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FUSION ALPHA-PARTICLE-DRIVEN ALFVÉN EIGENMODES IN JET D-T PLASMAS: EXPERIMENTS AND THEORY

S.E. Sharapov¹, M. Fitzgerald¹, H. J. C. Oliver¹, T. Barberis², B. N. Breizman³, M. Dreval⁴, R. Dumont⁵, J. Garcia⁵, V. Goloborod'ko⁶, Ye.O. Kazakov⁷, D. Keeling¹, V.G. Kiptily¹, J. Mailloux¹, F. Porcelli⁸, Ž. Štancar¹, D. Banerjee⁸, the JET contributors* and the EUROFUSION Tokamak Exploitation Team**

¹UKAEA, Culham Campus, Abingdon, Oxfordshire OX14 3DB, UK

²Princeton Plasma Physics Laboratory, Princeton, NJ, USA

³Institute for Fusion Studies, University of Texas at Austin, Austin, USA

⁴Institute of Plasma Physics, National Science Center, KIPT, Kharkiv, Ukraine

⁵CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

⁶Institute for Nuclear Research, Kiev, Ukraine

⁷Laboratory for Plasma Physics, LPP-ERM/ KMS, TEC Partner, Brussels, Belgium

⁸Department of Applied Science and Technology, Polytechnic University of Turin, Torino, Italy

*See the author list of C F Maggi et al., Nucl. Fusion 64 (2024) 112012

**See the author list of E Joffrin et al., Nucl. Fusion 64 (2024) 112019



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OUTLINE

- Introduction
- α -particle-driven toroidal Alfvén eigenmodes (TAEs) in the “beam afterglow” scenario of JET DTE2 plasmas
- Revisiting TAE radiative damping theory
- Modes excited in NBI modulation experiments aiming at α -particle bump-on-tail distribution
- Axisymmetric $n=0$ modes excited by α -particle energy gradients in JET D-T plasmas
- Summary

INTRODUCTION

Magnetic Fusion is moving now to the *era of burning plasmas*. The *plasma self-heating through the fusion-born α -particles* (He^4 nuclei of energy 3.52 MeV) is the most essential *new* part of the plasma physics.

Transport properties of α -particles are of crucial importance since they will determine the *plasma heating profiles*, the plasma dilution due to the '*helium ash*' *accumulation*, and the power load upon the *first wall*.

Largest uncertainty in α -particle transport is associated with possible *excitation of Alfvén eigenmodes (AEs)* that resonate with the super-Alfvenic α -population.

Investigation of *AEs excited by fusion α -particles* was one of the aims in *recent DTE2 and DTE3* experiments on JET



A very challenging task as α -pressure was only several % to the core plasma pressure!

FROM HIGH POWER DTE1 (1997) TO DTE2 & DTE3 ON JET

We did **not** detect any α -particle-driven AEs during DTE1 campaign in 1997 [1].

For DTE2 & DTE, we developed **internal diagnostics for AEs** on JET up to the frequency range of ~ 500 kHz:

- **Interferometry²** for measuring line-integrated δn_e ;
- **Sweep-frequency reflectometry³** measuring local $\delta n_e(R)$;
- **Multi-channel Soft X-Ray** for line-integrated combination of δT_e and δn_e .

Together with **Mirnov coils** measuring $\partial(\delta B_p)/\partial t$, these diagnostics provided a robust and reliable set for detecting α -particle-driven modes;

We also developed a **set of diagnostics for confined and lost alpha-particles** [4]

[1] S.E. Sharapov et al 2008 Fusion Science and Technology 53 1022;

[2] S.E. Sharapov et al 2004 Phys. Rev. Lett. 93 165001;

[3] S. Hacquin et al 2007 Plasma Phys. Control. Fusion 49 1371;

[4] V.G. Kiptily et al 2024 Nucl. Fusion 64 086059.

GRADIENTS OF α -PARTICLE POPULATION TO CONSIDER

- Growth rate γ for Alfvén eigenmode (AE) resonating with energetic particles depends on **energy gradient**, radial gradient, and **anisotropy** of the energetic particle distribution:

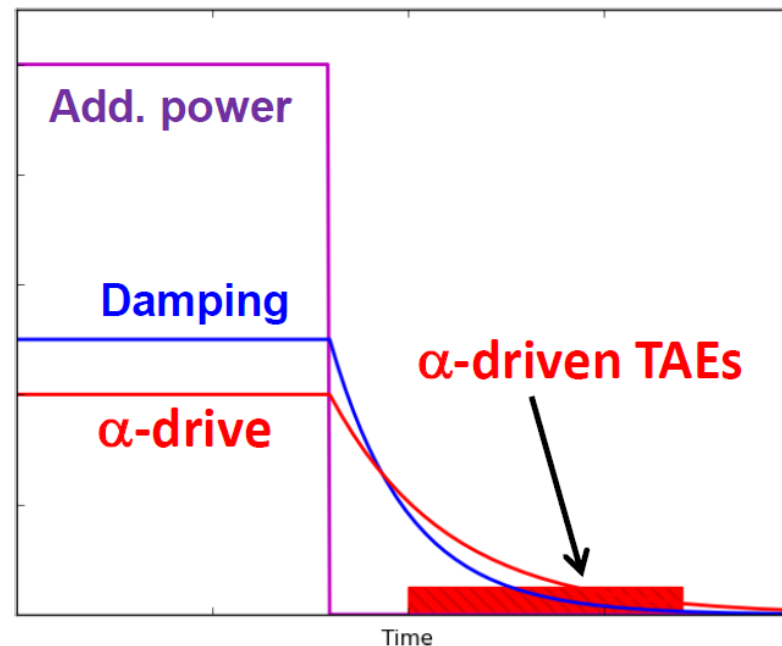
$$\frac{\gamma}{\omega} \propto \omega \frac{\partial f}{\partial E} + n \frac{\partial f}{\partial P_\phi} + l \frac{Ze}{m} \frac{\partial f}{\partial \mu},$$

$$P_\phi = mRv_\phi + Ze\psi$$

- Modes excited by different gradients impact fast particles in different ways and require distinct excitation and mitigation strategies.
- During DTE2 & DTE3, **three types** of AEs were excited by α -particles:
 - i) **Toroidal Alfvén Eigenmodes** excited due to the radial gradient **as expected**,
and two **unexpected** types of AEs:
 - ii) **on-axis kinetic AEs** excited due to the combined energy and radial gradients,
 - iii) **n=0 global AEs at the edge of plasmas** excited due to the energy gradient.

BEAM “AFTERGLOW” SCENARIO FOR α -DRIVEN TAEs ON JET

The “beam afterglow” (after NBI power is switched off) scenario similar to TFTR⁵



Cartoon showing the beam damping and α -drive evolution in the NBI afterglow scenario [5].

