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## Studies of Alfvén Eigenmodes on JET with both experimental measurements with the AEAD and modelling with GTC.

N. Fil<sup>1,2</sup>, M. Porkolab<sup>1</sup>, V. Aslanyan<sup>1</sup>, P. Puglia<sup>3</sup>, S. Dowson<sup>2</sup>, M. Fitzgerald<sup>2</sup>, S. E. Sharapov<sup>2</sup>, H. K. Sheikh<sup>2</sup>, J. Bao<sup>4</sup>, Z. Lin<sup>4</sup>, P. Blanchard<sup>3</sup>, A. Fasoli<sup>3</sup>, D. Testa<sup>3</sup>, J. Mailloux<sup>2</sup>, M. Tsalas<sup>2</sup>, M. Maslov<sup>2</sup>, A. Whitehead<sup>2</sup>, R. Scannell<sup>2</sup>, S. Gerasimov<sup>2</sup>, S. Dorling<sup>2</sup>, T. Blackman<sup>2</sup>, G. Jones<sup>2</sup>, A. Goodyear<sup>2</sup>, K. K. Kirov<sup>2</sup>, R. Dumont<sup>5</sup>, M. Podesta<sup>6</sup>, and JET Contributors<sup>\*</sup>

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

<sup>1</sup>MIT PSFC, 175 Albany Street, Cambridge, Massachusetts 02139, USA

<sup>2</sup>CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK

<sup>3</sup>Ecole Polytechnique Fédérale de Lausanne (EPFL), SPC, CH-1015 Lausanne, Switzerland

<sup>4</sup>Department of Physics and Astronomy, UCI, California 92697, USA

<sup>5</sup>CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

<sup>6</sup>PPPL, Princeton University, Princeton, New Jersey 08543, USA

### A. Introduction.

In magnetic fusion reactors, plasma reactivity is reached and sustained by the thermalization of the energy of fast particles, such as ions accelerated by neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH), or fusion produced alpha particles ( $\alpha$ 's). Enhanced transport and losses of suprathermal particles during slowing down can be expected in the presence of waves that resonate with their motion. To understand the interaction between plasma waves and fast particles is therefore critically important because of its influence on the performance (i.e., fusion gain) of a burning plasma [1].

The Alfvén Eigenmode Active Diagnostic (AEAD) [2,3] is unique in the fact that it can resonantly probe damped AEs (those where the energetic particle drive is insufficient to overcome the damping) and can therefore detect modes not visible on the usual suite of diagnostics, such as magnetic probes or reflectometry. On JET, the AEAD will be continuously operated in the full range of isotope experiments (DD and TT) preceding a full DT campaign which is anticipated to be one of the last opportunities to explore fast ion physics in fusing plasmas before ITER operation. The AEAD system will play a critical role in the upcoming JET DT experiments as the expected fusion gain  $Q$  will be low enough that AEs will be near marginal stability. Hence, the new upgraded AEAD system [4,5] with superior sensitivity and mode control will bring significant advantages in the exploration of the interaction between alphas and Alfvén modes in the absence of alpha-driven instabilities. Recent efforts have been made on JET to develop a scenario to observe unstable Toroidal AEs (TAEs) attributed to fusion  $\alpha$ 's in DT

\*See the author list of E. Joffrin *et al.* accepted for publication in Nuclear Fusion Special issue 2019, <https://doi.org/10.1088/1741-4326/ab2276>

Contact: [nicolas.fil@ukaea.uk](mailto:nicolas.fil@ukaea.uk) or [filn@psfc.mit.edu](mailto:filn@psfc.mit.edu)

plasma [6]. In preparation of these experiments, a wide range of experimental and theoretical studies have been undertaken to study AEs stability while using the synergy between the AEAD and modelling codes [7] such as the MHD code MISHKA [8] and the gyrokinetic code GTC [9]. The Gyrokinetic Toroidal Code (GTC) self-consistently treats bulk ions, energetic ions, electrons and fields which allows us to study both unstable AEs observed passively and stable AEs excited resonantly by the AEAD. In this paper we present evidence for this synergy and will illustrate its importance with initial AEAD measurements during the JET restart campaign.

