Fast Waves Excited by Runaway Electrons in Disruptive Plasmas

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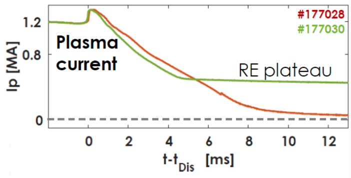
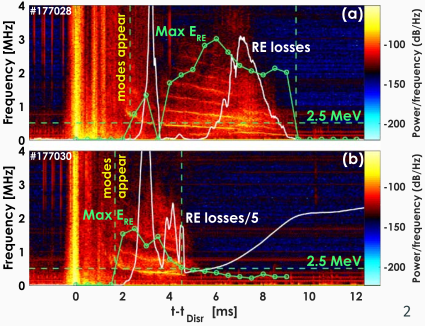
Direct observation of kinetic instabilities in the current-quench

- In DIII-D disruption experiments, low-frequency (0.1-3 MHz) kinetic instabilities are identified during current quench with Ar MGI.
    - Strong excitation of modes can lead to intense intermittent RE loss to the wall and the RE plateau will not build up.
    - Increase Ar density reduces the number of high-energy REs, suppresses instabilities, helps RE plateau survive.
- Kinetic instabilities through self-excitation or external drive provide a possible approach to mitigate RE formation.
- Kinetic instabilities are not observed in Ar pellet injection experiments in DIII-D.

Current evolution of two DIII-D shots with different Ar MGI



Observed magnetic perturbation spectrum and correlation with RE energy and RE loss



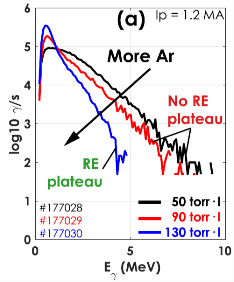
A. Lvovskiy et al., Plasma Phys. Control. Fusion 60, 124003 (2018).
C. Paz-Soldan, et al., Nucl. Fusion 59, 066025 (2019)

Mode excitation and RE plateau dissipation depend on RE energy

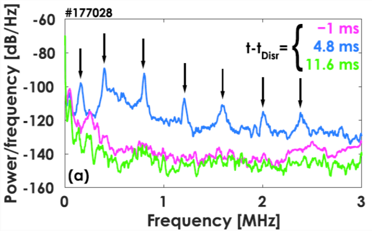
- RE energy spectrum diagnosed using gamma ray imager (GRI) show that excitation of modes and dissipation of RE plateau depend on the existence of high-energy REs.
  - Max $E_{RE} > 2.5 - 3$ MeV is required for the mode excitation.
  - RE plateau formation fails when max $E_{RE} > 6$ MeV.

- The modes spectrum shows discrete structures, with frequencies 0.1-2.4MHz with a spacing of 400kHz.
  - The frequencies are of the same order of Ar cyclotron frequency.
  - The discrete frequencies decrease during current-quench.

RE energy spectrum with different Ar MGI



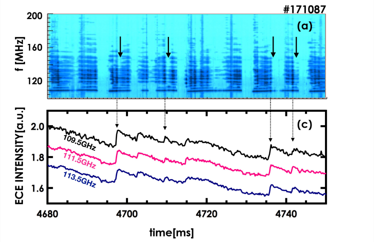
Mode power spectrum at different time



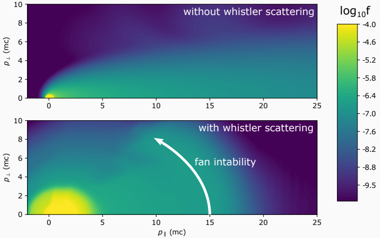
Previous studies on kinetic instabilities excited by REs in flattop

- Anisotropic distribution of RE tail can drive "fan instabilities" or anomalous Doppler instabilities (ADI).
- Whistler wave excited by REs have been directly observed in DIII-D flattop RE experiments
  - Excited modes have discrete spectrum and strong correlations with the ECE signals.
- Using quasilinear simulation, we studied the excitation of whistler modes self-consistently.
  - RE can interact with whistler waves in GHz frequency range, and the excited mode can cause large pitch angle scattering.
  - Avalanche can be suppressed by the scattering effect making the critical electric field larger than E_{CH}.

Frequency spectrum of whistler waves in DIII-D flattop



RE distribution function from quasilinear simulation without and with whistler wave scattering



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D.A. Spong et al., Phys. Rev. Lett. 120, 155002 (2018)

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REs can have resonances with MHz fast waves through precession motion

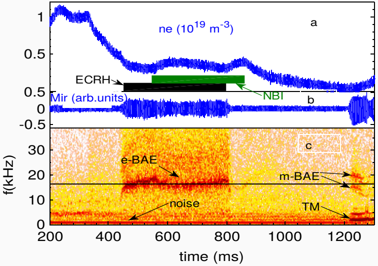
In order to transfer energy to fast waves, runaway electrons must have resonances with the modes.

