EUROfusion

Axisymmetric $(n = 0)$ high-frequency MHD oscillations at the pedestal of JET plasmas

L. Roque[1], P. Rodrigues[1], E. R. Solano[2] and JET Contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1] *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa , Portugal*

[2] *Laboratorio Nacional de Fusion, CIEMAT, 28040 Madrid, Spain*

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

Introduction

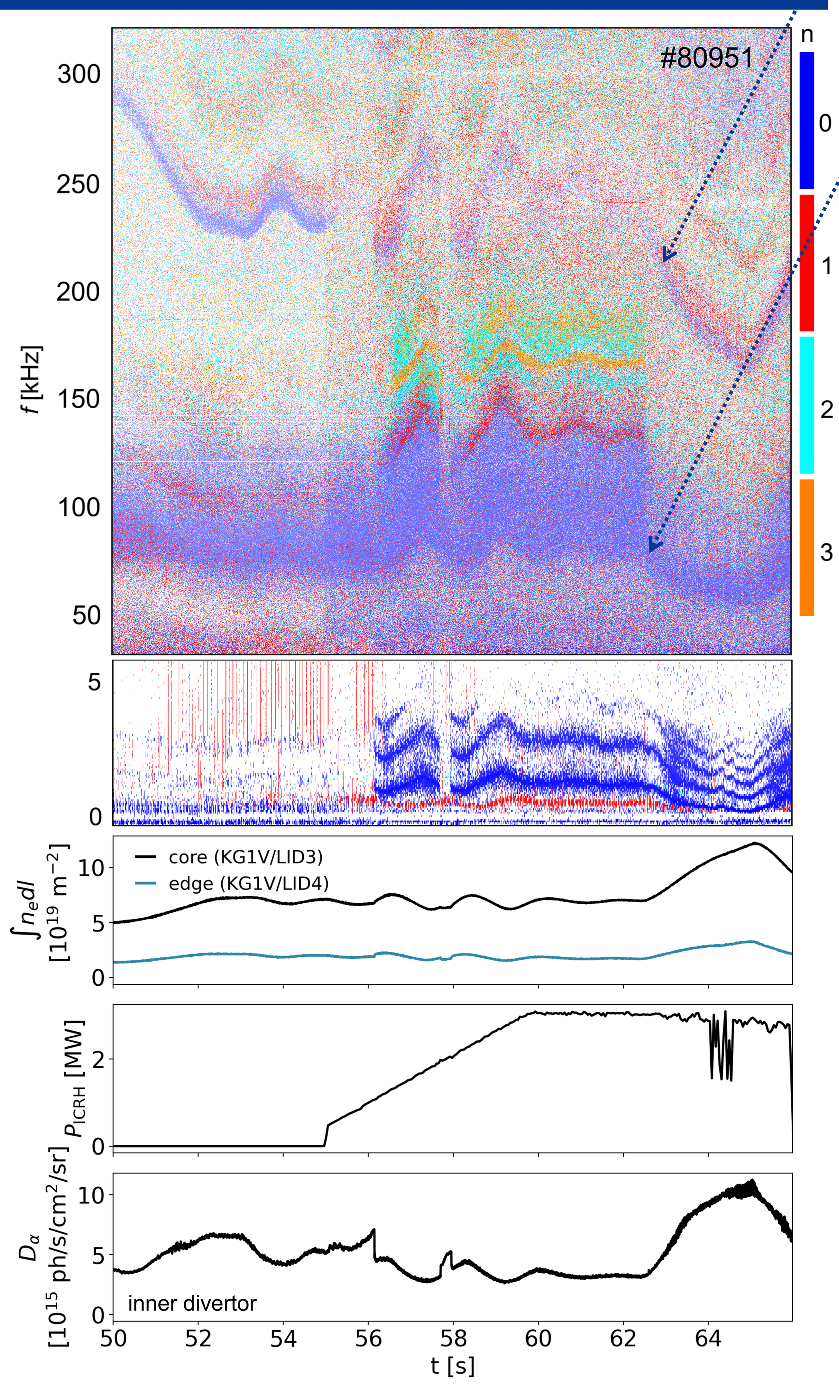
Long-lived axisymmetric ($n = 0$) quasi-coherent high frequency magnetic oscillations (HFOs, $50 - 500$ kHz**) in the TAE and EAE frequency range** have been reported **close to the L-H transition** at JET [1] and AUG [2] tokamaks. Despite some models [3], their nature remains **elusive**.

