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Edge-Localized Modes in KSTAR :

global structure and distinct evolution stages involving quasi-steady state and phase transitions

Gunsu S. Yun

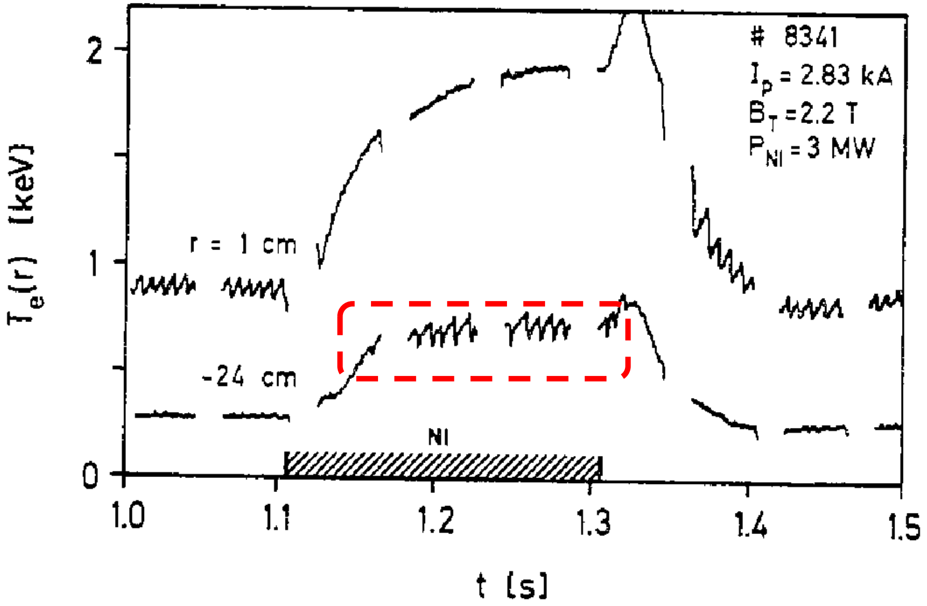
POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

J.E. Lee, S. Thatipamula, M.H. Kim (POSTECH),
J. Lee, H.K. Park (UNIST),
M.J. Choi, W. Lee (NFRI), and KSTAR Team

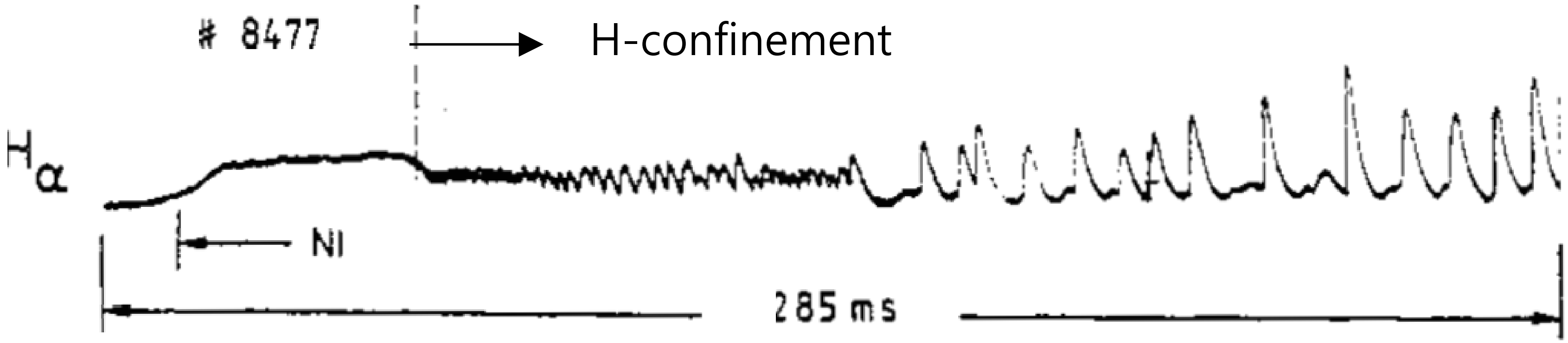
UNIST Ulsan National Institute of Science and Technology
NFRI National Fusion Research Institute
KSTAR

Edge Localized Modes (ELMs)

First used in ASDEX [Keilhacker 1984] to describe **semi-periodic edge-localized relaxation phenomena** (cf. PDX, Kaye 1984), following the discovery of ***high-confinement*** discharge type [Wagner 1982].

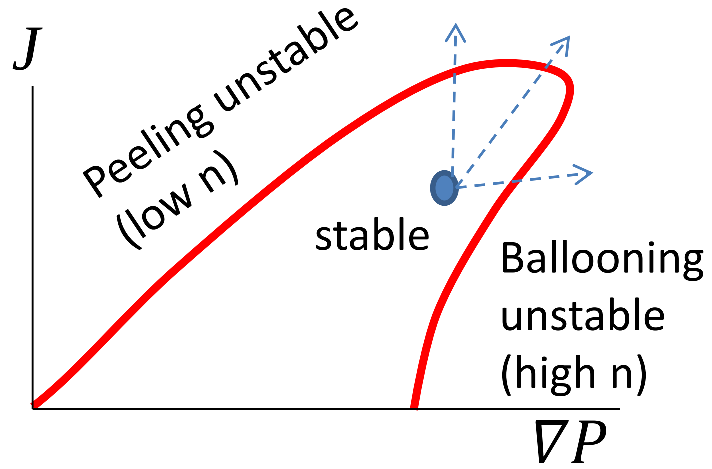


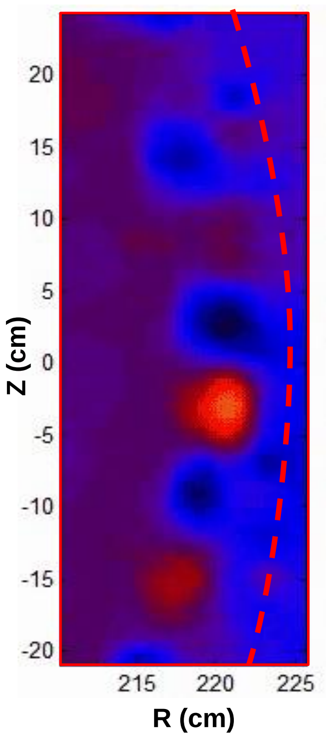
Easily identified as sharp spikes by edge diagnostics, e.g. H-alpha.



Edge Localized Modes (ELMs)

- Linear MHD theories/simulations identified the relaxation events with the growth of **the peeling-ballooning modes** in the pedestal region (high ∇P + high J).





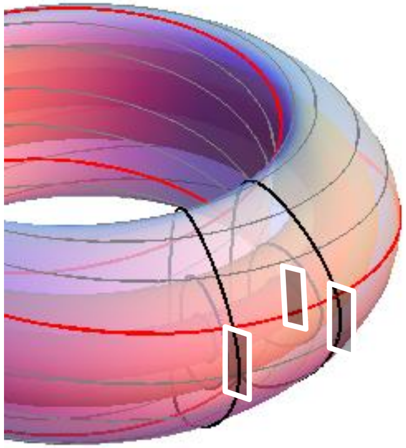
- Many observations† and nonlinear simulations‡ showed that the relaxation events are associated with ***edge-localized field-aligned filamentary modes.***

† e.g. Kirk 2004, Kurzan 2007, Yun 2011, …
‡ cf. M. Kim EX/P4-7, M. Becoulet TH/P1-24

