Runaway electron control via resonant wave-particle interaction

Xianzhu Tang[1], Nathan Garland[1], Qi Tang[1], Zehua Guo[1], Chris McDevitt[2], Carlos Paz-Soldan[3], Chang Liu[4], Jayhyun Kim[5], Hyun-Kyun Chung[5]

[1]Los Alamos National Laboratory, [2]University of Florida, [3]General Atomics, [4]PPPL, [5]NFRI, Korea

Theory & simulation supported by U.S. DOE through Tokamak Disruption Simulation (TDS) and SCREAM SciDAC Projects, & Base Theory Program

Outline

- ***What can be accomplished by active mitigation of runaway electrons via resonant wave-particle interaction (WPI)***
    - *Control runaway electron energy & current quench (CQ) duration*
- ***Physics basis from theory and simulation → experimental design options and constraints***
    - *How to limit runaway energy and current quench duration*
- ***Experimental motivation and basis (mostly passive mitigation)***
    - *Resonant WPI from runaway-excited waves → Enhanced pitch angle scattering, reduced runaway energy, increased runaway dissipation (avalanche threshold), shortened CQ duration*
- ***Future experimental plans (on active mitigation)***
    - *Compressional Alfven wave (CAE) and helicon (whistler)wave injection on DIII-D, helicon on KSTAR*

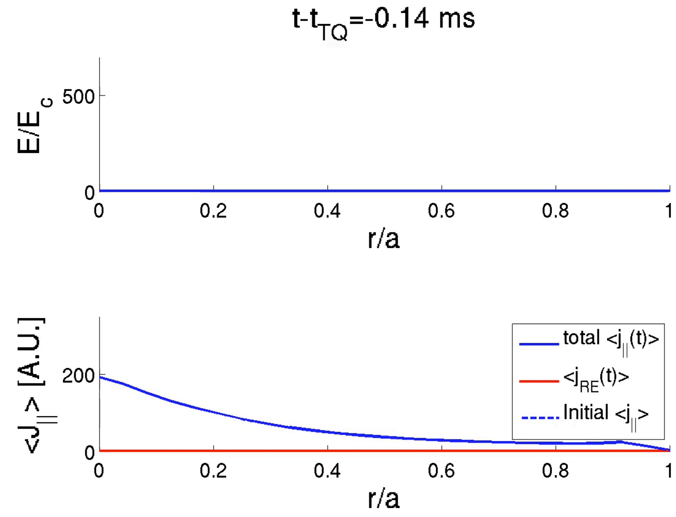
Why we are interested in resonant WPI for runaway control

- ***What can be accomplished by active mitigation of runaway electrons via resonant wave-particle interaction***
    - ***Control runaway electron energy & current quench (CQ) duration***
- *Physics basis from theory and simulation → experimental design options and constraints*
    - *How to limit runaway energy and current quench duration*
- *Experimental motivation and basis (mostly passive mitigation)*
    - *Resonant WPI from runaway-excited waves → Enhanced pitch angle scattering, reduced runaway energy, increased runaway dissipation (avalanche threshold), shortened CQ duration*
- *Future experimental plans (on active mitigation)*
    - *Compressional Alfven wave (CAE) and helicon (whistler)wave injection on DIII-D, helicon on KSTAR*

Two primary objectives in disruption mitigation if runaways are unavoidable

Limit the CQ duration on ITER

- ***Not too short > 30 ms → to avoid blanket module damage by eddy current***
  - ***Plasma's natural response against a fast CQ is to convert Ohmic current to runaways (far less dissipative)→ too short a CQ has not been a major concern (should it be?)***
- ***Not too long < 150 ms → to avoid too large a halo current and hence damage to vacuum vessel***
  - ***Long CQ → large halo current is sound physics-wise but 150 ms comes from an empirical scaling (how well does it extrapolate to ITER?), but good to be conservative (have knobs to shorten CQ).***



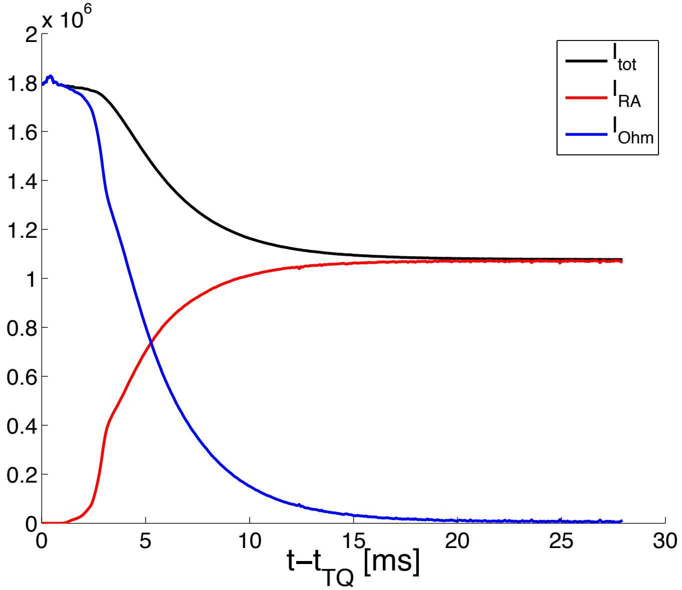
- The inductive electric field is evolved via

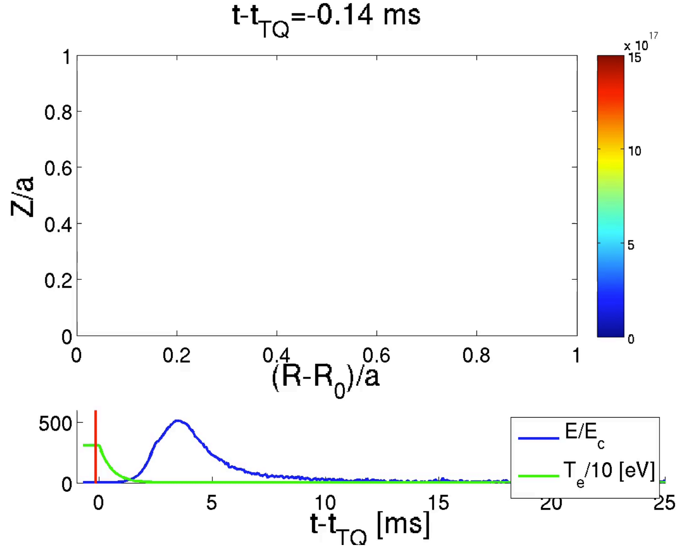
$$E_{\parallel} = \eta\left(j_p - j_{RA}\right)$$

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

- Seed formation due to hot tail electrons
- Once RE beam forms, electric field drops → hollow E-field profile forms due to peaked RE current profile
- Unmitigated H plasmas have long-lasting runaway plateau

TDS Simulation: McDevitt & Tang

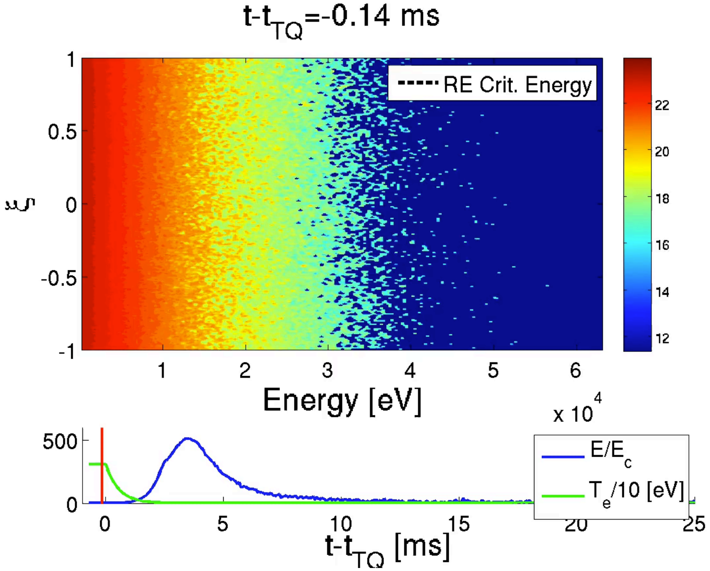




Two primary objectives in disruption mitigation if runaways are unavoidable

Limit the runaway energy on ITER

- ***Runaway current scales as runaway density multiplying light speed: n_{RE} c***
- ***Power load on material surface scales as runaway current multiplying the runaway kinetic energy: $n_{RE}\, c\, (\gamma-1) mc^2$***
  - ***High runaway energy: large γ leads***
    - ***More heat deposition on the wall for surface damage***
    - ***For given pitch, higher energy → deeper penetration into the wall → increased potential for costly subsurface damage***
- ***Active mitigation to drop γ from 20-30 to 2-3 would be impactful if possible***

