Energetic particle-driven ion cyclotron emission in MAST Upgrade

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Plasmas in the Mega-Amp Spherical Tokamak Upgrade (MAST-U) have toroidal magnetic field at the magnetic axis $B_0 \sim 0.6$T, plasma current $I_p = 0.45 - 1.0$MA, major radius $R_0 \approx 0.9$m, minor radius $a \approx 0.6$m, and elongation $\kappa \sim 2$ [1]. They are heated externally by on-axis and off-axis neutral beam injectors, each delivering up to ~1.7MW. Beam ions born at the primary injection energy of up to 70keV have speeds in the Alfvénic range and consequently can excite a wide range of instabilities, including ion cyclotron emission (ICE) close to harmonics of the ion (deuterium) cyclotron frequency f_{cD} [2]. In 2025 ICE was detected in MAST-U by adding a high sampling rate (250MHz) capability to one coil of an existing Mirnov

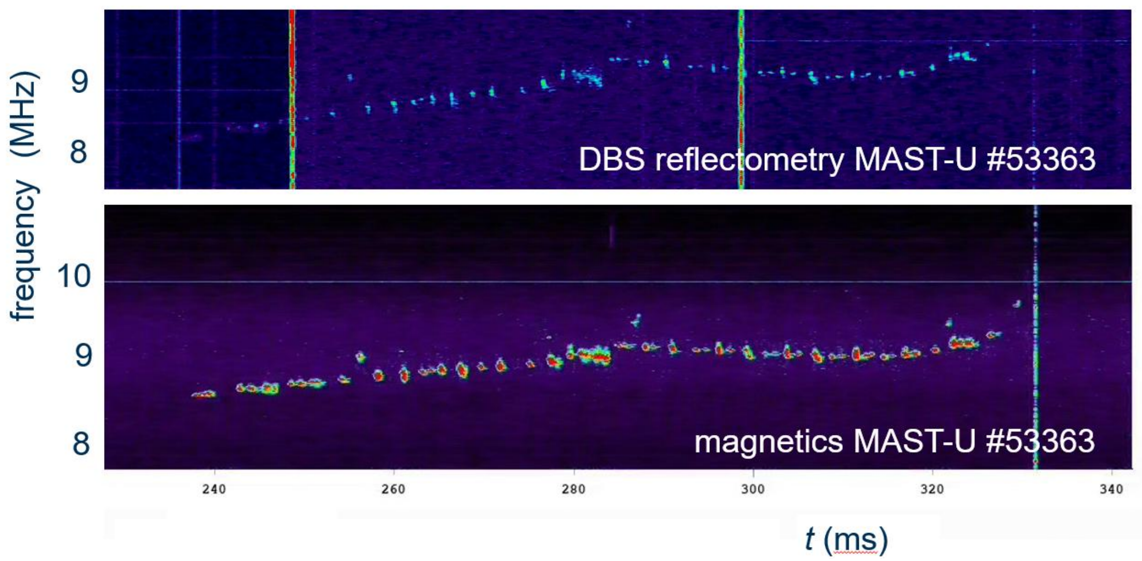

Fig. 1. ICE spectrograms obtained from MAST-U pulse #53363 using the UCLA DBS system (top) and one of the high sampling rate Mirnov coils (bottom).

array [3,4]. In 2026 a similar capability was added to other coils, making it possible to measure toroidal mode numbers n. Here we use the convention that $n > 0$ corresponds to propagation in the toroidal field direction, which in MAST-U is counter to the plasma current direction.

Fig. 1 shows bursting narrow-band ICE detected simultaneously using a Doppler backscattering (DBS) reflectometry system provided by UCLA [5] (top) and one of the high sampling rate coils (bottom). A sequence of bursts can be seen, with frequencies that track and are close to $2f_{cD}$ at the magnetic axis. The DBS signal is due to velocity fluctuations along a microwave ray path. It is thus possible to obtain spatial information on ICE other than that contained in the frequency alone. Analysis of DBS measurements of ICE in MAST-U to constrain the source region of the emission is ongoing. This technique has previously been used to detect ICE in the DIII-D tokamak [6].