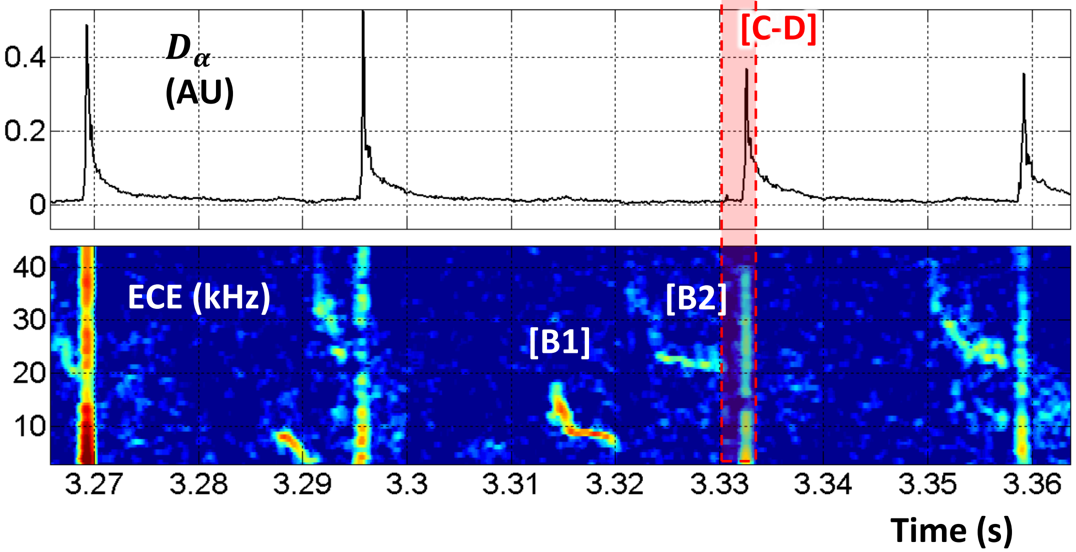
Part I

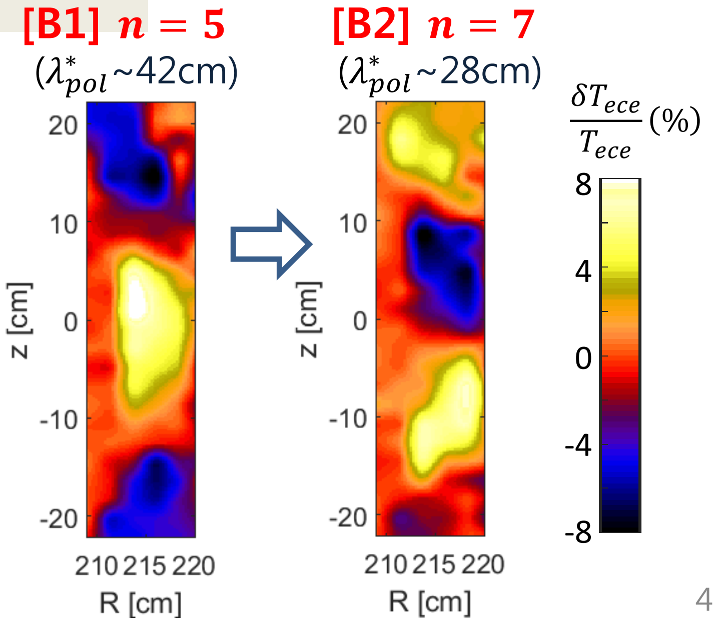
The ECE imaging diagnostics on the KSTAR tokamak revealed that the semi-periodic ELM cycle evolves through multiple stages:

- [A] Linear growth (rarely observable)
- [B] *Quasi-steady states (field-aligned filamentary modes)*
- [C] *Phase transition into low-n*
- [D] *Rapid collapse*

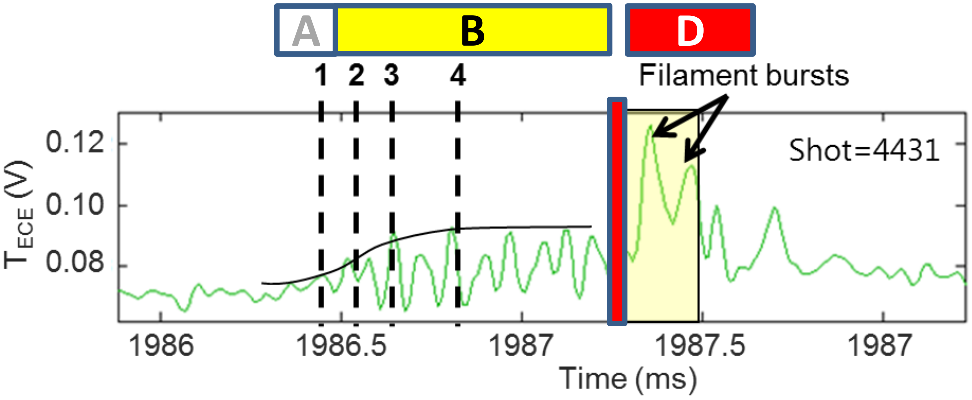


#13790: B_T = 1.8 T, I_p ~ 510 kA, κ ~ 1.7, q_{95} ~ 5.0



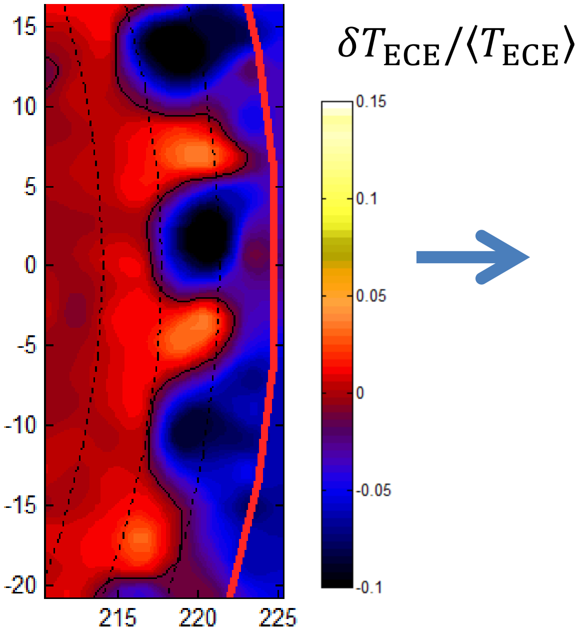


Transition to low-*n* solitary structure



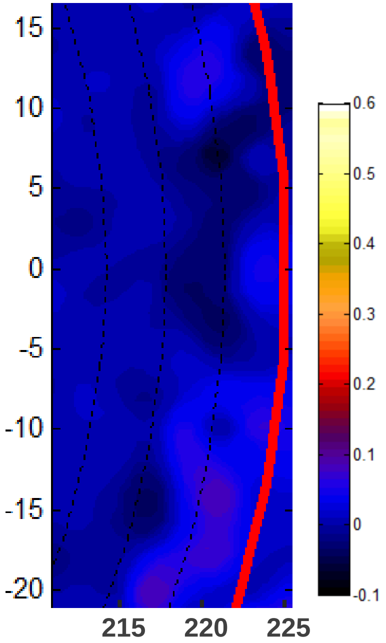
[B] Quasi-steady state*

(n~16; regular)



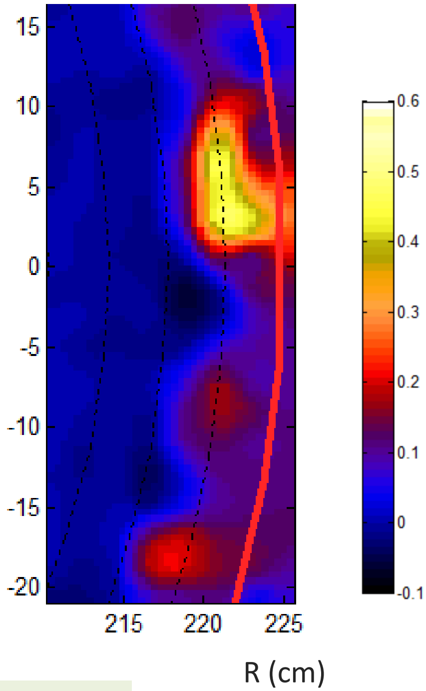
[C] Transition†

(short <~50 μs)



[D] Crash phase

(low *n*; solitary)‡



* Yun, PRL (2011); Yun, PoP (2012); Kim, NF (2014), Lee, PRL (2016)

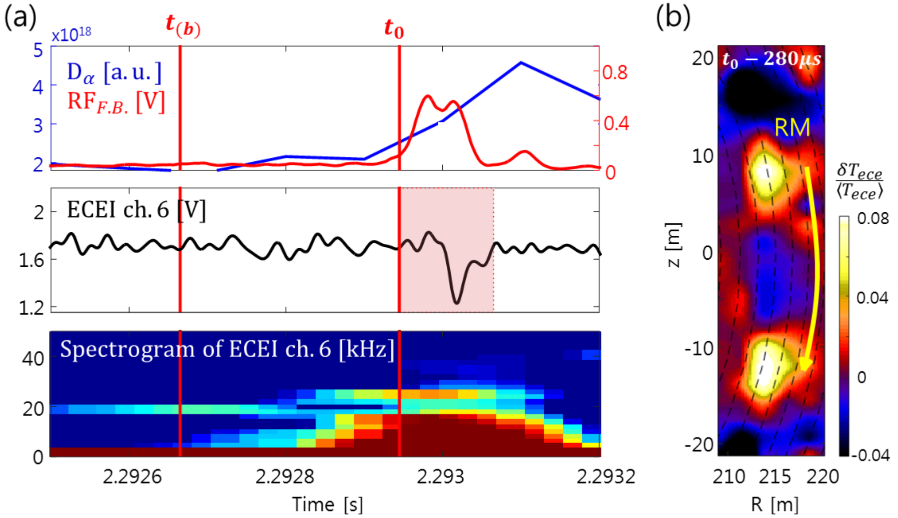
† cf. J.E. Lee, NF (2015)

