Parametric study of Alfvénic instabilities driven by runaway electrons during the current quench in DIII-D

Presented by

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with participation of

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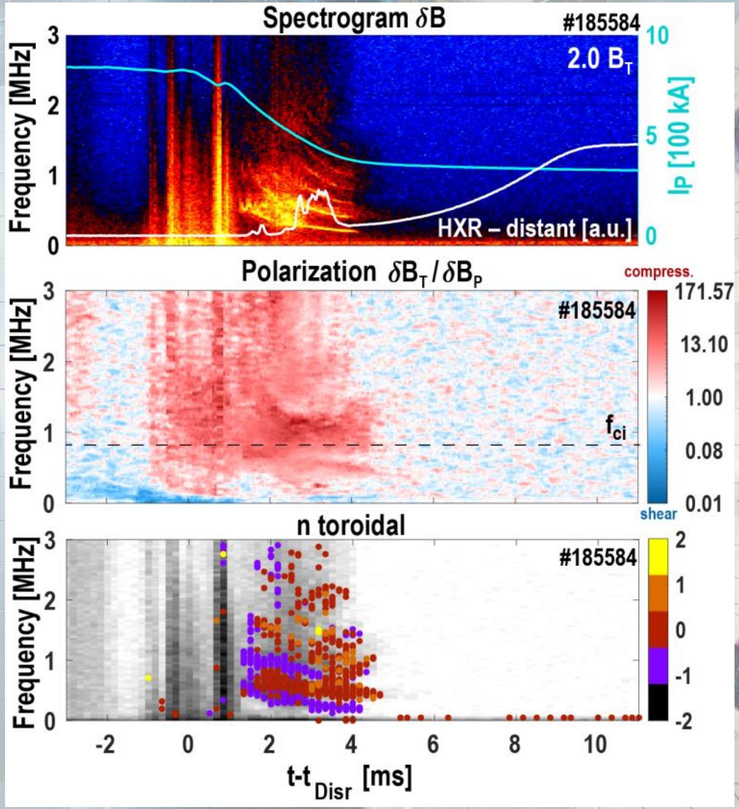

Second TM on Plasma Disruptions and their Mitigation
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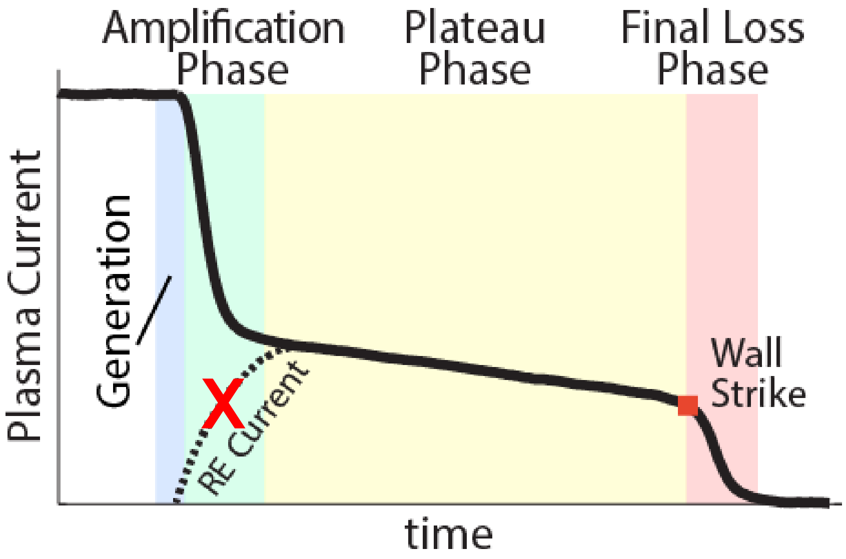
GENERAL ATOMICS

Increased RE loss during current quench is needed to tame avalanche amplification in high-current tokamaks



Formation and loss of RE beam

- **Massive material injection is adopted as a baseline disruption mitigation scheme in ITER**
- **It aimed to increase RE dissipation via collisions and may provide RE avoidance via dilution cooling**
- **Complimentary techniques, increasing RE loss during the current quench, may be beneficial to reduce the avalanche gain:**
  - MHD instability[1–3]
  - Passive coil[4–5] $\Rightarrow \delta B/B \uparrow$
  - **Interaction with waves[6–9]**

- **This talk: study of RE-driven Alfvénic instabilities in DIII-D**

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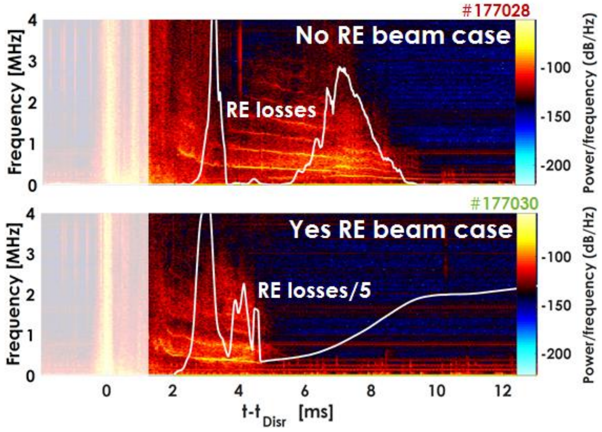
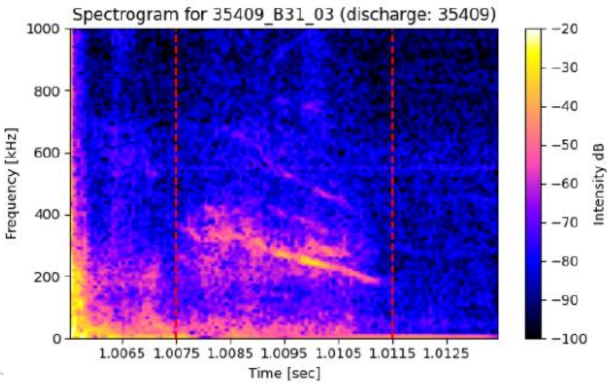
Alfvénic instabilities, observed in existing tokamaks and predicted in ITER, can increase RE loss

DIII-D



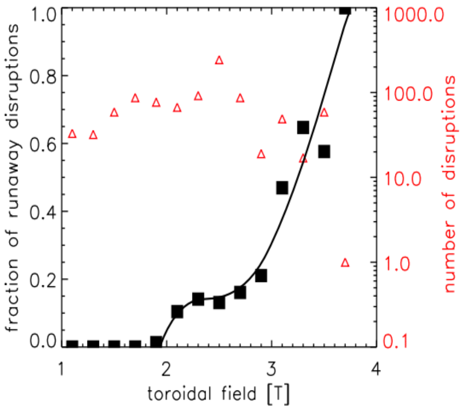
AUG



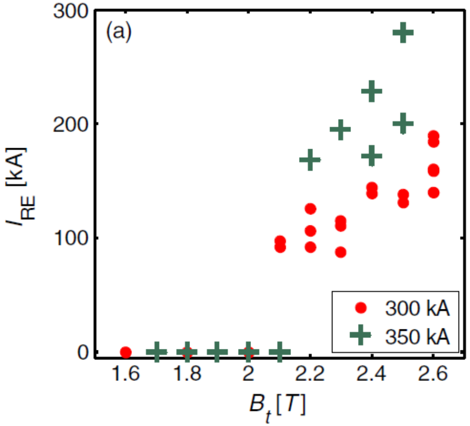
- **RE-driven Alfvénic instabilities were observed in DIII-D after Ar MGI[6]**
  - Correlate with increased RE loss
  - Energy of modes increases with RE energy
  - CAEs were proposed[6–7]
- **Alfvénic instabilities were also observed during the CQ in AUG[8]**
  - No clear effect on RE current was found
  - GAEs were proposed
- **α-driven Alfvénic instabilities are predicted in ITER[9]**
  - Amplitude of TAEs can be large enough to increase RE transport and reduce avalanche gain

