Simulation of compressional Alfven eigenmodes in tokamak disruptions and impact on runaway electron transport

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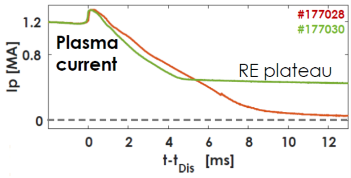
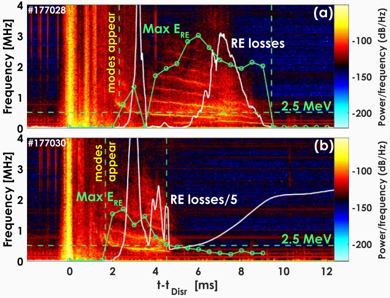
Current quench mode observed in disruption experiments

- 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 RE energy is high.
  - When modes are strong, no RE plateau formed in the end.
  - For Ne MGI, mode is more energetic but connection to RE loss is weak.
- The modes spectrum shows discrete structures, with frequencies spacing of 400kHz.
- CQ mode was also observed in ASDEX with frequency <400kHz
  - Only a single mode observed

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



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



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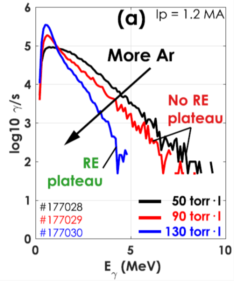
Mode excitation and RE plateau dissipation depend on RE energy

- 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.
  - High-energy RE associated with less injection, small B_T, and low pre-disruption T_e

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

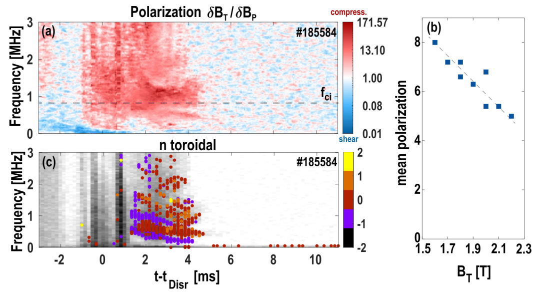
RE energy spectrum with different Ar MGI



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 $n = 0, \pm 1$, 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



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REs can have resonances with MHz compressional waves through precession motion

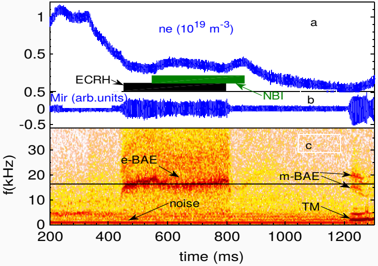
In order to transfer energy to Alfvén waves, runaway electrons must have resonances with the modes.

- Electron cyclotron frequency ($\omega_{ce} \approx 58$GHz) and transit/bounce frequencies (~ 13MHz) of relativistic electrons are both too large compared to mode ω (< 3MHz).
- Precession frequency (ω_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.

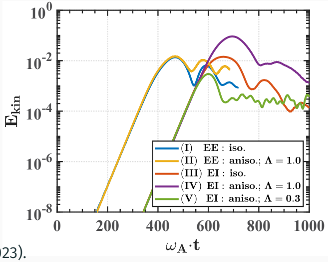
Experimental and simulation studies on Alfvén modes excited by energetic electrons

- 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



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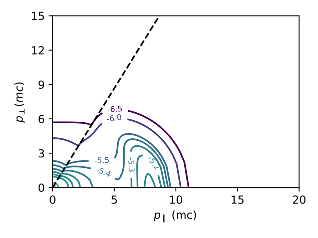
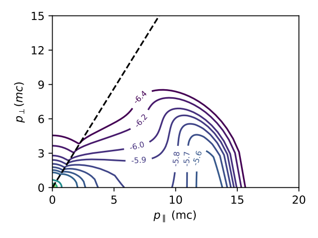
Trapped RE can be generated from pitch angle scattering with high-Z impurities

- 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.
- 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





