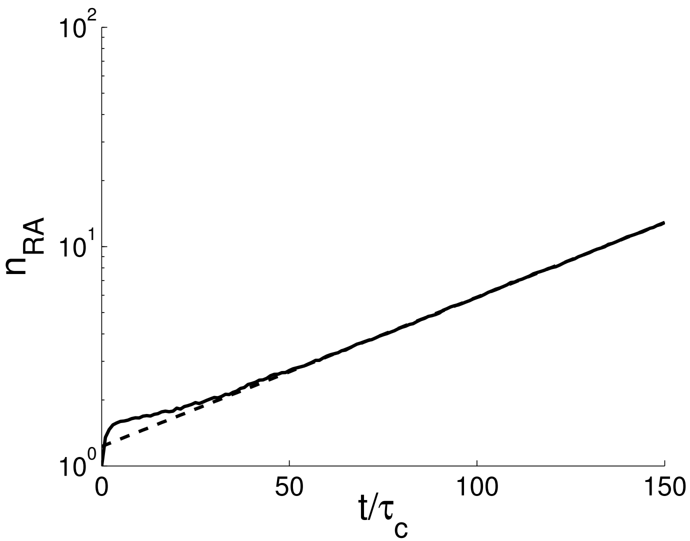


- Considering a ring of electrons initialized at a large radius (DIII-D like case)
  - Strong pitch-angle scattering leads to the formation of energetic particle population
  - Ware pinch convects a small fraction of energetic electrons inward
  - Inwardly convected electrons are detrapped ➔ run away
  - Provide "seed" for avalanche instability near $r/a \approx 0$
- Resulting runaway population strongly peaked near tokamak origin
  - Final state largely independent of phase space distribution of "seed" electron population

Formation of Runaway Spatial Eigenmode

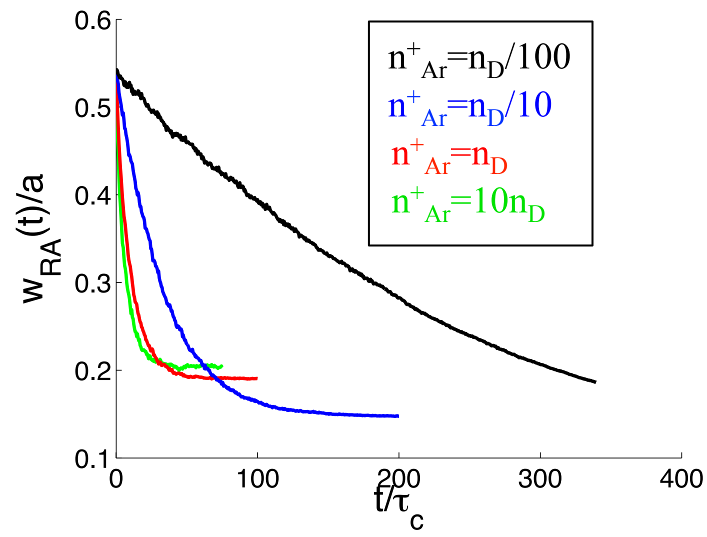
- Runaway electrons tend toward a spatial eigenmode in long time limit
- Focusing of runaway electrons near origin is due to:
  - Inward convection, primarily due to the Ware pinch
  - Peaking of the avalanche growth rate near $r/a \approx 0$
- Finite spatial spread determined by:
  - Diffusion of runaway electrons
  - Finite orbit width

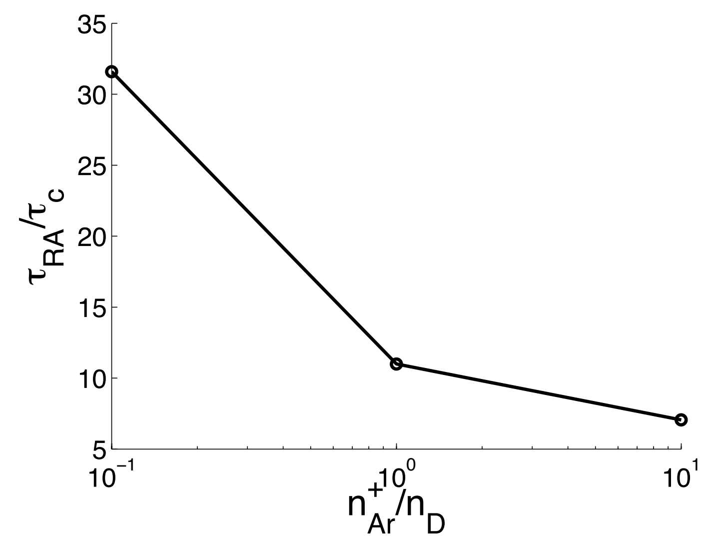




Eigenmode Width and Relaxation Time

- Width and relaxation time to a spatial eigenmode depends sensitively on the impurity fraction of the plasma
- Larger impurity fraction tends to increase the eigenmode width, reduce the timescale τ_{RA} for the relaxation to the eigenmode
- Pure hydrogen plasmas unlikely to collapse to runaway eigenmode on experimentally relevant time scales





Conclusions

- The transport of runaway electrons can be significant during conditions typical of actively mitigated disruption scenarios even when good flux surfaces are present
  - Requires extension of momentum space formulations to account for real space transport

- The presence of partially ionized impurities:
  - significantly enhances transport
  - aids in establishing centrally peaked runaway electron distribution

- In the long time limit, runaway electrons form a spatial eigenmode near the tokamak origin
  - Spatial eigenmode independent of runaway seed ⇔ enabled by spatial transport

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Impact of Self-Consistent Evolution of Inductive Electric Field

- Axisymmetric electric field evolved by:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$

- where $E_{\|} = \eta \left(j_p - j_{RA} \right)$
- Self-consistently computed inductive electric field has non-trivial structure
  - Conducting wall boundary condition forces inductive electric field to decay at larger radii
  - Rapid generation of runaways near $r/a \approx 0$ can result in a hollow profile
- Transient evolution of the runaway spatial profile strongly affected
  - Spatial mode width more weakly impacted