Energetic particle-driven ion cyclotron emission in MAST Upgrade

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*[6] See author list of J.R. Harrison et al., 2026 Nucl. Fusion 66 116005 (*Overview of the MAST Upgrade physics programme: testing novel concepts at low aspect ratio to inform future devices - IOPscience*)*
[7] See author list of N. Vianello et al. "Results from the last DD & DT JET campaigns in the framework of the EUROfusion Tokamak Exploitation Work Package Activity" 2026 Nuclear Fusion in press

Mega-Amp Spherical Tokamak Upgrade (MAST-U)

- $B_0 \sim 0.6\mathrm{T}$, $I_p = 0.45 - 1.0\mathrm{MA}$, $R_0 \approx 0.9\mathrm{m}$, $a \approx 0.6\mathrm{m}$, $\kappa \sim 2$
- On-axis & off-axis neutral beam injectors, each delivering up to ~1.7 MW, beam ions (deuterium) with primary injection energy ≤70 keV
  - ➢ beam ions have speeds in Alfvénic range & can therefore excite range of instabilities including ion cyclotron emission (ICE) at harmonics of ion (D) gyrofrequency f_{cD}
- In 2025 ICE was detected in MAST-U by adding high sampling rate (250 MHz) capability to one coil in existing Mirnov array [1,2]
- In 2026 similar capability was added to other coils, enabling measurement of toroidal mode numbers n: **NB $n > 0 \Rightarrow$ TF direction / counter I_p direction**

ICE detected using DBS reflectometry as well as coils

- Fig. 1 shows bursting narrow-band ICE detected simultaneously using UCLA Doppler backscattering (DBS) [3] reflectometry system (top) & high sampling rate coils (bottom); frequency tracks & is close to $2f_{cD}$ at magnetic axis
- DBS signal due to velocity fluctuations along microwave ray path
- ➢ possible to obtain spatial information on ICE other than that contained in frequency alone: analysis of DBS data is ongoing