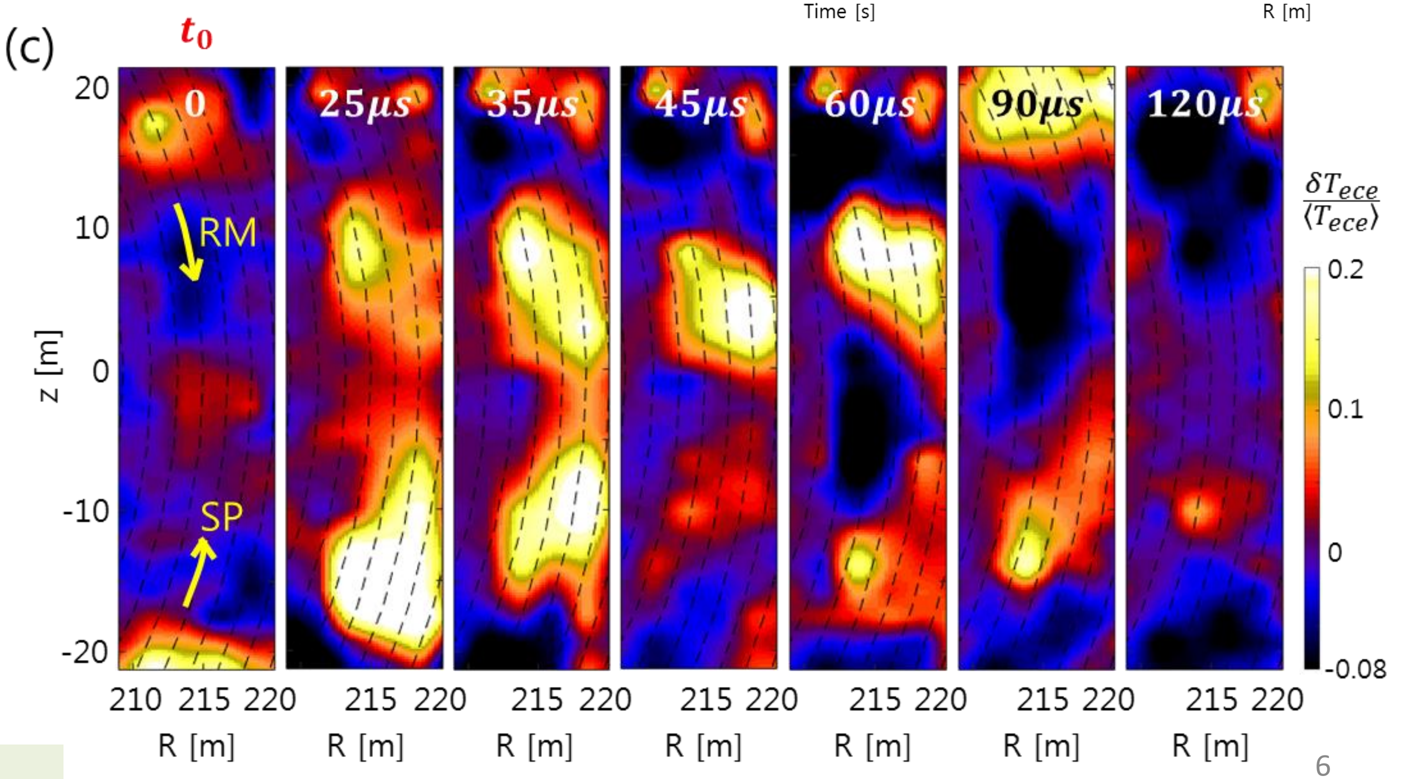
‡ cf. Solitary magnetic perturbation [Wenninger 2012]

Phase transition into *n=1* solitary structure toward the crash*

KSTAR#13250

B_T = 1.8 T, I_p ~ 600 kA, W=300 kJ, q_{95}=4.3





RM: regular filamentary mode

SP: solitary perturbation (*n*=1)

* J.E. Lee, submitted.

These distinct evolution stages are common feature of the ELM dynamics in the KSTAR:

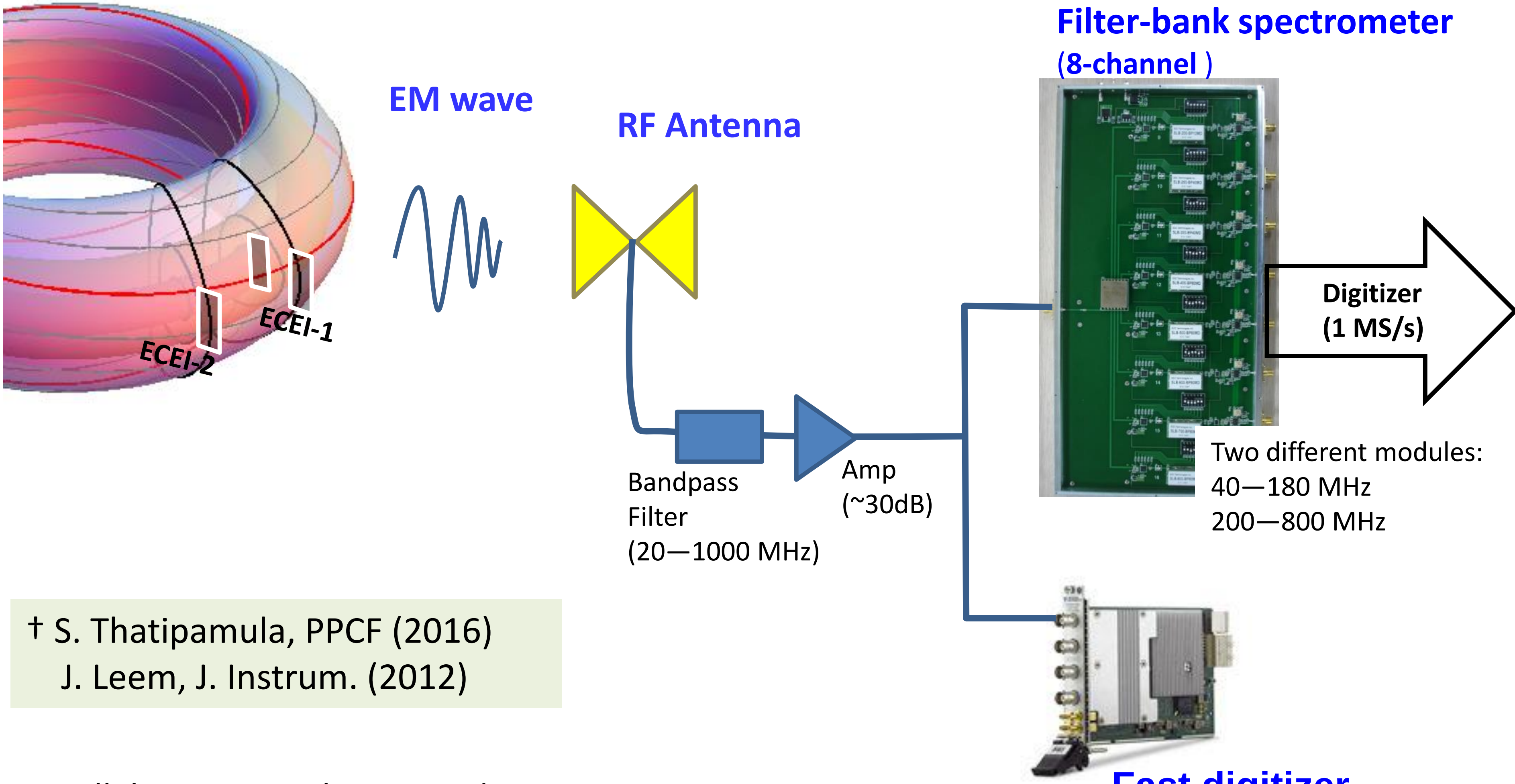
Initial growth (very short or not observable) → **Quasi-Steady States → Phase Transition into low-*n* mode → Crash through multiple bursts**

Note that the KSTAR H-mode discharges are highly shaped (δ>0.6, κ~1.5) with high rotation (~100 km/s at pedestal top).

In the following, "ELM" refers to the perturbation structure before crash and "ELM crash" refers to the final stage of the ELM cycle. (In literature, ELM often indicates edge transport events and the mode before crash is referred as *precursor mode*.)

Part II

Let’s examine the ELM dynamics more closely using “RF” diagnostics†.



