Experimental and computational investigations of Alfvén Eigenmode stability in JET plasmas through active antenna excitation

EX/P3-6

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*See author list of J Mailloux et al, "Overview of JET results for optimising ITER operation," to be published in *Nuclear Fusion* special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

Background: the Alfvén Eigenmode Active Diagnostic (AEAD)

- The interaction of AEs and energetic particles (EPs) will determine the success of future tokamaks, through EP-driven AEs and associated AE-induced EP transport
- The JET AEAD comprises two sets of four toroidally spaced, in-vessel antennas which actively excite *stable* AEs [1,2]
- Six amplifiers independently power and phase six (of the eight) antennas [3] with frequencies 25-250 kHz, toroidal mode numbers $|n| < 20$, and $|\delta B/B| \sim 10^{-3}$
- Fast magnetic probes measure stable AE frequencies $\omega_0 = 2\pi f_0$, net damping rates $\gamma < 0$, and toroidal mode numbers n
- The AEAD may be required to assess alpha drive in the upcoming JET DT campaign *if* the alpha population is insufficient to destabilize AEs

Summary + main takeaways

- Almost 7500 *stable* Alfvén Eigenmodes (AEs) were measured in almost 800 plasma discharges during the 2019-2020 JET deuterium campaign
- A statistical analysis shows continuum and radiative damping increase with edge safety factor, edge magnetic shear, and when including non-ideal effects
- A novel measurement of marginal stability is found for an edge-localized Ellipticity-induced AE (EAE) in a plasma with 25 MW of ICRH and NBI auxiliary heating
- *Unstable* electromagnetic modes with frequencies below Toroidicity-induced AEs (i.e. sub-TAE) are identified as beta-induced ion temperature gradient (BTG) modes
- MHD, kinetic, and gyrokinetic simulations agree well with experiment
- Similar studies are planned for the recent hydrogen and ongoing tritium campaigns, in preparation for the upcoming JET DT campaign

Database studies: damping rate and operational scenarios

- A statistical analysis was performed for ~7500 stable AEs measured in ~800 plasmas
- Normalized damping rates are well-correlated with…
  - Edge safety factor q_{95} → increased continuum damping [4]
  - Edge magnetic shear s_{95} → increased radiative damping [5]
  - Non-ideal parameter $\lambda = q_{95}\, s_{95} \sqrt{T_{e0}}/B_0$ [6,7] → radiative damping *(Fig 1a)*
- Both stable AE observations and their damping rates decrease with $|n|$ *(Fig 1b)*
  → More localized damping due to decreasing mode width $\propto 1/|n|$
  → Fast ion drive increases with n × (fast ion radial pressure gradient)
- The efficiency of active antenna excitation is reduced in X-point vs limiter magnetic configuration, likely due to increased edge shear [5]
- The intersection with an H-mode database [8] shows *no* stable AE excitations during H-mode (p-value = 0.076) → AEAD is only successful during L-mode

