Ion Cyclotron Harmonic Waves in the Boundary of Magnetized Plasmas

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POSTECH
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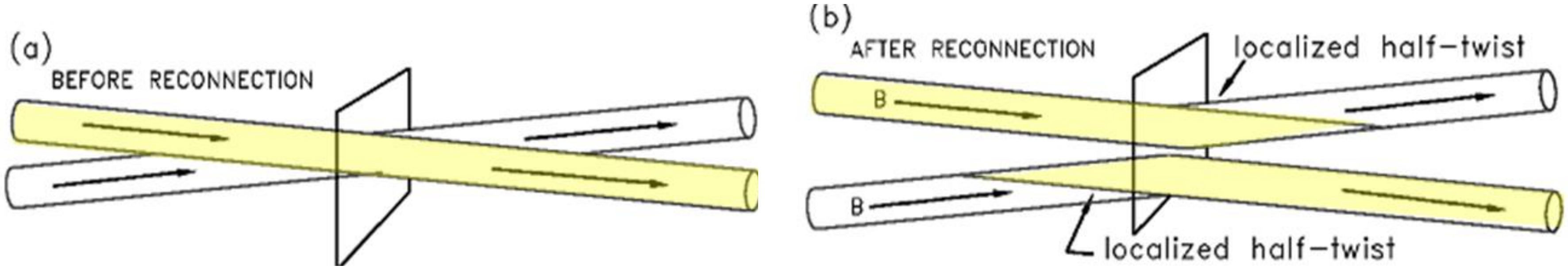
Contents

0. Motivation for fast RF diagnostics

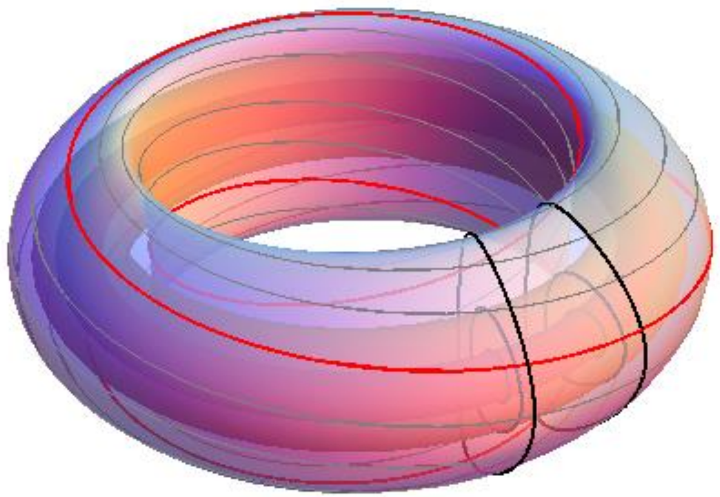
To understand the role of ***radiative dissipation and viscous damping***† in magnetic reconnection (MR) and subsequent macroscopic transport events in high-temperature magnetized plasmas (e.g. burst of edge-localized modes, sawtooth, disruptions in tokamaks)

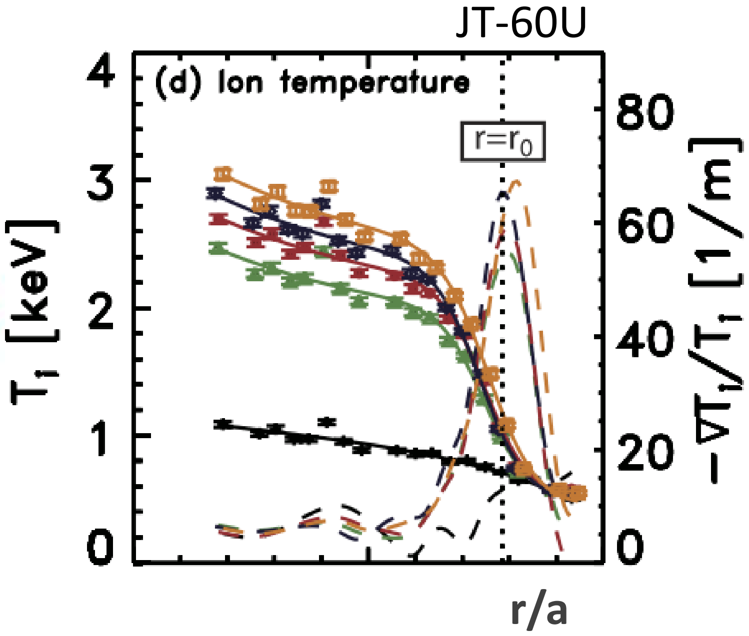
Patchy MR induces ***field-aligned localized current filaments =*** **shear Alfven waves and/or whistler waves [1]** → ***Radiation*** [2] and ***Viscous damping*** [3] of the waves → ***Fast reconnection***.



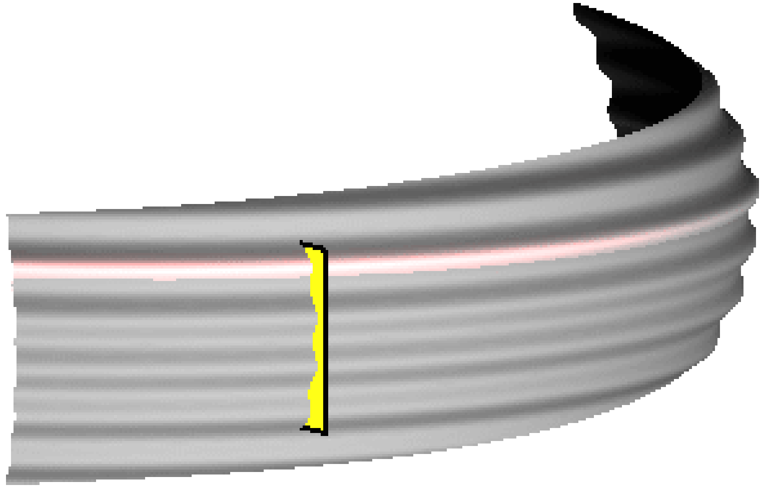
[1] Bellan, PoP 1998. [2] Yoon and Bellan, PoP 2018.
[3] Yun and Ji, arXiv

I. Edge-localized mode (ELM)





Tokamak plasmas often form an edge transport barrier called **pedestal** just inside the last closed flux surface, resulting in an overall enhancement of the confinement (so called H-mode).



→ **Edge-localized instability mode (ELM)†** can occur driven by large ∇p_0 (ballooning, interchange), J_0 (kink), and/or ∇V_0 (d'Angelo) in the pedestal.

† Kaye (PBX), 1984; Keilhacker (Asdex), Physica Scripta 1984; Kamiya (JT-60U), Sci. Rep. 2016

Common features in the ELM dynamics † on the KSTAR

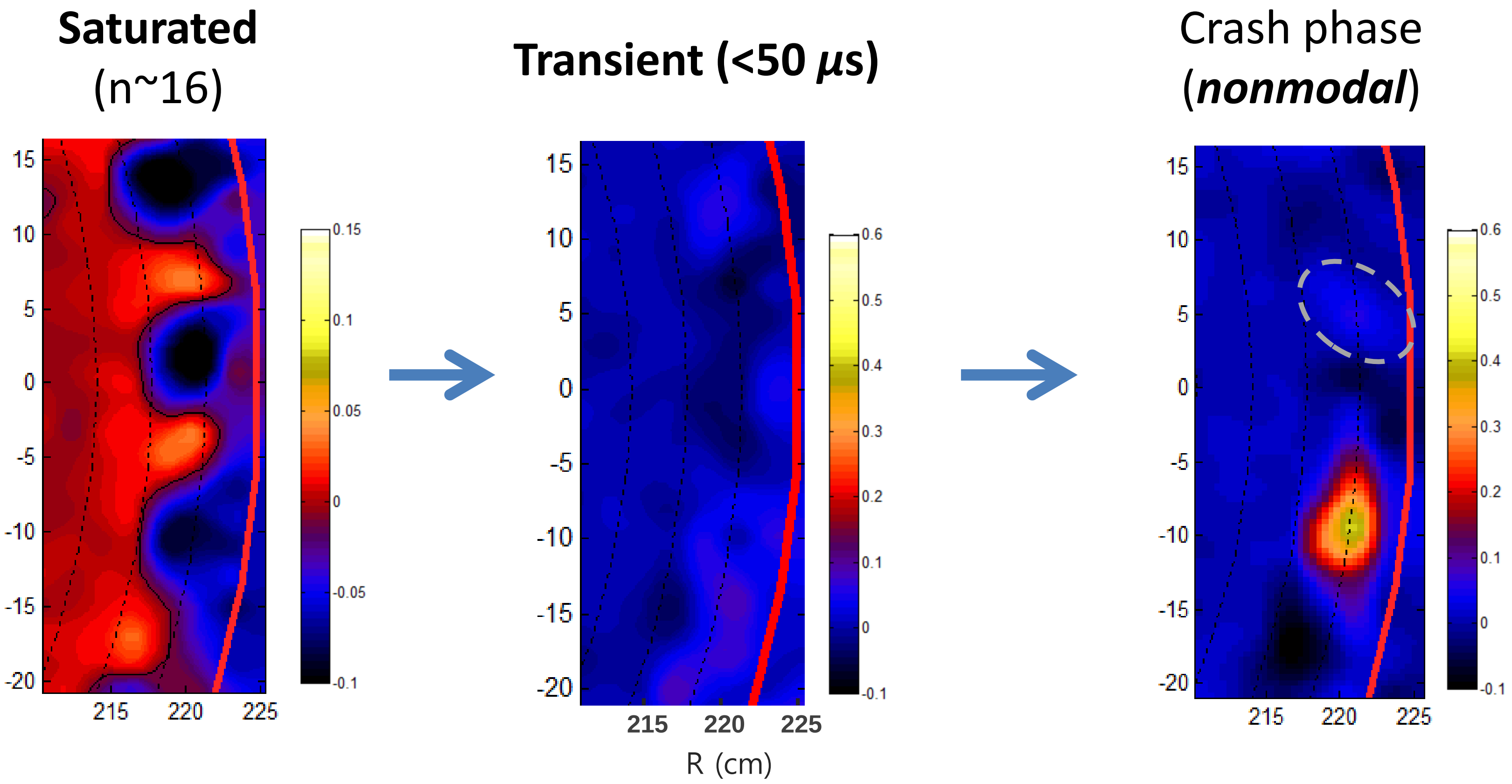
(1) Nonlinear saturation of eigenmode

(2) Abrupt structural transition into nonmodal state ‡

(3) Explosive localized burst and collapse of the pedestal.