EM wave

RF Antenna

Bandpass Filter (20—1000 MHz)

Amp (~30dB)

Filter-bank spectrometer (8-channel)

Digitizer (1 MS/s)

Two different modules:
40—180 MHz
200—800 MHz

Fast digitizer

- ✓ $F_{sampling}$: 5 (or 20) GS/s,
- ✓ BW: 0.1—1.5 (or 6) GHz

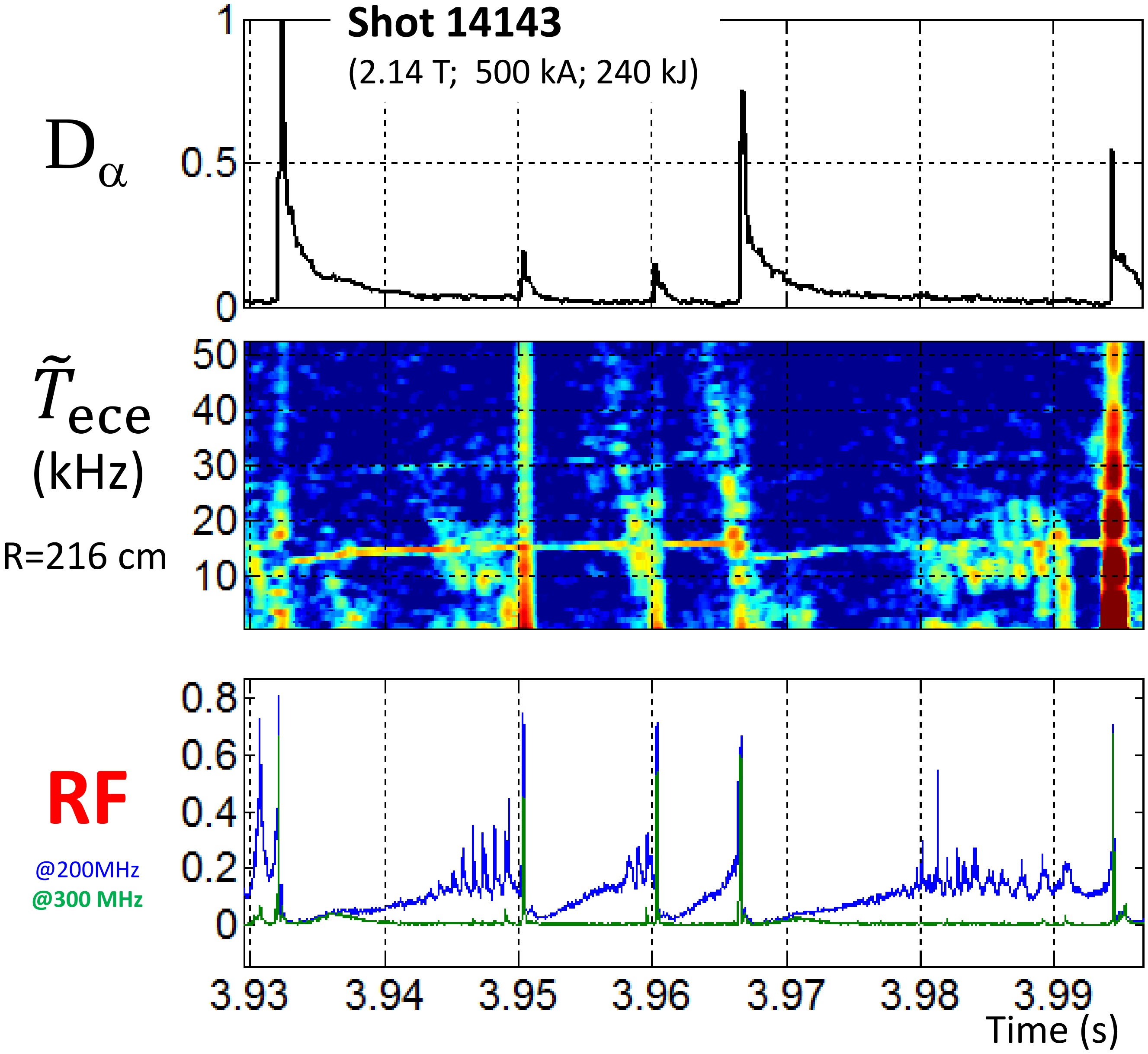
† S. Thatipamula, PPCF (2016)
J. Leem, J. Instrum. (2012)

In collaboration with KNU and NIFS

KNU KYUNGPOOK NATIONAL UNIVERSITY

核融合科学研究所
National Institute for Fusion Science

RF as a better diagnostics for ELM dynamics

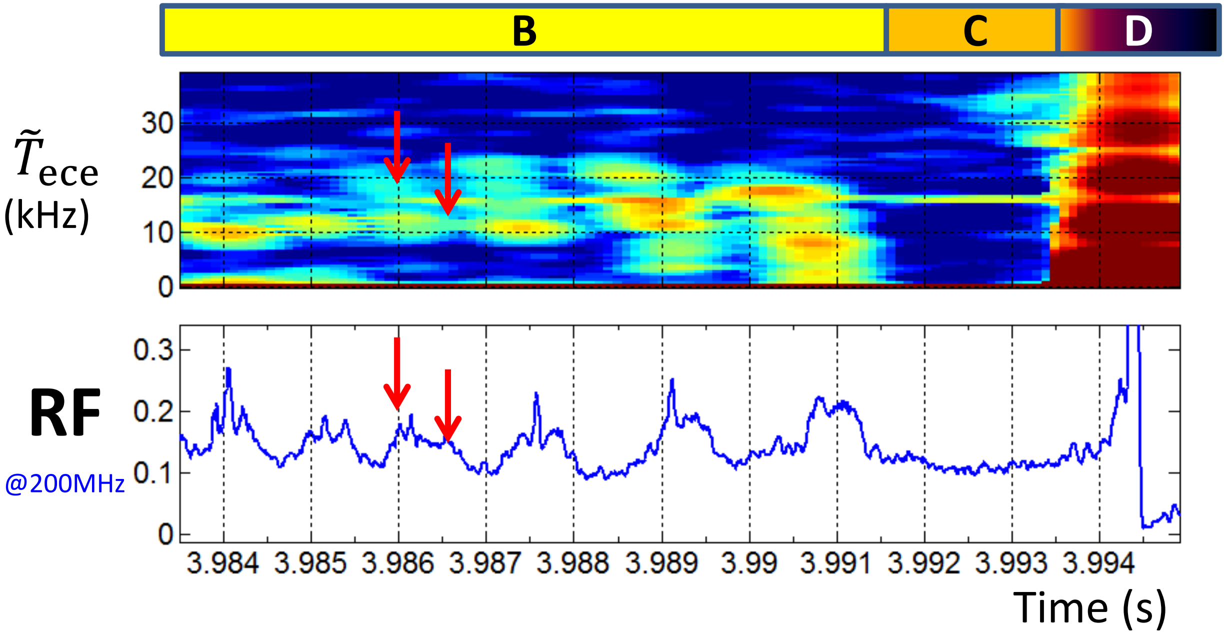


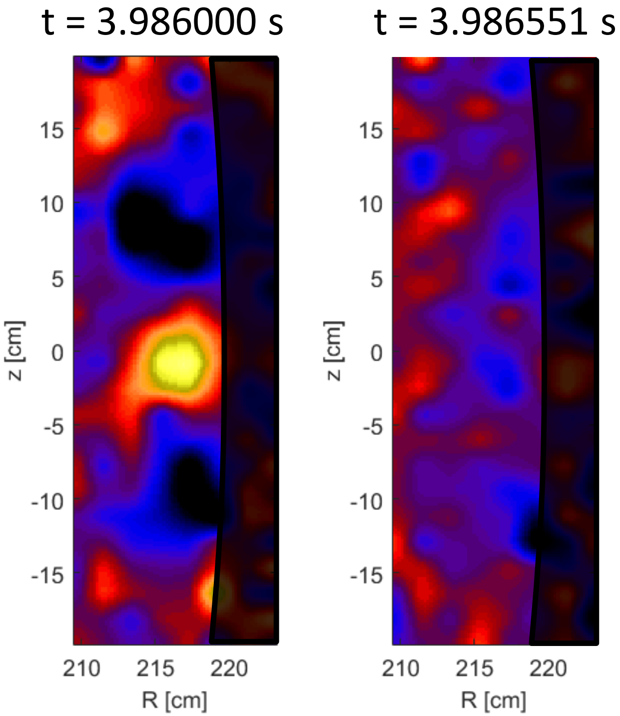
Dα signal is only an aftermath of crash

ECE signal spectrogram provides information on the mode activities.

RF signals capture the mode activities (narrow-band emission) and the exact moment of crash (broadband peaks).