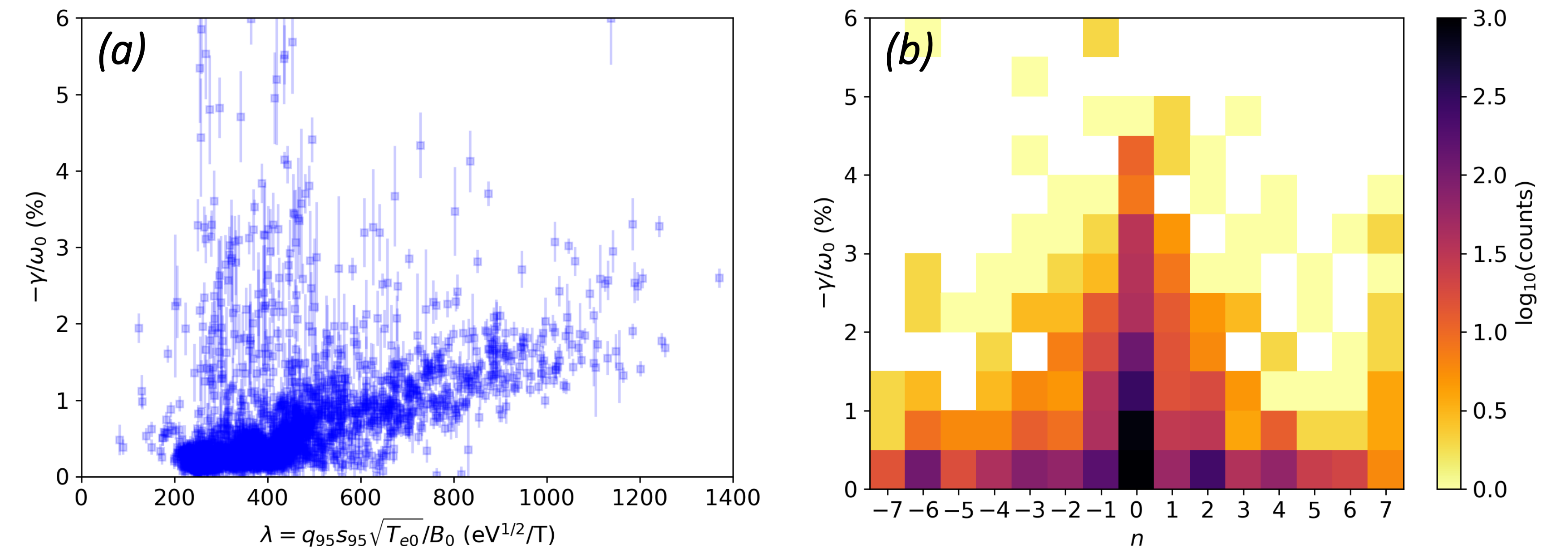

FIG. 1. (a) Normalized damping rate vs non-ideal parameter. (b) Number of stable AE observations (logarithmic) vs toroidal mode number ($|n| < 8$) and normalized damping rate ($|\Delta\gamma/\omega_0| < 0.5\%$).

Novel EAE stability measurement at high auxiliary heating

- Flattop: B_0 = 3.7 T, I_P = 2.5 MA, $n_{e0} \sim$ 8e19 m^{-3}, $T_{e0} \sim$ 5 keV *(Fig 2a)*
- 3-ion heating [9,10]: $P_{NBI} \sim$ 19-21 MW, $P_{ICRH} \sim$ 4.4 MW, $n_{He3}/n_e \sim$ 23%
- q(pressure-constrained), n_e,T_e(Thomson Scattering), f_{rot}(charge exchange) *(Fig 2b)*