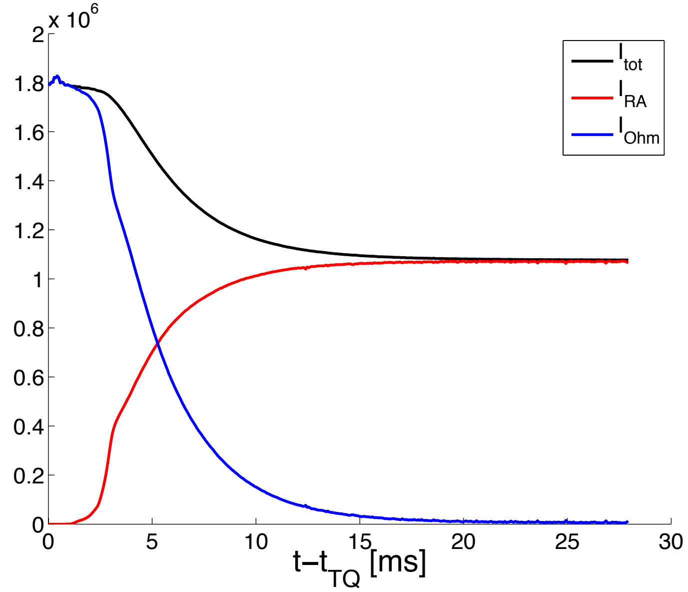


- The inductive electric field is evolved via

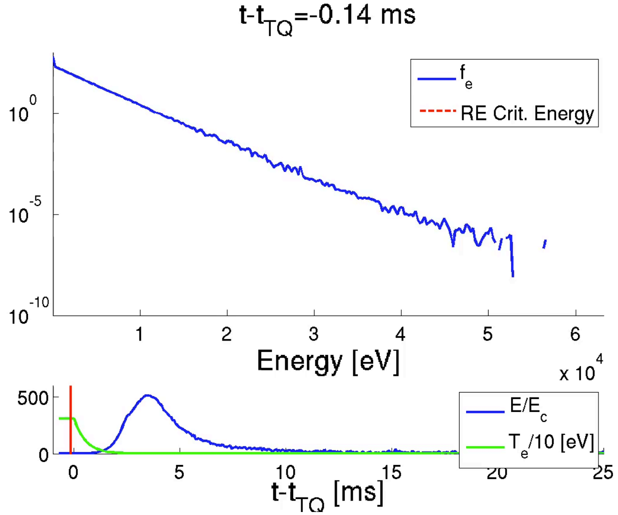
$$E_\parallel = \eta\left(j_p - j_{RA}\right)$$

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

- Seed formation due to hot tail electrons
- With a hot tail seed, avalanche amplifies the runaway current and runaway energy grows to 10’s of MeV in a beam-like distribution



TDS Simulation: McDevitt & Tang



Physics basis for controlling CQ rate & runaway energy by resonant WPI

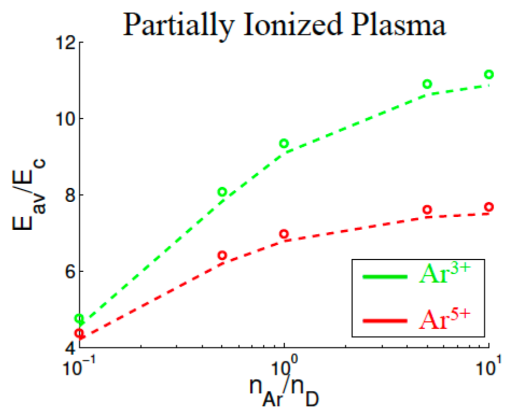
- *What can be accomplished by active mitigation of runaway electrons via resonant wave-particle interaction*
  - *Control runaway electron energy & current quench (CQ) duration*
- ***Physics basis from theory and simulation → experimental design options and constraints***
  - ***How to limit runaway energy and current quench duration***
- *Experimental motivation and basis (mostly passive mitigation)*
  - *Resonant WPI from runaway-excited waves → Enhanced pitch angle scattering, reduced runaway energy, increased runaway dissipation (avalanche threshold), shortened CQ duration*
- *Future experimental plans (on active mitigation)*
  - *Compressional Alfven wave (CAE) and helicon (whistler)wave injection on DIII-D, helicon on KSTAR*

What controls the current quench duration in the presence of runaways?

- ***Faraday's law →*** ***E field controls the CQ rate (duration)***
  - ***Loop voltage sets the rate for poloidal flux removal***
  - ***E· J sets the rate for magnetic energy dissipation***
- ***What sets the E field?***
  - ***During Ohmic→ runaway current conversion, cooling history through $\eta(T_e)$: $E = \eta\, j_{Ohmic}$***
  - ***After Ohmic→ runaway current conversion, avalanche threshold field: $E \approx E_{av}$***

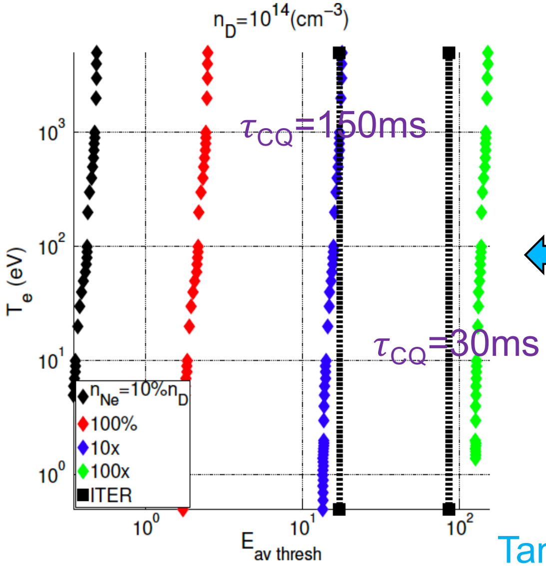
Standard design to raise E_{av} and hence shorten CQ on ITER (physics basis: collisional drag sets Connor-Hastie critical field)

- ***Raise the free electron density: massive D2 injection***
- ***Raise the bound electron density (partial screening & Bethe stopping): massive high-Z impurity injection***
  - ***Impurity density requirement is very high for ITER***
    - ***Side effect: Te must be radiatively clamped so low that runaway avoidance is impossible (fine if we can live with runaways)***



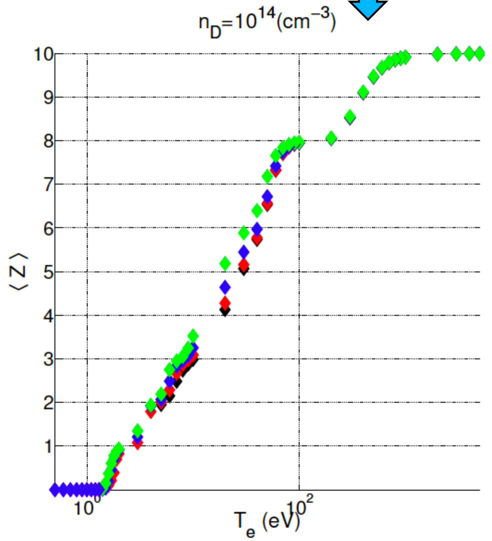
Fixed ion charge

TDS calculation: Given atomic densities of D and Ne, compute ion charge states for each Te using FLYCHK, and then evaluate E_{AV} solving an O-X merger model



τ_{CQ}=150ms

τ_{CQ}=30ms



Tang et al, TTF (2018)

How to access E> E_{AV} with resonant WPI after Ohmic-runaway conversion?

Momentum space dynamics of runaway vortex that sets E_{AV} !