- **We report dependence of Alfvénic instabilities in DIII-D on B_T, T_e, non-argon injection and their identification**

B_T threshold on RE beam generation may relate to the presence of Alfvénic instabilities



Probability of RE beam generation vs B_T on JET[15]



RE current vs B_T on TEXTOR[13]

- **Many tokamaks exhibit empirical B_T threshold for generation of RE beams[10]**
  - B_T > 2–2.2 T
  - Not a hard limit: KSTAR[11] and J-TEXT[12] observed RE beams at 1.3 T and 1.2 T
  - Ratio $\delta B/B_T > 10^{-4} - 10^{-3}$ is presumably more relevant metric[13–14]
- **Dependence of Alfvénic instabilities on B_T could explain this threshold**
  - Frequency shift of instabilities ($f \propto B_T$) may change the resonance condition and affect RE loss
  - Power of Alfvénic instabilities increases as Mach number increases ($\frac{v}{v_A} \propto \frac{1}{B_T}$)

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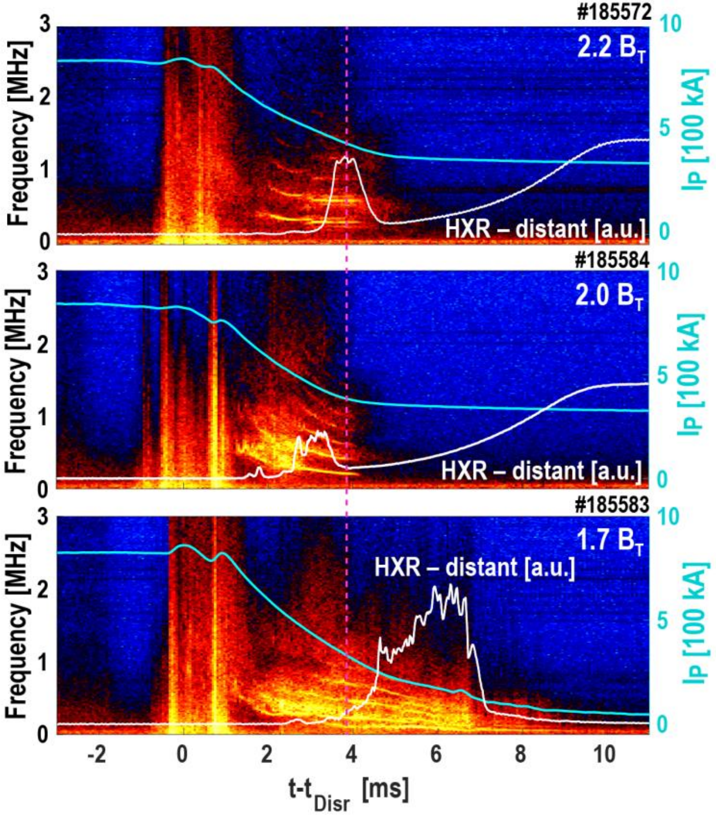
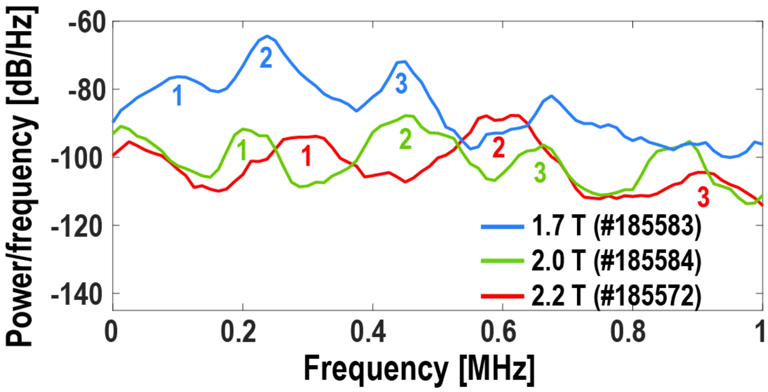
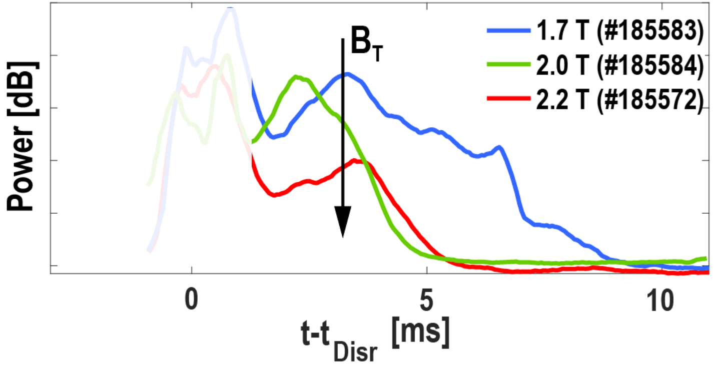
B_T Decreasing B_T pushes Alfvénic instabilities to lower frequencies and increases their power. No RE beam is observed below 1.8 T



- B_T was varied from 1.6 T to 2.2 T for typical DIII-D RE scenario
- No RE beam was observed below 1.8 T
- As B_T decreases:
  - modes shift to lower frequencies
  - spacing between modes decreases
  - RE loss becomes more prominent

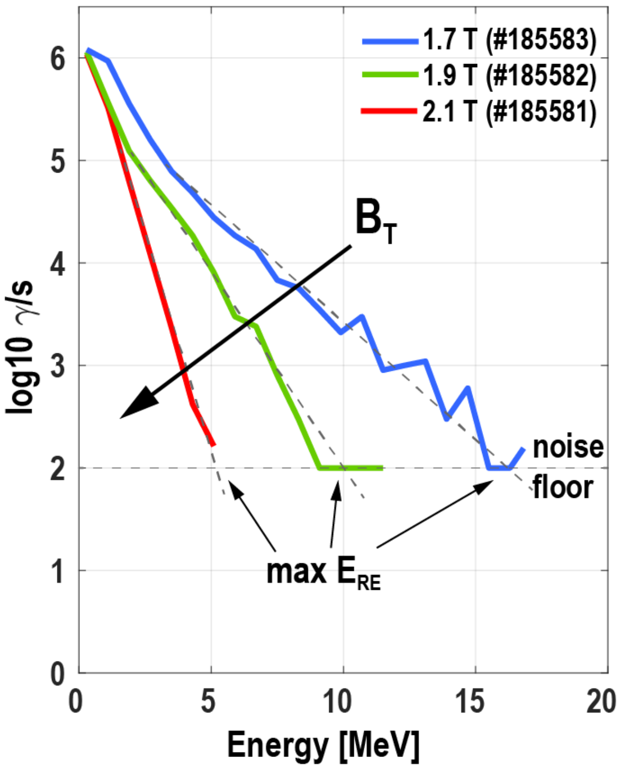
Decreasing B_T pushes Alfvénic instabilities to lower frequencies and increases their power. No RE beam is observed below 1.8 T #2