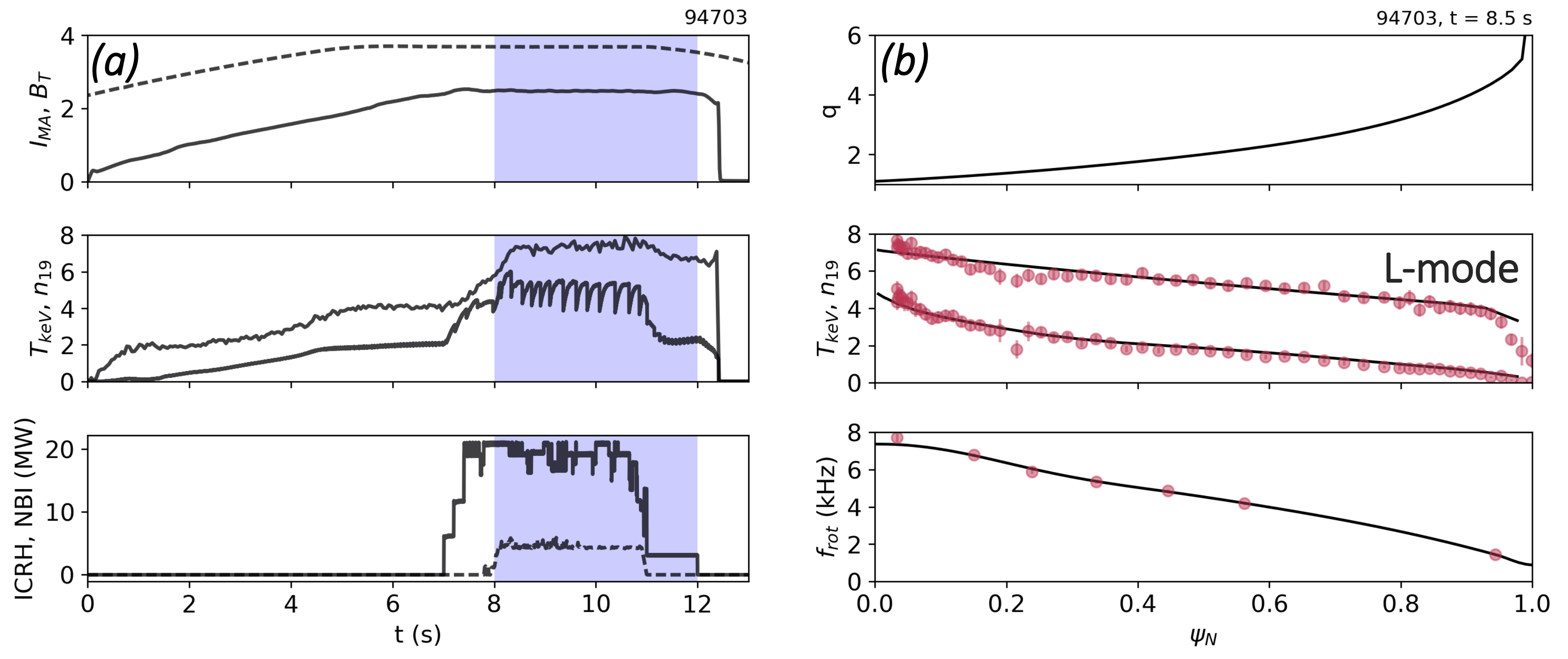

FIG. 2. (a) Plasma parameters for JPN 94703. A stable EAE was tracked during the shaded time interval. (b) Fitted profiles for t = 8.5 s. ψ_N is the normalized poloidal flux.

- Marginally stable AE is tracked in real time with odd AEAD phasing *(Fig 3a)*
- Frequency is $f_0 \sim$ 235-250 kHz, toroidal mode number is $n \sim 5$ (probe-dependent)
- Normalized damping rate is low: $-\gamma/\omega_0 \sim 0.25\%$ → 0.6 kHz *(Fig 3b)*

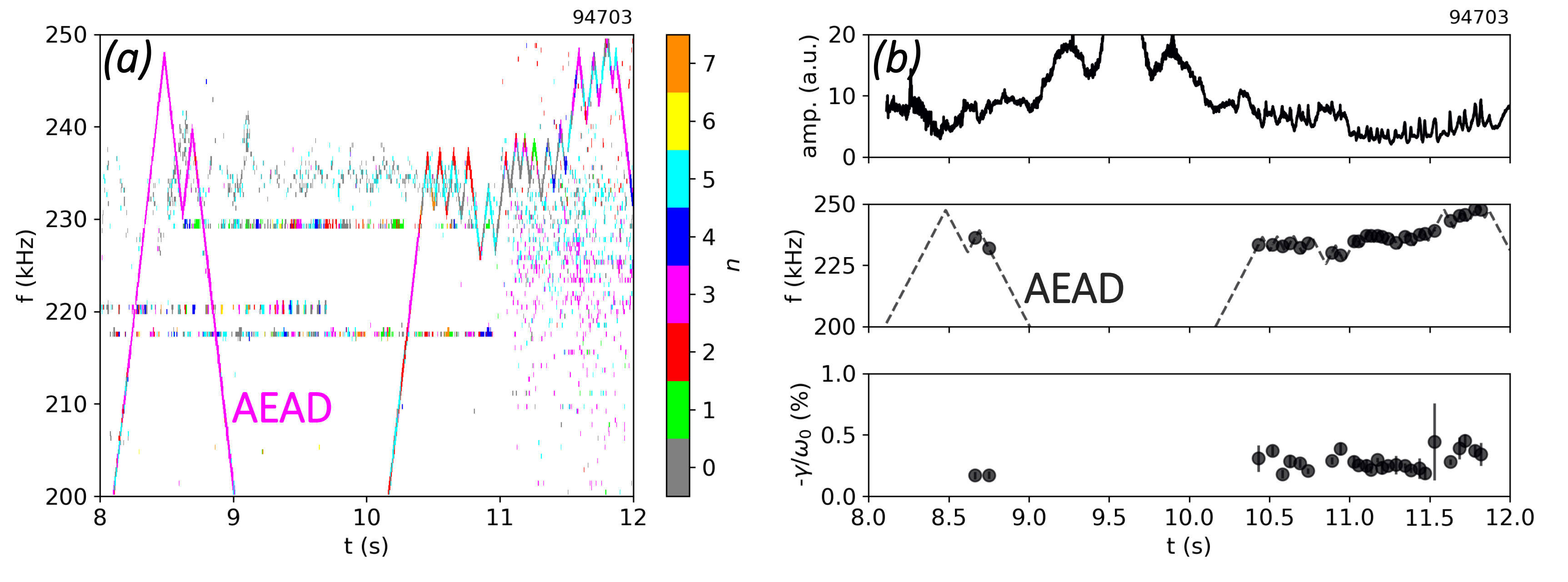

FIG. 3. (a) Spectrogram with toroidal mode number analysis. (b) Magnetic response amplitude, AEAD (dashed) and stable AE resonant frequencies (circles), and normalized damping rates.