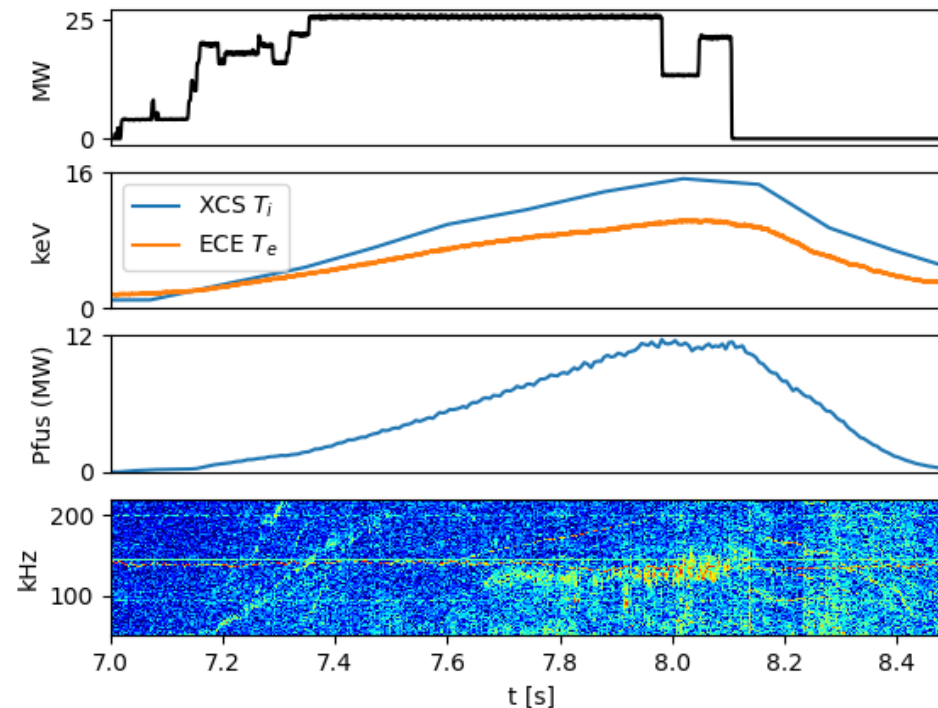
Major effort was made in developing this scenario first in deuterium plasmas with NBI only⁶

[5] R. Nazikian et al 1997 Phys. Rev. Lett. 78 2976;

[6] R.J. Dumont et al 2018 Nucl. Fusion 58 082005.

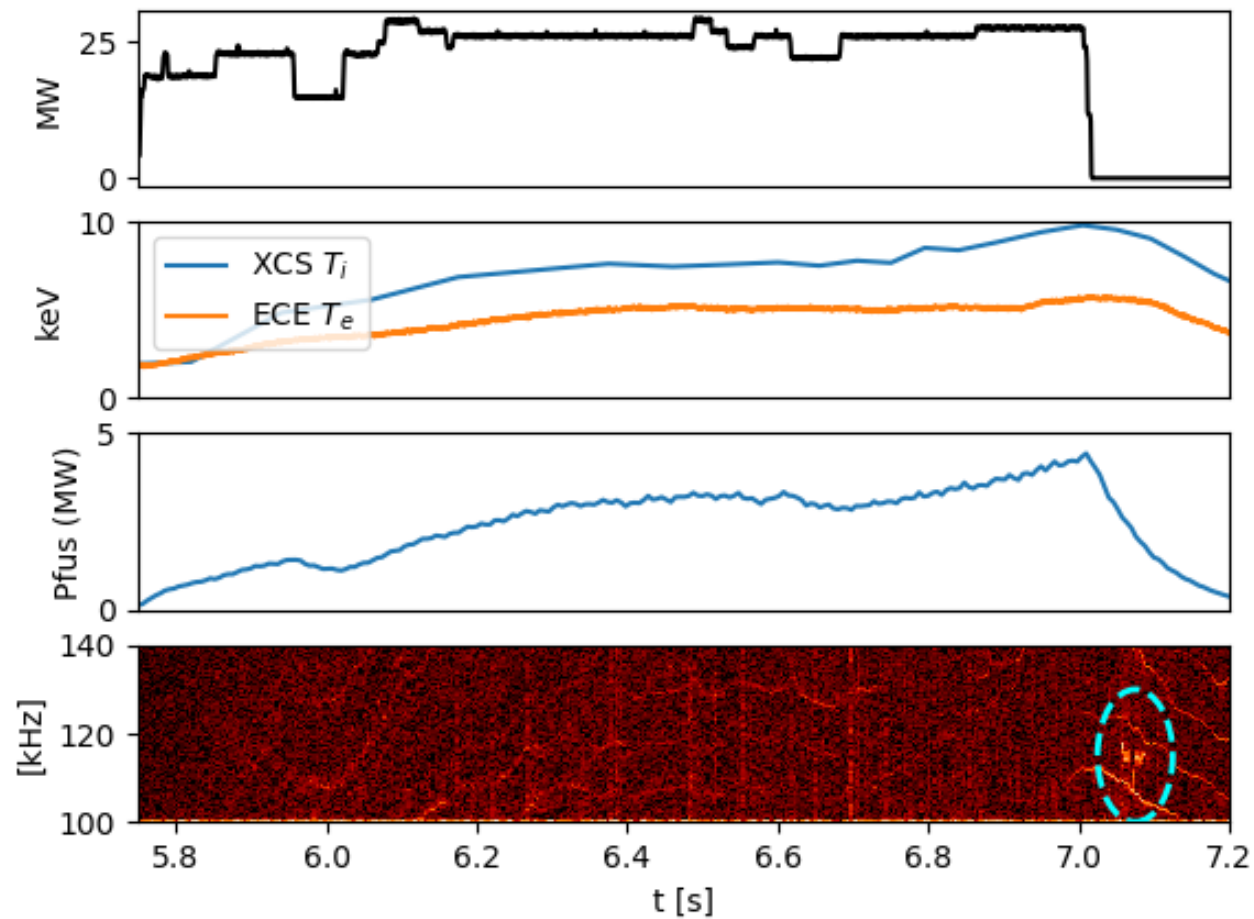
BEAM AFTERGLOW SCENARIO IN DTE2 PLASMA [7]

High DT fusion performance was obtained in the beam afterglow discharges, with the neutron rate up to $R^{DT} = 4.2 \times 10^{18} \text{ s}^{-1}$ at $P^{NBI} = 26 \text{ MW}$, which correspond to $P^{FUS} = 11.8 \text{ MW}$ of fusion power and $Q = P^{FUS} / P^{NBI} = 0.45$ (#99802).