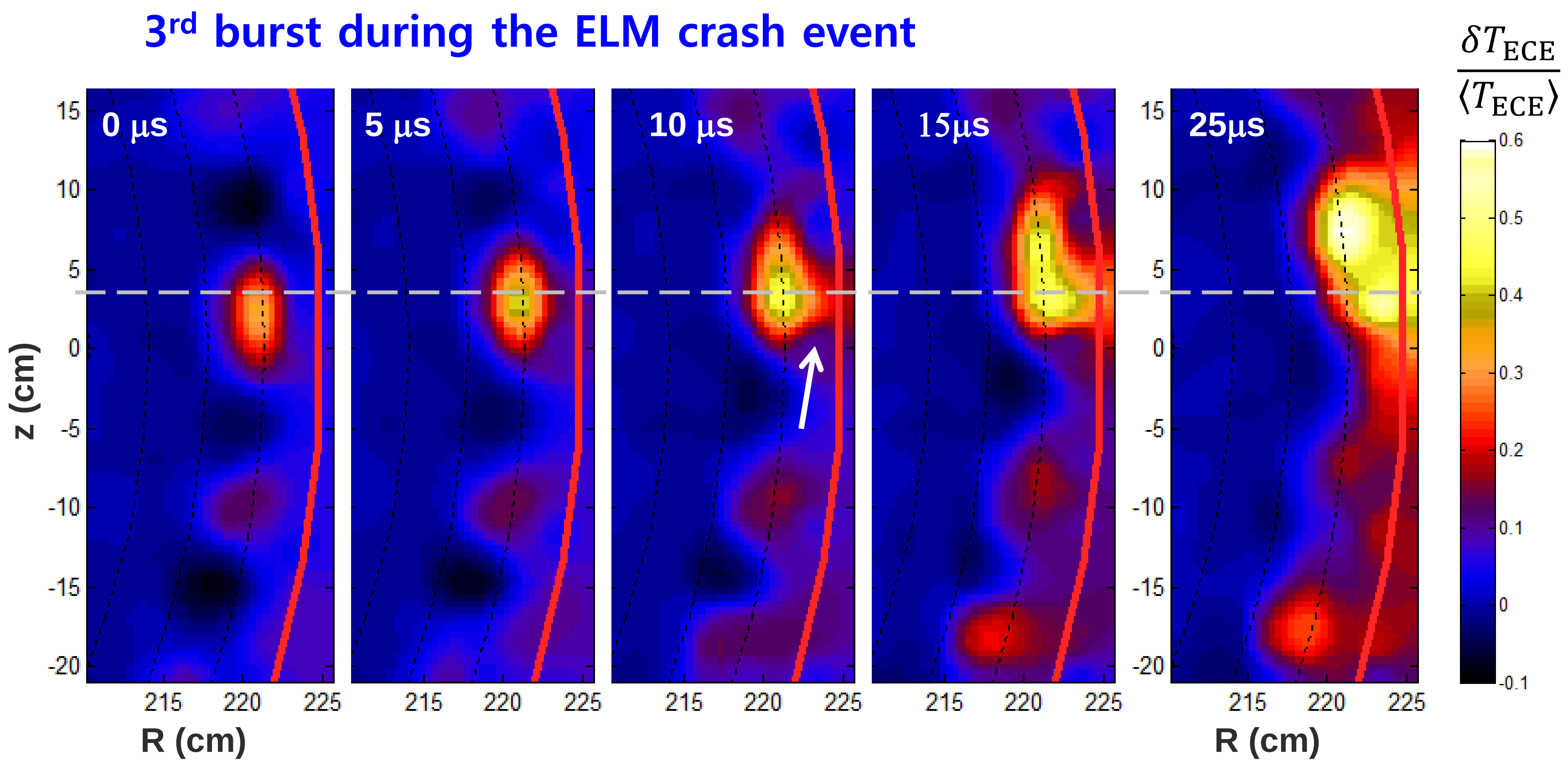
† Yun, PRL 2011;
Yun, PoP 2012;
Kim M, NF 2014;
Lee J, PRL 2016;

‡ Lee JE, NF 2015
Lee JE, Sci. Rep. 2017



KSTAR #4431.
Images taken by a mm-wave camera called **electron cyclotron emission imaging (ECEI)**

Burst of the nonmodal (solitary) filament



- **Fast burst < 10 μs**
- **Localized burst** (both poloidally and toroidally)
- **Convective transport**

*Yun, PRL 2011;
Lee JE, Sci. Rep. 2017

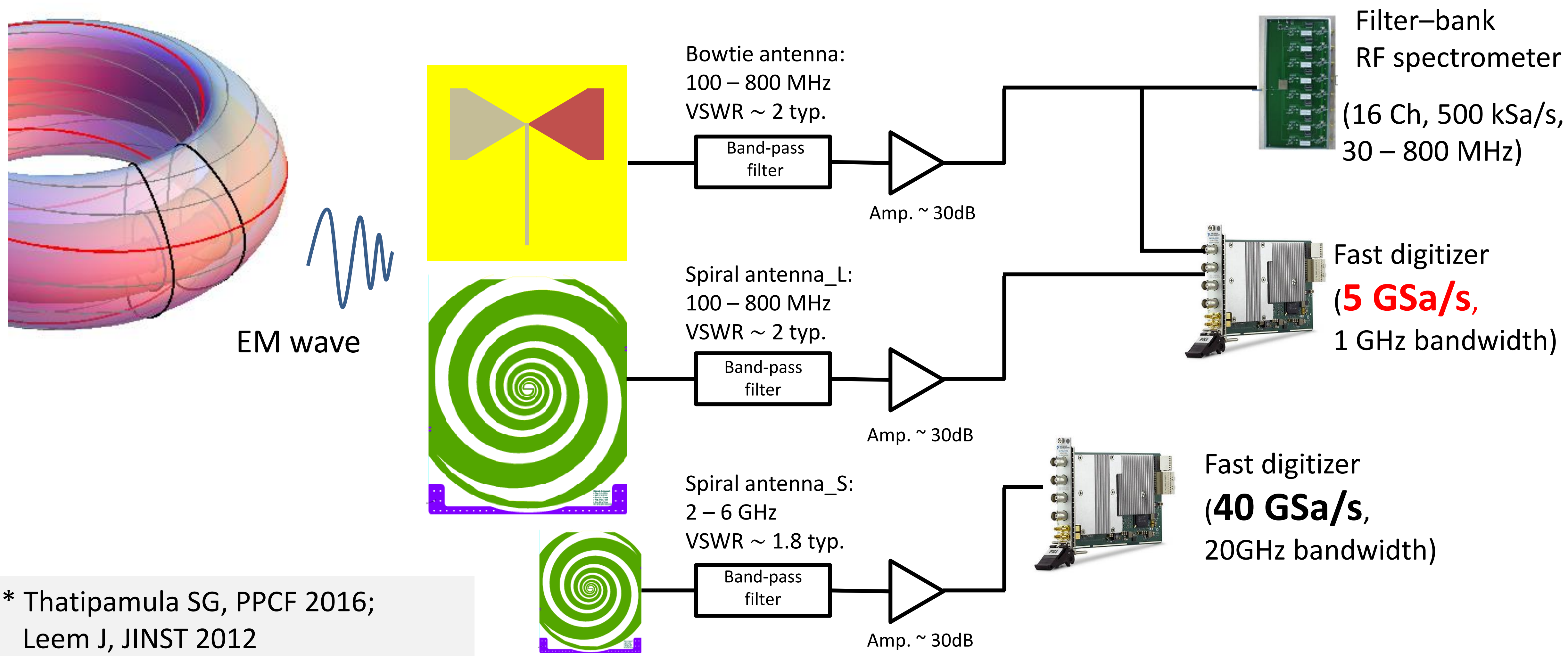
1) Why does the ELM saturate? †

2) What triggers the transition to nonmodal filament? †

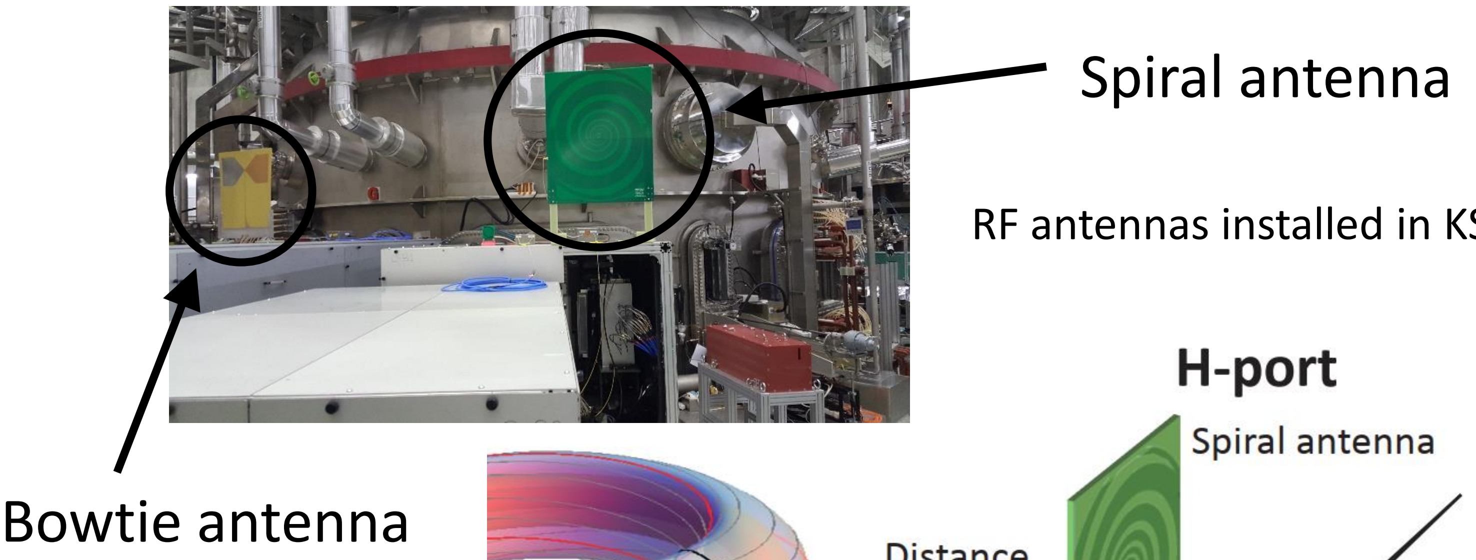
3) **Why is the burst so rapid and localized?**