- B_T was varied from 1.6 T to 2.2 T for typical DIII-D RE scenario
- No RE beam was observed below 1.8 T
- As B_T decreases:
  - modes shift to lower frequencies
  - spacing between modes decreases
  - RE loss becomes more prominent
  - power of modes increases
- Increased power of instabilities could be explained by changing resonant condition and growth rate, but this is not the whole story

B_T RE population becomes more energetic as B_T decreases



- **The driver of instabilities (REs) should be also considered**
- **As B_T decreases, HXR spectra from REs harden**

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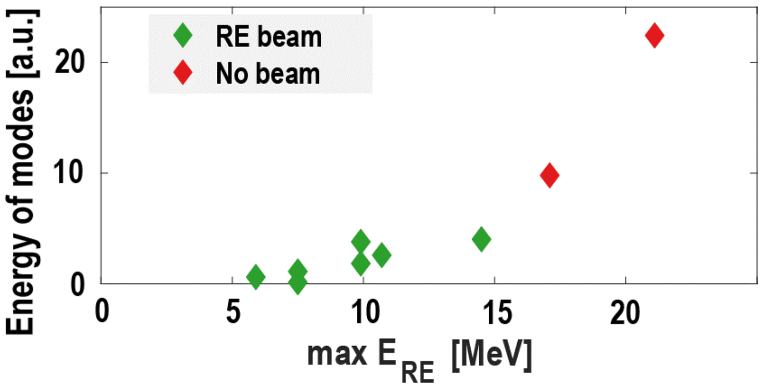
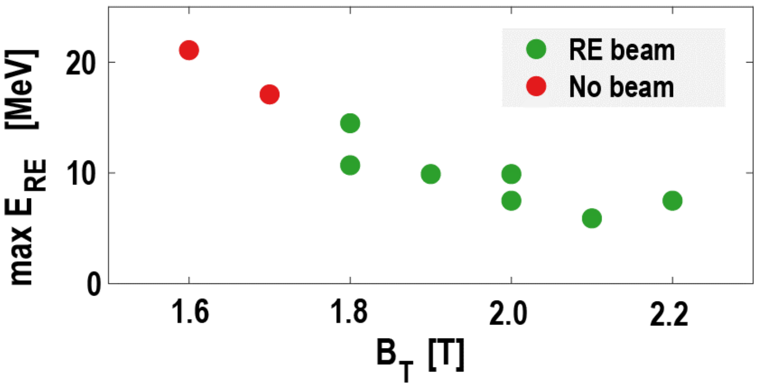
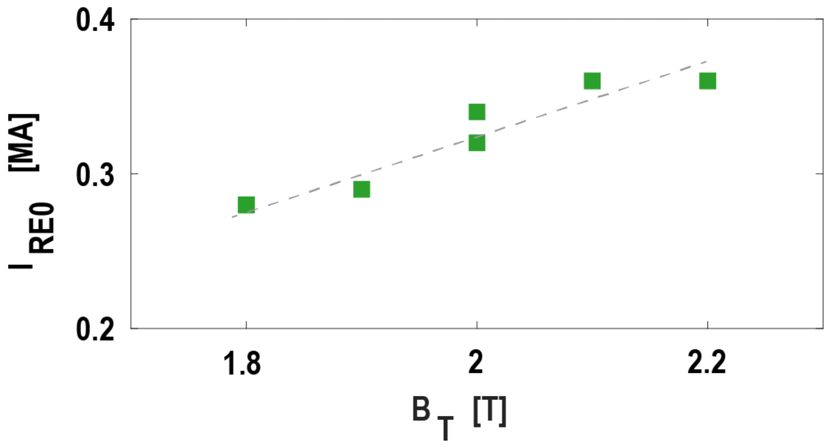
B_T Energy of modes non-linearly increases with max energy of REs





- The driver of instabilities (REs) should be also considered
- As B_T decreases, HXR spectra from REs harden
- Energy of modes non-linearly increases as maximum energy of REs increases
  - No RE beam if max $E_{RE} > 15\ MeV$
- Maximum energy of REs increases as B_T decreases

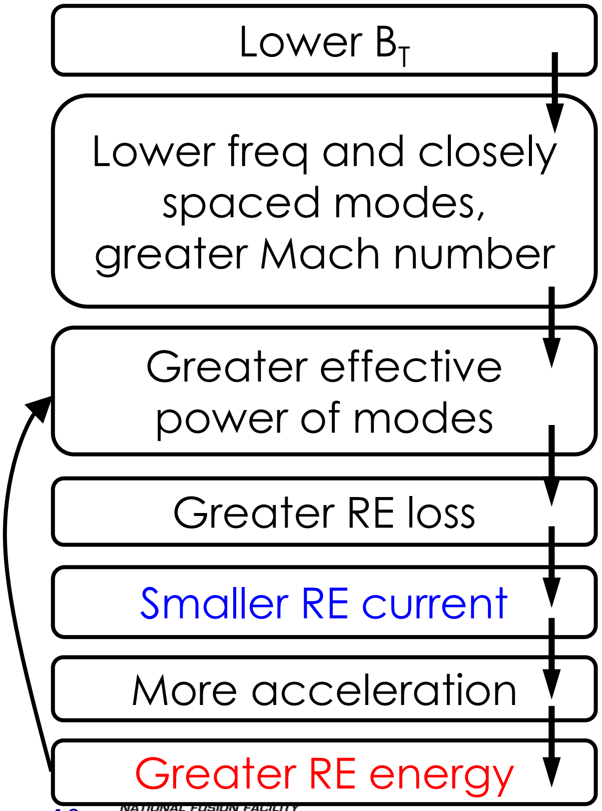
B_T Increasing RE energy with decreasing B_T is not completely understood



- Evolution of modes is consistent with expectations for Alfvénic instabilities
- Their do play a role in increasing RE loss
- The power of modes depends both on B_T and E_{RE}
- Increasing RE energy as B_T decreases has no clear understanding yet
- **Decreasing conversion from thermal to RE current as B_T decreases may be a hint**

