Active MHD Experiments on Alcator C-Mod

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Motivation and Background

Moderate n ~ 10 Toroidal Alfvén Eigenmodes (TAE's) are predicted to be unstable in ITER[1] and could have a number of effects:

- Rapidly transport α particles out of the core reducing the DT reaction rate
- Wall damage due to enhanced transport of a localized beam of fast particles

Fasoli's low $n \le 2$ Active MHD results on JET[2,3] inspired moderate n Active MHD experiments on C-Mod to

- Excite stable Alfvén eigenmodes at prescribed resonant frequencies
- Measure TAE damping rates and proximity to marginal stability at ITER toroidal fields, densities, and toroidal mode numbers
- Test TAE theories of damping rate scalings and dependencies

[1] N N Gorelenkov, *Nucl Fus* **43** (2003) 594

[2] A Fasoli, *et al Phys Rev Lett* **75** (1995) 645

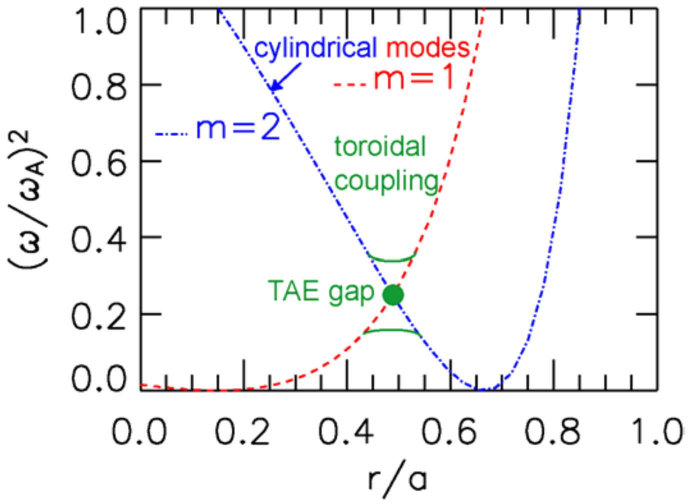
[3] A Fasoli, *et al PPCF* **44** (2002) B159

Alfvén Waves in Toroidal Plasmas

Alfvén continuum:

$$\omega^2(r) = k_{\parallel}^2(r) v_A^2(r)$$

In a cylinder provides strong damping to global modes



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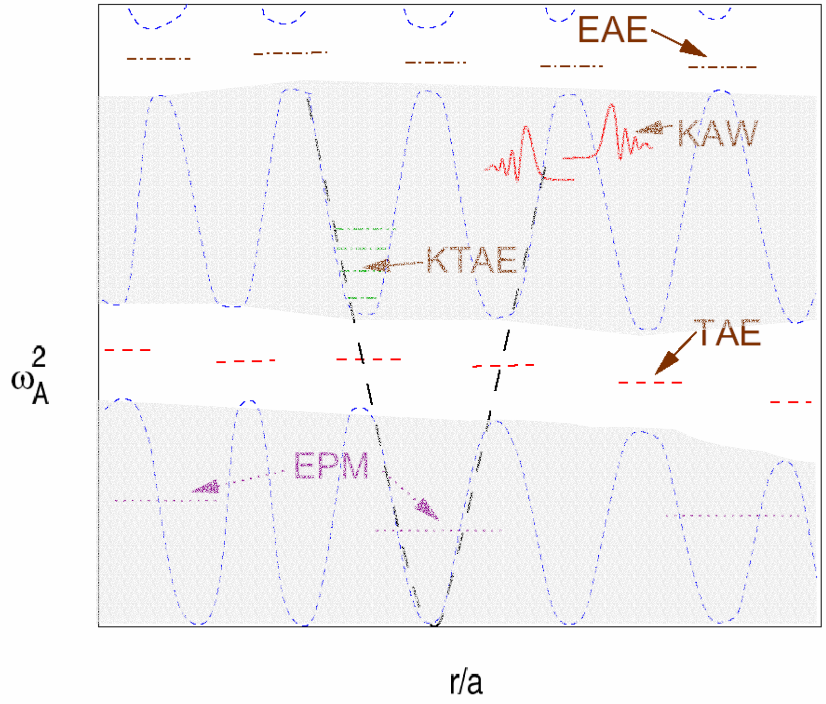
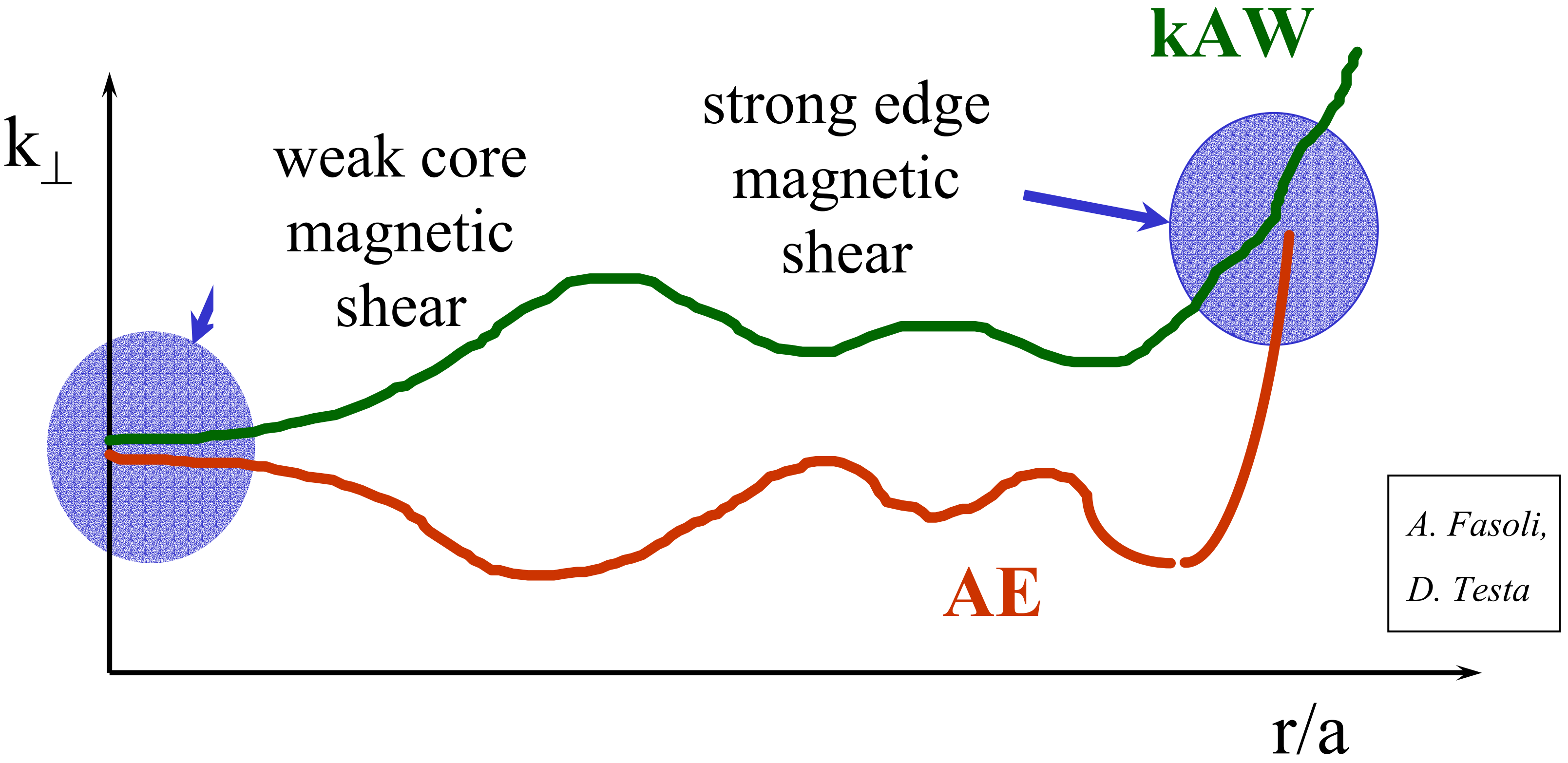
In a torus, coupling of poloidal harmonics gives

$$k_{\parallel}(r) = \frac{1}{R}\left(n - \frac{m}{q(r)}\right)$$

- ➢ Gaps in the continuum spectrum
- ➢ Weakly damped eigenmodes, e.g., Toroidal AE's, Elliptical AE's, etc



