Energy Loss and Radial Diffusion of Runaway Electrons due to Kinetic Instabilities

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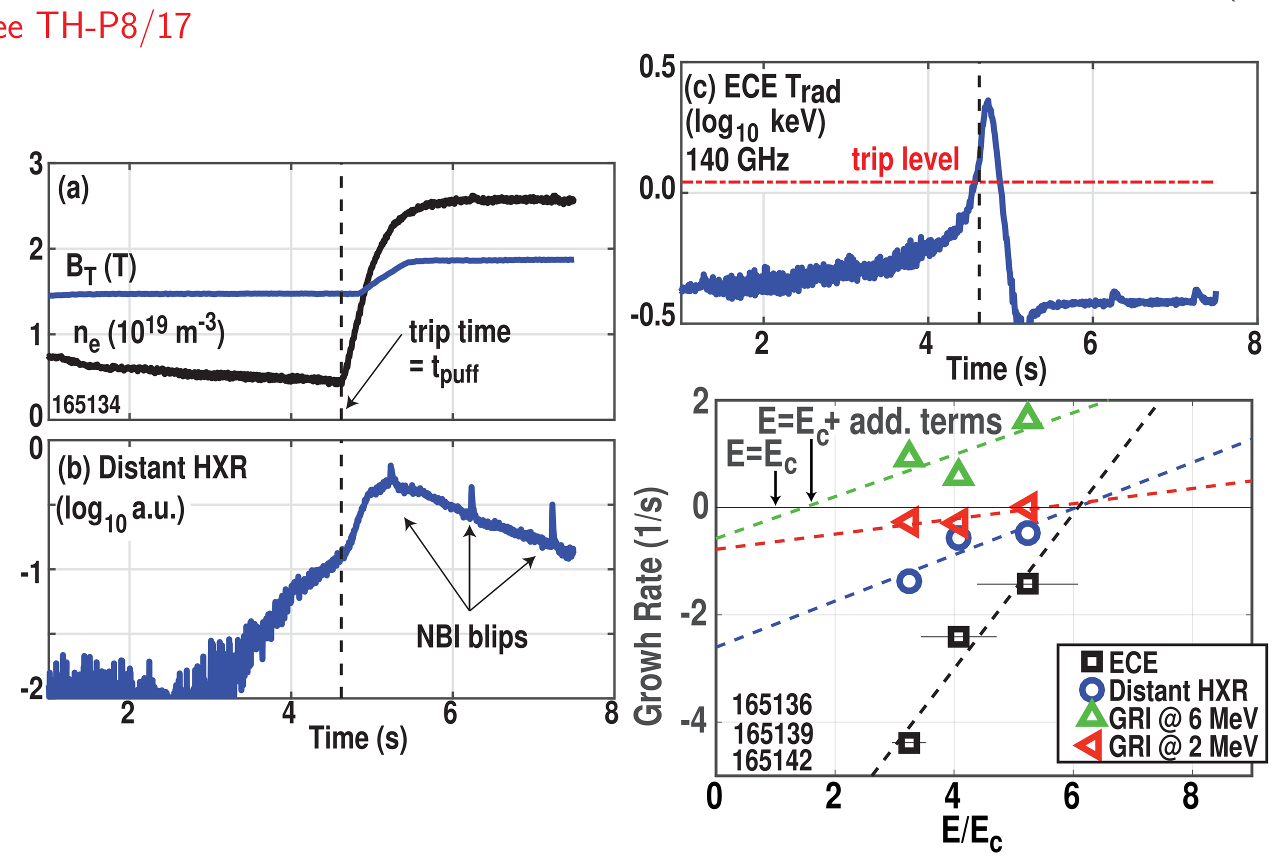
Highlights

- Fan instabilities can cause significant pitch-angle scattering of runaway electrons, which provides a new loss channel of runaway electrons in low energy, and raise the threshold electric field of avalanche.
- In disruptions with high-Z impurities injection, high-energy runaway electrons excite very-low-frequency compressional Alfven waves through transit-time magnetic pumping. The excited waves can cause significant radial diffusion of runaway electrons.