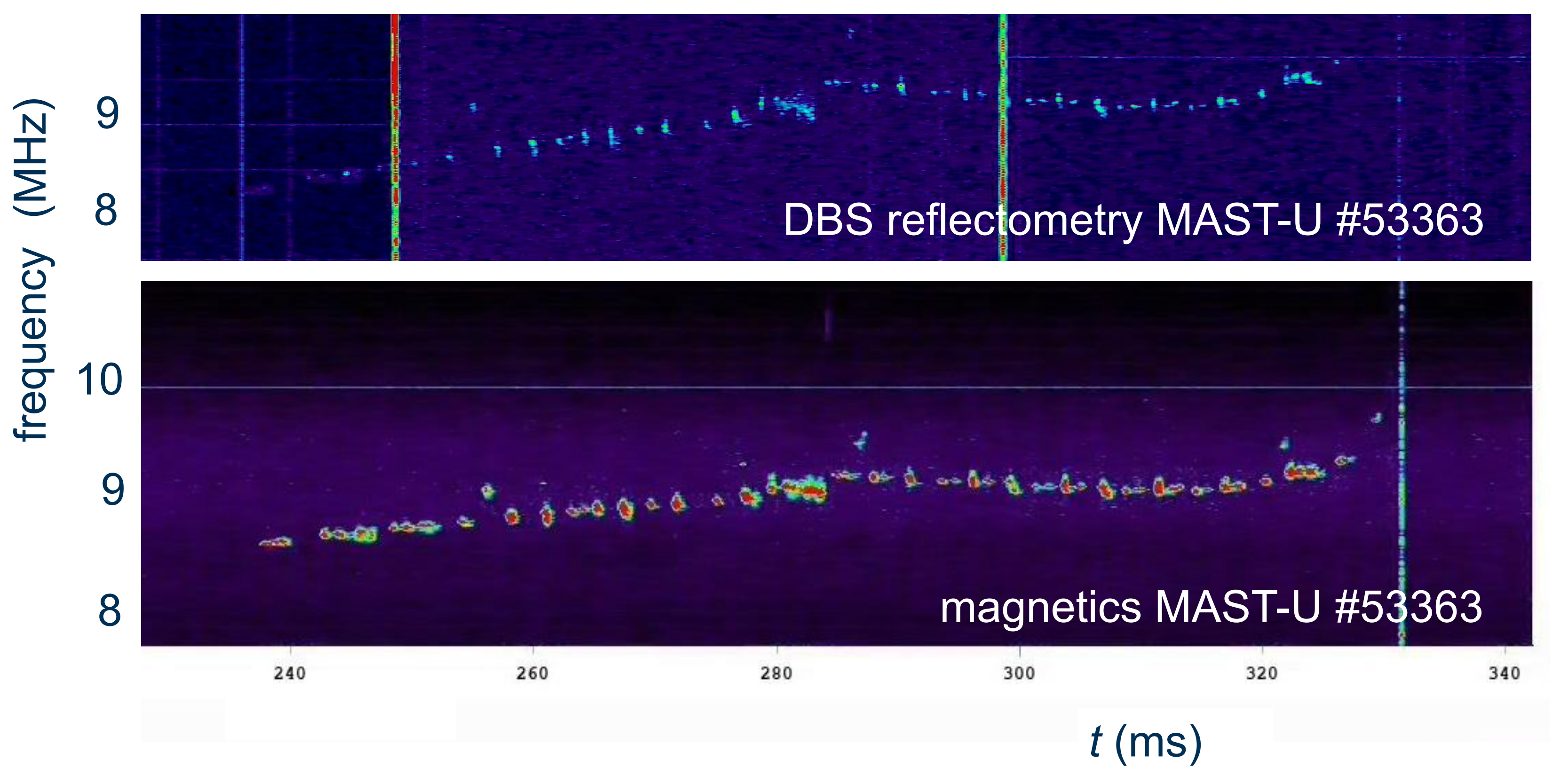

Fig. 1. ICE spectrograms obtained from MAST-U pulse #53363 using UCLA DBS system (top) & high sampling rate Mirnov coil (bottom).

ICE has wide range of toroidal mode numbers

- Fig. 2 shows n values (colour bar) of quasi-continuous broadband ICE at several harmonics in pulse #53593:10 MHz $\approx 3f_{cD}$ in outboard midplane
- Individual ICE bursts have duration $\sim 100\mu s$ & are correlated with mode activity in 50-100kHz range, likely to be toroidal Alfvén eigenmodes (TAEs)
- Modes with $-10 \leq n \leq 10$ have similar amplitudes **(CAVEAT: due to limited number of high frequency coils exact n values are uncertain)**
- At cyclotron resonance, drive of mode with frequency ω scales with gradients of beam ion distribution f_b in unperturbed constants-of-motion space:

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

  P_φ, E, μ - toroidal canonical momentum, energy & magnetic moment of beam ion with mass m_b & charge Ze; ℓ - cyclotron harmonic number

- ➢ **assuming strong correlation between drive & saturated amplitudes, Fig. 2 suggests that radial gradient term ($\partial f_b/\partial P_\varphi$) in (1) does not play strong role in ICE instability**
- ➢ **emission driven by population inversion ($\partial f_b/\partial E > 0$) &/or anisotropy ($\partial f_b/\partial \mu \neq 0$)**
- f_b in MAST-U is always anisotropic but ICE does not always occur during NBI
- ➢ **ICE due to $\partial f_b/\partial E > 0$ – could occur transiently due to energy-dependent redistribution of fast ions arising for example from TAEs, sawteeth or fishbones**

