Measurement of the Damping Rate of Medium-N Alfvén Eigenmodes in JET: Ideas and Possibilities for Comparisons of Experiments vs. Theory

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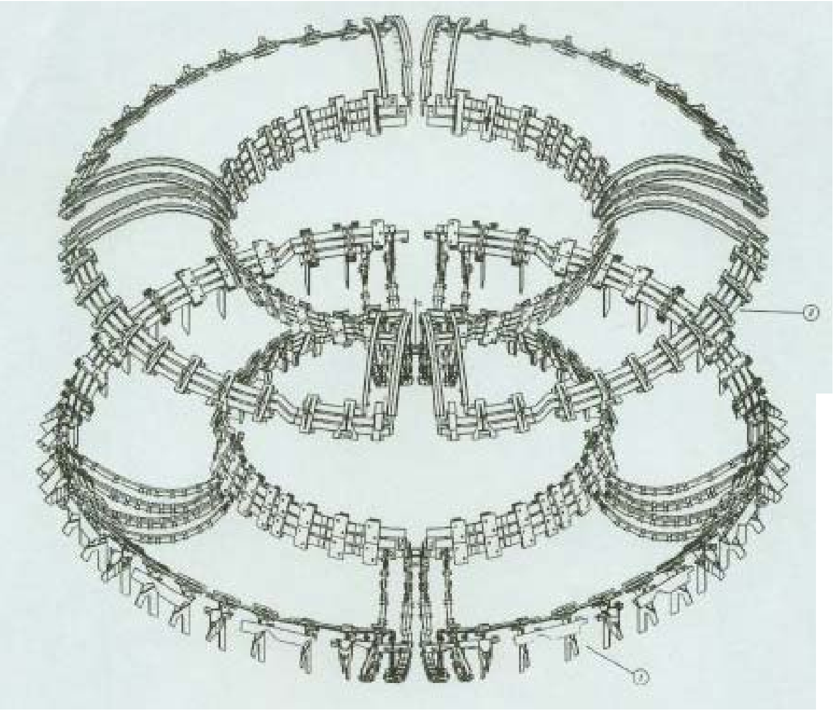
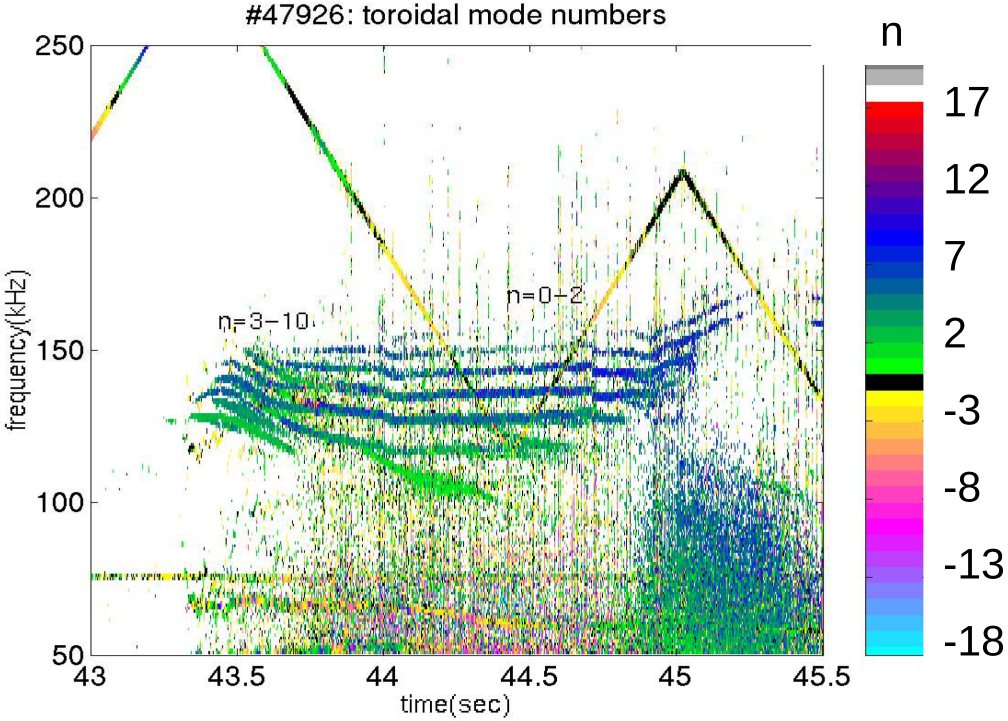
overview and summary

- low-n modes in JET: previous experiments vs. theory comparisons
  - **what we learnt on theory/models for n=0,1,2 AEs**
  - **need to move to active drive for medium/high-n modes**
- general overview of the new high-n AE antenna system on JET – KC1T diagnostic
- first measurements of the damping rate for n=3-10 AEs in JET
  - **what are we learning now from experiments for n=3-10 AEs**
- ideas and opportunities for comparisons with theory/models for medium-n AEs

active MHD antennas on JET: low-n studies with saddle coil system



- only excitation of low-n AEs (n=0,1,2) because of in-vessel geometry
- operational for ~10 years
- **>50'000 individual damping rate points**
- **n-number mismatch with most unstable modes: ex. ICRH-driven modes**



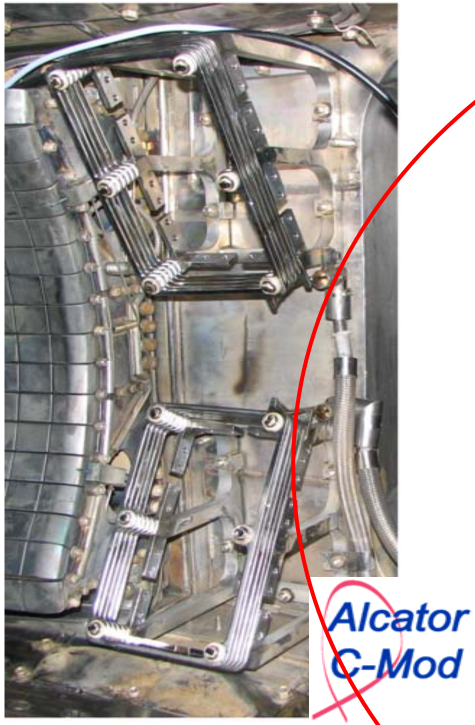
low-n studies with saddle coil system: what we learnt, experiments vs. theory

- edge damping mechanism: mode conversion to KAWs
  - shaping of edge flux surfaces ➔ increased edge magnetic shear ➔ increased mode conversion ➔ stronger damping
  - quantitative agreement (values and scaling) with gyro-kinetic code PENN
  - gyrokinetic code LIGKA reproduces measured eigenfunction and damping rate within 50% (but just one case tested)
  - also consistent with observed PNBI threshold for excitation of medium-n AEs
- core damping mechanism: mode conversion to kinetic AWs
  - scaling vs. plasma mass quantitatively reproduced by gyro-kinetic code PENN
  - also similar trend found with LIGKA but no direct comparison with measurements
  - transition in measured γ/ω for q_0~1 not reproduced by continuum γ/ω in CASTOR
- core damping mechanism: radiative damping, $\gamma/\omega=f(\rho_i)$
  - analytical approximation: wrong value and scaling vs. ρ_i
  - NOVA-K: correct frequency but much too small damping, wrong scaling vs. ρ_i
- many “pure” experimental scalings not compared with theory:
  - plasma beta, ion ∇B-drift direction, shear in toroidal rotation, T_i/T_e, q_0/q_{95}, ...

summary of low-n AE damping data: motivation for medium-n antennas

- >50’000 individual damping rate measurements for n=0-2 AEs
- experimental scaling obtained wrt plasma mass, edge shape and magnetic shear, plasma beta, core q_0, P_{NBI}, ∇B, rotation, ...
- **HOWEVER: only a handful of experimental points have been fully analysed in comparison with theory**
  - gyrokinetic codes (PENN, LIGKA) seem to be able to better reproduce measured damping rate and eigenfunction
  - fluid codes do not seem to have proper damping physics when AE gap structure is open (continuum damping not dominant)
- **HOWEVER: predictions on AE damping rate need to be improved and validated in ITER-relevant medium-n range**
- **design and build new medium-n antennas**

medium-n active MHD spectroscopy is developed on several tokamak devices



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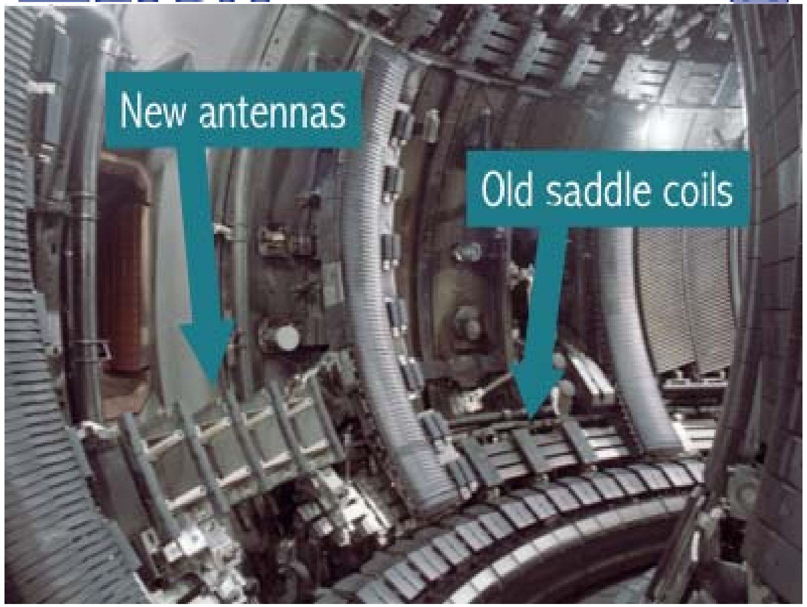
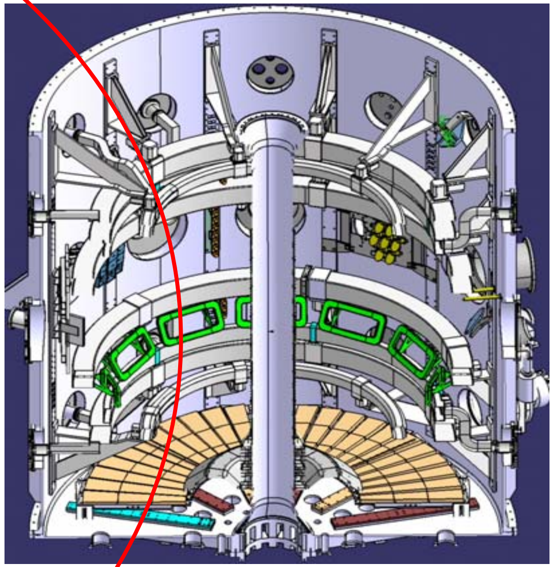


MAST



high field, high density, $T_e \sim T_i$

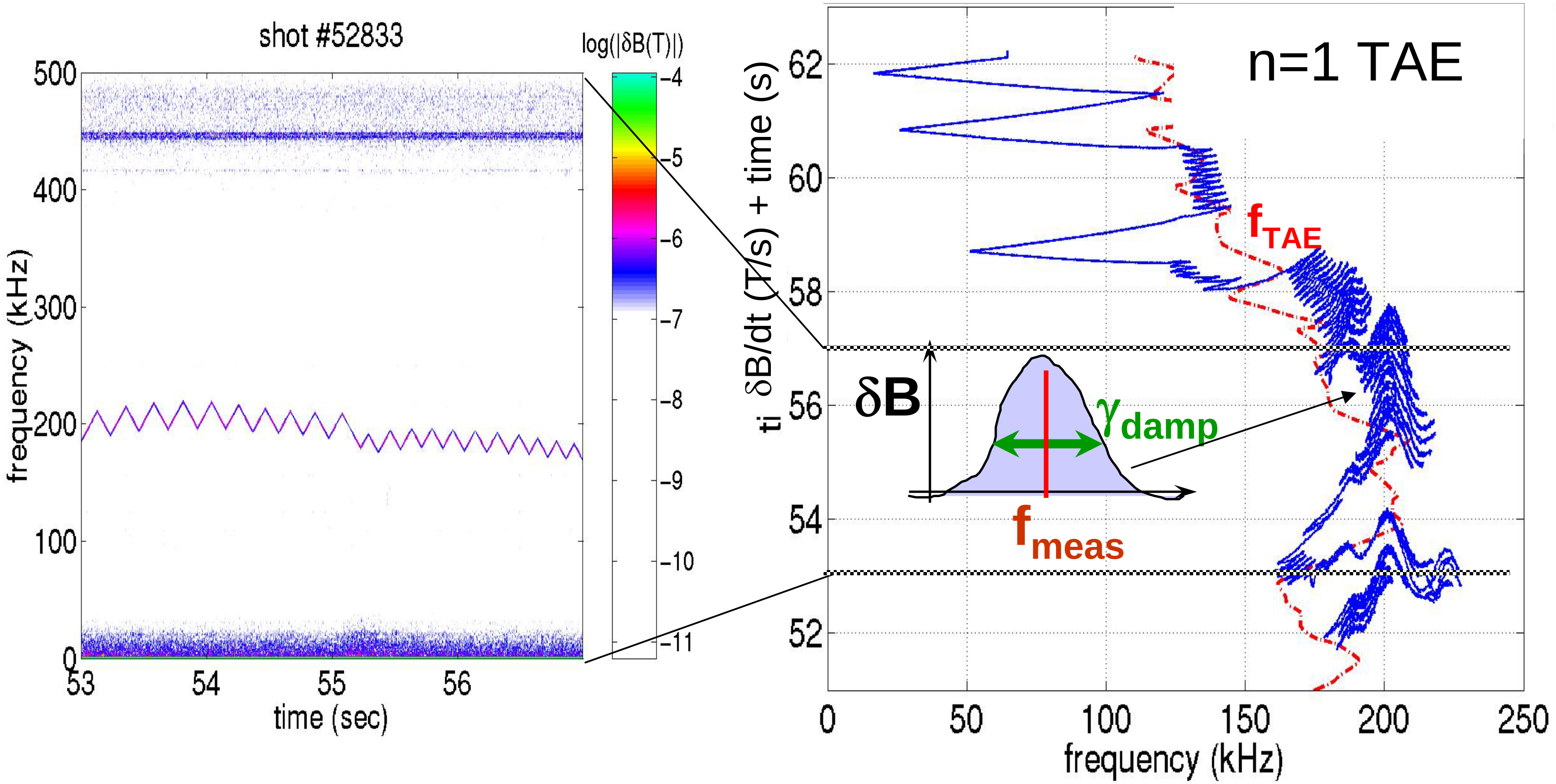
ITER-relevance for size and shape scaling, scenarios

tight aspect ratio, broad range of β

unique to JET: real-time tracking of driven modes allows to follow mode evolution as plasma parameters change

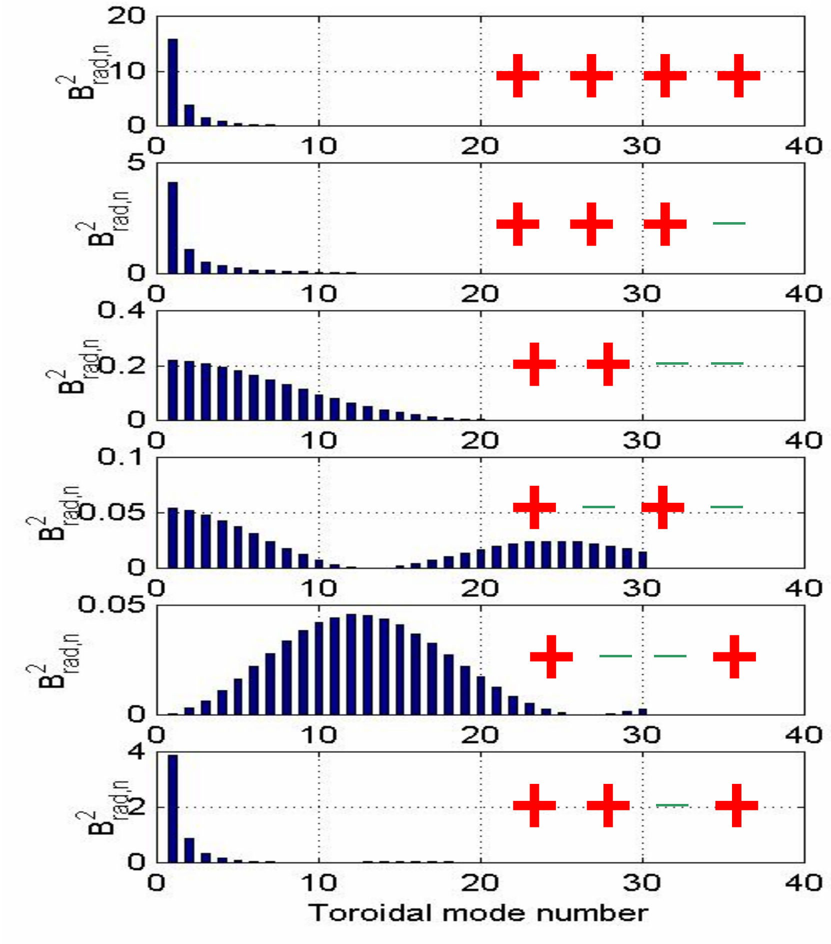
real-time tracking: γ/ω measurements

- global modes ≡ resonances in detected spectrum
- plasma response to antenna drive measured in real-time on B-field probes
    - *could be extended to other diagnostics (reflectometry, ...) with good SNR*
- evolution of AE frequency and damping rate followed in real-time (n_e, B, Ip)
    - *guarantees that the same n-mode is followed as the background changes*
    - *damping rate in real time can lead to burning plasma control scenarios*

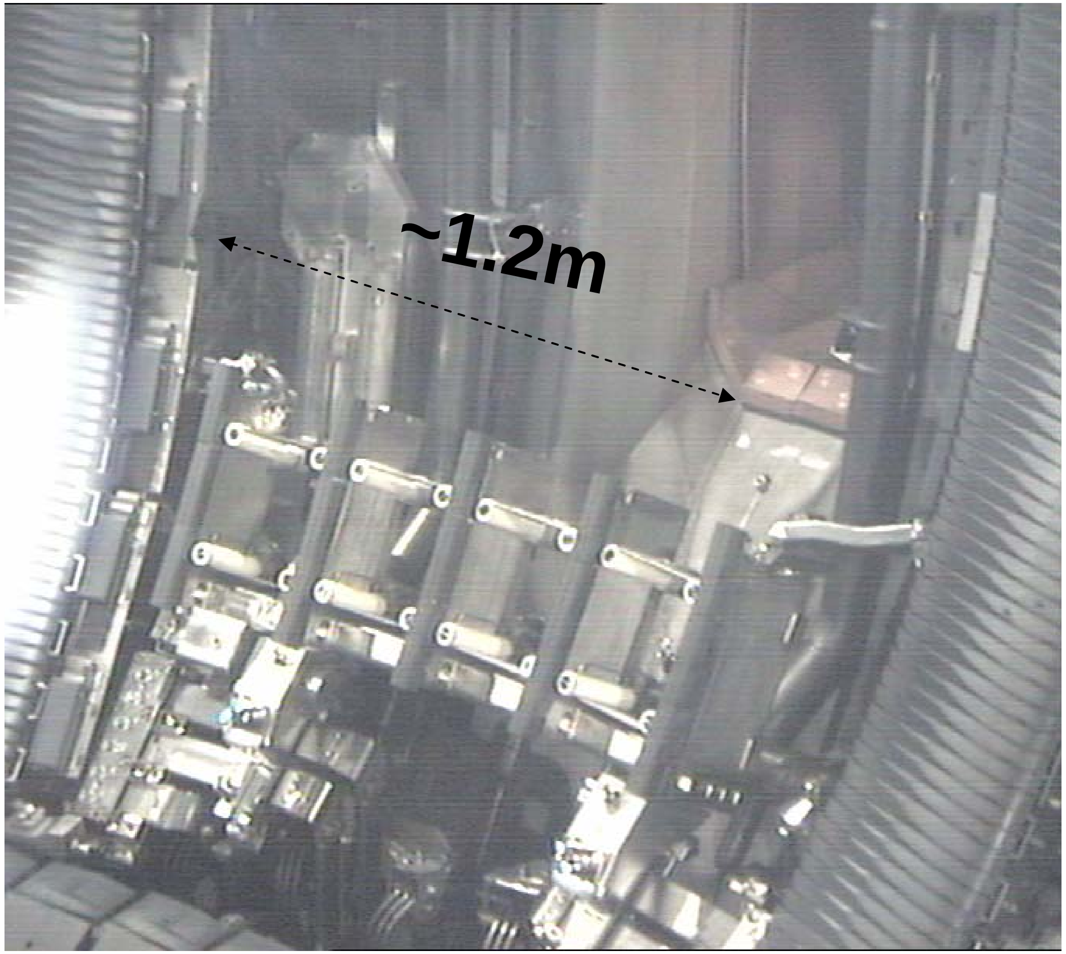


new antennas for medium-n AEs in JET

nominal vacuum n-spectrum

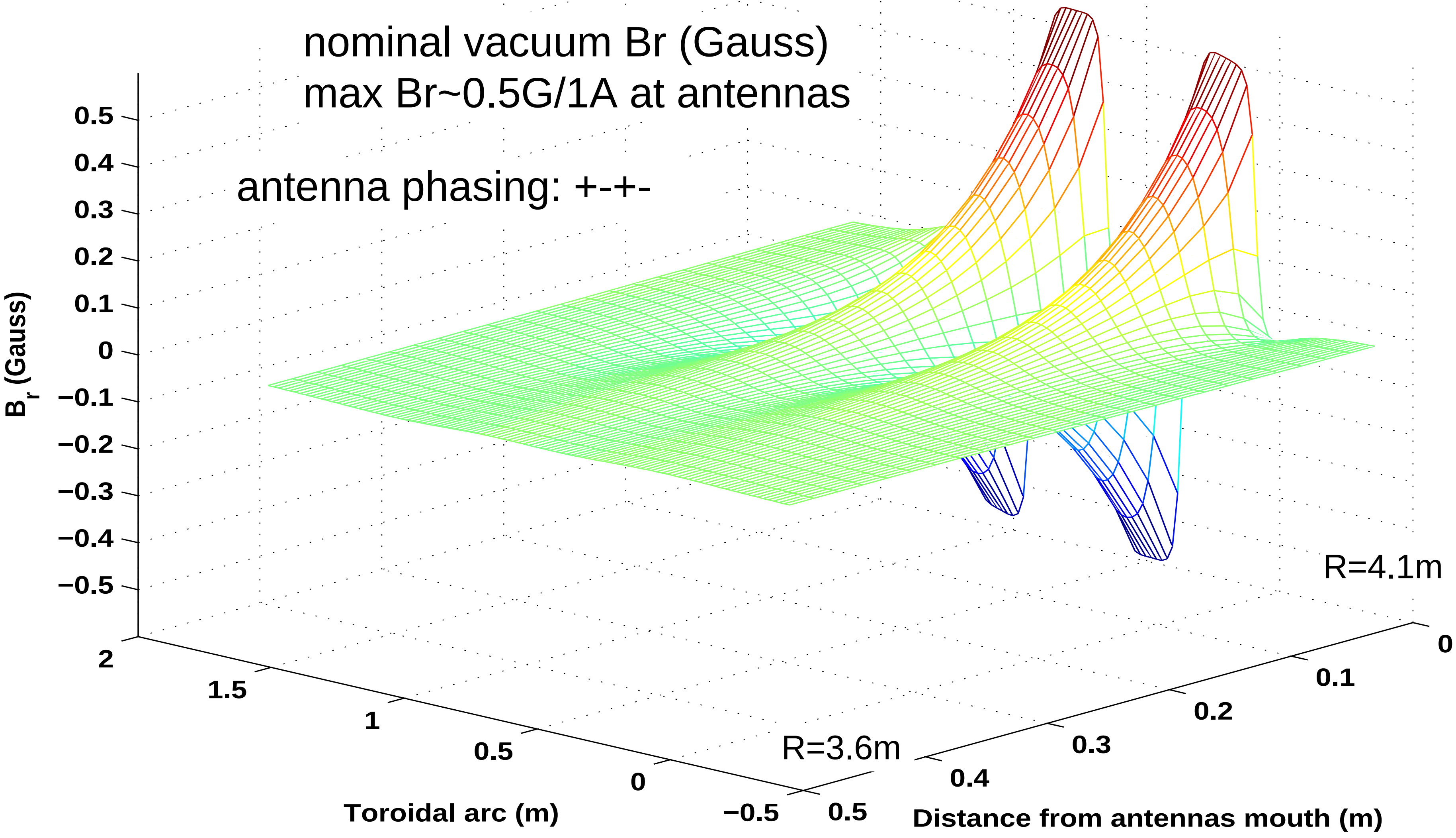


in-vessel position and mounting



- 2 groups of four antennas at opposite toroidal locations
- now fully running up to JET operational limits: I_{max}<15A (total), V_{max}<600V, 10-500kHz
- very broad excitation spectrum (HWHM~5) for all antenna phasing
- designed to achieve coupling for n=5 as n=2 by saddle coils (δB_{max}~1G at plasma edge)

