Simulation of CAW driven by RE using M3D-C1

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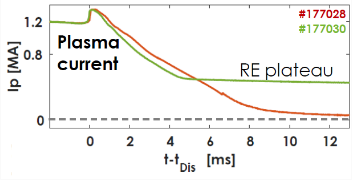
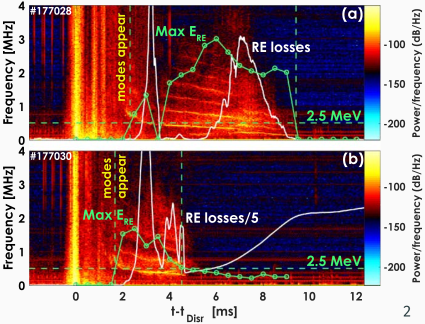
Current quench mode observed in DIII-D disruption experiments

- 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.

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



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



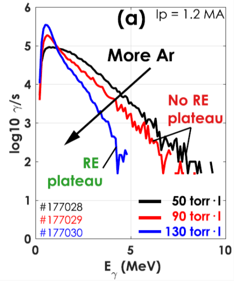
A. Lvovskiy et al., Plasma Phys. Control. Fusion 60, 124003 (2018).
C. Paz-Soldan, et al., Nucl. Fusion 59, 066025 (2019)

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.

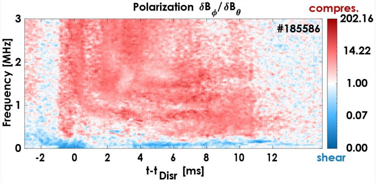
RE energy spectrum with different Ar MGI



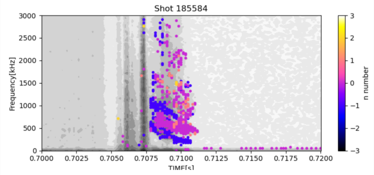
Toroidal mode number and polarization of the modes

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

Mode polarization measurement



Toroidal mode number measurement



REs can have resonances with MHz CAEs through precession motion

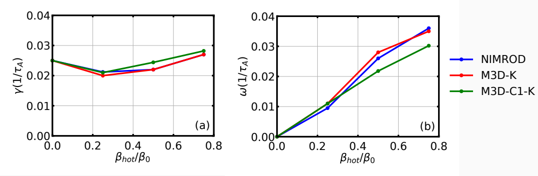
In order to transfer energy to CAEs, runaway electrons must have resonances with the modes.

- Electron cyclotron frequency ($\omega_{ce} \approx$ 58GHz) and transit/bounce frequencies ($\sim$ 13MHz) of relativistic electrons are both too large compared to mode ω (< 2MHz).
- Precession frequency (ω_d) of trapped 2.5MeV 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.
  - Assuming modes have the same n, then higher frequency mode correspond to larger ω_d and resonate with higher energy REs.
    - Consistent with the observation that higher frequency modes are excited later as RE energy grows.

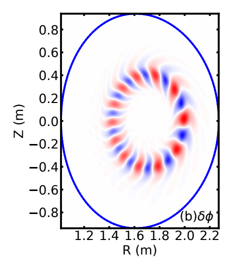
Introduction to M3D-C1-K

- 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



CAE can interact with REs through mirror forces

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

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

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

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

  - 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 $(\nabla\times(P_\perp\mathbf{b}/B))$.

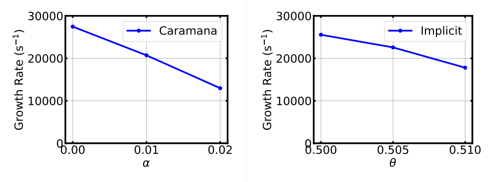
Challenge of simulating CAEs with implicit/semi-implicit codes

$$\rho_0 \frac{\partial \mathbf{V}}{\partial t} - \theta^2 \Delta t^2 \mathbf{L}\left(\frac{\partial \mathbf{V}}{\partial t}\right) = \mathbf{J} \times \mathbf{B} - \nabla p + 2\alpha \Delta t \mathbf{L}(\mathbf{V})$$

We have tried θ-implicit method ($\alpha = \theta$), modified-Caramana method ($\theta = 1$, small α) and implicit method with parameter θ to simulate CAEs.

- For Caramana method, the simulation linear growth rate depends sensitively on diffusion term α.
- For implicit method, growth rate depends sensitively on θ.
- Simulation is numerically unstable for θ-implicit with $\theta < 0.55$. For $\theta > 0.55$ mode growth is suppressed.