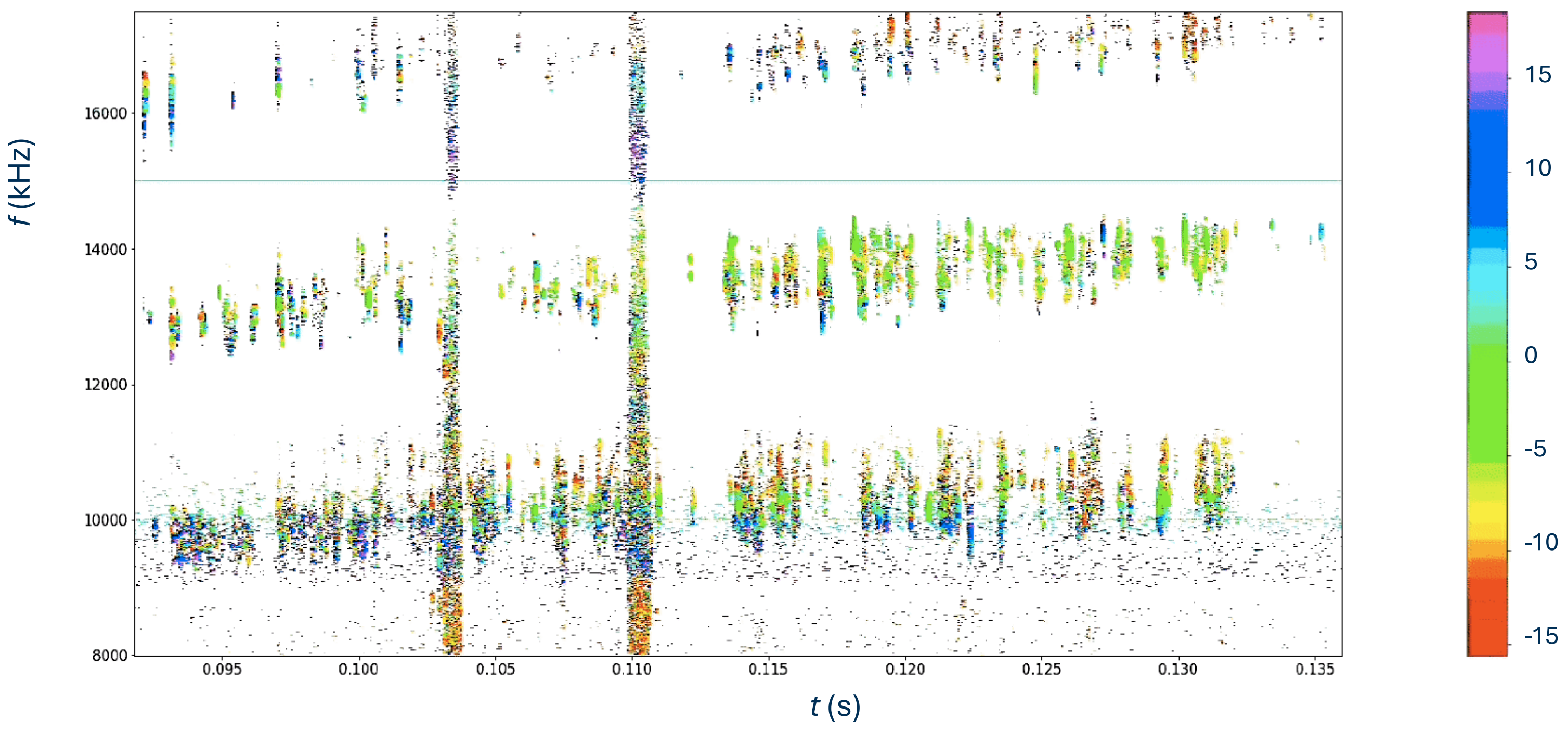

Fig. 2. Estimated toroidal mode numbers n of ICE in MAST-U pulse #53593. Propagation in co-current direction corresponds to $n < 0$.

Broadband ICE detected at up to six harmonics

- Top plot in Fig. 3 shows multiple harmonic broadband ICE in pulse #54046
- Bands of emission have mean $\Delta f \sim f_{cD}$ in outer midplane
- Cyclotron harmonics up to $\ell = 6$ detected
- Bottom plot shows that ICE is correlated with instabilities in shear Alfvén range < 300 kHz