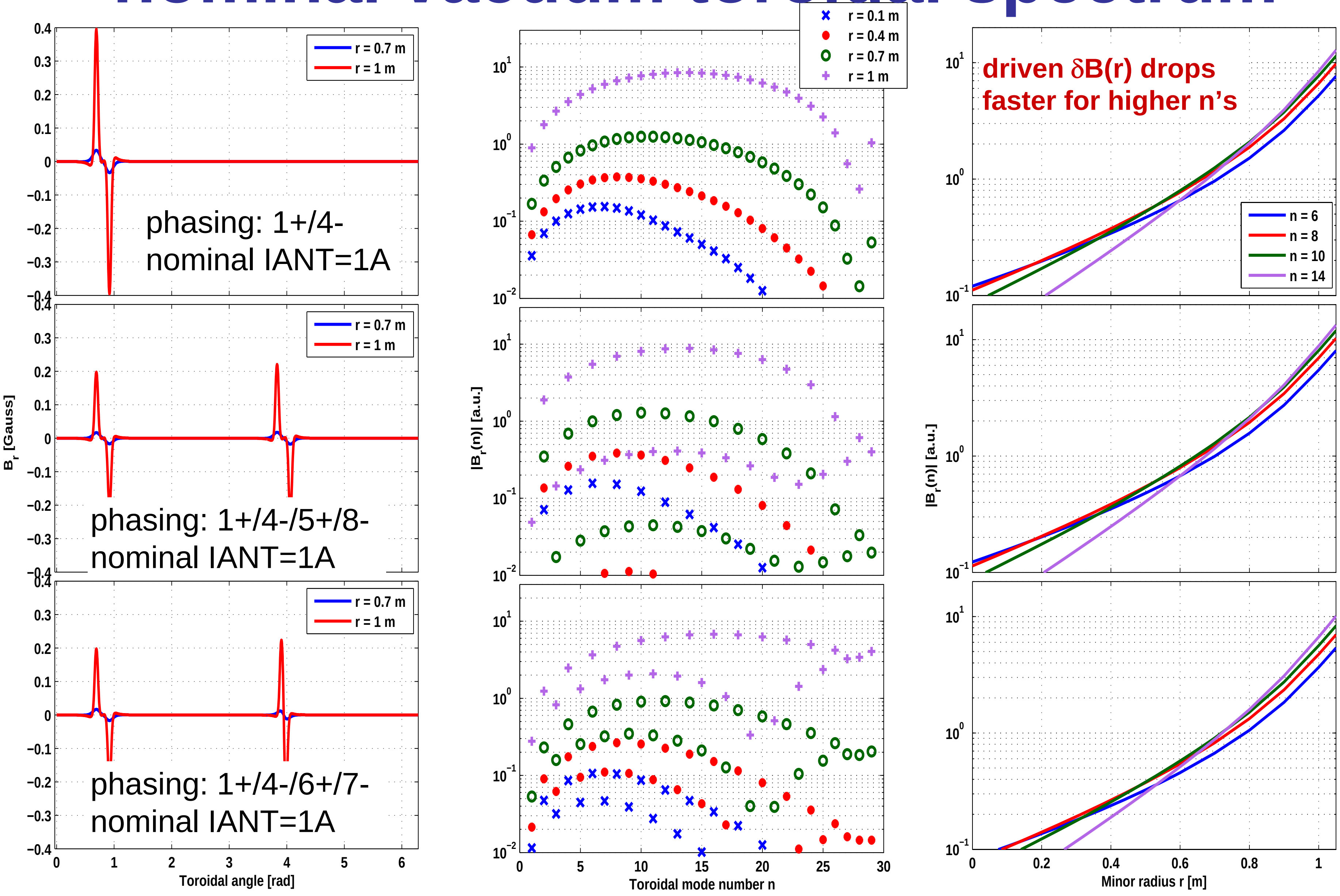
calculation of vacuum field produced by four neighboring antennas



nominal vacuum Br (Gauss)
max Br~0.5G/1A at antennas

antenna phasing: +-+-

nominal vacuum toroidal spectrum



phasing: 1+/4-
nominal IANT=1A

phasing: 1+/4-/5+/8-
nominal IANT=1A

phasing: 1+/4-/6+/7-
nominal IANT=1A

driven δB(r) drops faster for higher n's

- **broad excitation spectrum (HWHM>5) for all antenna phasing**

the Sparse Matrix method: SparSpec* post-pulse and real-time

- broad antenna driven spectrum ➔ need to separate different n's: $\gamma/\omega = f(n)$
- finding the solution with the sparsest spectrum on a **discrete (integer ≡ n!) frequency grid** using the minimization criterium:

$$\boxed{J(x) = {}^1\!/_2 \left\| \mathbf{y} - W\mathbf{x} \right\|^2 + \frac{\lambda}{\lambda_{Max}} \sum_{k=-K}^{K} \left| x_k \right|}$$

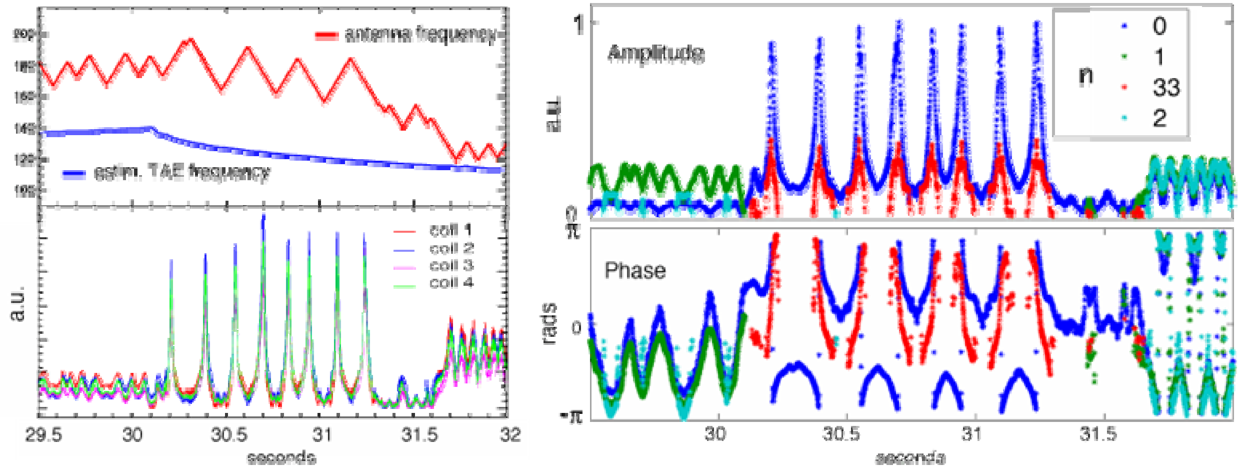
y: vector of data taken at time t_k (≡ position ϕ_k)
W: spectral window $\exp(i2\pi t_k f_n) \equiv \exp(i2\pi\phi_k n)$
x: vector of (I,Q) signals for with frequencies f_n
λ: parameter fixed to obtain a satisfactory sparse solution ➔ penalty criterion for invoking more modes to find adequate solution

- ideally suited for toroidal mode number analysis
  - allowable mode numbers are discretized: $|n| = 1,2,3\ldots$
  - uses all information (time history from FFT, amplitudes, phases)
  - specifically suited for un-evenly distribution of sensors
  - very efficient, very fast convergence ➔ ideal for RT applications
  - no restriction on n-range, number of modes not assumed a priori
  - **now implemented in JET real-time mode tracking algorithm**
    - already tested and working, some further optimization still needed

* S.Bourguignon, H.Carfantan, T.Böhm, Astronomy and Astrophysics **462** (2007) 379: **"SparSpec: A New Method for fitting multiple sinusoids with irregularly sampled data"**, http://www.ast.obs-mip.fr/Softwares

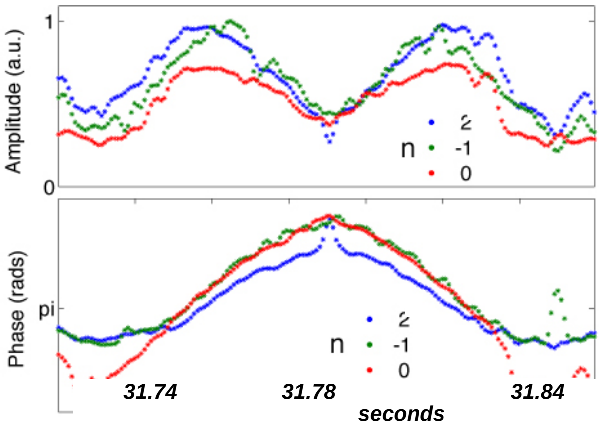
AE damping rates using SparSpec

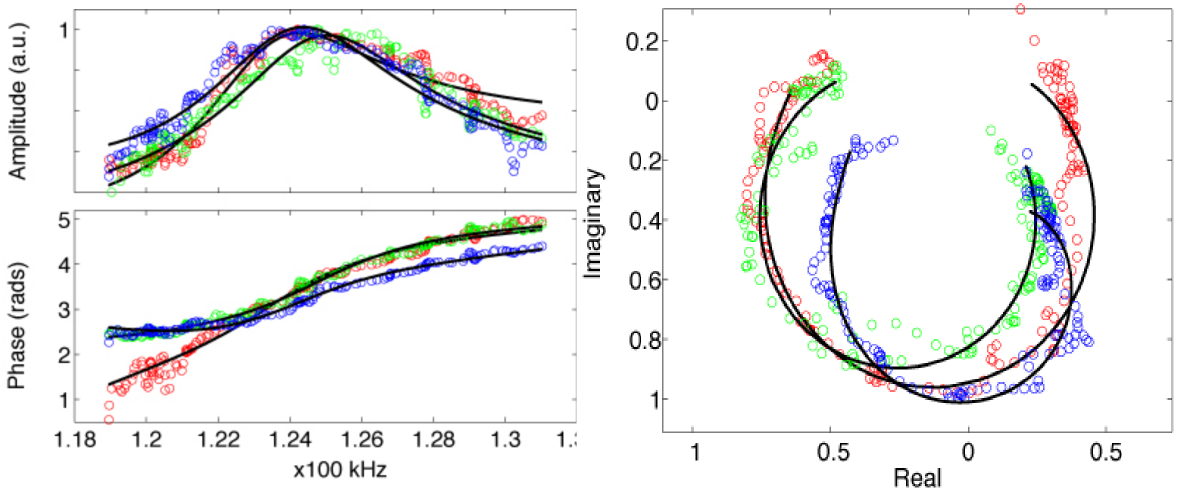
- independent TAEs with different n
- damping is a function of n
- with SparSpec: possible to get separate damping rate measurements for different n's found at same time



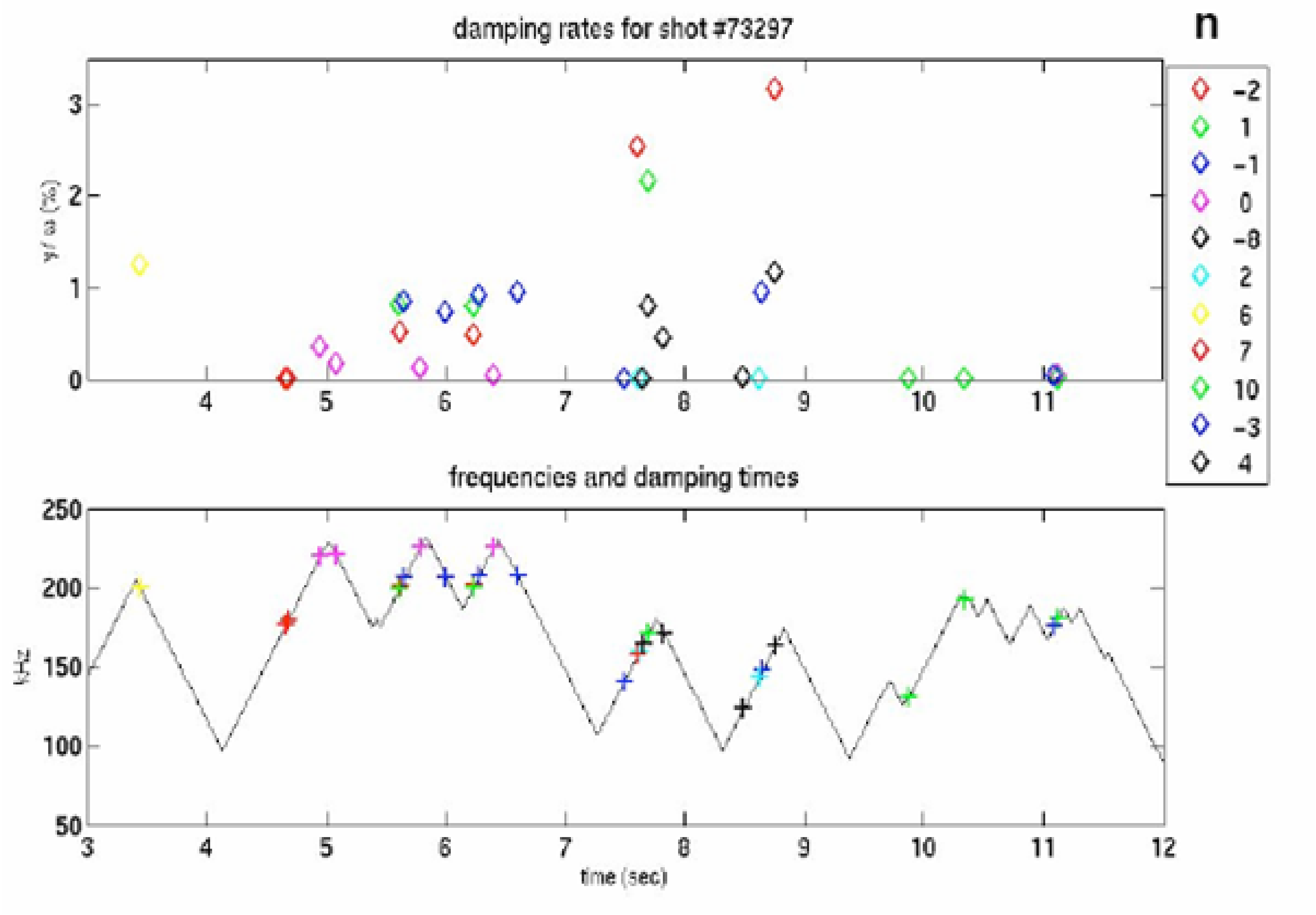
KC1T: TAE tracking during shot #69586➔ near t=32sec (right edge of window), three modes seen to be competing with almost equal amplitudes

damping rate obtained separately for the three modes (n=0,1,2)

