TAE ANTENNA FOR ALFVÉN MODE STUDIES ON MAST

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The physics of highly energetic particles in tokamaks and their associated Alfvén instabilities is an important issue for the fusion programme. Present-day STs, with low toroidal magnetic field, typically have super-Alfvénic NBI providing the possibility of studying these potentially dangerous instabilities and their influence on fast particle confinement. These instabilities are seen on MAST as discrete, weakly-damped, toroidal and elliptical Alfvén eigenmodes (TAEs and EAEs) with frequencies that follow the Alfvén scaling with equilibrium magnetic field and density, $f \sim B/n^{1/2}$, or they are detected as energetic particle modes (EPMs) whose frequencies sweep down on a time scale faster than the equilibrium parameters change.

Fig.1. One coil of the TAE Antenna array on MAST

Perturbative TAEs (80-150kHz) and EAEs (160-300kHz) have been studied intensively on MAST, both theoretically and experimentally [1]. These modes are supported by the thermal plasma in the absence of fast particles, and they can be destabilised by fast particles even for $\beta_{fast} << \beta_{thermal}$. Data from both MAST and START suggest that as $\beta_{thermal}$ increases, the core Alfvén instabilities weaken, and both the mode amplitude and number of unstable modes are reduced.

The naturally occurring spectra of the TAE, EAE and EP modes seen on MAST have significant overlaps through a wide range of the ($\beta_{fast}/\beta_{thermal}$; β_t) parameter space, making mode identification difficult and the extrapolation of AE data towards next-step burning plasmas less reliable. In addition, because of the large orbit width of the beam ions on MAST, it is only possible to excite modes with low toroidal mode numbers $n \leq 3$.

An alternative method of studying Alfvén Eigenmodes is to use an external antenna to excite these modes directly. This can help distinguish between TAEs and EPMs, and allows higher mode number AEs to be studied. Such experiments have previously been performed on JET [2] and more recently on C-Mod [3]. The first three coils of a TAE antenna array have been installed on MAST (a single coil is shown in figure 1). In this paper we describe the engineering and physics basis of the coil and array design, first experimental observations using the antenna array and future plans to expand the array to a system of eighteen coils.

MAST TAE Antenna Array

The trial installation of a TAE antenna array on MAST is designed to test the engineering behind the coil design, whilst still making it possible to perform useful physics studies. The antenna array consists of three coils with a relative toroidal position of 0°, 60° and 180°. Each coil is of a four turn rectangular pancake design 600mm long by 270mm, made from 20×9mm aluminium conductor with a separation between conductors of 4mm. The feed to the coil is co-axial made from an aluminium rod and tube, with an additional bellows and steel tube cover to protect the feed from the plasma.

The primary electrical insulation for the coil is a 20micron thick Al_2O_3 ceramic coating which is deposited on the coil using an electrolytic process, this provides insulation up to 3kV. The advantage of this coating is high hardness and high wear resistance (coated components are harder wearing than stainless steal). It is flexible, forming a good bond with the substrate; it can withstand temperatures up to 2000ºC and is highly resistant to thermal shock. To provide protection from the plasma and additional electrical isolation the whole coil is encased in a 15mm thick Boron Nitride shell. This cover is then painted externally with colloidal graphite to reduce reflections which would affect visible imaging diagnostics.

Figure 2 shows the poloidal location of the antenna array and its relation to a typical MAST equilibrium. The coils are mounted off brackets attached to the lower P5 poloidal field coil. An off mid-plane position has been chosen so as not to mask the views of mid-plane diagnostics or block ECRH/NBI plasma heating. In the location chosen the antenna is in the shadow of the P3 and P5 coils and so does not limit the size of MAST plasmas, it is also sufficiently far away from the P3 coil so as not to interfere with the merging compression plasma formation scheme used on MAST [4]. To date no significant plasma interaction with the TAE coils has been observed during normal operations or during plasma disruptions.

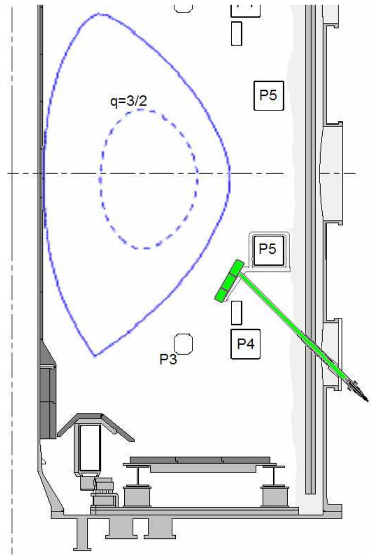

Figure 2: Position of the TAE antenna array w.r.t a typical MAST equilibrium. Pulse #10597, t=255ms

An additional constraint on the positioning of the coils was the need to reduce induced eddy currents which would reduce the effectiveness of the antenna array and modify the toroidal mode spectra produced.