HFOs **are not restricted to L-H transitions scenarios** and appear in a variety of plasma compositions (H, D, D-He^3, D-T) with a wide range of plasma parameters and under different heating schemes (pure Ohmic, NBI and ICRH). Modes of Alfvénic nature with similar properties were observed on MAST [4] and COMPASS [5].

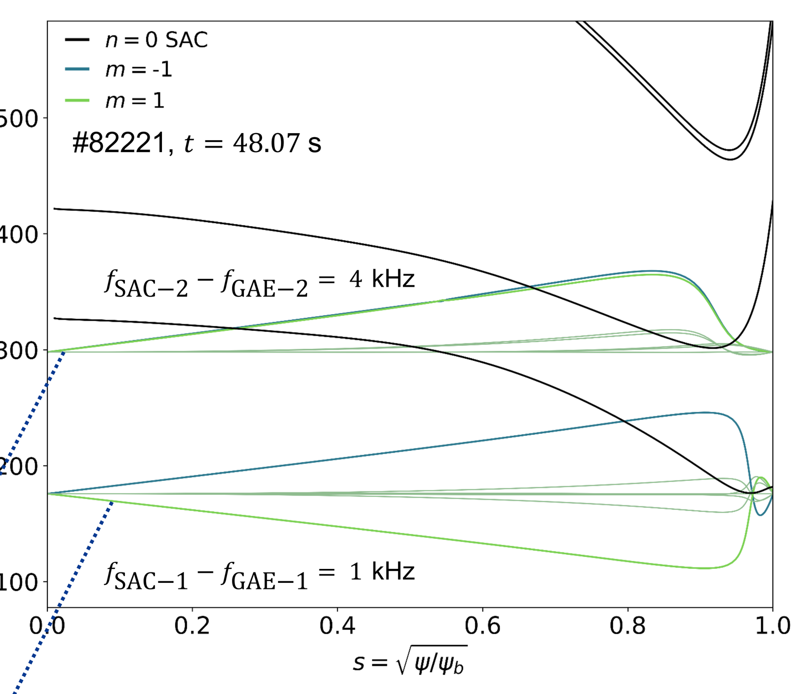
Here, we show that **axisymmetric HFOs** can be explained in light of **MHD theory** as $\boldsymbol{n = 0}$ **Global Alfvén Eigenmodes** (GAEs), whose frequencies we can robustly predict.

Experimental characterisation of HFOs

- HFOs appear **during L- and H-modes**;
- HFOs **persist for long periods** with relatively **low amplitude**;
- HFOs are **modulated by edge** $\boldsymbol{n = 0}$ $\boldsymbol{m = 1}$ **LFOs** emerging at the L-H transition;
  - M-mode [6] (or I-phase at AUG [2])
  - $f_{\text{M-mode}} \propto \frac{m}{r} v_A^{\text{poloidal}}$ [6]
- HFOs are present **before external heating power** is turned on, **while** it is on, and **prevail after** it is turned off;
- HFOs' signal is **stronger during Ohmic heating** phase;
- Generally, **NBI does not affect** HFOs;
- **ICRH** appears to **suppress** the 2$^{\text{nd}}$ HFO;
- 2$^{\text{nd}}$ HFO is considerably **attenuated during the H-mode**;
- Both $n = 0$ HFOs are often accompanied by analogous $n = 1$ (and faint $n = 2$) bands.



Axisymmetric shear Alfvén waves and continuum



Only a class of shear Alfvén Eigenmodes with $n = 0$ can exist: the **Global Alfvén Eigenmodes**. They arise due to and near a **local extremum of the shear-Alfvén continuum** (SAC) produced by **radial profiles** [7].

Cylindrical limit $n = 0$ SAC: $\omega^2 \approx \frac{B^2}{\mu_0 \rho} \frac{m^2}{q^2 R^2}$

Near the edge, $q \uparrow$ and $\rho \downarrow$ $\Longrightarrow \omega^2$ minimum

`MISHKA` [8] finds **two GAEs below the minimum** of the first two branches of the SAC computed by `CSMISH` [9] (left plot).

