Progress and first measurements from the upgraded Alfvén Eigenmode Active Diagnostic on JET

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Alfvén eigenmodes driven by fast particles are an important type of ideal MHD instability, frequently observed in tokamaks, particularly the Toroidal Alfvén Eigenmode (TAE). Unstable TAEs are of importance to fast particle confinement in future devices, such as ITER[1]. Models predicting the stability of such modes must be augmented by direct measurements of damping rates by external antennas. Such measurements on JET have been undertaken for over 20 years, starting with a Saddle Coil exciter[2].

The Alfvén Eigenmode Active Diagnostic (AEAD) has recently been upgraded[3] and commissioned with a set of 4 kW amplifiers and associated support hardware as shown in Fig. 1. In-vessel connections are currently available for one group of four antennas below the outboard midplane and another group of two located toroidally opposite. Each AEAD antenna consists of a rectangular coil with 18 turns of inconel wire. With antennas in each group separated

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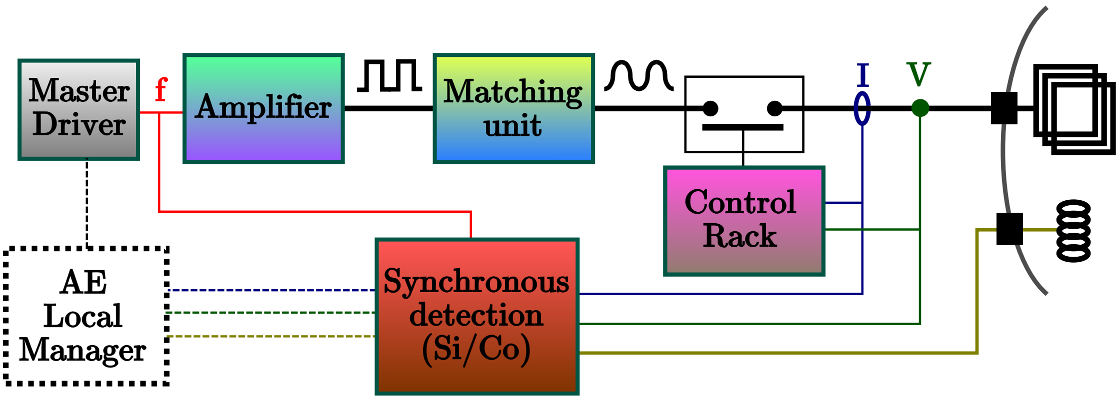

Figure 1: *Schematic diagram of the AEAD system, showing the generation and transmission of RF power to the antennas and the synchronous detection, control and protection systems.*

toroidally by 5°, the relative phasing of the individual driving amplifiers can be chosen to maximize the excitation of a particular toroidal mode number, up to $|n| = 15$. A matching unit is used to account for the strong frequency dependence of the impedance of antennas and transmission lines. Part of the unit is a low-pass filter used to remove the harmonics generated by the switching amplifiers, so that the AEAD operates in distinct frequency bands $f_0 < f < 2f_0$. At present the 125-250 kHz range has been commissioned, though work is being carried out to allow inter-shot switching of the frequency bands to the 75-150 and 25-50 kHz ranges.