Power Supplies

Each coil is powered by its own individual power amplifier, with each amplifier capable of producing 500W or ~3.3A into a 50Ω load. To match the TAE coil to the power supply, a matching circuit is fitted at the coil feed-through (see figure 3). This treats the coil as the inductor in a pi-network. Tests using a network analyser show a good match between load and amplifier with the load impedance remaining in the range 48-51Ω over a wide frequency range (50-700kHz). Further tests, monitoring the forward and reflected power seen by the amplifier, confirm this match with the fraction of reflected power remaining below 10%.

Note though, that the matching circuit can be further optimised if a smaller frequency range is selected for study. With the existing matching circuit, only ~30% of the current (i.e. 1A) flows through the coil and only a tiny fraction of the power is emitted as RF, the majority of the power being dissipated in the 50Ω resistor in the matching circuit.

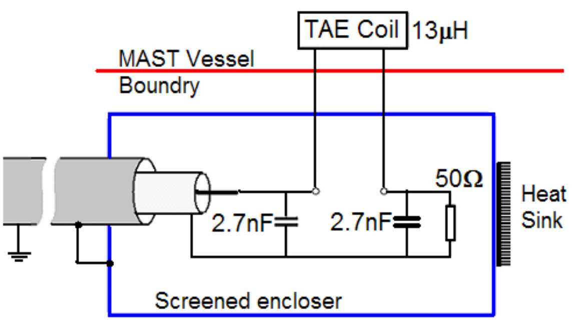

Figure 3: Schematic of the matching circuit used with TAE coil. The circuit is fitted in a screened enclosure mounted over the coaxial feed-through for the TAE coil.

The amplifiers are of type class "B". Although such units are reasonably efficient they can have a large cross- over distortion and hence the signal contains many harmonics. For the amplifiers used on MAST the amplitude of the third harmonic is typically 10% (-20dbc) of that of the fundamental. These higher harmonics can clearly be seen on the spectral plots shown below.

Toroidal Mode Spectrum Calculations

Using the poloidal position of the antenna array shown in figure 2, the toroidal mode spectra for various combinations of coils were calculated. These spectra were characterised by Fourier decomposition of the field perturbation perpendicular to the q=3/2 flux surface (B⊥) for a typical MAST equilibrium. With two coils at 0° and 180°, the spectrum contains either entirely odd or even modes depending on the relative phase of the current in the two coils. With the currents in phase the predominant mode is n=2, out of phase it is n=1.

Figure 4 shows B⊥ as a function of *n*, toroidal mode number, calculated for three coils in series at toroidal angle 0°, 60° and 180° with 4A.turn in each coil. The three plots show the different spectra produced when one coil is in anti-phase compared with the others, the legend indicates the phase of each coil. This result shows that with three coils it is possible to produce a spectrum which is predominantly either *n*=1, 2, or 3. It was decided on the basis of these calculations and taking into account cost, engineering effort and the physics requirements that three coils with a relative toroidal position of 0°, 60° and 180° would be optimal for initial tests.

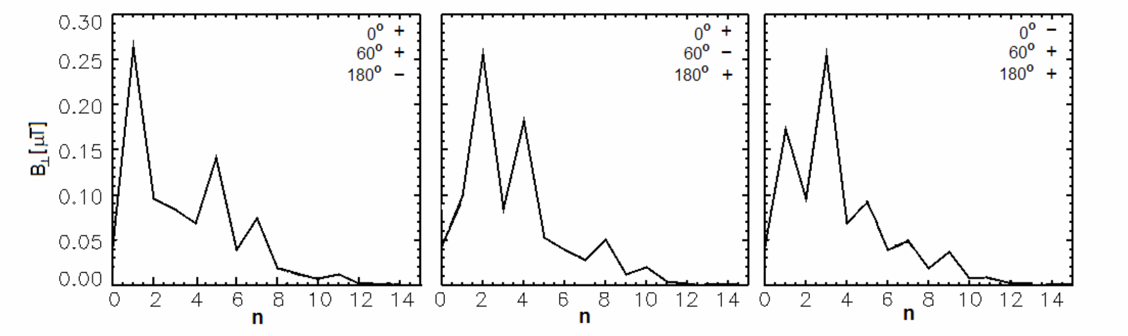

Figure 4: Amplitude of field perturbation calculated on the q=3/2 surfaces for various combinations of currents in the MAST three coil TAE antenna array. Coil current 4A.turn. In the three cases shown the dominant perturbation is either n=1, 2, or 3.