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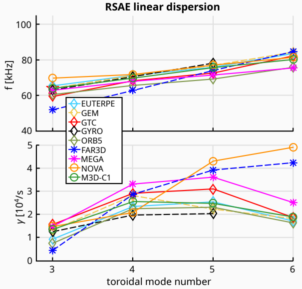
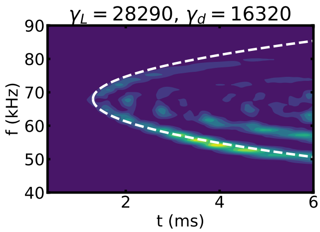
Introduction to M3D-C1-K

- 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.
- Several benchmark tests has been done including fishbone, TAE and RSAE.
- Nonlinear behavior of AE such as frequency chirping can be reproduced through nonlinear simulation.
    - Full-f simulation capability has been tested for 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

- For resonant trapped REs, P_ϕ can be changed by CAE perturbed fields through mirror forces and gradient drifts

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

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

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

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

- Perturbed RE current coupled into MHD,

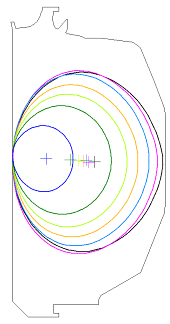
$$\rho\left(\frac{\partial \mathbf{V}}{\partial t}\right) + \rho(\mathbf{V}\cdot\nabla\mathbf{V}) = (\mathbf{J} - \delta\mathbf{J}_{RE})\times\mathbf{B} - \nabla p$$

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

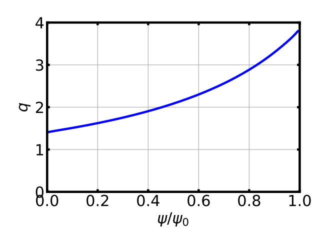
Setup for MHD simulation

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 Δp.
- 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.

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

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

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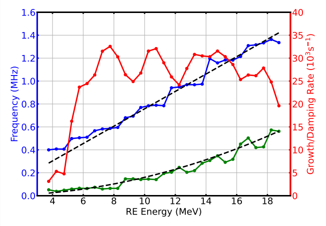
L. Hesslow, O. Embréus, G.J. Wilkie, G. Papp, and T. Fülöp, Plasma Phys. Control. Fusion 60(7), 074010 (2018).

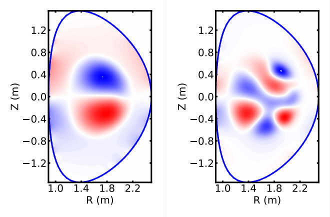
CAE mode frequency and growth rates for different RE energy

- In linear $n = 1$ simulations, CAE frequency f follows a staircase function of 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.
- Damping rate follows a quadratic law with f and RE energy
  - For very high frequency, resistive damping can suppress the mode growth.

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



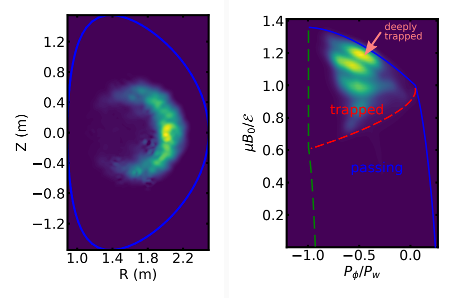
Eigenmode structure ($\delta B_{||}$) for $f = 0.50$MHz and $f = 0.93$MHz.



Resonant REs are deeply trapped

- Analysis of particle weight in δf simulation reveals that most REs resonating with the CAES are trapped particles.
- Mirror forces dominates the drive of low-frequency modes, while gradient drifts is more important for mode with $f > 0.8$MHz.

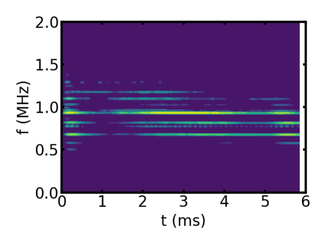
Particle weight distribution for REs in real and phase spaces



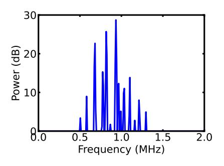
Multiple modes can be excited by REEs with wide range of energy distribution

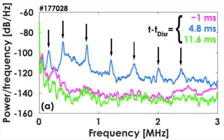
- Nonlinear full-f simulation conducted for $n = 1$ with wide RE energy spectrum (5MeV$< \mathcal{E}_{RE} <$ 20MeV)
  - Several discrete excited simultaneously with comparable amplitudes.
  - Three dominant mode with frequencies 0.68MHz, 0.82MHz, 0.93MHz
  - Frequency spacing between adjacent mode is 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.