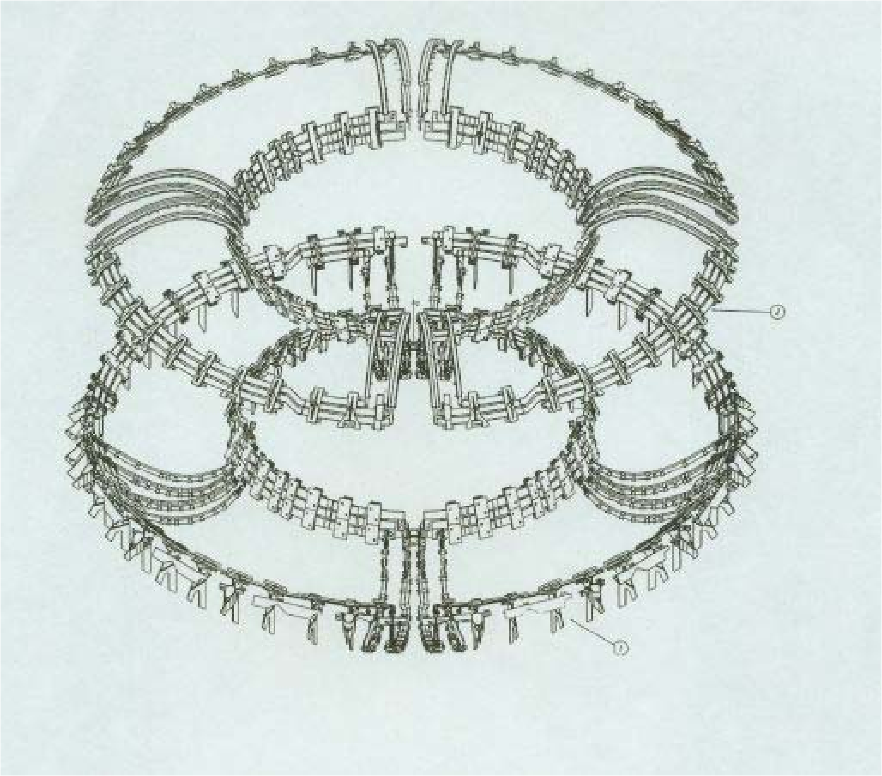
Test of AE Damping Mechanisms

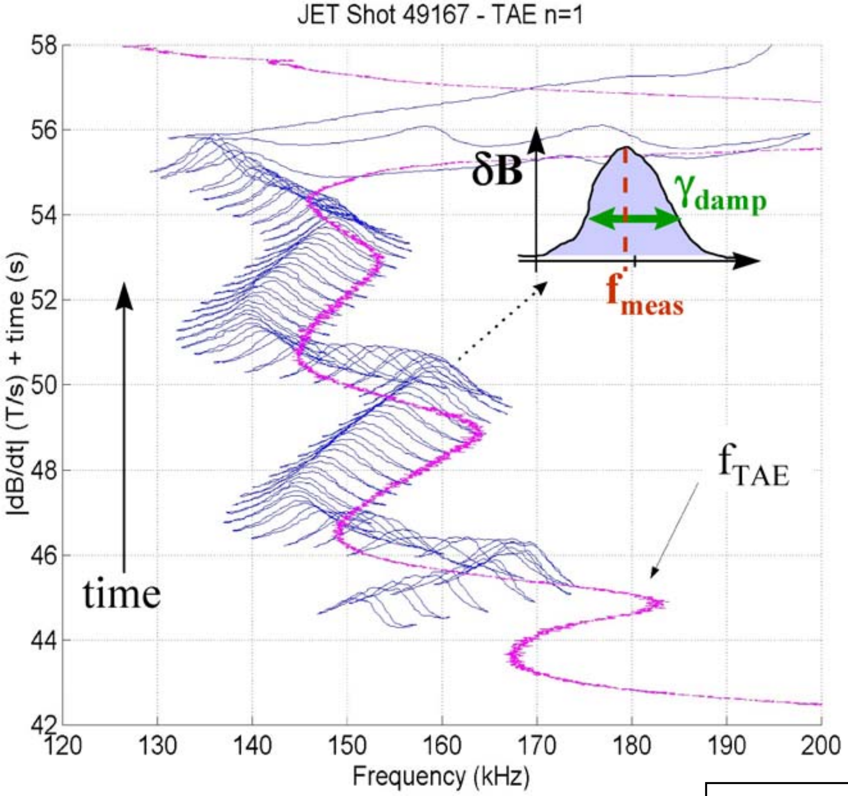


Stability of radially extended AE's vs edge magnetic shear

- AE damping mechanism: mode conversion to kinetic Alfvén waves then local Landau damping of kinetic Alfvén waves

Measurement of Damping of Stable Modes on JET





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External mode excitation with n=0, 1, 2 saddle coils

- Damping rate determined by the width of the measured resonance

Possible Feedback Control Signals

May be able to excite low frequency, low m, n MHD modes as plasma parameters approach stability limits to determine marginal stability of

- m=2, n=1 modes approaching density limits
- NTM’s approaching β limits

Then use the active MHD damping rate in real-time feedback control of

- The density to stay just below the limit
- The heating power to control β_N
- The localized LHCD/ECCD to attempt to keep the modes from becoming unstable

