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Experimental observations of fast-ion losses correlated with Global and Compressional Alfvén Eigenmodes in MAST-U

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Introduction

Measurements are reported of fast-ion losses associated with fast-ion driven modes at frequencies up to 2 MHz in MAST-U using the new recently scintillator-based Fast-Ion Loss Detector (FILD) [1]. A wide variety of Alfvén Eigenmodes (AEs) can be driven unstable by fast ions in tokamak plasmas due to resonant wave-particle interactions [1] while AEs increase the fast-ion losses [2]. In spherical tokamaks like MAST-U, plasma densities similar to those in conventional tokamaks are achieved with lower magnetic fields, resulting in lower Alfvén speeds (v_A). Since the Neutral Beam Injection (NBI) energy is similar to those in conventional tokamaks, the fast-ion velocities (v_b) can be close to or above the Alfvén speed and can therefore excite a wider range of Alfvénic instabilities. This is not only relevant for spherical tokamaks but also for future burning plasmas in conventional tokamaks, where fusion α-particles will have velocities near or exceeding the Alfvén speed. In MAST, energetic particle-driven modes were observed in a wide frequency range extending to above the on-axis ion cyclotron frequency of 2.5 MHz indicating these modes were Compressional Alfvén Eigenmodes (CAEs)

[3]. Modes of negative toroidal mode number, *n* (propagating counter-current, counter-beam) were observed at high values of magnetic field and identified as CAEs driven by normal Doppler resonance, while modes of positive *n* (propagating co-current, co-beam) were observed at low B and identified as CAEs driven by anomalous Doppler resonance with magnetic drift contribution [4]. Global Alfvén Eigenmodes (GAEs) have been reported to be excited in a similar frequency range in NSTX [5]. Direct measurement of fast-ion losses associated with these modes have not been reported yet but the scintillator-based Fast-Ion Loss Detector (FILD), recently installed in MAST-U [6], enables the detection of these losses. FILD consists of a probe near the edge at the Low Field Side (LFS) of the plasma that directly measures escaping fast ions, collimating them, and dispersing them onto a scintillator plate, from which their velocity-space (gyroradius and pitch angle) can be inferred. The use of a fast scintillator material and an Avalanche Photo-Diode (APD) camera, makes it possible to resolve the frequency of the losses up to 2 MHz.

Experimental results

In the first experimental campaign of MAST-U, the excitation of CAE/GAEs were explored in Double Null (DN) plasmas heated with on-axis and off-axis NBI at different plasma currents (I_p = [450 kA, 750 kA]) and toroidal magnetic field of 0.65 T at the geometric axis (R = 0.8 m). In those shots, the Mirnov coils at the LFS showed modes in the frequency range of 1.2-2 MHz, as it can be observed in figures 1c) and 1g), with features of CAEs/GAEs. Fourier analyses of the FILD signal revealed coherent fast-ion losses in the same frequency range matching the Mirnov coils, as can be observed in figure 1d) and 1h). This suggests that CAEs/GAEs may induce fast-ion losses and have an adverse impact on the fast-ion confinement. The number of operative Mirnov coils in the first campaign was not enough to resolve the toroidal mode number or the polarization so it could not be distinguished if the modes were CAEs or GAEs. However, figures 1g) and 1h) shows that fast-ion losses were not observed to be correlated with relatively lower (1.0 – 1.2 MHz) frequency modes whose frequency does not evolve parallel to each other and even intersect each other when the plasma parameters evolve, a feature previously observed in GAEs [5]. Thus, this suggests that the fast-ion losses may be driven by CAEs. The modes were observed to propagate co-current, co-beam, suggesting an anomalous doppler-shifted ion-cyclotron resonance with the fast-ions, although CAEs driven by normal Landau-Cherenkov resonance have been reported before [7] so it cannot be ruled out.