[B] Quasi-steady state



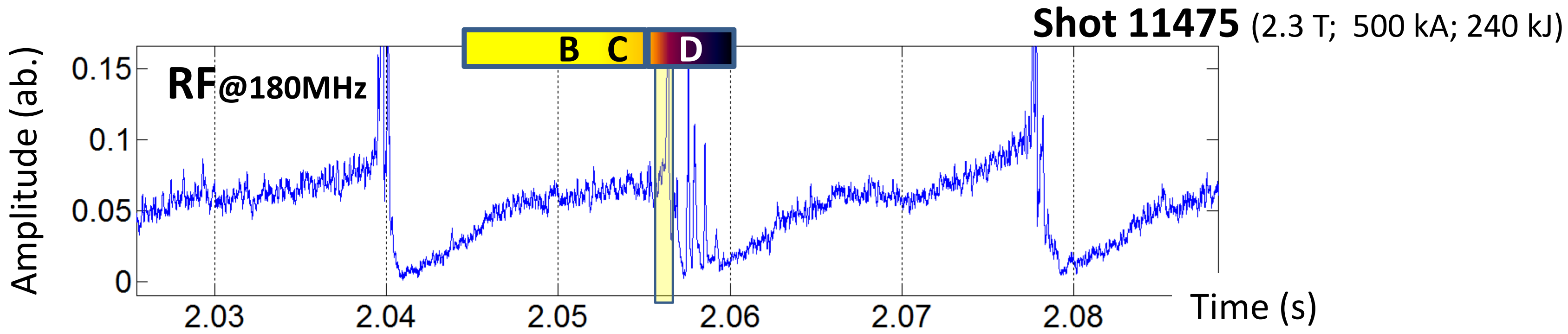


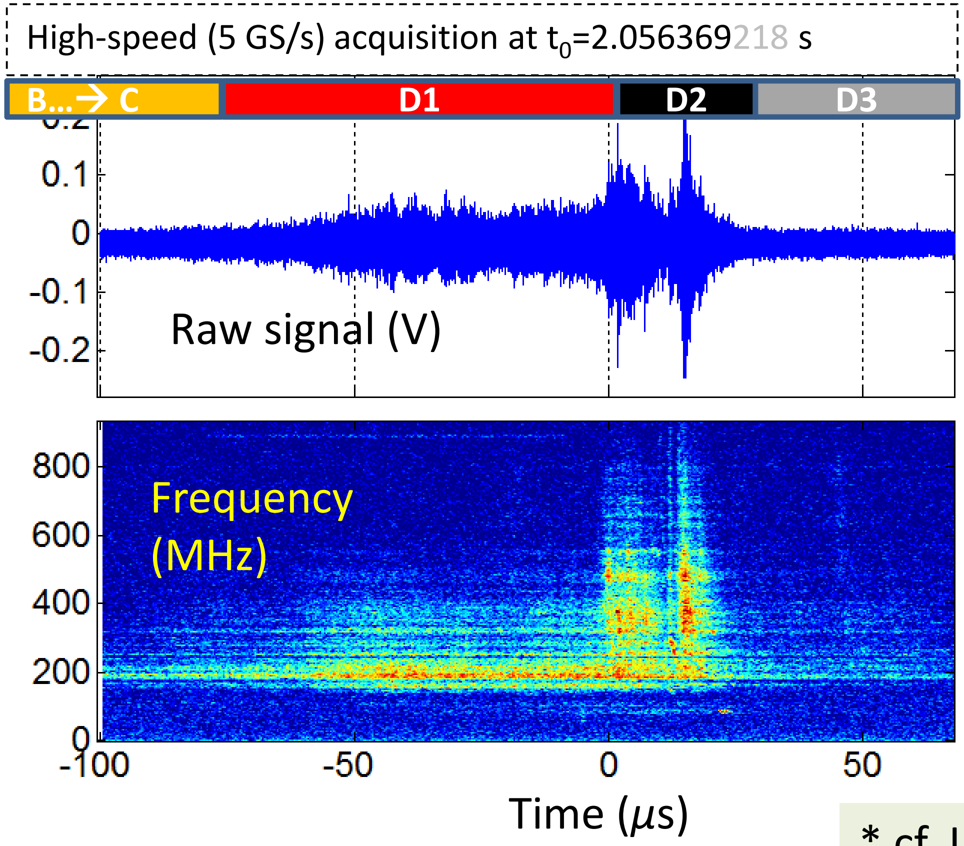
Mode Amplitude

~ RF Intensity:

Strong/weak mode amplitude at rising/falling RF intensity

Rapid change of the RF spectrum near crash





In the inter-crash period,

[B-C] Persistent emission ~200 MHz*

* cf. Lower hybrid freq in the pedestal,
f_{LH} = ~100 – 500 MHz

At intense RF peaks*,

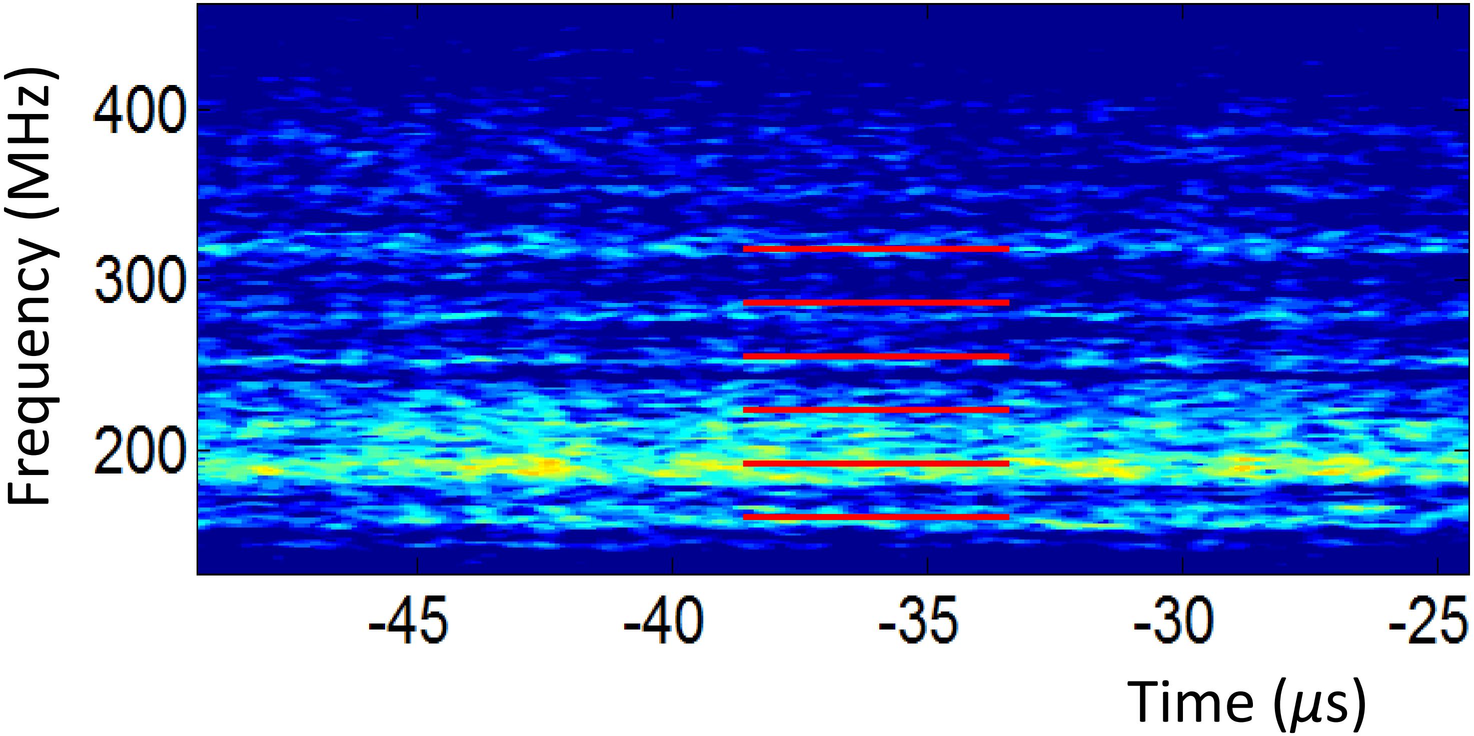
[D1] Harmonic ion cyclotron emission (ICE) lines

[D2] Broadband emission and/or *chirping* at the filament bursts

* cf. Intense bursts of microwave emission (BME) in the f_{ce} range at MAST [Freethy 2016].