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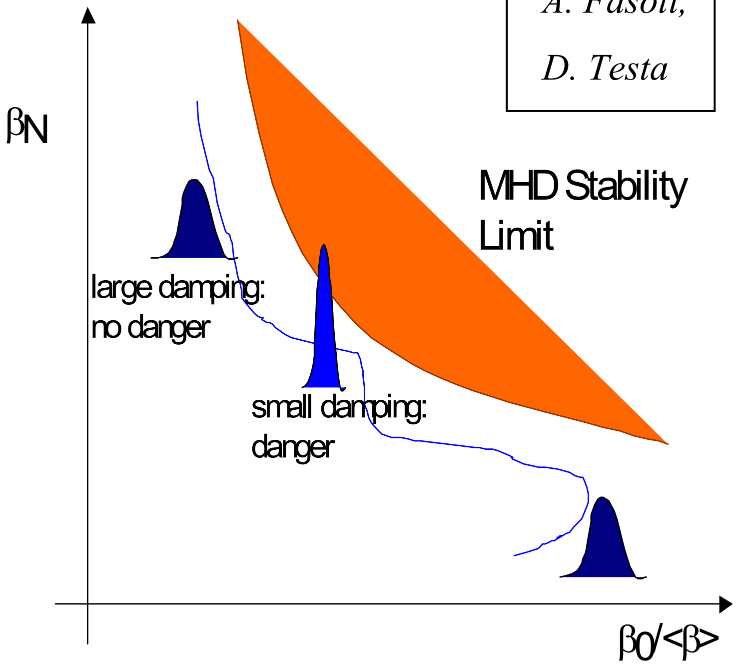
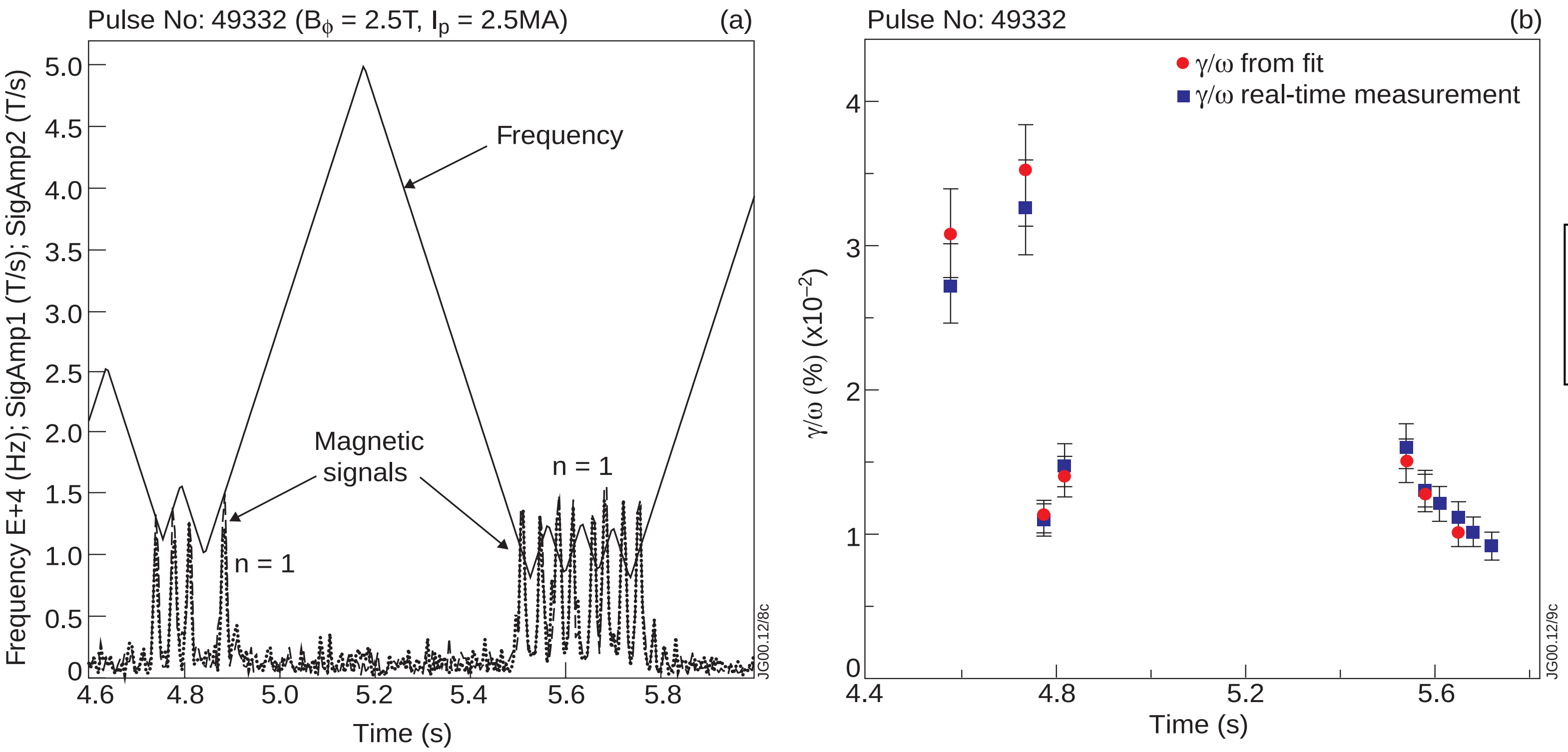


Low Frequency Active MHD Resonances on JET



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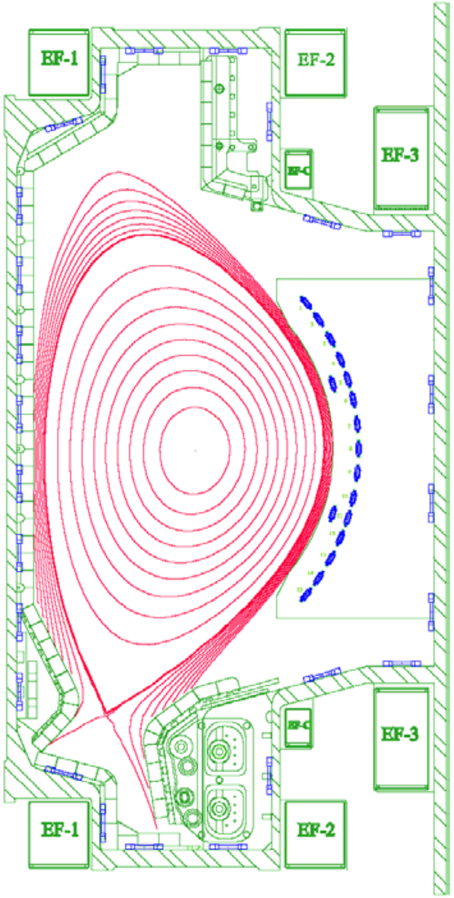
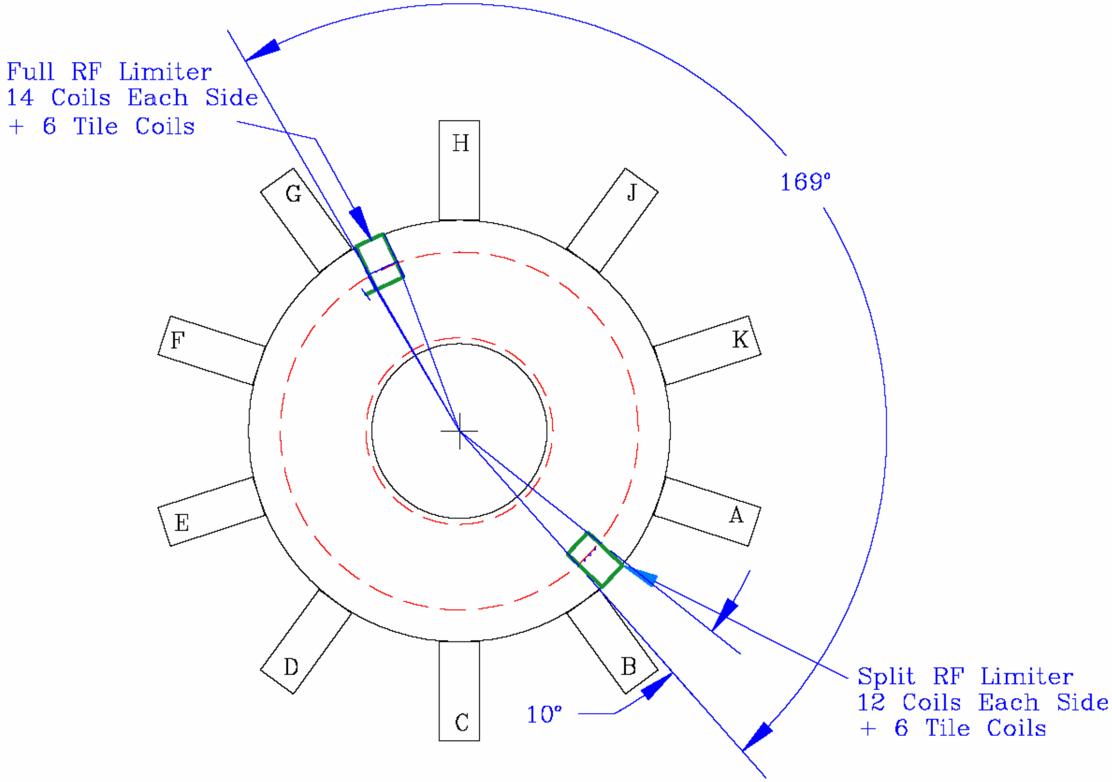
Measured damping rate of actively excited low frequency n=1 modes in JET to determine the proximity to marginal stability and provide a feedback signal to avoid instabilities in optimized shear plasmas