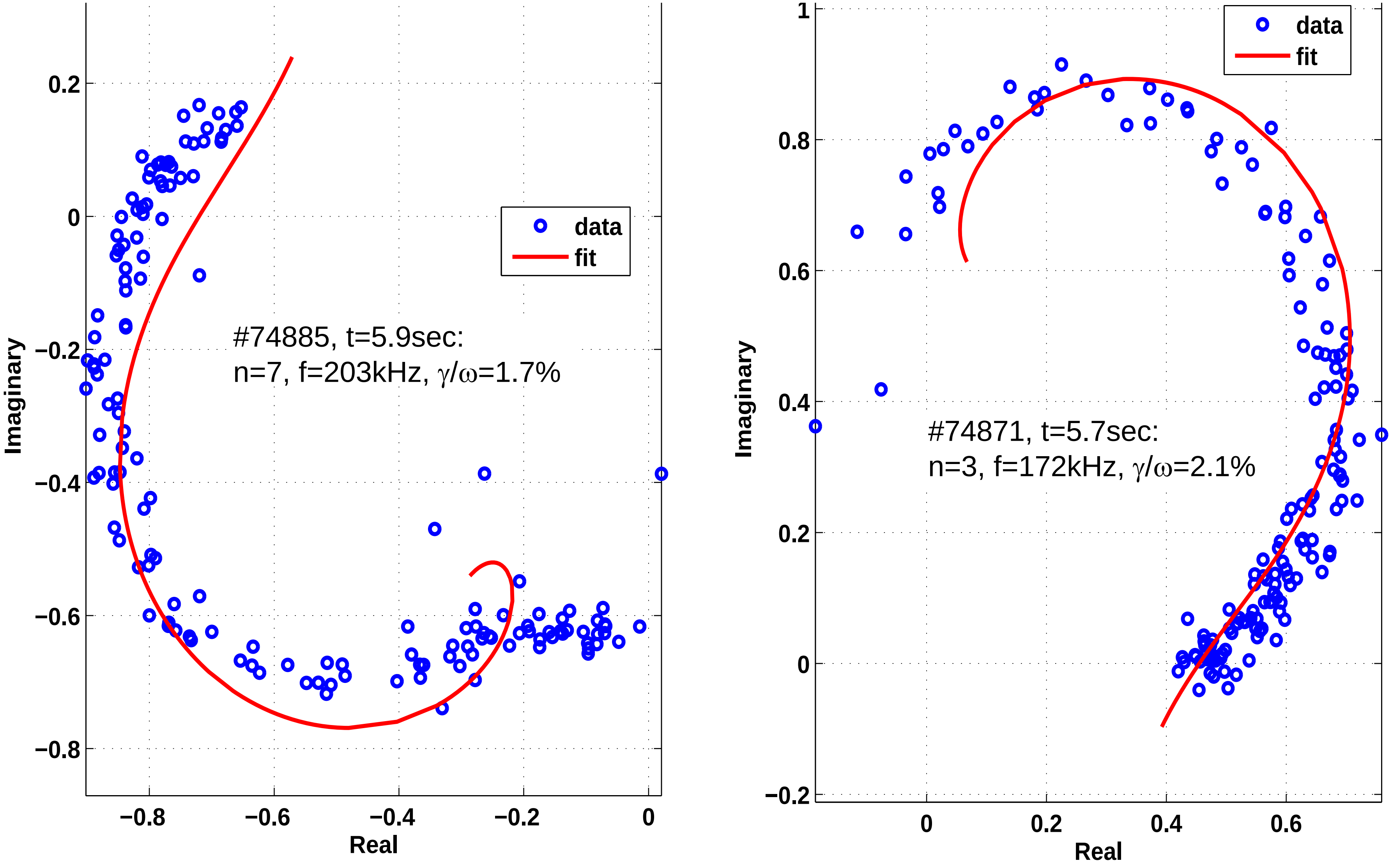




AE damping rates of different n’s can be measured independently

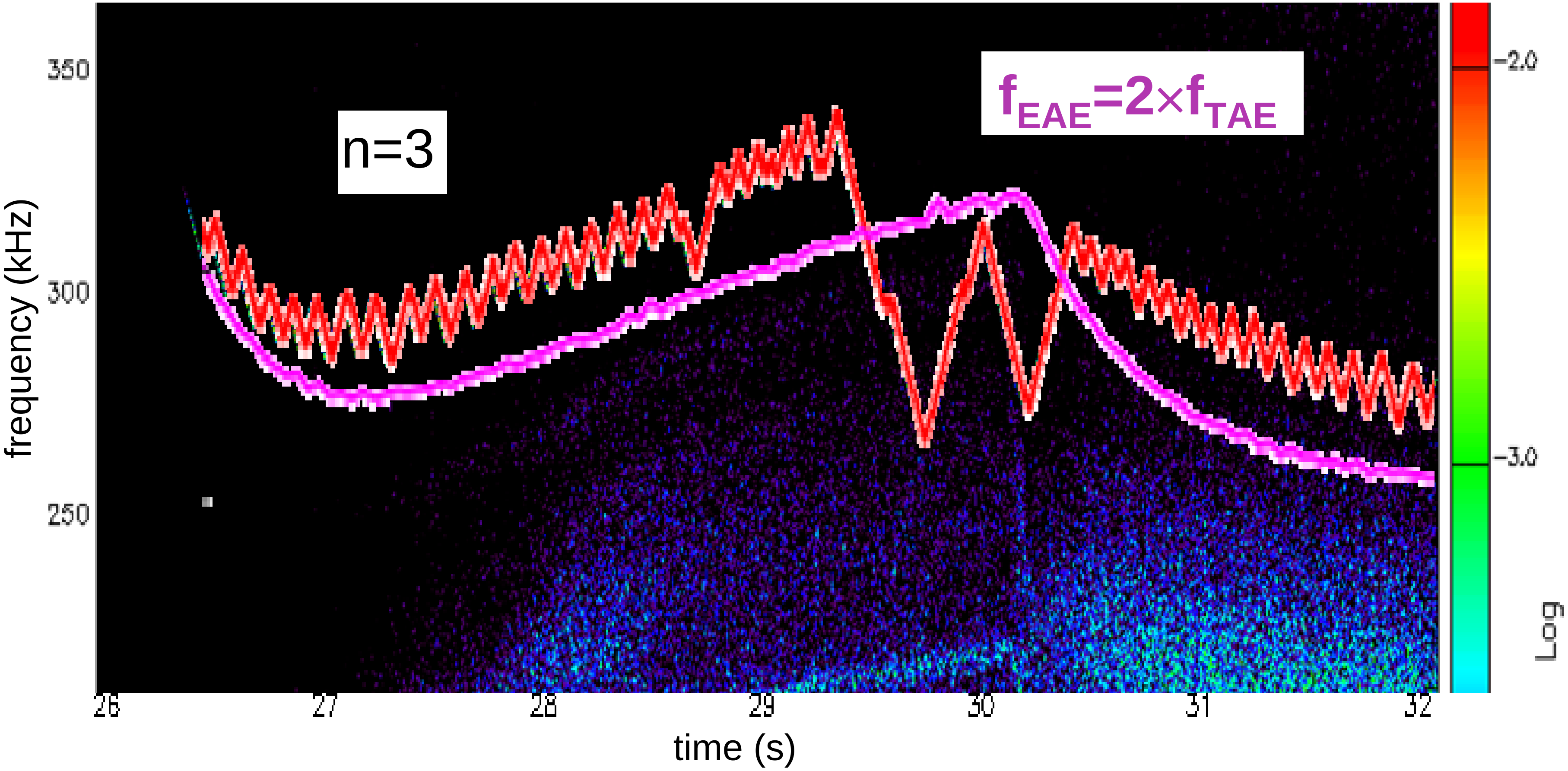


AE damping rates of different n's can be measured independently



new JET active antennas: mode tracking

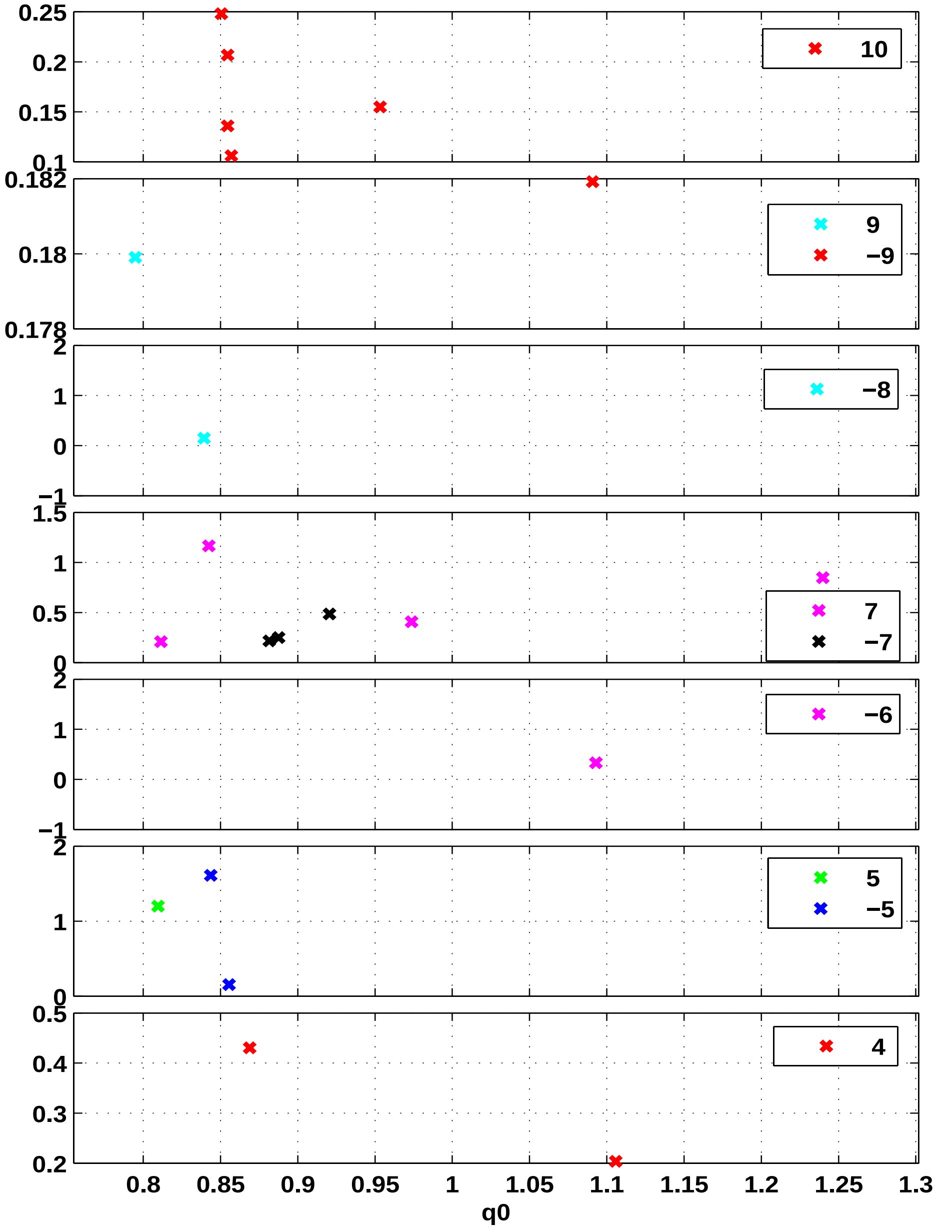
- tracking works throughout limiter and divertor phases
  - more than 100 resonances measured in one discharge (for n=0,1, more difficult for n>5)
  - unambiguous identification of Alfvénic nature of mode: ex. EAE
- **recently added: real-time identification and tracking of specific mode number using algorithm based on Sparse Matrix representation**
  - possibility for real-time measurement of γ/ω (proximity to stability limit) for medium-n AEs



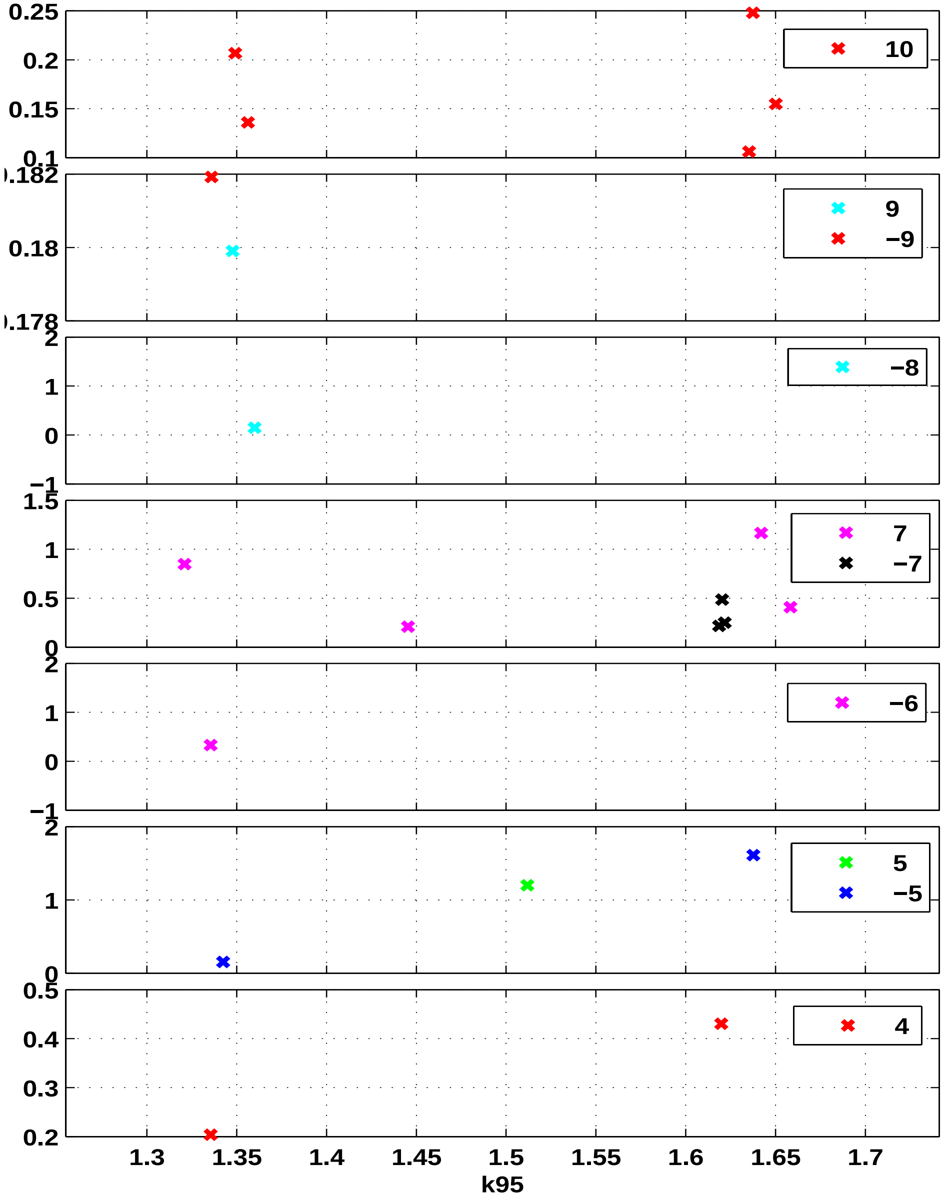
summary of the first results on damping rate measurements for medium-n AEs

- various antenna configurations are used to change excited n-spectrum:
  - 1+/4+/6+(-)/7+(-) gives dominant n<3, δB_{DRIVEN}~3×10^{-2}G at R~R_{mag}
  - 1-/4+/6+(-)/7-(+) gives dominant n~3-8, δB_{DRIVEN}~5×10^{-3}G at R~R_{mag}
- **medium-n modes (up to n~10) clearly driven by AE antennas and detected by pick-up coils fed into real-time controller (for tracking)**
- various dedicated scans in plasma parameters have been run:
  - 6sec-long elongation scan during ohmic phase, $1.25<\kappa95<1.65$ without IRCF
    - add ICRF with PRF=2MW and PRF=3MW, different phasing (dipole and +/-90)
    - add PRF modulations 2MW +1MW/300ms, different phasing (dipole and +/-90)
  - ohmic Bfield/ne scan, change RF deposition profile and edge continuum
    - add PRF with power ramp-up to 4.5MW, different phasing (dipole and +/-90)
- **real-time algorithm to select specific mode number for tracking has worked very well (exclusion of low-n modes, selection of specific n's)**
- database being compiled of $\gamma/\omega=$ f(n) as a function of plasma parameters and configurations
  - small differences in T_e, n_e profiles lead to large differences in γ/ω

γ/ω database vs. plasma parameters



damping rate vs. core q0



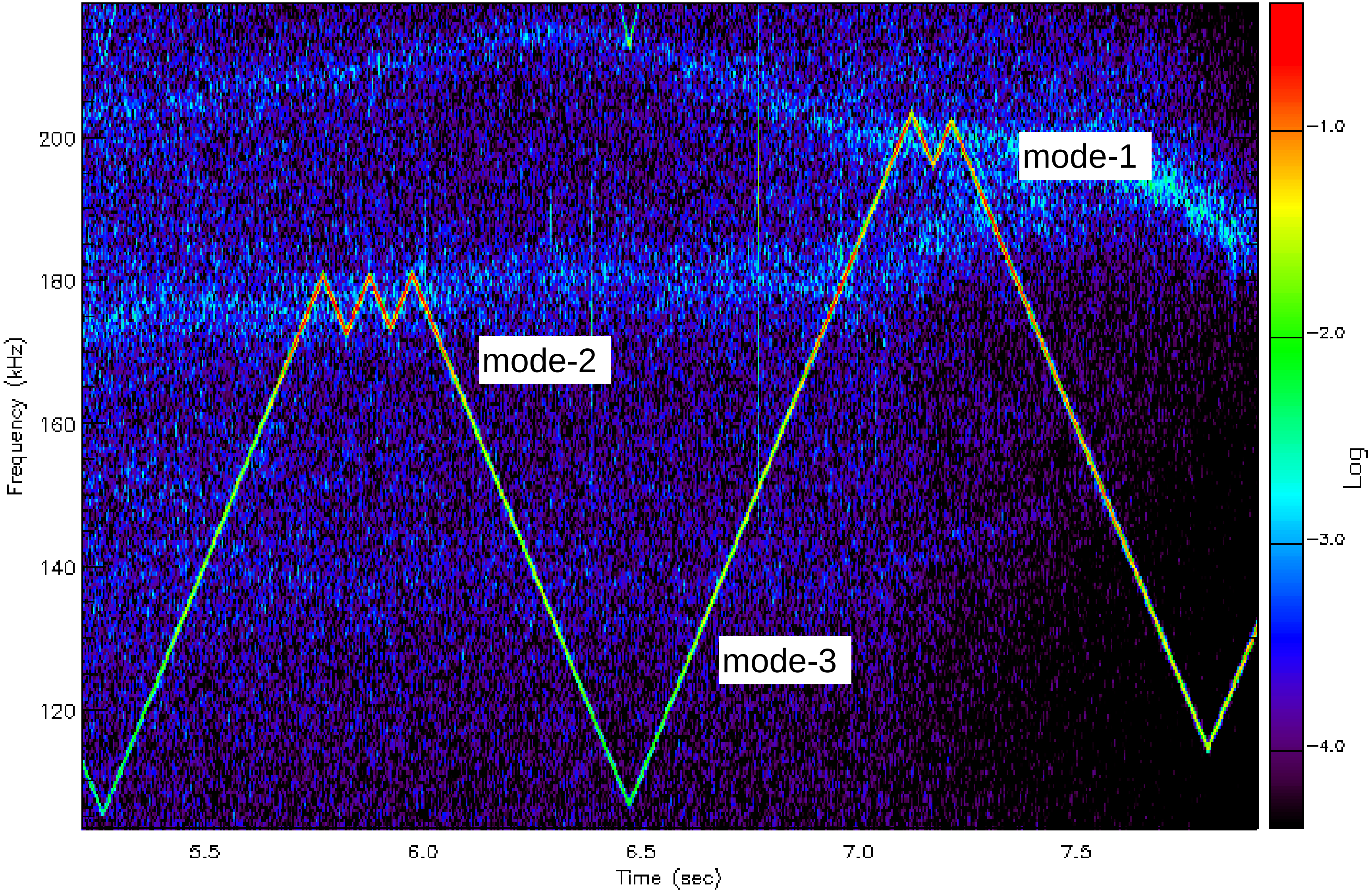
damping rate vs. edge elongation κ_{95}

ideas & possibilities for comparison experiments vs. theory

- establish operational scenarios for systematic comparisons theory vs. experiments:
  - clear separation of γ/ω for individual n's ➔ OK
  - *internal mode structures* ➔ *not yet*
- construct n-specific damping rate databases to provide pure experimental scalings
  - possibly in conjunction with other devices equipped with active MHD systems, e.g. C-Mod, MAST, LHD,…

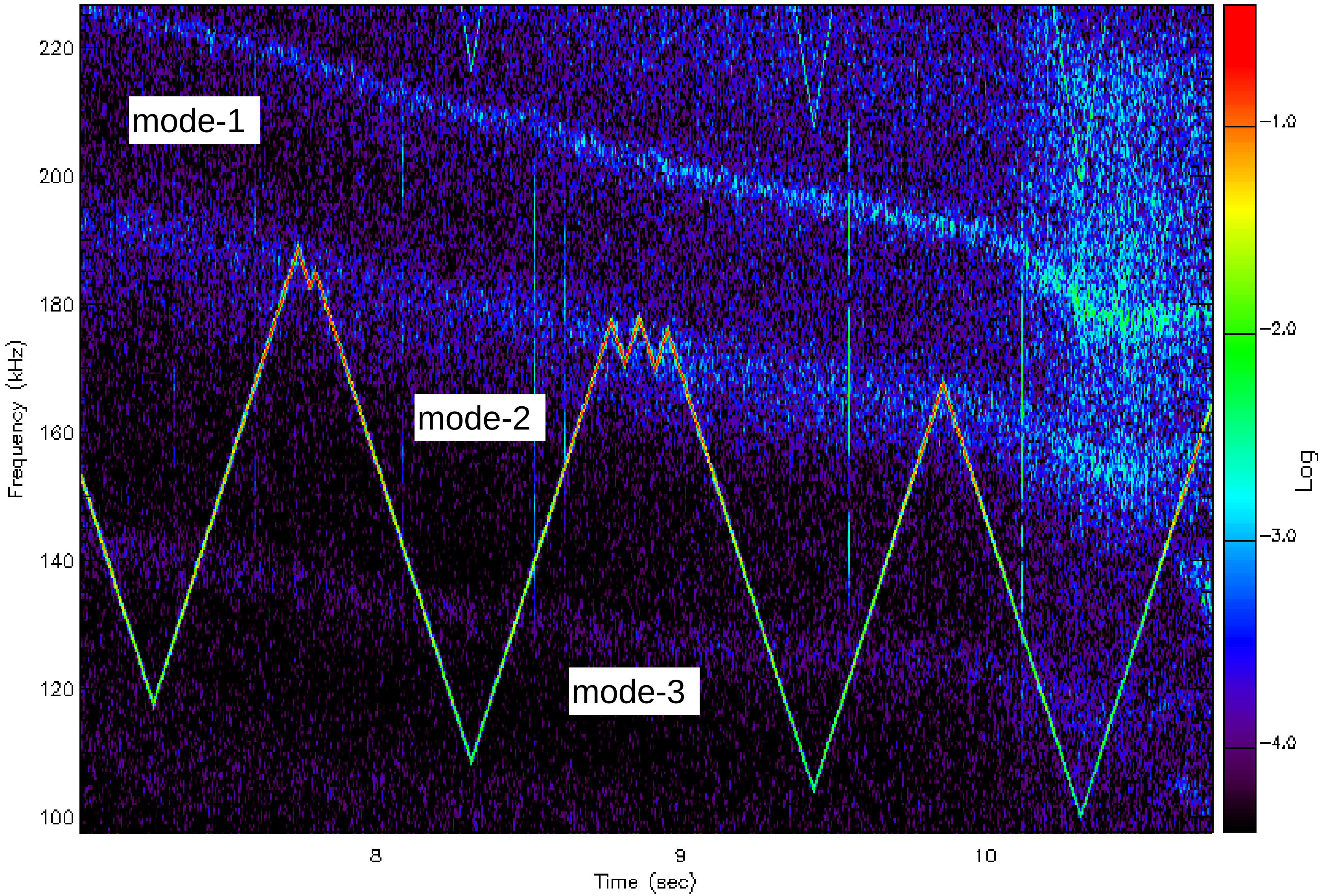
1. **can theory confirm the existence of the same (multiple) modes we find in the AE gaps?**
2. **for the (multiple) modes we detect in the AE gaps, can theory get the measured n's and γ/ω?**
3. **…**

experiments vs. theory: test example 1



- n and γ/ω clearly determined when antenna locks onto background turbulence band
- otherwise turbulence band is multi-harmonics ➔ no definite n’s are found

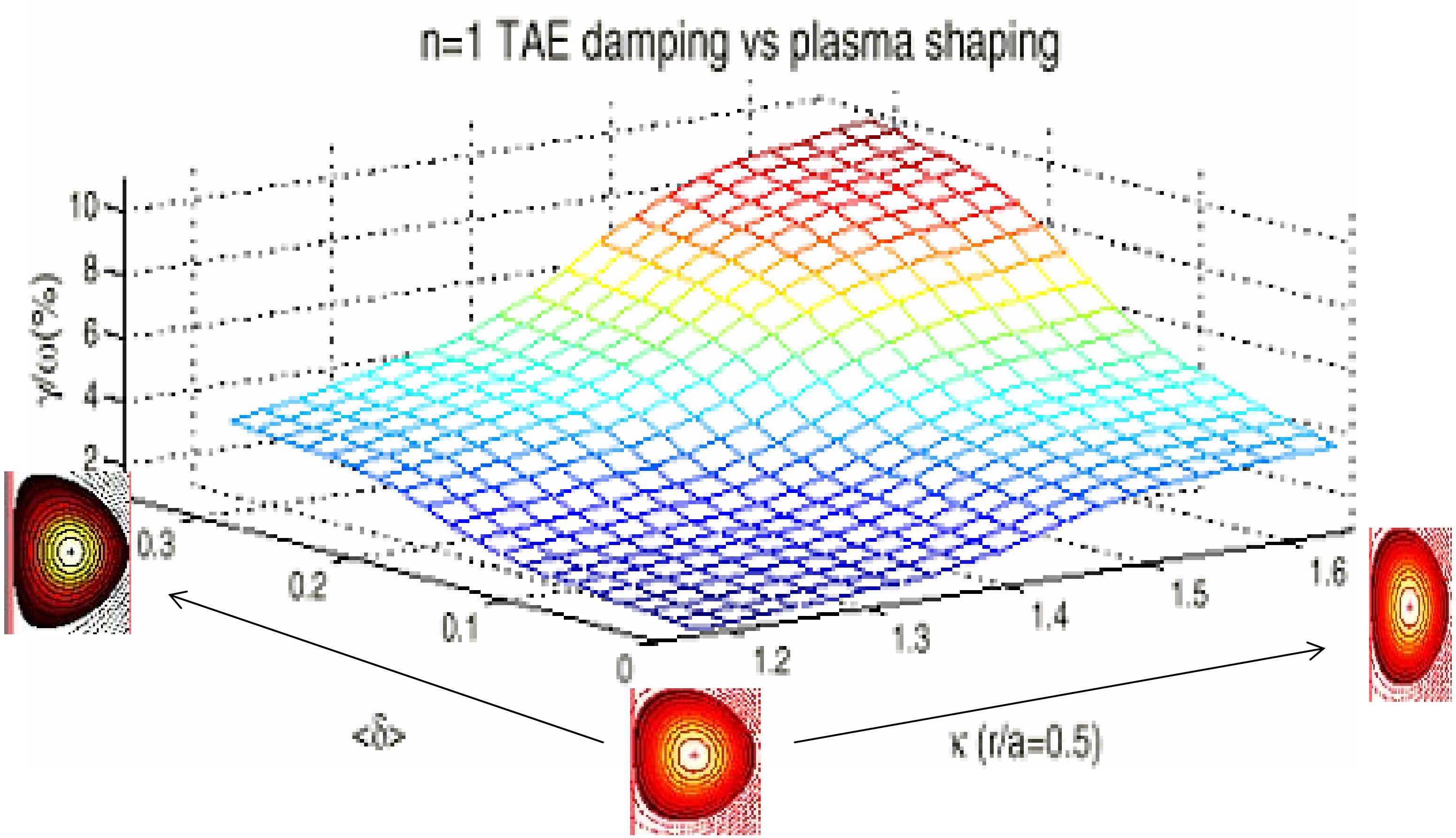
experiments vs. theory: test example 2



- n and γ/ω clearly determined when antenna locks onto background turbulence band
- otherwise turbulence band is multi-harmonics ➔ no definite n's are found

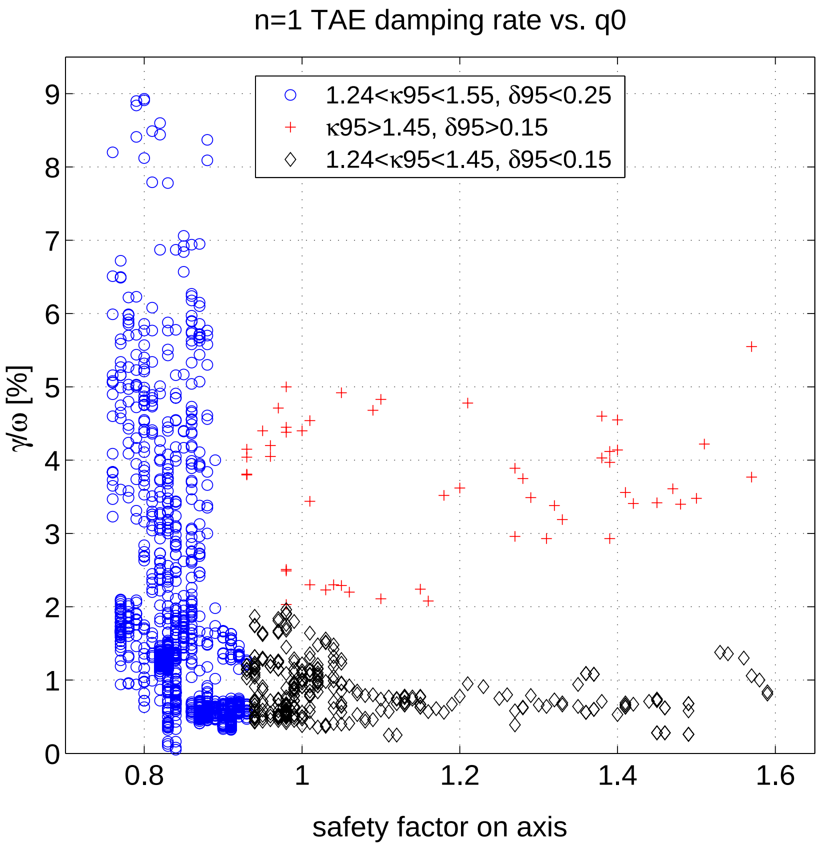
thank you for your attention!