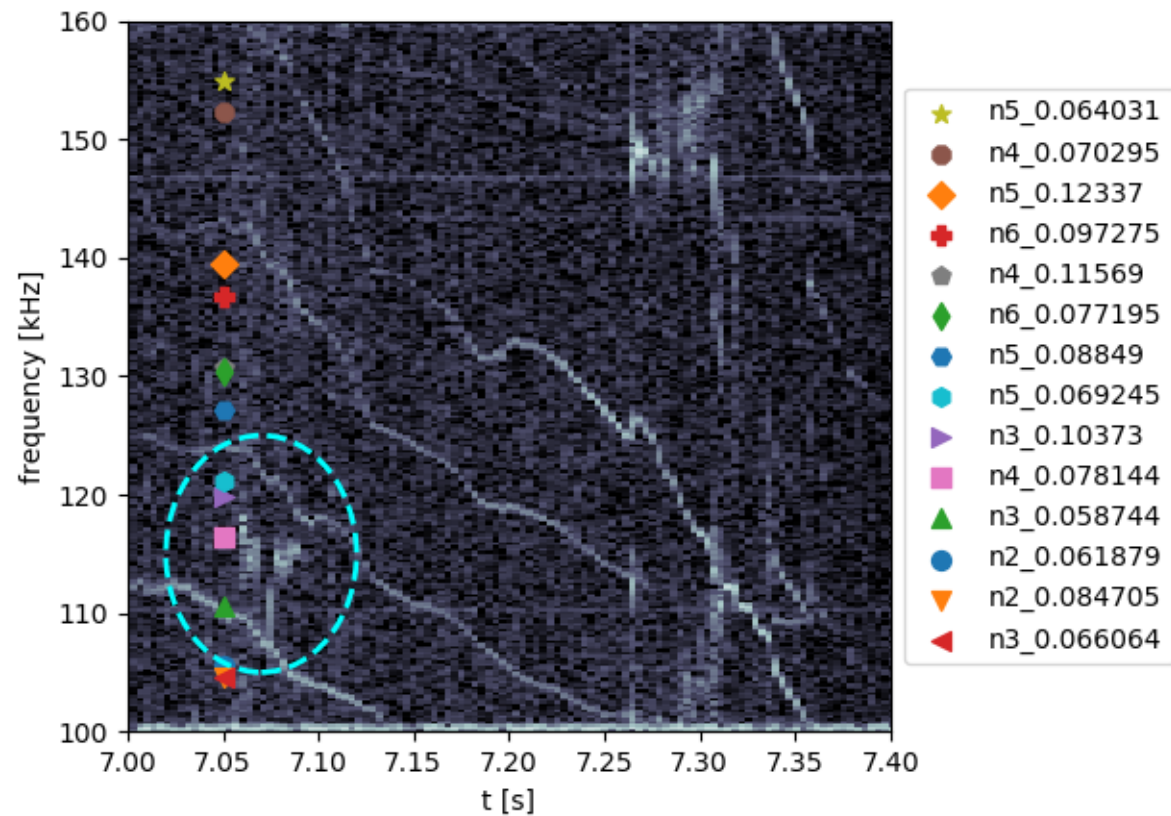


[7] M. Fitzgerald et al 2023 Nucl. Fusion 63 112006;

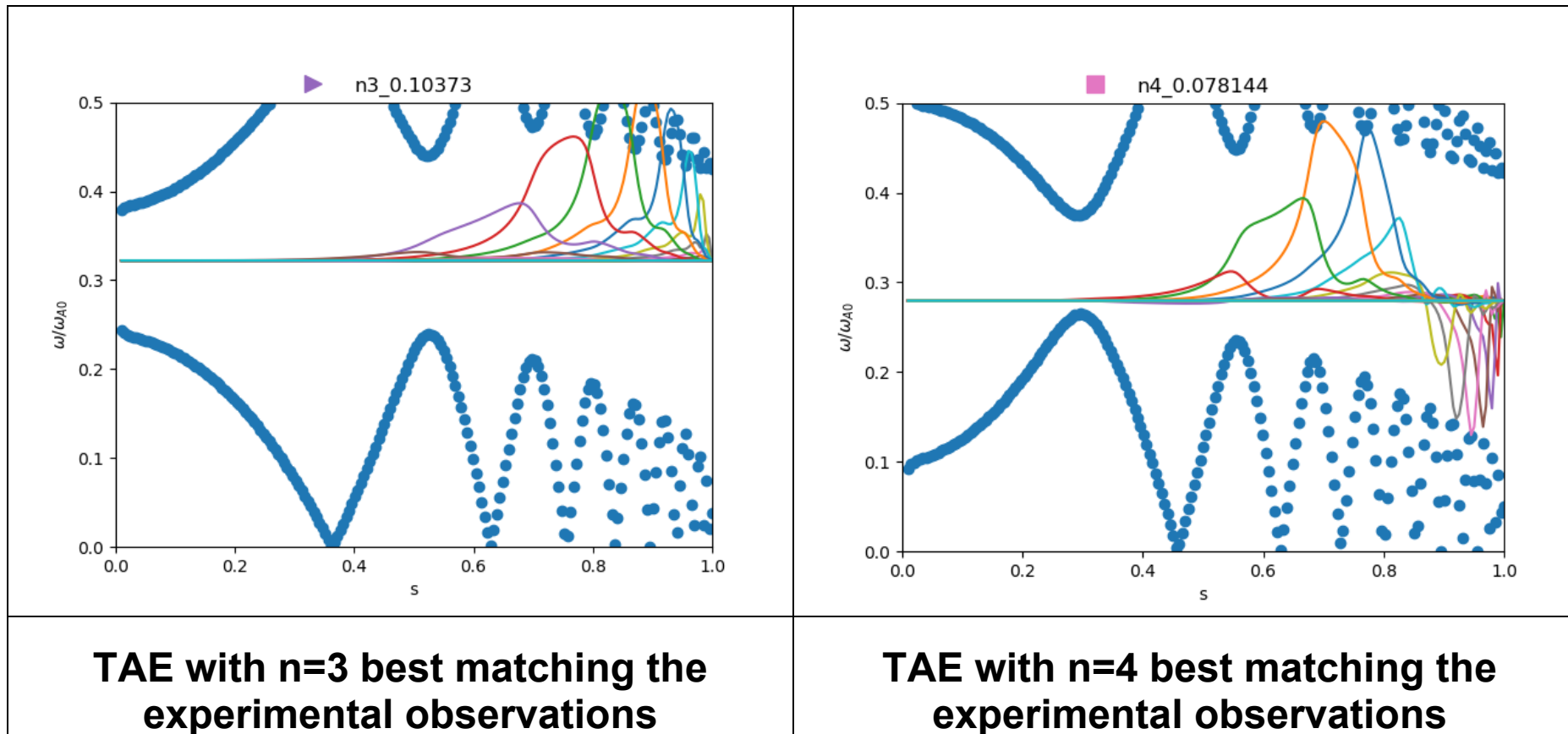
TAEs EXCITED BY α -PARTICLES IN BEAM AFTERGLOW SCENARIO⁷



ZOOM OF THE OBSERVED TAEs IN THE BEAM AFTERGLOW



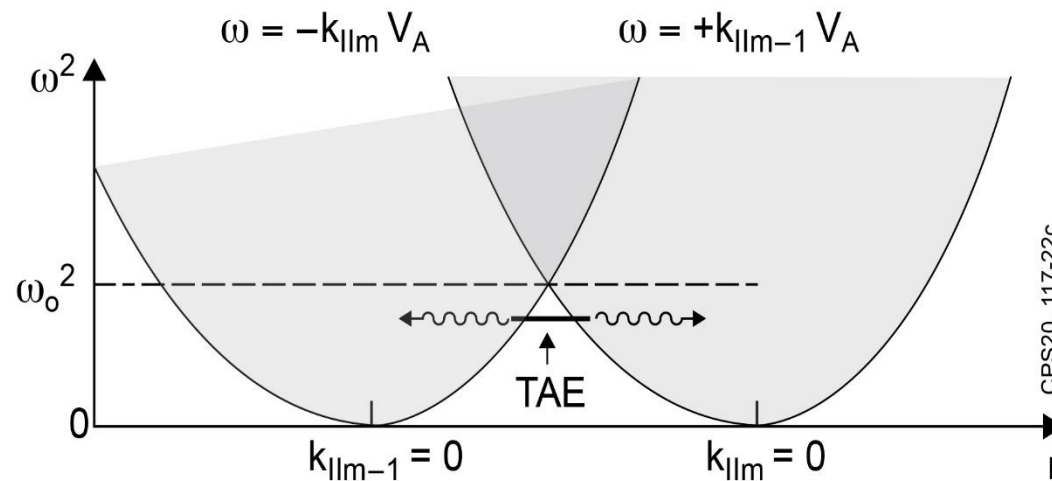
TAEs COMPUTED WITH HELENA+MISHKA FOR THIS CASE