† Oh YM, AIP Adv. 2018;
Leconte M, Contrib. Plasma Phys. 2016;

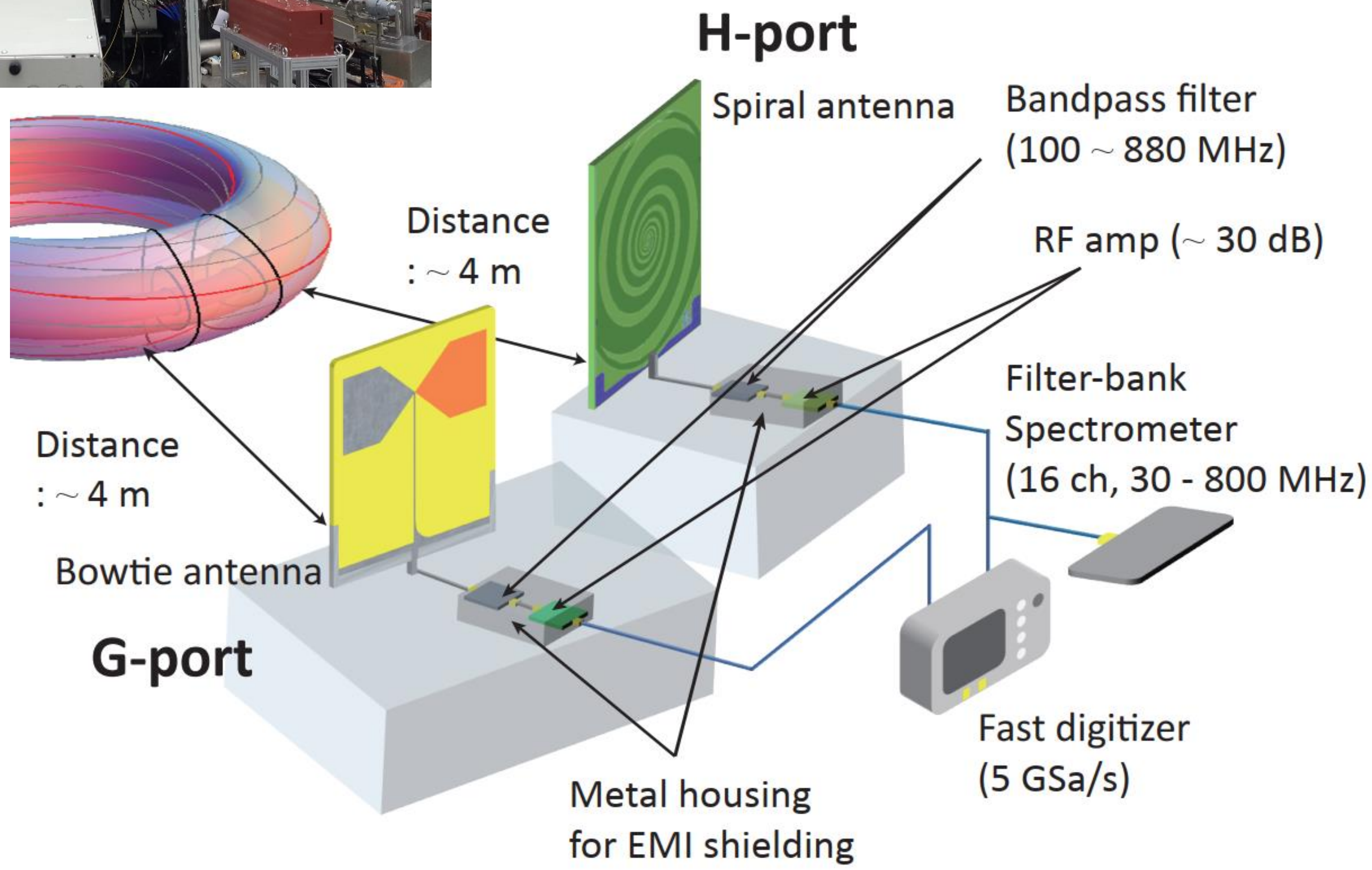
II. Fast RF diagnostics* assisted by ECEI



* Thatipamula SG, PPCF 2016;
Leem J, JINST 2012

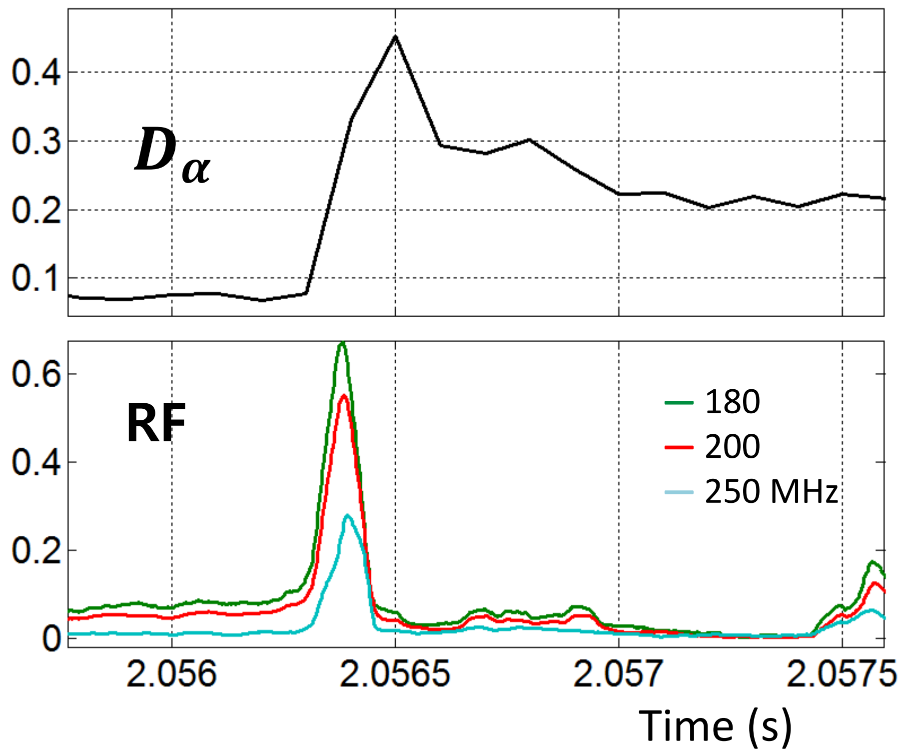


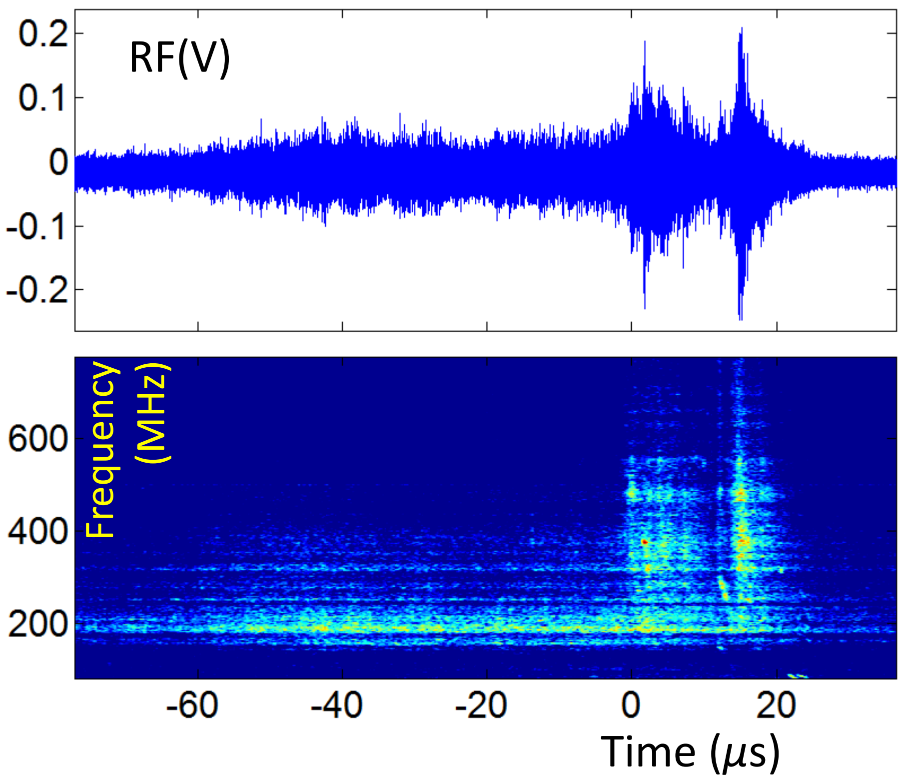
RF antennas installed in KSTAR (2017)