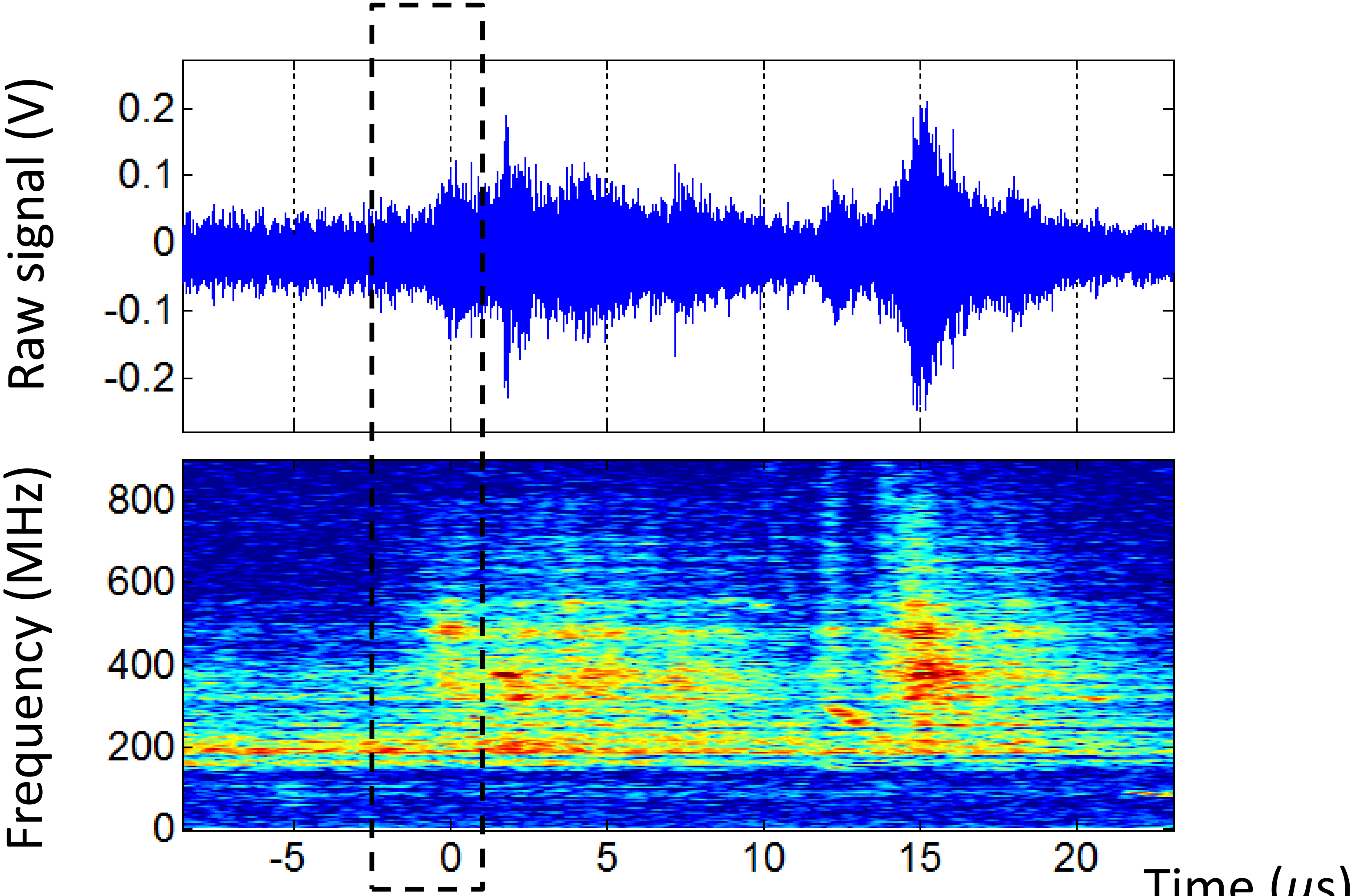
[D1] Harmonic Ion Cyclotron Emission (ICE)† lines on top of the 200 MHz component near the onset of crash.

In this example, the ICE spacing is $\sim f_{c,\mathrm{H\ (edge)}} = 25$ MHz.
But, ICEs with spacing $\sim f_{c,\mathrm{D\ (edge)}}$ are more common.



† [EXW-P6] D'Inca et al. for multi-machine ICE comparisons.
APS-DPP 2016 [GP10.00093] Chapman, Dendy et al. Numerical simulation of ICE.

[D2] Extremely rapid onset of broad-band emission at the onset of crash (burst). ICE structure† is also present.



† **APS-DPP 2016 [GP10.00093]** Chapman, Dendy et al. Numerical simulation of ICE.

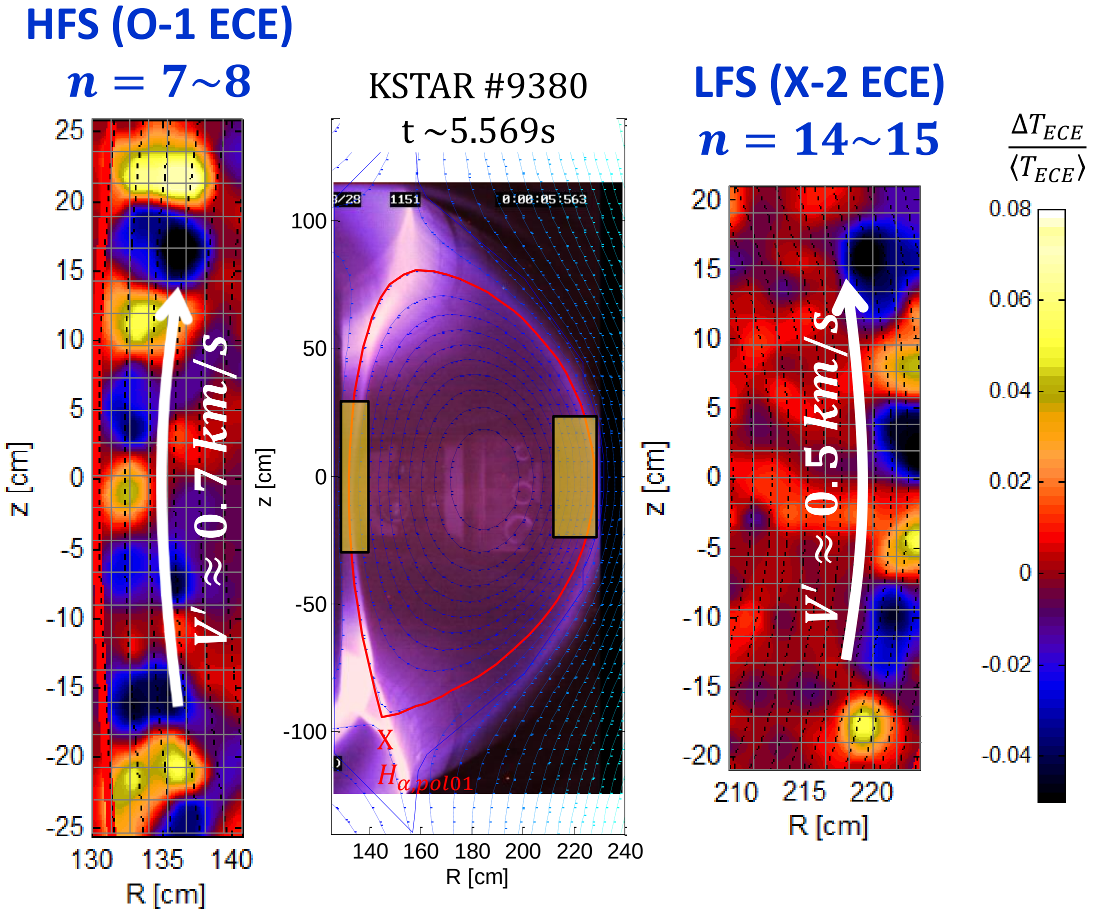
Part III

Global structure of the quasi-steady ELM†

Finite mode amplitude at the HFS!

(1) Different toroidal mode number*

(2) Opposite mode rotation (opposite $v_\perp$): Large flow shear if the modes are located at different flux surfaces.



➔ These differences may indicate different instability drives btw LFS and HFS.

† J. Lee, Yun, in preparation

* J. Lee, RSI (2014)

Summary

(1) “ELM” is more than an explosive relaxation event, involving a complex evolution through distinct stages

- **Quasi-steady state(s)** **(*Rarely in a linear growth phase*)**
- **Phase transition(s):** **regularly spaced filaments → low-*n* solitary filaments**
- **Crash:** **Multiple localized bursts**

(2) RF emission provides time-resolved information on the ELM dynamics

- **Persistent emission** **(~200 MHz) in the inter-crash period**
- **Harmonic ICE** (spaced by $f_{\mathrm{c,H}}$ or $f_{\mathrm{c,D}}$) **near the onset of crash**
- **Broadband and/or chirping emissions at individual bursts**

(3) The ELM dynamics are nonlinear and multi-scaled; far more complicated than the static picture based on peeling and ballooning instabilities.