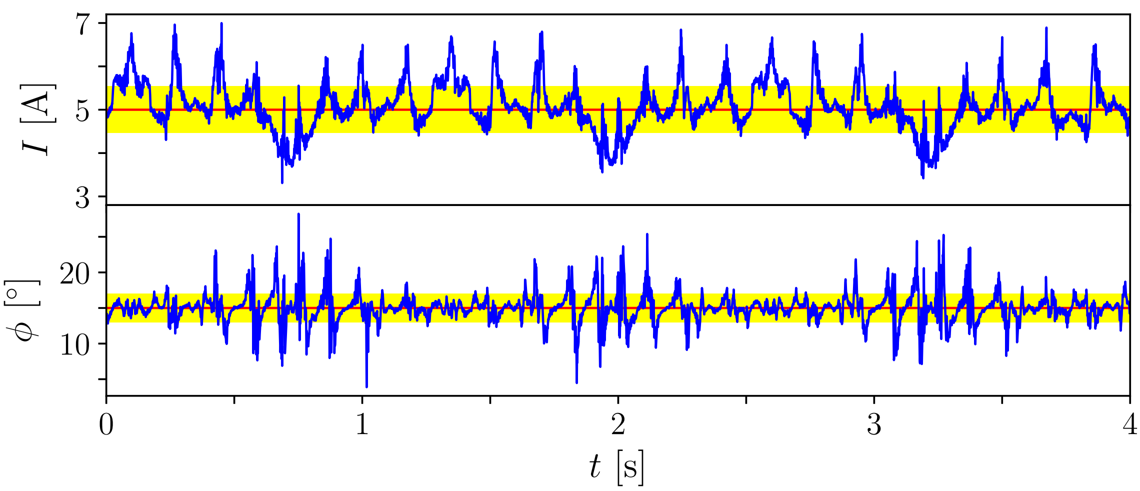

Figure 2: *Measured (blue) current amplitude and phase delivered on plasma by antenna 2 in JPN #92414. The phase is defined relative to antenna 1 and the target parameters of $|I| = 5$ A, $\phi = 15°$ are indicated in red. The RMS deviation is highlighted in yellow. The frequency was swept at the maximum rate of 200 kHz/s.*

The most important parameters of AEAD are the antenna currents and their phases, which correspond linearly to the magnetic field produced. Direct control of all antenna currents is performed by the Master Driver, based on a Field-Programmable Gate Array (FPGA). Low voltage digital reference signals are sent to the amplifiers along with analog gain. A new feed-forward control system based on the frequency response has been implemented in two antennas, resulting in improved current control as shown in Fig. 2. This paradigm will be extended to the remaining antennas and a similar algorithm implemented for phase control. The voltage, current and magnetic coil signals are detected synchronously by in-phase and quadrature electronic integrators. In order to protect the vacuum feedthroughs, limits of 15A and 1.1 kV are enforced by a high-speed control rack with a robust independent detection system.

Marginally stable modes are detected and their damping rates measured as resonances in the magnetic probe signals as the antenna frequency is scanned across the mode. An example of a resonance, measured after the NBI phase of a JET divertor pulse, is shown in the complex-plane in Fig. 3. A transfer function[2] has been fitted to obtain a normalized damping rate of $\gamma/\omega = 2.74 \pm 0.59\%$. This measurement is an upper bound to the damping of $0.2 \lesssim \gamma/\omega \lesssim 0.5\%$ predicted by the CASTOR-K code, which does not include continuum damping. Frequency sweeps are controlled through the Alfvén Eigenmode Local Manager (AELM)[4]. This algorithm is able to detect resonances and identify their mode numbers in real time, thereby selectively tracking modes of interest. This capability has been extensively tested post-upgrade with prominent $n = 0$ modes in limiter plasmas, as shown in Fig. 4. However, mode identification has been challenging since commissioning was completed, due to the availability of only three high-resolution toroidal magnetic probes; replacement of failed coils is due to be completed in the 2017 JET shutdown. A total of 13 coils will be available, allowing mode number identification up to $|n| \leq 15$.

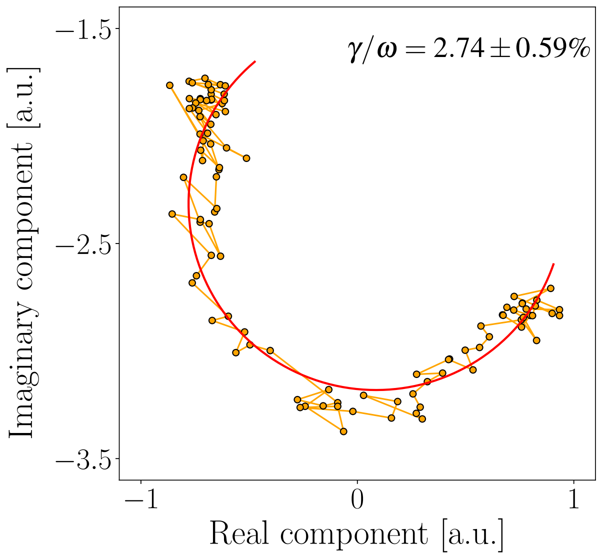

Figure 3: *Magnetic probe signals of a resonance in a deuterium plasma captured during the 2016 campaign in JPN #92416. A transfer function[2] has been fitted this data as shown.*