B_T RE energy evolution with B_T can be of different nature

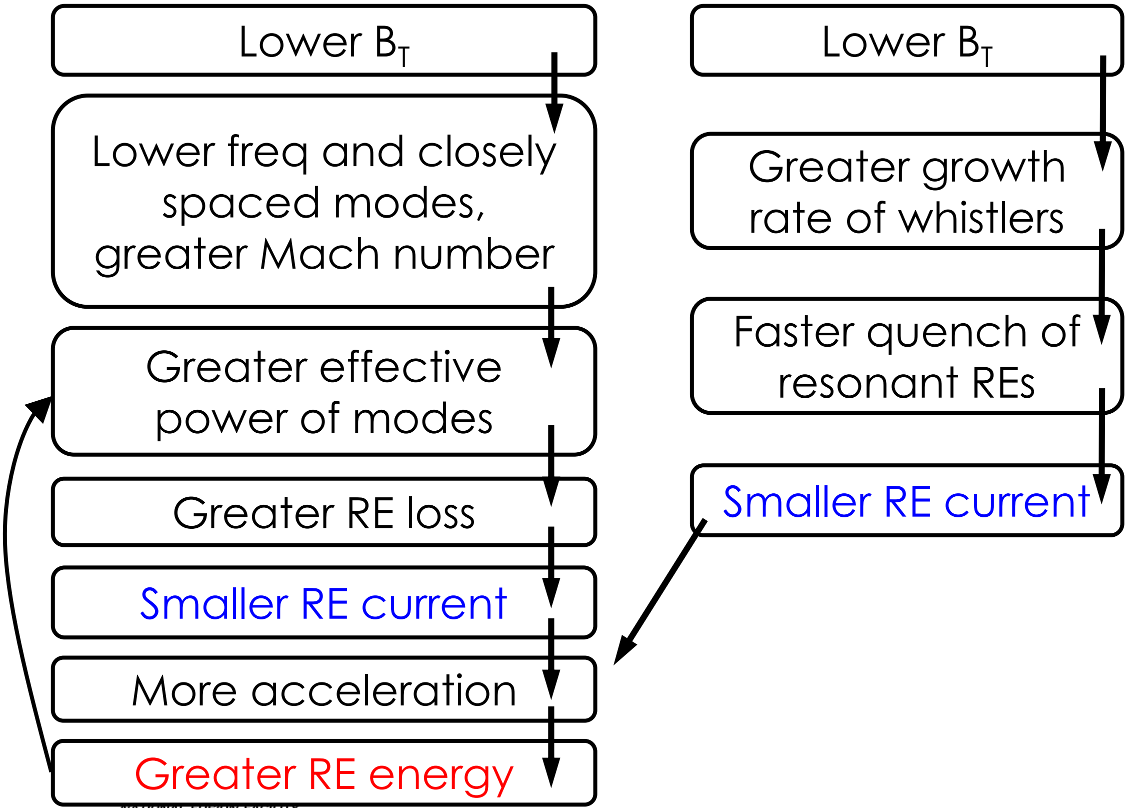
Vicious cycle



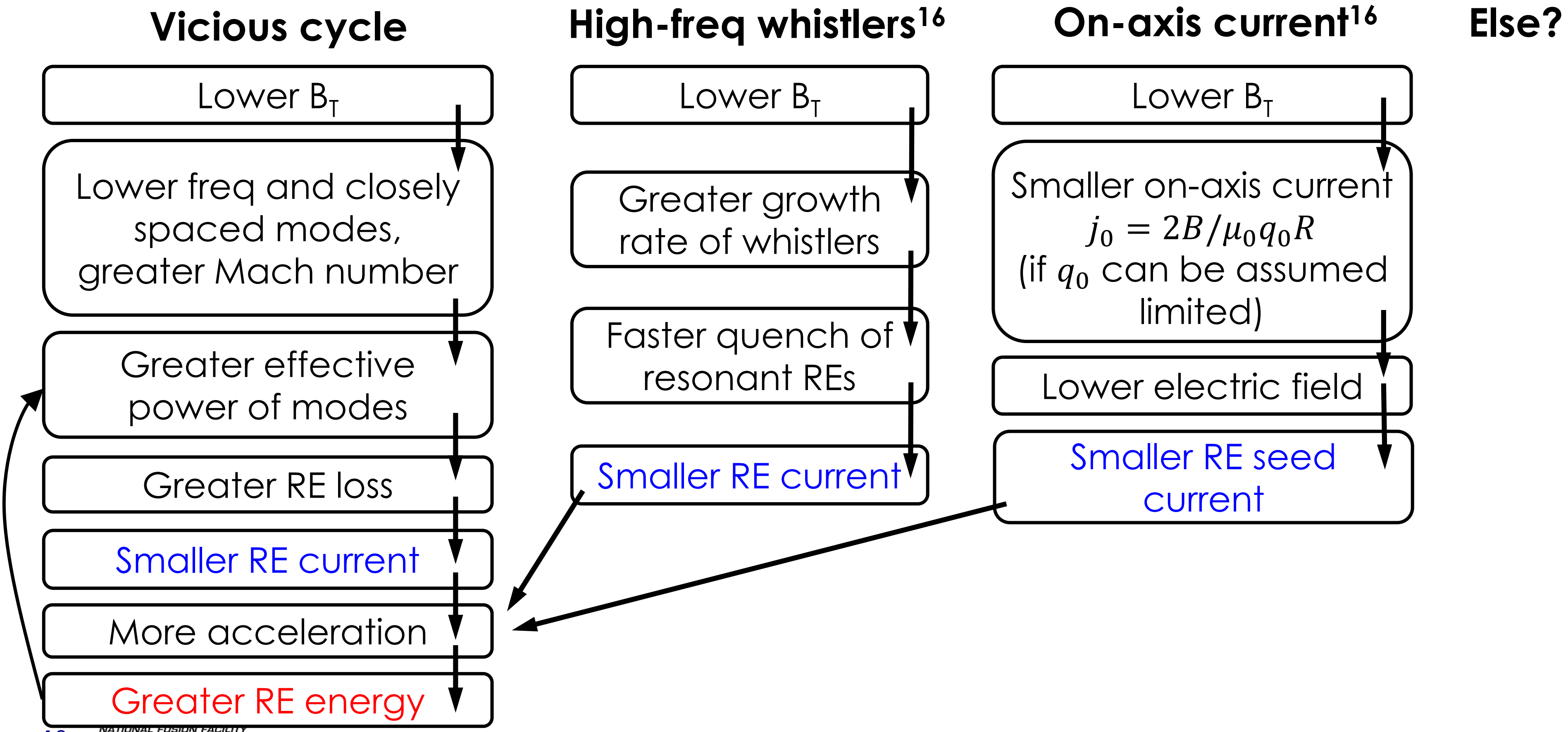
B_T RE energy evolution with B_T can be of different nature

Vicious cycle

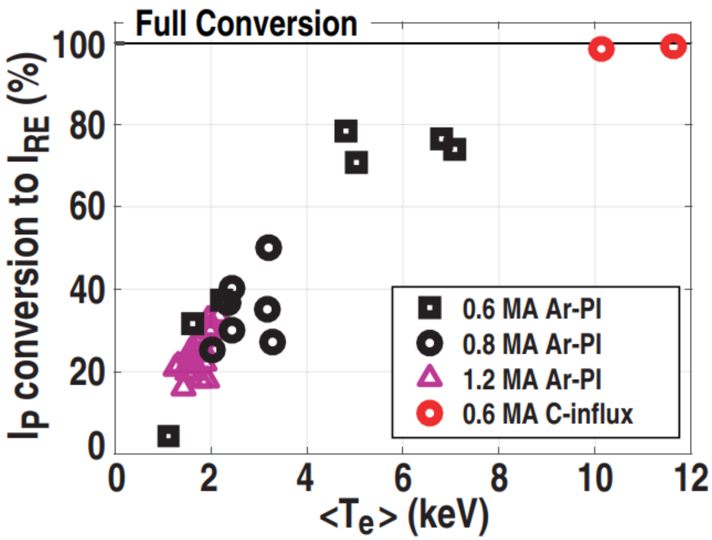
High-freq whistlers[16]