Strong radiative damping was established as main stabilising effect on core-localised TAEs⁷

TAE RADIATIVE DAMPING RATE REVISED⁸

When TAE couples to kinetic Alfvén waves with non-zero radial group velocity, part of TAE energy radiates away with the outgoing KAWs → “radiative damping”



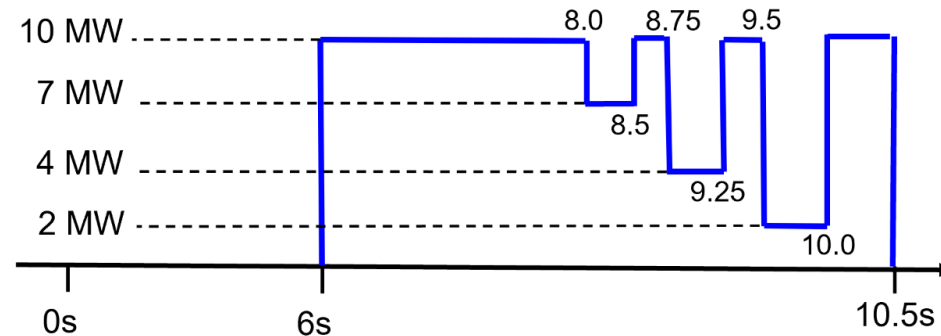
We developed a real-space analytic calculation of radiative damping that provided more transparent formalism than the pre-existing Fourier-space approach, with more accurate numerical factor (~33% lower) in the damping → **Good for benchmarking numerical codes.**

[8] B.N. Breizman, S.E. Sharapov 2025 Fund. Plasma Physics 13 100086

CREATING α -PARTICLE BUMP-ON-TAIL VIA NBI MODULATION⁹

- For TAE excitation via α -distribution *energy* gradient, we created bump-on-tail (BOT, $dF_\alpha/dE > 0$) α -particle distribution in DTE2 pulses.
- The critical question: whether a BOT distribution of α 's could shift notably the TAE instability zone.

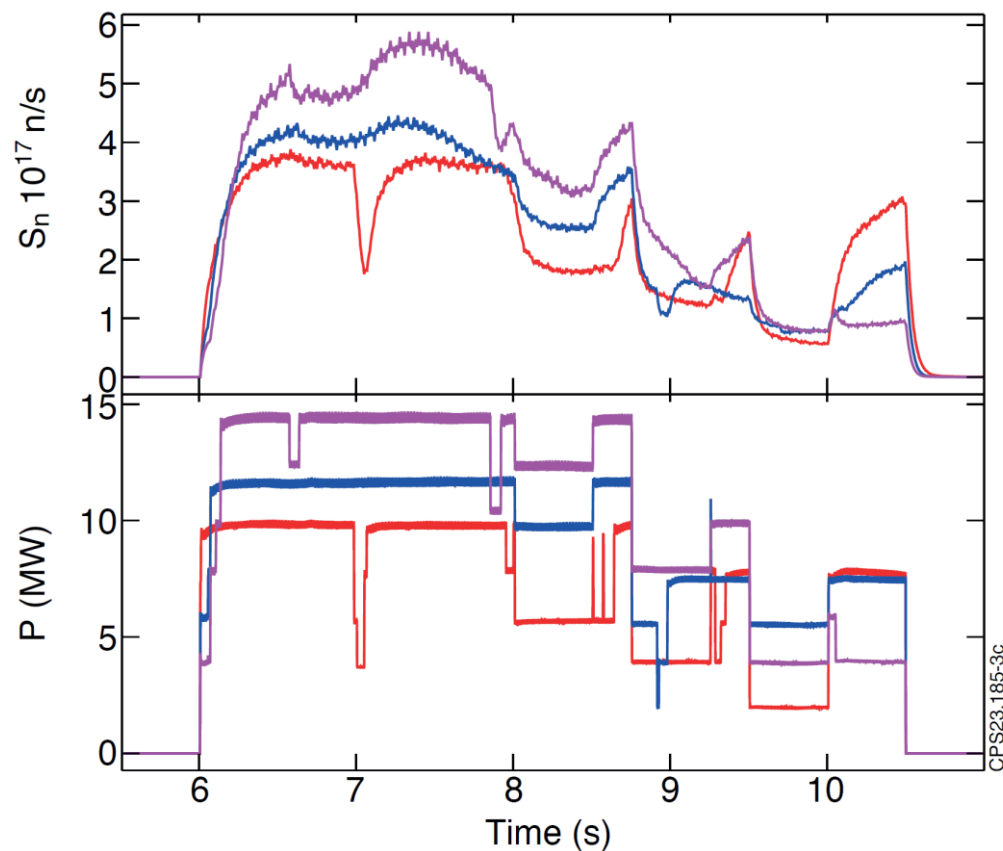
NBI only discharges were employed with the power modulation:



The UNEXPECTED result: we did observe modes, BUT... not TAEs!

[9] S.E. Sharapov et al 2023 Nucl. Fusion 63 112007

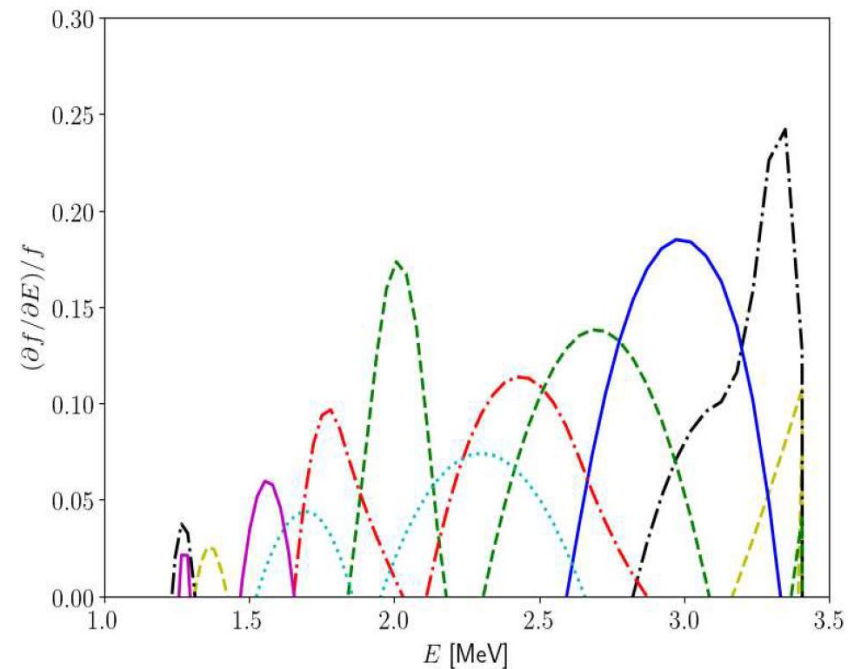
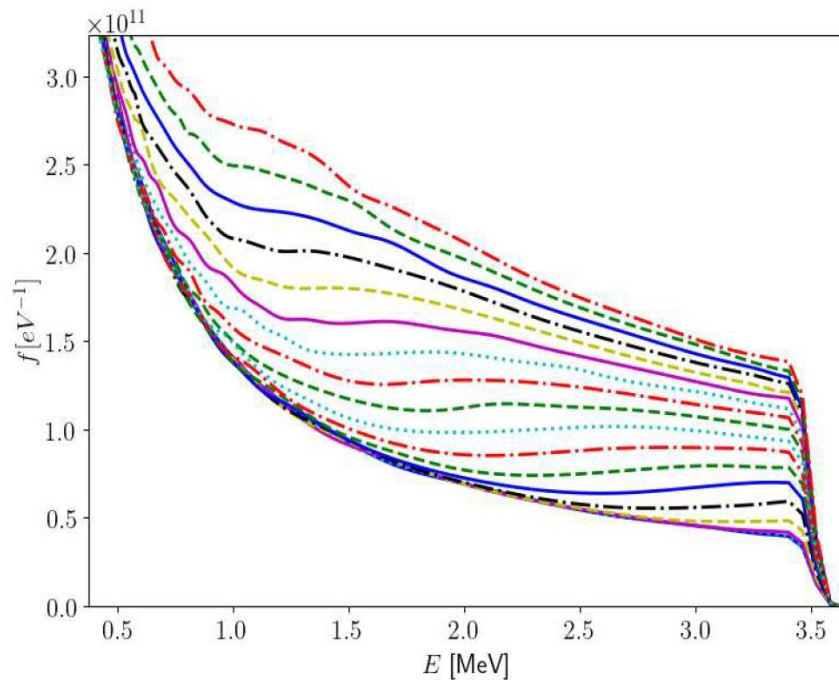
PULSES WITH D-BEAM OF INCREASING POWER LAUNCHED INTO T-RICH PLASMAS



