Active and Passive MHD Spectroscopy on Alcator C-Mod

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Motivation and Background

Unstable TAE's in C-Mod first observed in 1996 with current rise ICRF

- Low density ramping up with I_p ➔ fast ion tail ~ 150 keV
- Upward and downward frequency chirping with $150 < f < 450$ kHz , $n \leq 3$
- Low or reversed shear q profiles maintained with ICRF

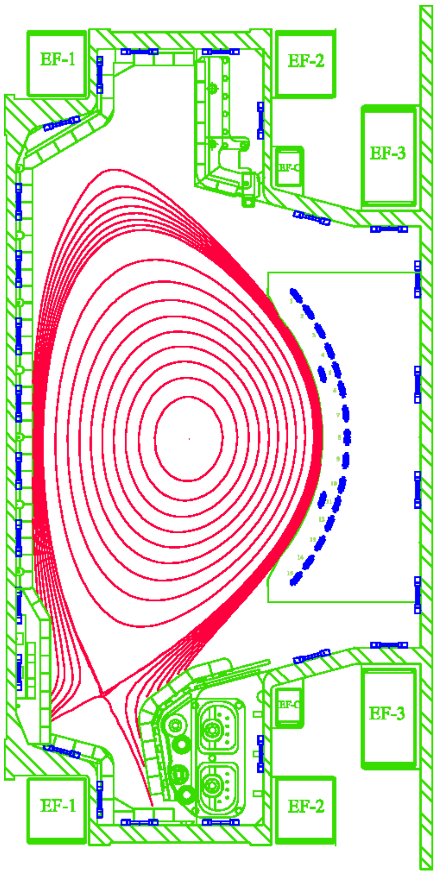
AE's also found in ICRF heated Enhanced D_α H-modes (EDA)

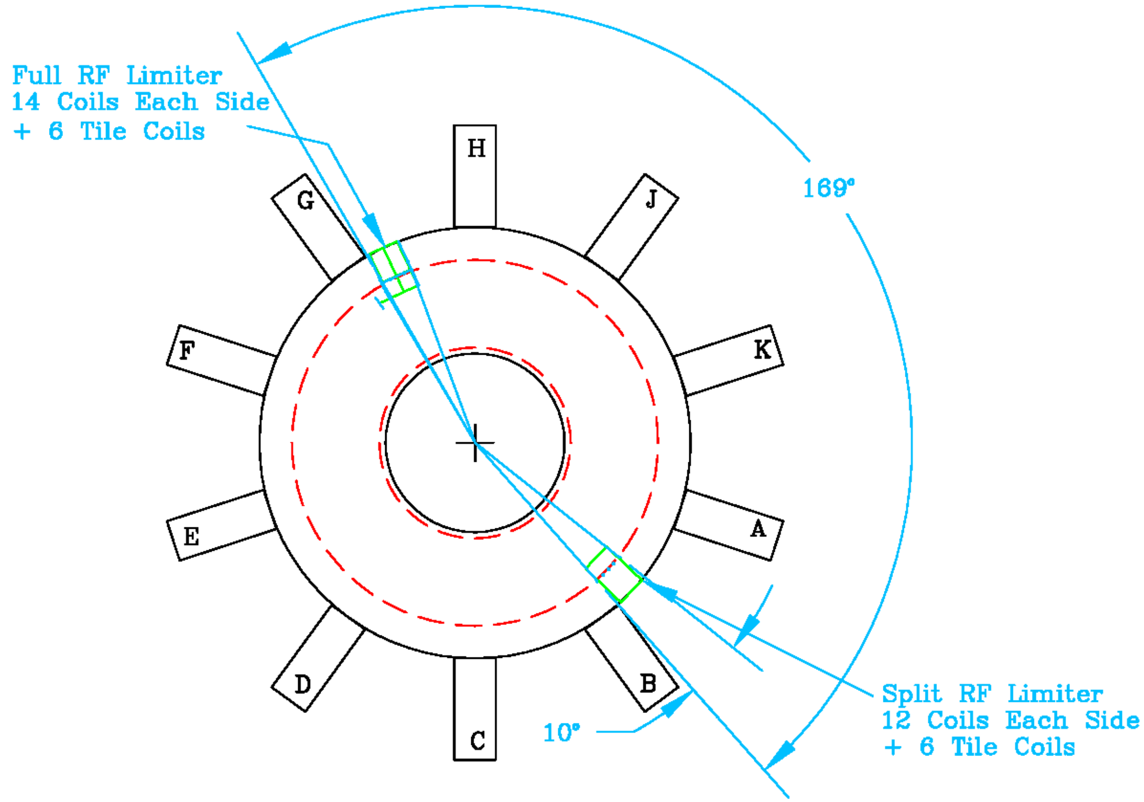
- High density $> 2 \times 10^{20}\ m^{-3}$ ➔ weak fast ion tail ~ 50 keV
- Constant frequency in the range $600 < f < 900$ kHz, $n = 5 - 7$

Fasoli's Active MHD results on JET inspired C-Mod Active MHD

- Excite stable Alfvén eigenmodes at prescribed resonant frequencies
- To measure TAE damping rates at ITER toroidal fields and densities

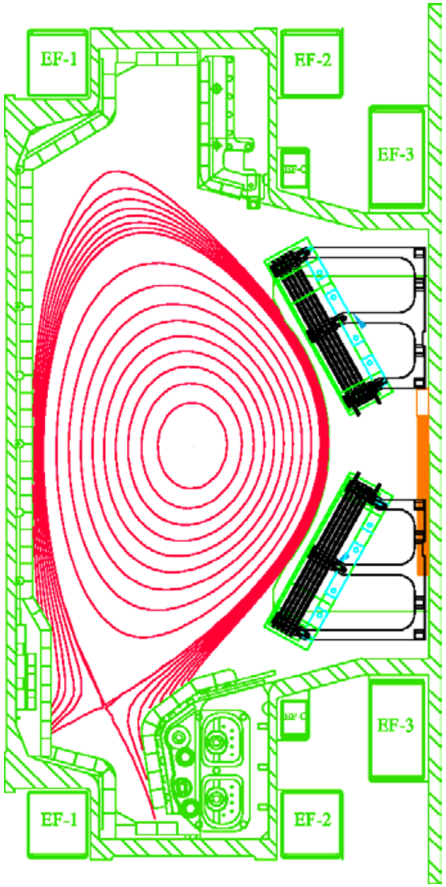
Experimental Setup – Pick-up Coils

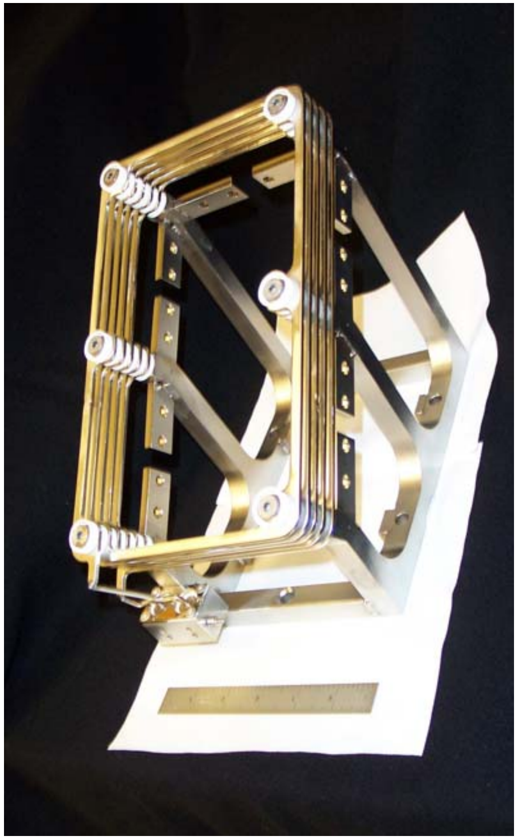




- 65 poloidal field pick-up coils in poloidal and toroidal arrays
- Can measure m < 14 and n < 75, sampling between 1 – 2.5 MHz