- ***Emergence of runaway vortex (an effective runaway retainer) allows avalanche growth → threshold physics***
  - ***With a normal hydrogen plasma, vortex size does not matter much → threshold is mostly a topological transition***
  - ***With massive impurity injection, vortex size does matter → threshold has a geometrical dependence***
    - ***Why: p_X is upshifted (by enhanced drag) so p_O must be large enough to kick secondaries into runaway vortex***
    - ***Consequence: magnetic trapping and pitch angle scattering obtain more prominent roles***

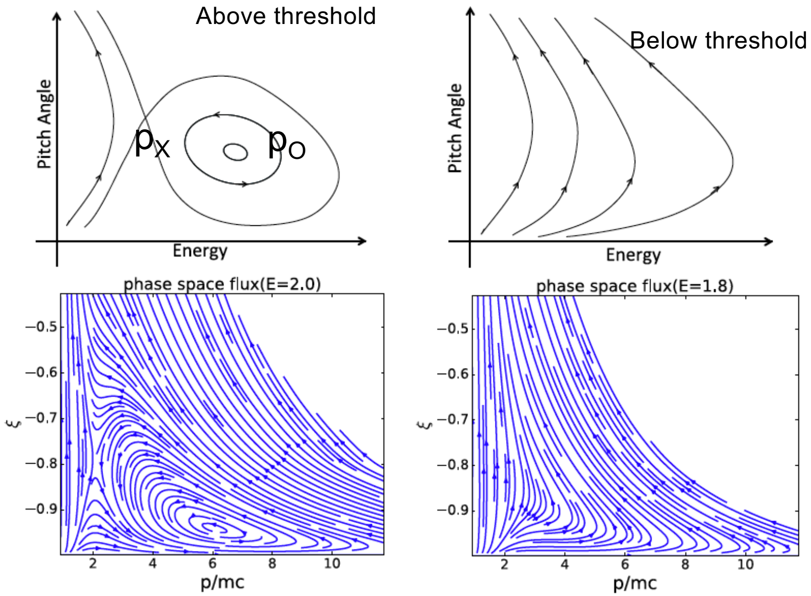
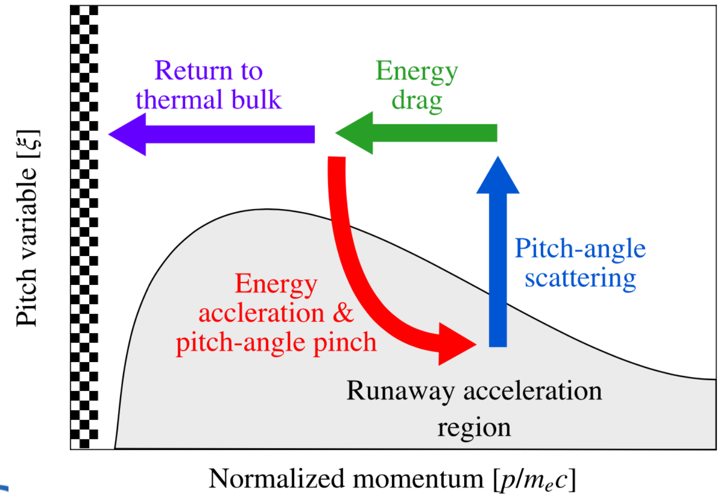
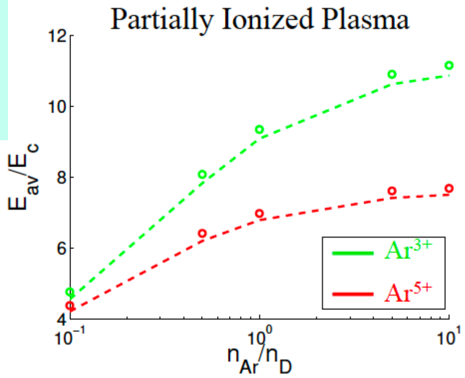
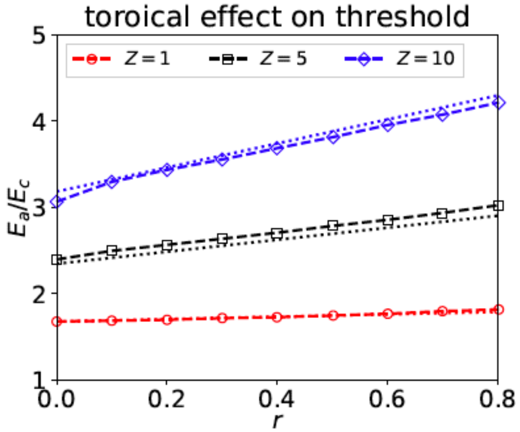


Figure 1. Momentum space topology of the primary runaway population before (top and bottom left) and after (top and bottom right) the O–X merger. The parameters are $Z_{\text{eff}} = 1$, $v_{Te}/c = 0.1$, and $\alpha = 0.2$.



Guo, McDevitt, Tang, PPCF (2017);
McDevitt, Guo, Tang, PPCF (2018, 2019);
Guo, McDevitt, Tang, PoP (2020)





resonant WPI → pitch angle scattering

Use resonant WPI to create a momentum space drain to access E > E_{AV}

With a trapped zone in moment space, Doppler-shifted cyclotron resonance → pitch-angle scattering → runaways are drained into the trapped region → return to bulk

$$\frac{\partial f}{\partial t} = \gamma_{av}\, f + \frac{\partial}{\partial \zeta} D_{\zeta\zeta} \frac{\partial f}{\partial \zeta} \quad \rightarrow \gamma = \gamma_{av} - k_{\zeta}^{2}\, D_{\zeta\zeta}$$

→ Access E>E_{av} operation → shorten CQ

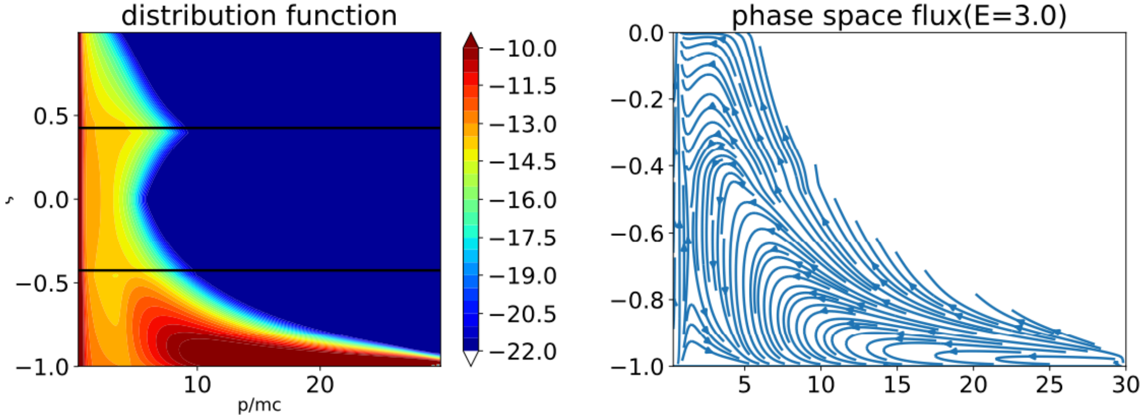


Figure 6.8: No wave injection, just toroidal effect. $\epsilon = 0.1, w_0 = 0, E = 3E_c, v_t = 0.1c, \alpha = 0.1$.

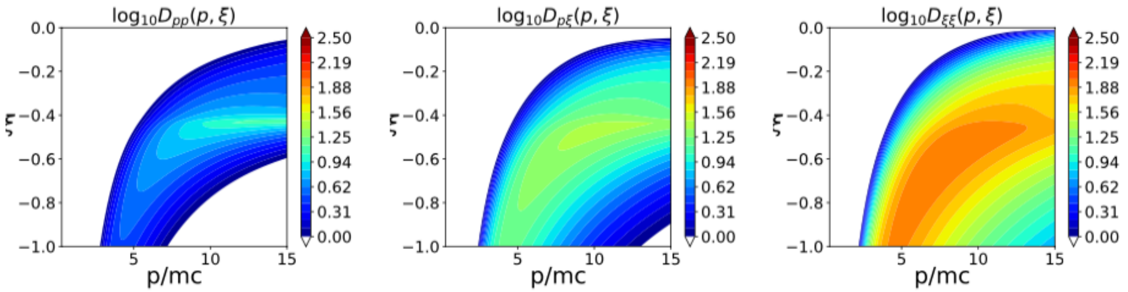


Figure 6.7: Contour plot of the bounce-averaged quasilinear diffusion operator with $w_0 = 2.5e-11, k_{\parallel 0} = 0.2, k_{\perp 0} = 0.1, \Delta k_{\parallel} = 0.05, \epsilon = 0.1$.

$$\boxed{\omega - k_{\parallel} v_{\parallel} = \Omega/\gamma;\ k_{\parallel} v_{\parallel} < 0}$$