Experimental Setup on C-Mod – Pick-up Coils

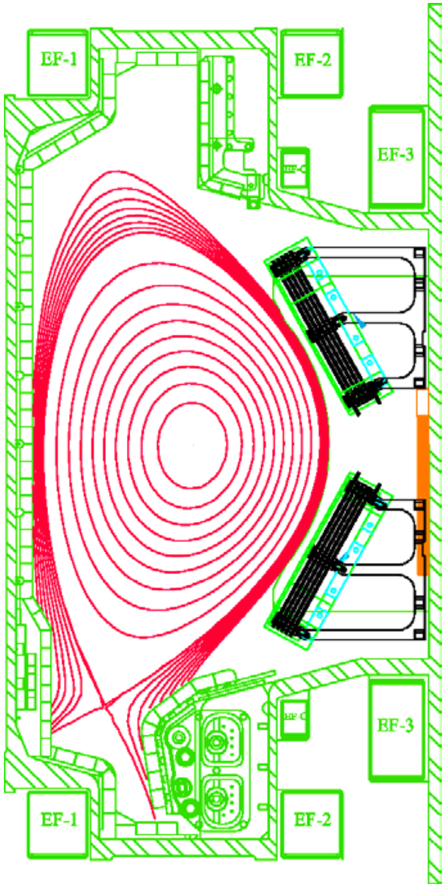


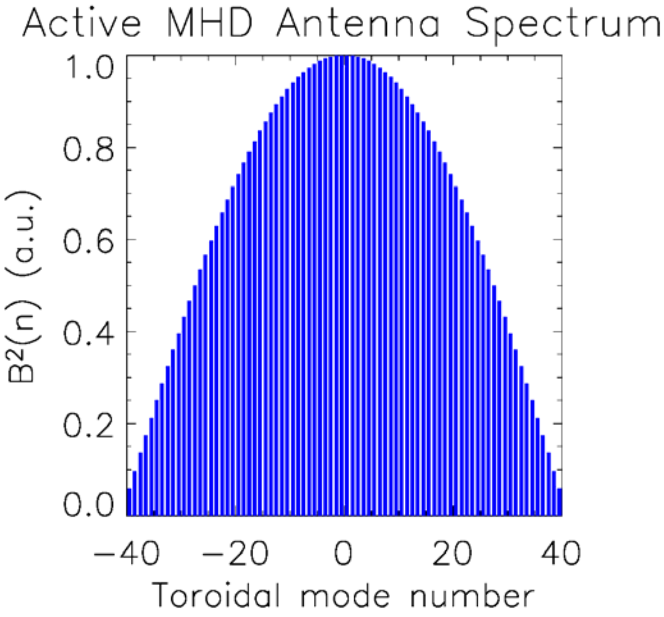


Outboard Limiter Coils Toroidal View

- 65 poloidal field pick-up coils in poloidal and toroidal arrays
- Can measure m < 14 and n < 75, sampling between 1 – 2.5 MHz

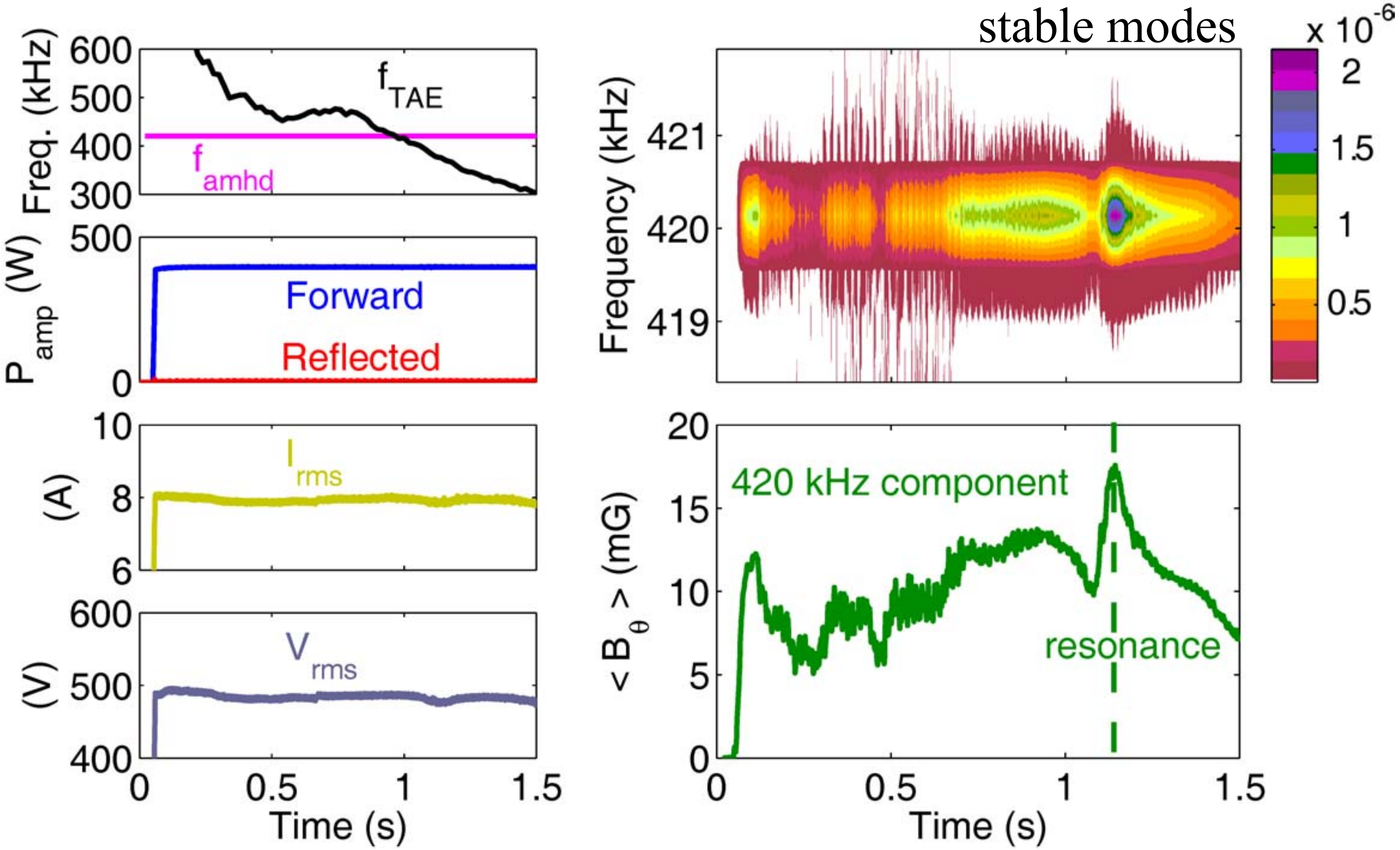
Experimental Setup – Active MHD Antennas