B_T RE energy evolution with B_T can be of different nature



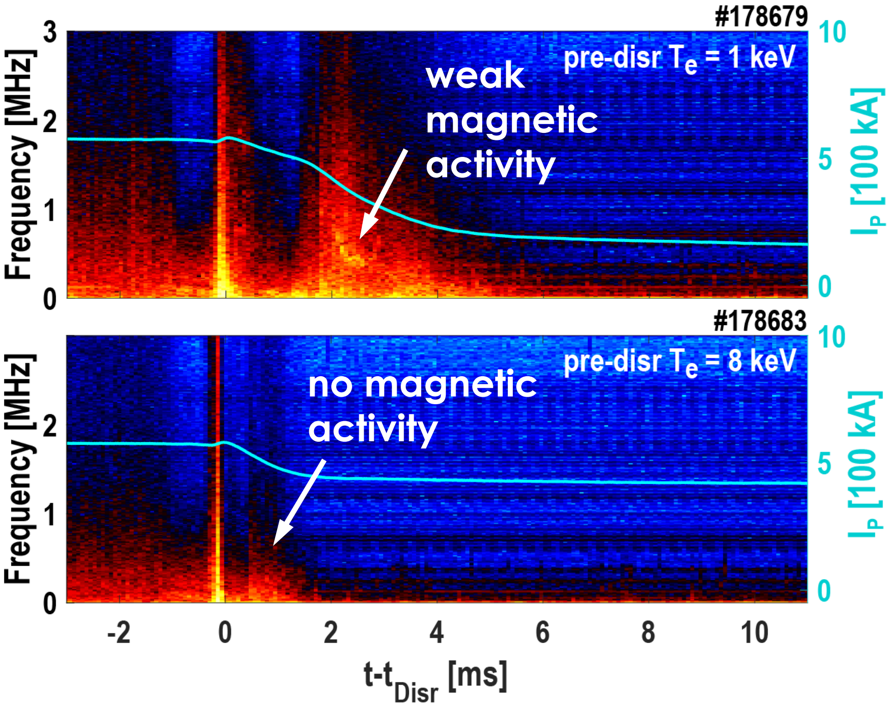
T_e High temperature RE scenario leading to increased current conversion may cause different picture of Alfvénic instabilities



Conversion of thermal to RE current increases with core T_e[17]

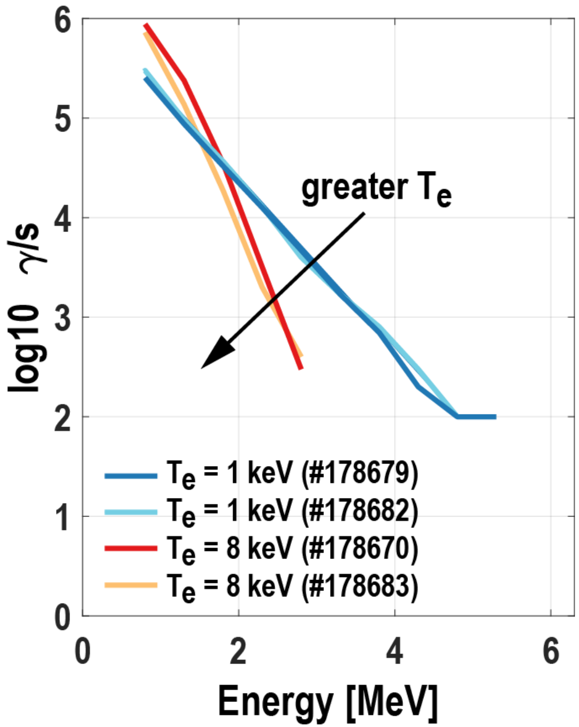
- **Typical RE studies on DIII-D employ low temperature scenario (T_e≈1−2 keV)**
- **In the past, no dependence of RE population and Alfvénic instabilities on the pre-disruption T_e was observed[6]**
  - But T_e was limited by 4 keV
- **Recently, new scenario with reactor relevant temperatures (T_e≈10 keV) was developed on DIII-D[17]**
- **Does this change the drive of Alfvénic instabilities?**

T_e Magnetic activity for hot disruption is negligible, current conversion much higher



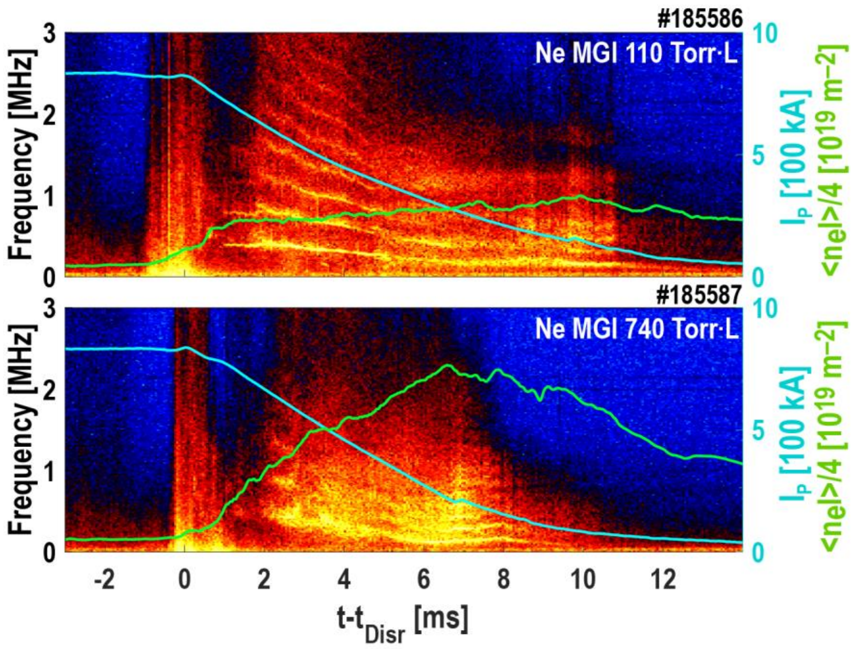
- T_e was varied from 1 keV to 8 keV
- T_e = 1 keV leads to 20% curr. conversion, T_e = 8 keV causes 80% conversion
- **Hot disruption shows no magnetic activity**

T_e RE HXR spectra are much softer in hot disruptions



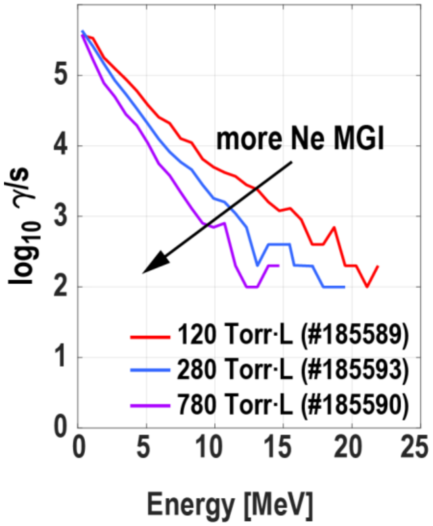
- T_e was varied from 1 keV to 8 keV
- T_e = 1 keV leads to 20% curr. conversion, T_e = 8 keV causes 80% conversion
- Hot disruption shows no magnetic activity
- High T_e leads to less energetic RE population
- This supports hypothesis that greater conversion leading to less energetic REs is beneficial for lack of Alfvénic instabilities