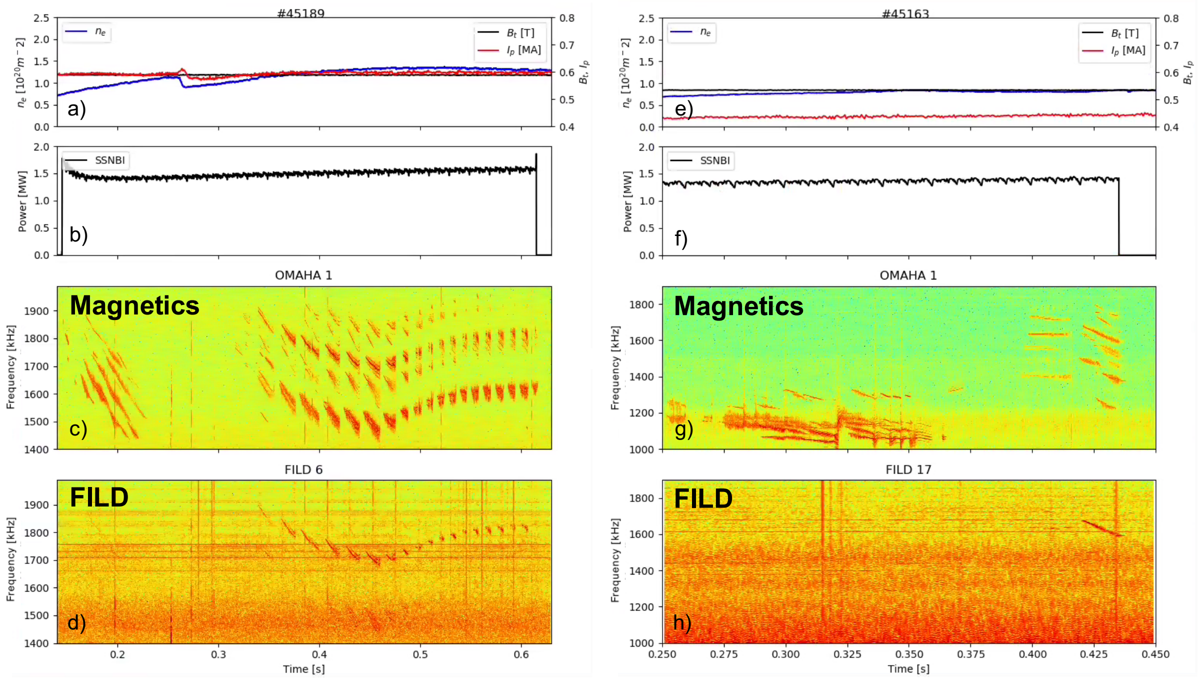

Figure 1: *(From top to bottom) Line-integrated density, toroidal magnetic field and plasma current, NBI power, spectrogram of a Mirnov coil and spectrogram of FILD for MAST-U shots #45189 (left) and #45163 (right).*

Figure 1c) clearly shows that the mode frequencies are clustered in two different frequency scales (separated around 150 kHz and 10 kHz from each other, respectively), as expected for CAEs [7]. The FILD spectrograms do not reveal all the frequencies observed in the magnetic data and it is sensitive to specific modes in the 2 frequency clustering scales, thus suggesting that the losses are driven by very specific resonance conditions. The Doppler Backscattering Spectroscopy (DBS) diagnostic has been used to localise two modes (with and without fast-ion losses) in shot #45208. The mode which does not produce fast-ion losses extends up to $\psi_n^{1/2} = 0.7$ whereas the mode that produces fast-ion losses extends up to $\psi_n^{1/2} = 0.9$, showing that FILD is more sensitive to modes which extend closer to the edge. To fully assess the effect of CAEs on the confined fast ions, confined fast-ion diagnostics, such as the Neutron Camera (NC), will need to be compared with models which accurately estimate the neoclassical transport, as events such as sawteeth or ELMs have a more deleterious effect on the fast-ion profile.

Some features of the FILD signal are not fully understood yet, such as measuring the high-frequency losses in all the APD channels simultaneously. Several explanations have been proposed, where cross-talking between channels seems the most probable. However, careful review of the FILD data is necessary to make sure that the results here presented are not contaminated by pick-up or by capacitive coupling with the plasma RF waves themselves.

Conclusions & Outlook

Fourier analyses of FILD signals from the 1st MAST-U campaign reveal fast-ion losses whose frequencies are clearly correlated with that of CAEs and GAEs. To date, this is the most direct evidence of fast-ion losses induced by CAEs and GAEs, suggesting that CAEs/GAEs may have an adverse impact on the fast-ion confinement. Understanding these losses might be relevant for ITER, where due to finite-orbit effects near the edge, anisotropic α-particle and NBI distributions with velocities close to the Alfvén velocity could drive GAEs and CAEs unstable [8]. These measurements have motivated dedicated experiments in the second MAST-U campaign, with increased diagnostic capabilities, which will make it possible to resolve the mode number and polarization, and the velocity-space of the losses. The modelling efforts will involve analysis of the fast-ion distribution and losses with the ASCOT orbit following code and eigenfrequency and eigenmode structure with the two-fluid stability code MISHKA3.

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