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POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Collaborators:

Jaehyun Lee, Minwoo Kim, Hyeon K. Park (UNIST)

Minjun Choi, Woochang Lee (NFRI), Kang-wook Kim (KNU)

NFRI UNIST Ulsan National Institute of Science and Technology KNU KYUNGPOOK NATIONAL UNIVERSITY

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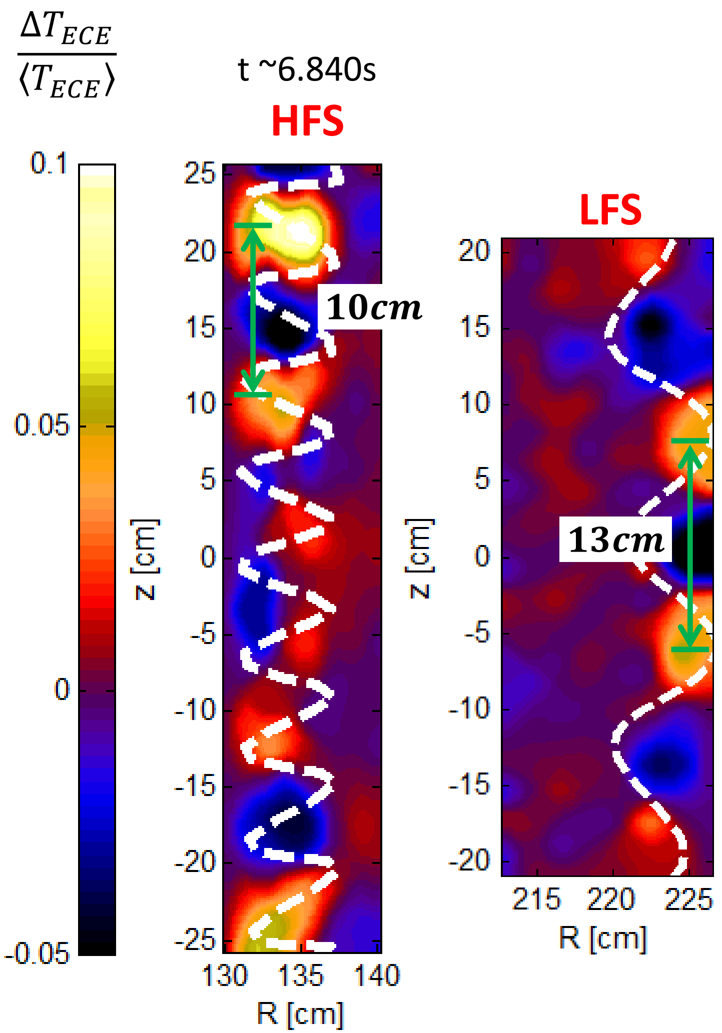
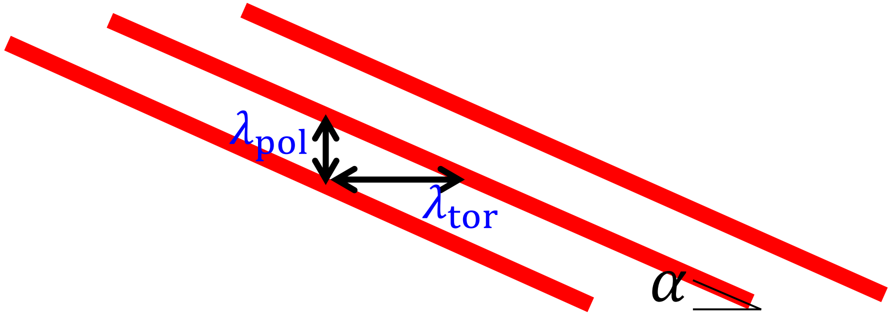
Two issues with the HFS ELM

(1) Different toroidal mode number*



$$n = \frac{2\pi R_*}{\lambda_{\text{tor}}} = \frac{2\pi R_*}{\lambda_{\text{pol}}} \frac{\lambda_{\text{pol}}}{\lambda_{\text{tor}}} = \frac{2\pi R_*}{\lambda_{\text{pol}}} \cdot \tan(\alpha_*)$$



	R_* $[cm]$	λ_{pol} $[cm]$	$\tan\alpha_*$	***n***
LFS	225	13	0.13	**14–15**
HFS	132	10	0.09	**7–8**

from ECEI

from EFIT

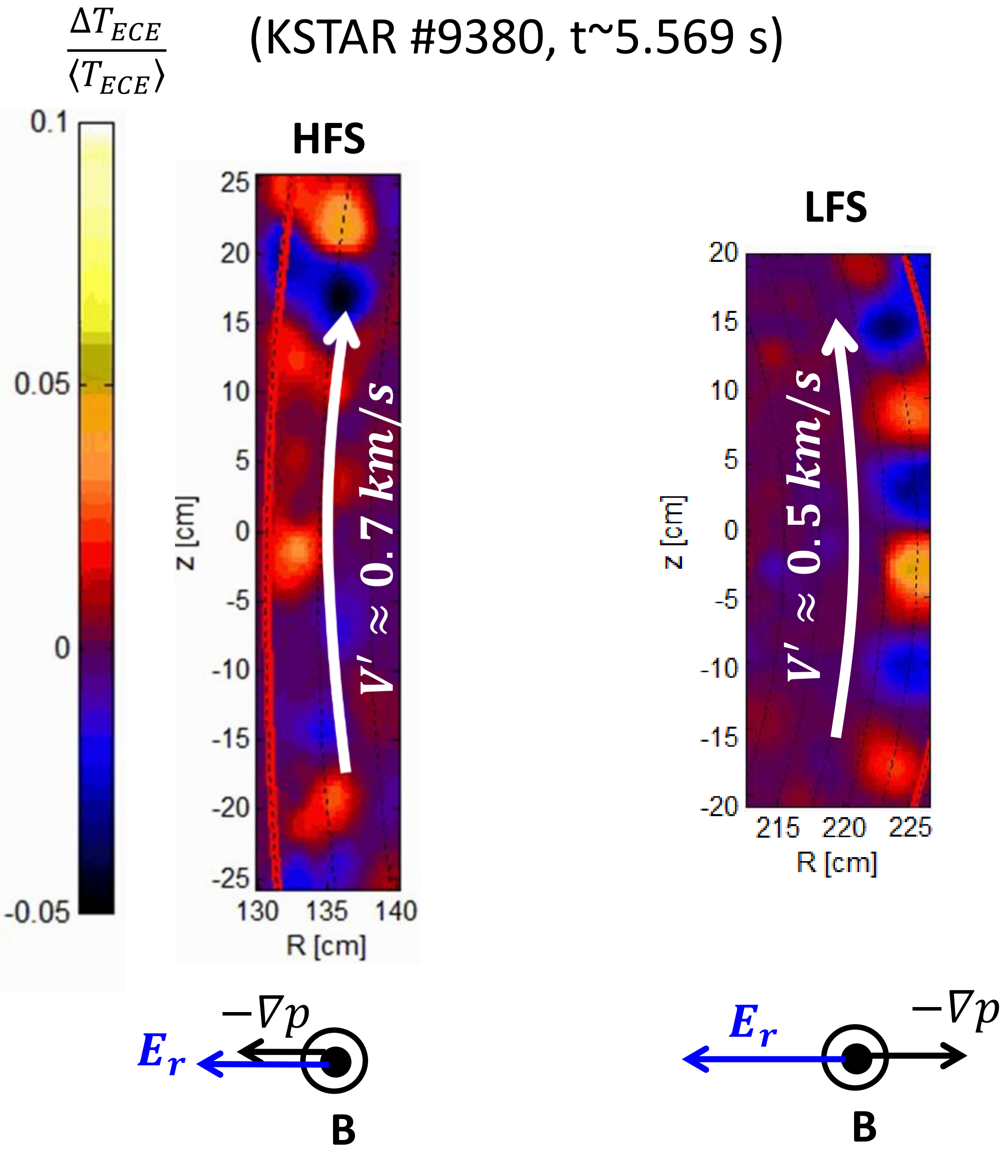
*J. Lee, RSI (2014)

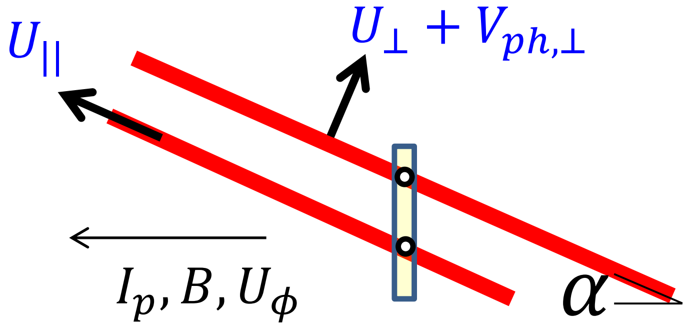
(KSTAR #9380)

Two issues with the HFS ELM

(2) Opposite rotation direction

(KSTAR #9380, t~5.569 s)





Pattern velocity :