- $\omega_{ce} \approx$ 58GHz$\gg \omega$, so Doppler resonance ($\omega = n\omega_{ce}$) is unlikely.
- Transit and bounce frequencies of relativistic electrons ($\sim$ 13MHz) are too large compared to ω.
- Precession frequency (ω_d) of trapped runaway electrons is about 0.3MHz, so the resonance condition $\omega = n\omega_d$ can be satisfied.
    - Unlike transit and bounce frequencies, precession frequency is proportional to the RE energy.

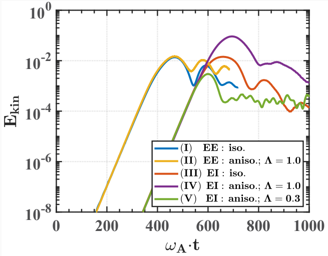
Experimental and simulation studies on Alfvén modes excited by energetic electrons

- Shear Alfvén waves can have resonance with the low energy part of RE tail with steep density profiles.
- Beta-induced Alfvén eigenmode (BAE) and toroidal eigenmode (TAE) excited by energetic electrons have been identified in HL-2A experiments in flattop.
    - Trapped electrons can be produced by ECRH and have wave-particle interaction at precession frequencies.
    - TAEs driven by deeply trapped energetic electrons have been simulated using kinetic-MHD code MEGA.

HL-2A experiment with BAE driven by energetic electrons



Kinetic energy evolution of $n = 4$ TAE driven by energetic electrons (EE) or energetic ions (EI) from MEGA simulation

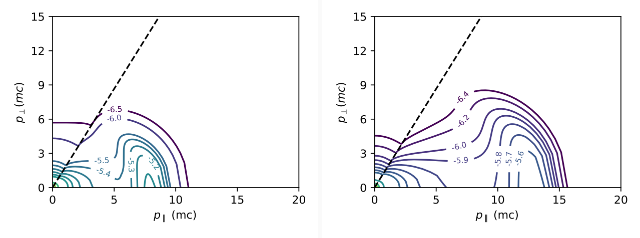


T. Fülöp and S. Newton, Phys. Plasmas 21, 080702 (2014)
W. Chen, et al., Phys. Rev. Lett. 105, 185004
L.M. Yu, et al., Phys. Plasmas 25, 012112 (2018)
J. Wang, Y. Todo, H. Wang, and Z.-X. Wang, Nucl. Fusion 60, 112012 (2020)

Trapped RE can be generated from pitch angle scattering with high-Z impurities

- With partially ionized high-Z impurities, the slowing-down and pitch angle scattering of REs in high energy regime is significantly enhanced due to partially-screening.

RE momentum space distribution in kinetic simulation of hot-tail generation with partially-screening

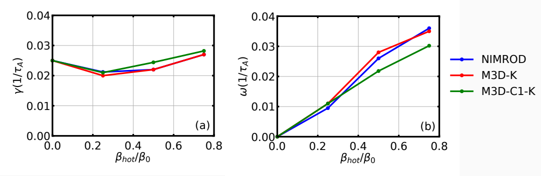


C. Liu, et al., Nucl. Fusion (2020) (2014)

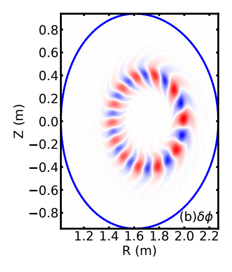
Introduction to M3D-C1-K

- M3D-C1-K is a kinetic-MHD code based on M3D-C1 that uses PIC method to simulate the kinetic particles and couples the particle moments with MHD, which is similar to M3D-K.
- We have done several benchmark tests with other codes, including fishbone, TAE and RSAE.

Growth rates and frequencies of linear fishbone simulation from M3D-C1-K, comparing with NIMROD and M3D-K



Mode structure of $n = 4$ RSAE in DIII-D from M3D-C1-K simulation

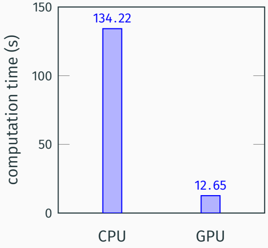


M3D-C1-K is suitable for simulating RE interacting with MHD

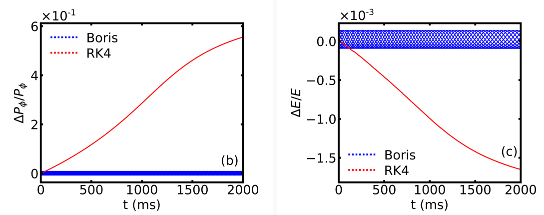
The large velocity of runaway electrons poses a challenge for kinetic simulation using PIC.