Dynamic RF spectrum at the ELM burst

t_0=2.056369218 s



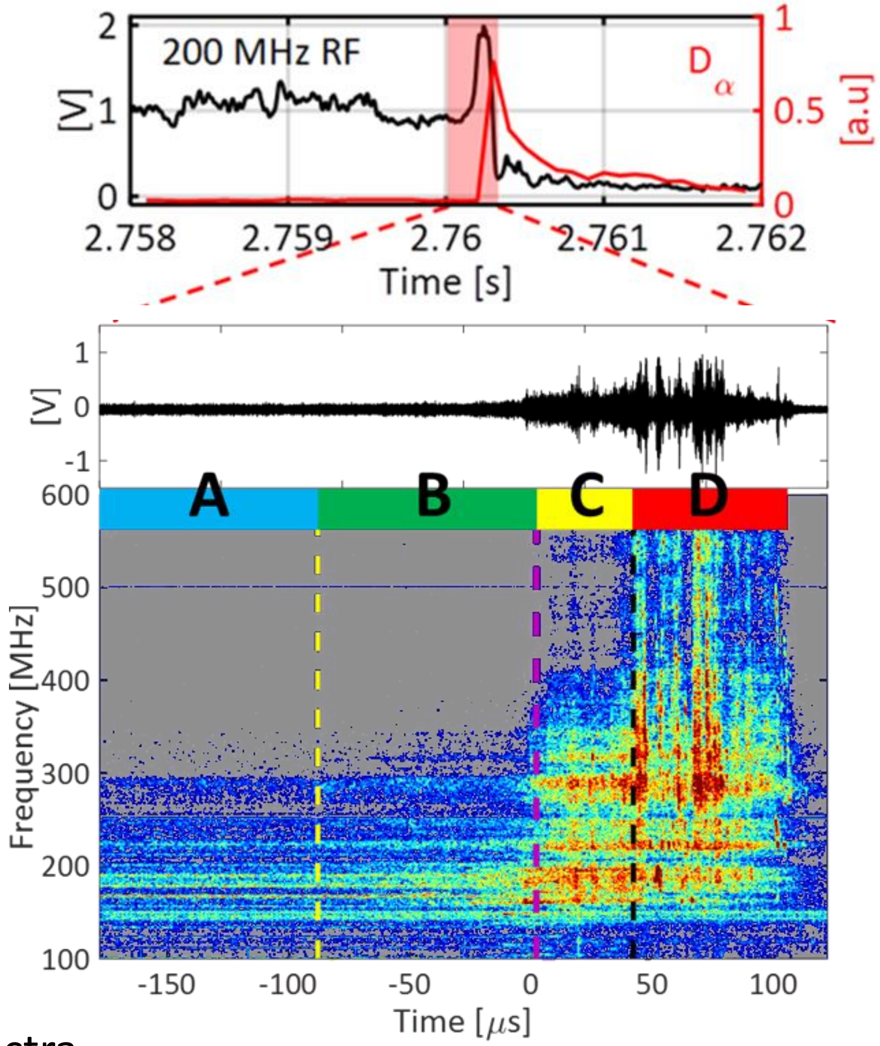


Shot #11475. H-mode discharge

$B_0 = 2.3$ T, $I_P = 500$ kA, $n_{e0} \sim 2.5\text{e}19$ m^{-3},
$W_{tot} = 240$ kJ, NBI = 1.5 MW

III. RF emission spectra during ELM evolution

A. **Harmonic Ion cyclotron emission (ICE)** before the appearance of nonmodal filament
B. **Intensified high-harmonic ICE** with the appearance of **nonmodal filament**
C. **Rapid transition** into **wide-band** emission at the onset of **the filament burst**
D. **Short burst *with frequency chirp*** during the pedestal collapse

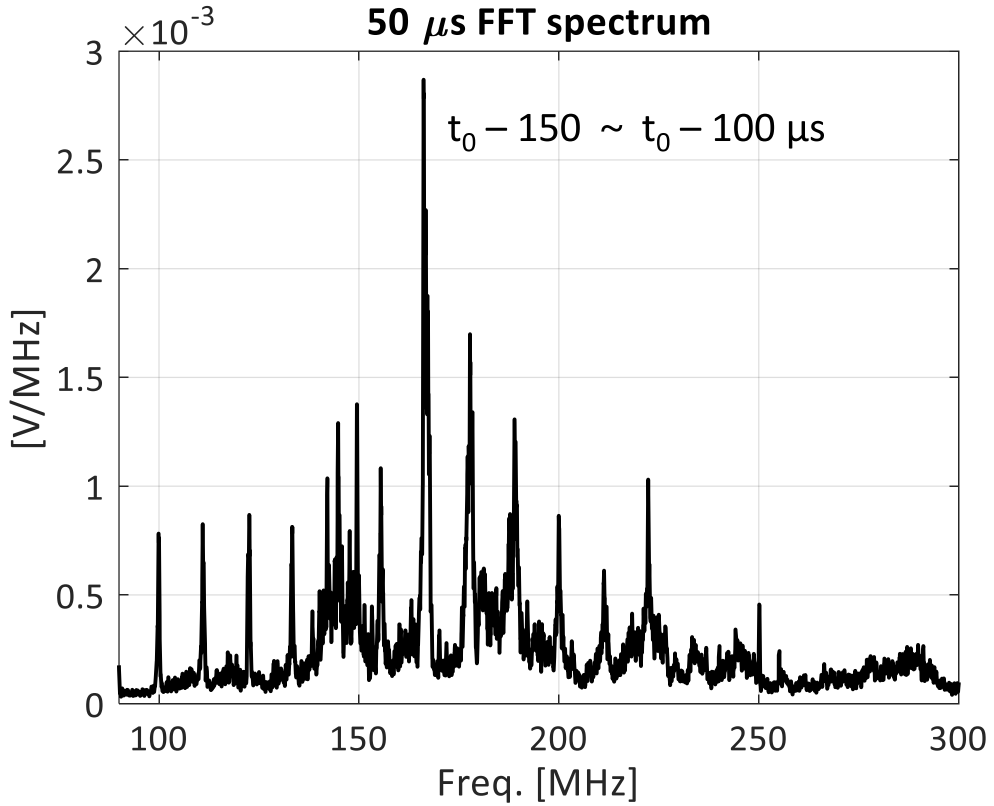


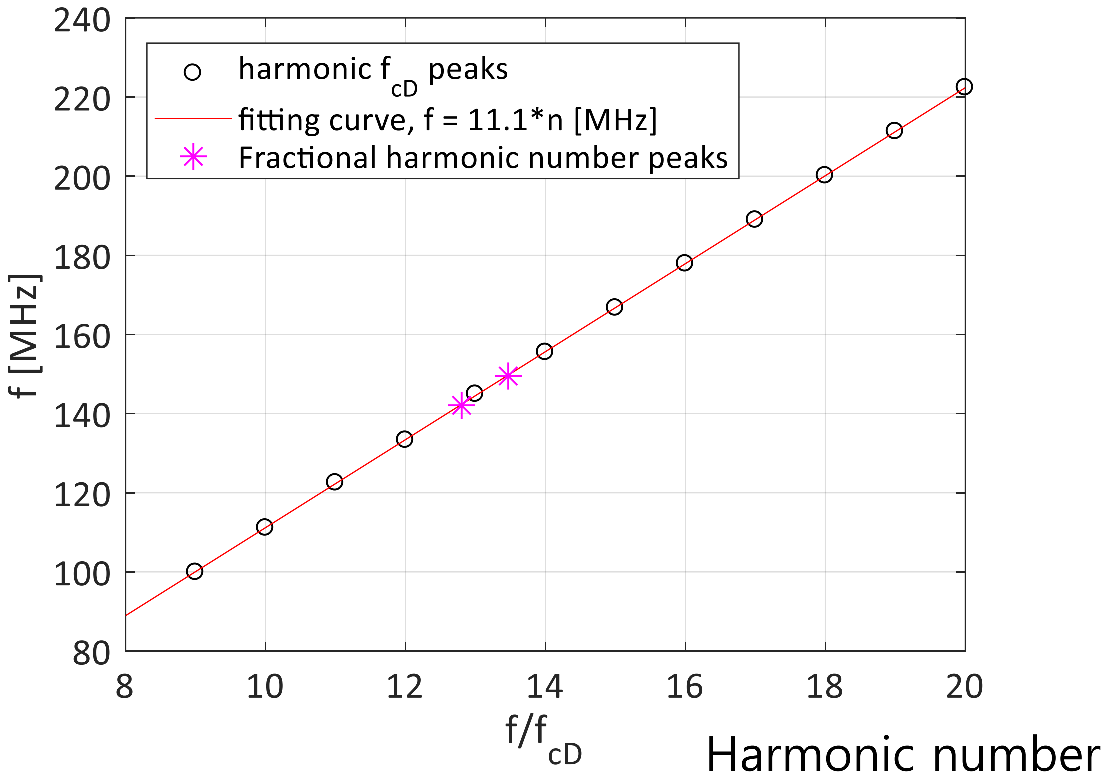
* Kim Minho, NF 2018

KSTAR#16176, RF spectra

(t_0 = 2.760179 s: onset of the collapse)

Stage A: Harmonic ICE





The spacing between the peaks is **deuterium cyclotron frequency** (f_{cD}) at the outboard edge region. (R = 221 ± 2.3 cm, f_{cD} = 11.1 ± 0.1 MHz for this example)