Runaway electron experimental result indicates presence of kinetic instabilities

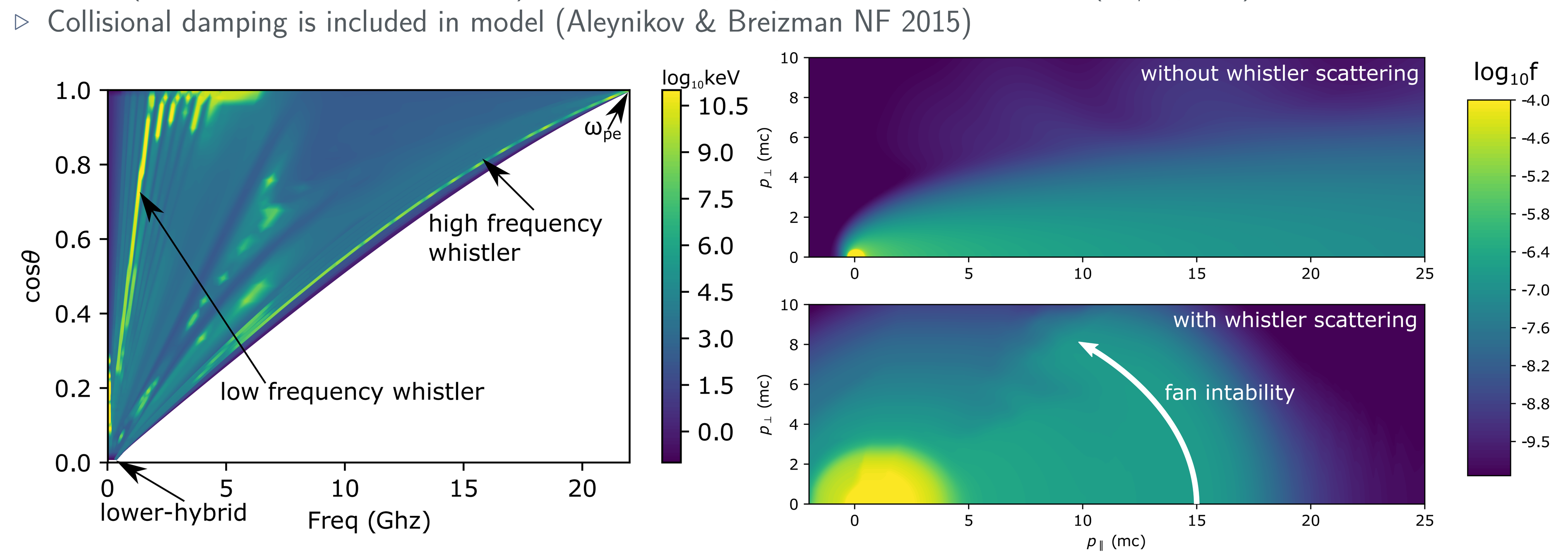
- Highly energetic runaway electron (RE) beam can be generated in tokamak disruptions, which can be destructive to tokamak like ITER.
- Discrepancies between experiment and theory on RE avalanche are found in recent studies of kinetic RE physics. See EX/6-1 Thursday 10:45
  - Critical E field for RE growth threshold from experiments ($\sim 6E_{CH}$) higher than expected ($\sim 2E_{CH}$) (Granetz PoP 2014, Paz-Soldan PoP 2014, PoP 2018)
  - REs in low energy decay faster in case of small E/E_{CH} (Paz-Soldan PRL 2017).
  - ECE signals from REs shows prompt growth and overwhelms ECE from thermal electrons.
- In recent DIII-D experiments, whistler waves are directly observed with frequency range 100-150MHz. (Spong PRL 2018, Heidbrink I5.J602) See TH-P8/17



Quasilinear simulation of whistler wave excited by runaway electrons

QUADRE (QUAsilinear Diffusion of Runaway Electrons) is a newly-developed code to study evolution of electron distribution (f_e), mode energy (E_k), and the wave-particle interaction (WPI) self-consistently.