### B. Commissioning of the AEAD during the restart of JET 2019 campaign.

The AEAD is composed of two arrays of four antennas located in two toroidally opposite octants (Oct 4 and 8), below the two Neutral Beam Injection (NBI) ports. Each antenna is fed with an individual 4kW amplifier. Schematic diagrams of the AEAD are presented in Refs. [4] and [5] (Figs.1) along with a detailed description of the diagnostic. Three filters are currently in use:  $f_c = 50, 150$  and  $250$  kHz, with the bandwidth of each filter being  $f_c/2$ . Each wire-loop antenna is equivalent to an oscillating magnetic dipole which produces a magnetic perturbation proportional to the antenna currents, typically with  $\delta B/B_0 \sim 10^{-5}$  at the plasma edge. When an AE resonance is met we can measure the response on magnetic probes. The digitized magnetic probe signals are used by the Alfvén Eigenmode Local Manager (AELM) software [10] to detect and classify AEs in real time and selectively reverse the direction of the frequency sweep, thereby continuously tracking the evolution of a mode during a pulse. This real-time detection and rapid post-pulse analysis allow the “inter-shot” optimization of the antenna parameters to achieve the relevant physics objectives. During the JET restart the AEAD has been commissioned and we have optimized the control of the RF current and voltage as well as the phase between the antennas for the three set of filters. We have also operated the AEAD during NBI, ICRH, ILA (ITER-like Antenna) commissioning and pellets injection where we have detected many resonances due to the AEAD excitation.

As an example, below we present a study of the effect of the RF phase change on the AEAD response during a pulse. JPN#93662 and #93663 are similar JET restart pulses with  $B = 2.7$  T,  $I = 2.0$  MA,  $n_e(0) \cong 10.0 \cdot 10^{19} m^{-3}$ ,  $T_e(0) \cong 2.7 - 3.1$  keV,  $6.0 MW < P_{NBI} < 10.0 MW$  and  $P_{ICRH} = 0.0$  MW. When we change the phase between antennas, the power deposited on specific toroidal mode number ( $n$ ) varies. In JPN #93662 at  $t = 43$  s we switched the phase from  $0^\circ$  to  $180^\circ$  for the antennas 5 and 7 on Octant 8 (see Figure 1) which triggers a power deposition on odd  $n$  ( $43.5 < t[s] < 47.5$ ) instead of even  $n$  ( $40.5 < t[s] < 43.0$ ). In JPN #93663, the RF phase of the antennas in Octant 8 have been set to change from  $180^\circ$  to  $0^\circ$  (odd to even  $n$ ) at the same time as in JPN #93662. In Figure 1, we show the responses of two magnetic pick-up coils (T009 and I802) where the peaks represent the resonances – these resonances have also been observed on the other coils available around the vessel. From the phase changes between

the antennas, the resonances appear to be even  $n$  since they disappear when we deposit the RF power on odd  $n$ .