Spectrogram of $n = 1$ full-f simulation



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





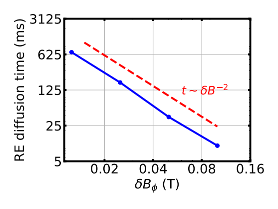
RE diffusion loss due to kinetic instabilities

- 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.
  - Gradient drifts dominates RE transport
- RE diffusion time estimation

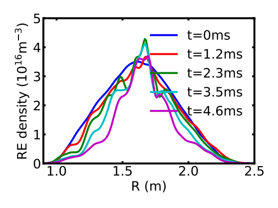
$$T_{\mathrm{diff}} \approx \frac{r^2}{(v_d t_p)^2}\frac{1}{\Delta f} \approx \left(\frac{r}{R}\right)^2 \left(\frac{2eB_0 rc}{\gamma m_e v_\perp^2}\right)^2 \left(\frac{B_0}{\delta B_\parallel}\right)^2 \frac{1}{\Delta f}$$

- In order to get diffusion time less than 10ms, $\delta B_\parallel$ must be larger than 0.65T.
- RE get transported outward and inward simultaneously, resulting in a peaked profile.

Scaling law of measure RE diffusion time with δB



Evolution of RE density profile during diffusion



Summary

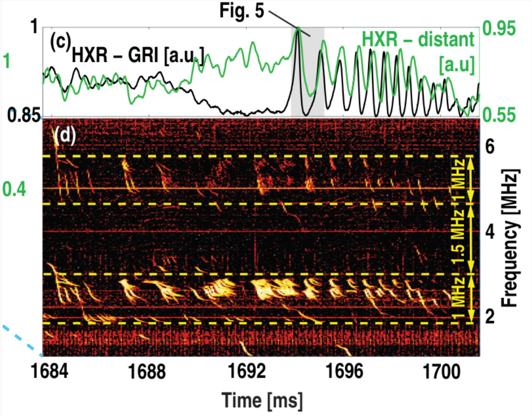
- Kinetic-MHD simulation using M3D-C1 shows multiple $n = 1$ CAEs with discrete frequencies can be driven by trapped REs at different energies, consistent with DIII-D experiments.
  - Mode frequency follows a linear relationship with resonant RE energy.
- Gradient drifts and mirror forces due to $\delta B_{||}$ can lead to wave-particle interaction and spatial diffusion of REs, though smaller than observed.
- Excitation of CAEs is a signal of existence of high-energy REs with large pitch angles, which can be used for RE diagnostics
  - Further simulations can help understand difference of CQ modes for different devices
- 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

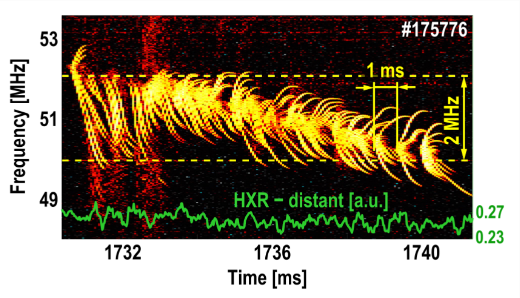
C. Liu, A. Lvovskiy, C. Paz-Soldan, S.C. Jardin, and A. Bhattacharjee, accepted by PRL, arXiv:2303.03622 (2023).

Future work

- Continue full-f simulation including RE generation and collisions, and evolution of plasma equilibrium
  - Avalanche RE source can give birth to large pitch-angle REs
- Conducting scan over B_T and pre-disruption T_e
- Study the excitation of low-frequency MHD modes driven by RE drift current, and their impact on RE transport
- Simulate the excitation of CAEs in Ne injection scenarios
- Understand the frequency chirping observed in post-disruption after D2 injection
- Explore driving AE externally and inducing RE diffusion

Mode frequency chirping in post-disruption





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