- The code is used to study **whistler waves** excited by RE beam through wave-particle resonance.
  $\omega - k_\parallel v_\parallel = \omega_{ce}/\gamma$
  - $n = 0$ (Cherenkov resonance), waves are driven by bump-on-tail ($\partial f/\partial p_\parallel > 0$).
  - $n < 0$ (Anomalous Doppler resonance), waves are driven by anisotropic distribution ($\partial f/\partial \xi > 0$).
  - Collisional damping is included in model (Aleynikov & Breizman NF 2015)

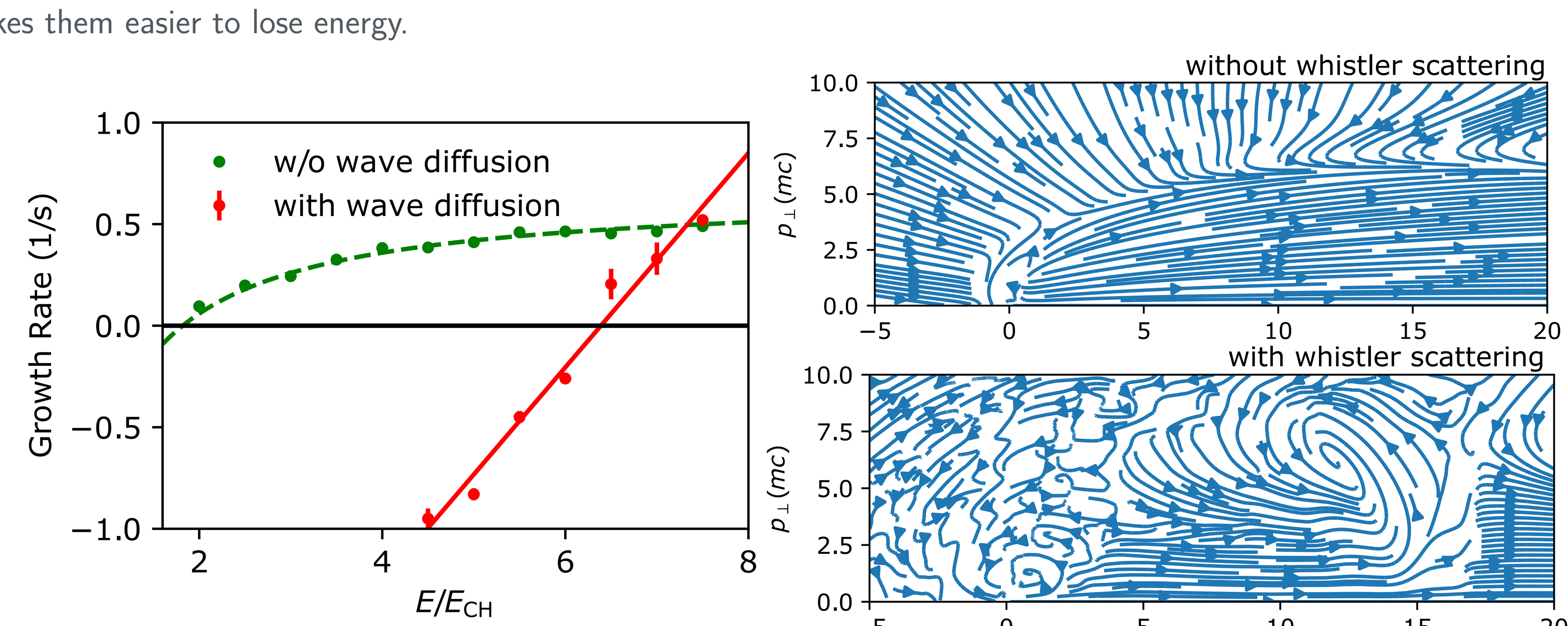


- Simulation results show that both the low frequency and high frequency branches of whistler waves can be excited through anomalous Doppler resonance.
- Excited whistler waves can cause fast pitch-angle scattering of REs, called "**fan instability**".
  - Low frequency waves scatter REs in high energy and stop them further gaining energy.
  - High frequeny waves scatter REs in low energy, create a new loss channel to counter the avalanche.

Increase of critical electric field of RE avalanche

After including whistler wave scattering, we find the critical electric field for RE population to grow is around 6 E_{CH}, which is close to experimental observation.

- New channel of RE loss: Whistler waves scatter electrons to large pitch angle and form vortices in momentum space, which makes them easier to lose energy.