Fig. 2 shows n values (colour bar) of quasi-continuous broadband ICE detected at several harmonics in pulse #53593. For this pulse and time slice, the three harmonics plotted correspond to $3f_{cD}$, $4f_{cD}$ and $5f_{cD}$ in the outboard midplane. Individual ICE bursts have duration $\sim 100\mu s$ and are correlated with mode activity in the 50-100kHz range, likely to be toroidal Alfvén eigenmodes (TAEs). Modes with $-10 \leq n \leq 10$ have similar amplitude. It should be noted that the exact n values are uncertain due to the limited number of high frequency coils. At cyclotron resonance, the instability drive γ of a mode with frequency ω scales with gradients of the beam ion distribution f_b in the space defined by the unperturbed constants-of-motion [7]:

$$\gamma \sim n\frac{\partial f_b}{\partial P_\varphi} + \omega\frac{\partial f_b}{\partial E} + \ell\frac{Ze}{m_b}\frac{\partial f_b}{\partial \mu} \tag{1}$$

where P_φ, E and μ are toroidal canonical momentum, energy and magnetic moment of a beam ion with mass m_b and charge Ze and ℓ is the harmonic number of the cyclotron resonance. Assuming a strong correlation between drive and saturated amplitudes, Fig. 2 suggests that the radial gradient term ($\partial f_b/\partial P_\varphi$) in Eq. (1) does not play a strong role in the ICE instability. The emission is thus likely to be driven by population inversion ($\partial f_b/\partial E > 0$) and/or anisotropy ($\partial f_b/\partial \mu \neq 0$). However, ICE does not always occur during NBI in MAST-U despite f_b invariably being anisotropic, which suggests that the key driver is $\partial f_b/\partial E > 0$. This could occur transiently due to energy-dependent redistribution of fast ions arising, for example, from TAEs, sawteeth or fishbones.

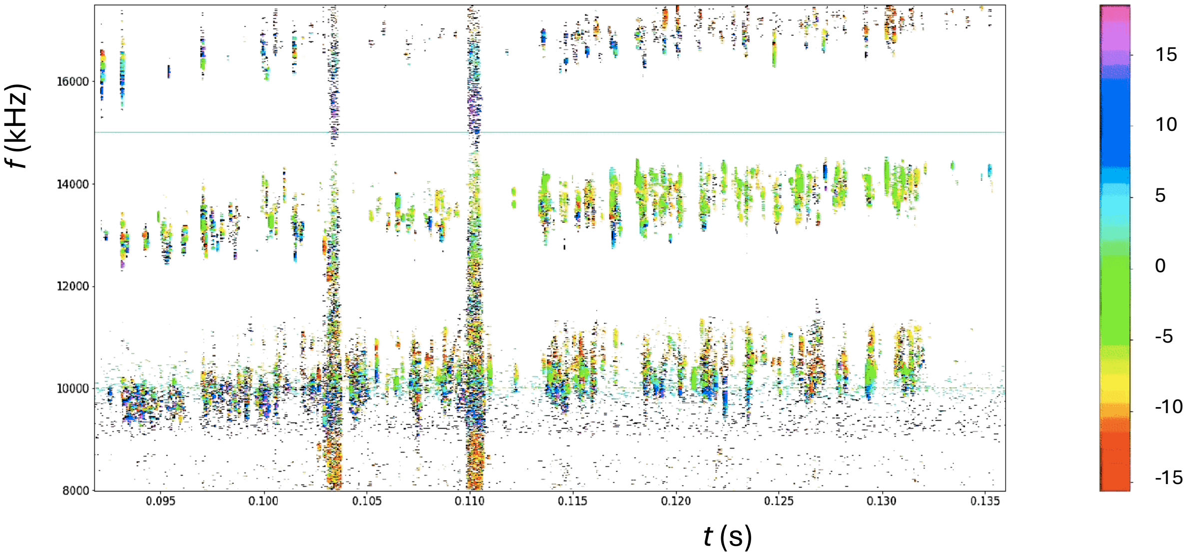

Fig. 2. Spectrogram of ICE in MAST-U pulse #53593, showing estimated toroidal mode numbers n (colour bar). Propagation in the co-current direction corresponds to $n < 0$.

