Fast Waves Excited by Runaway Electrons in Disruptive Plasmas

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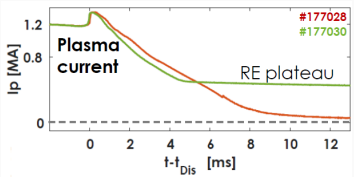
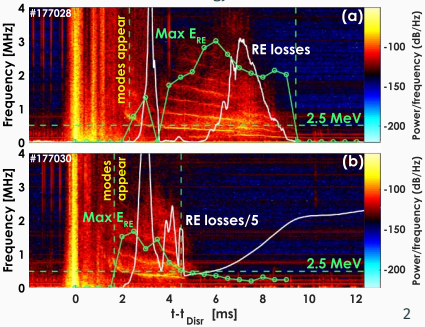
Direct observation of kinetic instabilities in the current-quench of disruption

- In DIII-D disruption experiments, current quench modes with frequency 0.1-3 MHz are identified during with Ar and Ne MGI.
  - For discharges with no runaway electron plateau formation, strong excitation of CQ modes are observed
  - Increase Ar density reduces the number of high-energy REs and suppresses the instabilities.
  - The discrete frequencies decrease with time during current-quench.
- It is believed that kinetic instabilities excited by energetic runaway electrons can provide a possible approach to mitigate RE formation.

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



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

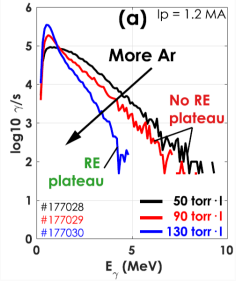


A. Lvovskiy et al., Plasma Phys. Control. Fusion 60, 124003 (2018).
C. Paz-Soldan, et al., Nucl. Fusion 59, 066025 (2019)

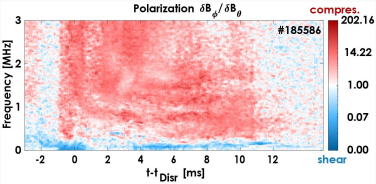
Mode excitation and RE plateau dissipation depend on RE energy

- 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.
- Using the new RF diagnostics, the CQ magnetic fluctuations are identified to have clear compressional polarization

RE energy spectrum with different Ar MGI



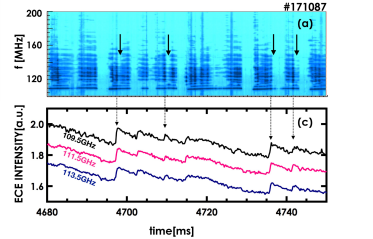
Mode polarization measurement



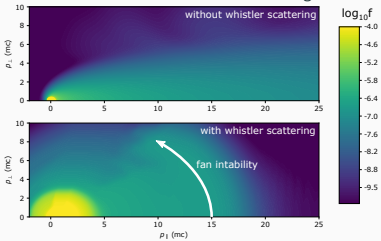
Previous studies on kinetic instabilities excited by REs in quiescent experiments

- 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 quiescent 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 QRE



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



T. Fülöp, et al., Phys. Plasmas 13, 062506 (2006)

P. Aleynikov and B. Breizman, Nucl. Fusion 55, 043014 (2015)

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

C. Liu, et al., Phys. Rev. Lett. 120, 265001 (2018)

REs can have resonances with MHz fast waves through precession motion

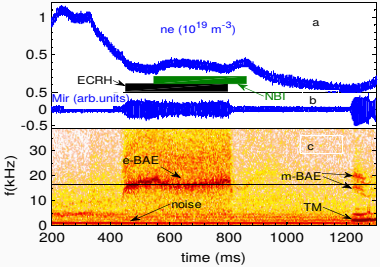
In order to transfer energy to fast waves, runaway electrons must have resonances with the modes.

- $\omega_{ce} \approx 58\text{GHz} \gg \omega$, so cyclotron resonance ($\omega = n\omega_{ce}$) is unlikely.
- Transit and bounce frequencies of relativistic electrons ($\sim$ 13MHz) are too large compared to ω (< 2MHz).
- 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.

