# Kinetic-MHD simulation of compressional Alfvén eigenmodes excited by runaway electrons in current quench

Chang Liu, Stephen Jardin, Amitava Bhattacharjee, Andrey Lvovskiy, Carlos Paz-Soldan

Princeton Plasma Physics Laboratory
General Atomics
Columbia University

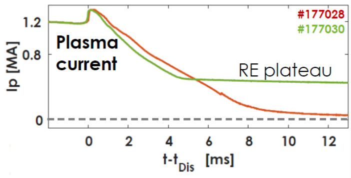
10th Runaway Electron Meeting

Jun 20 2023

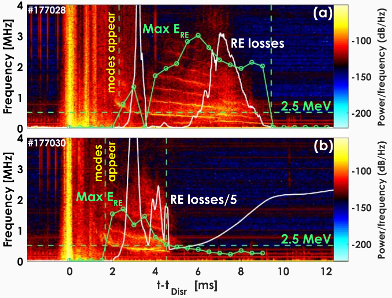
# Current quench mode observed in DIII-D disruption experiments

- In DIII-D disruption experiments, current quench modes with frequency 0.1-3 MHz are identified during with Ar and Ne MGI.
    - CQ modes are strongly excited when large number of high energy REs are generated.
    - When the modes are strong, there is intermittent RE loss during the current quench and there is no RE plateau formed in the end.
- The modes spectrum shows discrete structures, with frequencies spacing of 400kHz.

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




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



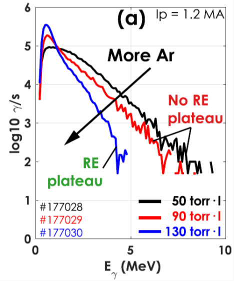


A. Lvovskiy et al., Plasma Phys. Control. Fusion 60, 124003 (2018).
C. Paz-Soldan, et al., Nucl. Fusion 59, 066025 (2019)
P. Heinrich, G. Papp, P. Lauber, O. Linder, M. Dunne, V. Igochine, et al. (2021). 17th Technical Meeting on Energetic Particles and Theory of Plasma Instabilities.

# 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.
- Increasing injected argon decreases RE energy and increases the success rate of the RE current formation

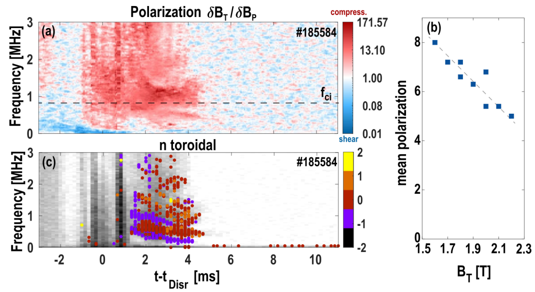
RE energy spectrum with different Ar MGI



# Toroidal mode number and polarization of the modes

- Using the new RF-loops diagnostics, the CQ magnetic fluctuations are identified to have clear compressional polarization ($\delta B_T \gg \delta B_p$)
- Measurement of the toroidal mode number shows that all the modes are dominated by $n = 0, \pm1$, no matter the frequency.
    - This is different from our previous assumption that different frequency mode should correspond to different $n$ number

Measurement of CQ mode polarization and toroidal n number




A. Lvovskiy, C. Paz-Soldan, et al., Nucl. Fusion 63(4), 046011 (2023).

# REs can have resonances with MHz compressional waves through precession motion

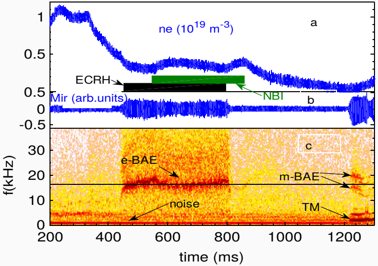
In order to transfer energy to Alfven waves, runaway electrons must have resonances with the modes.

- Electron cyclotron frequency ($\omega_{ce} \approx 58$GHz) and transit/bounce frequencies ($\sim 13$MHz) of relativistic electrons are both too large compared to mode $\omega$ (< 3MHz).
- Precession frequency ($\omega_d$) of trapped 10MeV runaway electrons is about 1.2MHz, so the resonance condition $\omega = n\omega_d$ can be satisfied.
  - Unlike transit and bounce frequencies, precession frequency is proportional to the RE energy.
    - Consistent with the observation that higher frequency modes are excited later as RE energy grows.
- This resonance mechanism cannot explain the excitation of $n = 0$ modes.