Analytic expression for the two lowest branches of the coupled SAC

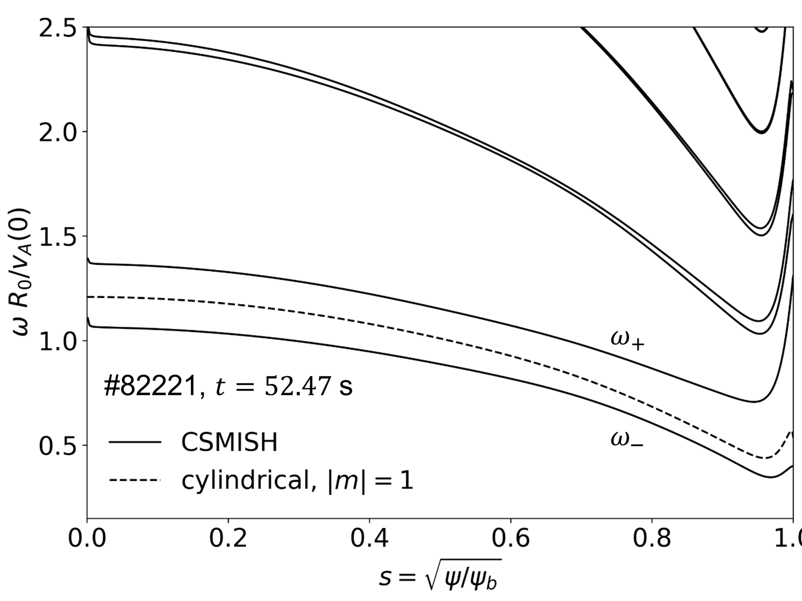
Motivation: $f_{\text{SAC}} \approx f_{\text{GAE}}$

Incompressible SAC $\equiv$ set of eigenvalues ω^2 that yields non-trivial solutions for [10]

$$\left[\frac{\omega^2 \rho |\nabla\Psi|^2}{B^2} + \boldsymbol{B}\cdot\nabla\left(\frac{|\nabla\Psi|^2}{B^2}\boldsymbol{B}\cdot\nabla\right)\right]\xi^A = 0$$

Analytic local magnetic equilibrium model [11]:

$$\Psi(r,\theta) = \Psi_b S_0 r^2 [\Theta_0(\theta) + \varepsilon r \Theta_1(\theta)]$$



In a first approach, the two lowest branches come from the **coupling of the Fourier harmonics** $\boldsymbol{m = \pm 1}$ $\Longrightarrow \xi^A = \xi^A_{-1} e^{-i\theta} + \xi^A_1 e^{i\theta}$. Up to first order terms in κ_s and ε,

$$\begin{bmatrix} e^{-i\theta} & e^{i\theta} \end{bmatrix} \begin{bmatrix} \frac{(1+\tilde{\rho}\tilde{\omega}^2 q^2)\kappa_s}{2q^2} & \tilde{\rho}\tilde{\omega}^2 - \frac{1}{q^2} \\ \tilde{\rho}\tilde{\omega}^2 - \frac{1}{q^2} & \frac{(1+\tilde{\rho}\tilde{\omega}^2 q^2)\kappa_s}{2q^2} \end{bmatrix} \begin{bmatrix} \xi^A_{-1} \\ \xi^A_1 \end{bmatrix} = 0$$

Equating the determinant to zero yields

$$\boxed{\tilde{\omega}^2_\pm = \frac{2 \pm \kappa_s}{\tilde{\rho} q^2 (2 \mp \kappa_s)}}$$

This analytic formula recovers previous numerical results [12]

$\varepsilon = \frac{a}{R_0}$ $\begin{cases} a \equiv \text{minor radius} \\ R_0 \equiv \text{magnetic axis position from torus axis} \end{cases}$

$\Theta_0(\theta) = 1 + \kappa_s \cos 2\theta + \kappa_a \sin 2\theta$

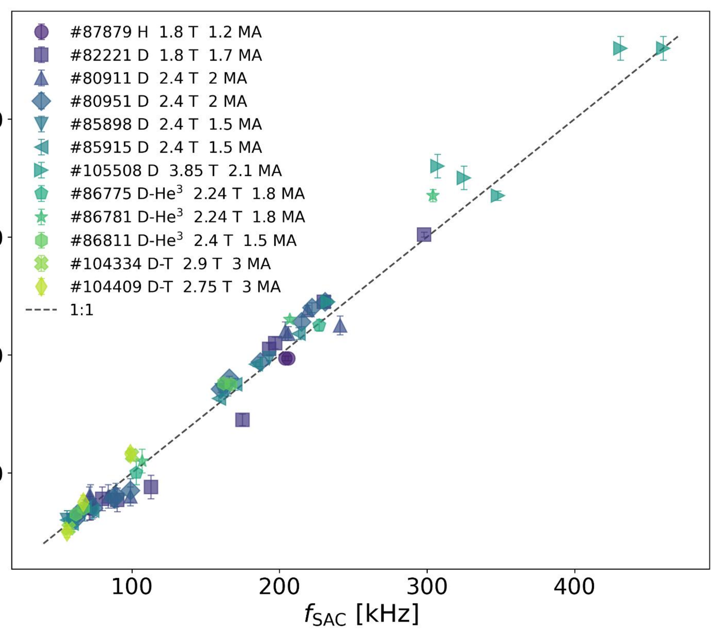
$\Theta_1(\theta) = \Delta_s \cos\theta + \frac{1}{4}\kappa_a \sin\theta + \eta_s \cos 3\theta + \eta_a \sin 3\theta$