* Kim Minho, NF 2018

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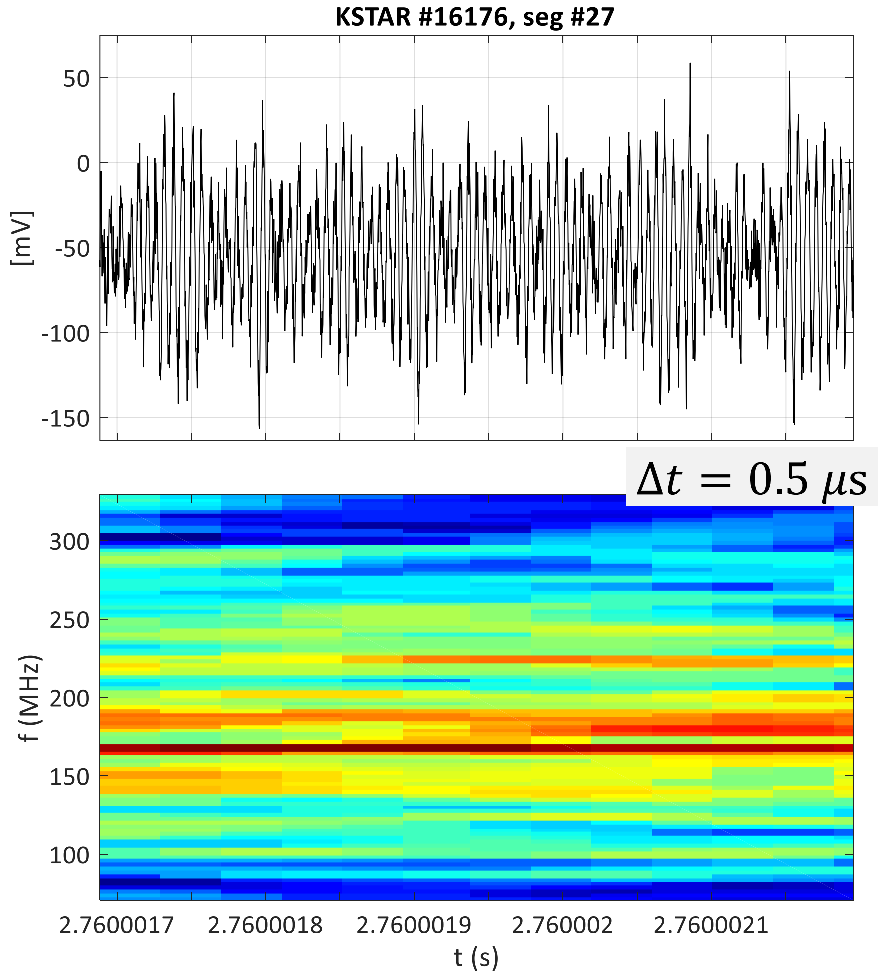
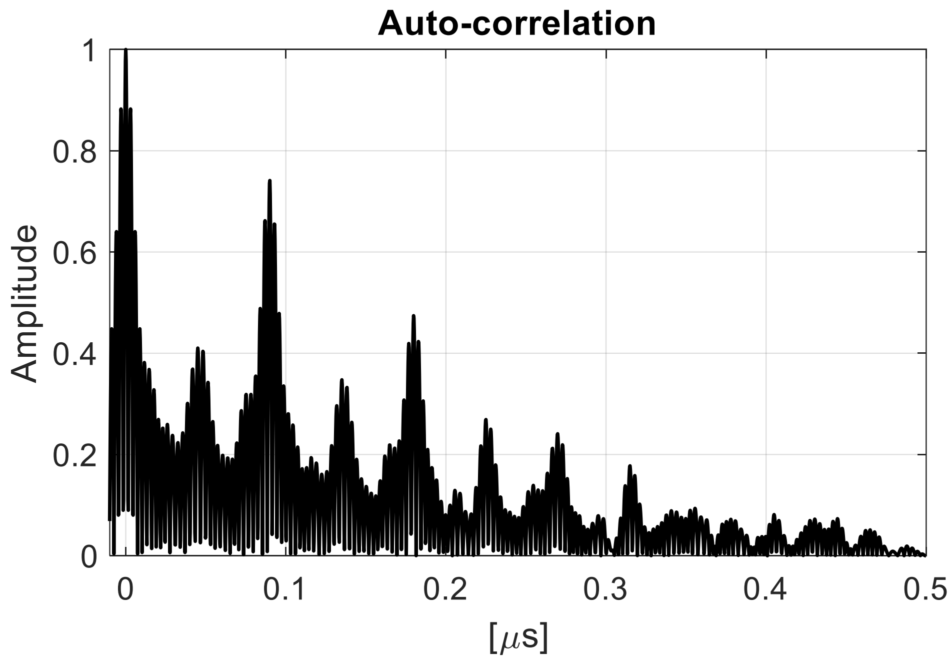
Phase relationship among the harmonics? YES



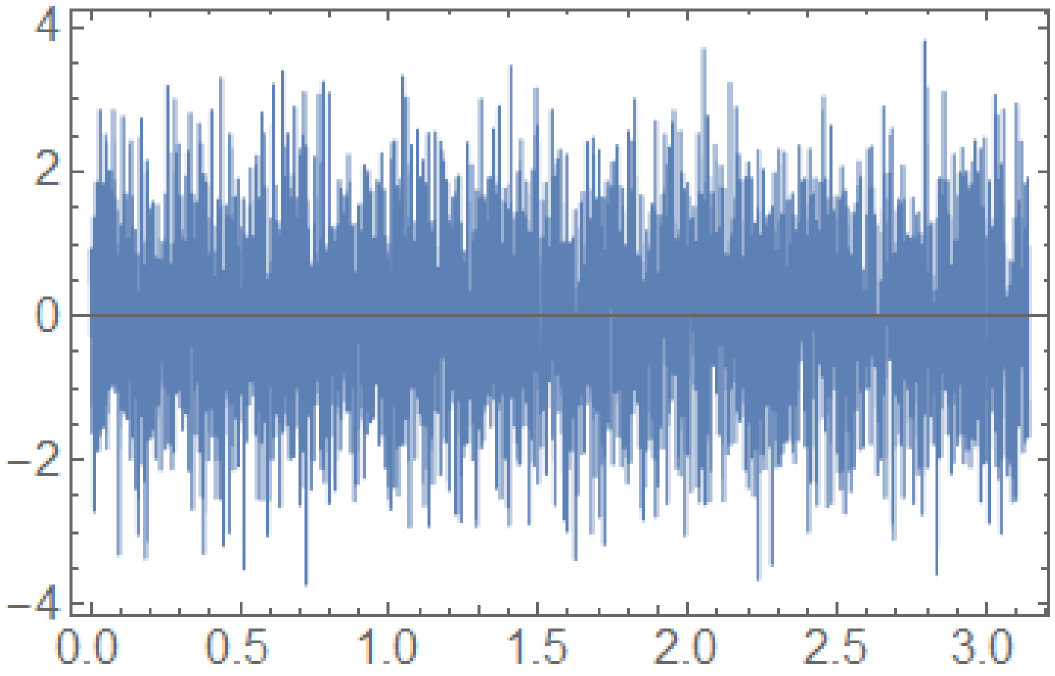
- Amplitude modulation with f_{cD}
- Peaks spaced by $\tau_{cD} = 1/f_{cD}$ in auto-correlation

→ **Temporally (or spatially) *localized excitation***



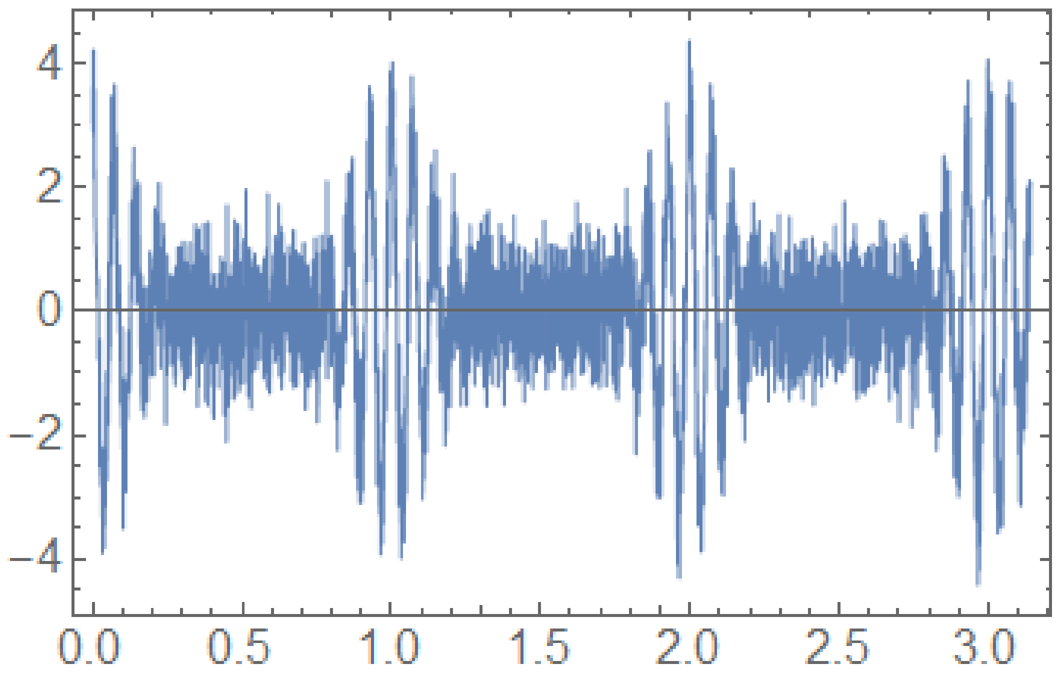
Random Phase

$$\sum_{m=8}^{20} e^{-\frac{(m-14)^2}{4}} \cos(2\pi m t + \delta(t)) + \text{noise}(t)$$