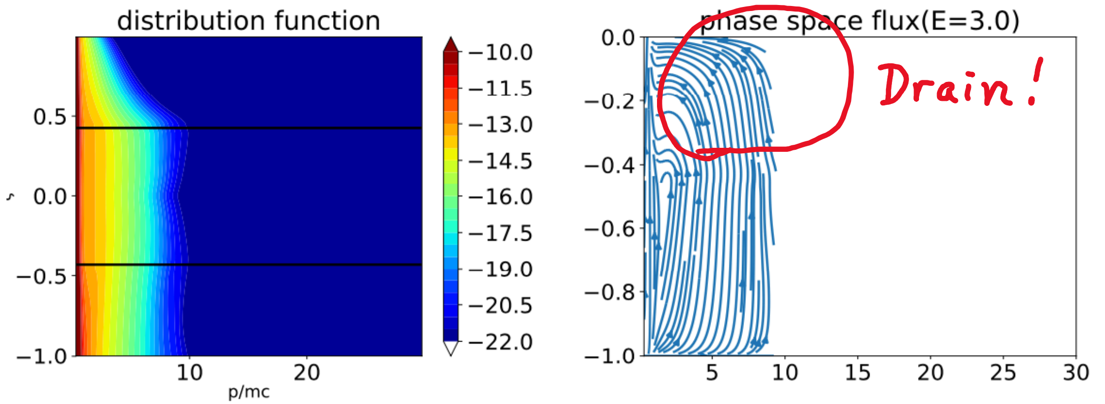
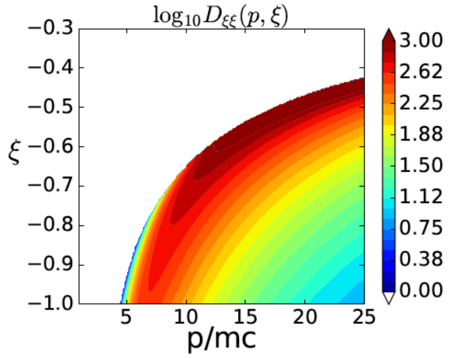


Figure 6.10: With wave injection, $\epsilon = 0.1, w_0 = 5e-11, k_{\parallel 0} = 0.2, k_{\perp 0} = 0.1, \Delta k_{\parallel} = 0.1, \epsilon = 0.1$.

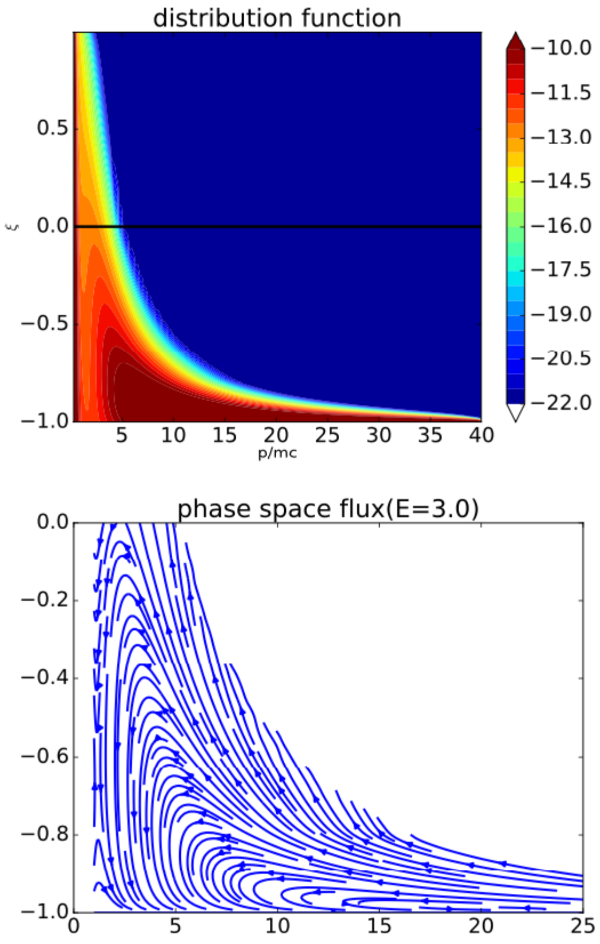
TDS Simulation: Guo & Tang

Moment space drain needs large trapped regions to be most effective

- **On magnetic axis where there is no trapped region, the same wave mixture reshapes the runaway vortex but can not shrink it sufficiently to avoid avalanche growth.**
- **This is because the runaways have to be pitch angle scattered across the ζ=0 boundary, where there is no resonant WPI in low to medium relativistic range**

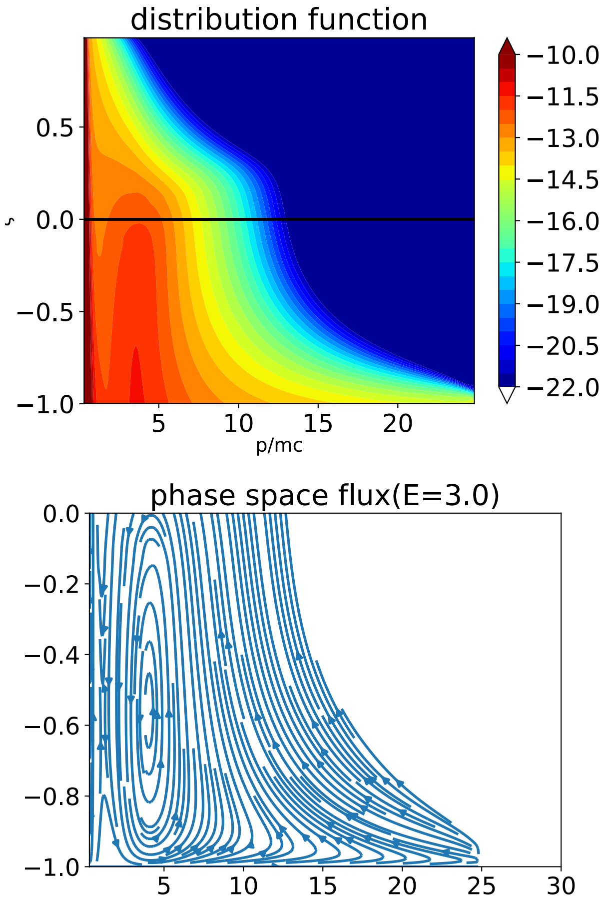


No wave



$E = 3E_c, \alpha = 0.2, v_t = 0.1c$, Z=1

With wave



$\epsilon = 0, same\ waves\ as\ in\ Fig. 6.10\ (slide\ 9)$

TDS Simulation: Guo & Tang

Spatial transport due to resonant WPI can allow access E > E_{AV}

- Spatial transport → runaway drain in configuration space → effectively damp avalanche growth rate
  - Assume a spatial eigenmode for runaway avalanche growth, Helander, Eriksson, Andersson (PoP, 2000) illustrated avalanche damping by runaway deconfinement

$$\frac{\partial n_{RE}}{\partial t} = \gamma_{av}\, nR_E + \frac{\partial}{\partial r} D_{rr} \frac{\partial n_{RE}}{\partial r} \quad \rightarrow \gamma = \gamma_{av} - k_r^2 D_{rr}$$

- Runaways → magnetic trapping → radial transport of trapped runaways is actually not an effective pathway for runaway deconfinement
  - Why: for large E required for ITER, Ware pinch is strong → runaways from outer flux surfaces becomes trapped and then Ware pinched inward to provide the seed runaway in the interior → how spatial eigenmode with central peaked current density profile is formed (McDevitt, Guo, Tang, PPCF, 2019)
- Radial loss of passing runaways is required for effective avalanche damping
  - Stochastic B field is a favorite mechanism for passing runaway loss (most studied)
  - Resonant WPI → pitch angle scattering → produce radial transport of passing runaways
    - Which one is more effective in damping avalanche rate
      - Momentum space drain or configuration space drain
    - Current research explores a variety of ways for enhanced radial loss of passing runaways (e.g. CAE)

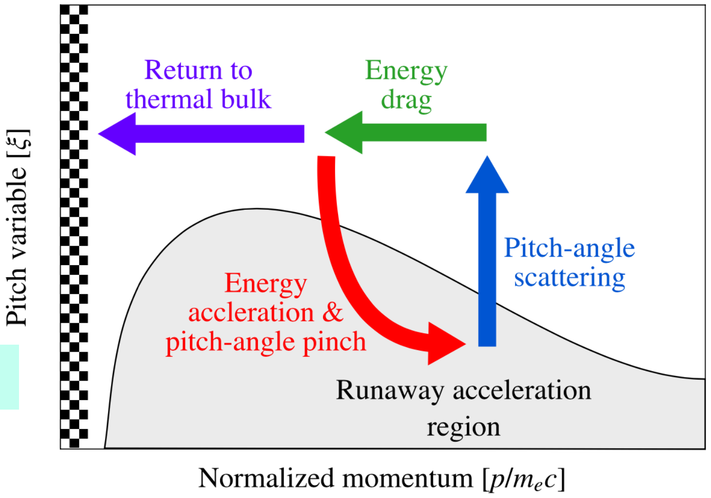
What controls the runaway energy (upper bound) for given E field?