$\kappa \approx \sqrt{\frac{1+\kappa_s}{1-\kappa_s}}$ $\begin{cases} \kappa \equiv \text{elongation} \\ \kappa_s \equiv \text{ellipticity} \end{cases}$

$\xi^A = \boldsymbol{\xi}\cdot\frac{\boldsymbol{B}\times\nabla\Psi}{|\nabla\Psi|^2} = \sum_m \xi^A_m(\Psi) e^{im\theta}$

$\tilde{\omega} = \omega R_0 / v_A(0)$, $\quad \tilde{\rho} = \rho/\rho(0)$

Experimental measurements versus numerical predictions



The experimentally measured **HFOs frequency ($\boldsymbol{f_{\text{HFO}}}$) agrees** with the **frequency of the SAC minima ($\boldsymbol{f_{\text{SAC}}}$)** computed by `CSMISH`.

The analysis was carried out for a comprehensive set of discharge covering a wide set of plasma compositions (H, D, D-He^3, D-T), plasma parameters ($I_p = 1.2 - 3.0$ MA, $B = 1.8 - 3.85$ T, $n_e(0) = 2.4 - 6.8$ m^{-3}), and heating schemes.

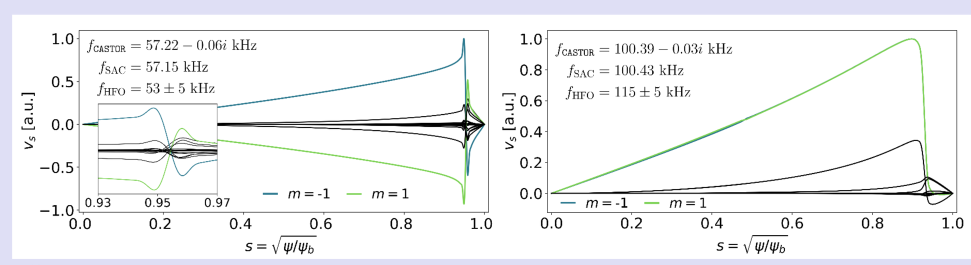
Ideal MHD can accurately predict the frequencies of axisymmetric HFOs

Estimation of GAEs' frequency from the SAC minima is a more **useful** and **robust** approach than mode calculation: `MISHKA` did not always converge to discrete modes.

Non-ideal terms for numerical GAE structure calculation

Numerically, as the pedestal grows steeper, the frequency of the GAEs increases, eventually stepping into the SAC $\Longrightarrow$ `MISHKA` converges to singular solutions.

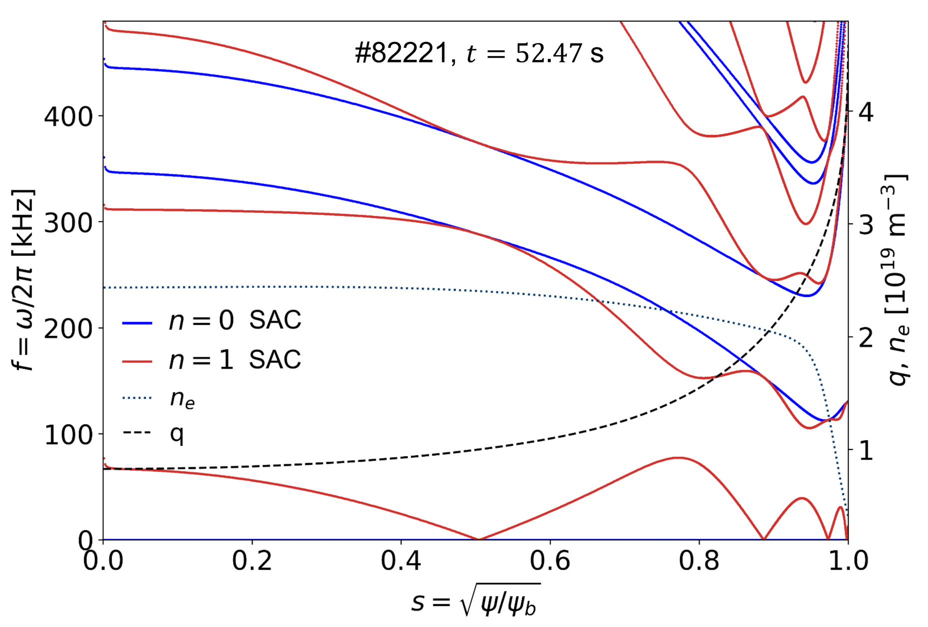
Resistive `CASTOR` [13] computes global modes with $\Re\mathfrak{e}(f)$ close to the SAC (from ideal MHD).