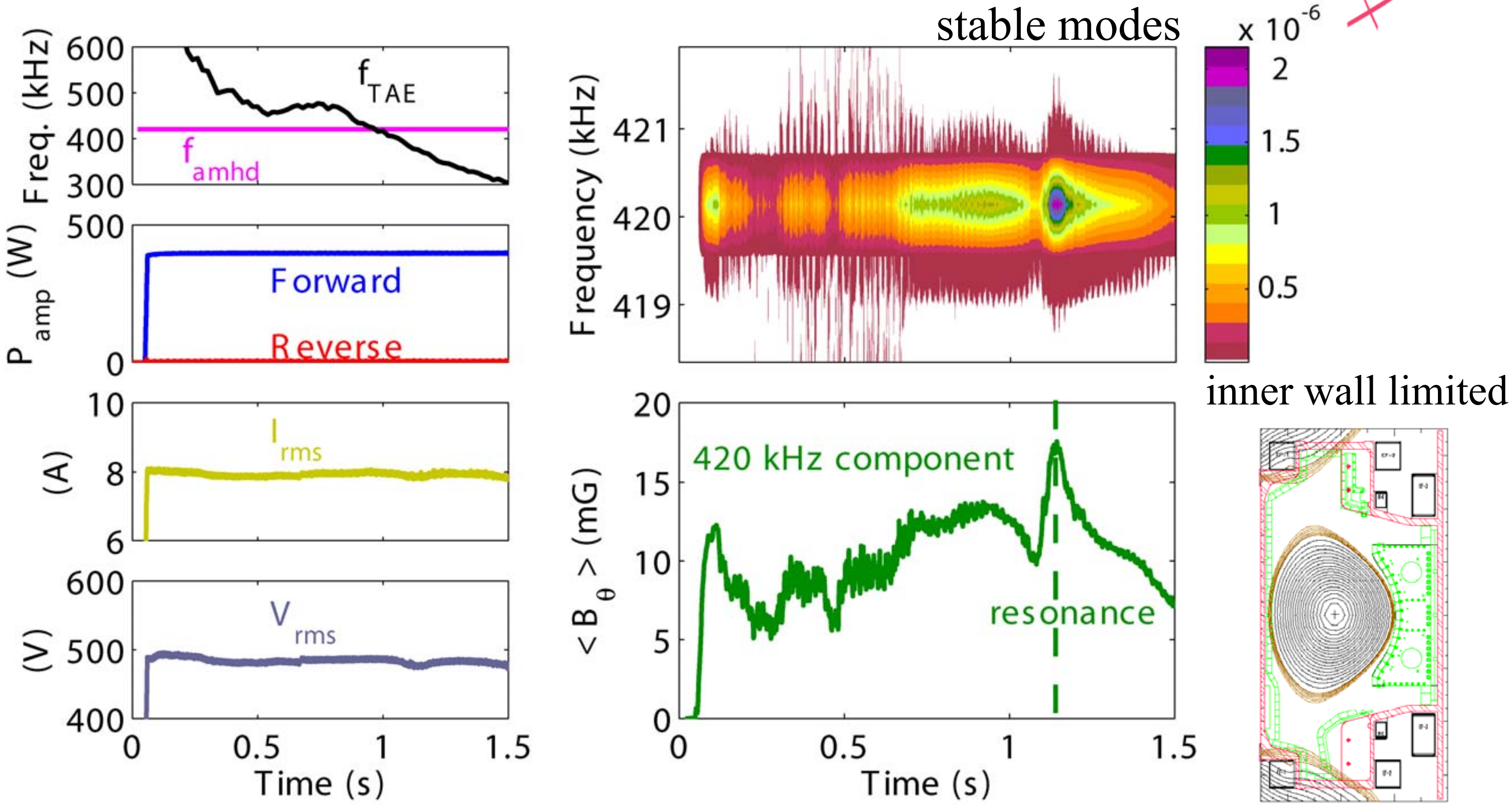
Experimental Setup – Active MHD Antennas





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

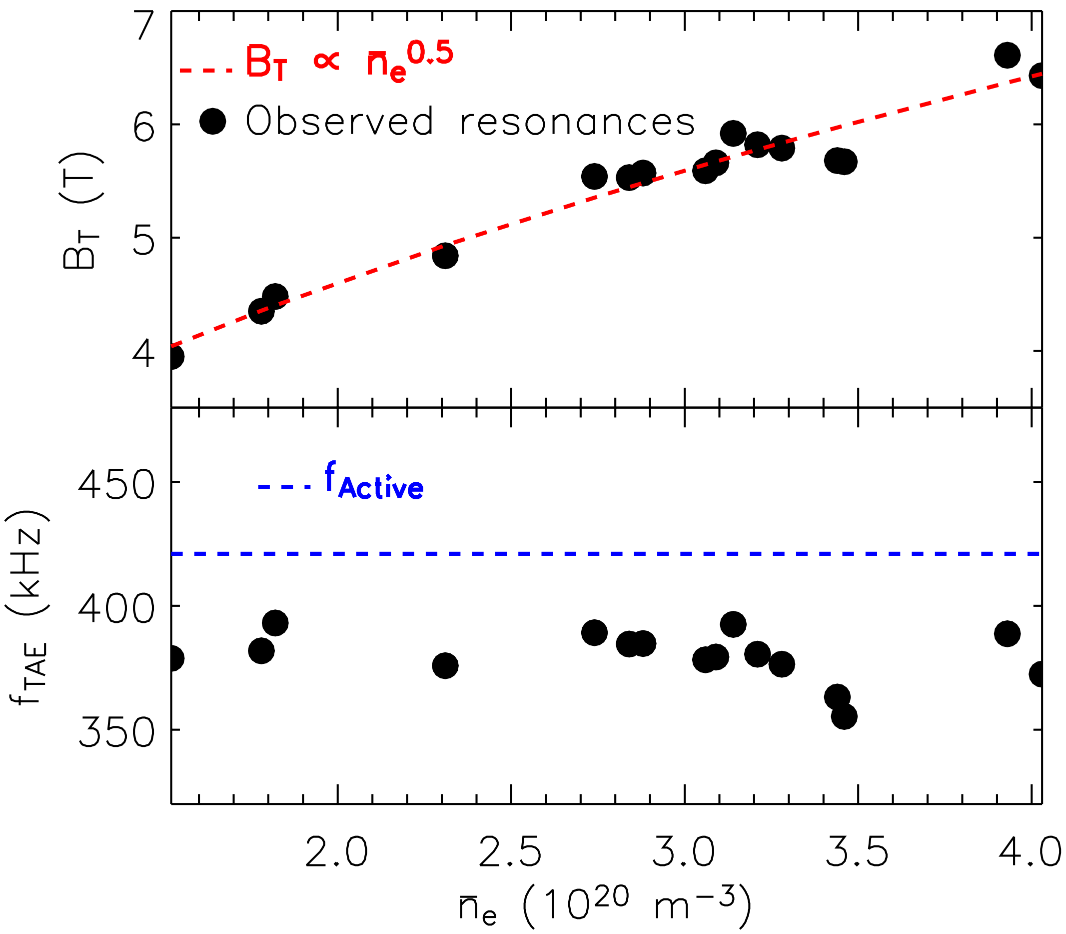
Active MHD Spectroscopy at Constant Frequency