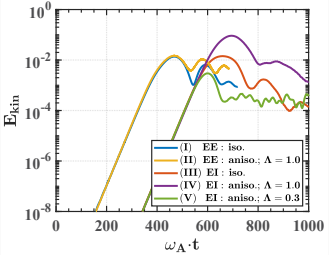
Experimental and simulation studies on Alfvén modes excited by energetic electrons

- 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



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W. Chen, et al., Phys. Rev. Lett. 105, 185004
L.M. Yu, et al., Phys. Plasmas 25, 012112 (2018)
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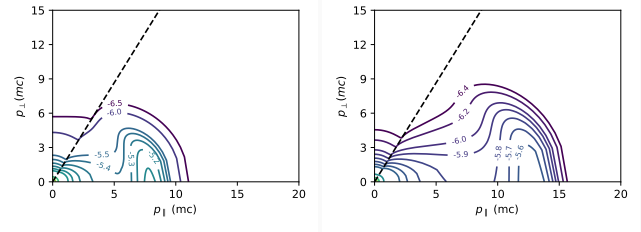
Trapped RE can be generated from pitch angle scattering with high-Z impurities

- 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



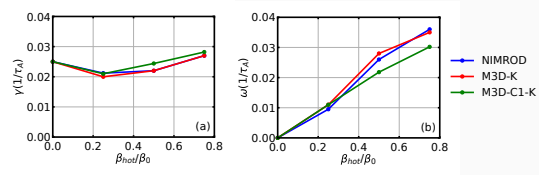
C. Liu, et al., Nucl. Fusion (2020)

Introduction to M3D-C1-K

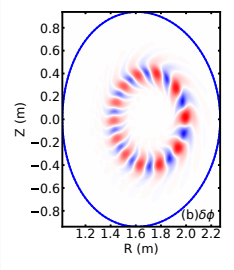
- M3D-C1-K is a kinetic-MHD code based on M3D-C1 that uses PIC method to simulate the kinetic particles and couples the particle moments with MHD, which is similar to M3D-K.

- We have done several benchmark tests with other codes, including fishbone, TAE and RSAE.
- Recently we have participated collaborative simulation for EP-driven fishbone and AE in ITER and DIII-D validation shots with ISEP.

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

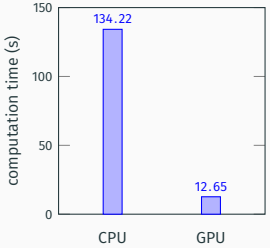
The large velocity of runaway electrons poses a challenge for kinetic simulation using PIC.

- 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.

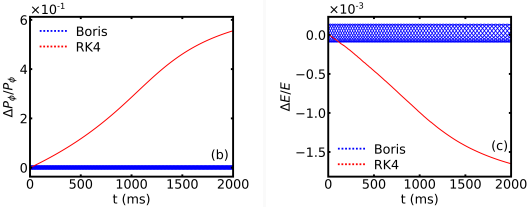
The semi-implicit method widely used in MHD simulation codes can significantly damp on the CAEs.

- We utilized Caramana method with small time step ($\Delta t \approx 0.02\tau_A$) to reduce artificial damping.

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



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J. Xiao and H. Qin, Comput. Phys. Commun. 265, 107981 (2021).
C. Liu, et al., Plasma Phys. Control. Fusion 63, 125031 (2021).

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

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

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

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

  - 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.

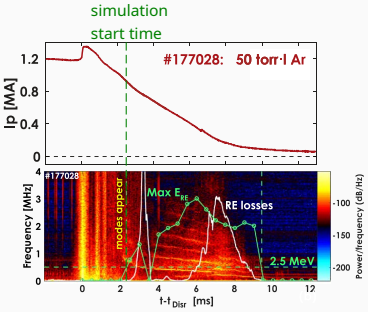
- Perturbed RE current coupled into MHD,

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

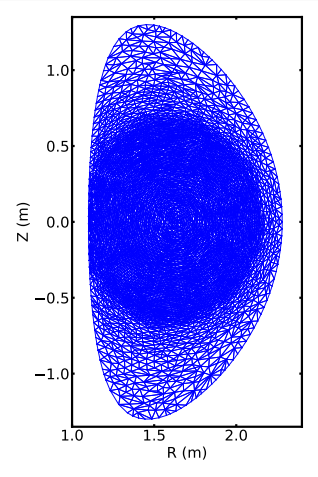
  - $\delta J_{RE,\perp}$ comes from the gradient and curvature drift of REs and magnetization current ($\nabla \times (P_\perp \mathbf{b}/B)$).

Simulation setup

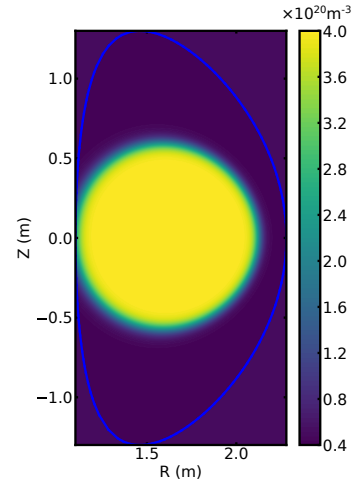
The equilibrium is read using EFIT results from DIII-D shot #177028 at 1208ms.