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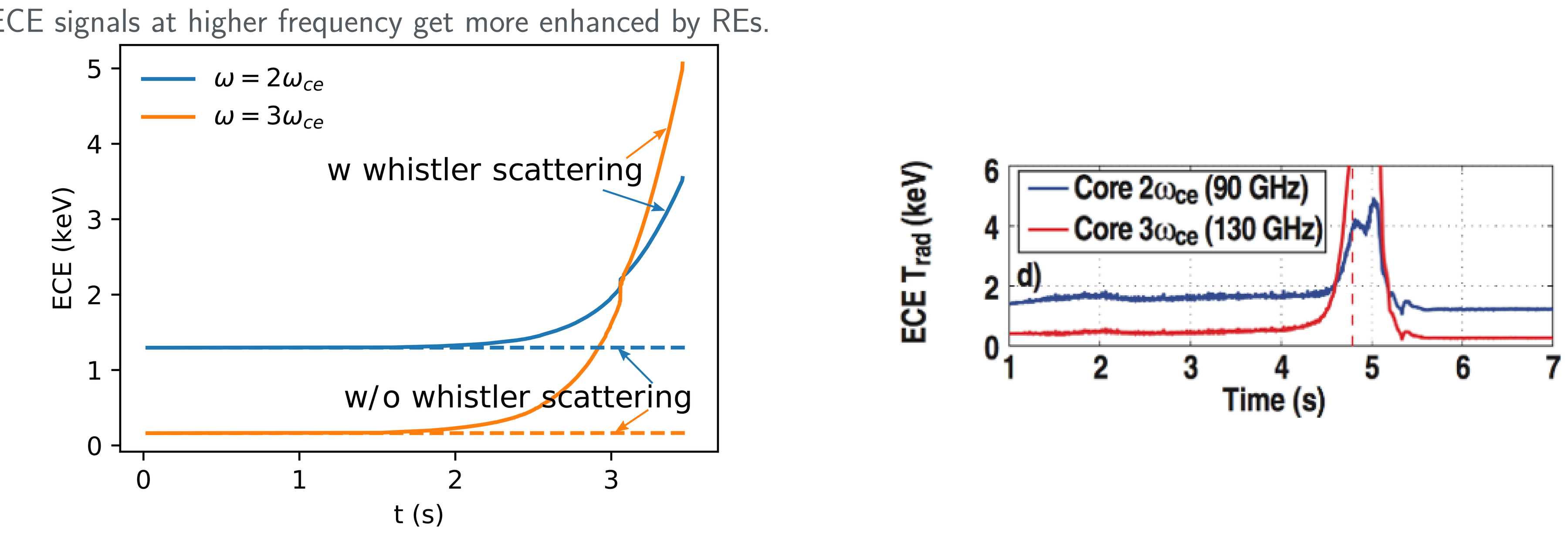
ECE signals from REs affected by whistler waves

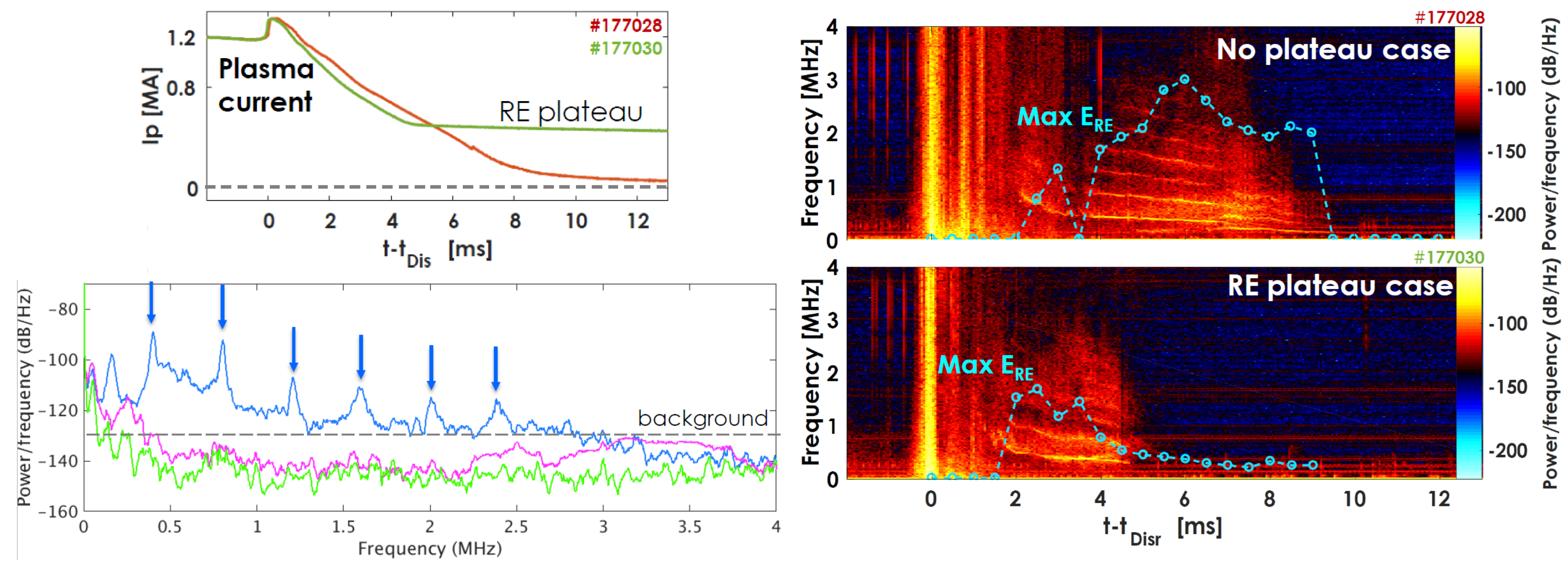
A new synthetic diagnostic code is developed to understand the ECE signals from REs.