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

Observed Resonances agree with TAE Frequency

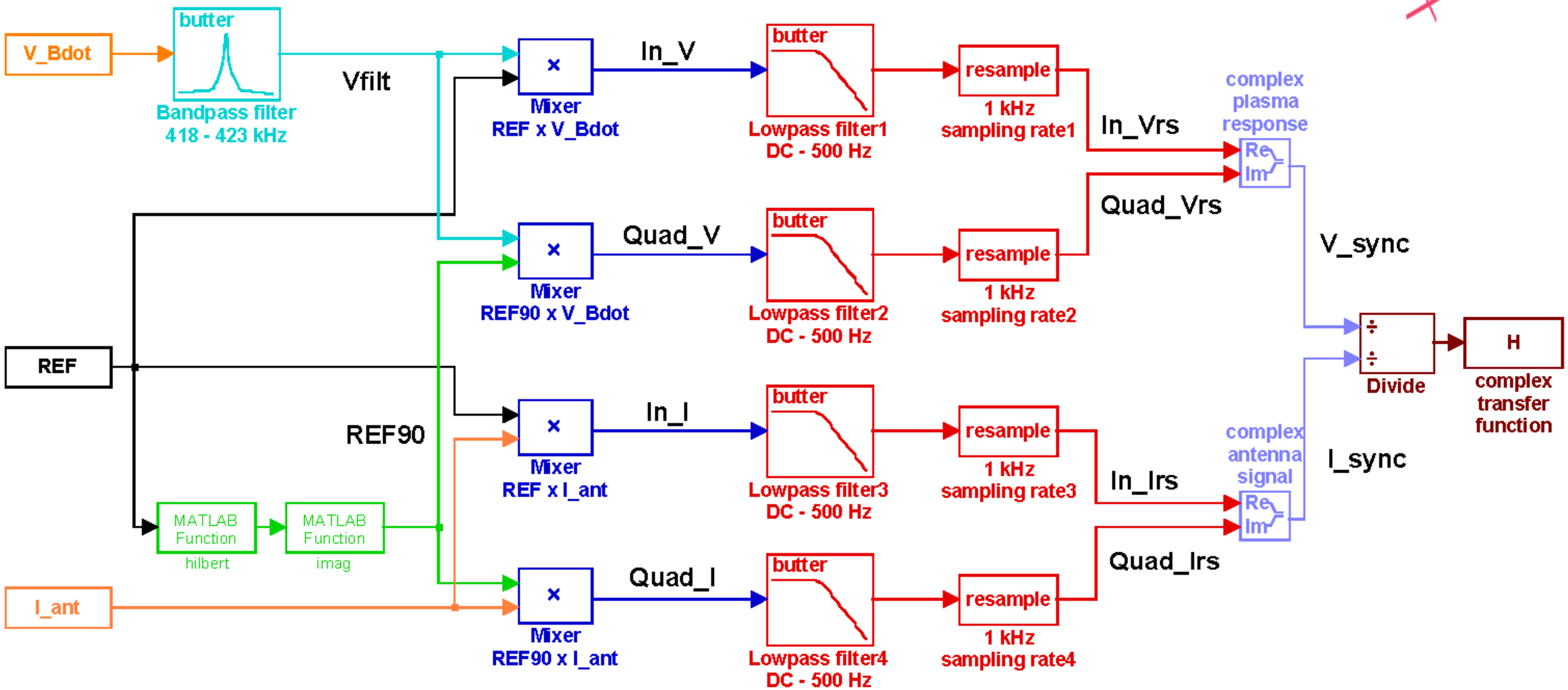
Alcator C-Mod



- 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

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

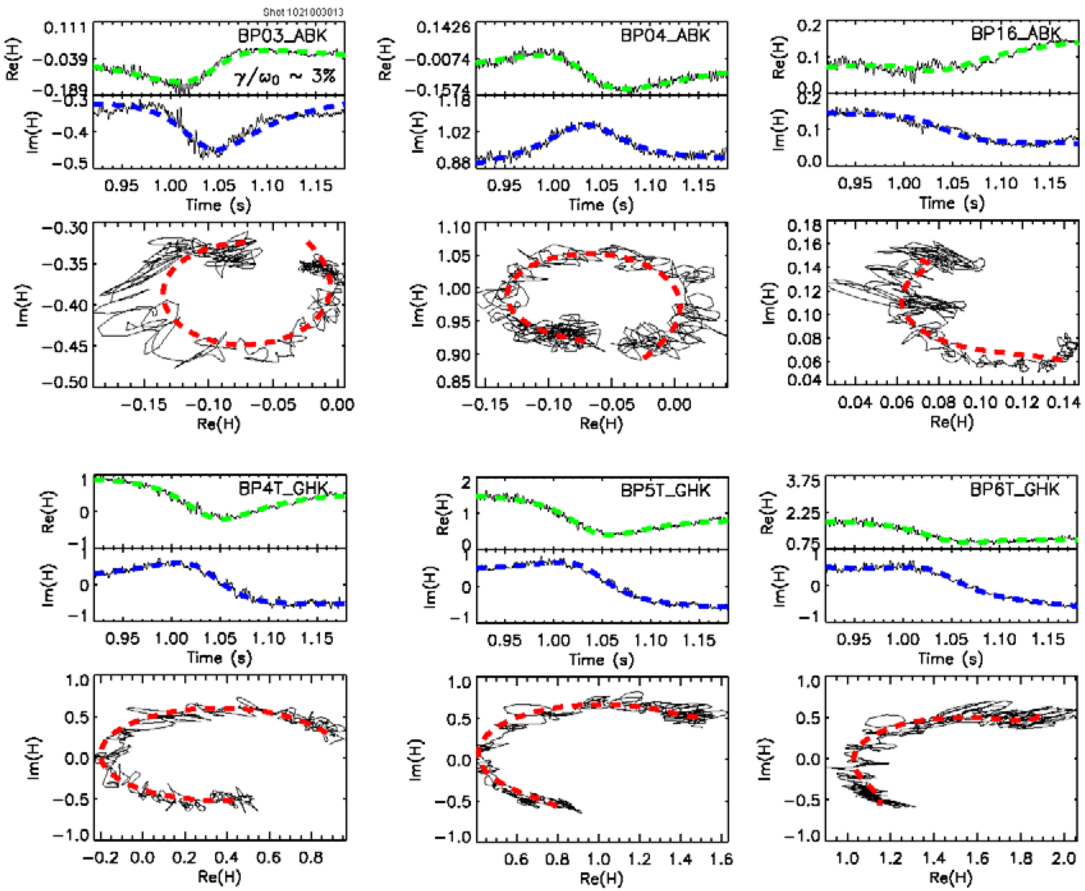
Software Synchronous Detection Algorithm

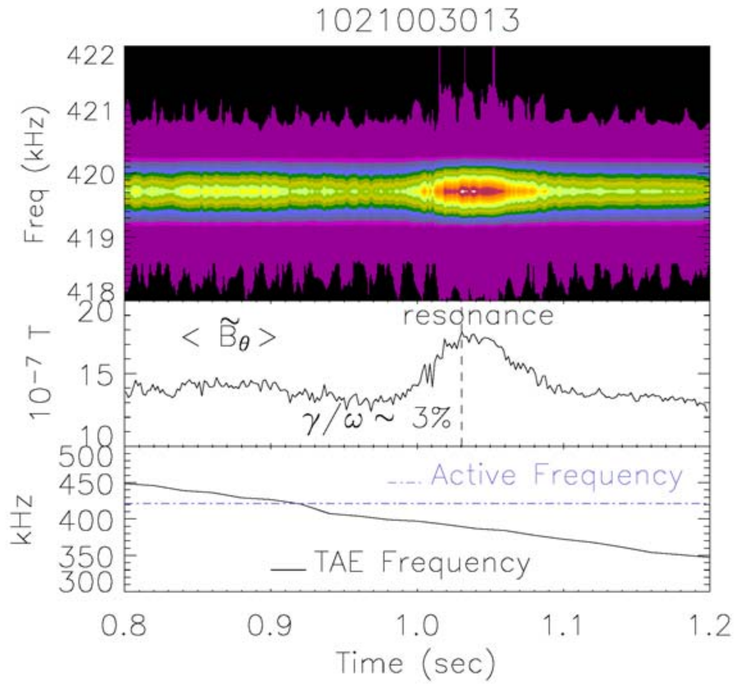


- Pick-up coils synchronously detected in software with Active MHD antenna current to calculate the complex transfer function