- In M3D-C1-K the particle pushing is developed using particle-based parallelization and can run efficiently on GPUs, which has a significant speedup compared to CPUs.
- A slow manifold Boris algorithm is utilized in the particle pushing, which can conserve momentum and energy numerically and make the long time simulation result more reliable.

Computation time for pushing 4 million particles for 50 steps



Numerical error of P_ϕ and energy from particle simulation using Boris method and RK4



Fast wave can interact with REs through mirror forces

- Resonant trapped RE can be pushed radially by the mirror force from fast wave perturbed fields

$$\delta \dot{f} = -\frac{df_0}{dt} = \frac{dP_\phi}{dt}\frac{\partial f_0}{\partial P_\phi} + \frac{dE}{dt}\frac{\partial f_0}{\partial E},$$

$$\dot{P}_\phi = q\dot{\psi} + R\frac{B_\phi}{B}\left(qE_\parallel - \mu \mathbf{b}\cdot\nabla B\right)$$

$$\dot{E} = q\mathbf{v}\cdot\mathbf{E} + \mu\frac{\partial B_\parallel}{\partial t}$$

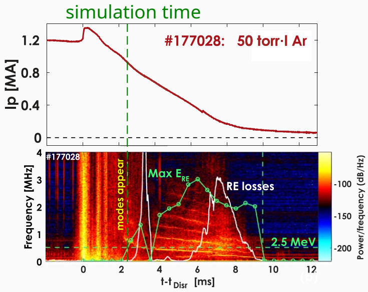
  - Mirror force ($\mu\nabla B$) can change P_ϕ of resonant trapped REs but not the energy, so REs can move radially which is similar to Ware pinch.
- The runaway electrons using current coupling.

$$\rho\left(\frac{\partial \mathbf{V}}{\partial t}\right) + \rho(\mathbf{V}\cdot\nabla\mathbf{V}) = (\mathbf{J} - \mathbf{J}_{RE}) \times \mathbf{B} - \nabla p$$

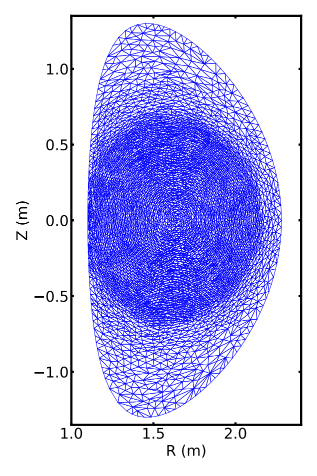
  - $J_{RE,\perp}$ comes from the gradient and curvature drift of REs and magnetization current ($\nabla \times (P_\perp \mathbf{b}/B)$).

Simulation setup

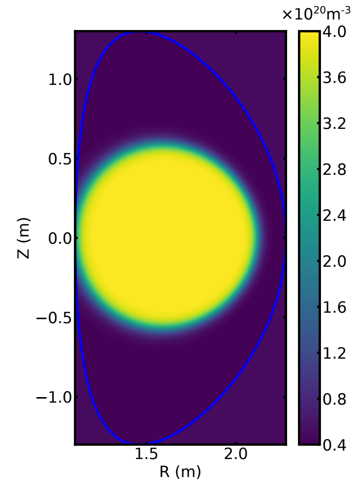
The equilibrium is read using EFIT results from DIII-D shot #177028 at 1208ms.



Simulation mesh

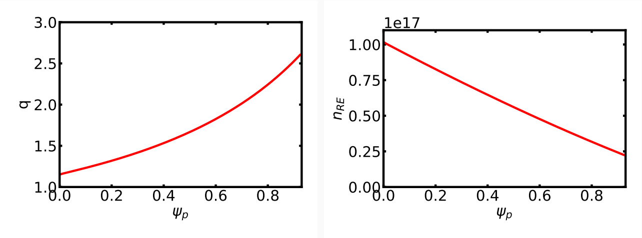


Plasma density



Simulation setup (cont'd)