- The prompt growth of RE ECE is connected with fan instabilities.
- Most of ECE comes from REs in low energy with large pitch angles, which are mostly generated by scattering from high frequency whistler waves.
- ECE signals at higher frequency get more enhanced by REs.



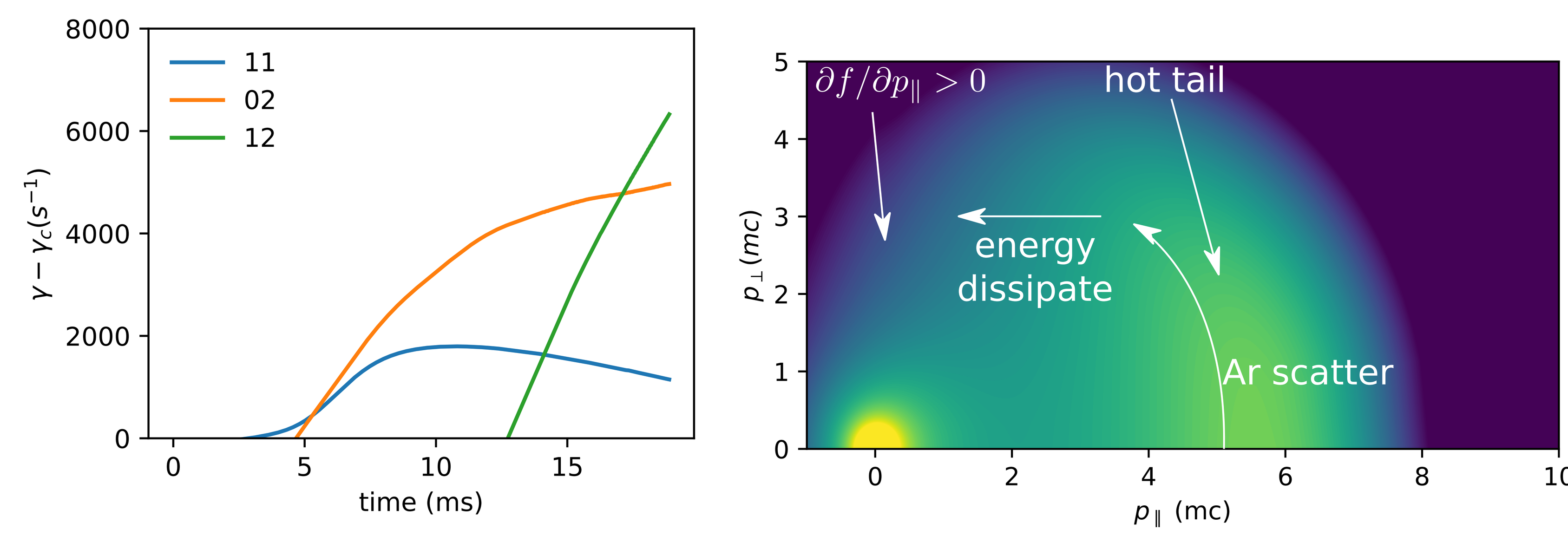
Formation of RE plateau is affected by compressional Alfven modes

- In DIII-D, RF-diagnostic and gamma-ray imager, the connection between RE plateau formation and kinetic instabilities are identified (Lvovskiy PPCF 2018).
  - When low-frequency ($\omega \sim \omega_{ci}$) compressional Alfven modes are strongly excited, RE plateau will not build up.
  - Increase Ar injection reduces high-energy REs and suppress kinetic instabilities, thus help form plateau.