Simulations with kinetic-MHD code NOVA-K [11-13]

- Several AEs modeled (n = 3-6), but best agreement is found with $n = 5$ *(Table 1)*
- Localization is consistent with improved AEAD coupling with edge modes [5] *(Fig 4)*
- Dominant contributions are electron Landau and continuum damping
- Negligible damping from NBI fast ions <100 keV is due to injection velocities < $v_A/3$
- These are (expectedly) different from the damping mechanisms of some core-localized TAEs studied in JET [14], dominated by ion Landau and radiative damping

Damping, γ/ω_0 (%)	$n = 5$, f_0 = 236.4 kHz
Continuum	-0.116
Radiative	0.000
Electron collisional	-0.010
Electron Landau	-0.198
Ion Landau	~0.000
NBI fast ion	-0.017
Total	-0.341

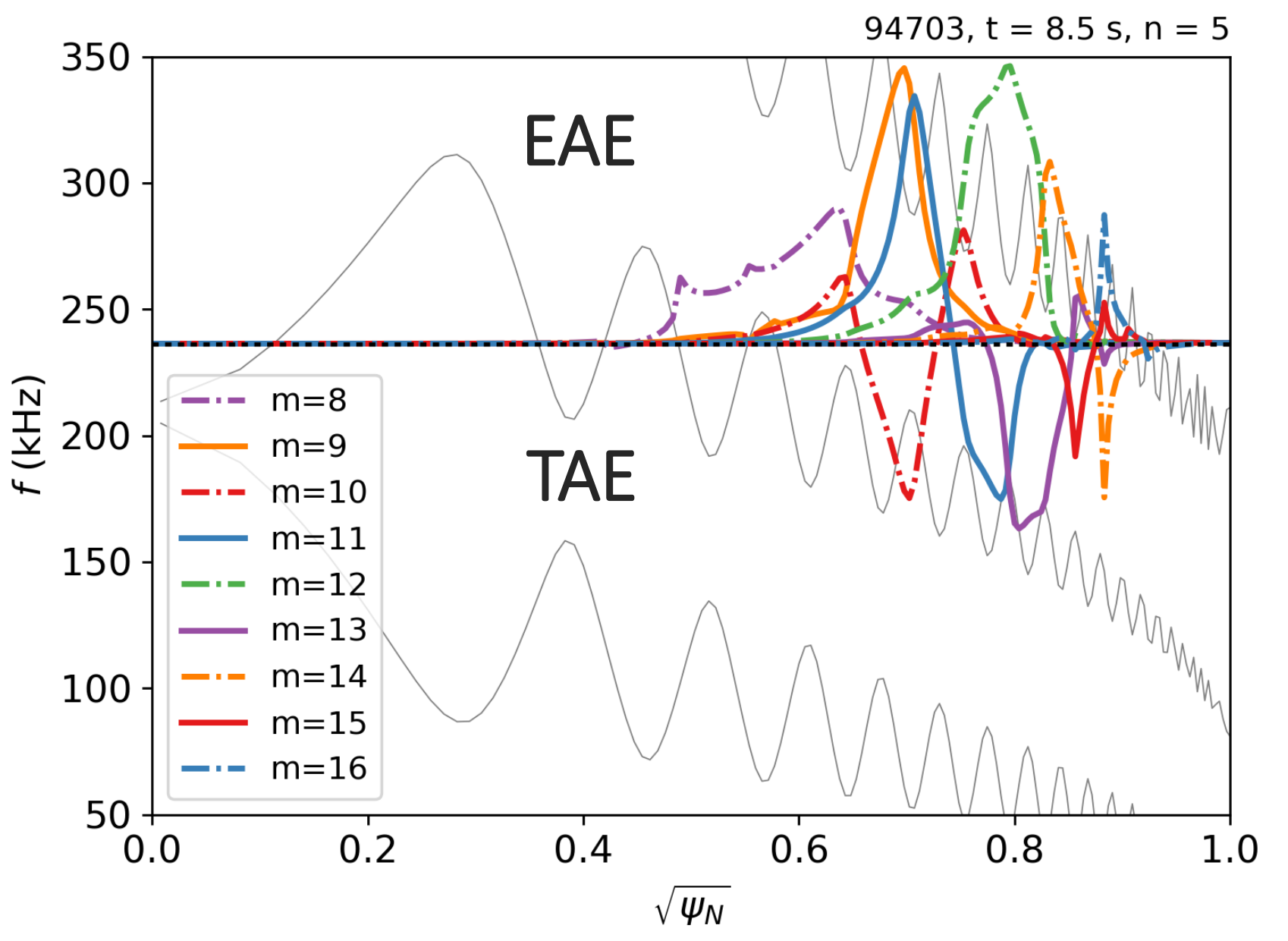

TABLE 1. Normalized damping rate (%) calculated by NOVA-K. FIG. 4. Continua (thin lines) and poloidal mode structure from NOVA-K for the same edge-localized n = 5 EAE (lab frame). ψ_N is the normalized poloidal flux.