$$\frac{\partial f_e}{\partial t} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\Gamma_p\right) + \frac{1}{p}\frac{\partial}{\partial \xi}\left(\sqrt{1-\xi^2}\,\Gamma_\xi\right) = 0.$$

$$\Gamma_p = \Big[\underbrace{-\xi\bar{E}}_{\text{E field acceleration}} \overbrace{-C_F}^{\text{collisional friction}} \underbrace{-\alpha p\gamma\left(1-\xi^2\right)}_{\text{synchrontron radiation force (damping)}} \overbrace{+C_A\frac{\partial \ln f_e}{\partial p}}^{\text{energy diffusion}}\Big] f_e$$

$$\Gamma_\xi = -\sqrt{1-\xi^2}\Big(\overbrace{\bar{E}}^{\text{E field pitch pinching}} \underbrace{-\alpha\frac{p}{\gamma}\xi}_{\text{synchrontron radiation pitch pinching}} + \overbrace{\frac{p}{2}\nu_D\frac{\partial \ln f_e}{\partial \xi}}^{\text{pitch angle scattering}}\Big) f_e.$$

Pitch-angle scattering holds the key for vortex turn-around at high p



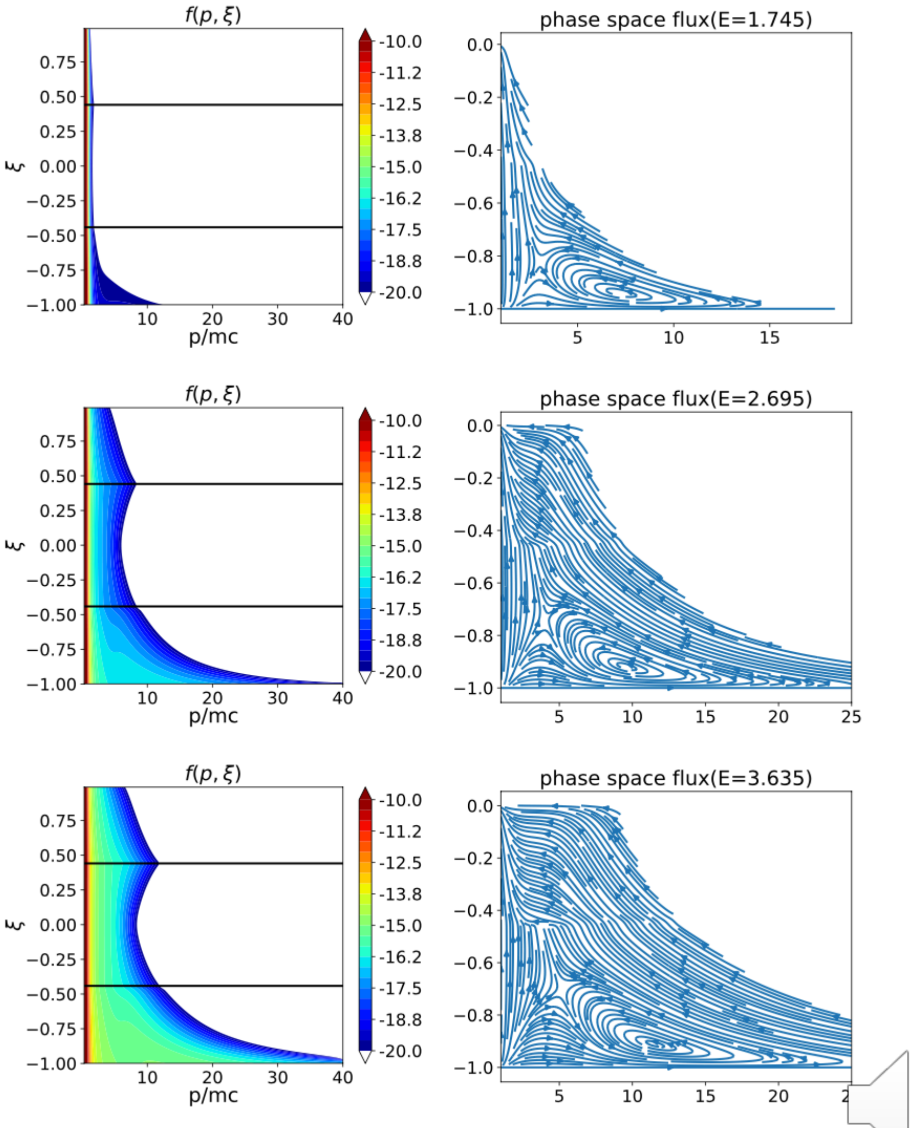


Figure 6.19: Primary runaway electron distribution and fluxes at the avalanche threshold when $\epsilon = 0.1$. Top: $Z = 1$, Middle: $Z = 5$, Bottom: $Z = 10$.

TDS Simulation: Guo, Garland, Tang

Runaway energy control by resonant WPI is less demanding than raising E_{av}

Broad spectrum/resonance region, not high enough amplitude to suppress avalanche, but adequate to drastically lowers the runaway energy

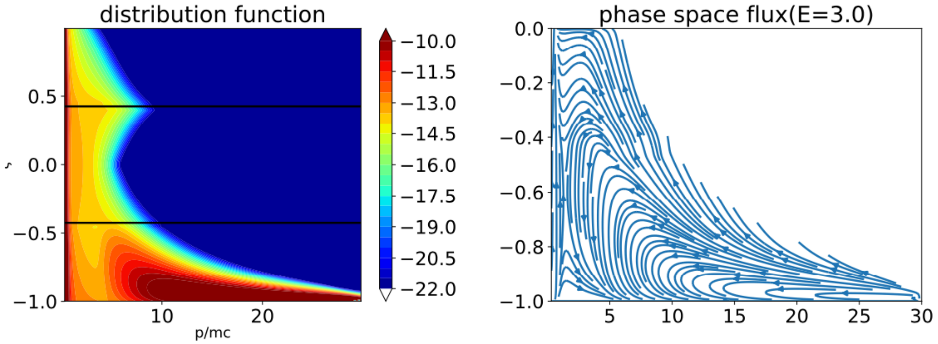


Figure 6.8: No wave injection, just toroidal effect. $\epsilon = 0.1, w_0 = 0, E = 3E_c, v_t = 0.1c, \alpha = 0.1$.

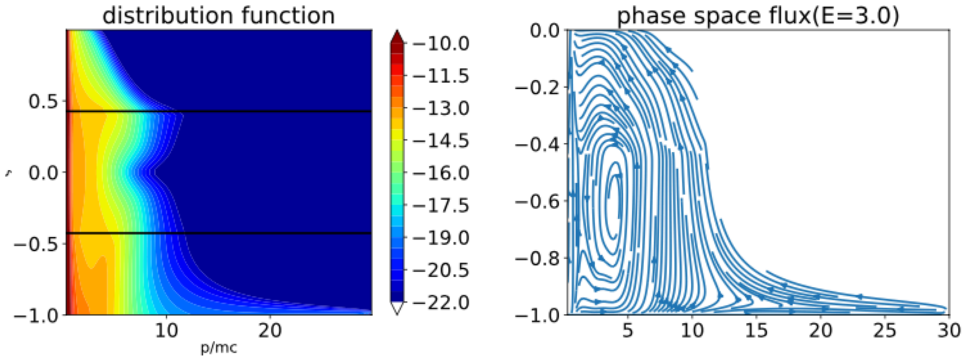


Figure 6.9: With wave injection. $\epsilon = 0.1, w_0 = 1e-11, k_{\parallel 0} = 0.2, k_{\perp 0} = 0.1, \Delta k_{\parallel} = 0.1$.

Narrow resonance layer can perform runaway vortex surgery at precisely targeted (low) runaway energy upper bound

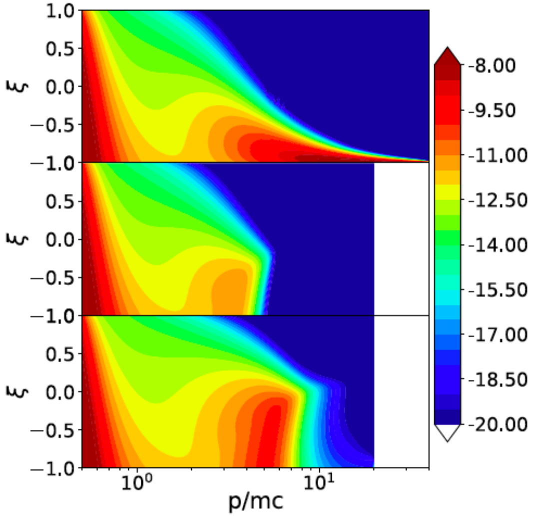
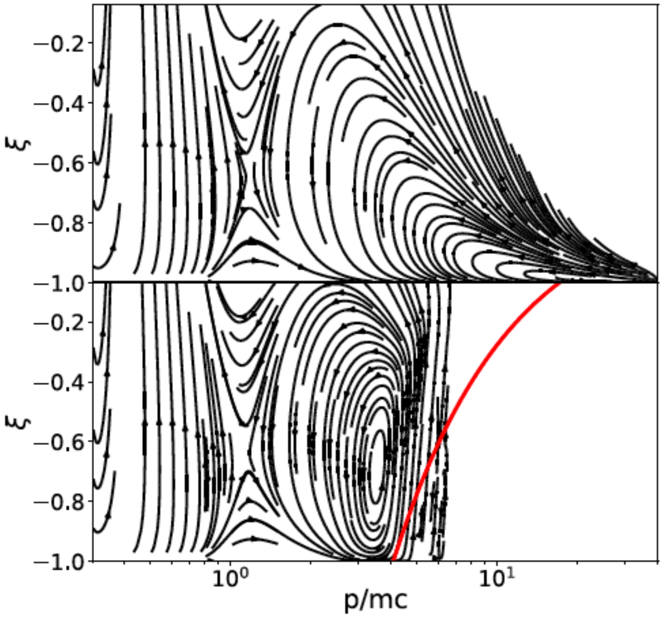