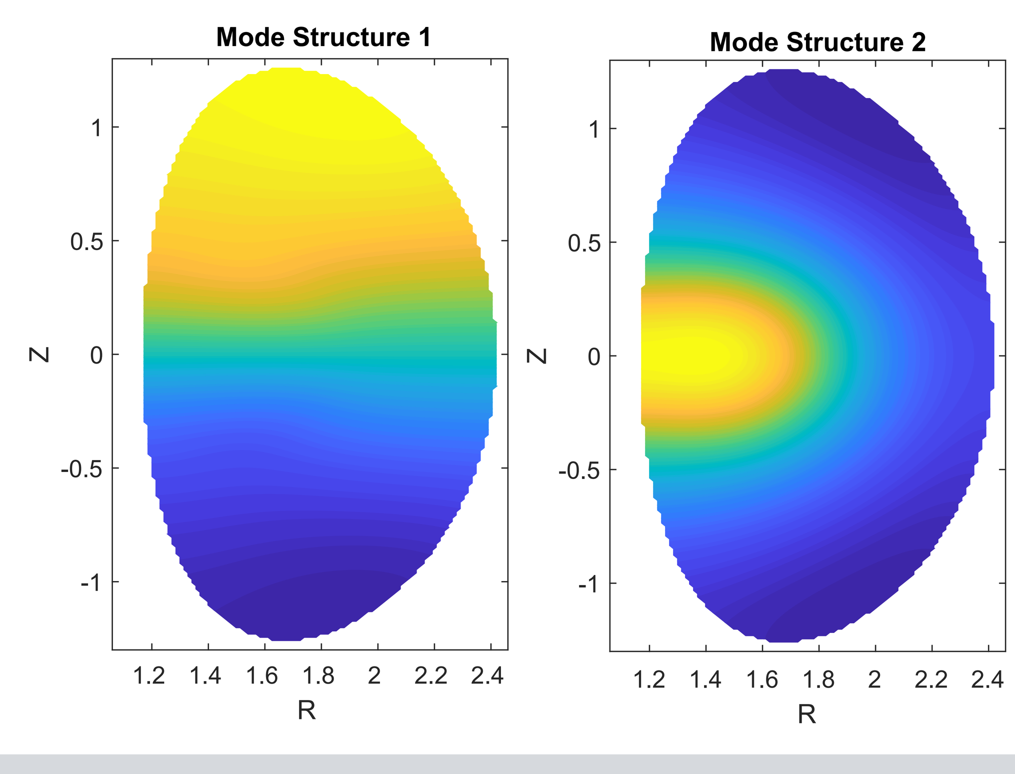
Magnetosonic-whistler modes excited by runaway electrons through TTMP

- Pitch-angle scattering of high-energy REs can be significantly enhanced by high-Z impurities due to partially-screening (Hesslow PRL 2017)
- Quasilinear simulation shows that compressional Alfven waves can be excited by REs through transit-time magnetic pumping.
  - TTMP is similar to bump-on-tail instabilities, but the resonate particles are driven by mirror force ($\mu \nabla B$).
  - Compressional Alfven waves are driven by electrons with $\mathcal{E} \sim 1.6$MeV and $p_\perp \gg p_\parallel$, which come from scattering and energy dissipation of hot tail ($\mathcal{E} \sim 3$MeV).



Mode structure of compressional Alfven wave excited by REs

- Using CAE code (E. D. Fredrickson 2013), the mode structure of excited compressional Alfven wave can be calculated by solving Helmholtz equation.
  - The eigen frequencies of the modes match experimental observation.
- The mode can have resonance with REs moving in flux surface with $q \approx 1$.
- The mode frequencies can vary with time due to changes of B, n_e and Z_{eff}.



Summary

- Using a new quasilinear simulation model for wave-particle interaction, we find RE tail generated in tokamaks can excite fan instabilities and compressional Alfven instabilities.
- REs affected by fan instabilities can be scattered and lose energy, resulting in a new threshold electric field higher than predicted by avalanche theory.
- Alfven modes excited by REs in disruptions can enhance radial diffusion of REs and dissipate the RE plateau. This can be used as a new strategy to mitigate REs in ITER.
- Future work: collaborate with other tokamak groups to validate the theory, and give predictions for ITER disruptions.