Simulation mesh

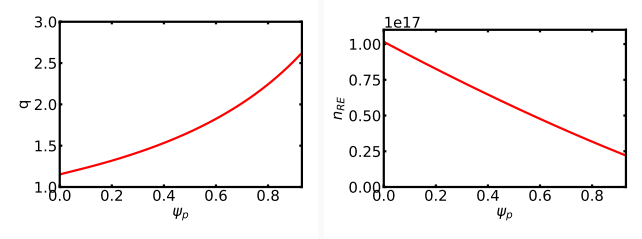


Plasma density



Simulation setup (cont'd)

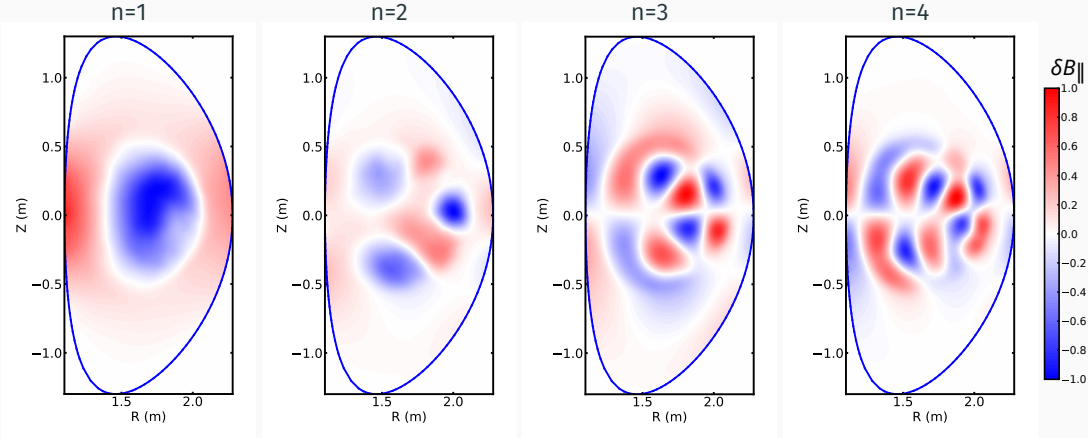
$B_0 = 2.18\text{T}$ $\quad n_0 = 4 \times 10^{20}\text{m}^{-3}$ $\quad m_{ion} = m_{Ar} = 40$ $\quad Z_{eff} = 2$ $\quad T_e = 10\text{eV}$



$$f_{RE} = n_{RE}(\psi) \exp\left[-\left(\frac{p - p_0}{\Delta p}\right)^2\right] \exp\left(\frac{\xi - 1}{\Delta \xi}\right)$$

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

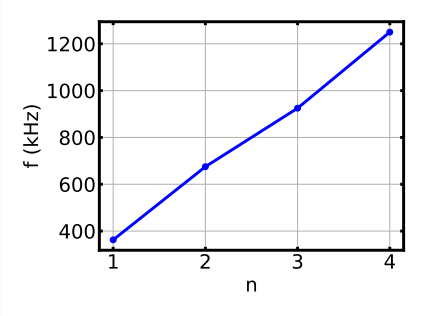
Mode structure



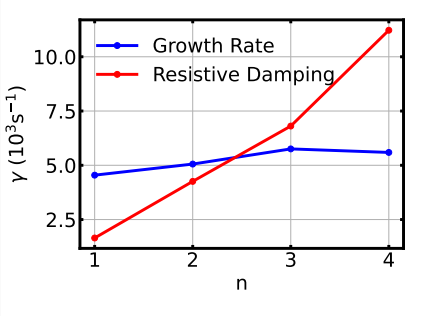
- Analysis of $\delta\mathbf{B}$ shows that $\delta B_{\parallel} \gg \delta B_{\perp}$, indicating they are compressional Alfvén eigenmodes (CAEs).