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

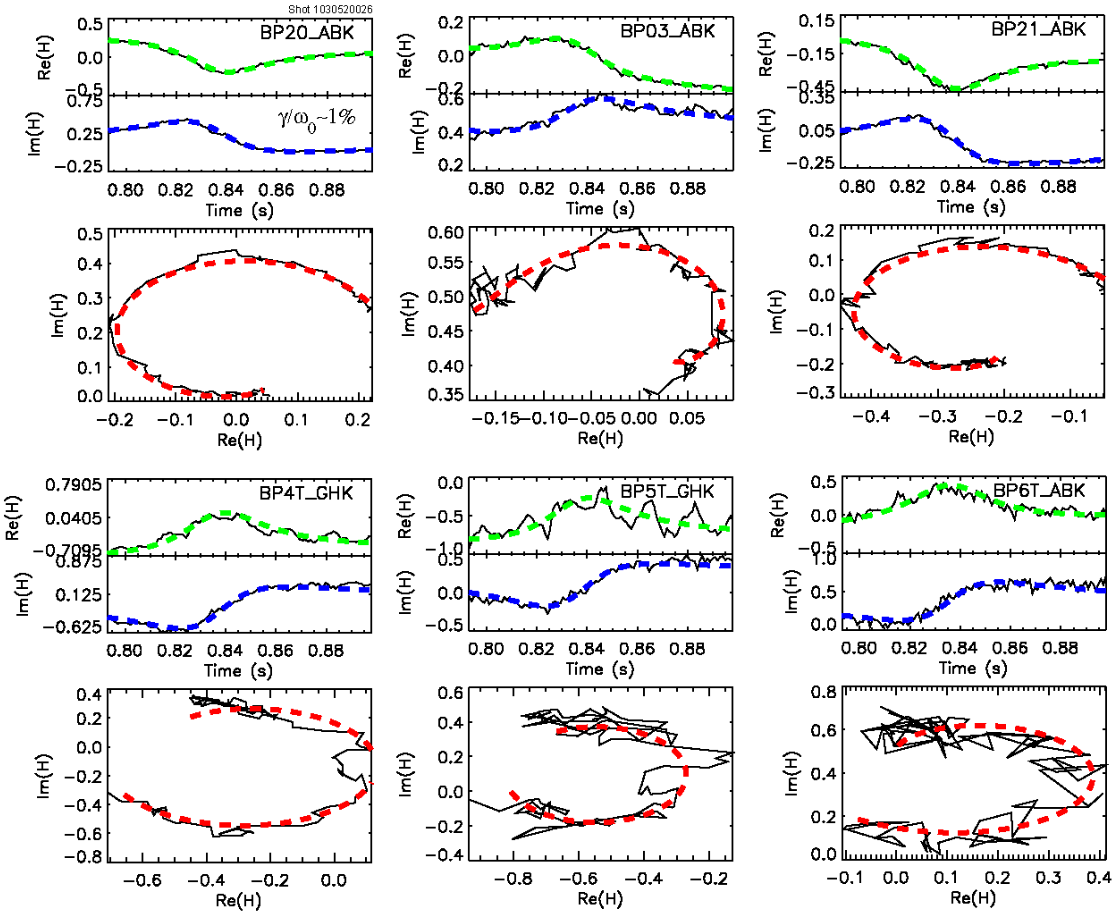
Synchronous Detection with Multiple Coils

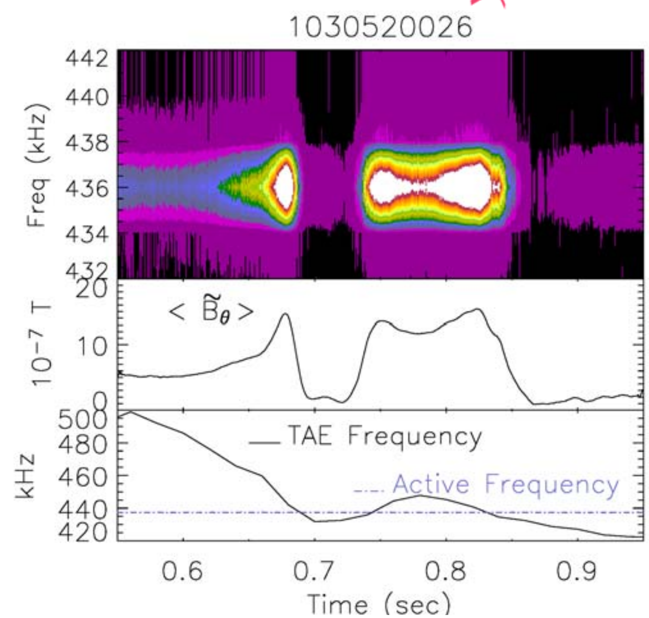


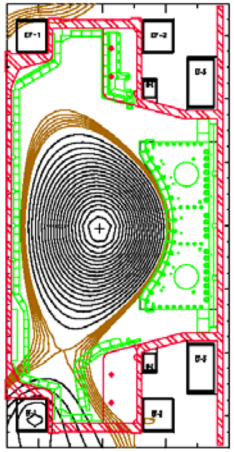


- Multiple pick-up coils synchronously detect an active TAE resonance in an inner wall limited plasma. Best fit gives $\gamma/\omega \sim 3\%$ and n=4.

Active TAE Resonances in Diverted Plasmas



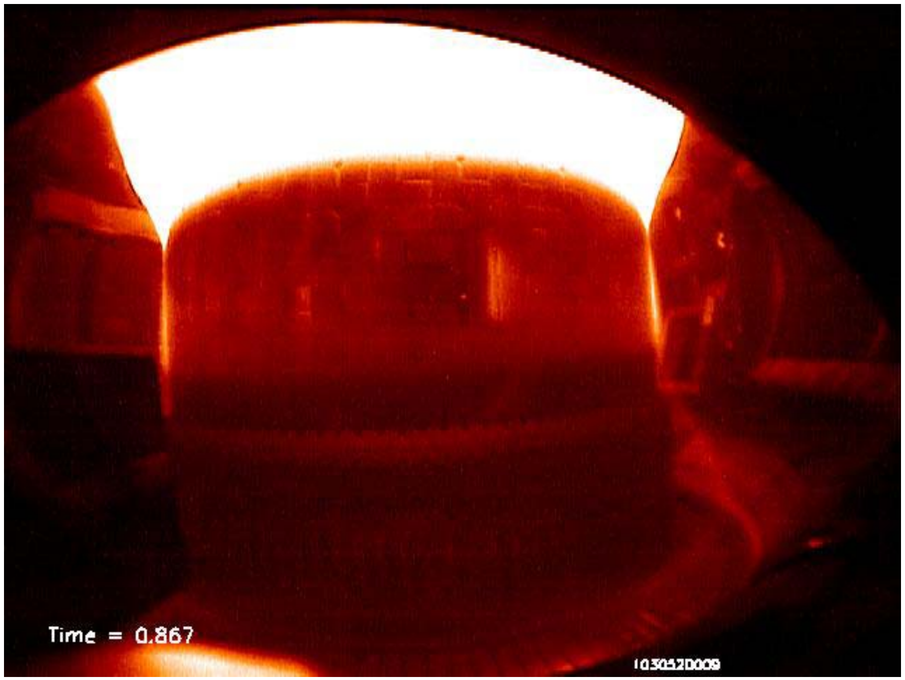




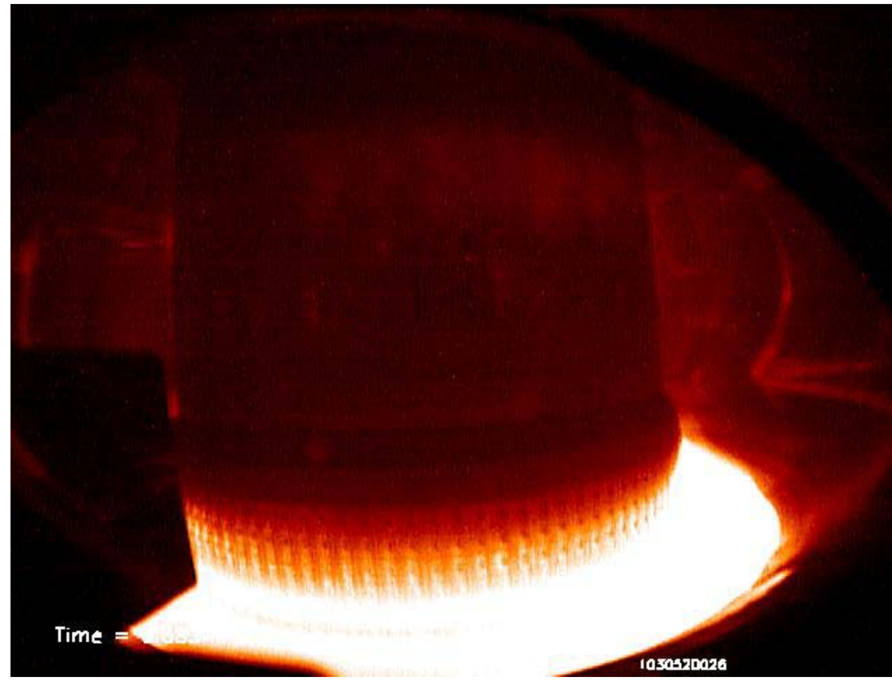
➢ Three TAE resonances as f_{TAE} crosses the active frequency in a diverted plasma with outer gap < 2.5 mm