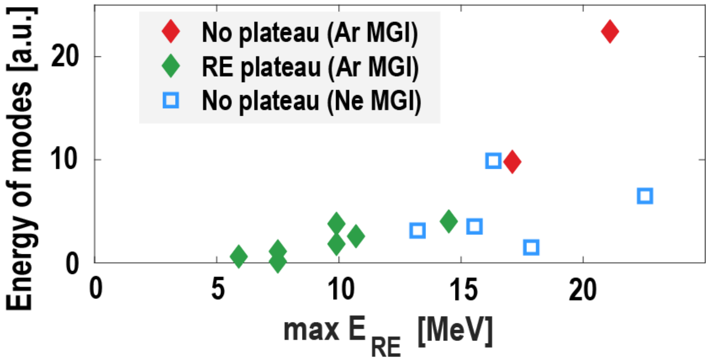
Ne No sustained RE beam is observed after Ne MGI



- **Historically, deliberate injections other than Ar produced no RE beams**
- **Could Alfvénic instabilities be involved in here?**
- **Same parameters as in Ar MGI experiment, but with massive injection of Ne or D_2 from 100 Torr*L to 800 Torr*L**
- **No sustained RE beam after Ne**
  - Great modes during the CQ
  - With plasma density increasing, freq of modes decreases (as expected)

Ne Injected Ne decreases energy of REs, but it still stays elevated

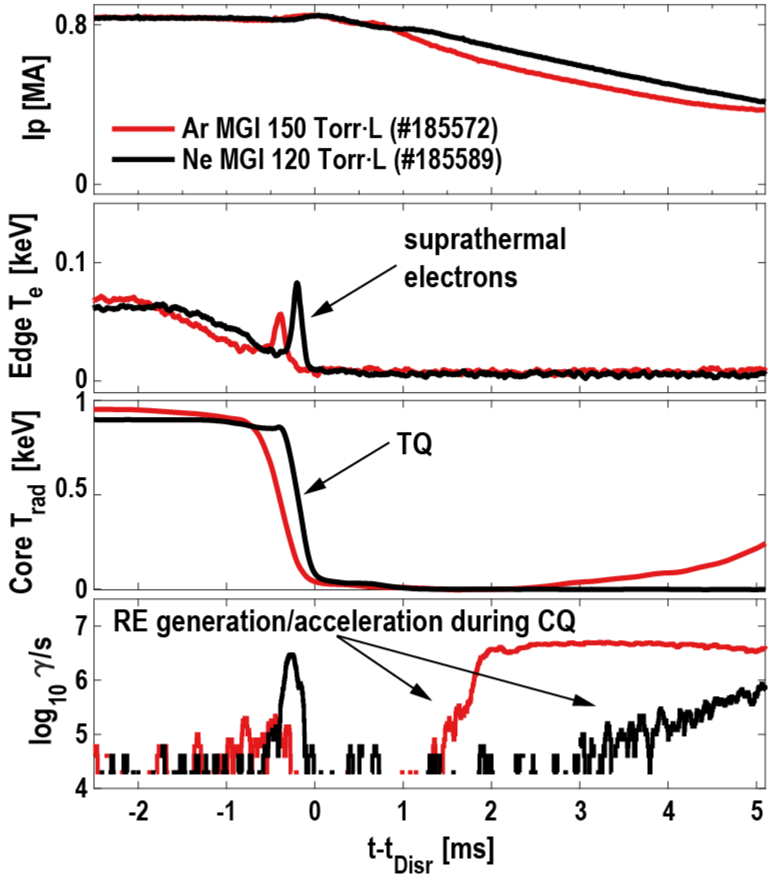




- **RE population becomes less energetic as Ne qty increases (similar to Ar MGI)**
  - However, Ne does not reduce the energy of REs to the same extent as Ar MGI
  - RE energy is above 13 MeV even after the maximum qty of Ne

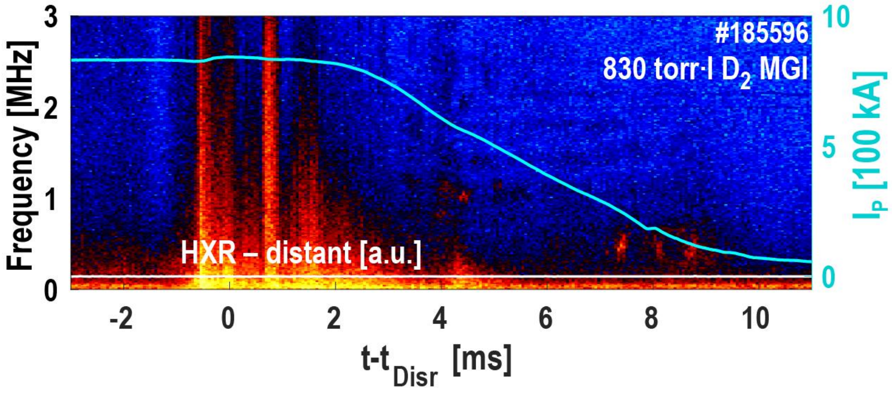
- **The dependence of the energy of modes on the maximum E_{RE} is vague**

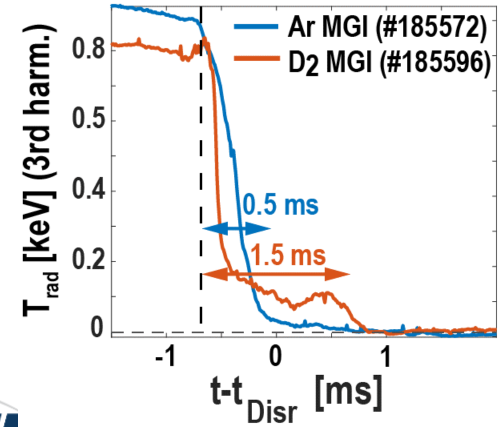
Ne Smaller RE seed or its poor survival could be the reason of no RE beam after Ne MGI



- **The role of instabilities after Ne MGI is presumably minor**
- **Disruptions caused by Ne MGI are different compared to ones after Ar MGI**
- **HXR signal is delayed and less steep after Ne likely indicating smaller RE seed or poor RE seed survival**
- Without diagnosis of RE seed it is difficult to draw a conclusion whether Ne MGI indeed supplies fewer seed REs

D_2 No Alfvénic instabilities are observed after D_2 MGI
Too slow plasma cooling is proposed as the reason of no RE beam





- **No instabilities are observed during the CQ after D_2 MGI**
- **No RE loss is observed either**
- **There is no signal from confined REs too**
- **Lack of REs can be explained by too slow plasma cooling: 1.5 ms vs 0.5 ms (D_2 MGI vs Ar MGI respectively)**
- Alfvénic instabilities were observed in past H-mode shots after D_2 SPI, but they are yet to be studied

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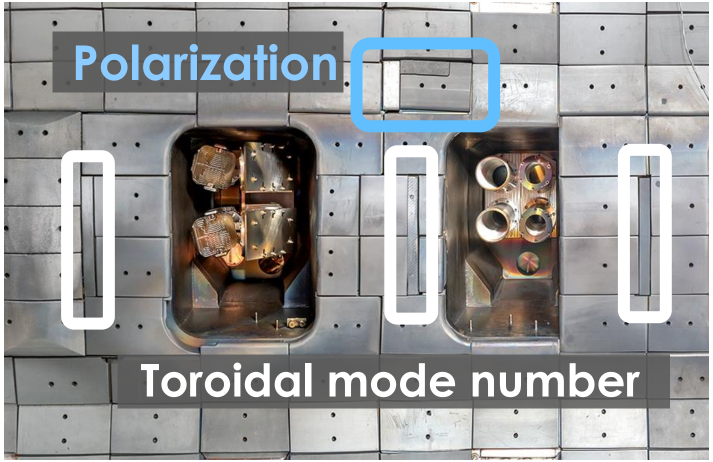
ID