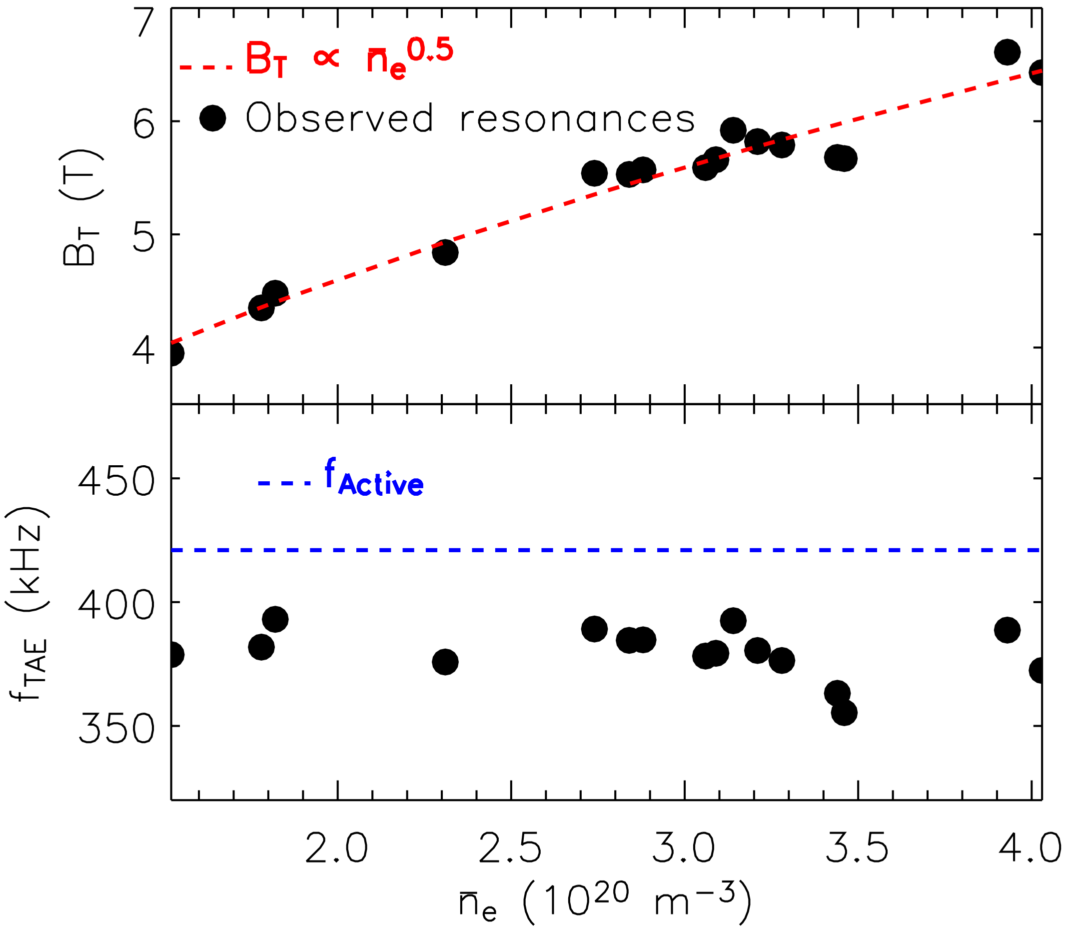
- Presently 2 antennas above and below the outboard midplane
- Previous amplifier drives ~ 12 A producing $\tilde{B}_r$ ~ 0.5 G at q=1.5
- 1 kHz < f < 1 MHz, broad toroidal spectrum n ~ 20 FWHM

Active MHD Spectroscopy at Constant Frequency



- ➢Initial experiments at constant excitation frequency f_{amhd} ~ 420 kHz
- ➢Ramping B_T makes f_{TAE} cross f_{amhd} at observed resonance condition

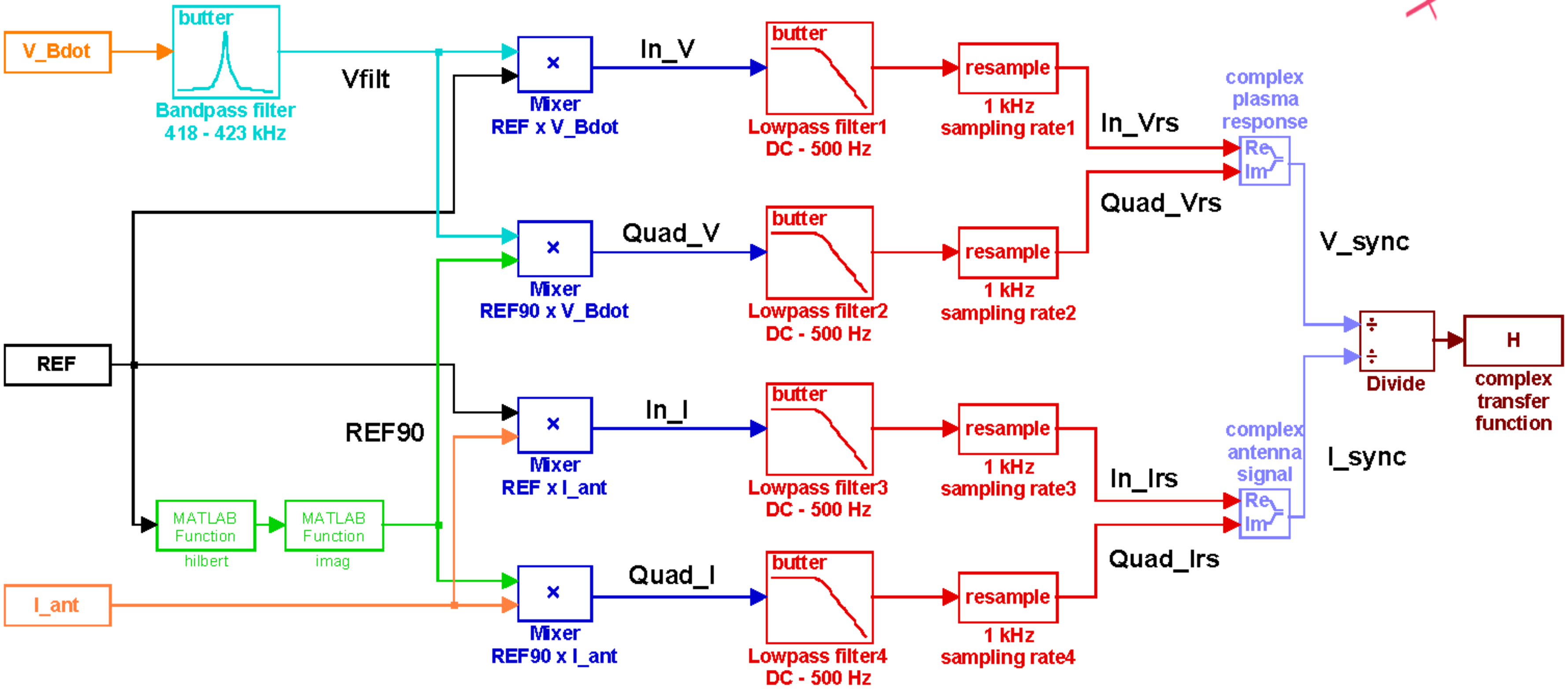
Observed Resonances agree with TAE Frequency



- Ramping B_T from 6 – 4 T
- Shot-to-shot density scan
- Contant f_{Active} = 420 kHz
- $B_T \propto n_e^{1/2}$ at resonances
- Observed resonant frequencies fall within the TAE gap 10 – 15% above the center of the gap at q=1.5

$$\omega_{TAE} = \frac{v_A}{2qR} \propto \frac{B_T / n_e^{1/2}}{2qR}$$

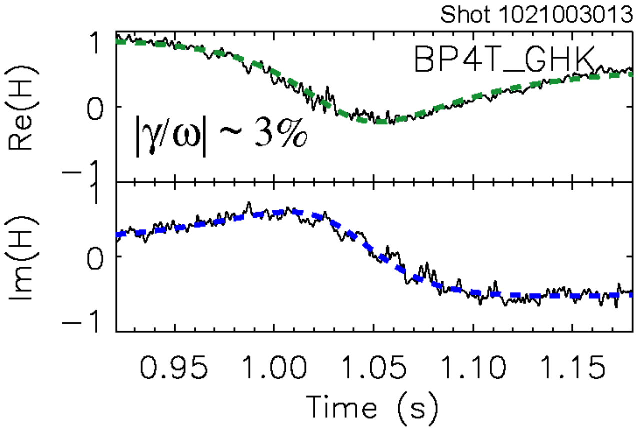
Software Synchronous Detection Algorithm