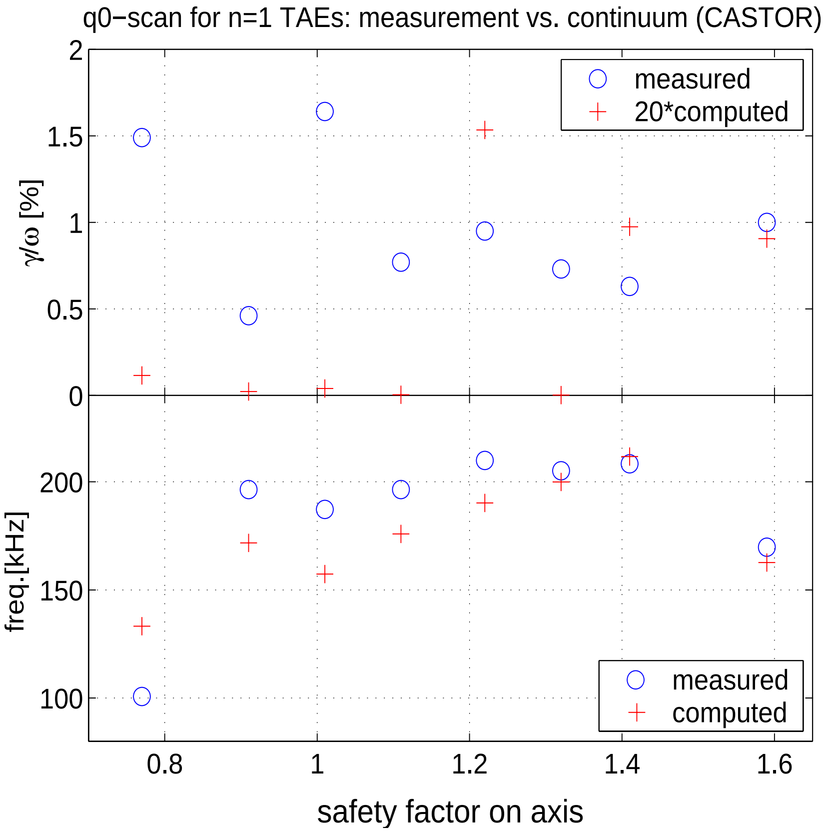
low-n AEs: experimental evidence for role of edge damping mechanisms



- shaping of edge flux surfaces ➔ increased edge magnetic shear ➔ increased mode conversion ➔ stronger damping
- quantitative agreement with gyro-kinetic code PENN
- also consistent with observed P_{NBI} threshold for excitation of medium-n AEs

experimental evidence for low-n AE core damping mechanisms: γ/ω vs. q_0





- about 1500 measurement points for n=1 TAE damping rate vs. q_0~0.76-1.6
  - background plasma: $2.5<q_{95}<4.75$; $1.24<\kappa_{95}<1.55$; $0<\delta_{95}<0.25$; $1.35<n_{e0}(10^{19}m^{-3})<4.2$; $n_{e95}/n_{e0}=0.1$; $1.1<T_{e0}(keV)<5.6$; $T_{e95}/T_{e0}=0.1$; [Ti~Te]
- **clear transition for q_0~1 not reproduced by continuum γ/ω in CASTOR**

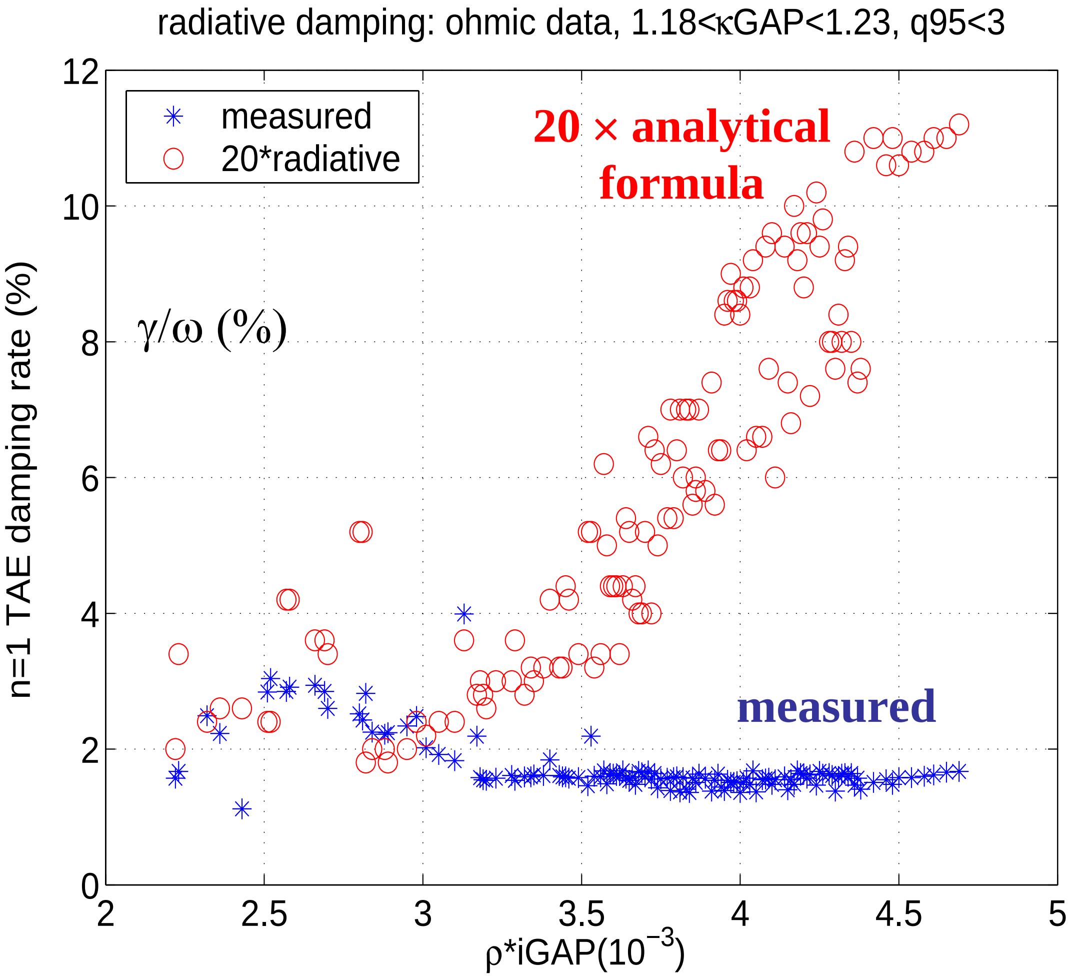
further evidence for low-n AE damping mechanisms in the core: γ/ω vs. ρ_i

- radiative damping mechanism in the plasma core

$$\left(\gamma/\omega\right)_{RAD} = \frac{\pi^2}{8}\varepsilon_m\sigma^2 \times \exp\left(-\frac{\pi^3\sigma^2}{2^{7/2}\lambda}\right)$$

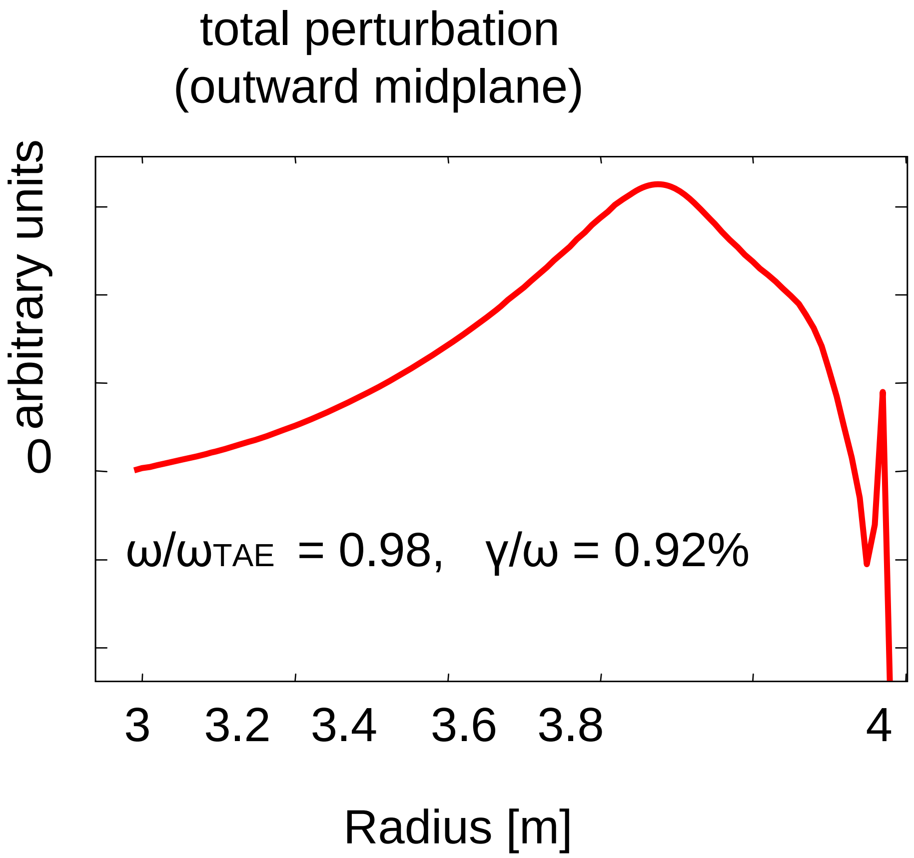
$$\lambda = 4\frac{m\sigma}{r\varepsilon_m^{3/2}}\left(\frac{3}{4}+\frac{T_e}{T_i}\right)^{1/2}\rho_i$$

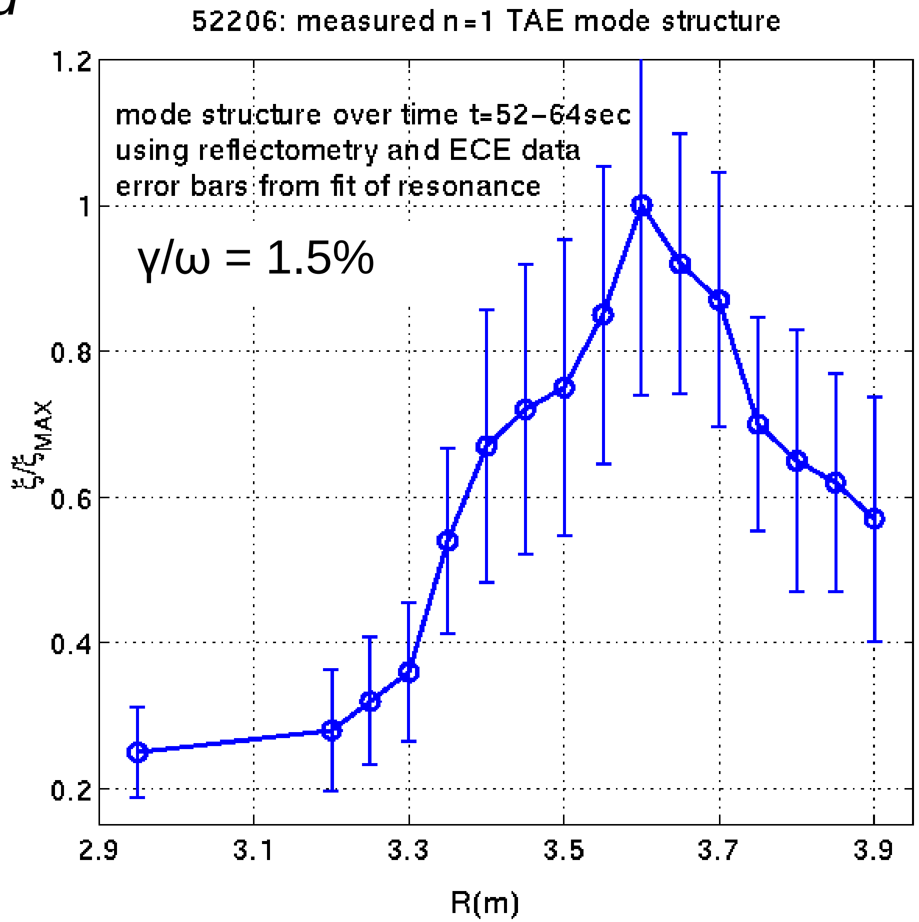
- experimental test:
  - scan |B| to change ρ_{*i} at fixed q_{95} and edge shape (low edge shear)
- analytical approximation:
  - wrong value and scaling
- NOVA-K results:
  - including ion and electron Landau damping, collisional and trapped electrons damping, radiative damping, ...
- **correct frequency but much too small damping (x20 for el. Landau, x100 for radiative)**
- **wrong scaling vs. ρ_i**



results from LIGKA: low-n comparison with JET data, eigenfunction and γ/ω

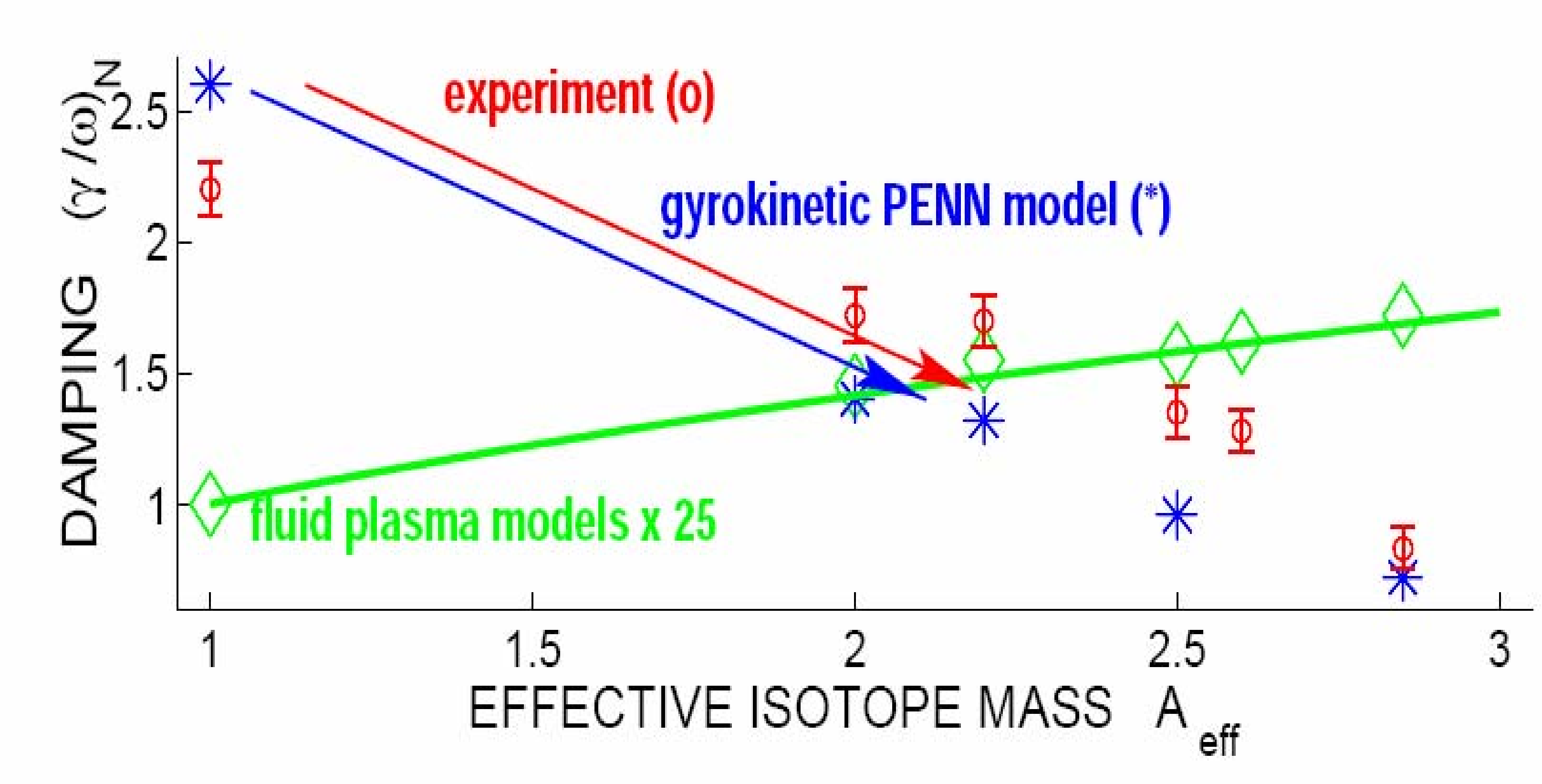
- gyrokinetic code LIGKA reproduces measured eigenfunction and damping rate within 50%
  - *but only one single case tested*





core damping mechanism: mode conversion to KAWs in a region of low magnetic shear

- scaling of damping rate vs. plasma mass not reproduced by fluid models
  - mass scaling OK with kinetic and hybrid models

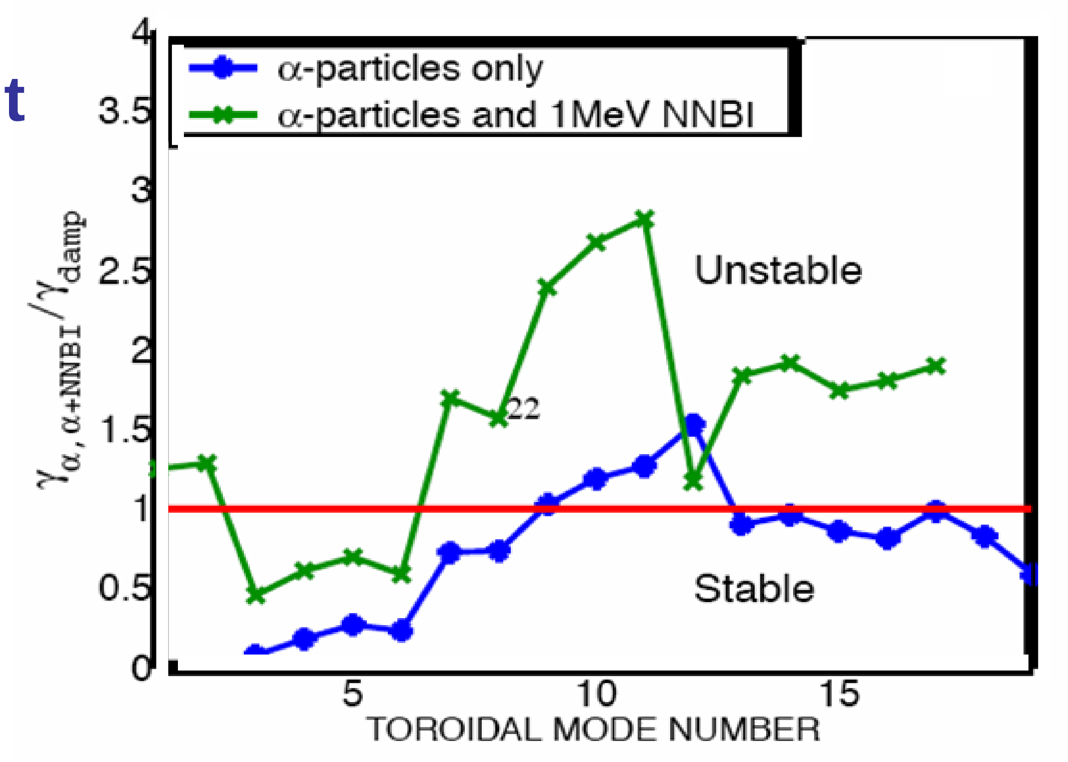


predictions of AE linear stability for ITER

- predictions on TAE stability in ITER baseline H-mode scenario with $\beta_\alpha(0)$~1% (NOVA-K code)
- **the crucial toroidal mode number range is n~5-15**

predictions on damping need to be improved and validated in ITER-relevant intermediate n range