The top plot in Fig. 3 shows multiple harmonic broadband ICE in pulse #54046. Cyclotron harmonics of f_{cD} in the outer midplane up to $\ell = 6$ can be seen. The bottom plot shows that the ICE was correlated with instabilities in the shear Alfvén range f< 300 kHz.

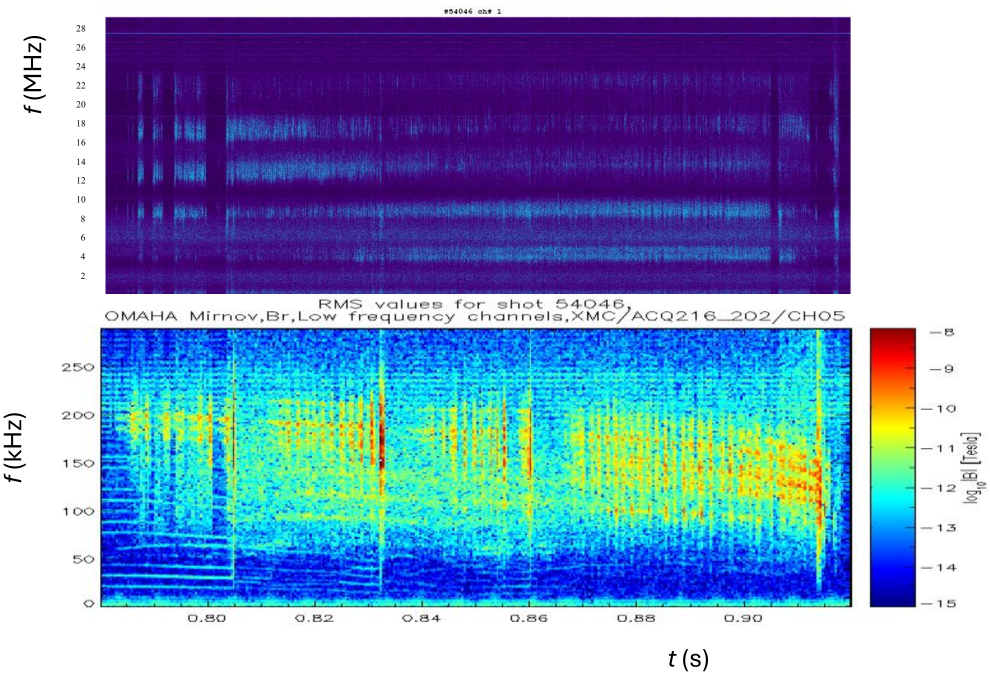

Fig. 3. Top: multiple harmonic broadband ICE in pulse #54046. Harmonics of f_{cD} in the outer midplane up to $\ell = 6$ can be seen. Bottom: instabilities at f < 300 kHz in the same time window.

The top plot in Fig. 4 shows global Alfvén eigenmodes (GAEs) in pulse #53626 (the colour bar again indicates n values of the excited modes) while the middle plot shows a series of ICE bursts at a frequency slightly below $2f_{cD}$ at the magnetic axis. The bottom plot shows line-integrated soft X-ray emission for chords passing close to the magnetic axis (red) and the plasma edge (blue), indicating sawtooth-induced transport of electron thermal energy from the core to the edge. Comparing the three parts of the figure, it is evident that the sawtooth crashes terminated the GAEs and then triggered the ICE: this strongly suggests sawtooth-induced redistribution of the fast ions driving the GAEs to the ICE-emitting region. The duration of each ICE burst (~1ms) was around tens times longer than the sawtooth crash time (~100μs).