FIG. 3. The contour plots for steady-state distribution of primary runaway electrons with and without whistler waves. The figure shows the contour of $\log_{10} f(p, \xi)$ without waves (top) and with waves (middle with $\alpha = 0.2$ and bottom with $\alpha = 0.05$).



$$\omega - k_{\parallel} v_{\parallel} = \Omega/\gamma;\ k_{\parallel} v_{\parallel} < 0$$

Laurent & Rax (1990): ω=0 version (field ripples) → damp extremely high energy runaways → Tore Supra observation

$$|k_{\parallel} v_{\parallel}| = \Omega/\gamma$$

Avalanche electrons follow primary runaway vortex in energy distribution

Avalanche electron distribution tends not to have the bump in primary distribution. In f(v) plot, red line is f(p,ζ=-1) and black line is pitch integrated.

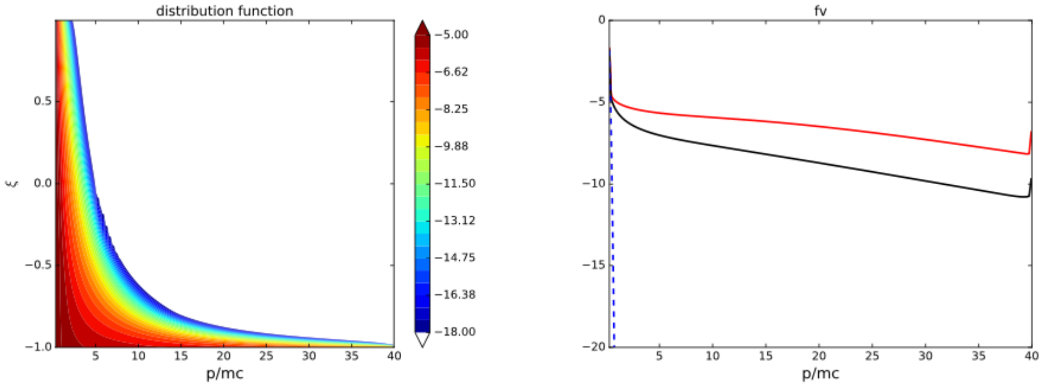
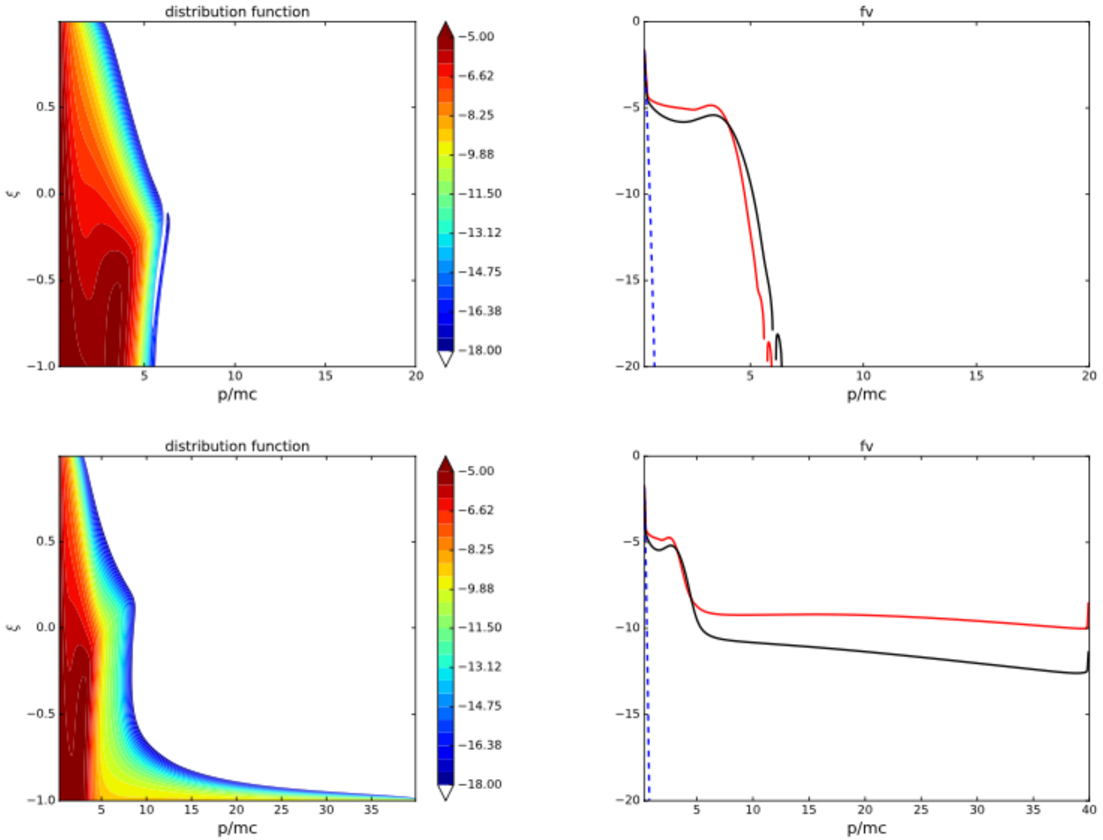


Figure 5.21: Contour plot of the electron distribution at $J_{re} \simeq 2.5MA/m^2$ without whistler waves. The parameters are $E = 3.0E_c$, $\alpha = 0.2$, $v_t = 0.1c$.

The resonant WPI energy barrier in momentum space not only limits runaway energy in avalanche growth, but also drains the pre-existing high energy runaways. Works even better at outer flux surfaces (larger trapping zone)

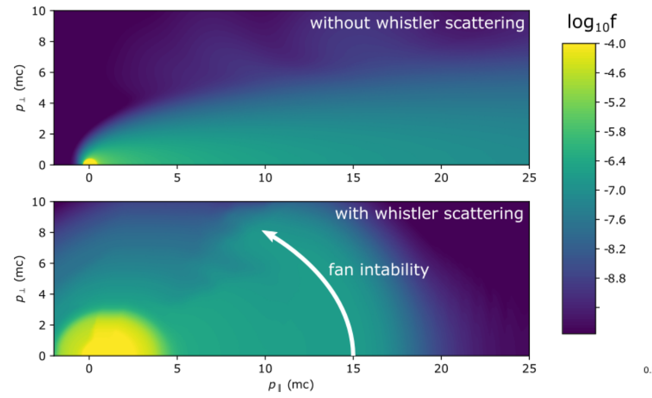


Same wave field energy density. Bottom plot has resonance at lower p than top plot, hence wave amplitude becomes sub-critical

What we do differently in active versus passive mitigation?