Limited vs Diverted Plasma Outer Gap Scan

inner wall limited

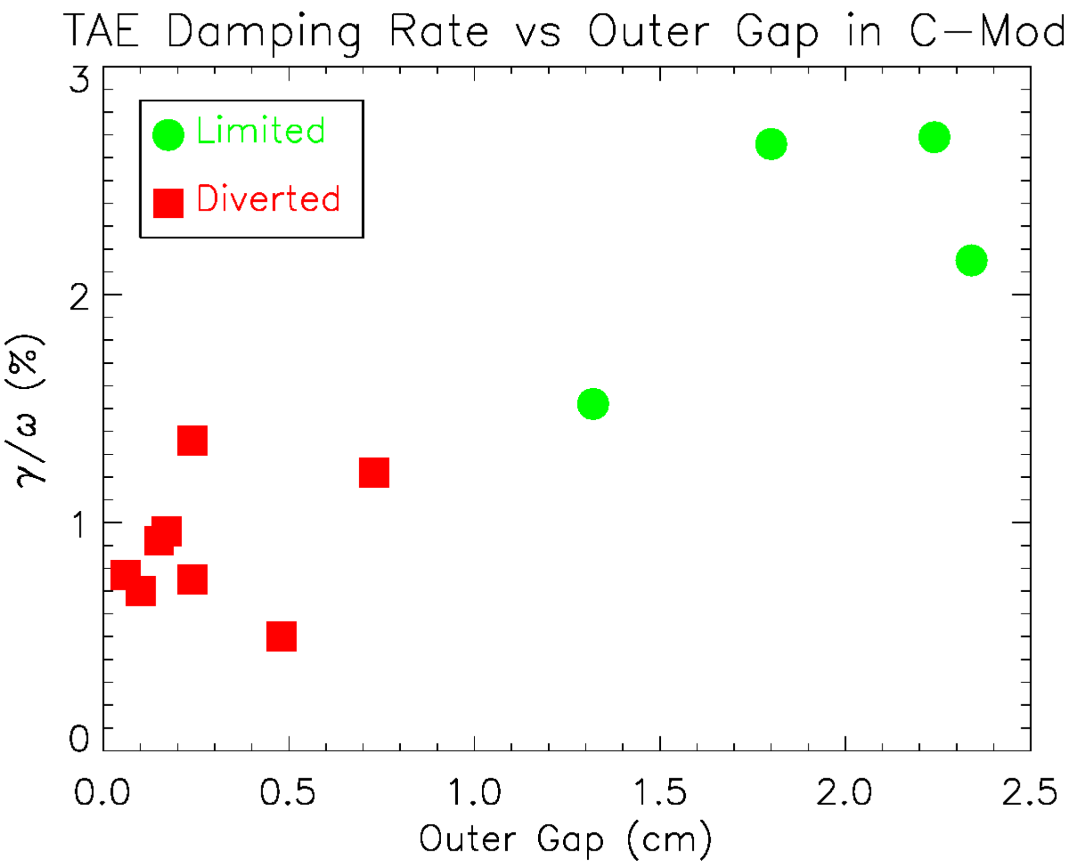


diverted with <1 mm outer gap



- Even with < 1 mm outer gap the lower single null diverted plasma remains clearly diverted with no interaction on the inner or outer walls compared to a strong plasma interaction with inner wall limited plasma

Limited vs Diverted Plasma Outer Gap Scan

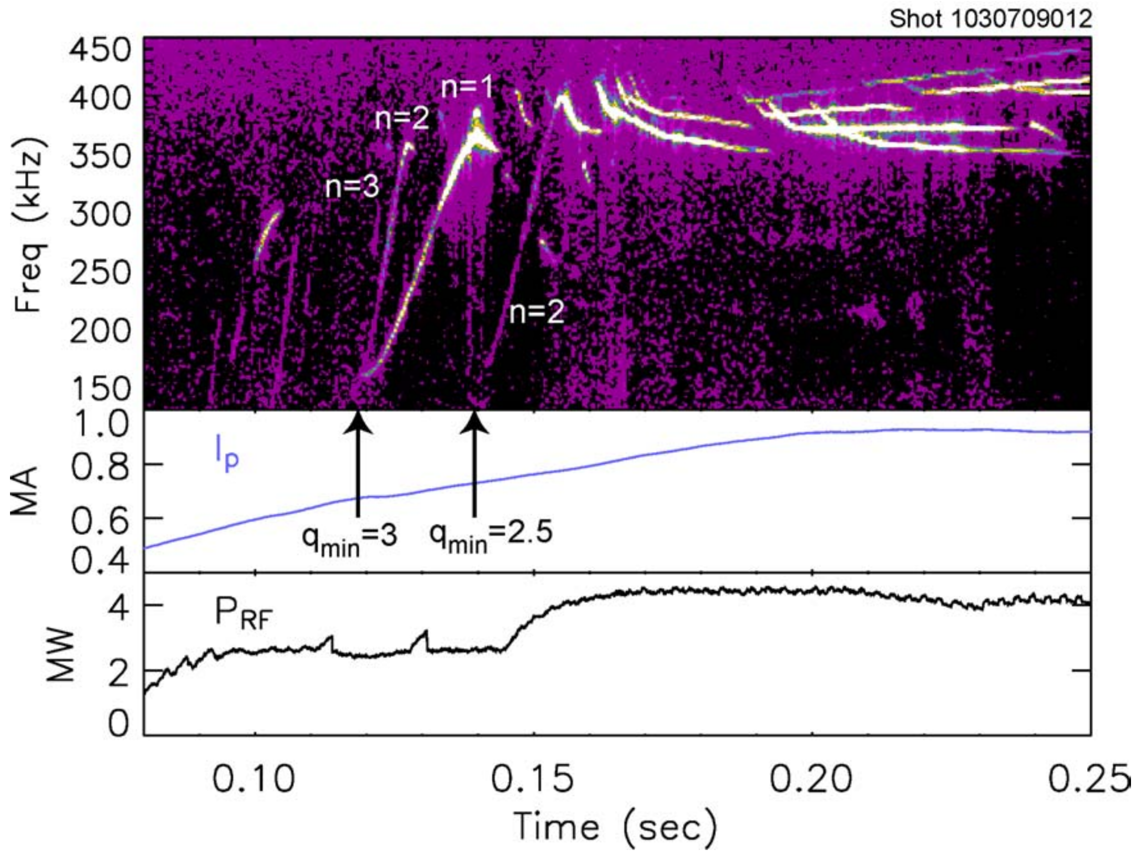


Active TAE resonances were only observed

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

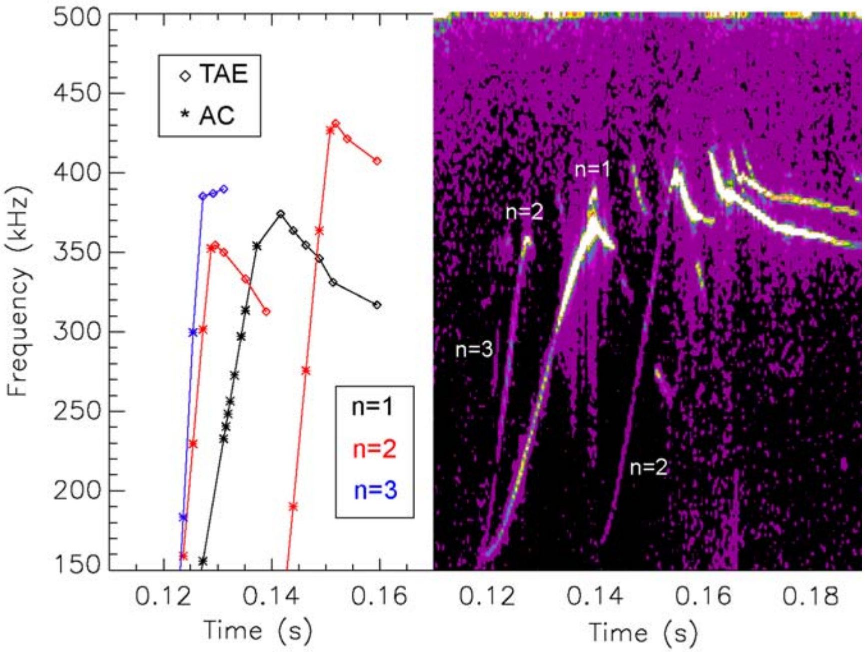
Damping rates are in the same range as those found in JET limited plasmas