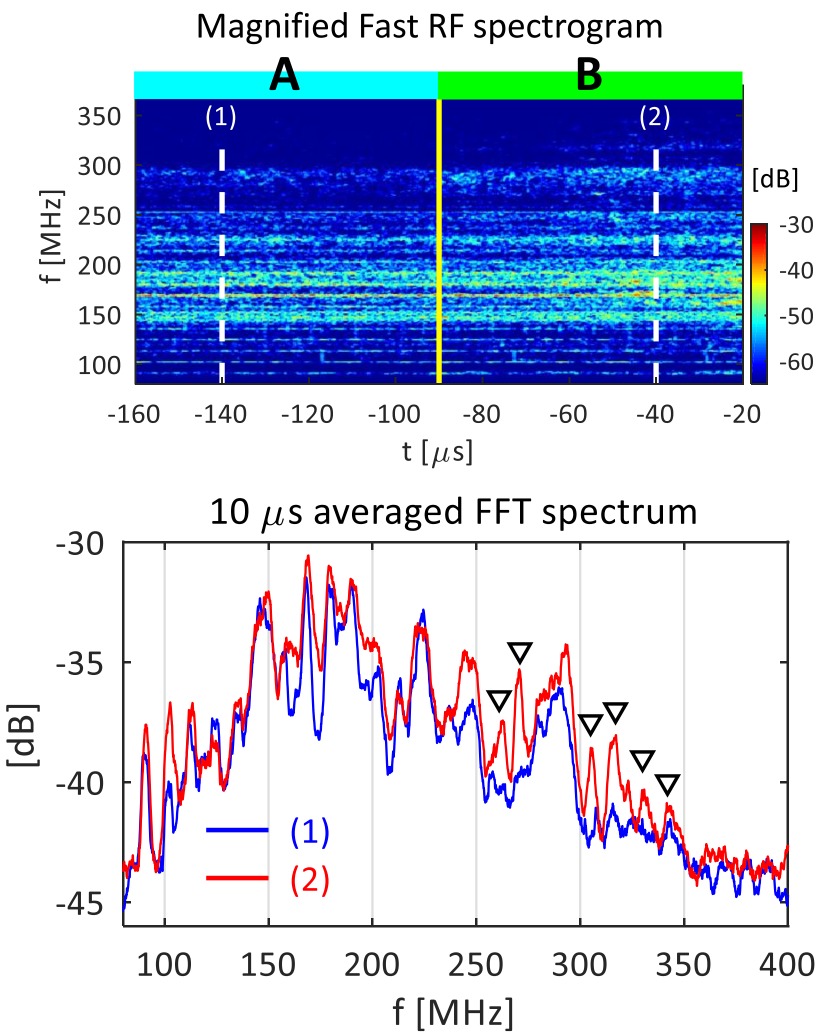


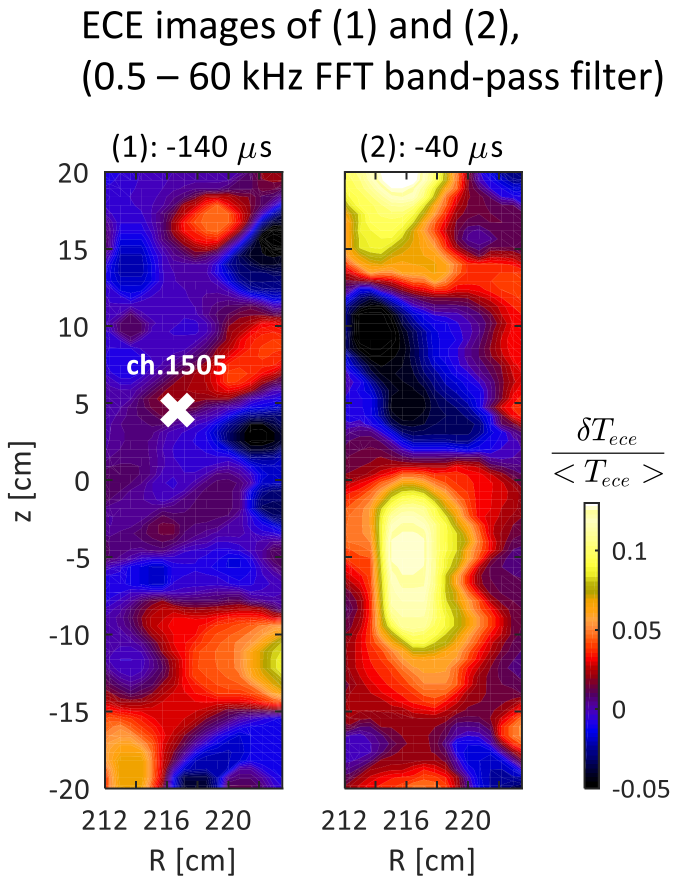
Fixed Phase

$$\sum_{m=8}^{20} e^{-\frac{(m-14)^2}{4}} \cos(2\pi m t + \delta_0) + \text{noise}(t)$$



Stage →B: Intensification of high-harmonic ICEs

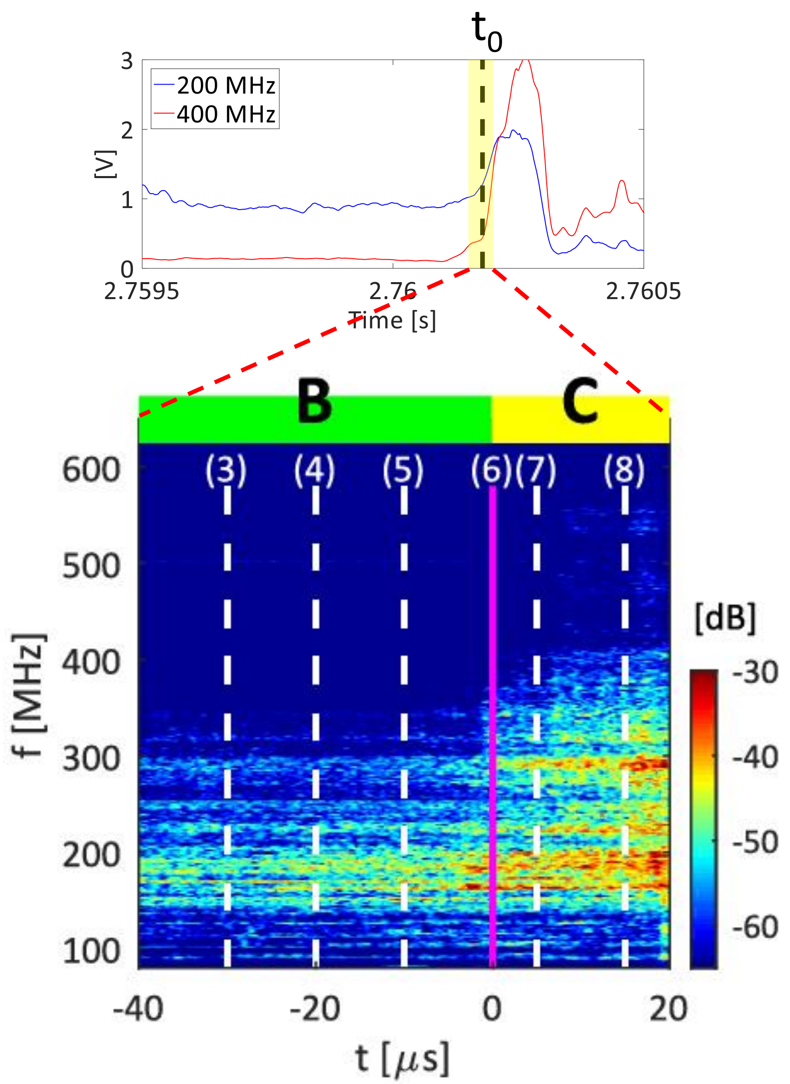




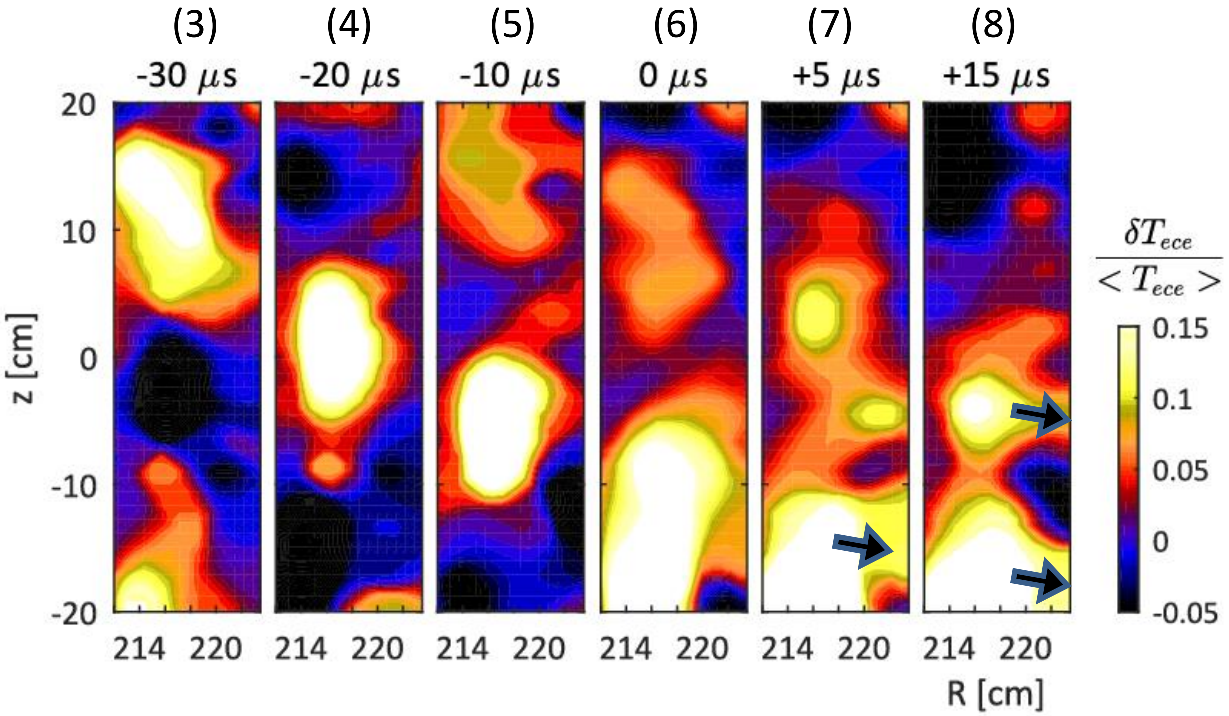
coincides with the emergence of a nonmodal filament.

* Kim Minho, NF 2018

Stage →C: Rapid transition into wide-band emission



coincides with the burst of the nonmodal filament.