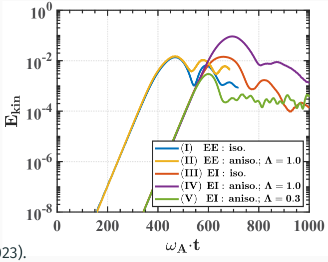
# Experimental and simulation studies on Alfvén modes excited by energetic electrons

- 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



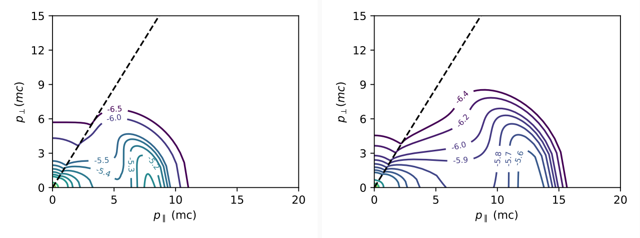


T. Fülöp and S. Newton, Phys. Plasmas 21, 080702 (2014)
W. Chen, et al., Phys. Rev. Lett. 105, 185004
J. Wang, Y. Todo, H. Wang, and Z.-X. Wang, Nucl. Fusion 60, 112012 (2020)
A. Lier, G. Papp, P.W. Lauber, I. Pusztai, K. Särkimäki, and O. Embreus, Nucl. Fusion 63(5), 056018 (2023).

# 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.
- For DIII-D disruption experiment with Ar injection, the induction $E$ field is slightly larger than threshold field for avalanche, making the RE distribution dominated by hot-tail-generated bump-on-tail.

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

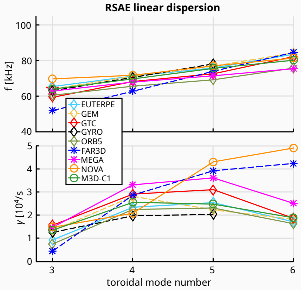



L. Hesslow, O. Embréus, G.J. Wilkie, G. Papp, and T. Fülöp, Plasma Phys. Control. Fusion 60(7), 074010 (2018).
C. Liu, et al., Nucl. Fusion (2020)

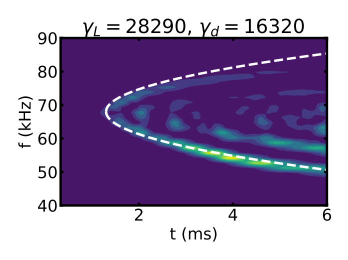
# Introduction to M3D-C1-K

- 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 (current, pressure) with MHD, which is similar to M3D-K.
- We have done several benchmark tests with other codes, including fishbone, TAE and RSAE.
- Nonlinear behavior of AE such as frequency chirping can be reproduced through nonlinear simulation.

Benchmark of RSAE simulation using DIII-D parameters




Simulation of mode frequency chirping of n=4 RSAE in DIII-D



# CAE can interact with REs through gradient drifts and mirror forces

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

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

$$\dot{P}_\phi = q\dot{\psi} + R\frac{B_\phi}{B}\dot{p}_\parallel$$

$$\dot{p}_\parallel = qE_\parallel - \mu \mathbf{b} \cdot \nabla B$$

$$\dot{\psi} = \left( v_\parallel \frac{\delta \mathbf{B}}{B_0} + \mathbf{v}_{E\times B} + \mathbf{v}_{\mathrm{grad}} + \mathbf{v}_{\mathrm{curv}} \right)$$

  - Mirror force ($\mu \nabla B$) can change $P_\phi$ of resonant trapped REs, so REs can move radially which is similar to Ware pinch.
- Perturbed RE current coupled into MHD,

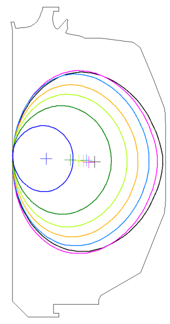
$$\rho \left( \frac{\partial \mathbf{V}}{\partial t} \right) + \rho(\mathbf{V} \cdot \nabla \mathbf{V}) = (\mathbf{J} - \delta \mathbf{J}_{RE}) \times \mathbf{B} - \nabla p$$

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

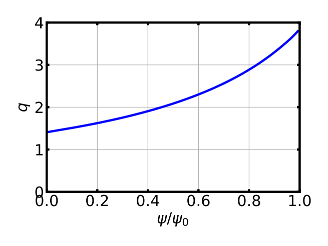
# Setup for MHD simulation

The equilibrium is read using EFIT results from DIII-D shot #177028 at 1208ms (2ms after disruption).

Shrinking of LCFS during DIII-D disruption



q profile




- RE density is initialized following current profile.
- The equilibrium was assumed fixed in both linear and nonlinear simulations.