**Top: DT neutron rates in discharges #99501 (pink), #99503 (red), and #99627 (blue).
Bottom: the corresponding waveforms of the modulated NBI power.**

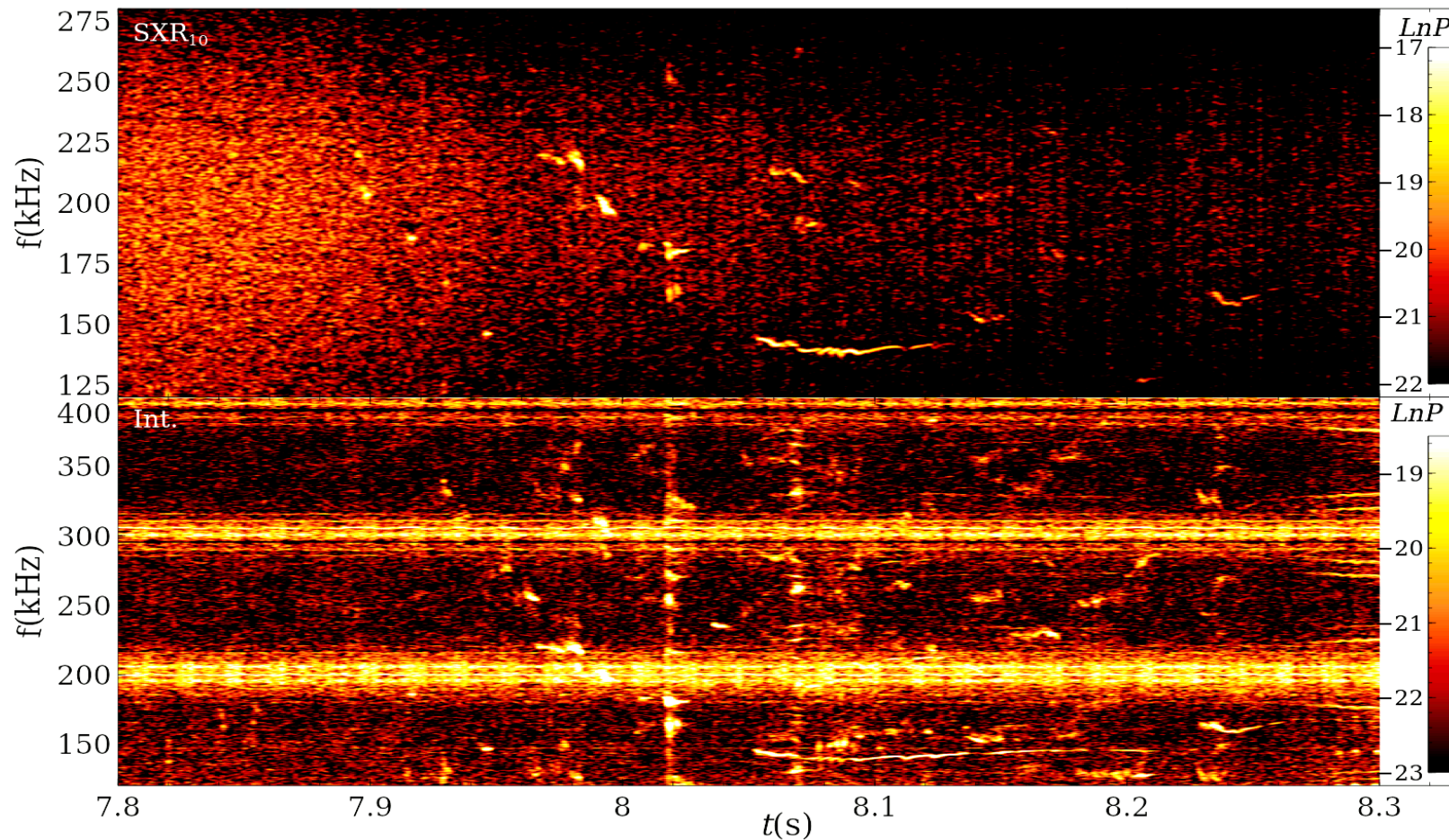
A BUMP-ON-TAIL IN ALPHAS CONFIRMED BY TRANSP ANALYSIS (FINE TIME STEPS AND HIGH STATISTICS USED):

Positive gradients present at wide range of energies

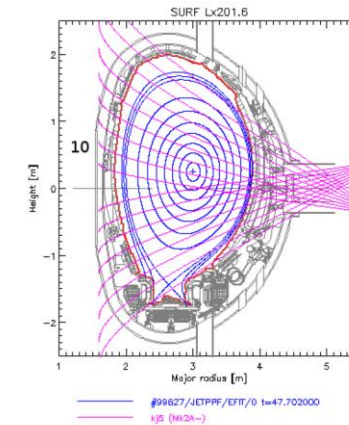
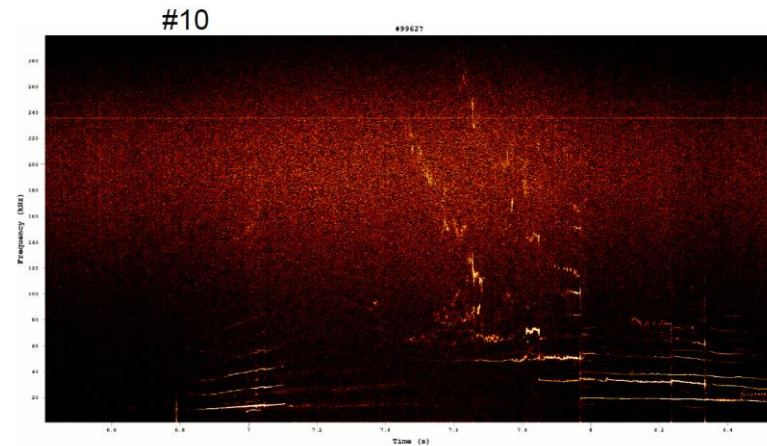