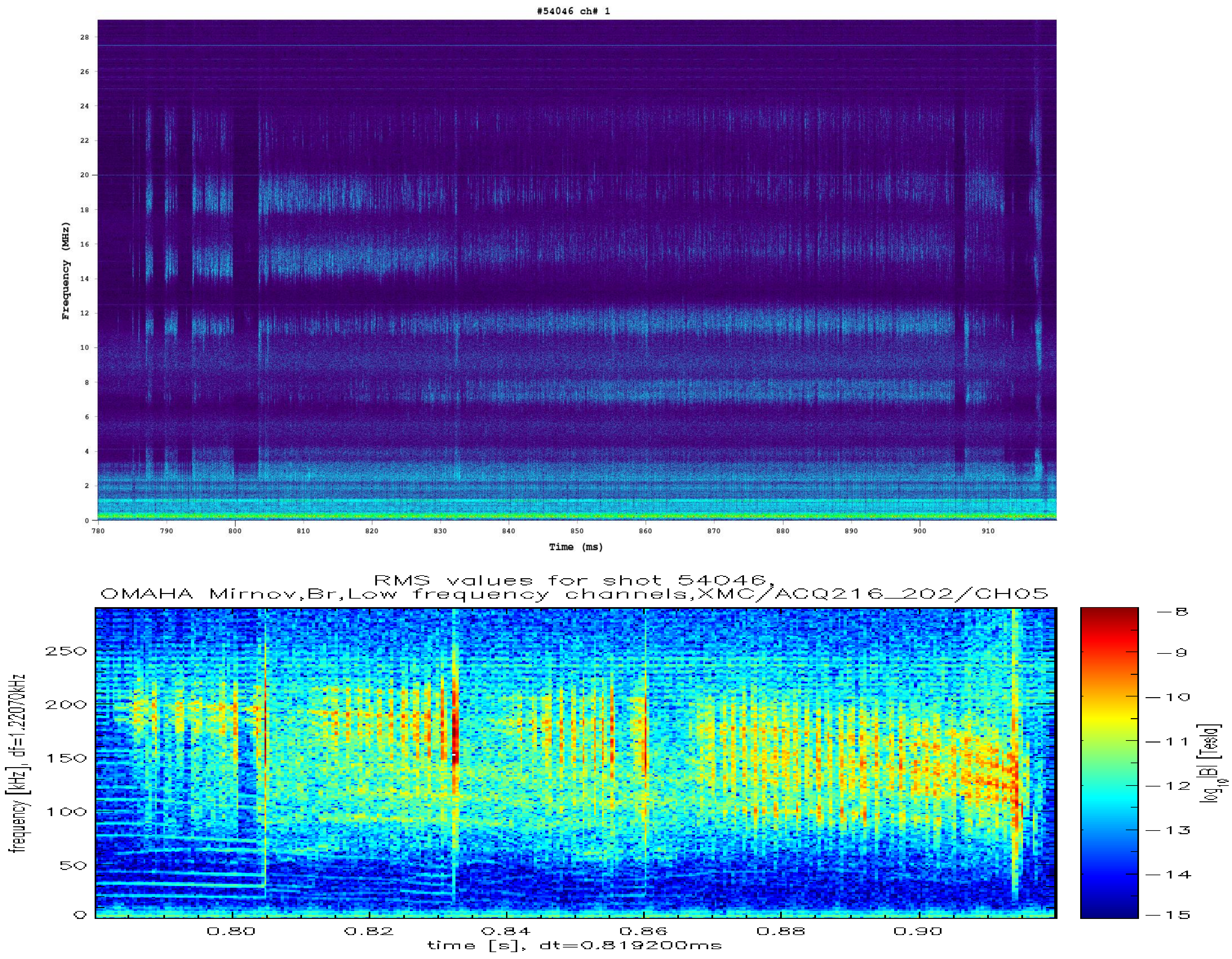

Fig. 3. Top: multiple harmonic broadband ICE in pulse #54046. Bands of emission have $\Delta f \sim f_{cD}$: harmonics up to $\ell = 6$ can be seen. Bottom: instabilities at $f < 300$ kHz in same time window.

Sawteeth terminated GAEs then excited ICE

- Top plot in Fig. 4 – global Alfvén eigenmodes (GAEs) in pulse #53626
- Middle plot – ICE: frequency slightly below $2f_{cD}$ at magnetic axis
- Bottom plot – line-integrated soft X-ray emission for chords passing close to magnetic axis (red) & plasma edge (blue), showing sawtooth-induced transport of electron thermal energy from core to edge
- Duration of ICE bursts ~1ms ~10 × sawtooth collapse time ~ 100μs
- ➢ **sawtooth-induced redistribution of fast ions driving GAEs to ICE-emitting region**