N.Gorelenkov et al., NF 43, 594 (2003)



measurement of γ/ω from resonance fitting

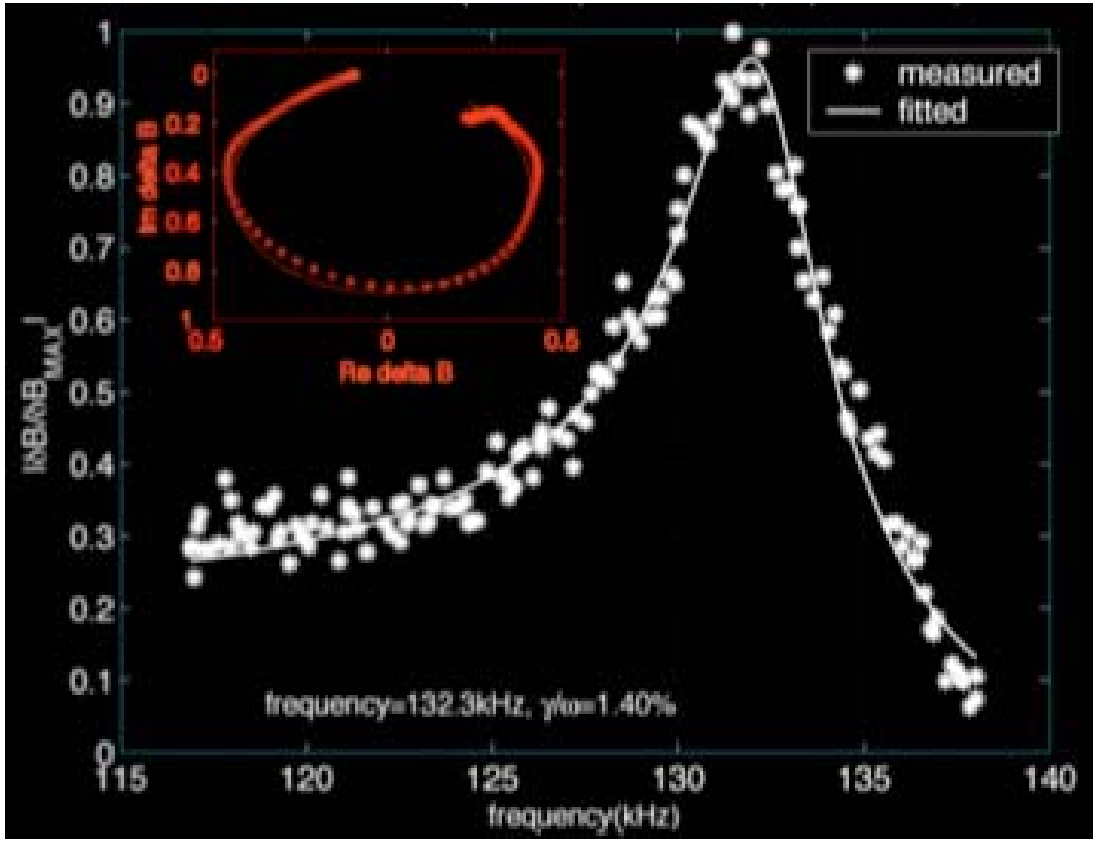
- $H(\omega)$: complex transfer function between antenna current and diagnostic signal
- $H(\omega,x)$ $= \sum_{k=1}^{N} \frac{1}{2}\left(\frac{r_k(x)}{i\omega - p_k} + \frac{r_k^*(x)}{i\omega - p_k^*} \right) + D(\omega,x)$ $= \frac{B(\omega,x)}{A(i\omega)}$

- Global mode

$\Leftrightarrow$Resonance

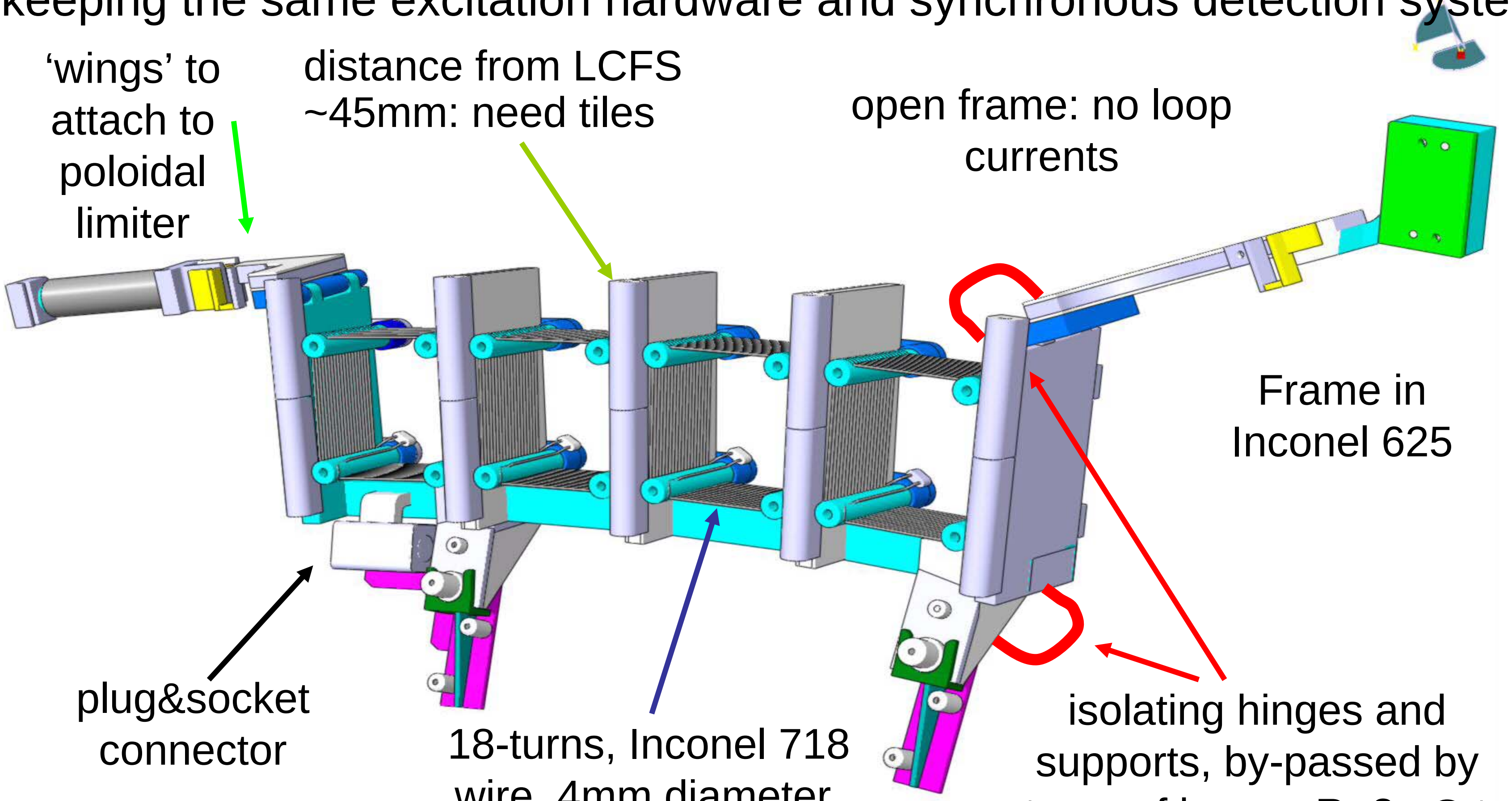
$\Leftrightarrow$pole $p_k = i\omega_k + \gamma_k$

- Ex. of TAE resonance
- |H| vs.frequency and in complex plane



active MHD antennas on JET: new antennas foir medium-n excitation

- two 4-coils antenna systems on octant 4 and octant 8
- fully compatible with remote handling installation
- keeping the same excitation hardware and synchronous detection system



‘wings’ to attach to poloidal limiter

distance from LCFS ~45mm: need tiles

open frame: no loop currents

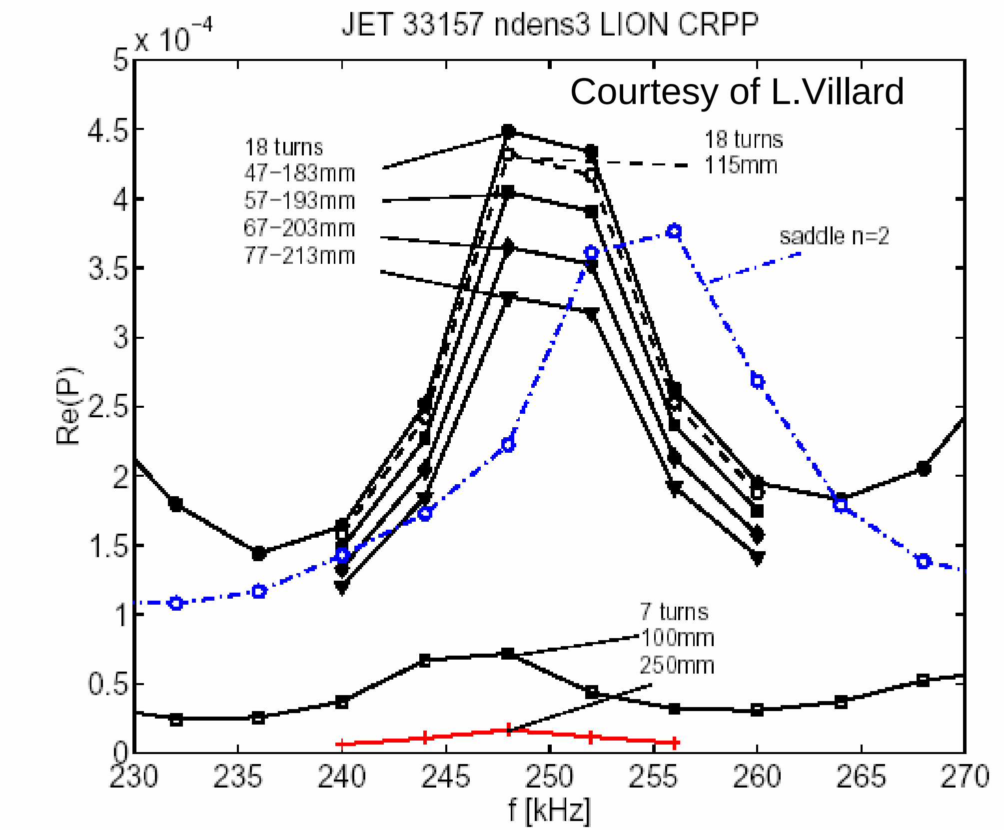
Frame in Inconel 625

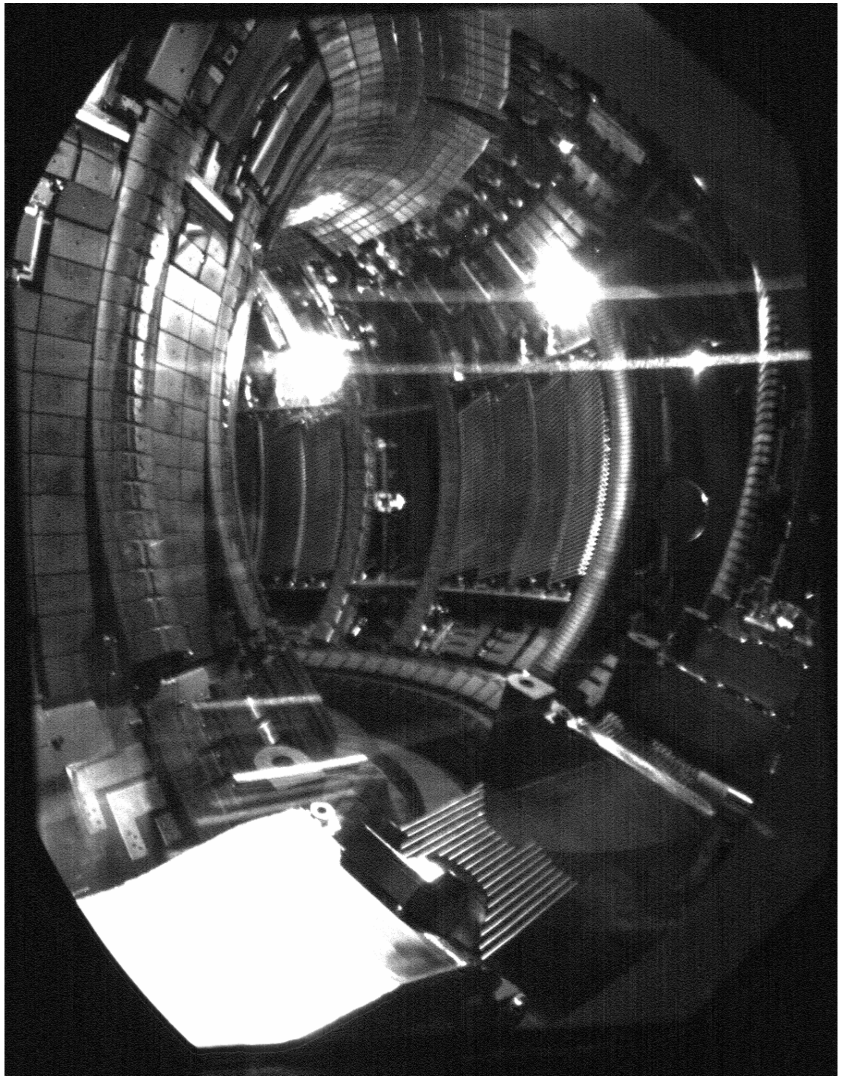
plug&socket connector

18-turns, Inconel 718 wire, 4mm diameter, 4mm spacing

isolating hinges and supports, by-passed by straps of known R~3mΩ to balance halo currents

new JET active MHD antennas distance from plasma and coupling

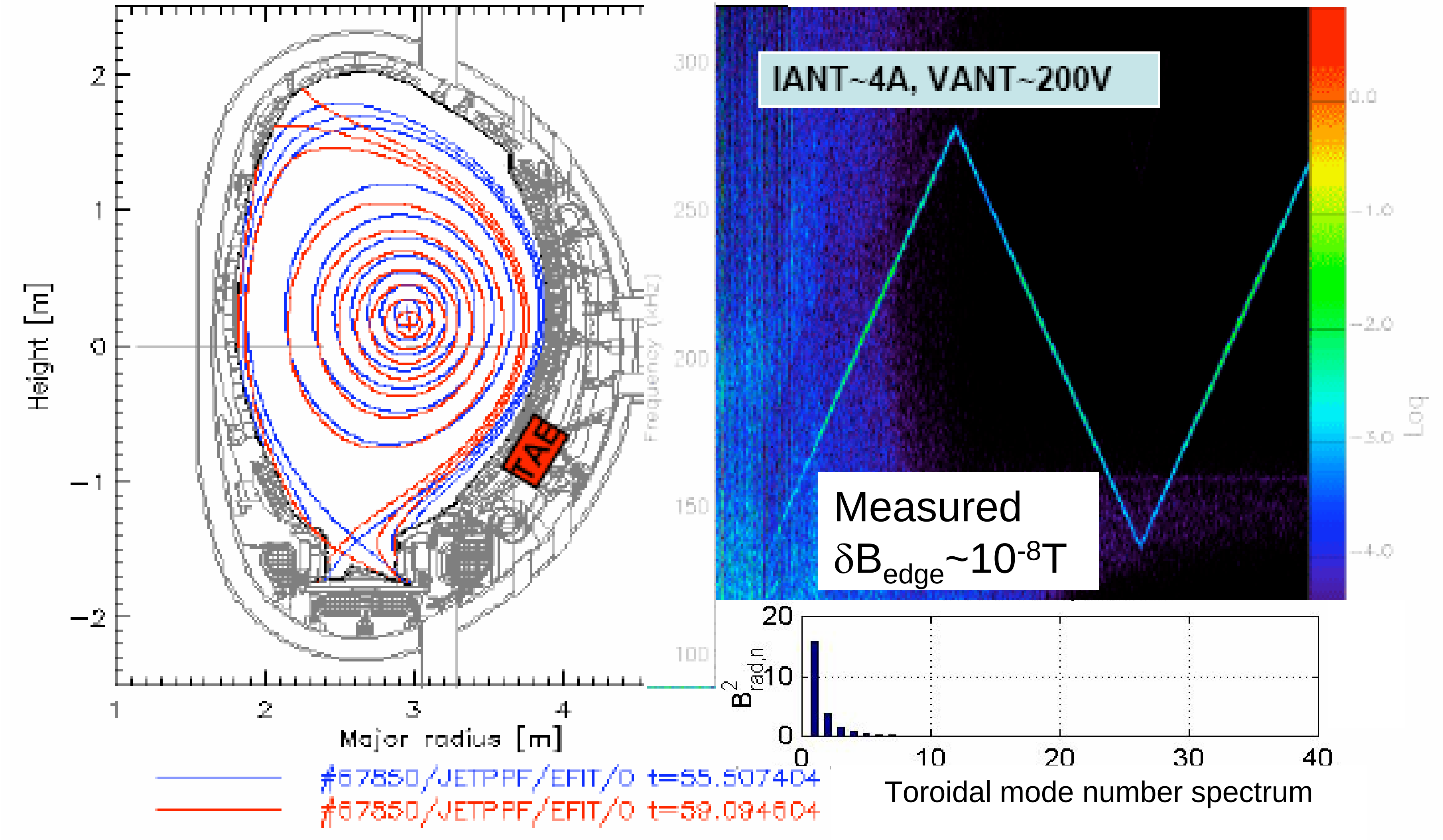




- distance from LCFS: 45mm
  - coupling for n=5 expected to be similar to that of n=2 by saddle coils
  - at surface δB_{max}~1G