* Kim Minho, NF 2018

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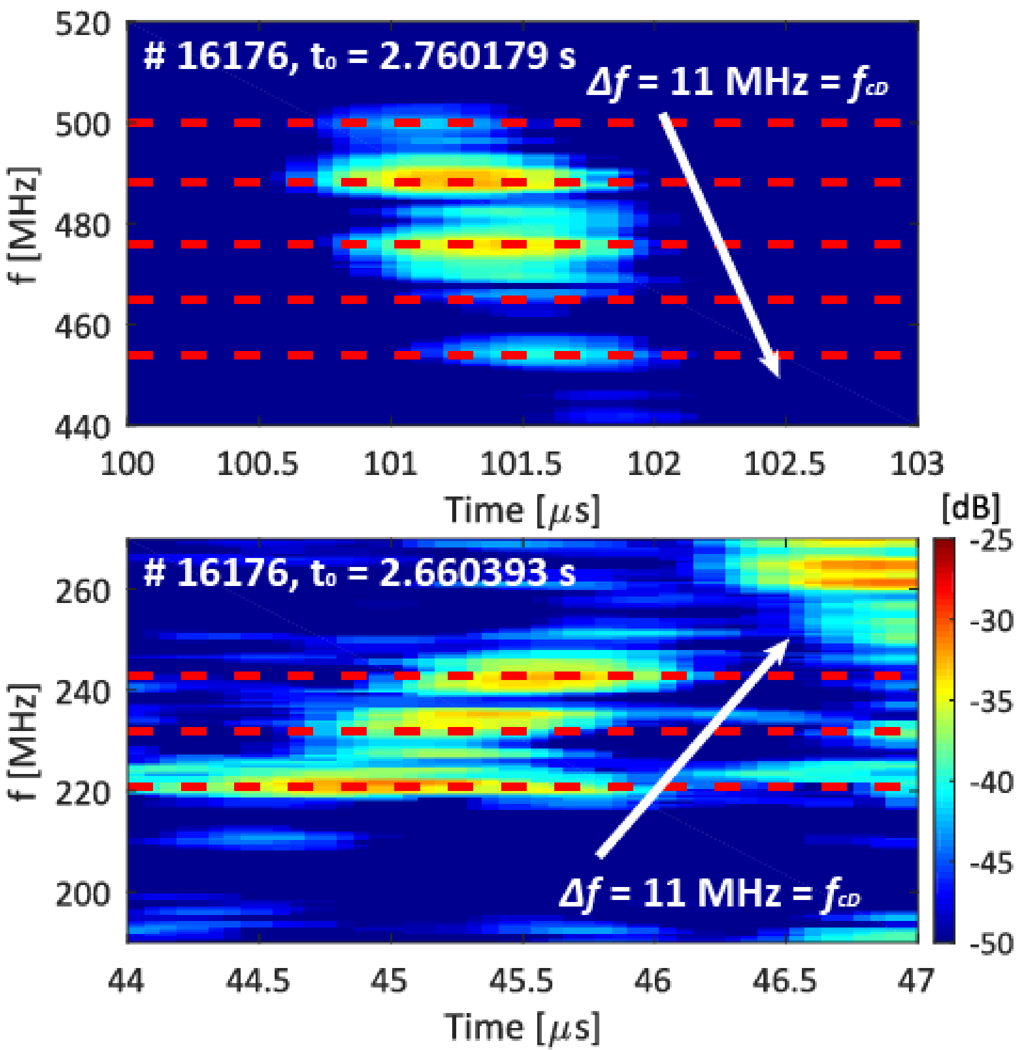
Stage D: Additional short bursts with chirping



- During the pedestal collapse, additional filament bursts occur several times with **rapid up/down chirp** in RF spectrum.
- The chirping occurs in step of f_{cD} at outboard mid-plane edge region.
- Sometimes, chirpings with f_{cH} are also observed.*

* Thatipamula SG, PPCF 2016
Chapman B, NF 2017

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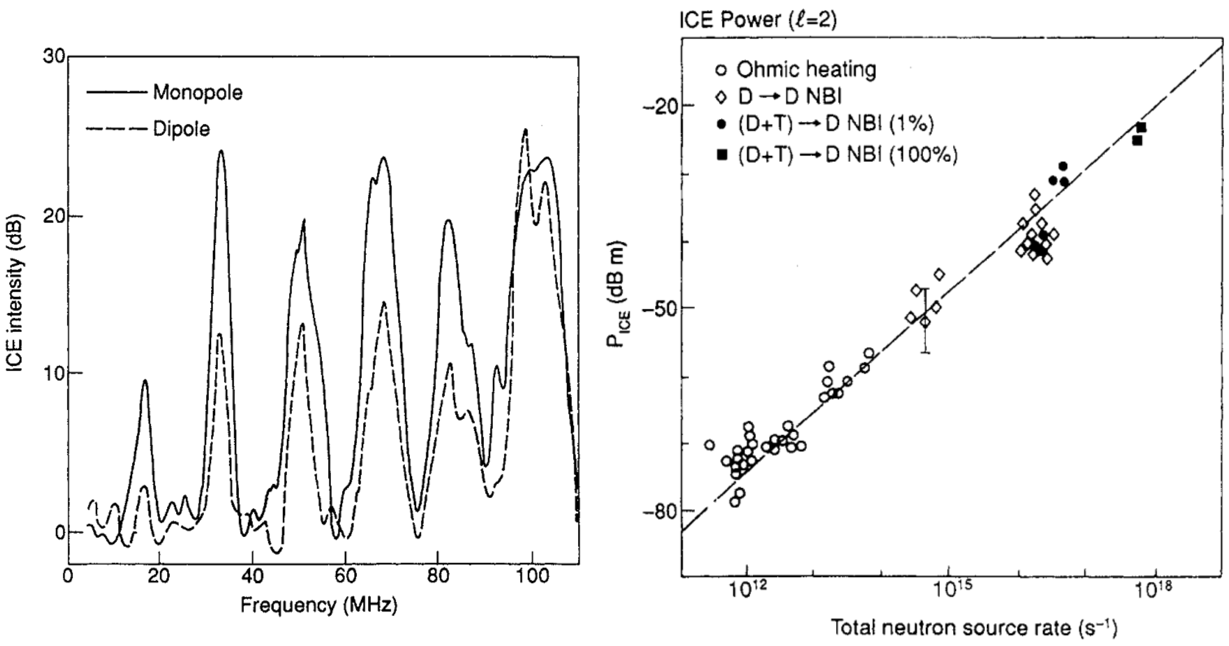
What is causing the harmonic ICE?

- Energetic beam ions or fusion-born ions → Magneto-acoustic Cyclotron Instability (MCI)
- Finite E_r → IC waves (w/ finite k_z)
- Parallel shear flow (Mikhailenko PoP2017)

Candidate #1: Magneto-acoustic ion cyclotron instability (MCI)



(left) ICE spectrum measured by ICRH antenna
(right) ICE intensity vs. neutron source rate

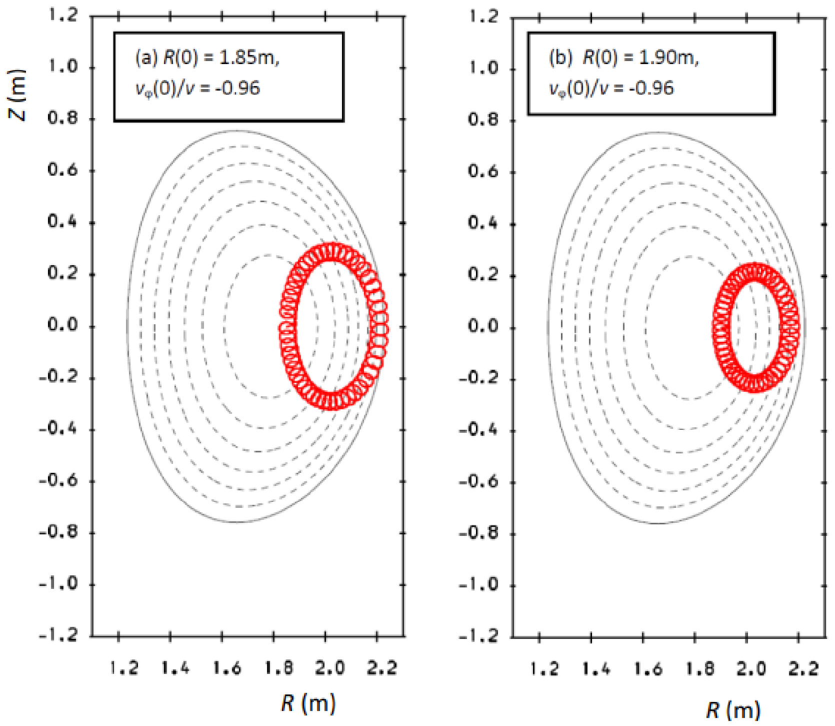
Cottrell GA, NF, 1993

- In 1990s, harmonic ICEs were observed in JET deuterium-tritium (D-T) experiments:
  1) Harmonics of $f_{c\alpha}$ (or half-harmonics of f_{cH}) in the outboard edge region are detected.
  2) ICE intensity (2nd harmonic) linearly proportional to the neutron source rate.

- These observations imply that the **fusion-born α particles** may be associated with ICE in JET D-T experiments.

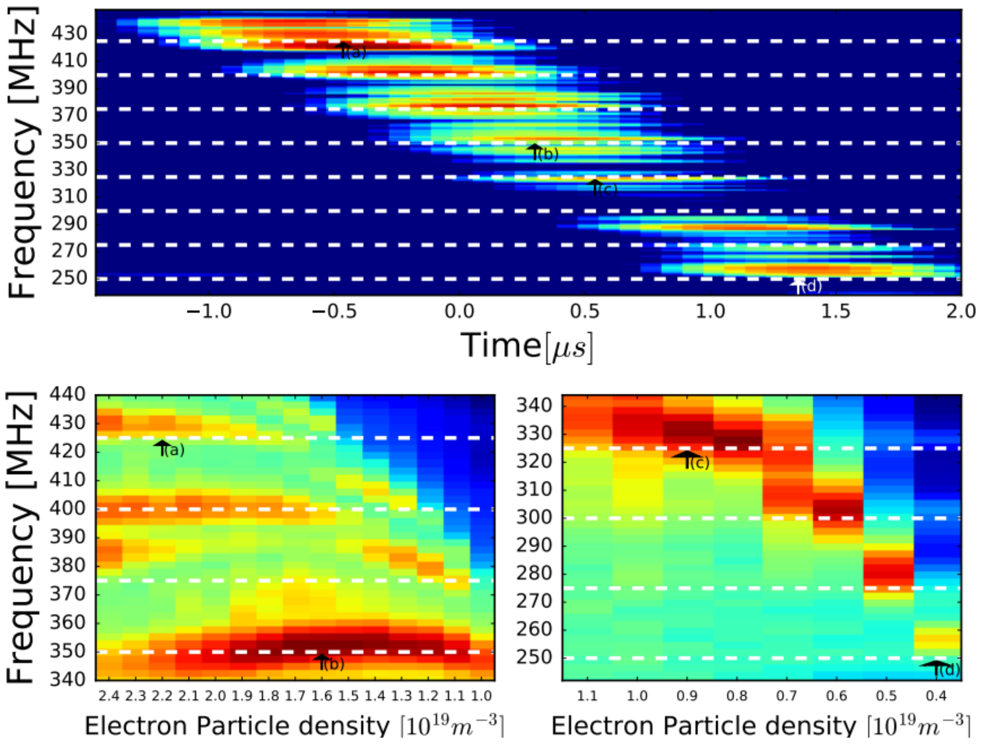
- Fast ions with large radial excursion can make the population inversion in velocity space at the outer mid-plane edge region. This can drive a fast-Alfvénic instability called magneto-acoustic cyclotron instability (MCI)†.