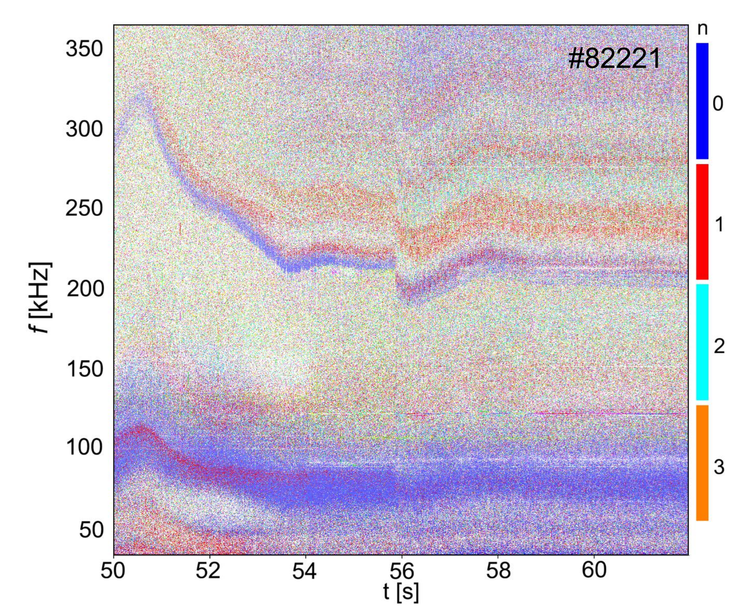


#104334, $t = 45.62$ s

Non-axisymmetric HFOs

The frequency modulation and value of $\boldsymbol{n \neq 0}$ **HFOs** suggest they **are AEs** as well.
1$^{\text{st}}$ HFOs: $f_{\text{n=1}} \lesssim f_{\text{n=0}}$; 2$^{\text{nd}}$ HFOs: $f_{\text{n=1}} > f_{\text{n=0}}$ $\longrightarrow$ similar to the SAC branches.





Conclusions and future prospects

Pragmatic interest of HFOs:

- HFOs appear in a variety of plasma scenarios and span a long time window
- f_{HFOs} agree with f_{SAC} at the minima
- Analytical expression for $n = 0$ SAC
  - relates f_{HFOs} with κ_s, q, and ρ

MHD marker for reliable equilibrium reconstruction at the plasma edge

References

[1] N. Vianello *et al.*, 42$^{\text{nd}}$ EPS Conference on Plasma Physics (2015)
[2] D. I. Réfy *et al.*, Nucl. Fusion **60**, 056004 (2020)
[3] O. Grover *et al.*, Nucl. Fusion **64**, 026001 (2024)
[4] K. G. McClements *et al.*, Nucl. Fusion **42**, 1155 (2002)
[5] T. Markovič *et al.*, 44$^{\text{th}}$ EPS Conference on Plasma Physics (2017)
[6] E. R. Solano *et al.*, Nucl. Fusion **57** 022021 (2017)
[7] L. Villard and J. Vaclavik, Nucl. Fusion **37**, 351 (1997)
[8] A. Mikhailovskii *et al.*, Plasma Phys. Rep. **23**, 844 (1997)
[9] G. T. A. Huysmans *et al.*, Phys. Plasmas **8**, 4292 (2001)
[10] C. Z. Cheng and M. S. Chance, Phys. Fluids **29**, 3695 (1986)
[11] P. Rodrigues and A. Coroado, Nucl. Fusion **58**, 106040 (2018)
[12] H. J. C. Oliver *et al.*, Phys. Plasmas **24**, 122505 (2017)
[13] W. Kerner *et al.*, Journal of Computational Physics **142**, 271 (1998)

JET

Acknowledgments

IPFN activities were supported by FCT—Fundação para a Ciência e Tecnologia, I.P. by project reference UID/50010/2025, UID/PRR/50010/2025, UID/PRR2/50010/2025 and LA/P/0061/2020. This research was supported in part by grant PID2021-127727OB-I00, funded by MICIU/AEI/10.13039/501100011033 and by ERDF/EU.

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

AGENCIA ESTATAL DE INVESTIGACIÓN

EPS 26 PLASMA PHYSICS EDINBURGH

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.