Mode linear growth rate as function of implicit parameter

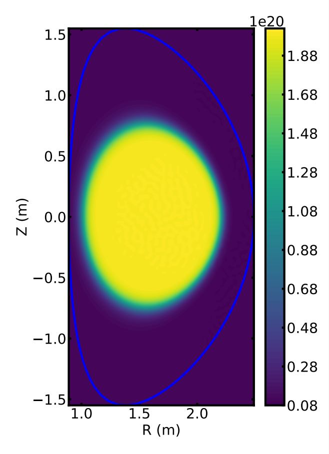


The working options are Caramana with $\alpha = 0$ and Crank-Nicolson ($\theta = 0.5$).

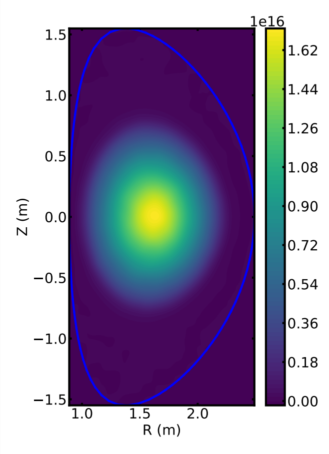
Simulation setup

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

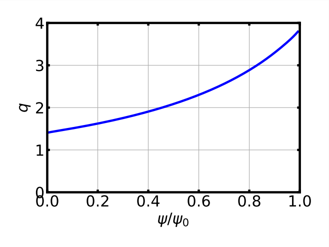
Ion density



RE density



q profile



Simulation setup (cont'd)

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

- RE has energy distribution ranging from 5MeV to 15 MeV.
- 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.

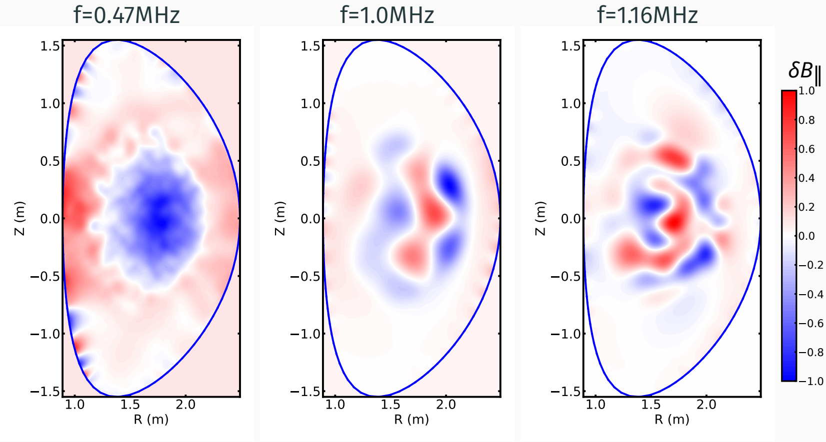
$$f_{RE} \sim \exp(A\xi) \qquad A(p) = \frac{2E}{\nu_D}\frac{p^2}{\sqrt{p^2+1}}$$

$$\nu_D = Z_{eff} + 1 + \sum_j \frac{n_j}{n_e}\left(Z_j^2 - Z_{0j}^2\right)\frac{\ln a_j p}{\ln \Lambda}$$

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, 074010 (2018)

Mode structure

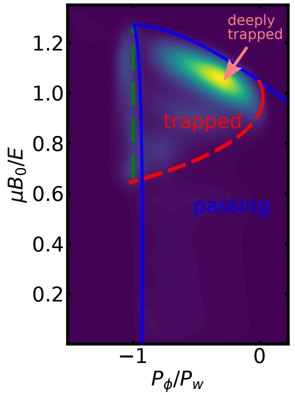


- Even with only $n = 1$, multiple CAEs can be excited with different frequencies and mode structures.
  - The fastest growing mode depends on the RE energy

Resonant REs are deeply trapped

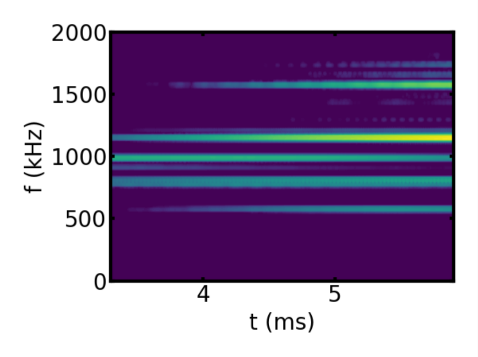
- By plotting the RE distribution with δf weight in $P_\phi - (\mu B_0/E)$ map for $n = 1$ simulation, it is found that most REs with large weight are deeply trapped particles.