Z. Stancar and J. Oliver.

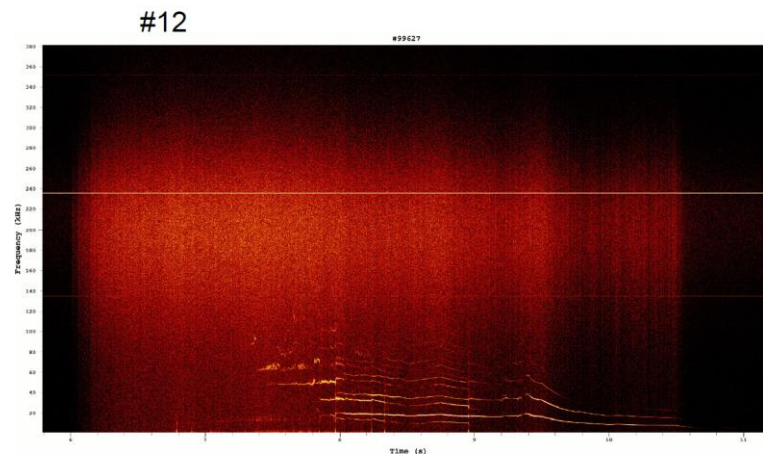
HIGH FREQUENCY MODES WERE DETECTED IN ALL DISCHARGES WITHOUT EXCEPTION IN INTERFEROMETRY, SXR, REFLECTOMETRY, BUT NOT IN MIRNOV COILS → NO INFORMATION ON n 's. #99502:



SOFT X-RAY DIAGNOSTICS SHOW THAT THESE MODES ARE HIGHLY LOCALIZED AROUND THE MAGNETIC AXIS:

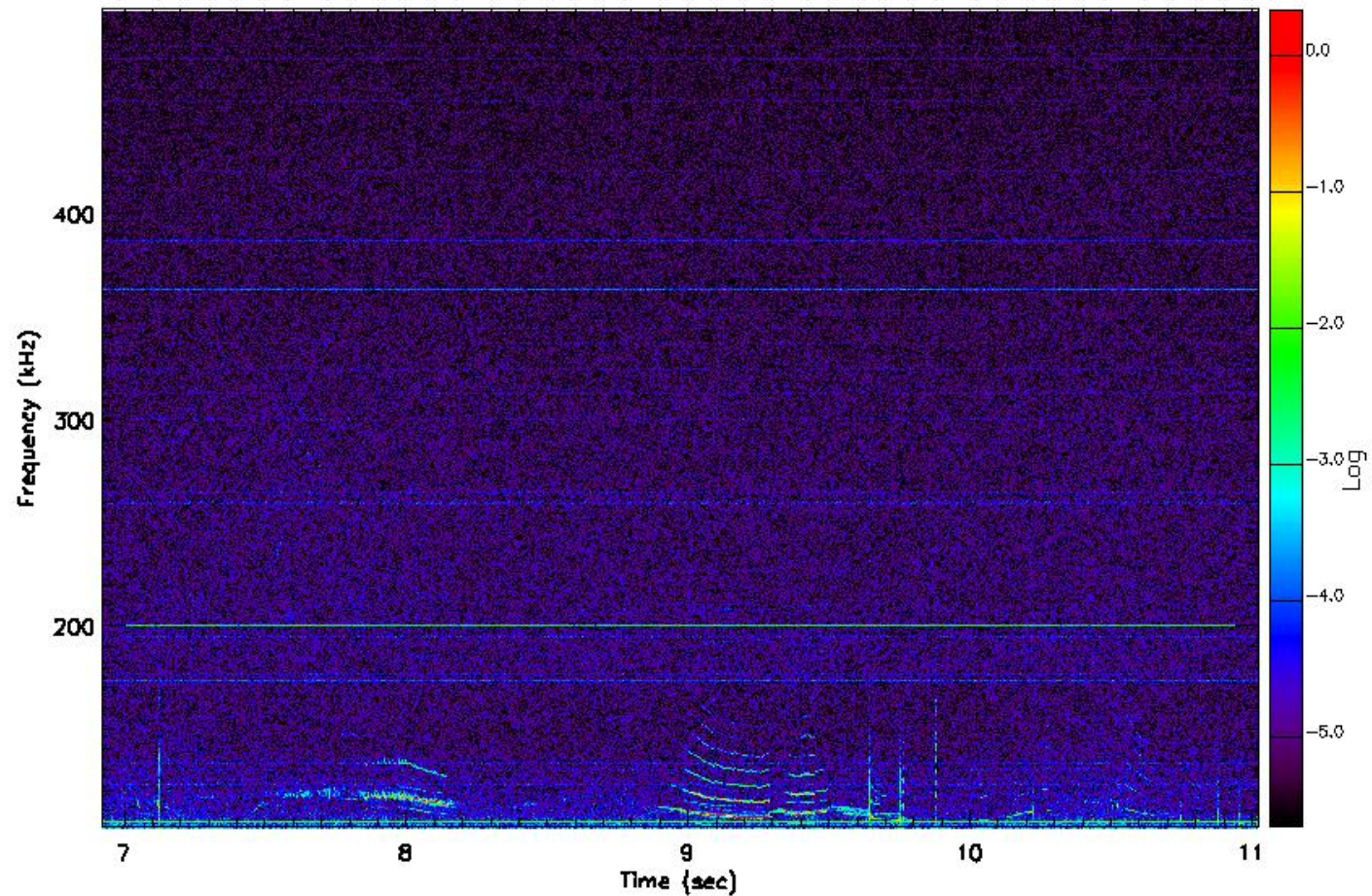


7.4-8s modes >100kHz
are core localized



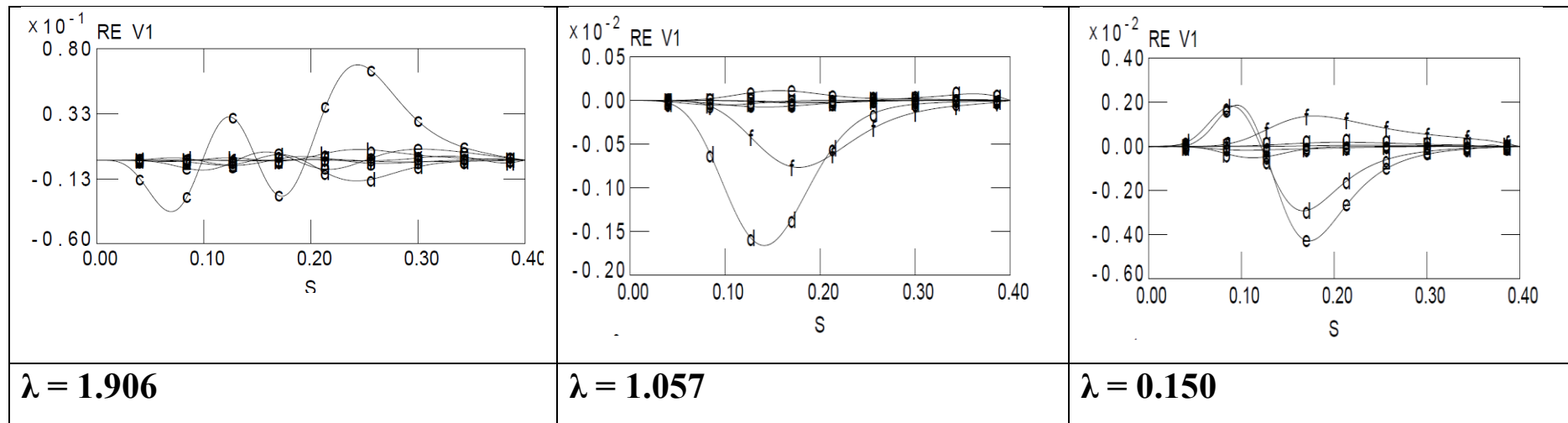
The modes are seen in SXR Channel 10, but not in Channels ≥ 12