Experimental results

Initial observations have concentrated on monitoring the effect of plasma operations on the power supplies and commissioning of the control system; to date this has been done for single and two coil operations (180° separation). Diagnostics include current and voltage sensors on the coils along with measurement of the forward and reflected power measured by the amplifiers. The amplifiers are driven from a reference waveform generator with externally controlled FM modulation. Figure 5 shows typical operation of the antenna taken during pulse #18303. The drive signal is gated to operate between t=[0.1,0.3]s. The low reflected power measurement of ~5W compared to the forward power 460W, shows there is a good match to the load even in the presence of the plasma though, as can be seen from the TAE coil voltage monitoring, there is significant induced e.m.f due to modes in the plasma, in this case tearing modes with a

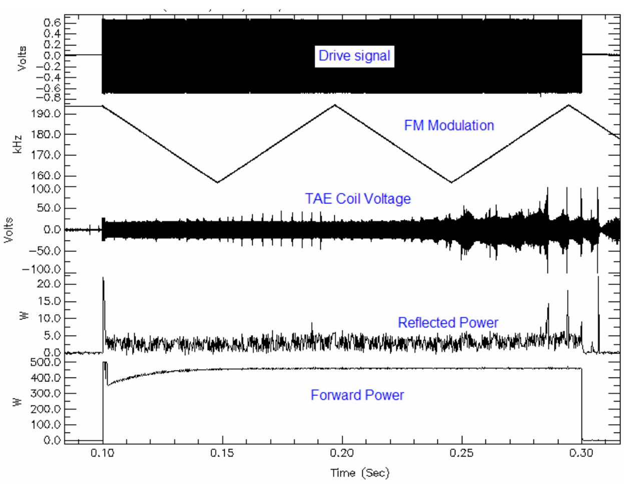

Figure 5. Signals from TAE coil and power supply monitoring diagnostics for pulse 18303.

frequency in the range 15-25kHz. In calculating toroidal mode spectra we have assumed that the same current flows in each coil (either in or out of phase). Fourier analysis of the currents for two coil operation showed phase agreement to be excellent.

MAST is uniquely placed to study TAE perturbations with a large number of Mirnov coils available in both poloidal and toroidal arrays. In particular the OMAHA array of Mirnov coils is specifically designed to measure fluctuations in the range 100kHz-4MHz and is capable of determining toroidal mode numbers up to $n = 20$. Figure 6 shows spectral analysis of a single Mirnov coil with and without plasma (pulse #18433 and #18430 respectively; the injected frequency is 212kHz). In the presence of the plasma, the low order harmonics (up to order ~4) are clearly enhanced, for example in the case shown the amplitude of the fundamental and second harmonic are at least 15 times larger than in vacuum case.

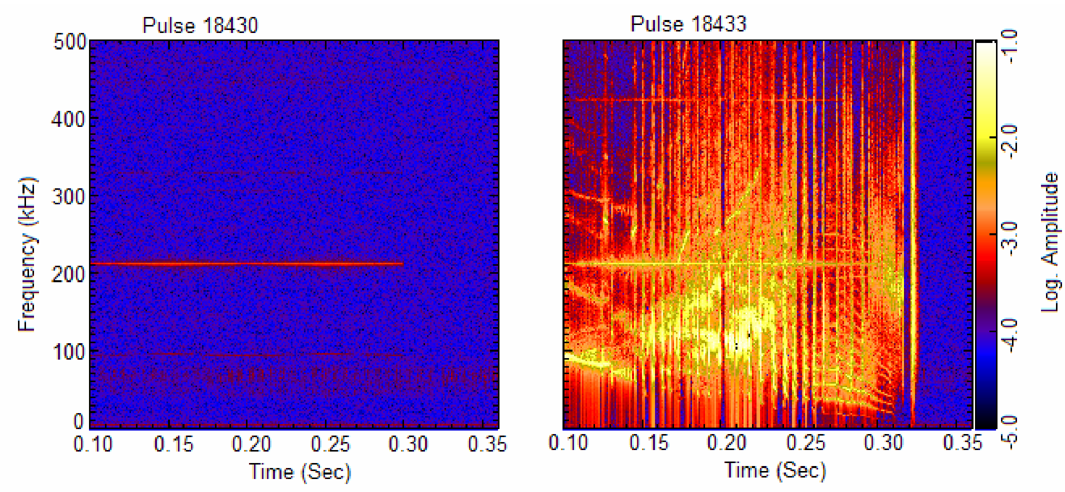

Figure 6: Spectral analysis of signal from Mirnov coil – OMAHA 5.2, for a pulse with (#18433) and without (#18430) plasma. Injection frequency 212kHz.

Conclusions and Future Plans

A 3 coil TAE antenna system has been installed on MAST. Using these coils the feasibility of a much larger antenna array has been investigated, ultimately containing 12 (upper) +6 (lower) coils, one which can be used for both ELM mitigation studies and TAE measurements. The first stage of this upgrade, 6+6 coils, is well under way and will be installed on MAST later this year.

Results from initial experiments have proven very promising showing the whole system to be very robust. Work continues on the analysis of these data with the aim to improve the experimental procedure and the design of the control system for the TAE antenna array. In particular it is hoped to be able to determine optimum frequency ranges and sweep rates needed to determine TAE and EAE damping rates.

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