Weight distribution for REs

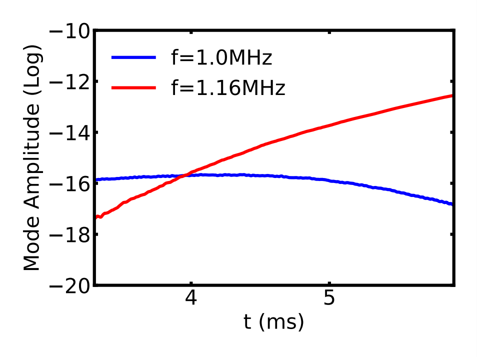


Multiple modes can be excited by REs for a single n_{tor}

Mode spectrogram for $n = 1$ simulation



Evolution of amplitude for two dominant modes

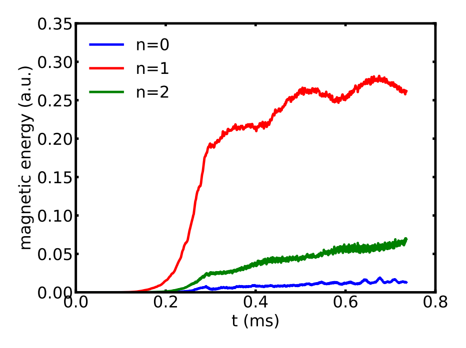


- By doing kinetic-MHD simulation with $n = 1$, we find that after the initial fasted growing mode saturates, other subdominant modes can continue growing and become the dominant mode in the later time.

No strong $n = 0$ mode excitation found in full torus simulation

- We did full torus simulation to examine the mode-mode interaction.
  - It is necessary to add small hyper diffusion on v_ϕ to suppress numerical instabilities at edge.
- Even with very large $\delta B/B$, there is no strong excitation of $n = 0$ mode in our simulation.

Magnetic energy of different *n* from nonlinear simulation



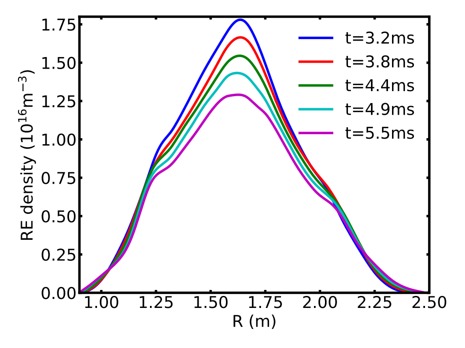
RE diffusion loss is weak when using the δB from experiment

- In addition to $\delta B_{\parallel}$, CAE can also give rise to a smaller $\delta B_{\perp}$ that can lead to diffusion loss of both resonant and non-resonant REs.
- The random walk step of REs driven by $\delta B_{\perp}$ can be estimated by $c(\delta B_{\perp}/B_0)t_{\mathrm{transit}}$, where $t_{\mathrm{transit}} \approx R/c$ is the transit time of RE. The correlation time is about $1/\omega$. Then, the diffusion time can be estimated as

$$T_{\mathrm{diff}} \approx \left(\frac{a}{R}\right)^2 \left(\frac{B_0}{\delta B_{\perp}}\right)^2 \frac{1}{\omega}$$

- In the $n = 1$ simulation, $\delta B_{\perp}/B_0 \approx 10^{-2}$, $T_{\mathrm{diff}} \approx 1\mathrm{ms}$.
- In recent DIII-D experiments there was direct measurement of $\delta B_{\perp}/B \approx 10^{-4} \sim 10^{-5}$ at edge. With this value the diffusion of passing REs is ignorable.

Diffusion of RE density with $\delta B_{\perp}/B \approx 10^{-2}$



Summary

- By doing kinetic-MHD simulation using M3D-C1-K, we get the excitation of CAEs with multiple frequencies for $n = 1$ using REs with a wide energy spectrum, which was observed in experiments.
- Nonlinear simulation can give a finite saturation value of $\delta B/B$. However, this value is not enough to drive RE transport observed in experiments.
- The excitation of $n = 0$ modes after $n = 1$ was not found in simulations.
- Future work:
  - Study the dependence of mode excitation and RE diffusion and RE energy and pitch angle distribution
  - Study other (possibly hidden?) MHD and wave instabilities which can give bigger impact for passing REs.