antenna phasing and measured coupling -1

low-n configuration: + + + +

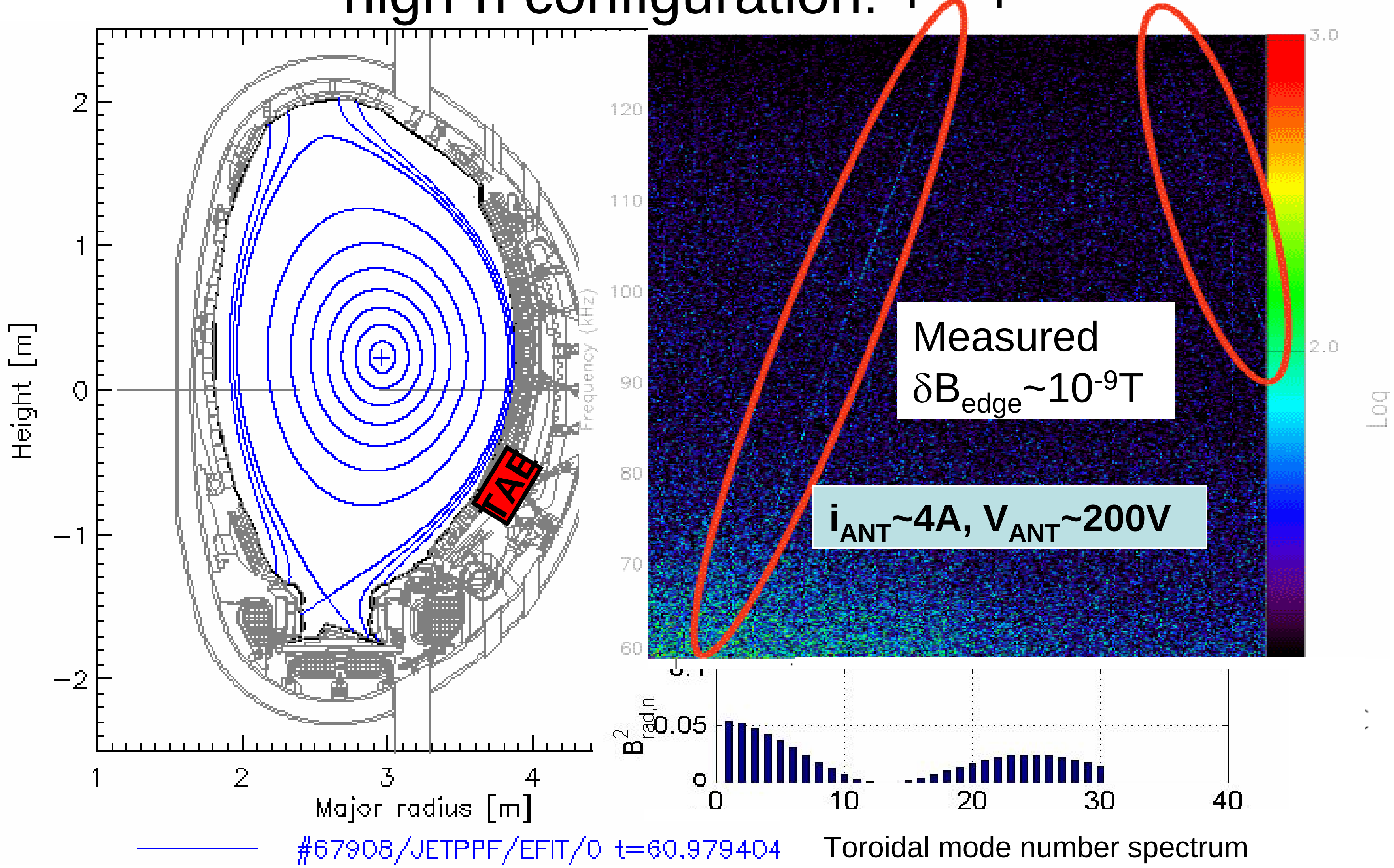


IANT~4A, VANT~200V

Measured δB_{edge}~10^{-8}T

antenna phasing and measured coupling -2

high-n configuration: + - + -

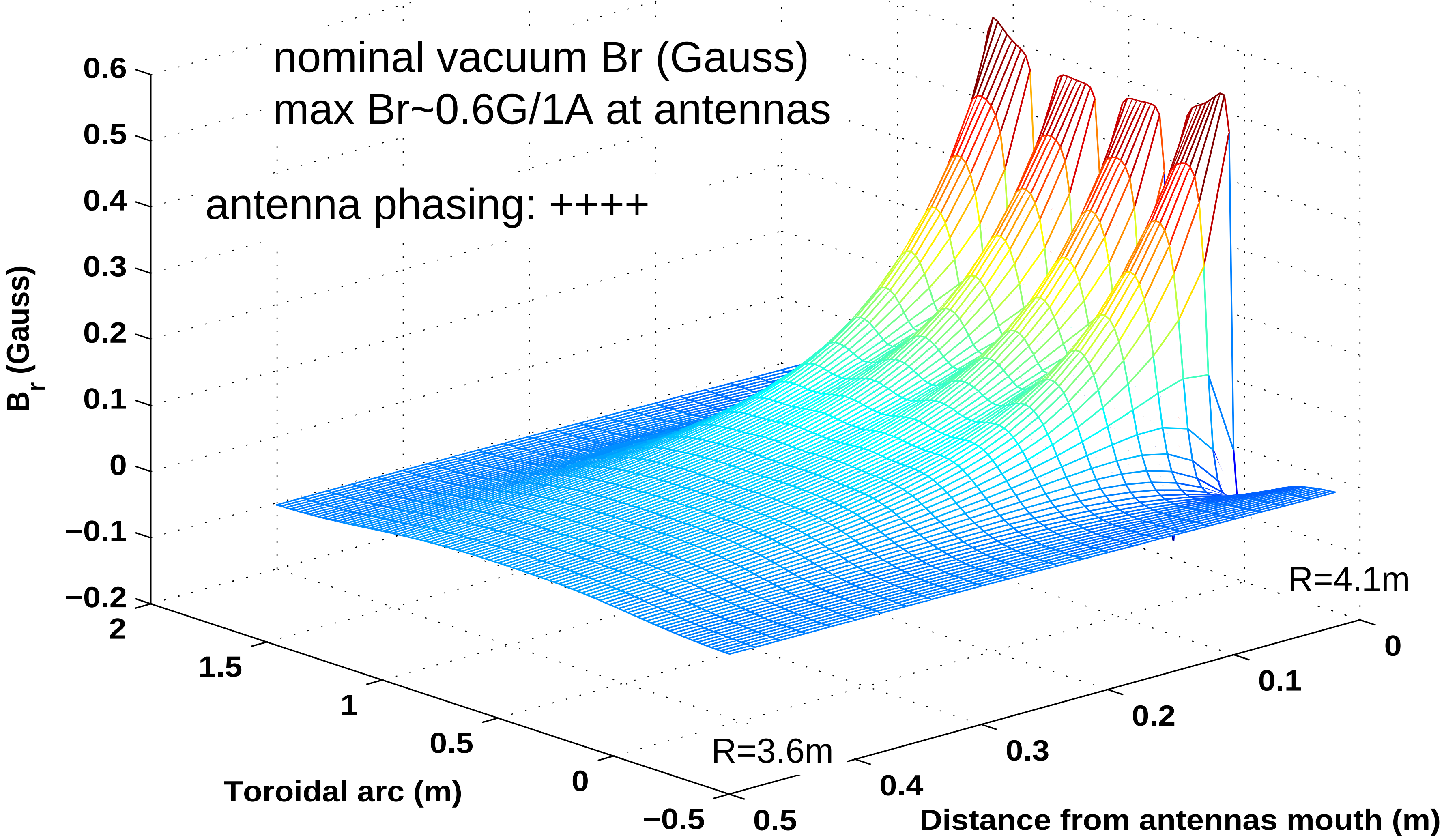


Measured δB_{edge}~10^{-9}T

i_{ANT}~4A, V_{ANT}~200V

Toroidal mode number spectrum

calculation of vacuum field produced by four neighboring antennas

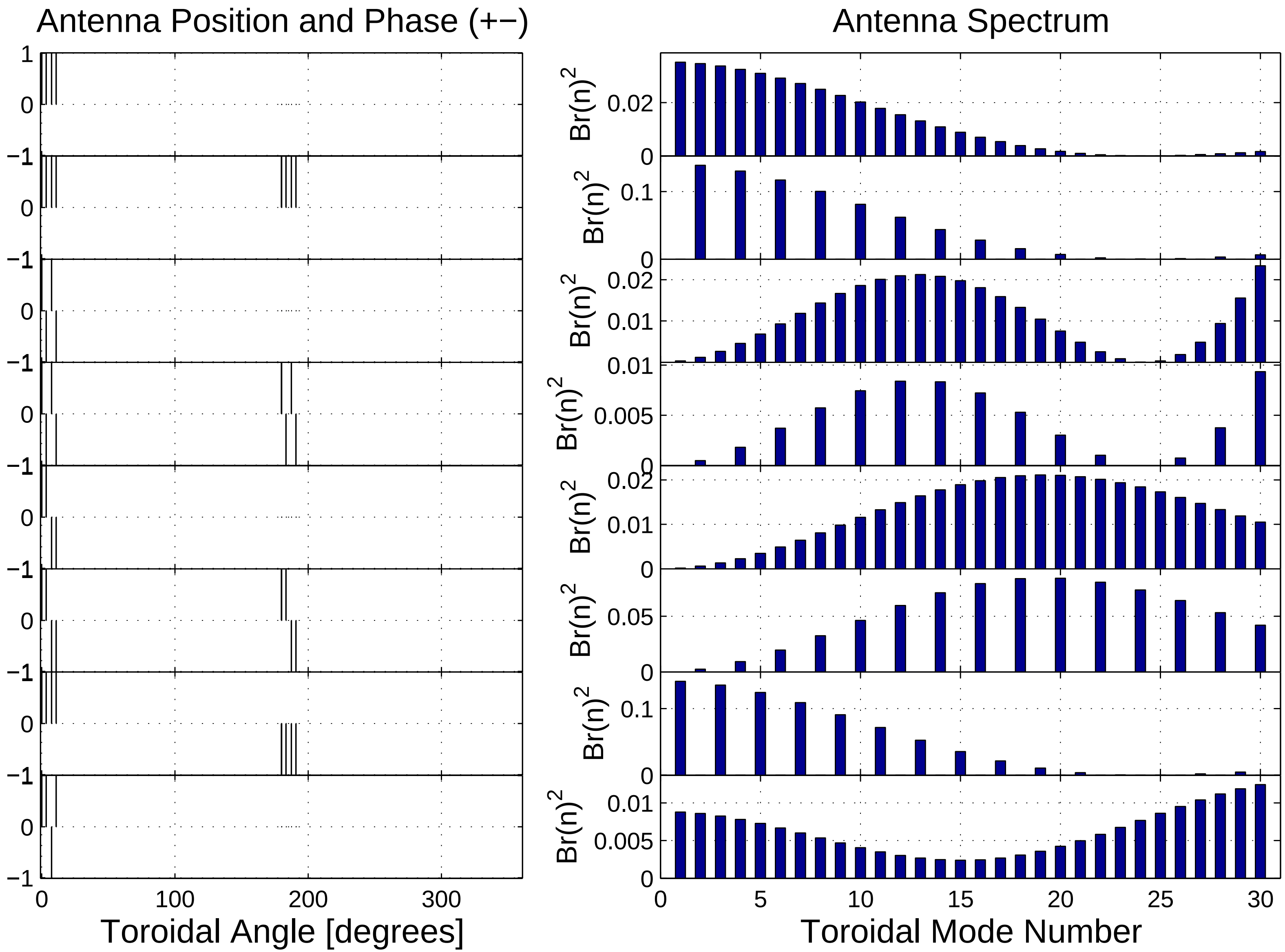

nominal vacuum Br (Gauss)
max Br~0.6G/1A at antennas

antenna phasing: ++++

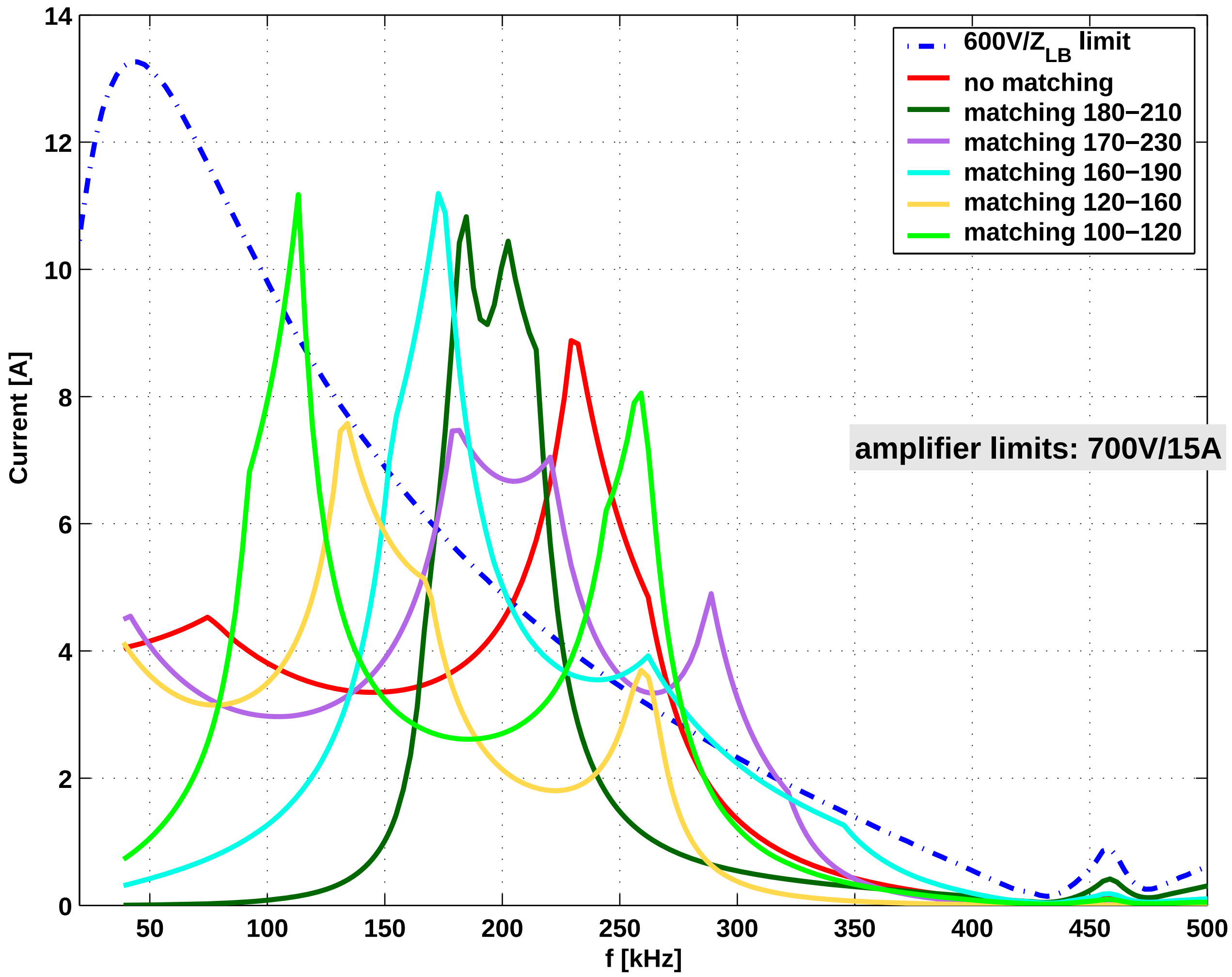
R=4.1m

R=3.6m

nominal vacuum spectrum: 4 vs. 8 antennas

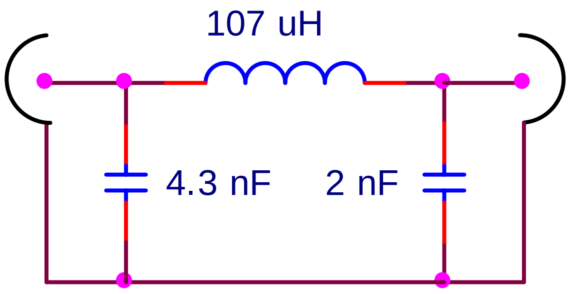


improving antenna currents using discrete band matching networks



Ex. of matching circuit

180–210 kHz band



the SparSpec* method

- Finding the solution with the sparsest spectrum on a **discrete frequency grid**
- Minimizing criteria:

$$\boxed{J(x) = {}^{1}\!/_{2}\left\|\mathbf{y} - W\mathbf{x}\right\|^{2} + \frac{\lambda}{\lambda_{Max}} \sum_{k=-K}^{K} \left|x_k\right|}$$

$\mathbf{y} = \{y_1, y_2 \ldots y_K\}^T$ = vector of data taken at ~~time~~ t_k, position ϕ_k

$\mathbf{W}$ = $K \times 2N+1$ matrix with elements $W_{n,k}$ = ~~exp(i 2 π~~ $t_k f_n$) exp(i 2 π $\phi_k n$),

mode numbers

$\mathbf{x} = \{x_{-n}, \ldots x_n\}^T$ = vector of complex amplitudes associated with ~~frequencies~~ f_n, n = -N…N.

λ = parameter fixed to obtain a satisfactory sparse solution (penalty for invoking more modes)

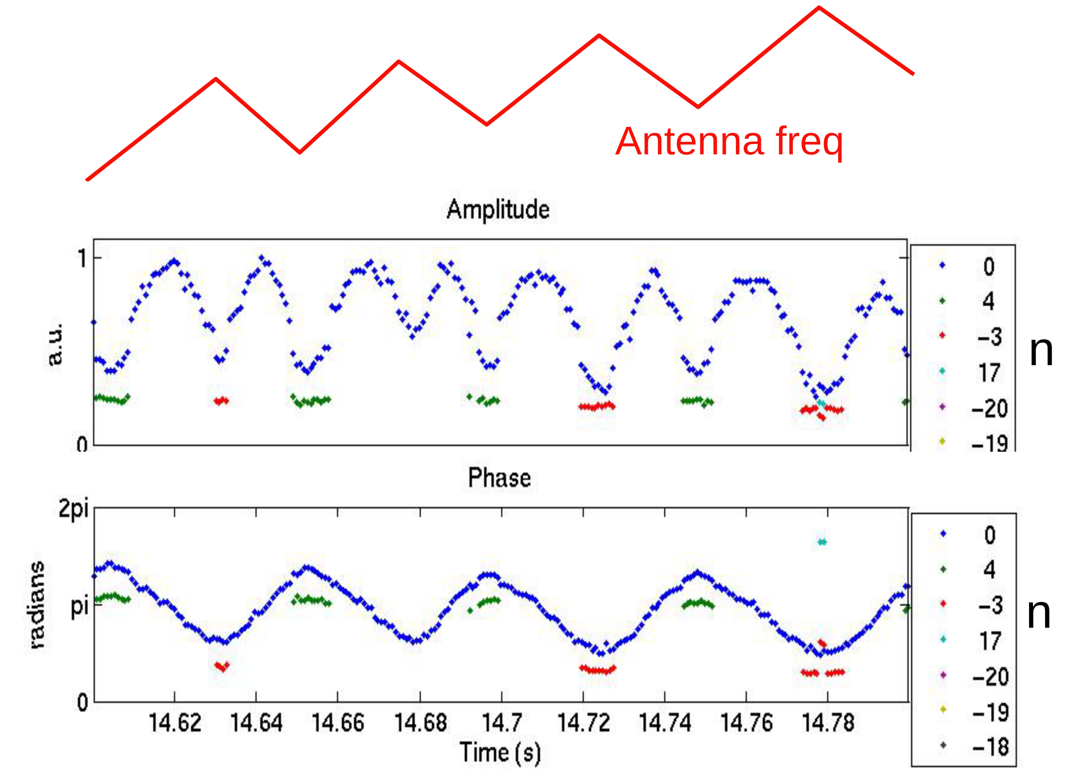
⇒ Convex criterion, with no local minima

⇒ BCD algorithm quickly finds solution

* S.Bourguignon, H.Carfantan, T.Böhm, Astronomy and Astrophysics **462** (2007) 379: **"SparSpec: A New Method for fitting multiple sinusoids with irregularly sampled data"**, http://www.ast.obs-mip.fr/Softwares

AE tracking based on SparSpec method

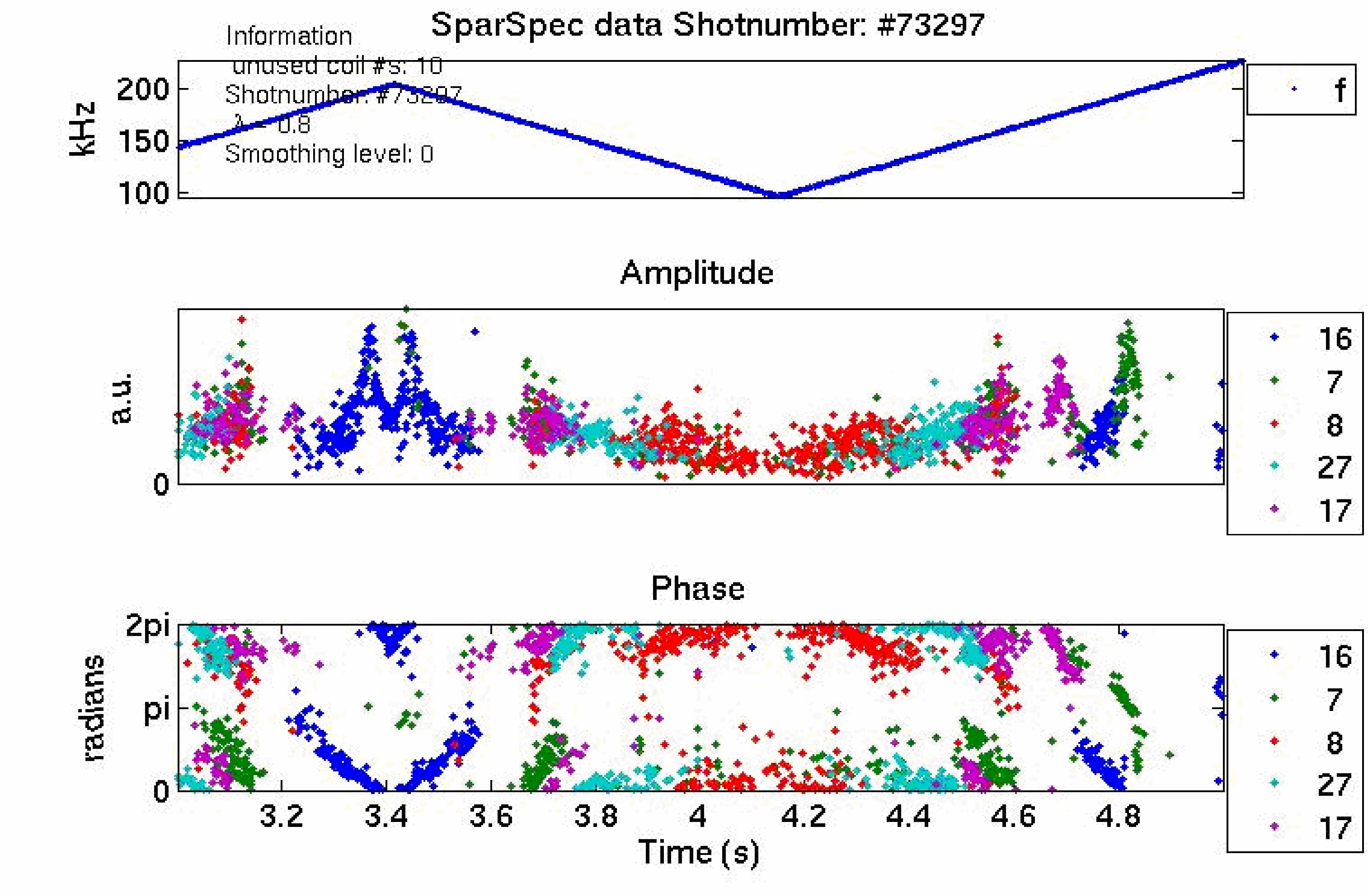
- Tracking algorithm locks on n=0,1, ignoring/missing n=2,3,4,…
- Resonance detection and tracking: requires 1ms loop rate
- 8 synch signals used in AELM
- SparSpec calculation <1msec
  - SparSpec module already in C code, same as AELM
- Can target specific n's
- Can be set to ignore n<2



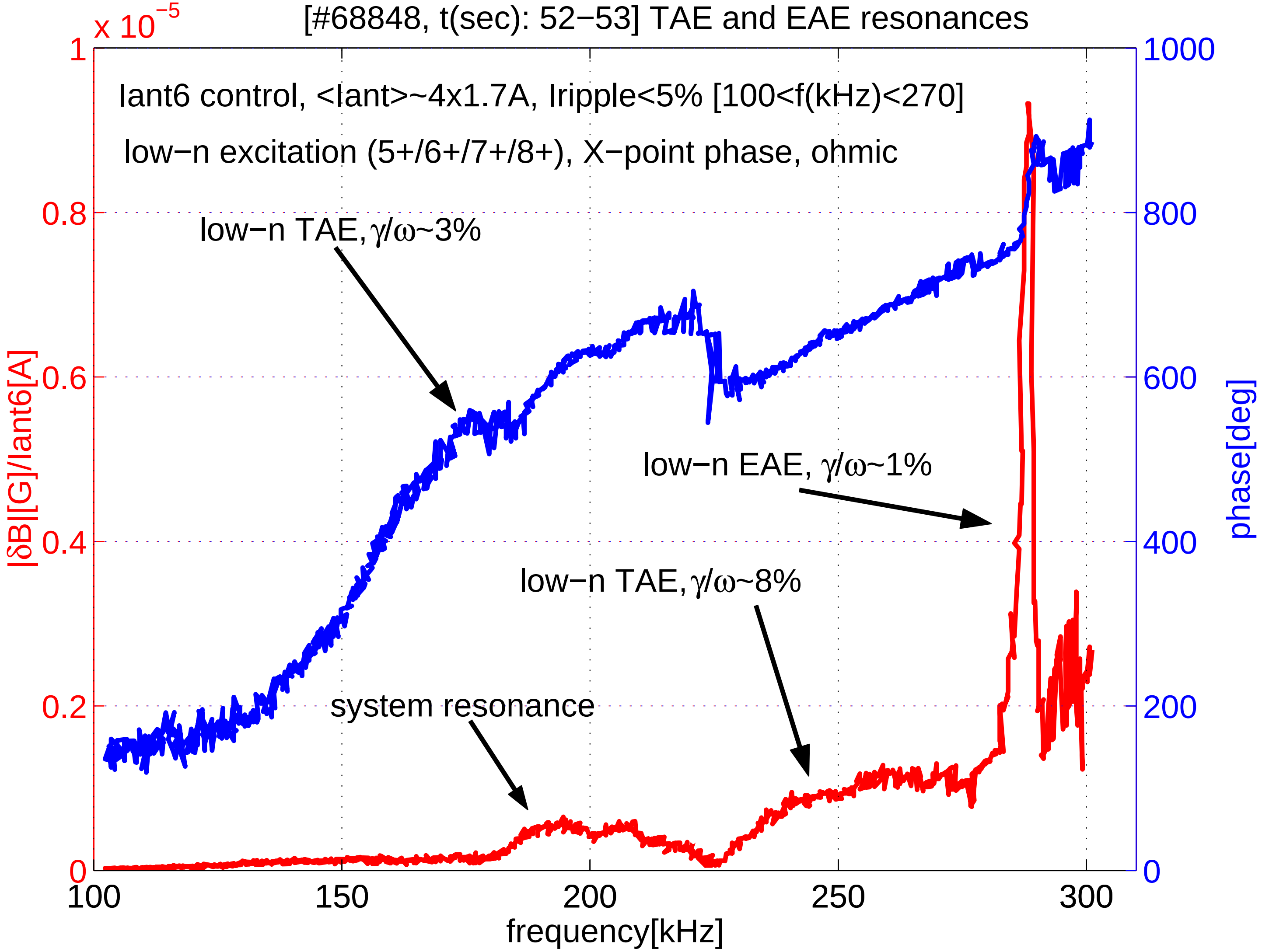
Typical scenario: tracking on n = 0 mode: before medium n resonance is fully explored, antenna frequency turns around