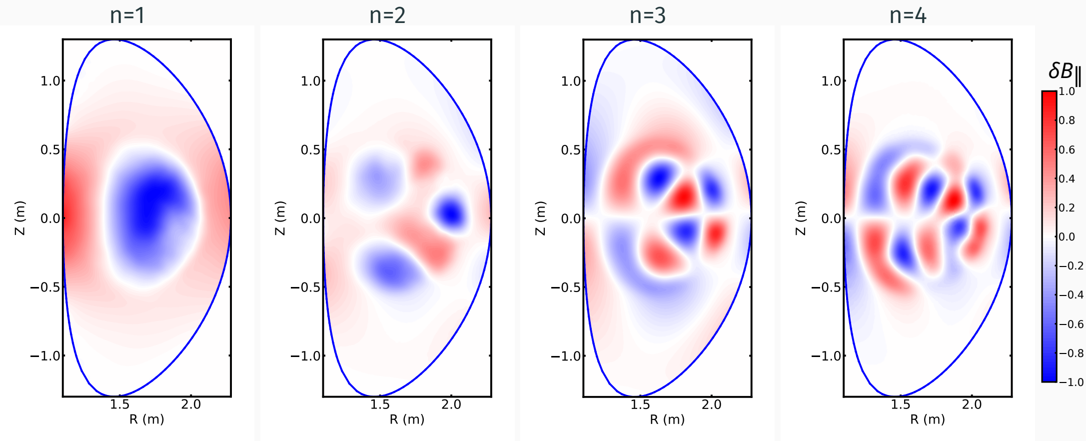
$$B_0 = 2\text{T} \qquad n_0 = 4 \times 10^{20}\,\text{m}^{-3} \qquad m_{ion} = m_{Ar} = 40 \qquad Z_{eff} = 2 \qquad T_e = 10\text{eV}$$



$$f_{RE} = n_{RE}(\psi)\exp\left[-\left(\frac{p - p_0}{\Delta p}\right)\right]\exp\left(\frac{\xi - 1}{\Delta \xi}\right)$$

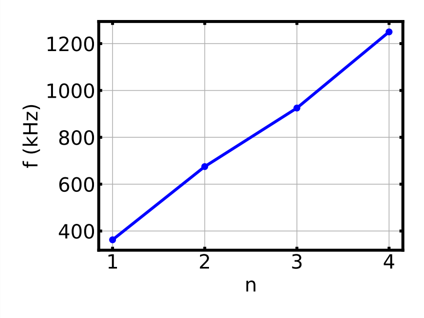
$$p_0 = 7m_e c \quad (\sim 3.5\text{MeV}) \qquad \Delta p = 2m_e c \qquad \Delta\xi = 0.5$$

Mode structure

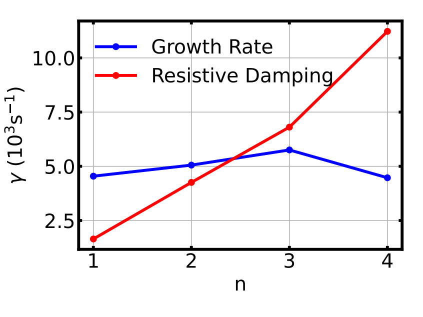


- Analysis of $\delta\mathbf{B}$ shows that $\delta B_{\parallel} \gg \delta B_{\perp}$, indicating they are compressional Alfvén eigenmodes (CAEs).

Mode frequency

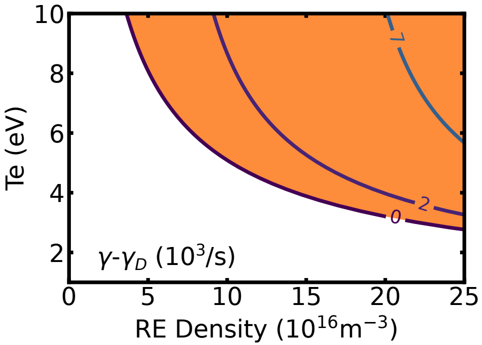


Growth rate and damping due to resistivity



Stability map of $n = 1$ mode

Assuming growth rate $\gamma \sim n_{RE}$ and damping rate $\gamma_D \sim T_e^{-3/2}$, the stability map of $n = 1$ mode looks like



Summary

- Fast waves can be excited by trapped REs through precession resonance.
- Linear simulation of M3D-C1-K shows that the $n = 1$ mode can become unstable for $n_{RE} > 4 \times 10^{16}\mathrm{m}^{-3}$ in 10eV Ar plasma. Higher n mode can also become unstable with higher threshold, and mode frequencies agree with experiments.
- Future work:
  - Continue linear simulations to study the dependence of mode excitation on plasma parameters and RE distribution
  - Try nonlinear simulation to study the coupling of multiple modes and effects on RE transport.