NO SIMILAR MODES IN D-REFERENCE DISCHARGE #100797



JET Shot: 100797 : Chn: DF/G1F-VERT<003
Time: 6.9226 to 11.022 npts: 3.00000e+07 nats: 2048 nfft: 4096 f1: 102.0 f2: 498.9
specview v12.0 (qplink) - User: carlos - Sat Aug 30 14:41:43 2023

THE MODES OBSERVED ARE IDENTIFIED AS THOSE PREDICTED BY ROSENBLUTH AND RUTHERFORD [10]



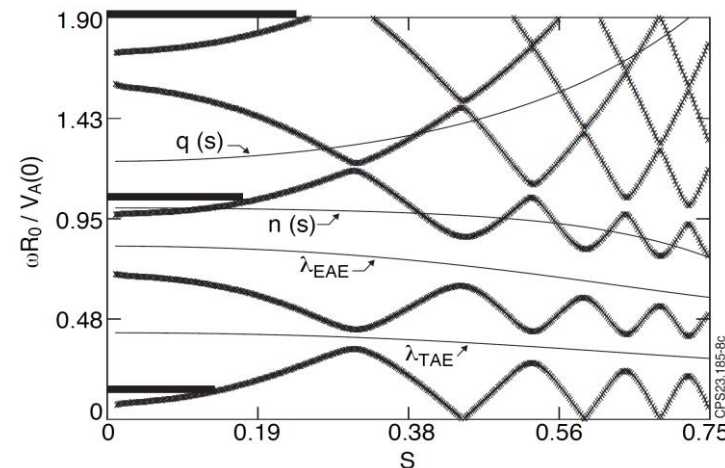
The “Complex Resistivity” [11] MISHKA modelling: The variable $s \cdot V^1$ as a function of $s = (\psi_P / \psi_P(a))^{1/2}$ for $n = 5$ modes computed for $q(0) = 1.22$. The normalised frequency is $\lambda = \omega R_0 / V_A(0)$. All modes are within $s \approx r/a = 0.4$.

The RR-modes are found to exist over a wide range of frequencies similarly to the experimentally observed range.

[10] M.N. Rosenbluth and P.H. Rutherford 1975 Phys. Rev. Lett. 34 1428;

[11] J.W. Connor et al 1994 Non-ideal Effects on Toroidal Alfvén Eigenmode Stability. In: Proceed. of 21st EPS Conf., vol. 18B, page 616.

USE OF RR-MODES FOR MHD SPECTROSCOPY IN BURNING PLASMAS



Alfvén continuum structure for $q(0)=1.22$ in #99502. RR-modes marked with three horizontal thick lines exist in the potential “wells” on-axis.

The MISHKA modelling shows a **rather restrictive range of $q(0)$ values** for RR-mode existence:

$$\frac{m}{n} < q(0) < \frac{m+1/2}{n}$$

In the case of, e.g., $n=5$ RR-mode this implies the following **windows for the mode existence**:

$$1.4 < q(0) < 1.5; \quad 1.2 < q(0) < 1.3; \quad 1 < q(0) < 1.1$$

As $q(0)$ decreases in time, the observed temporal evolution of RR-modes makes it potentially possible to use the mode observations for MHD spectroscopy of $q(0)$ and α -particles.

ANOTHER UNEXPECTED: AXISYMMETRIC $n=0$ EIGENMODES EXCITED BY ENERGY GRADIENTS OF ALPHA-PARTICLES¹²

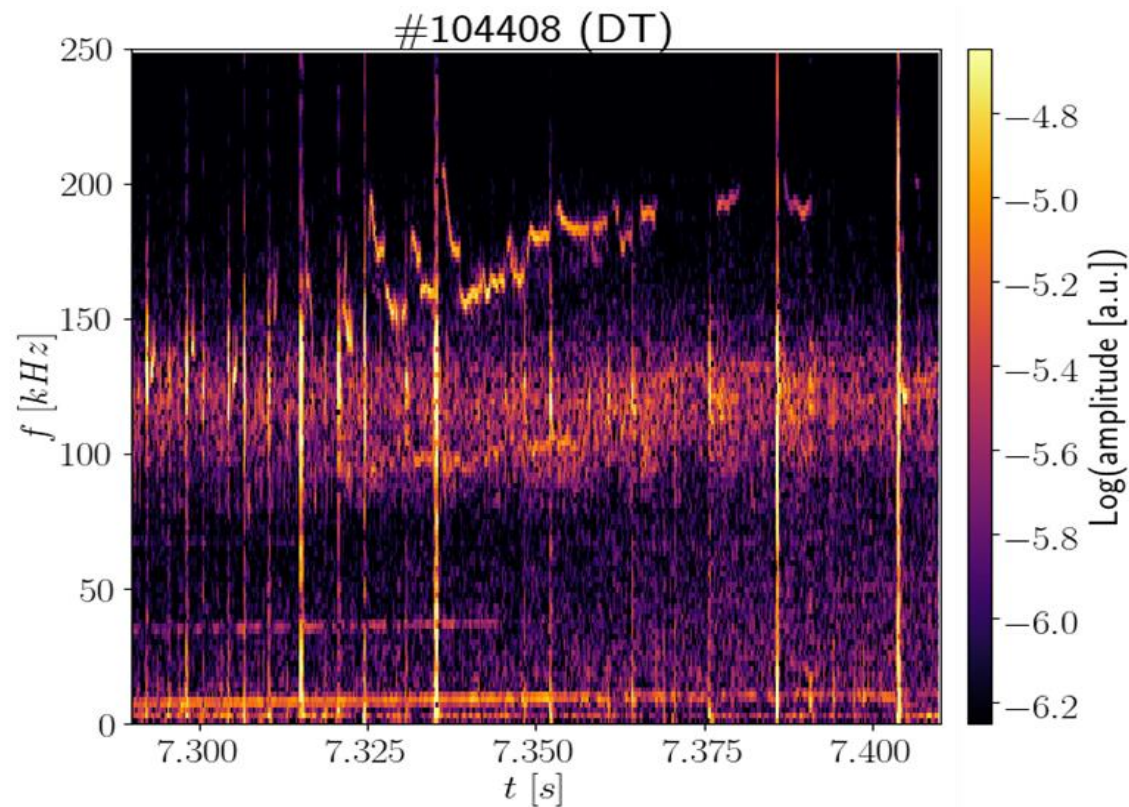
- Hybrid plasmas developed to explore W screening at edge [*].
- High power D neutral beam injection required to access screening conditions.
 - also generates high fusion yield!
- Injected into ~20/80 D/T fuel ion mix.
- High magnetic field $B_0 = 3.85 \text{ T}$. Plasma current $I_p = 2.1 \text{ MA}$.
- ICRH only starts after time of interest.

[*] D. King et al., in preparation (2025), J. Hobirk et al. *NF*, **63** (2023)

[12] H.J.C. Oliver et al 2025 Phys. Rev. Lett. (submitted).

THE OBSERVATIONS OF $n=0$ MODES

- Modes appear in data from magnetic probes from $7.28 \leq t [s] \leq 7.41$.
- Signal strong enough to measure toroidal mode numbers: $n = 0$ and $n = 1$.