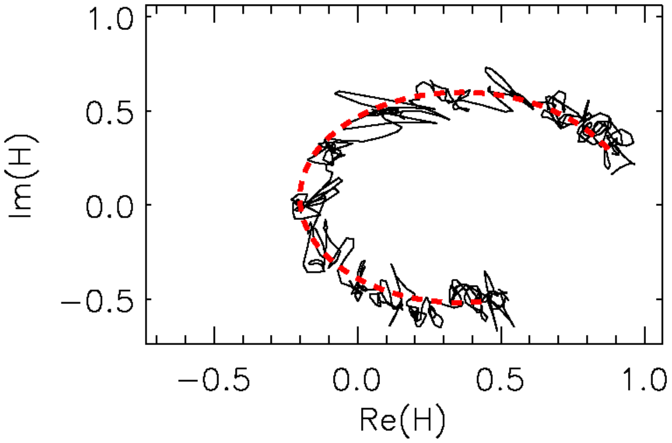


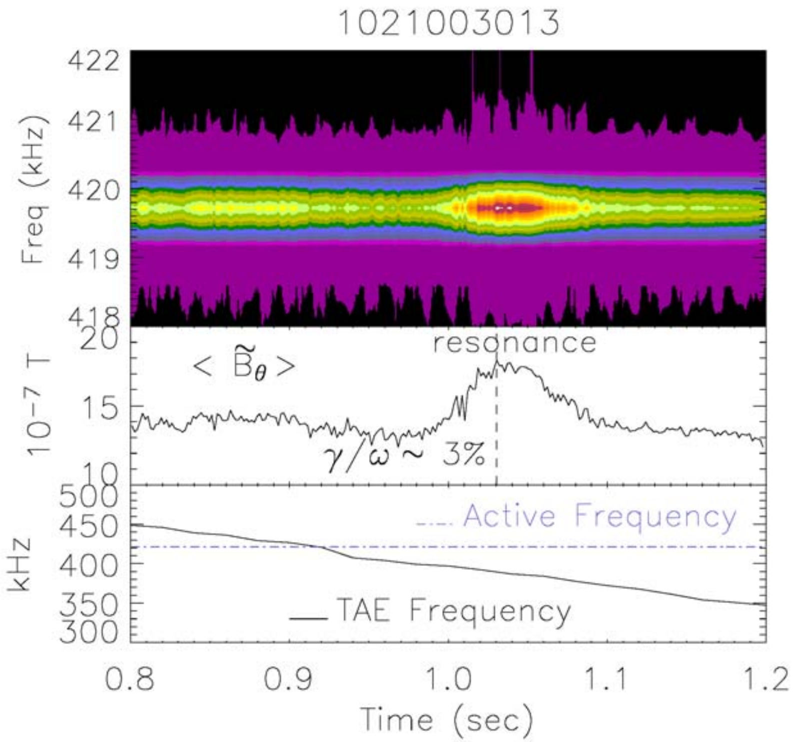
- Pick-up coils synchronously detected in software with Active MHD antenna current to calculate the complex transfer function

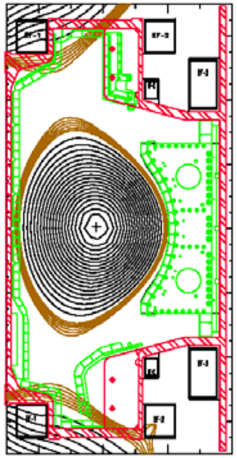
$$H(\omega,x)=\frac{V_{sync}}{I_{sync}}=\frac{1}{2}\left[\frac{r(x)}{i\omega-p}+\frac{r^{*}(x)}{i\omega-p^{*}}\right]+D(\omega,x)=\frac{B(\omega,x)}{A(\omega)}$$