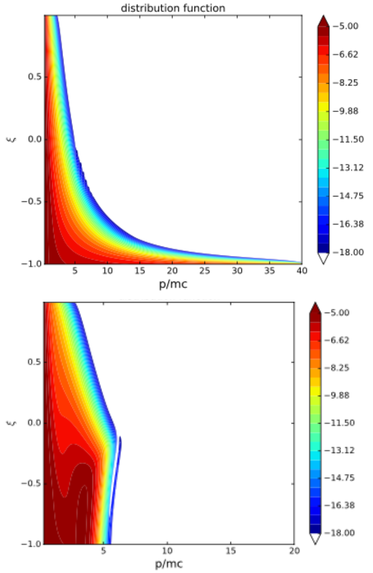
- **Passive mitigation by runaway self-generated wave instabilities (long history of research)**
  - Instability drive is high energy tail (for the narrower pitch spread) through the anomalous Doppler-shifted cyclotron resonance
    - Waves co-propagate in runaway direction
  - Pitch-angle scattering is on tail runaways
  - What about bump on tail?
    - Avalanche appears to remove the bump in primary runaway distribution, if not, bump-on-tail instability would
- **Active mitigation by externally injected waves**
  - Target <u>low energy runaways</u> via the normal Doppler-shifted cyclotron resonance → limit the runaways to much lower energy by design
    - Waves counter-propagate in runaway direction
  - Static error field approach by Rax et al necessarily push the resonance to much higher runaway energy
  - A more recent proposal is to target barely passing runaways near the trapped-passing boundary and/or trapped runaways via Landau resonance with CAE

$$\omega - k_{\parallel} v_{\parallel} = -\frac{\Omega}{\gamma};\ k_{\parallel} v_{\parallel} > 0$$



Liu, et al, PRL, 2018

$$\omega - k_{\parallel} v_{\parallel} = \frac{\Omega}{\gamma};\ k_{\parallel} v_{\parallel} < 0$$



$$k_{\parallel} v_{\parallel} = \Omega/\gamma$$

$$\omega - k_{\parallel} v_{\parallel} - k_{\perp} v_{\perp} = 0$$

Guo, McDevitt Ta

Collisional damping of the waves is a big issue → sets power requirement

- **Earlier estimate (Guo, McDevitt, Tang, PoP, 2018) of 800 KW power requirement for ITER**
  - Too conservative: it assumes multi-pass absorption so the wave field fills the entire chamber
  - Too optimistic for Te>10 eV range for high-Z impurity injection as the charge state is much higher
    - Additional complication: hard runaways (many MeVs) can boost the charge number at low Te (QED boosted-Zeff regime)

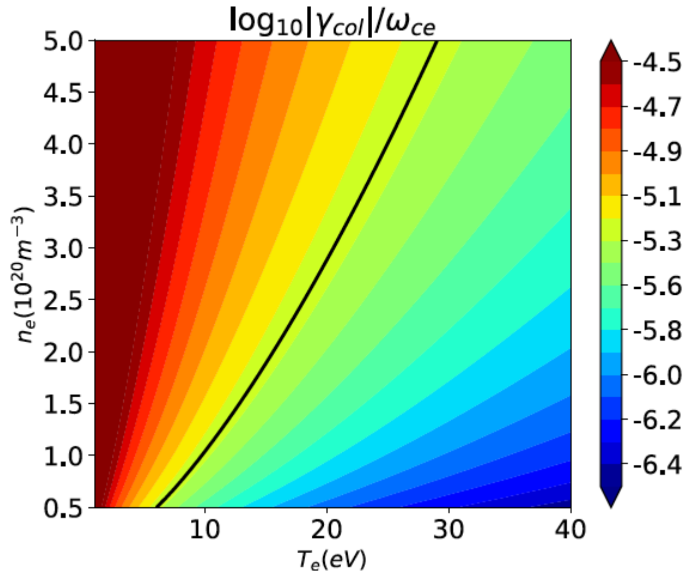
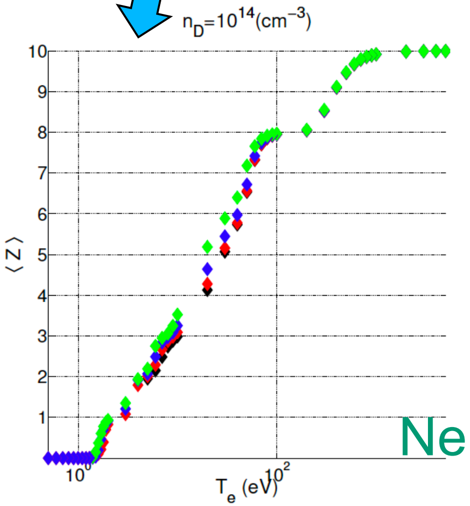
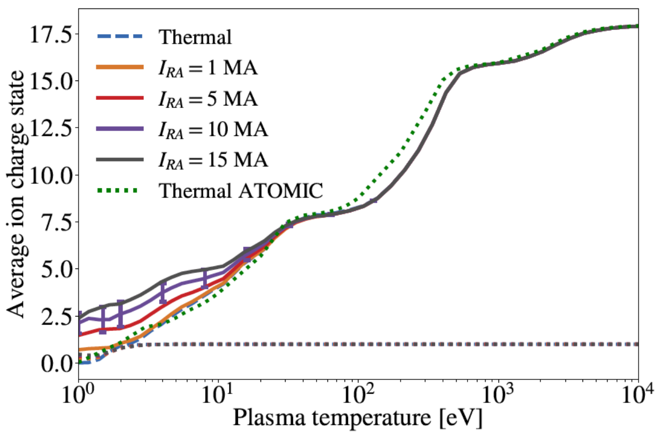


FIG. 10. The collisional (γ_{col}) damping rates as a function of plasma density and temperature for the desired whistler wave with $\omega = 0.05\omega_{ce}, kc/\omega_{ce} = 0.24, \theta = 0.1\pi$.





Garland, Chung, et al, Tang, PoP (2020)

- ***Potential work-arounds***
  - ***Localize wave mitigation at outer flux region where trapped zone is large***
  - ***Purge high-Z with D2 secondary injection***
  - ***Burn through the QED boosted-Zeff regime***

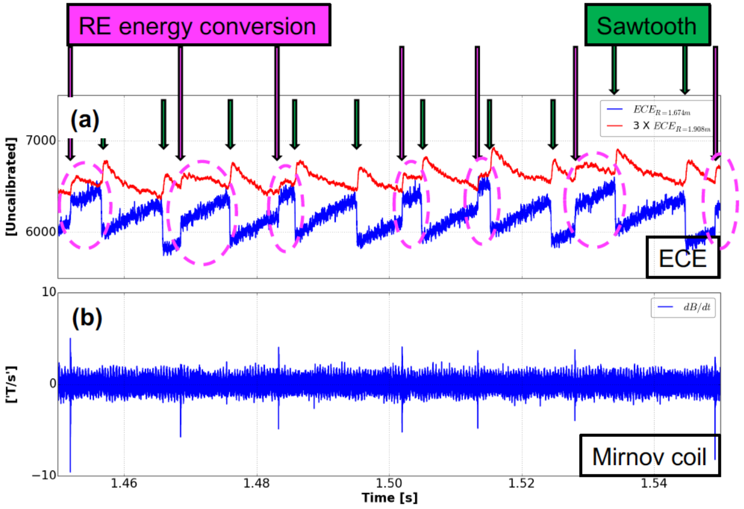
Experimental evidence of resonant WPI on runaways

- *What can be accomplished by active mitigation of runaway electrons via resonant wave-particle interaction*
  - *Control runaway electron energy & current quench (CQ) duration*
- *Physics basis from theory and simulation → experimental design options and constraints*
  - *How to limit runaway energy and current quench duration*
- ***Experimental motivation and basis (mostly passive mitigation)***
  - ***Resonant WPI from runaway-excited waves → Enhanced pitch angle scattering, reduced runaway energy, increased runaway dissipation (avalanche threshold), shortened CQ duration***
- *Future experimental plans (on active mitigation)*
  - *Compressional Alfven wave (CAE) and helicon (whistler)wave injection on DIII-D, helicon on KSTAR*

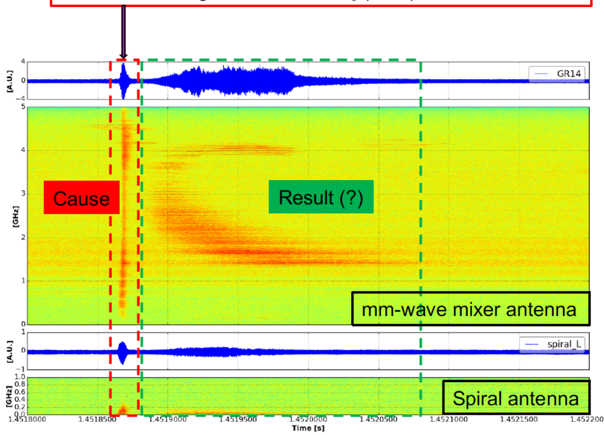
Experimental evidence of resonant WPI with runaways

- **Enhanced pitch angle scattering**
  - **KSTAR (Jayhyun Kim, ITPA-EP, 2020)**
  - **Textor (Finken, XVI EPS, Venice, 1989)**
- **Lowered runaway energy**
  - **Tore Supra (Chatelier, XVI EPS, Venice, 1989)**
  - **DIII-D (Spong, et al, PRL 2018; Liu, et al, PRL 2018)**
- **Raised E_{AV}**
  - **DIII-D (Paz-Soldan et al, PoP 2018; Liu, et al, PRL 2018)**
- **Shortened CQ duration**
  - **Textor (Zeng et al, PRL 2013): magnetic turbulence**
  - **DIII-D (A. Lvovskiy et al, PPCF 2018): CAE**
  - **JET also saw shortened CQ duration with less Ar (less collisional dissipation (Reux et al, 2020): no fast wave diagnostics though**

KSTAR, J. Kim



Just at the timing of short burst, T_e (ECE) starts to be raised.