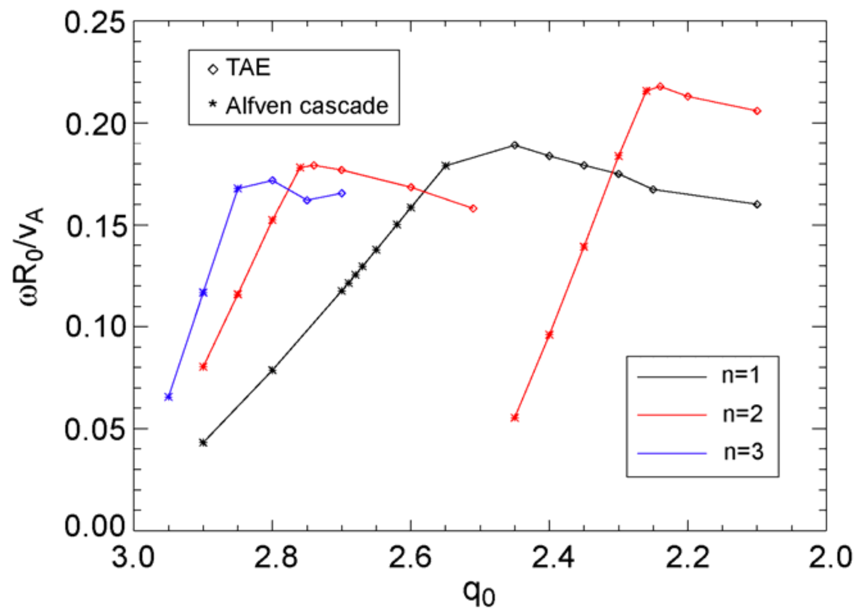
Alfvén Cascades in the Current Rise



- Rapidly chirping Alfvén Cascades in the current rise with strong ICRF heating at low density indicate a reversed shear q profile and determine the minimum q value at the minimum mode frequency

MISHKA Modeling of Alfvén Cascades



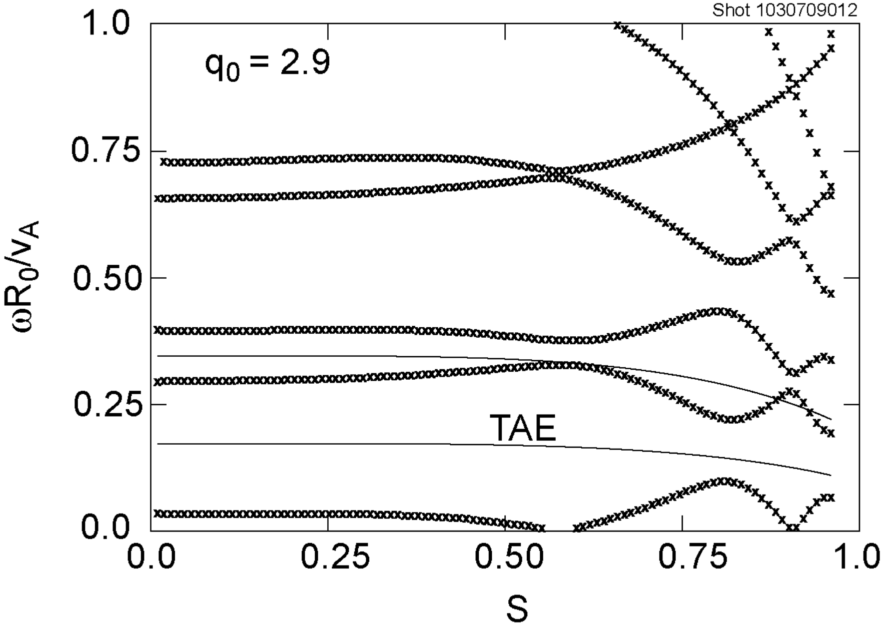


- From the frequency evolution of the Alfvén Cascades the evolution of the minimum q value can be modeled by the MISHKA[1] code
- The rapidly upward frequency chirping Alfvén Cascades develop into slowly varying TAE modes as the frequency peaks