In summary, the AEAD has been successfully upgraded, with new excitation and control

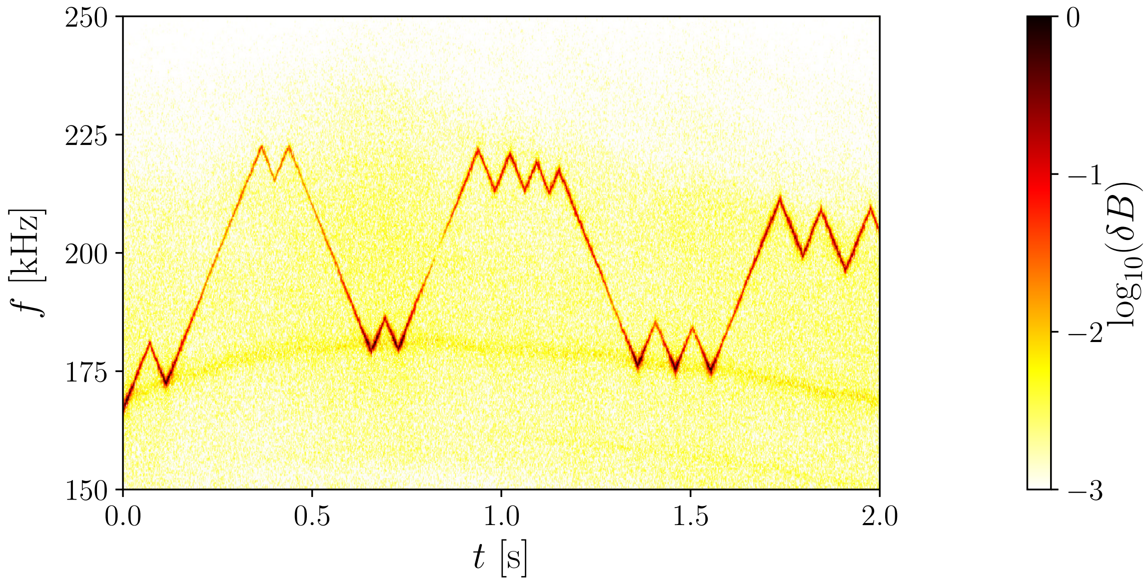

Figure 4: *Magnetic spectrogram from the Ohmic phase of JPN #92087 showing the antenna waveform, with the AELM tracking* $n = 0$ *modes, one of which is faintly visible around 175 kHz.*

hardware, and commissioned, demonstrating the ability to detect and track modes. Currents of ≥ 5 A have been demonstrated in all active antennas; continued optimization of the feed-forward control system will enable further increases in current and phase control. Modifications to the low-pass filters currently underway will allow the probing of low frequency modes, such as the Beta Alfvén Eigenmode (BAE) and Geodesic Acoustic Mode (GAM), which are relevant to future experiments.

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References

[1] M. Fitzgerald, S.E. Sharapov, P. Rodrigues and D. Borba, Nucl. Fusion **56**, 112010 (2016).

[2] A. Fasoli, D. Borba, G. Bosia, *et al.*, Phys. Rev. Lett. **75**, 645 (1995).

[3] P. Puglia, W. Pires de Sa, P. Blanchard, *et al.*, Nucl. Fusion **56**, 112020 (2016).

[4] D. Testa, H. Carfantan, A. Fasoli, *et al.*, Fusion Engineering and Design **86**, 381 (2011).