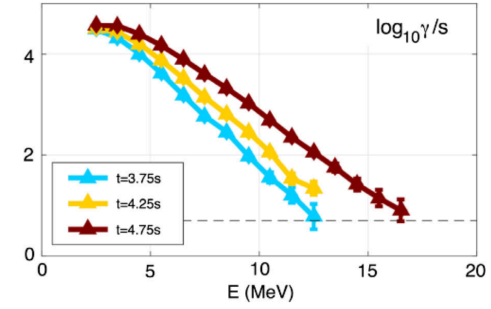
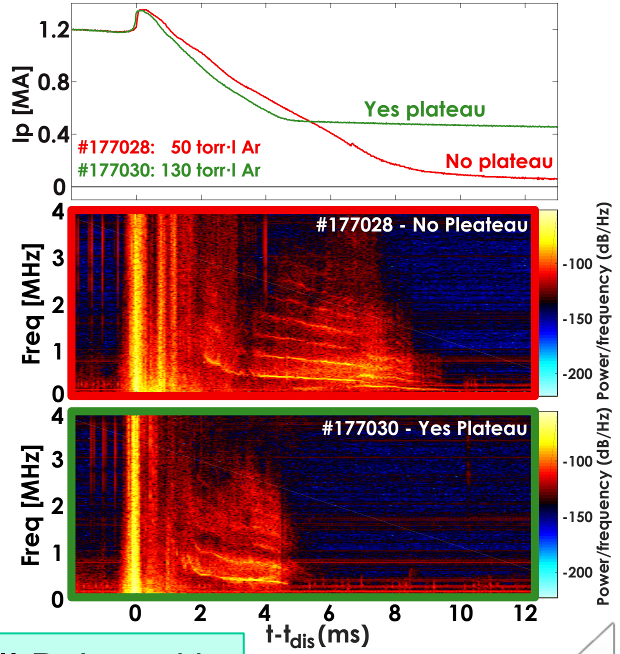


FIG. 6. Time evolution of runaway generated hard x-ray gamma energy spectrum for discharge No. 171089 of Fig. 5(a). Whistlers were present for $t = 3.75$, 4.25, and absent for $t = 4.75$ sec.

DIII-D, Spong, PRL, 2018



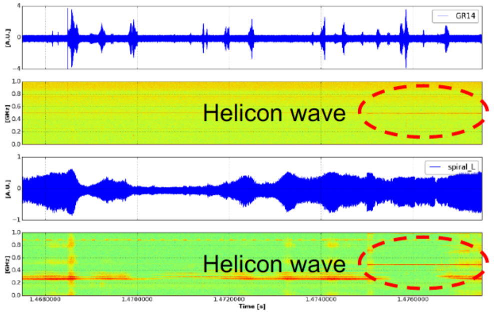
DIII-D, Lvovskiy

Future experimental plan on active mitigation by wave injection

- *What can be accomplished by active mitigation of runaway electrons via resonant wave-particle interaction*
    - *Control runaway electron energy & current quench (CQ) duration*
- *Physics basis from theory and simulation → experimental design options and constraints*
    - *How to limit runaway energy and current quench duration*
- *Experimental motivation and basis (mostly passive mitigation)*
    - *Resonant WPI from runaway-excited waves → Enhanced pitch angle scattering, reduced runaway energy, increased runaway dissipation (avalanche threshold), shortened CQ duration*
- ***Future experimental plans (on active mitigation)***
    - ***Compressional Alfven wave (CAE) and helicon (whistler)wave injection on DIII-D, helicon on KSTAR***

Future experimental plans on active mitigation by wave injection

- **DIII-D (led by Carlos Paz-Soldan)**
  - **Both Alfvenic and helicon wave injection**
- **KSTAR (led by Jayhyun Kim)**
  - **Helicon injection first attempt in 2018 campaign: poor coupling to plasma**

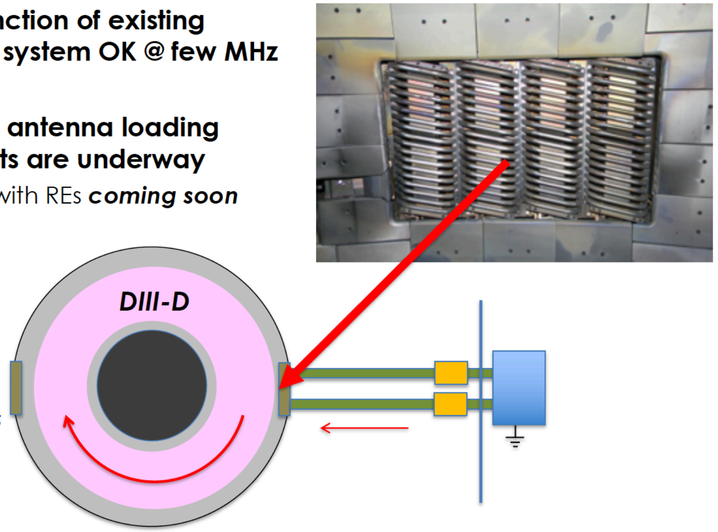


- Look for additional experimental collaboration on resonant WPI for runaway control
  - We can provide design tool & model interpretation
  - Contact Carlos Paz-Soldan for ITPA joint activity MDC-26 in this area of research

Initiative Started at DIII-D to Assess Feasibility of ~ 1 MHz-wave Launch with Mothballed ICRF Antennas

- **Transfer function of existing DIII-D ICRF system OK @ few MHz**
- **Low power antenna loading experiments are underway**
  - 1st time with REs *coming soon*

100 W Power



23

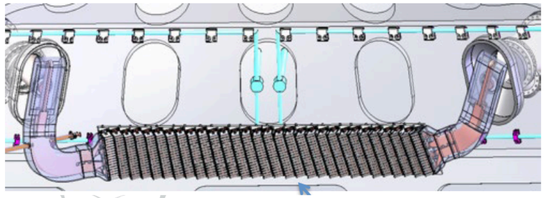
Paz-Soldan/ITPA/10-2019

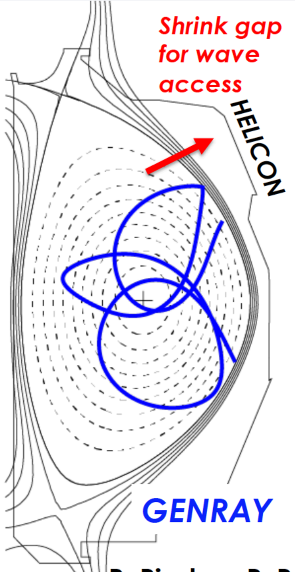
T. Akiyama, M. Brookman, R. Pinsker

DIII-D Helicon antenna will be used for a Proof-of-Principle Test in FY2020 run

- **Use "Quiescent" scenarios**
  - Good wave access and propagation
- **Phase 1: can we predict effect of existing D3D wave actuator**
- **Phase 2: Optimization for best ω,k**
  - Calculations in progress to see if 480 MHz is decent ω,k

Helicon antenna will be ready for 2020





1 MW Power

27

Paz-Soldan/ITPA/10-2019

R. Pinsker, P. Parks
X.Z. Tang, C. McDevitt, Z. Guo

Summary

- *Resonant WPI with runaways can greatly enhance pitch angle scattering of relativistic runaway electrons, resulting in runaway depletion through magnetic trapping and/or deconfinement*
- *Much experimental evidence exist for modified runaway electron properties due to self-excited wave instabilities*
  - *Both self-excited whistler waves and Alfvenic waves are observed*
- *By targeting low-energy as opposed to tail runaways through normal Doppler-shifted cyclotron resonance, we can control the runaway energy and CQ duration via external wave injection*
  - *If runaways can not be avoided on ITER, limiting their energy to MeV range while shortening the CQ to acceptable duration is likely the best one can hope for in disruption mitigation*
- *Collisional damping and hence wave accessibility in the CQ phase are a big challenge, but there are potential work-arounds.*
  - *Only targets the outer flux surfaces (large trapped zone), D2 purge of high-Z impurity*
- *Planned experiments on DIII-D and KSTAR will allow first tests*
  - *Initial focus is to demonstrate the physics in warm plasma regime*
  - *Follow-up experiments will address the wave power requirement issue in post-thermal quench plasmas.*
- *The physics basis is sound and interesting. We welcome collaboration opportunities to help field runaway WPI experiments on other tokamaks*