Identification of sub-TAE electromagnetic modes as BTGs [15]

- Beta-induced ion temperature gradient (BTG) modes are characterized by…
  1. High β_i with a significant ∇T_i (often related to an Internal Transport Barrier)
  2. Localization near a rational q-surface with a low magnetic shear
  3. Strong thermal ion dependence, scaling with the ion drift frequency
  4. Coupling among Alfvén, acoustic, and drift waves
- In [15], these are consistent with the analytical theory of BTG modes [16] as well as linear gyrokinetic simulations with the Gyrokinetic Toroidal Code (GTC) [17]
- A good example is JPN 95649, a recent D plasma dedicated to scenario development for the study of EPs and EP modes in DT [18,19] *(Fig 5)*
- Investigations of the relation between BTGs and the neutron "roll-over" are underway

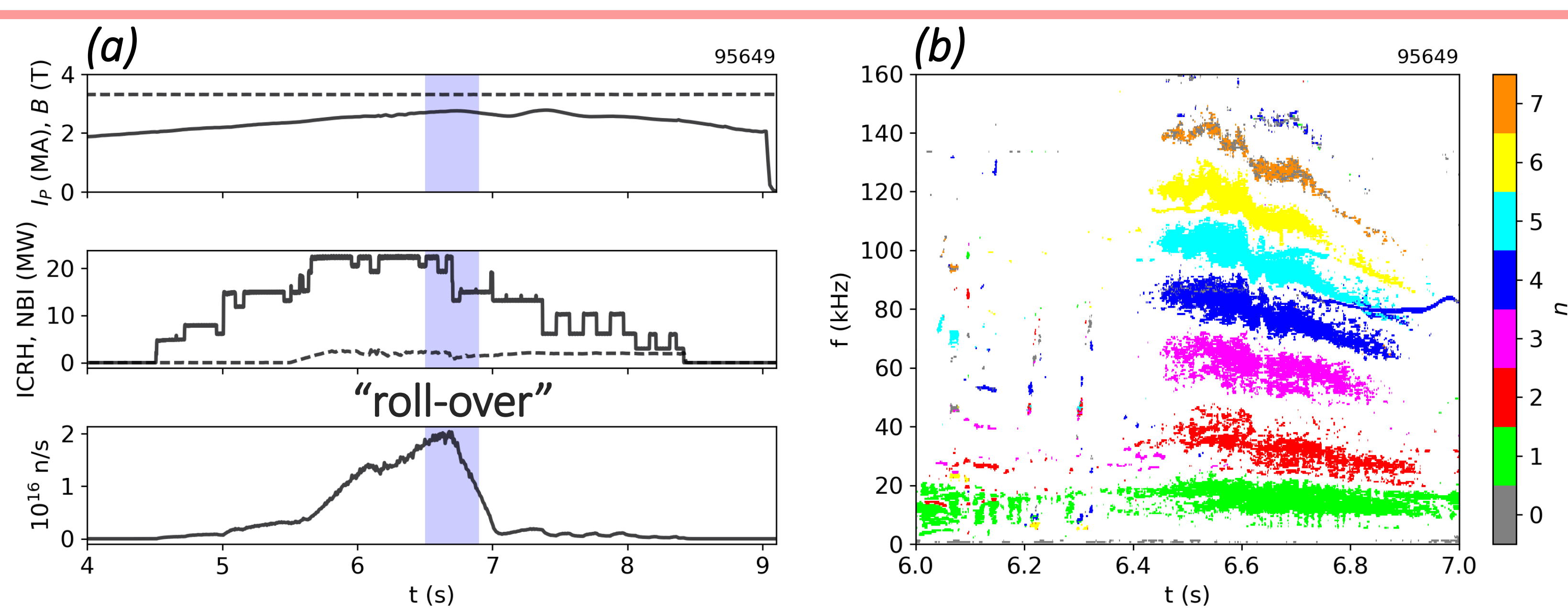

FIG. 5. (a) Plasma parameters for JPN 95649. Unstable sub-TAE BTG modes were observed during the shaded time interval. (b) Spectrogram with toroidal mode number analysis.

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This work was supported by US DOE through Grants DE-FG02-99ER54563, DE-AC05-00OR22725, and DE-AC02-05CH11231.