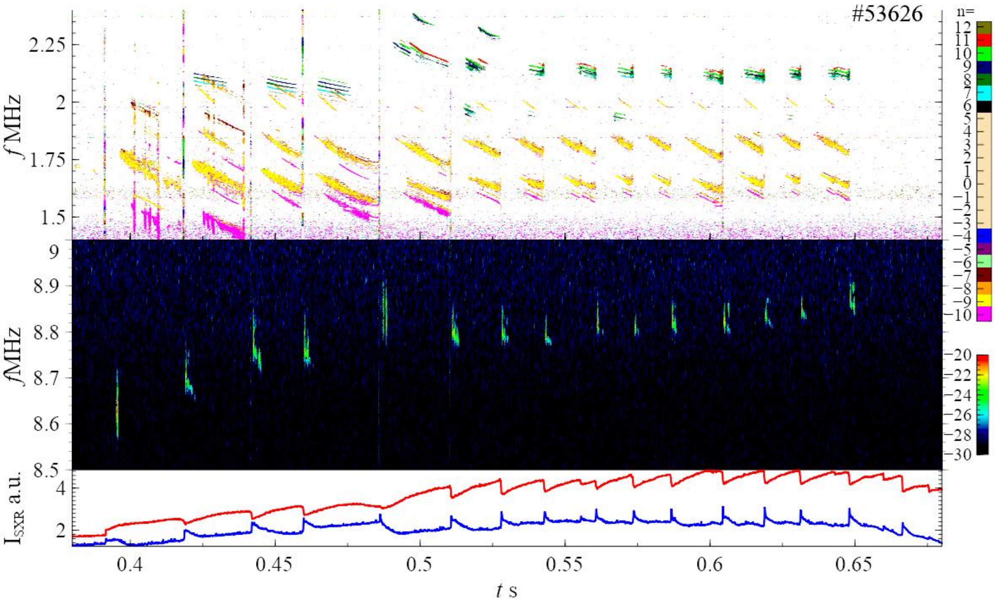

Fig. 4. GAEs (top), ICE (middle) and soft X-ray (SXR) emission (bottom) in pulse #53626. GAE n's are indicated by colours. SXR signals are for chords passing close to magnetic axis (red) & plasma edge (blue).

To summarise, ICE frequently occurs during NBI in MAST-U at frequencies close to beam ion cyclotron harmonics. It is transient, occurring immediately after MHD activity and/or fast ion-driven instabilities at lower frequency. As illustrated by Fig. 4, the temporal behaviour of ICE in MAST-U is clearly distinct from that of other cyclotron resonance-driven instabilities such as GAEs and compressional Alfvén eigenmodes (CAEs) [8]. This suggests that an ICE detection capability in future DT fusion devices could provide a robust, sensitive diagnostic of non-classical α-particle transport that could pose a threat to the fusion burn.

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[1] J.R. Harrison *et al.,* Nucl. Fusion **64** (2024) 112017; [2] K.G. McClements *et al.* Nucl. Fusion **55** (2015) 043013; [3] M.J. Hole, L.C. Appel and R. Martin, Rev. Sci. Instrum. **80** (2009) 123507; [4] M.B. Dreval *et al*., Plasma Phys. Control. Fusion **68** (2026) 035014; [5] T.L. Rhodes *et al.* Rev. Sci. Instrum. **93** (2022) 113549; [6] N.A. Crocker *et al.* Nucl. Fusion **62** (2022) 026023; [7] M. Fitzgerald and B.N. Breizman, Fundamental Plasma Physics **13** (2025) 100084; [8] S.E. Sharapov *et al*. Phys. Plasmas **21** (2014) 082501