# Setup for RE simulation

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

- RE has bump-on-tail momentum distribution with a Gaussian profile centered at $p_0$ and width $\Delta p$.
- RE pitch angle distribution is calculated based on balance between electric force and pitch angle scattering. Enhancement of collisional pitch angle scattering due to partially screening effect is taken into account.

$$f_{RE} \sim \exp\left(A\xi\right) \qquad A(p) = \frac{2E}{Z^* + 1}\frac{p^2}{\sqrt{p^2+1}}$$

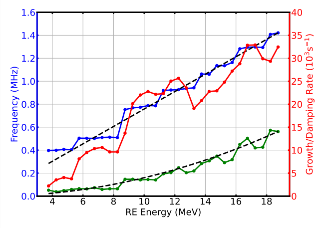
$$Z^* = Z_{\mathrm{eff}} + \frac{1}{\ln\Lambda}\frac{n_{\mathrm{Ar}}}{n_e}\left[\left(Z_{\mathrm{Ar}}^2 - Z_{\mathrm{eff}}^2\right)\ln\left(\bar{a}_{\mathrm{Ar}}p\right) - \frac{2}{3}\left(Z_{\mathrm{Ar}} - Z_{\mathrm{eff}}\right)^2\right]$$

P. Aleynikov and B.N. Breizman, Phys. Rev. Lett. 114, 155001 (2015).
L. Hesslow, O. Embréus, G.J. Wilkie, G. Papp, and T. Fülöp, Plasma Phys. Control. Fusion 60(7), 074010 (2018).

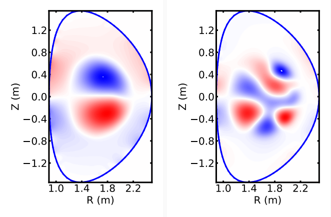
# CAE mode frequency and growth rates for different RE energy

- In linear $n = 1$ simulations, excited CAE freuqnecies follows a staircase function with RE peak energy ($\sim p_0$) with a linear trend.
  - Each level of staircase represents an eigenmode with different poloidal structure.
  - Very high frequency mode ($f > 1.5$MHz) cannot be reproduced in linear simulations with limited RE energy (<20 MeV).
    - These frequencies are higher compared to Ar ion cyclotron frequency so MHD description may not be accurate.
- Both linear growth rate and damping rate caused by resistivity increases with mode frequency.
  - Damping rate follows a quadratic law with $f$, meaning that for very high frequency resistive damping can suppress the mode growth.

Frequencies (blue), growth rate (red) and damping rate(green) from CAE linear simulations



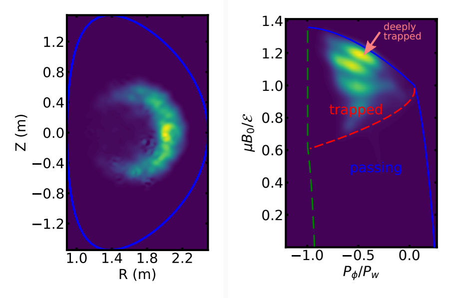

Eigenmode structure ($\delta B_{||}$) for $f = 0.50$MHz and $f = 0.93$MHz.



# Resonant REs are deeply trapped

- Analysis of particle weight in $\delta f$ simulation reveals that most REs resonating with the CAES are trapped particles.

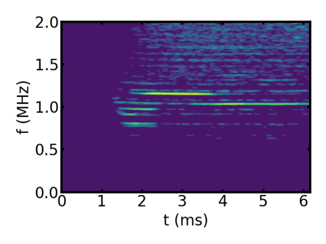
Particle weight distribution for REs in real and phase spaces



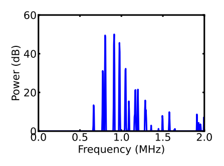
# Multiple modes can be excited by REs with wide range of energy distribution

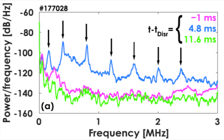
- By doing nonlinear simulation with $n = 1$ with a wide RE energy spectrum (5MeV$< \mathcal{E}_{RE} <$ 20MeV) we find that several discrete modes can be excited simultaneously with comparable amplitudes, and last for several ms.
    - Dominant mode has frequency around 1 MHz.
    - The frequency spacing between adjacent mode is about 0.1-0.2 MHz, smaller than experiments.
    - No frequency chirping is observed.
- In full-torus simulation, we did not find strong excitation of $n = 0$ mode.