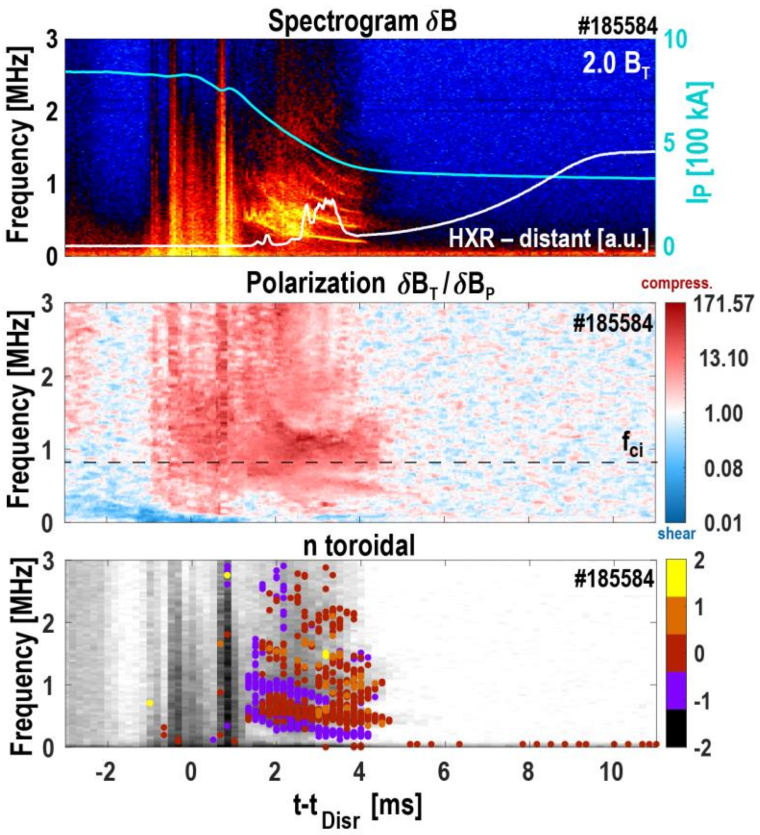
Polarization and n-number of modes can help to identify them



RF diagnostic[19]:
magnetic loops by group

- There is a whole zoo of Alfvénic instabilities[18]
- Frequency analysis helps to limit the circle of suspects, but more measurements are needed to further narrow down the list
- Polarization measurements ($\delta B_T/\delta B_P$) can separate compressional (CAEs) and shear (GAEs, TAEs, etc.) waves
- Toroidal mode number measurements are useful to validate modeling[7]
- Upgraded set of RF magnetics provides such measurements[19]

ID Polarization and n-number supports observation of CAEs



- **Polarization of instabilities is predominantly toroidal (compressional)**
- **This supports previous estimates and modeling (suggesting CAEs) and likely excludes shear TAEs and GAEs**
- **Toroidal mode number n = −1, 0, +1**
  - This partially supports the modeling presently showing no n = 0 mode[7]
- Lack of mode-like structures in the plots is presumably caused by insufficient resolution

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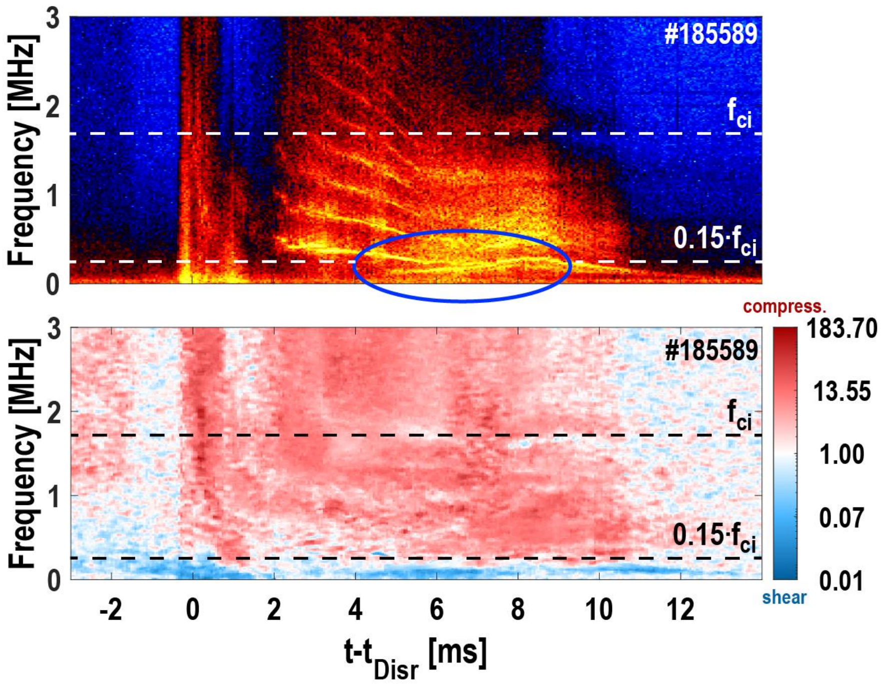
ID Lower frequency modes are presumably GAEs



- While CAEs have compressional polarization from core to edge, shear GAEs can also show compressional signals at the edge
- GAEs can be excluded above f_{ci}, but both CAEs and GAEs are possible below it
- Drive of GAEs at low frequencies would explain observation of modes evolving in different directions
- This would also explain transition from shear to compressional polarization at low frequencies

CQ modes are observed in major DIII-D disruptions except for high T_e cases and low-Z injections in low-energy plasma

Primary inj.	RE beam	CQ modes
Ar PI	mostly ✓	mostly ✗
Ar MGI	✓ / ✗	✓
Ne MGI	✗	✓
D_2 MGI	✗	✗
Ne SPI	✗	✓
D_2 SPI	✗	✓
Ne+D_2 SPI	✗	✓
C influx	✗ / ✓	✓ / ✗
solid plastic C+W shell pellet C+B shell pellet	✗	✓

- **Decreasing B_T leads to increasing energy of REs and power of CQ modes. No RE beam is observed above threshold**
  - Reduced current conversion is proposed
- **Increasing T_e causes opposite and stronger effect: no modes, low-energy REs and high RE current at T_e = 8 keV**
- **Both instabilities and poor RE seeding are likely responsible for no RE beam after Ne MGI**
- **Too slow plasma cooling may explain no REs after D_2 MPI**
- **Instabilities are presumably CAEs at high frequencies and GAEs at low frequencies**

What does it mean for ITER?