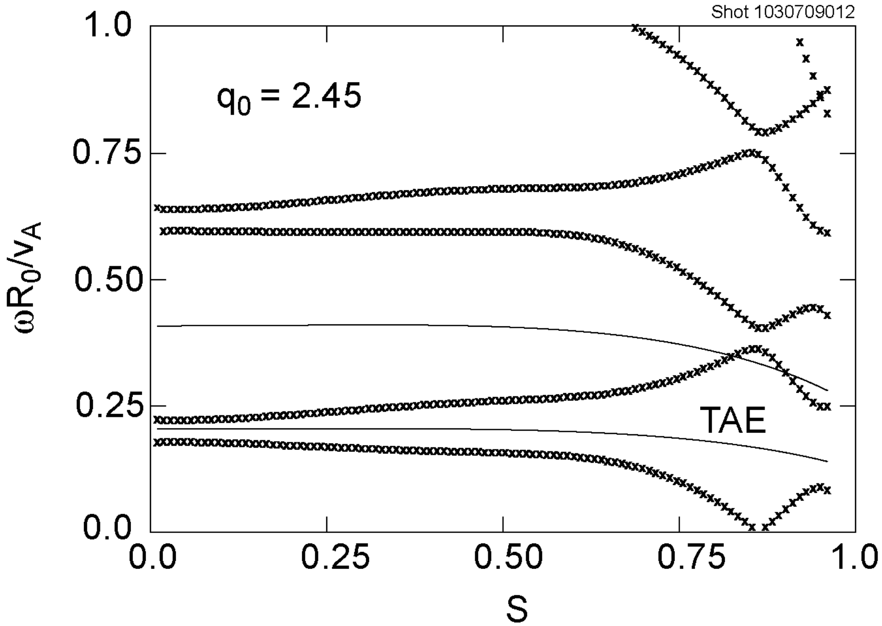
[1] S E Sharapov

n=1 Alfvén Cascade Gap Structure

Alfvén Cascade

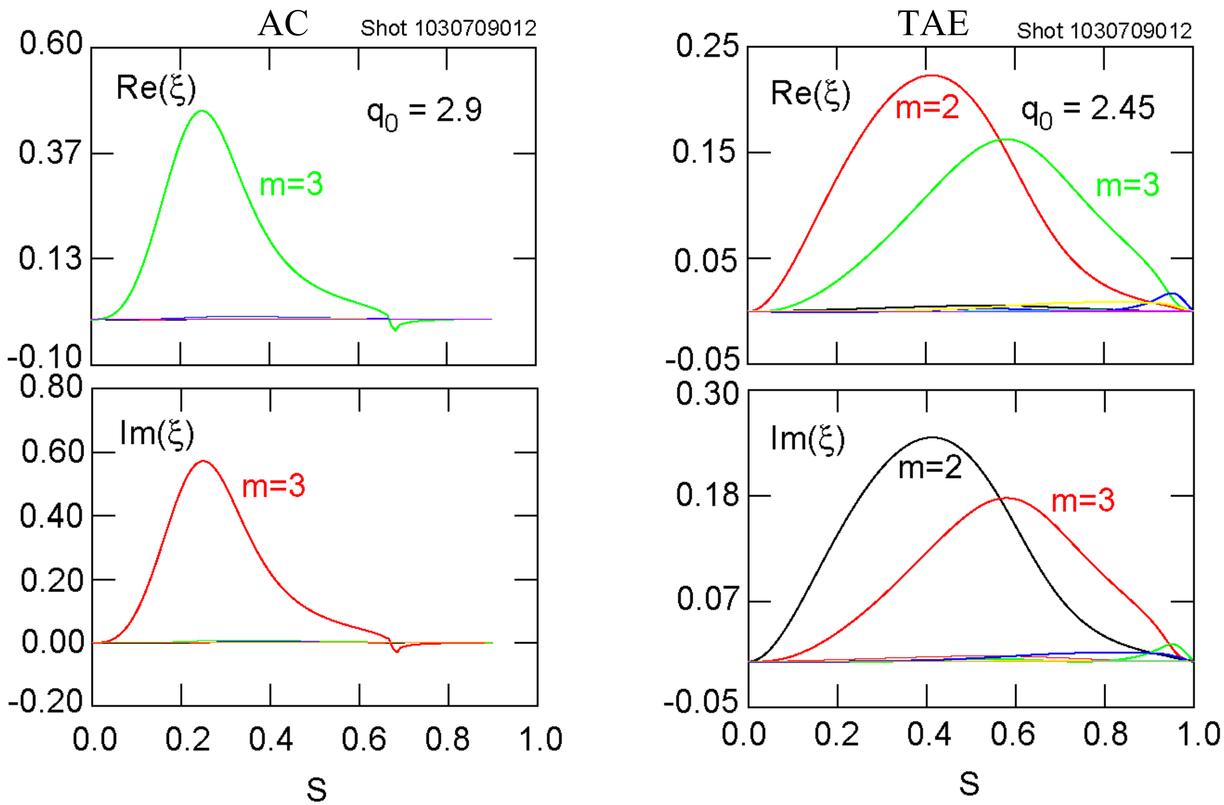


TAE



- At near integer q_0 the n=1 gap is wide allowing the Alfvén cascade frequency to sweep up to the TAE frequency
- As q_0 evolves to near a half integer value, the n=1 gap narrows to meet the TAE frequency as the Alfvén cascade becomes a TAE

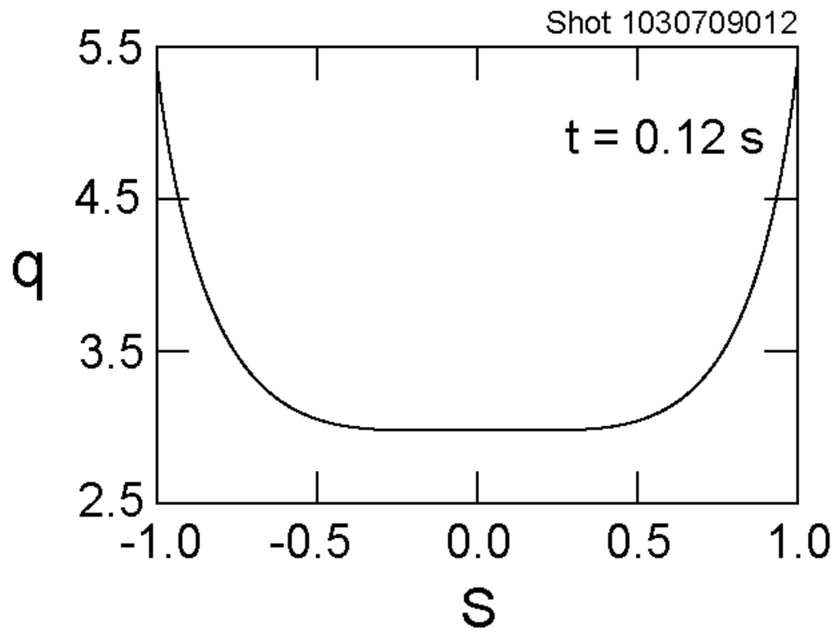
n=1 Alfvén Eigenmode Radial Structure



- The MISHKA code calculated TAE has multiple m structure at $q_0 = 2.45$ and is closer to the edge than the single m Alfvén Cascade at $q_0 = 2.9$
- This agrees with the increasing amplitude n=1 mode as q_0 decreases

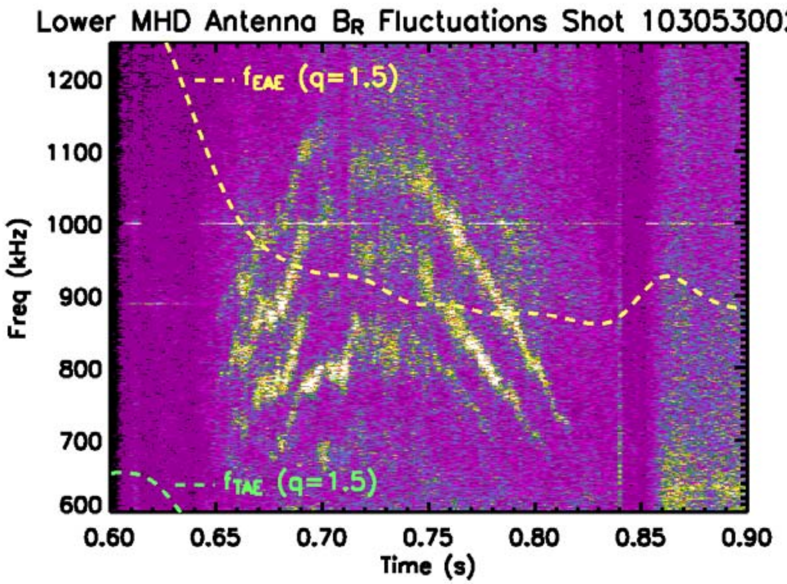
HELENA Equilibrium q Profile Calculation

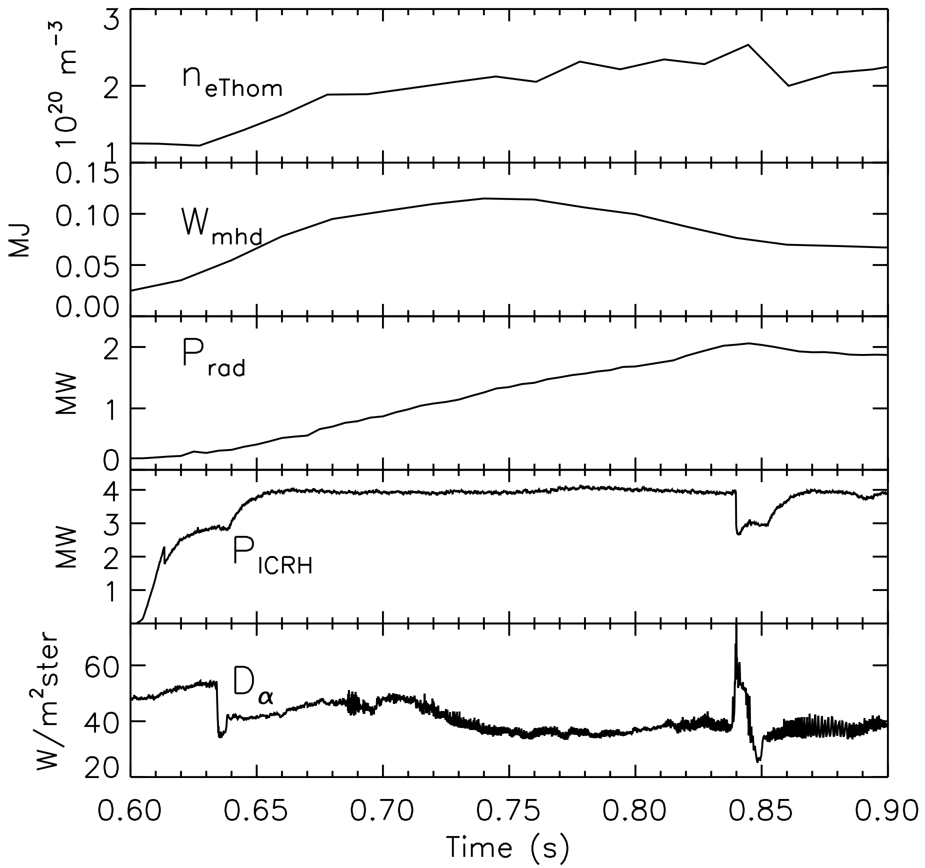
Alcator C-Mod



- The Alfvén Cascades together with some EFIT equilibrium parameters help to constrain an estimate of the q profile
- The data indicate a slightly reversed shear profile with $q_{min} = 3$ at the bottom of the n=1 Alfvén Cascade (t = 0.12 s)