SEARCH FOR THE $n=0$ MODE EXPLANATION

Two possible $n=0$ types of high-frequency modes were investigated: **Global Alfvén Eigenmode (GAE) and Vertical Displacement Oscillatory Mode (VDOM)**¹³

The codes MISHKA¹² and NIMROD¹³ were employed for this study

Connections to other $n=0$ observations^{14,15} are being studied

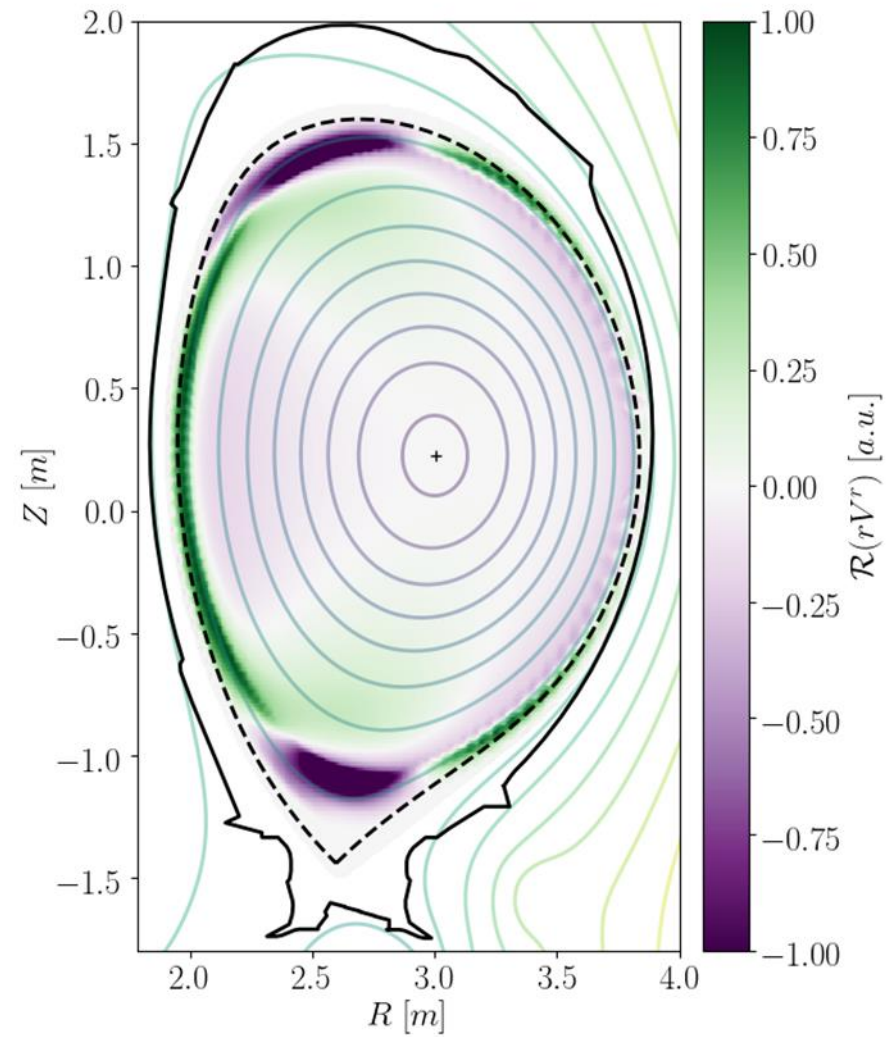
[12] H.J.C. Oliver et al 2025 Phys. Rev. Lett. (submitted).

[13] F. Porcelli et al 2025, This Conference.

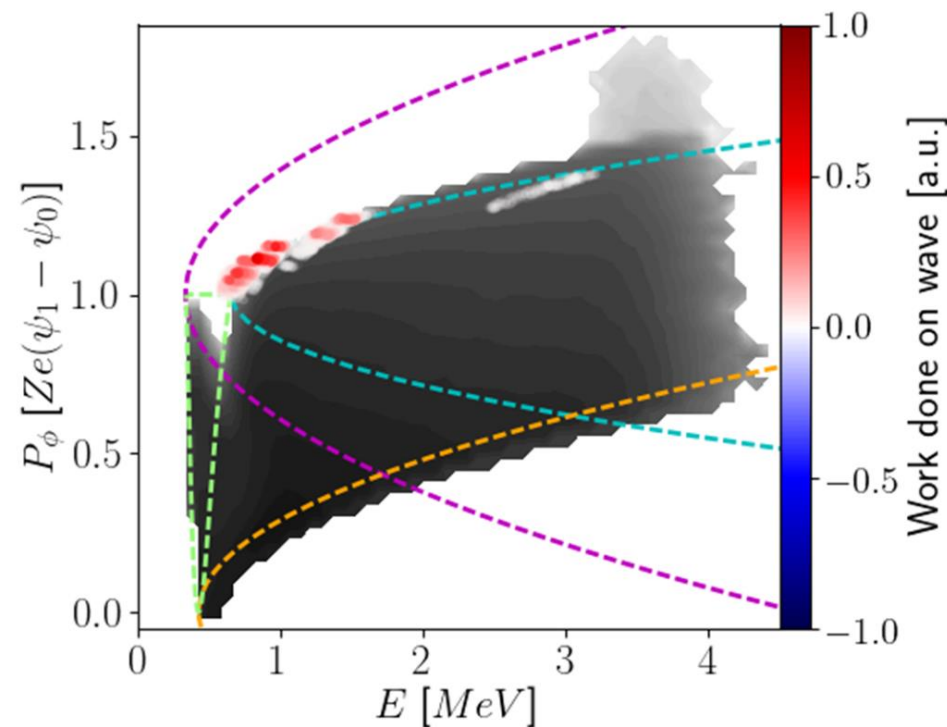
[14] Z. Chang et al 1995 Nucl. Fusion 35 1469.

[15] D.I. Refy et al 2020, Nucl. Fusion 60 056004.

n=0 GAE localised at the edge¹² is a possibility:



THE DRIVE FOR THE $n=0$ MODE COMES FROM $dF/dE > 0$ FOR ALPHA-PARTICLES AT THE EDGE:



The α -particles have sufficiently large orbit widths to access the mode location, while beam ions with narrower orbits cannot reach the plasma edge to damp the mode.

CONCLUSIONS

- “**Beam afterglow**” scenario was developed for TAE. This scenario resulted in $P^{\text{FUS}} = 11.8 \text{ MW}$, $Q=0.45$. TAEs were excited by α 's $\sim 50 \text{ ms}$ after NBI.
- TAE stability calculations showed a major role of the radiative damping.
- The radiative damping theory of TAE was revisited for low-shear plasmas thus developing a benchmark case for codes computing TAEs.
- The DTE2 experiments on α -particle bump-on-tail via NBI power modulation exhibited numerous near-axis modes in wide frequency range up to 450 kHz. The modes were detected in interferometry, reflectometry, and SXR.
- These modes were identified as on-axis α -particle-driven kinetic Alfvén modes predicted by Rosenbluth and Rutherford [10].
- Axisymmetric $n=0$ modes driven by positive energy gradients of α 's were observed in JET DT hybrid plasmas with NBI.
- These $n=0$ modes were identified as GAEs at the edge.
- Similar modes excited in burning plasmas may induce energy diffusion in phase space thus enhancing losses of α 's near trapped-passing boundary or the separatrix.