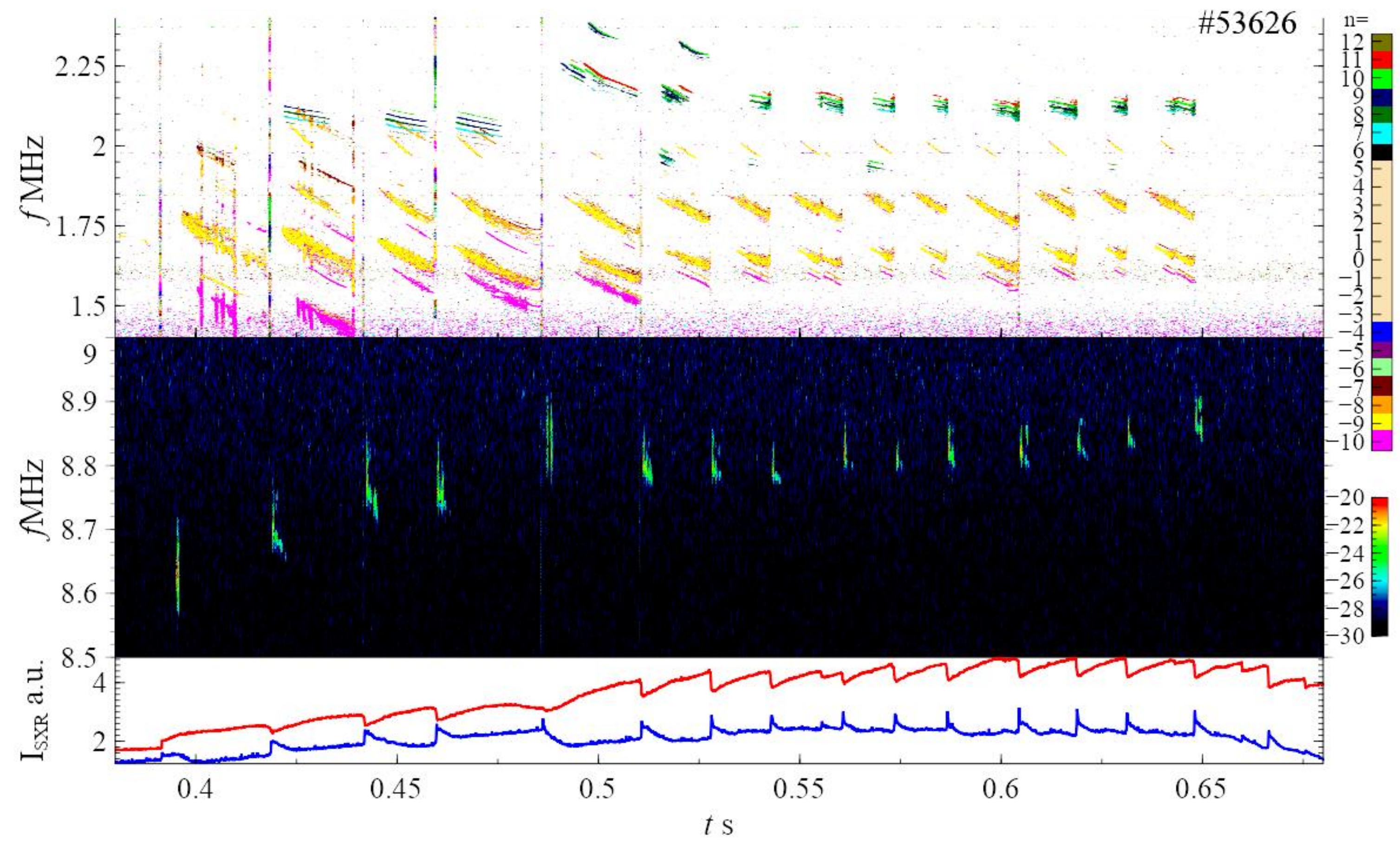

Fig. 4. GAEs (top), ICE (middle) & soft X-ray (SXR) emission (bottom) in pulse #53626. GAE n's are indicated by colours. SXR signals are for chords passing close to magnetic axis (red) & plasma edge (blue). ICE frequency is slightly below $2f_{cD}$ at magnetic axis ($\approx$ 8.85 MHz @ $t = 0.4s$).

Concluding remarks

- ICE frequently occurs close to harmonics of f_{cD} during NBI in MAST-U; generally transient & occurs immediately after MHD activity or fast particle-driven instabilities
- MAST-U ICE is clearly distinct from other cyclotron resonance-driven instabilities such as GAEs & compressional Alfvén eigenmodes (CAEs), e.g. it is much more transient

[1] MJ Hole *et al*. Rev. Sci. Instrum. **80** (2009) 123507; [2] MB Dreval *et al*. Plasma Phys. Control. Fusion **68** (2026) 035014; [3] TL Rhodes et al. Rev. Sci. Instrum. **93** (2022) 113549

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