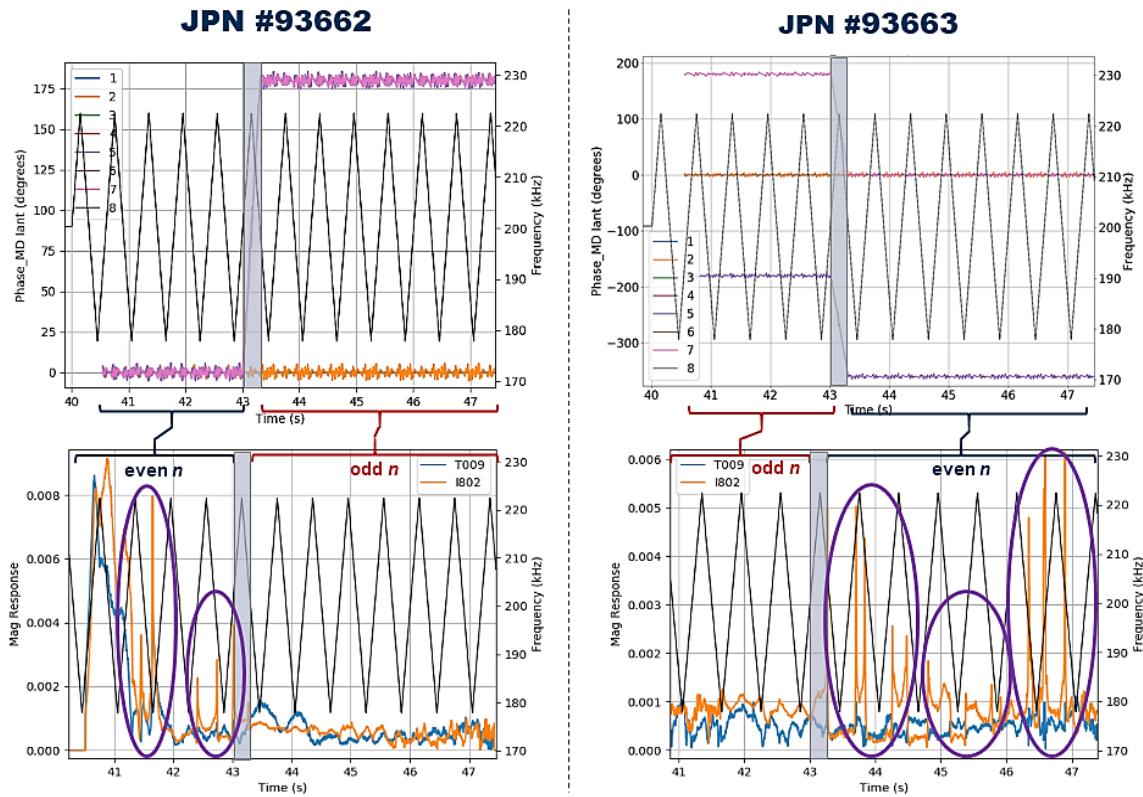


Figure 1 – JPN#93662-93663 – restart pulse – AEAD commissioning – study of the effect of phase change during a pulse. (top left) The RF phase of the antennas in Octant 8 have been set to change from  $0^\circ$  to  $180^\circ$  (which change the power deposited from even to odd  $n$ ). (top right) The RF phase of the antennas in Octant 8 have been set to change from  $180^\circ$  to  $0^\circ$  (odd to even  $n$ ). (bottom) the resonances observed on two magnetic pick-up coils (T009 and I802). These resonances appear to be even  $n$ .

Each resonance can be fitted to obtain the frequency and the damping rate of the mode [7]. The AEAD has also been operated during first experiments of JET C38 campaign where we observed marginally destabilized Alfvén modes on Mirnov pick-up coil spectra while measuring the frequency and damping rates of the same modes with the AEAD. More effort will now be made on the excitation of higher  $n$  modes by tuning the phases between antennas and by modes in real-time. The AEAD will also be used in future experiments to detect and measure low frequency modes such as Beta-induced AEs (BAEs), Beta-induced Alfvén Acoustic Eigenmodes (BAAEs), Geodesic Acoustic Mode (GAMs), and Reverse-Shear AEs (RSAEs).

### C. Modelling, MHD and gyrokinetic codes.

In support of the JET experiments, theoretical studies are undertaken with modelling codes such as MISHKA [8] and GTC [9] to study the stability of TAEs as well as low frequency modes excited by energetic particles or the AEAD. The use of GTC has been motivated by the advantage of the gyrokinetic approach in comparison with the conventional approach to numerical investigations of AEs and their growth and damping rates. The conventional approach is to

compute the eigenmode structure and real frequency, often with an ideal-MHD code like MISHKA, and perturbatively compute dissipative rates and the contributions of energetic particles. The advantage of the gyrokinetic approach is the self-consistent solution to the structure and drive/damping mechanisms, even in the presence of a significant population of energetic ions (or ‘fast’ ions). Initial results of GTC simulations, including a comparison to JET experiments from last campaign have been published recently [7].

A robust workflow has been setup to verify and validate the equilibrium and plasma profiles used as inputs to our modelling codes to appropriately compare our experimental results with theoretical predictions. We have a synthetic antenna model in GTC to determine the stability of predicted modes in a similar fashion as the resonant excitation of modes by the AEAD. We can also separate and identify different damping/driving mechanisms such as continuum, radiative, and Landau damping, and instability drive by the fast ion gradients in GTC.

#### **D. Summary and Conclusions.**

A wide variety of modes such as TAEs, BAEs, BAAEs, GAMs and RSAEs are studied with the AEAD during JET experiments, forming an important synergy with theoretical models as well as with other JET diagnostics. This will help to prepare and optimize alpha physics studies in the planned JET DT experiments and will improve the accuracy of extrapolations to ITER.

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