Mode frequencies and linear growth rates

Mode frequency

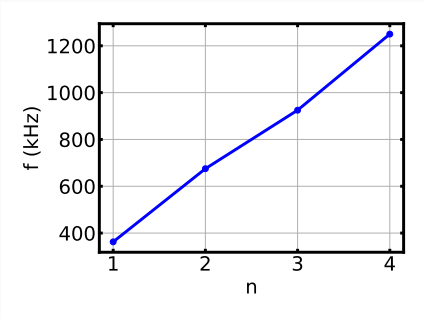


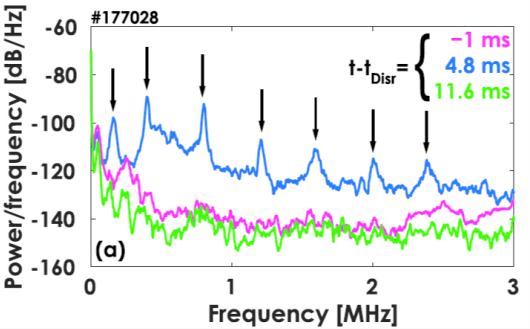
Growth rate and damping due to resistivity



Mode frequencies and linear growth rates

Mode frequency

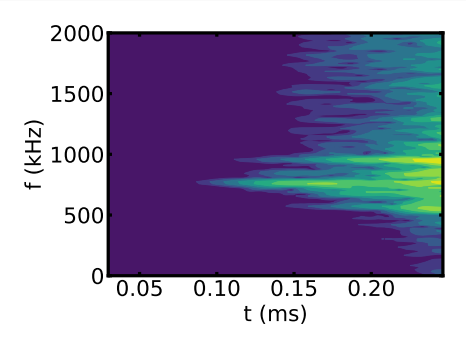




Multiple modes can be excited by REs for a single n_{tor}

- Continue the simulation with one single toroidal mode number and particle non-linearity, it is found that after the dominant mode saturates, other CAEs become dominant and nonlinear interaction can happen.

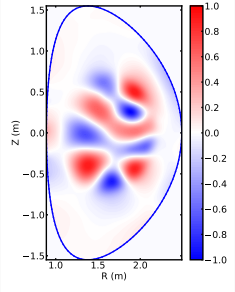
Mode spectrogram for $n = 3$ simulation



The resonant modes depend on both precession and bounce motion

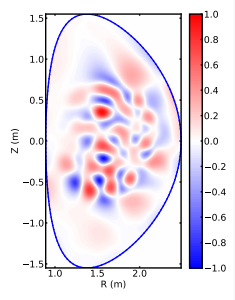
- By using pseudo-electron with 100x mass and 0.1c velocity, we find that the dominant mode has much larger k and frequency, which indicates that the dominant modes depends on both electron precession frequency and orbit width.

Dominant mode of $n = 3$ for $m = m_e$, $v = c$



$f = 765$kHz

Dominant mode of $n = 3$ for $m = 100m_e$, $v = 0.1c$

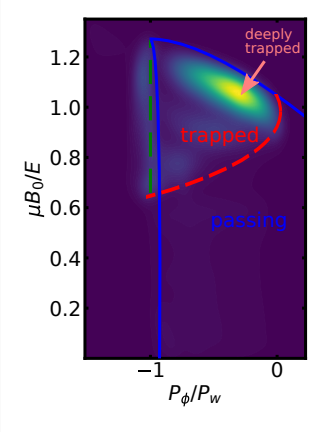


$f = 1575$kHz

Resonant REs are deeply trapped

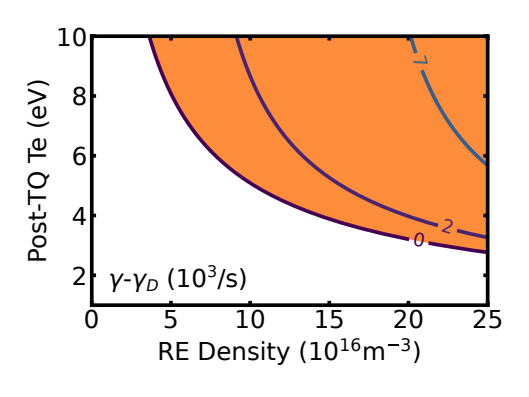
- By plotting the 3.5 MeV RE distribution with δf weight in $P_\phi - (\mu B_0/E)$ map for $n = 1$ simulation, it is found that most REs with large weight are deeply trapped particles.

Weight distribution for 3.5MeV particles



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

- Current quench modes observed in DIII-D can be modeled as fast wave (CAE) which 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.
- Nonlinear simulation with a single n does not show significant transport of parallel streaming REs induced by the mode.
- Future work:
  - Using an eigenvalue code to calculate the CAE mode structure and compare with M3D-C1 simulation.
  - Scan over BT and RE energy to see the effect on mode growth.
  - Try nonlinear simulation to study the coupling of multiple modes and effects on RE transport.