Synchronous Detection in a Limited Plasma



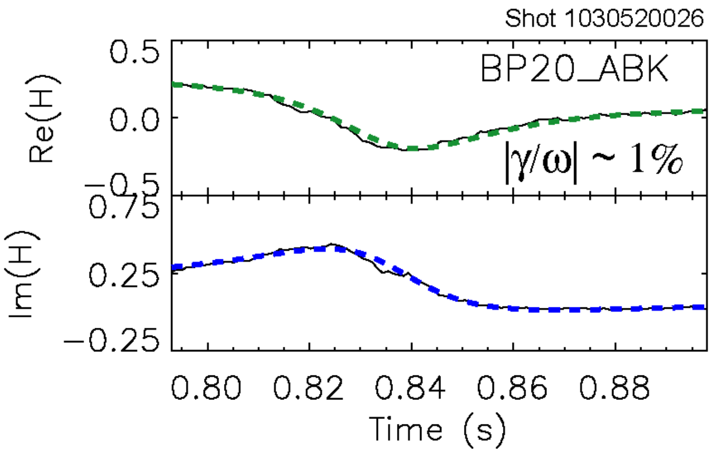


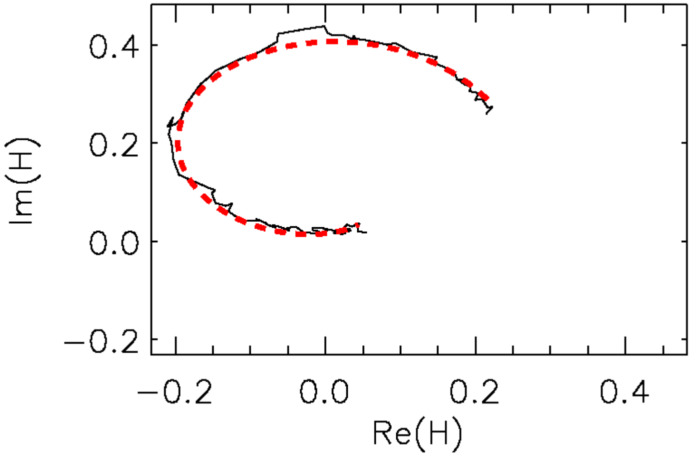


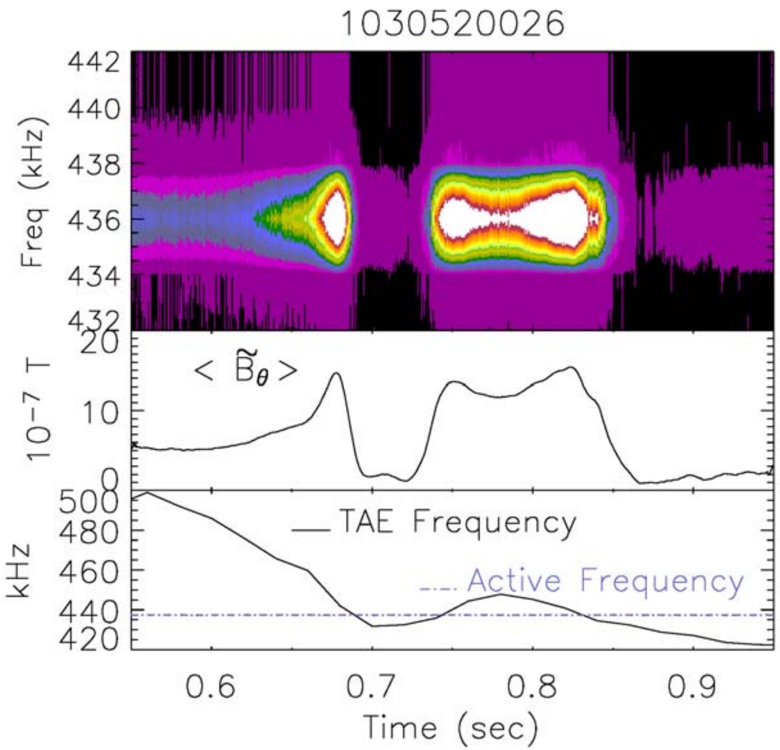


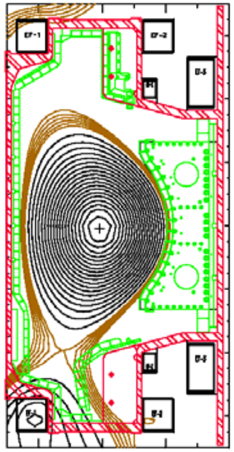
- Multiple pick-up coils synchronously detect an active TAE resonance in an inner wall limited plasma. γ/ω ~ 3%, n=4.

Active TAE Resonances in Diverted Plasmas



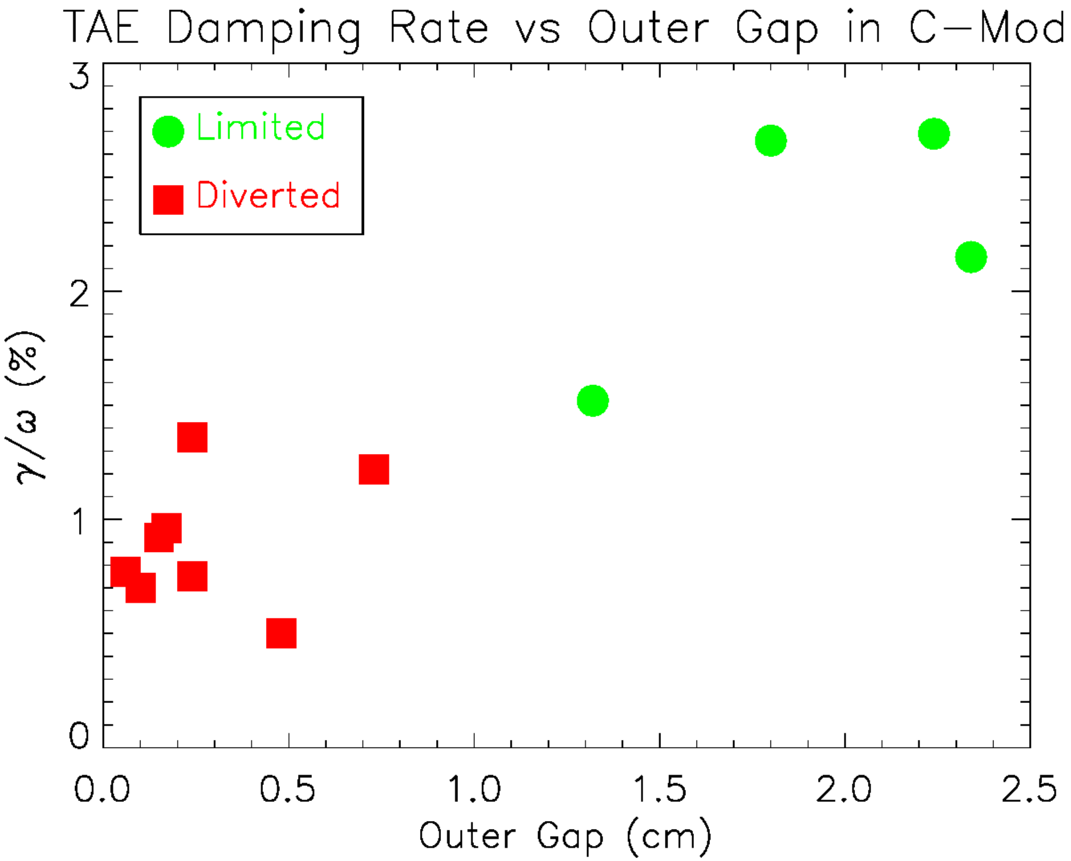






- Three TAE resonances as f_{TAE} crosses the active frequency in a diverted plasma with outer gap < 2.5 mm have $|\gamma/\omega| \sim 1\%$

Limited vs Diverted Plasma Outer Gap Scan

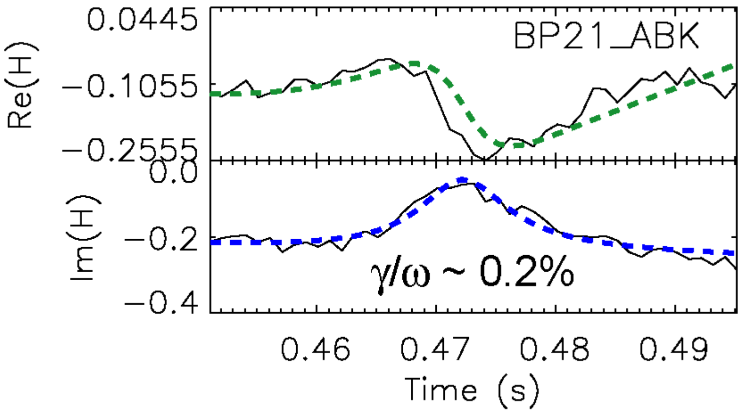


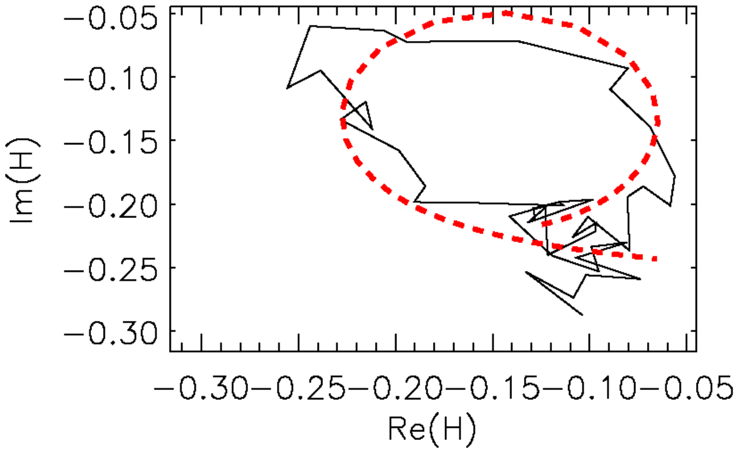
Active TAE resonances were only observed