† Dendy RO, NF 1994;
Dendy RO, EPS 2017
* Chapman B, NF 2017



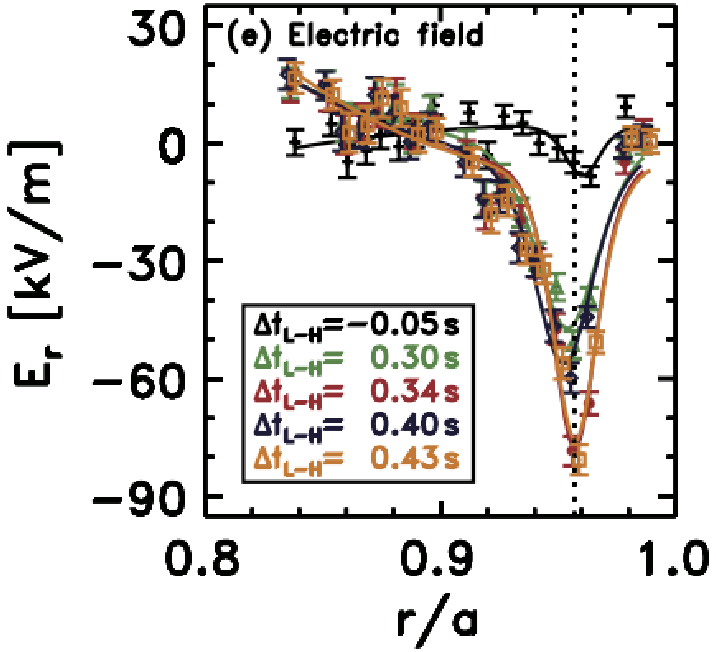
Poloidal projection of 3 MeV fusion proton orbits (produced by D-D fusion)

(Stage D) The rapid f_{cH} chirping can be caused by the rapid decrease/increase of local electron density during the pedestal collapse.*



Candidate #2: IC waves driven by E_r

- In H-mode discharges, strong radial electric field ($E_r \sim 10$ kV/m, $V_E \sim 10$ km/s) with large gradient ($\partial V_E \sim 1$ MHz) is formed near the plasma periphery[1,2].
- $\mathbf{E} \times \mathbf{B}$ velocity and its shear can be intensified near the onset of the pedestal collapse[3].
- Experiments[4] and modeling[5] for ionospheric plasma suggested that localized $\mathbf{E} \times \mathbf{B}$ flow can drive IC waves.



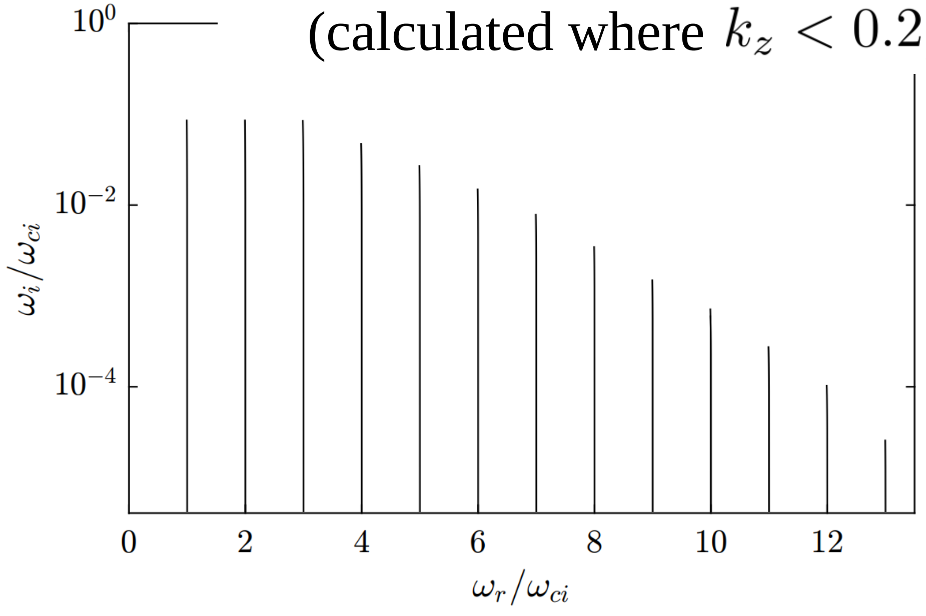
(1) Kamiya, Sci. Rep 2016; (2) Lee KC PoP 2017.
(3) Morales JA, NF 2016
(4) Tejero EM, PRL 2011
(5) Peñano, J. Geophys. Res. 2002

Maxwell-Boltzmann distribution + Integration along the unperturbed trajectory

$$\mathcal{D}\left(x,\,\omega,\,k\right)\;=1+\sum_\sigma \frac{\mathrm{e}^{-\frac{x}{L_\sigma}}}{k^2\lambda_{D\sigma}^2}\left(1+\alpha_{0\sigma}\mathrm{e}^{-\Lambda_\sigma}\sum_{n=-\infty}^{\infty} I_n\left(\Lambda_\sigma\right)Z\left(\alpha_{n\sigma}\right)\right)$$

$$\omega_i=-\frac{\mathcal{D}_i(\omega_r)}{\left(\partial\mathcal{D}_r/\partial\omega\right)_{\omega=\omega_r}}\simeq\frac{\sqrt{\pi}}{2}k_z v_{Ti}$$

Spectrum at $E_0\sim-12\ \mathrm{kV/m}$
(calculated where $k_z<0.2/r_{Li}$)



✓ For given $E_0(x), \omega_r$, and k_y, the wavenumber k_z can be determined from the dispersion relation.

$$\Lambda_\sigma=k_y^2 r_{L\sigma}^2,\ \alpha_{n\sigma}=\frac{\omega-\omega_\sigma^*-n\omega_{c\sigma}}{k_z v_{T\sigma}}$$

$$Z\left(\alpha_{n\sigma}\right)=\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty}\mathrm{d}\xi_\sigma\frac{\exp\left(-\xi_\sigma^2\right)}{\xi_\sigma-\alpha_{n\sigma}}:\ \text{plasma dispersion function}$$

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V. Summary

- **Ion cyclotron harmonic waves are easily excited in the boundary of tokamak plasma.**

  Strongly correlated with edge MHD instabilities:

  - Intensified high harmonic ICE ~ Nonmodal filament

  - Wide-band emission ~ Filament burst (magnetic reconnection)

- **Useful for study (diagnostic) of edge MHD instabilities and energetic ions in magnetized plasma.**

Implication of whistler waves and ICEs on magnetic reconnection

$$\eta_\pi = \mu_0 \delta_e^2 / \tau_\pi \quad \text{: viscous resistivity}$$

$$\eta_{\rm rad} \sim \mu_0 \delta_e^2 / \left(\frac{m_e}{m_i} \tau_{rec} \right) \quad \text{: radiative resistivity}$$

$$\eta_{\rm coll} \sim \mu_0 \delta_e^2 / \tau_{ei} \quad \text{: collisional resistivity}$$

$$\tau_\pi = \frac{1}{3\pi\breve{\pi}} \lambda_{||} / v_{Te}$$

$$\tau_{rec} : \text{reconnection time, experimental}$$

$$\tau_{ei} : \text{electron} - \text{ion momentum collision time}$$

$$\frac{\partial}{\partial t}\left(\frac{\tilde{B}^2}{2\mu_0}\right) = \boxed{-\tilde{\mathbf{J}} \cdot \tilde{\mathbf{E}}^*} - \nabla \cdot \left(\frac{\tilde{\mathbf{E}}^* \times \tilde{\mathbf{B}}}{\mu_0}\right)$$

$$\Re\left[\tilde{\mathbf{J}} \cdot \tilde{\mathbf{E}}^*\right] \approx \delta_e^2 \mu_0 \left(\frac{3\breve{\pi}}{2} k_{||} v_{Te} \tilde{J}_{||}^2\right) + \Re\left[\tilde{\mathbf{U}}^* \cdot \left(\tilde{\mathbf{J}} \times \mathbf{B}_0\right)\right]$$

Viscous dissipation *Work done by $J \times B$ force*

† Yun and Ji (to be upload to ArXiv)

In high-temperature magnetized plasma, typically $\eta_\pi \sim \eta_{\rm rad} \gg \eta_{\rm coll}$ ➔ Fast reconnection.

e.g. For a magnetic reconnection event with length and time scales $\lambda_{||} = 1$ m, $\tau_{rec} = 10\ \mu s$ in high-temperature hydrogen plasma with $T_e = 2$ keV and $n_e = 5 \times 10^{19}$ m^{-3} ($\rightarrow \delta_e \approx 1$ mm, $\tau_{||} \approx 0.015\ \mu s, \gg \tau_{ei} \approx 40\ \mu s$)

$$\begin{matrix} \eta_\pi \sim 5 \times 10^{-5}\ \Omega \cdot \text{m} \\ \eta_{\rm rad} \sim 10 \times 10^{-5}\ \Omega \cdot \text{m} \end{matrix} \gg \eta_{\rm coll} \sim 2 \times 10^{-8}\ \Omega \cdot \text{m}$$

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