n-number analysis using SparSpec demonstrates excitation of high-n AEs

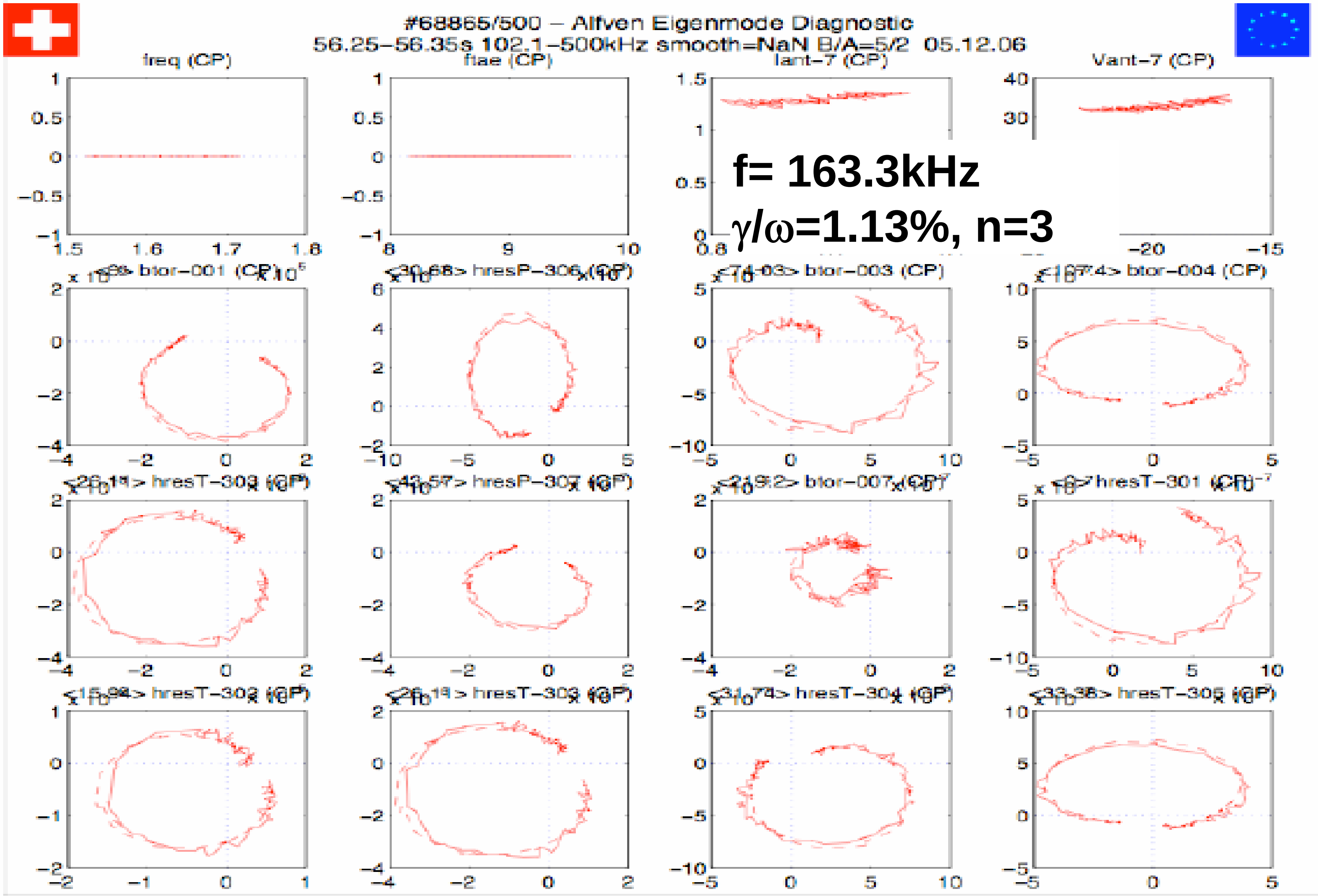
- low-n modes completely absent from detected B-spectrum
- concurrent measurement of γ/ω for n=7, n=8 and n=16 TAEs



first damping rate measurements with the new medium-n AE antennas



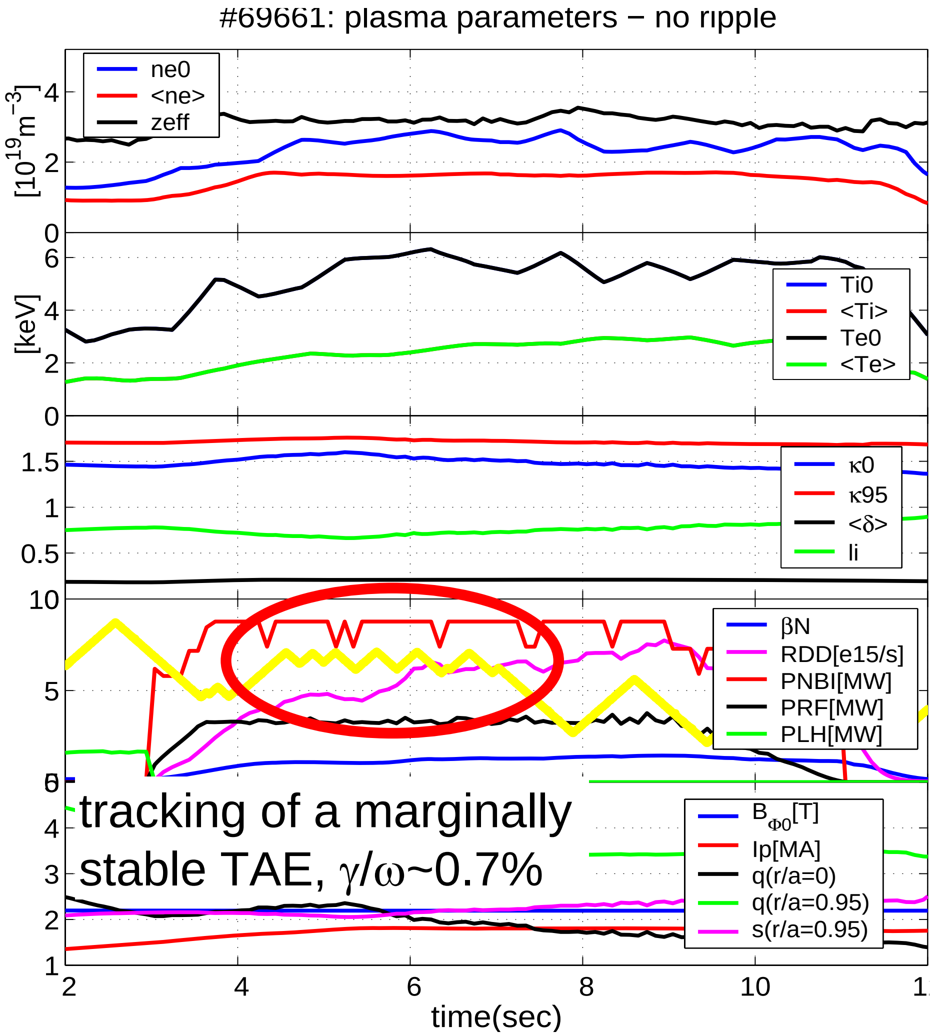
first antenna driven medium-n AEs



f= 163.3kHz

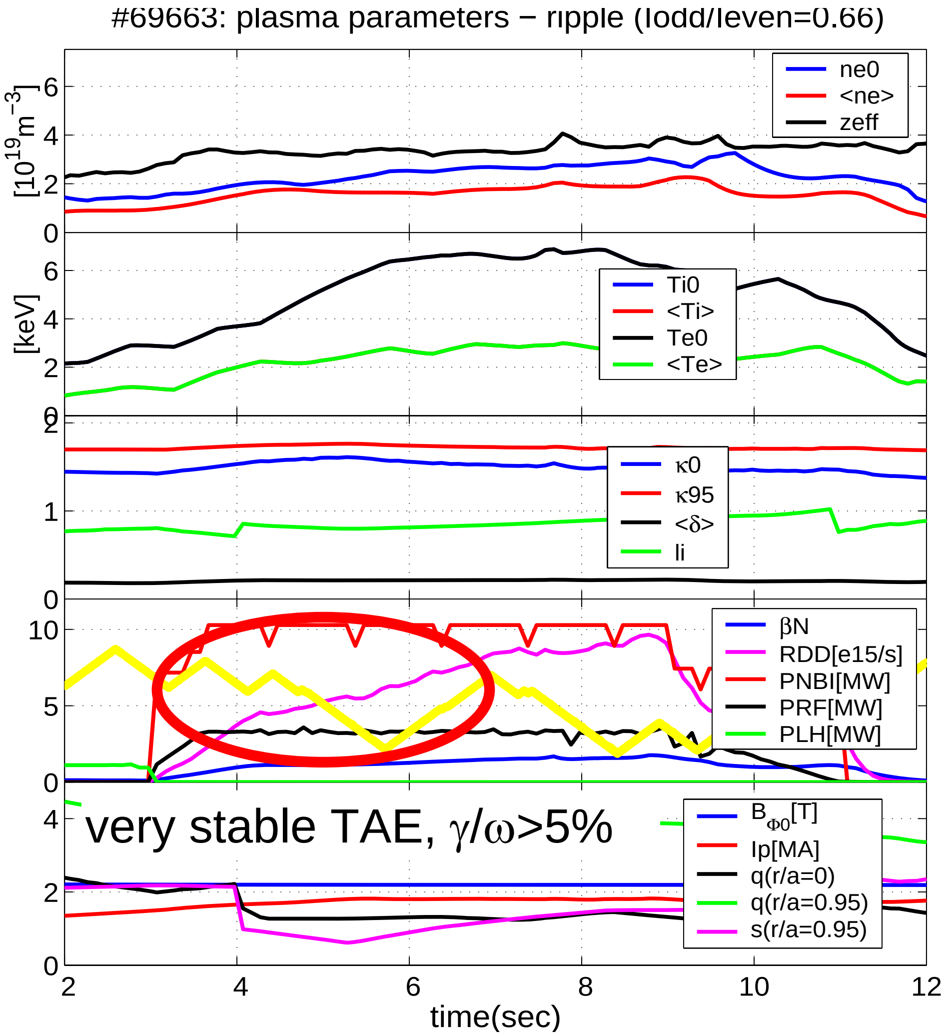
γ/ω=1.13%, n=3

effect of magnetic field ripple on medium-n AE damping (1)



#69661: plasma parameters − no ripple

tracking of a marginally stable TAE, γ/ω~0.7%

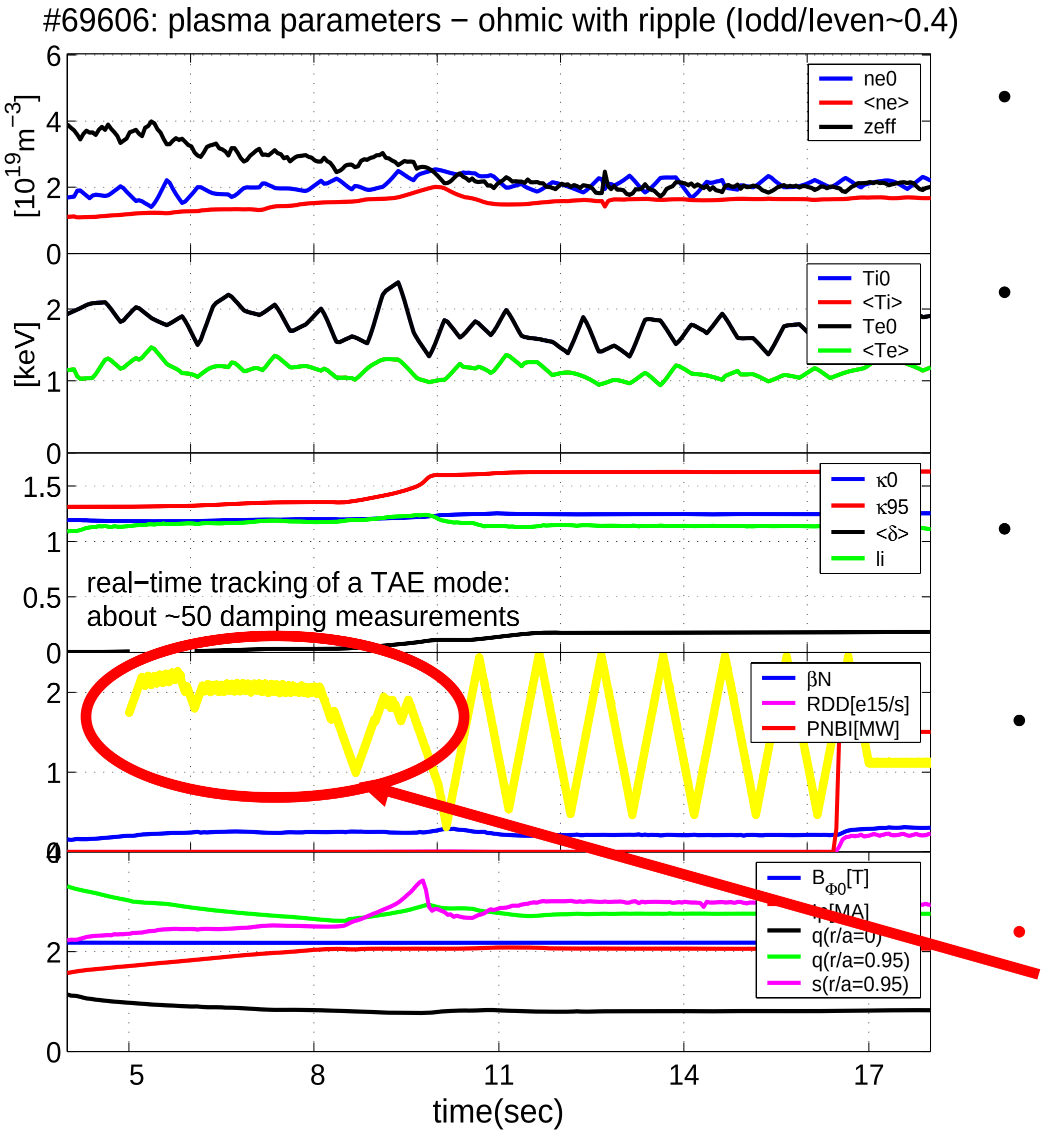


#69663: plasma parameters − ripple (Iodd/Ieven=0.66)

very stable TAE, γ/ω>5%

- antenna configuration: 5+/6-/7-/8+, I_{ANT}~4A-peak (total), excitation of medium-n modes
- clear effect ripple in the magnetic field on fast ion drive

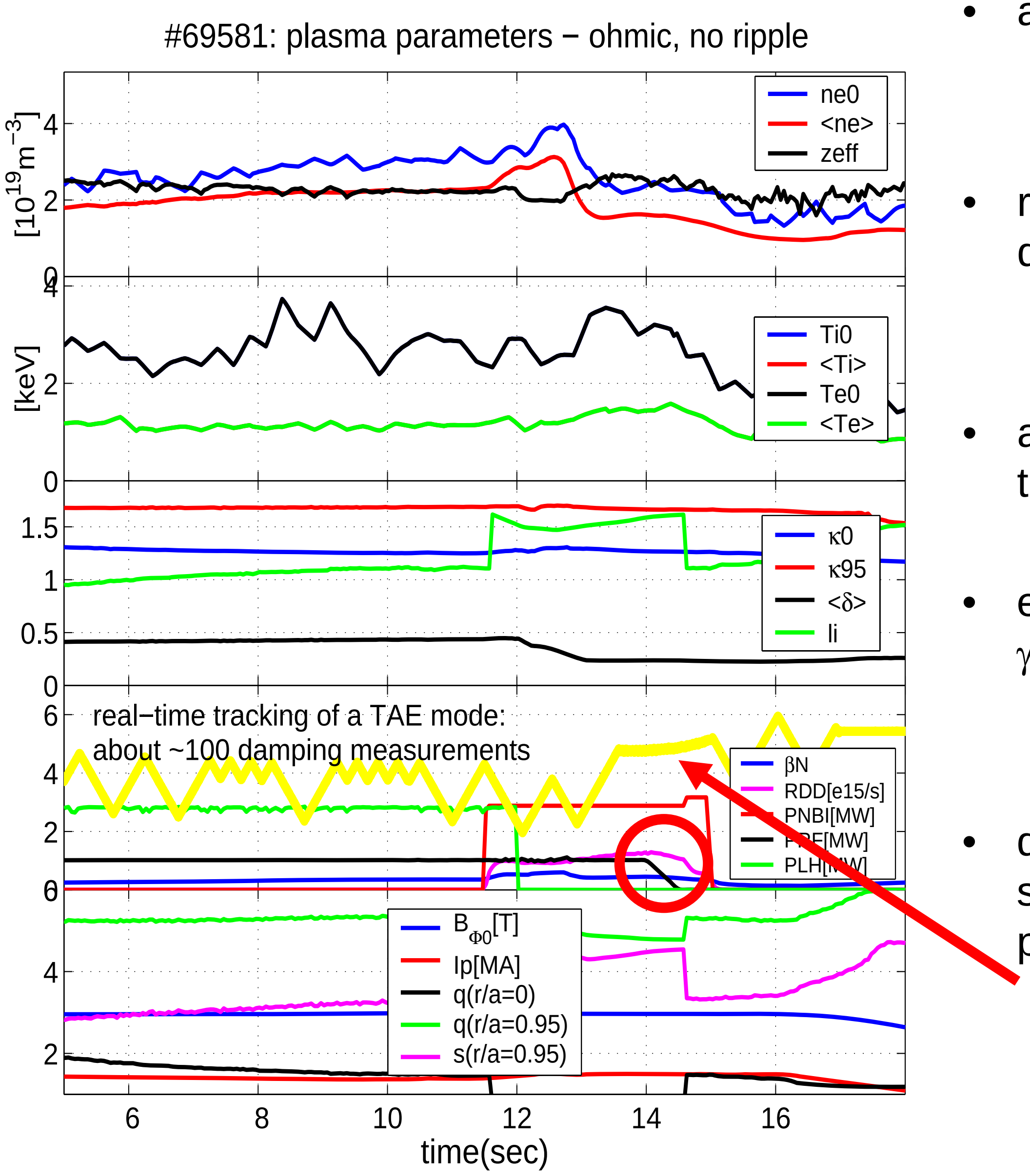
effect of magnetic field ripple on medium-n AE damping (2)



- antenna configuration: 5+/6-/7-/8+
  - antenna current ~4A-peak (total)
  - excitation of medium-n modes, driven |δB| spectrum peaks around n~10+/-5
- real-time tracking of a medium-n TAE during ohmic and heating phase
  - some uncertainties in mode number determination, to be resolved using recent re-calibration of pick-up coils
- about 50 damping rate data obtained in this single shot!

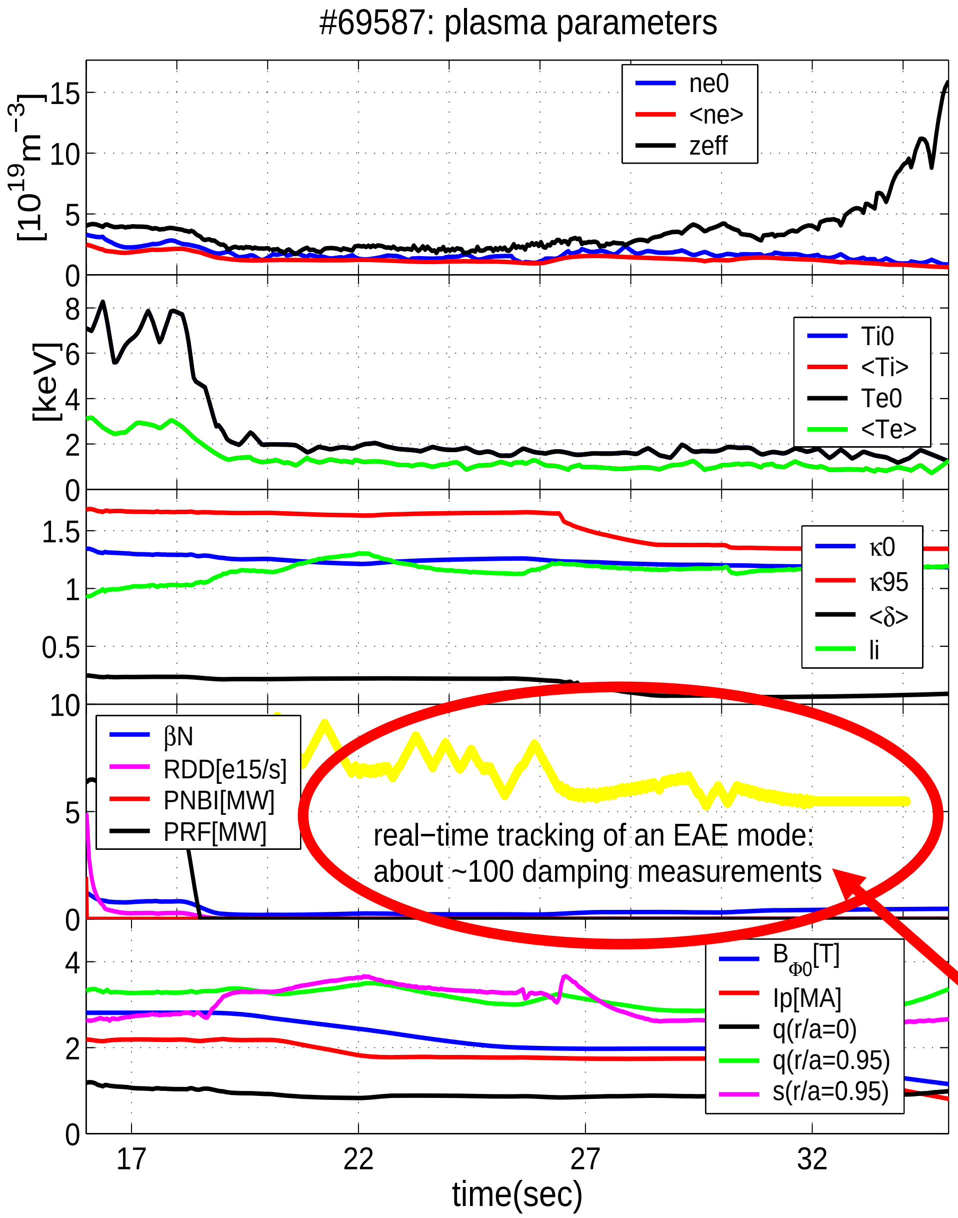
- estimated damping rate in ohmic phase is γ/ω~0.8% with edge elongation κ_{95}~1.35
  - compare with values on similar shot without Bfield ripple (/ω~0.8% with κ_{95}~1.55)
- **similar values of damping rate obtained at lower κ_{95} with Bfield ripple suggest changes in edge continuum**
  - density e-folding length in the SOL?