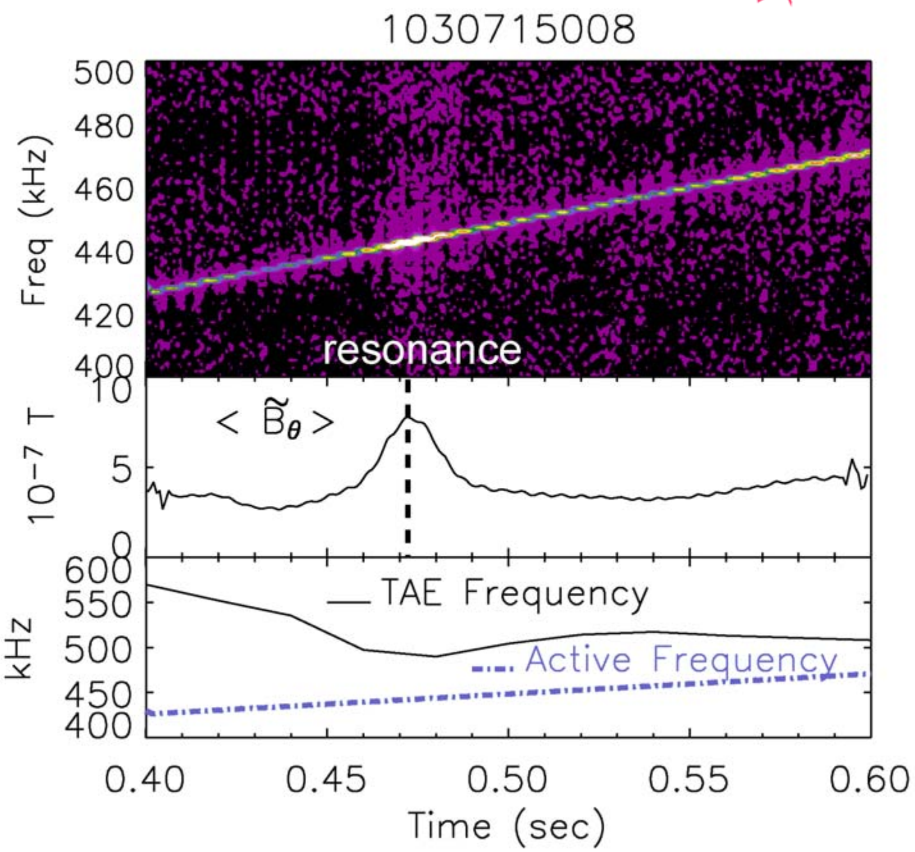
- ● with moderate outer gaps in inner wall limited plasmas or
- 🟥 with small outer gaps in diverted plasmas

Damping rates are in the same range as those found in JET limited plasmas

Sweeping Frequency Active TAE Resonance

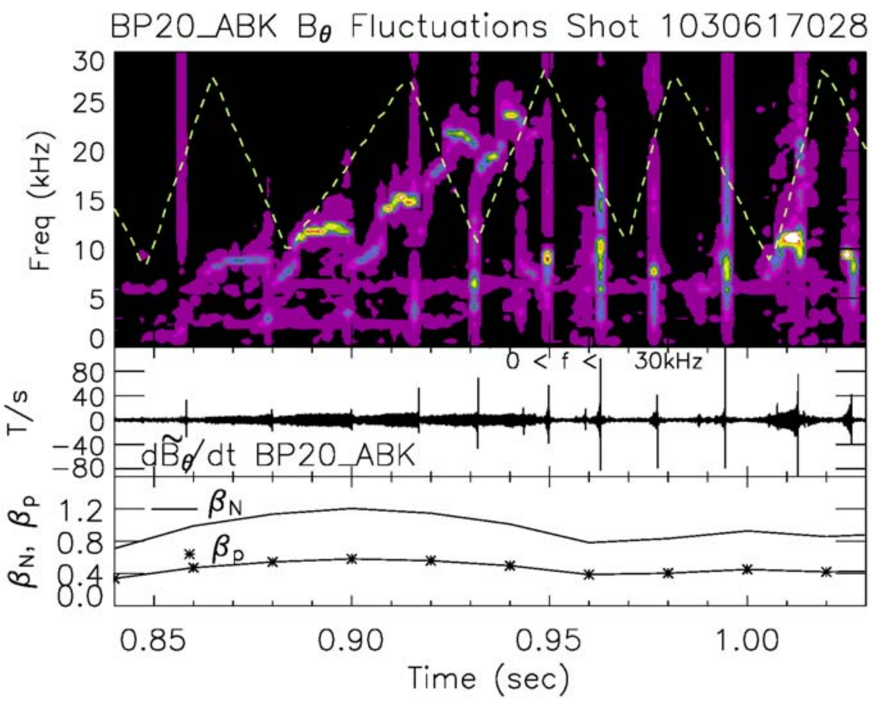


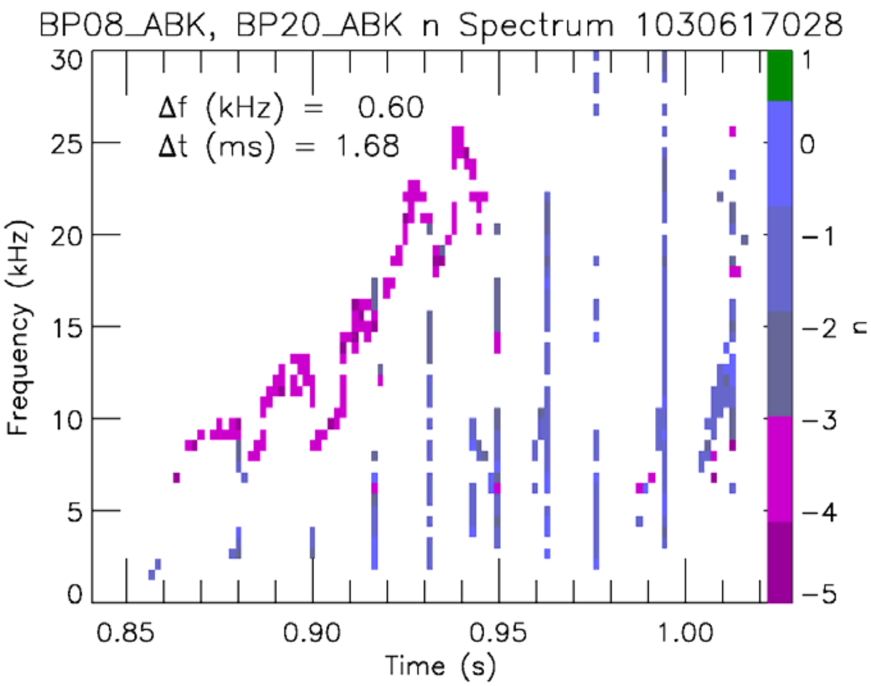




- Sweeping frequency TAE resonance as f_{TAE} approaches the active frequency in a diverted plasma with outer gap < 5 mm, $|\gamma/\omega| \sim 0.2\%$

Active Low Frequency Sweeping at High β





- Active sweeping from 5 – 30 kHz at $\beta_N = 1.2$ in the presence of unstable n=3 modes
- No clear stable mode resonances were observed

Active MHD Upgrades

- Power supply just upgraded to ±125 V, 25 A DC supply capable of driving 4 antennas simultaneously
- Amplifier being upgraded to provide
  - automatic capacitor switching with input frequency to maintain good matching to the changing antenna impedance up to 20 A
  - 2 kHz < f < 1 MHz frequency range covered in 8 octave steps
- New digital control computer for C-Mod operation will provide real-time feedback control of the TAE frequency
- Future plans for an additional set of 2 to 4 Active MHD antennas 180° away toroidally to provide even/odd toroidal mode selection as well as high n ~ 10 mode selection

Conclusions

- Stable TAE resonances at q=1.5 are actively excited with a single moderate n antenna in both limited and diverted discharges in the range of toroidal fields and densities expected in ITER
- Software synchronous detection provides good fits to the stable TAE resonances on multiple pick-up coil signals with $0.5\% < \gamma/\omega < 4\%$
- Damping rates agree with JET for inner wall limited discharges
- For outer gaps < 1 cm, diverted discharges have very low damping rates with $0.5\% < \gamma/\omega < 1.5\%$ possibly indicating that moderate n TAE's have lower damping rates than the low n TAE's in JET
- Initial experiments at lower MHD frequencies near β limits have not excited clear resonant stable modes
- Power supply and antenna upgrades will increase S/N by ~10 times