- High B_T and high T_e are favorable for weak instabilities and sustained RE beam ☹
- High current/high energy content plasma is favorable for modes and no RE beam ☺
- Both Ne and D_2 injections can drive modes in high performance plasma and also presumably cause weak RE seed formation ☺
- Modeling is needed to weigh these factors and extrapolate to ITER!
- Also more studying of D_2 and Ne injections is needed
- Even if there are no natural Alfvénic instabilities in ITER, exploring of external launch of waves similar to CAEs and GAEs is worth considering

Acknowledgments and Disclaimer

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Backup

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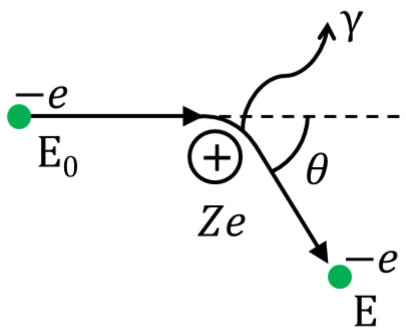
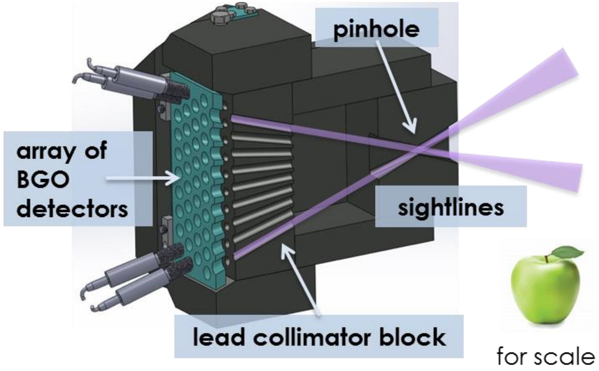
Bremsstrahlung radiation provides information on energy and distribution of REs





- When electron changes its trajectory it emits photons
- MeV electrons → MeV γ rays
- γ rays (HXRs) are forward beamed based on RE energy
- $f_e(E_\parallel, E_\perp)$ produces unique bremsstrahlung spectrum
- DIII-D Gamma Ray Imager (GRI) provides 2D view of RE bremsstrahlung emission [1−4]
- New detectors with MHz counting capabilities [5,6] allow obtaining of HXR spectra during current quench

[1] Pace *et al*. RSI 2016
[2] Cooper *et al*. RSI 2016
[3] Paz-Soldan *et al*. PRL 2017
[4] Paz-Soldan *et al*. PoP 2018
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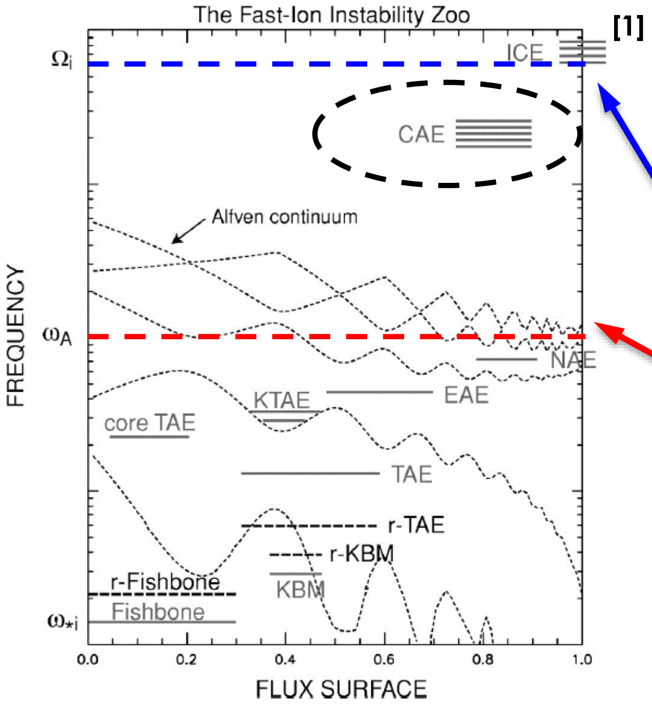
[6] Dal Molin *et al*. RSI 2021

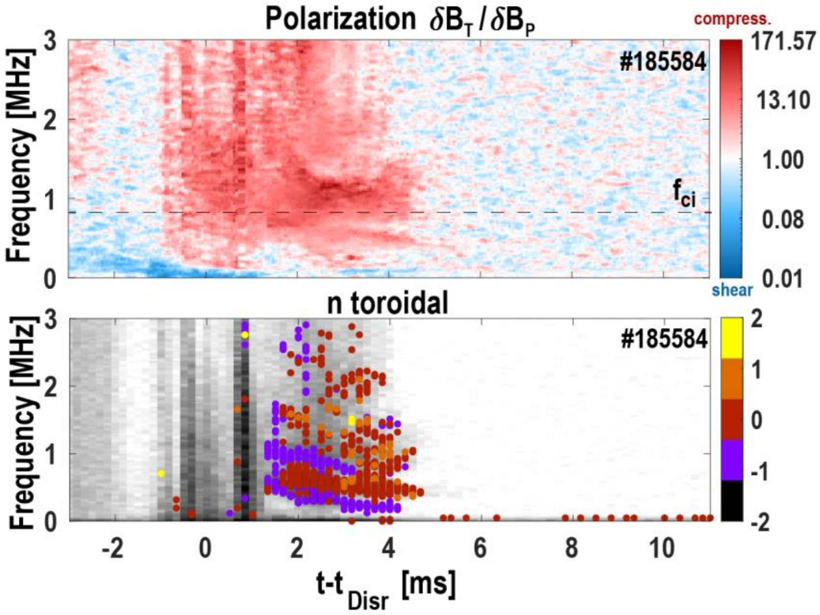
Compressional Alfvén eigenmodes were proposed based on the frequency range

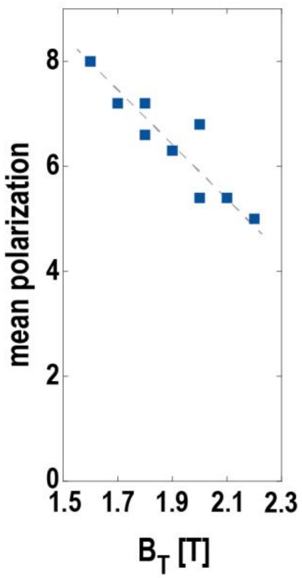


- Previously, compressed Alfven eigenmodes were proposed as candidate instabilities based on observed frequencies:
  - $f_{modes} = 0.1 \ \dots 3$ MHz
- Since for given plasma parameters:
  - $f_{ci} \approx 10$ MHz
  - $f_A \approx 0.1$ MHz
- This simple estimate was supported by modeling [2]
- However, more experimental data needed to exclude, for example, observation of higher harmonics of TAEs or GAEs

[1] Heidbrink 2002 *PoP*
[2] Chang Liu *et al* 2021 *Nucl. Fusion*

Mean polarization increases as B_T decreases





CQ modes are observed in major DIII-D disruptions except for high T_e cases and low-Z inj. in low-energy plasma

Primary inj.	RE beam	CQ modes	Comments
Ar PI	mostly ✓	mostly ✗	Usually modes are only when there is no plateau
Ar MGI	✓ / ✗	✓	Modes are typically always present
Ne MGI	✗	✓	No plateau even for MGI >1100 torr*l
Ne SPI	✗	✓	Both in elongated IWL and Super-H
D_2 MGI	✗	✗	Only low-perfomance plasmas surveyed
D_2 SPI	✗	✓	Only in (Super) H-mode
Ne+D_2 SPI	✗	✓	Only in (Super) H-mode
C influx	✗ / ✓	✓ / ✗	No modes at high T_e (>8 keV)
solid plastic C+W shell pellet C+B shell pellet	✗	✓	Only (Super) H-, Hybrid mode surveyed