damping rate vs. ICRF power



- antenna configuration: 5+/6-/7-/8+
  - antenna current ~4A-peak (total)
  - excitation of medium-n modes, driven |δB| spectrum peaks around n~10+/-5
- real-time tracking of a medium-n TAE during ohmic and heating phase
  - some uncertainties in mode number determination, to be resolved using recent re-calibration of pick-up coils
- about 100 damping rate data obtained in this single shot!
- estimated damping rate in ohmic phase is γ/ω~0.8% with edge elongation κ_{95}~1.55
  - compare with values on similar shots with Bfield ripple
- damping rate increases at ICRF power switch off for constant NBI power and plasma parameters
  - direct measurement of the fast ion drive
  - measured γ/ω increases from γ/ω=0.3% (P_{ICRF}=1MW) to γ/ω=0.7% (P_{ICRF}=off)

damping rate data for EAEs



#69587: plasma parameters

real−time tracking of an EAE mode: about ~100 damping measurements

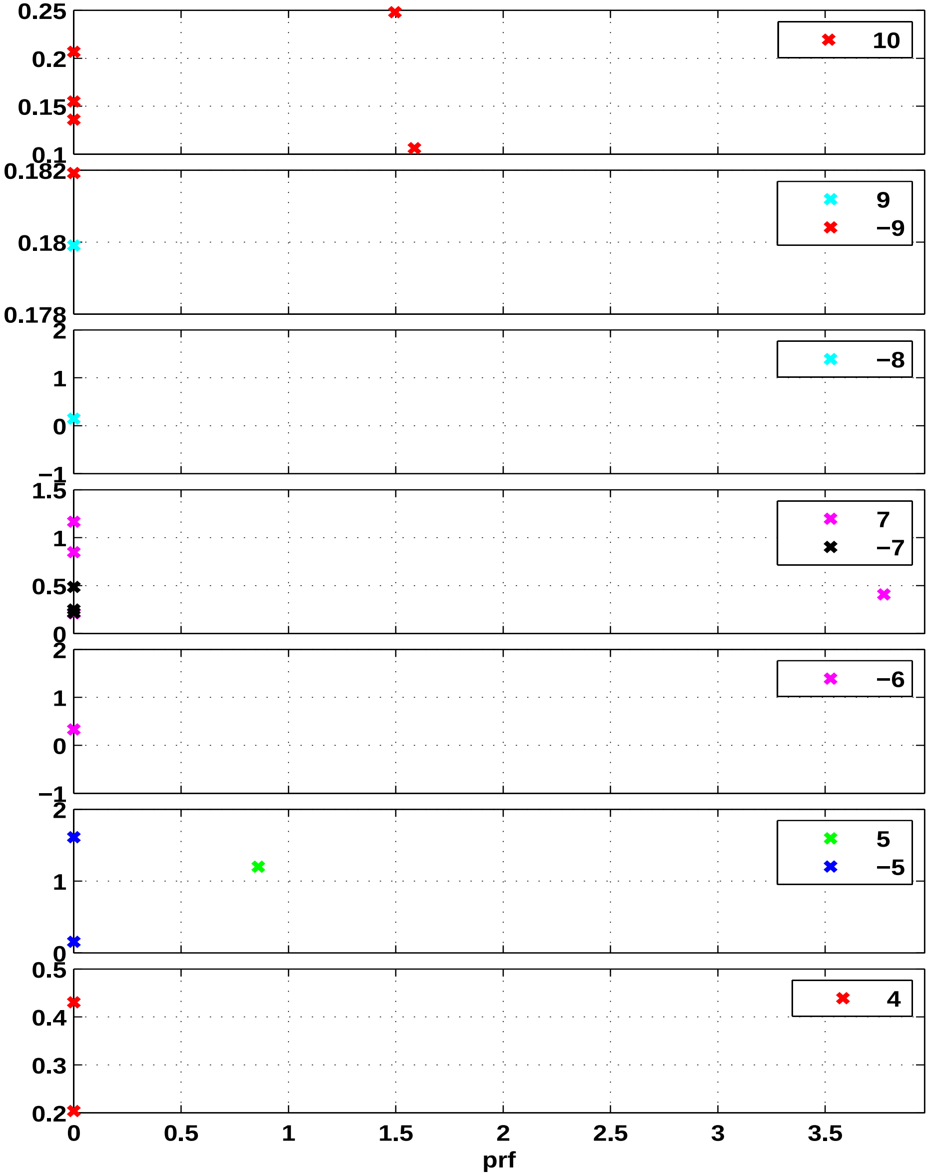
- antenna configuration: 5+/6-/7-/8+
  - antenna current ~1.5A-peak (total)
  - excitation of medium-n modes, driven $|\delta B|$ spectrum peaks around n~10+/-5
- real-time tracking of a medium-n EAE during ohmic phase can be achieved with very little antenna current (<2A in total) for mode excitation because of much lower level of background turbulence (noise) in EAE frequency range
- about 100 damping rate data obtained in this single shot!

- estimated damping rate in ohmic phase is γ/ω~0.5% with edge elongation κ_{95}~1.55
  - need to get some data for EAE on similar shots with Bfield ripple

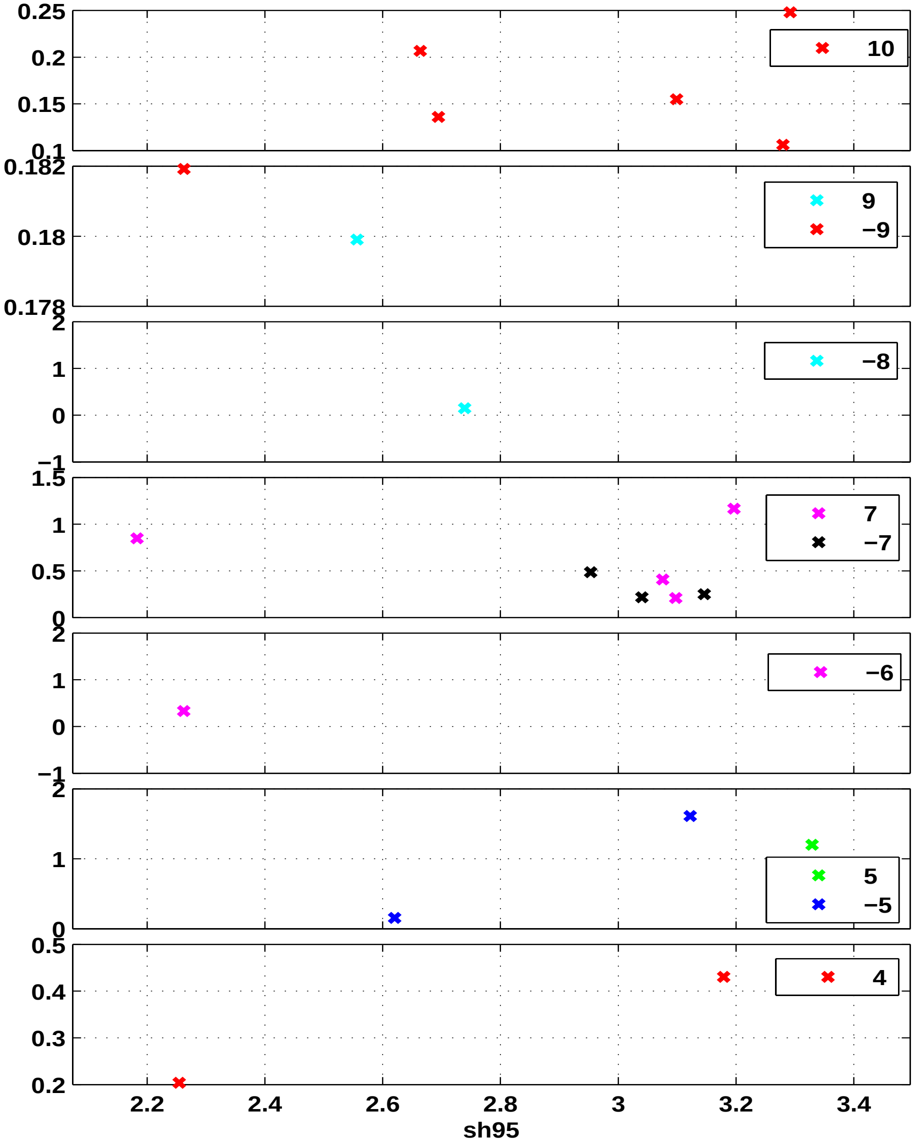
summary of the first results on damping rate measurements for medium-n AEs

- damping rate for medium-n (n=3-7) TAEs as function of edge elongation, with/out PRF (different phasing)
- damping rate for medium-n (n=3-7) TAEs at ICRF power switch off with constant plasma parameters
  - direct measurement of MeV-ions drive to the modes
- effect of ripple in the magnetic field:
  - fast ion losses (resonant NBI ions with $V_{||}$~$V_A/3$), affect drive for the modes (direct evidence)
  - change density scale length at plasma edge, affect the edge continuum (damping mechanism – hypothesis to test theories)
- tracking of marginally stable modes ($\gamma/\omega<0.5\%$) with different n's
  - very seldom observed with previous saddle coil system, driving n=1 modes
  - is this evidence for turbulence energy transfer in the Alfvén frequency range for medium and high-n modes?
- large database (>1000 data points) already being compiled of $\gamma/\omega=$ f(n) as a function of parameters and configurations
  - small differences in T_e, n_e profiles lead to large differences in γ/ω
- *no clear measurements of internal mode structure yet*

γ/ω database vs. plasma parameters

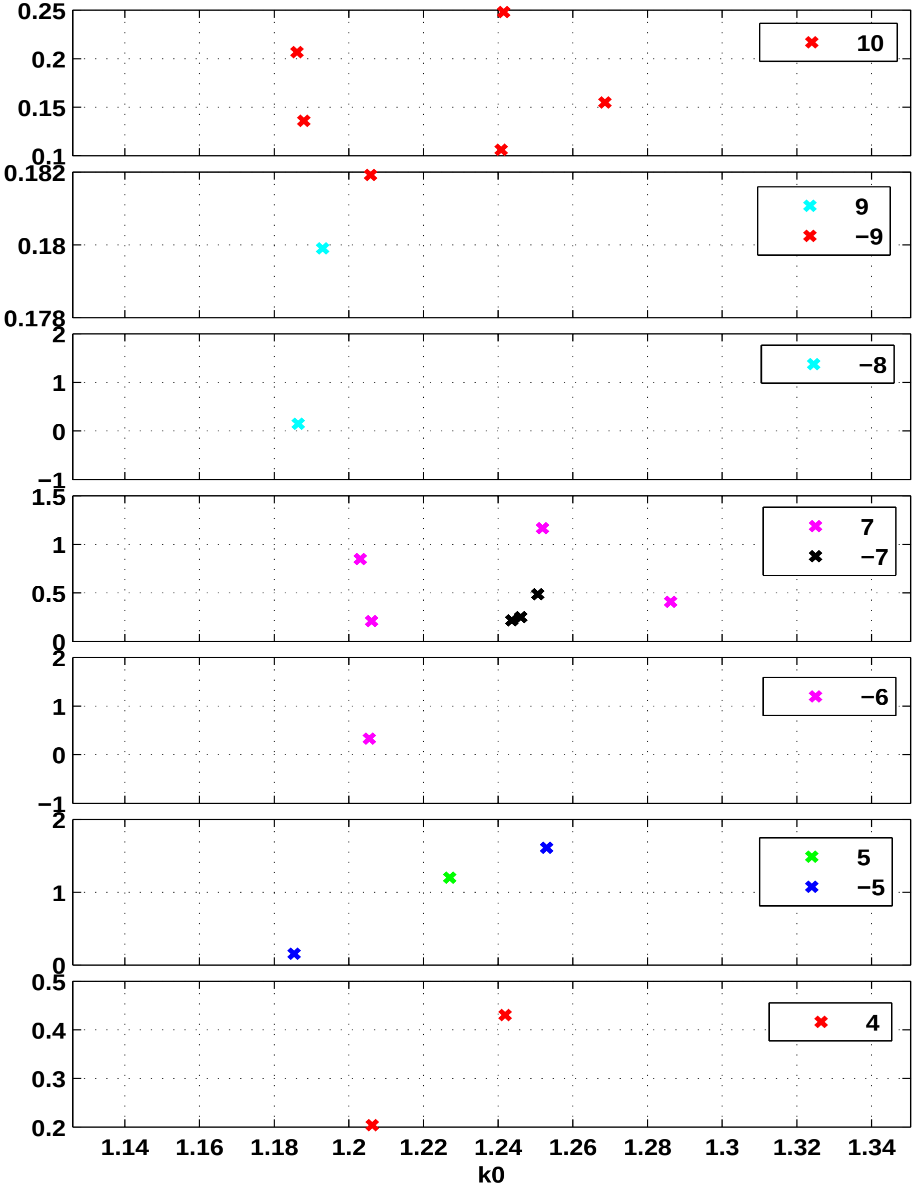


damping rate vs. ICRF power

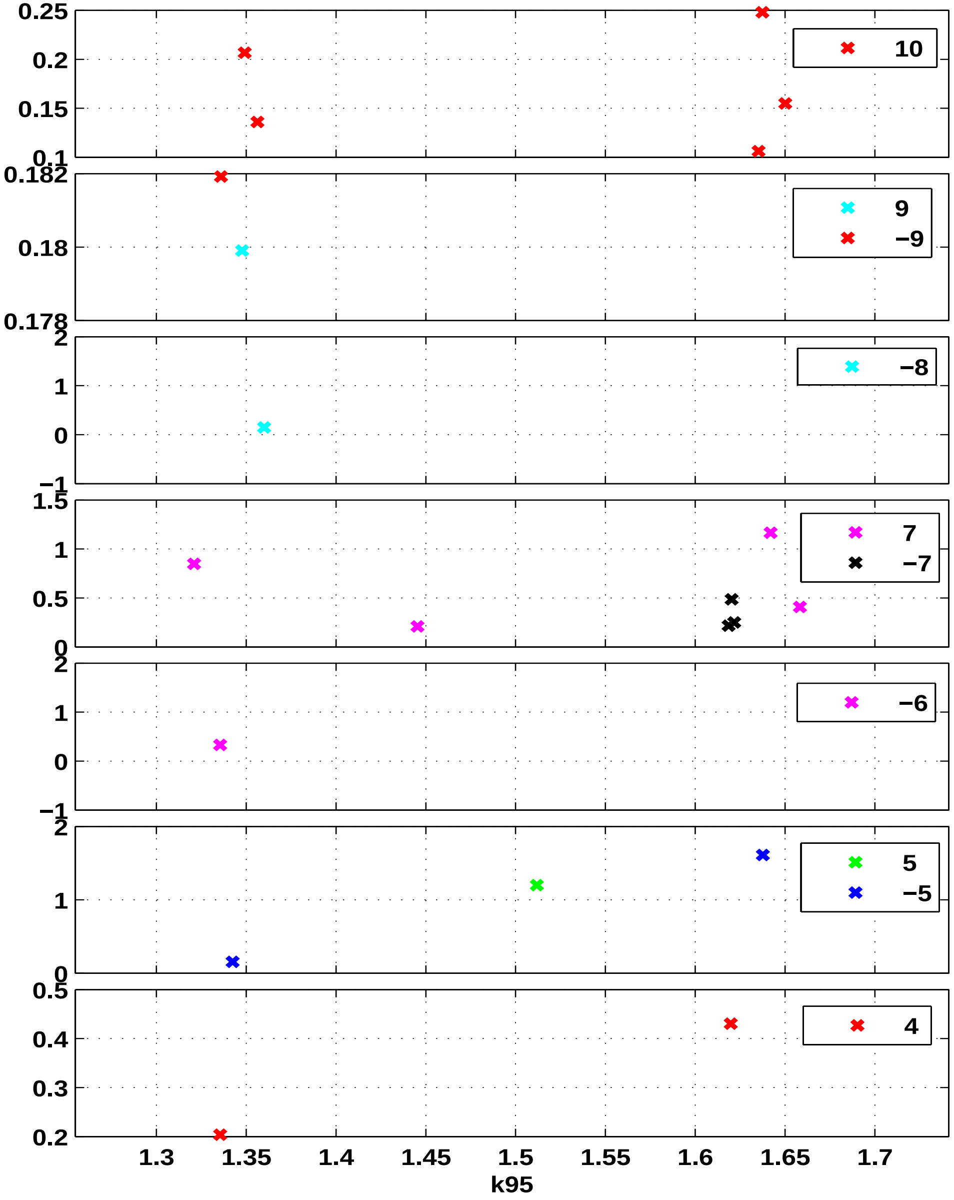


damping rate vs. edge shear s95

γ/ω database vs. plasma parameters

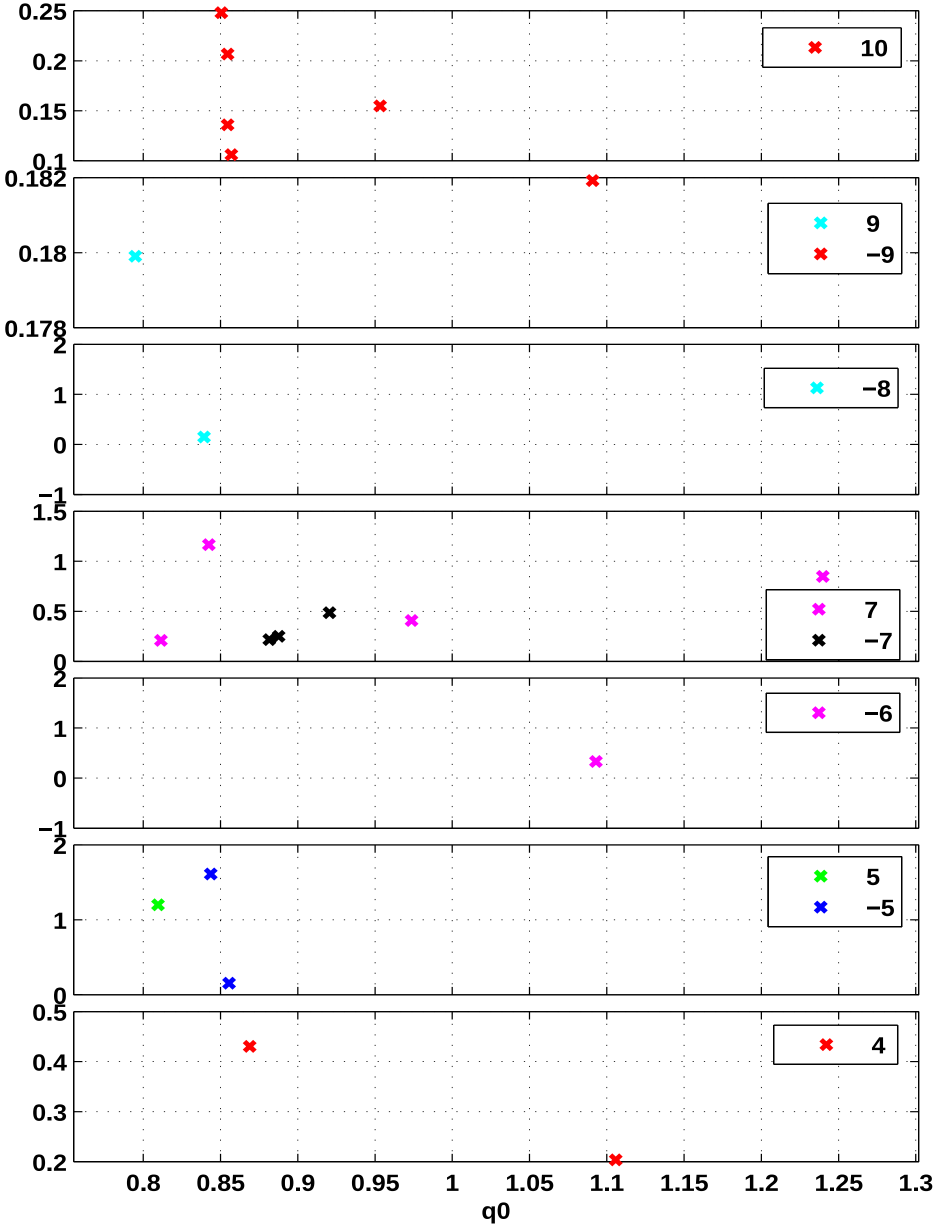


damping rate vs. core elongation κ_0

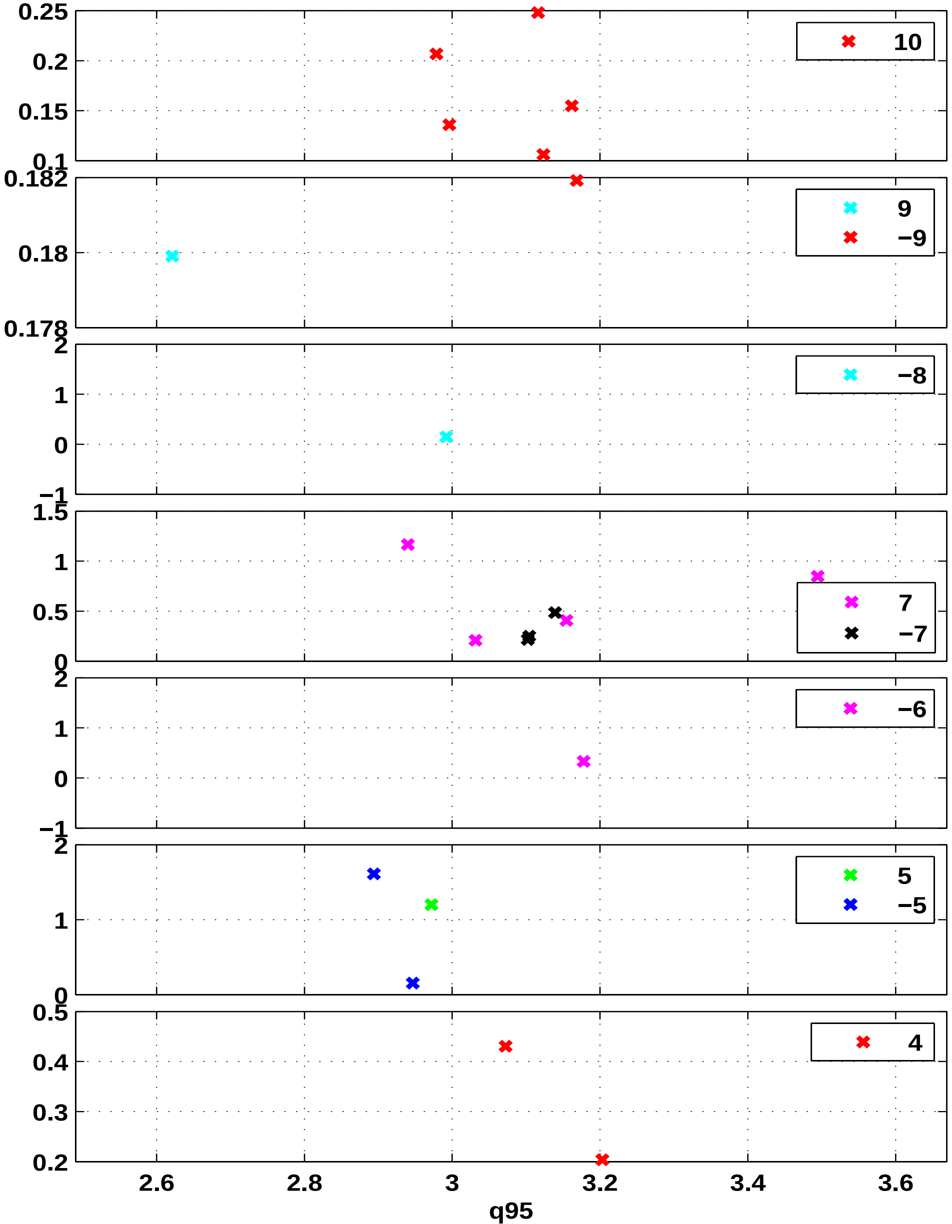


damping rate vs. edge elongation κ_{95}

γ/ω database vs. plasma parameters



damping rate vs. core q0



damping rate vs. edge q95