Mode spectrogram for nonlinear simulation of $n = 1$




Mode spectrum at $t = 1.5$ms from simulation, compared to experiments



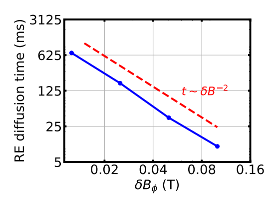
# RE diffusion loss due to kinetic instabilities

- Perturbed fields from CAEs can lead to spatial diffusion of REs through: $E \times B$ drifts, parallel streaming ($v_{\parallel}\delta\mathbf{B}/B_0$), and gradient drifts.
    - It is found that the gradient drifts provide dominant contribution.
- The diffusion time REs driven by gradient drift can be estimated as

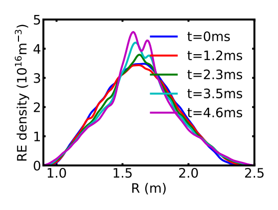
$$T_{\mathrm{diff}} \approx \frac{r^2}{(v_d t_p)^2}\frac{1}{\Delta f} \approx \left(\frac{r}{R}\right)^2 \left(\frac{2eB_0 rc}{\gamma m_e v_\perp^2}\right)^2 \left(\frac{B_0}{\delta B_\parallel}\right)^2 \frac{1}{\Delta f}$$

- In order to get diffusion time less than 10ms, $\delta B_\parallel$ must be larger than 0.65T.
    - This value of much larger compared to the measured $\delta B_\phi$ using RF loop outside plasma
- In nonlinear simulation with strong CAE modes, RE get transported outside and inside simultaneously, resulting in a peaking profile.

Scaling law of measure RE diffusion time with $\delta B$



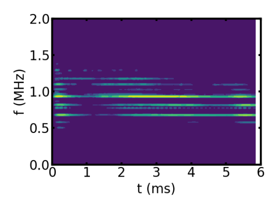

Evolution of RE density profile during diffusion



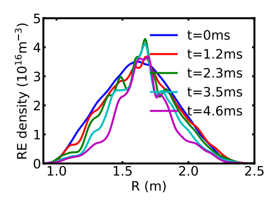
# Primitive results of CAE excitation of RE diffusion using full-$f$ simulation

- To better simulate the CAE excitaion in nonlinear stage, we conducted full-$f$ simulation for $n = 1$ modes.
  - The results are more accurate when RE density deviate significantly from its equilibrium
- Both the excitation of multiple modes and the evolution of RE density profile are consistent with $\delta f$ simulation results.
  - 3 dominant modes: 0.68MHz, 0.82MHz, 0.93MHz
  - Still, no frequency chirping is observed.
- We will add the RE pitch-angle scattering, avalanche source and the electric field drive to the full-$f$ simulation to check the effects on CAE excitation.

Spectrogram of $n = 1$ mode in nonlinear full-$f$ simulation



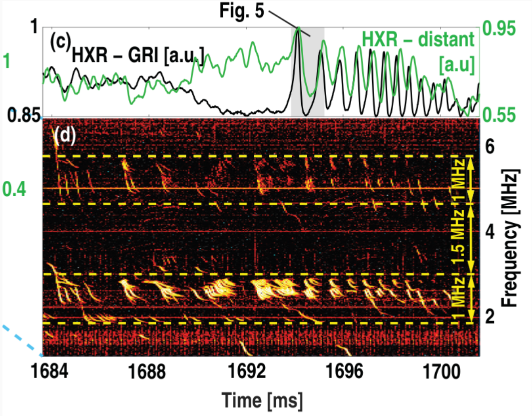

Evolution of RE density profile during diffusion

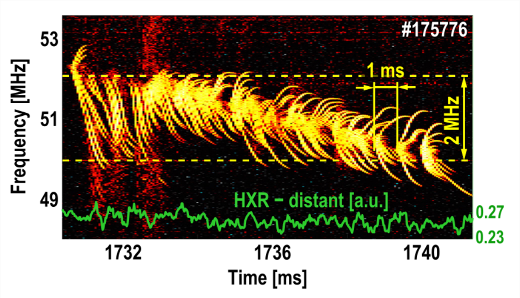


# Summary

- Kinetic-MHD simulation using M3D-C1-K shows CAEs with multiple discrete frequencies for $n = 1$ can be driven by trapped REs, consistent with DIII-D experiments.
  - Mode frequency and linear grwoth rate follows a linear relationshop with resonant RE energy, while damping rate follows a quadrative law.
- Curvature drifts from $\delta B_{\|}$ can lead to spatial diffusion of REs, though smaller than observed.
- Remaining issues:
  - High frequency modes ($f > 1.5$MHz) was not found in simulation. (maybe high-order harmonics of low-frequency mode?)
  - Frequency chirping not found
- Future work:
  - Continue full-$f$ simulation including RE generation and collisions, and evolution of plasma equilibrium
  - Study the excitation of low-frequency MHD modes and their impact on RE transport
  - Simulate the excitation of CAEs in Ne injection scenarios
  - Understand the frequency chirping observed in post-disruption with D2 injection

# Mode frequency chirping in post-disruption




A. Lvovskiy, W.W. Heidbrink, C. Paz-Soldan, D.A. Spong, A.D. Molin, N.W. Eidietis, M. Nocente, D. Shiraki, and K.E. Thome, Nucl. Fusion 59(12), 124004 (2019)