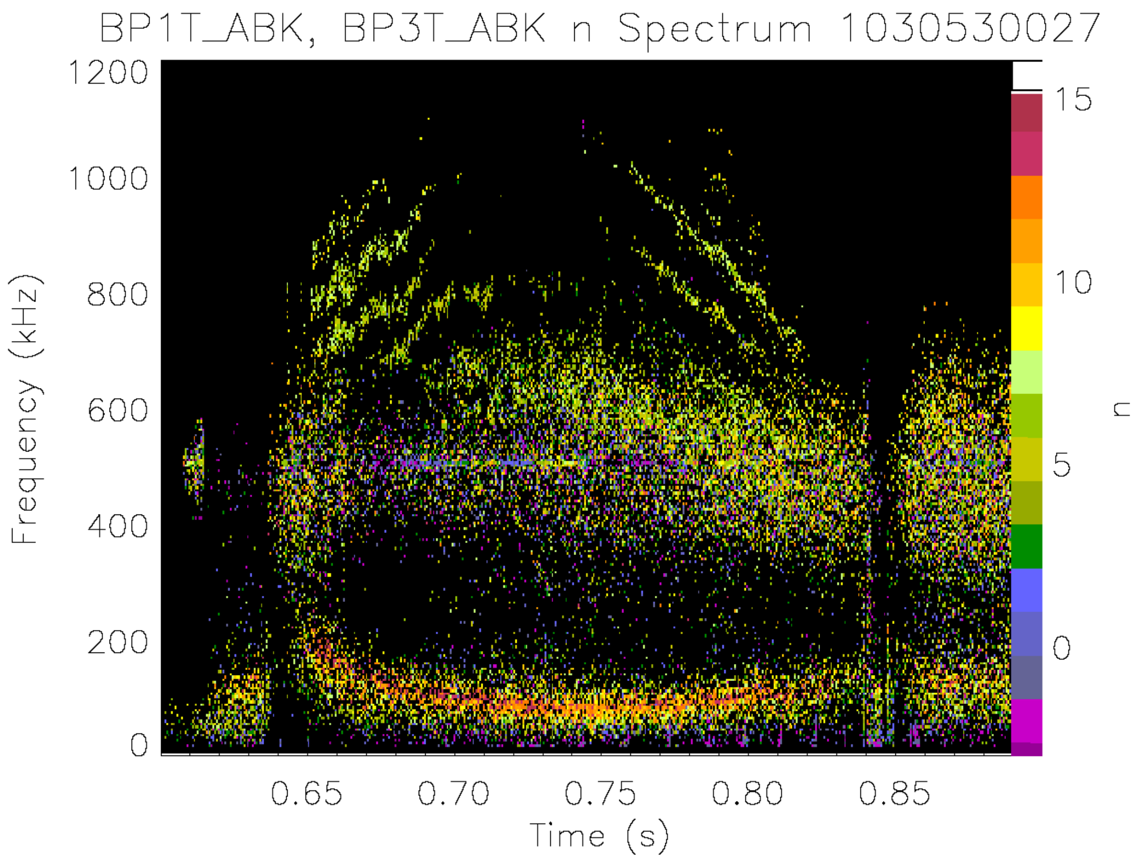
Unstable Modes in the EAE Frequency Range in Low Density High ICRF Heated EDA H-mode





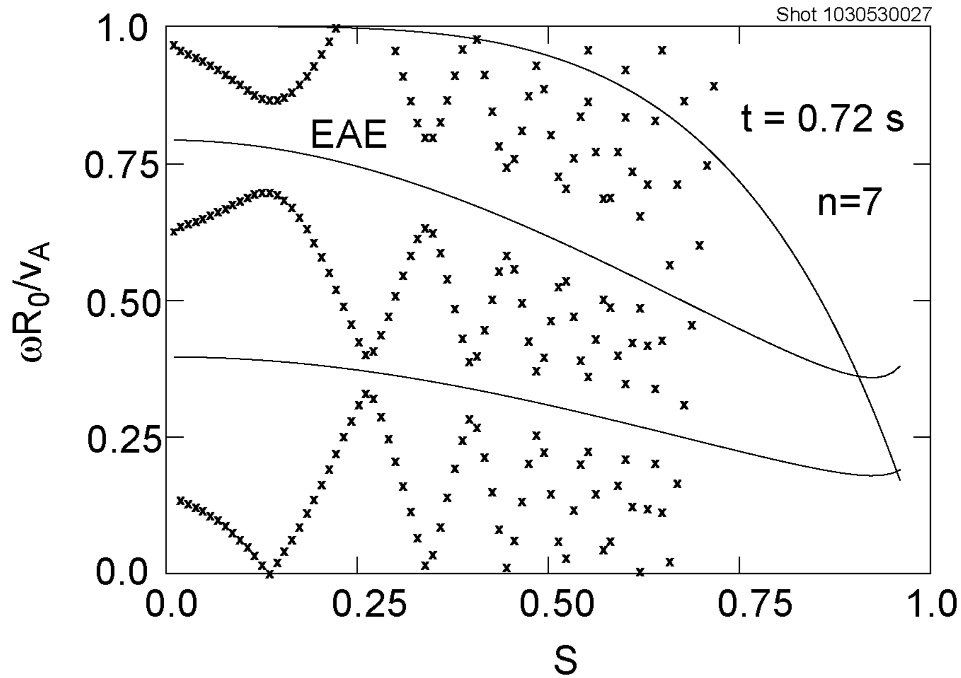
- Multiple modes 700 < f < 1100 kHz
- Low density ($n_e \approx 2 \times 10^{20}$ m^{-3})
- High ICRF power (4 MW)
- Centered on the EAE gap at q=1.5

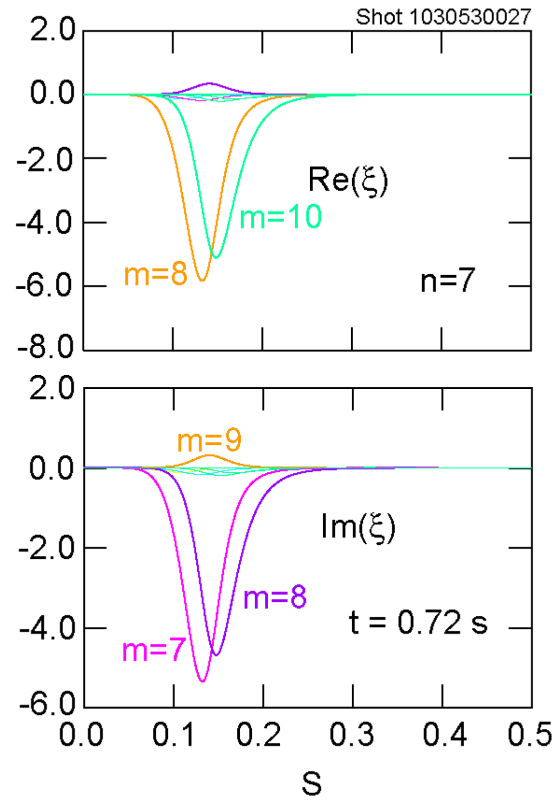
EAE Frequency Modes have 4 < n < 9



- EAE frequency modes have 4 < n < 9 and rotate in the electron diamagnetic drift direction similar to the n ~ 15 quasi-coherent mode

MISHKA Finds Core Localized EAE's





- MISHKA modeling finds core localized EAE's, e.g., n=7 EAE at $\omega R_0/v_A \sim 0.75$ which corresponds to $f_{EAE} \approx 1$ MHz

Conclusions

- Stable TAE resonances at q=1.5 are actively excited with a single high 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 $0.5\% < \gamma/\omega < 4\%$
- Diverted discharges require an outer gap < 1 cm to see the resonance
- Alfvén Cascades are observed in the current rise at low density with strong ICRF heating indicating slightly reversed shear with $q_{min} = 3$
- Results agree well with MISHKA modeling of the Alfvén Cascades
- Modes are also observed in the EAE frequency range ~ 1 MHz in relatively low density EDA H-modes rotating in the electron direction