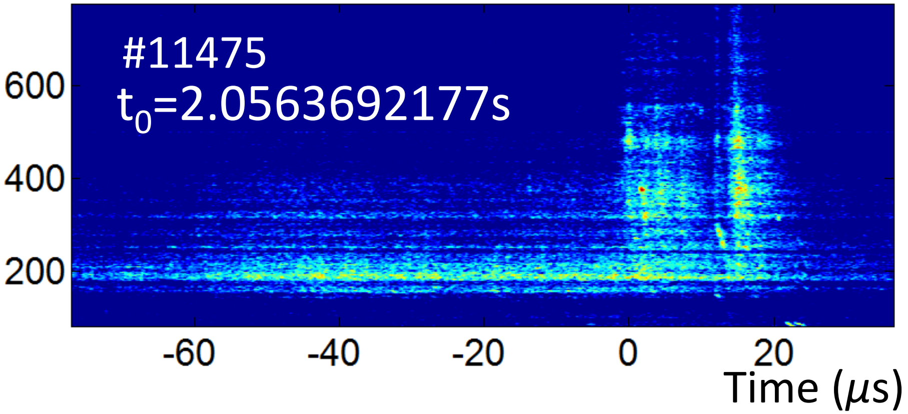
$$V' = (U_\perp + V_{ph,\perp})/\cos\alpha$$

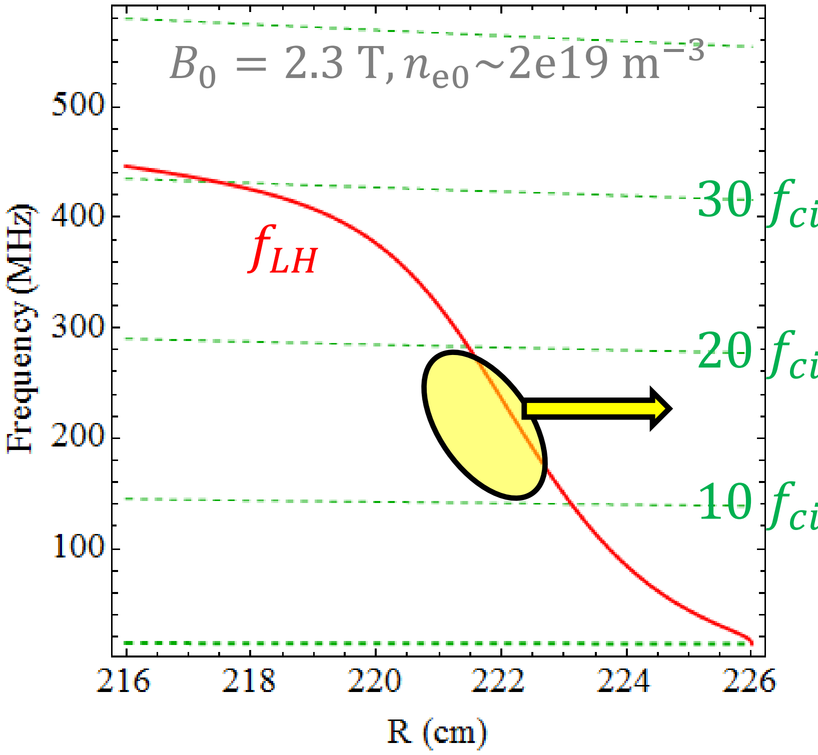
cf. For ideal ballooning mode

[J. Morales, Phys. Plasmas **23**, 042513 (2016)]

$$\begin{aligned} U_\perp + V_{ph,\perp} &\approx V_{E\times B} + V_i^*/2 \\ &\approx V_{E\times B}/2 = -\frac{\nabla_r P_i}{2enB} \end{aligned}$$

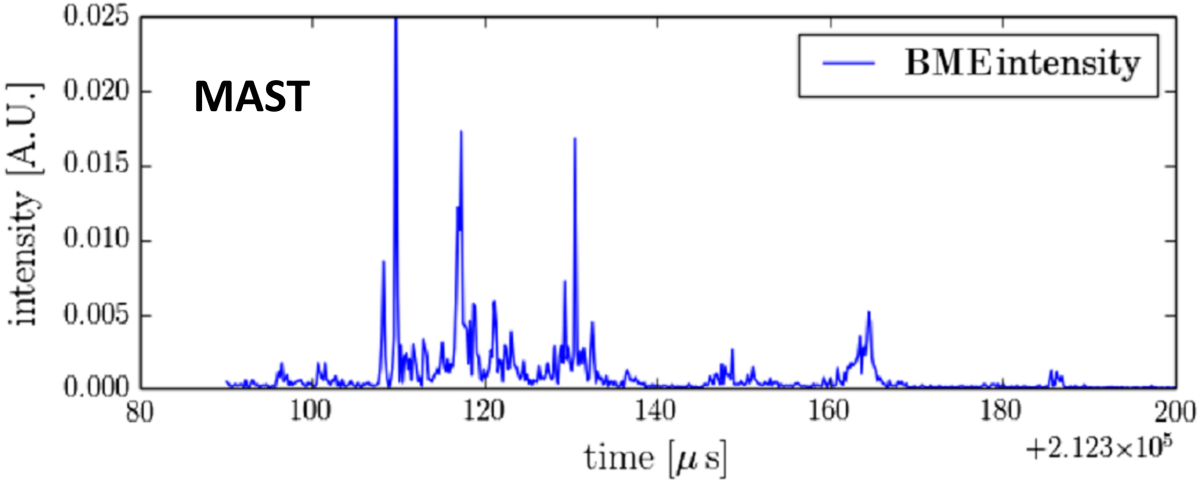
Strong emission at ~200 MHz ($\sim f_{LH}$)



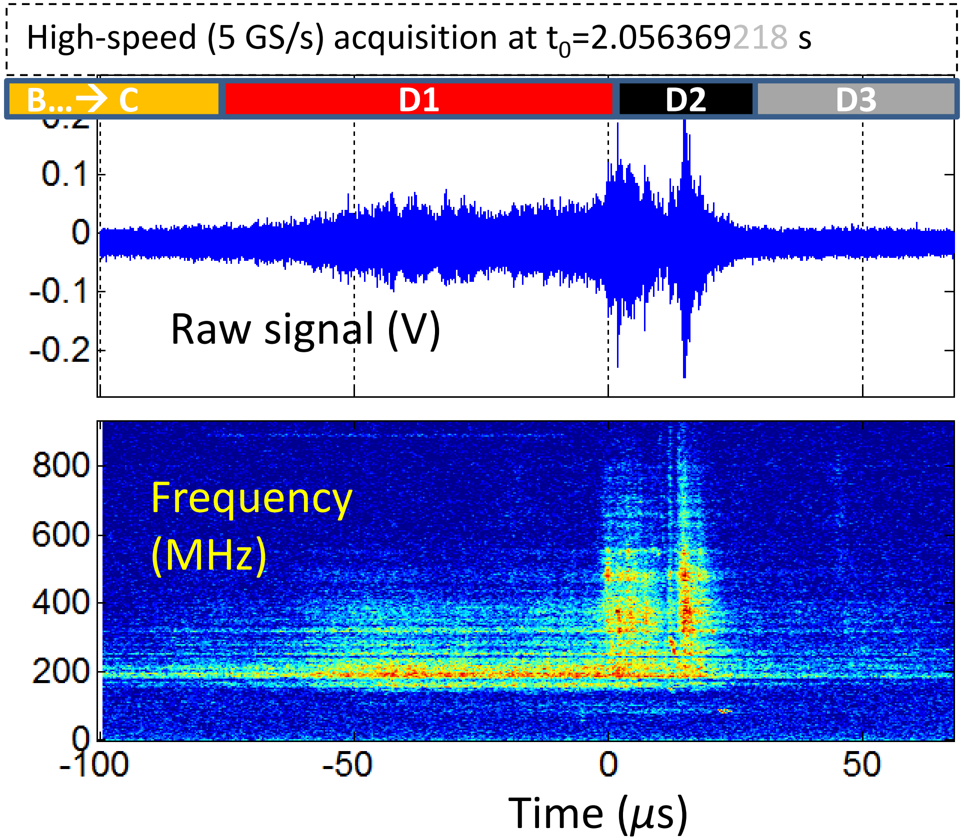


Lower hybrid ~ compressional Alfven waves?

$$f_{LH} \approx f_{pi}/\sqrt{1+f_{pe}^2/f_{ce}^2} \sim f_{pi}$$

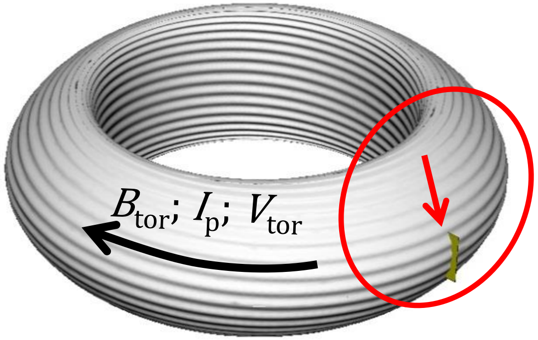


KSTAR


High-speed (5 GS/s) acquisition at t_0=2.056369218 s

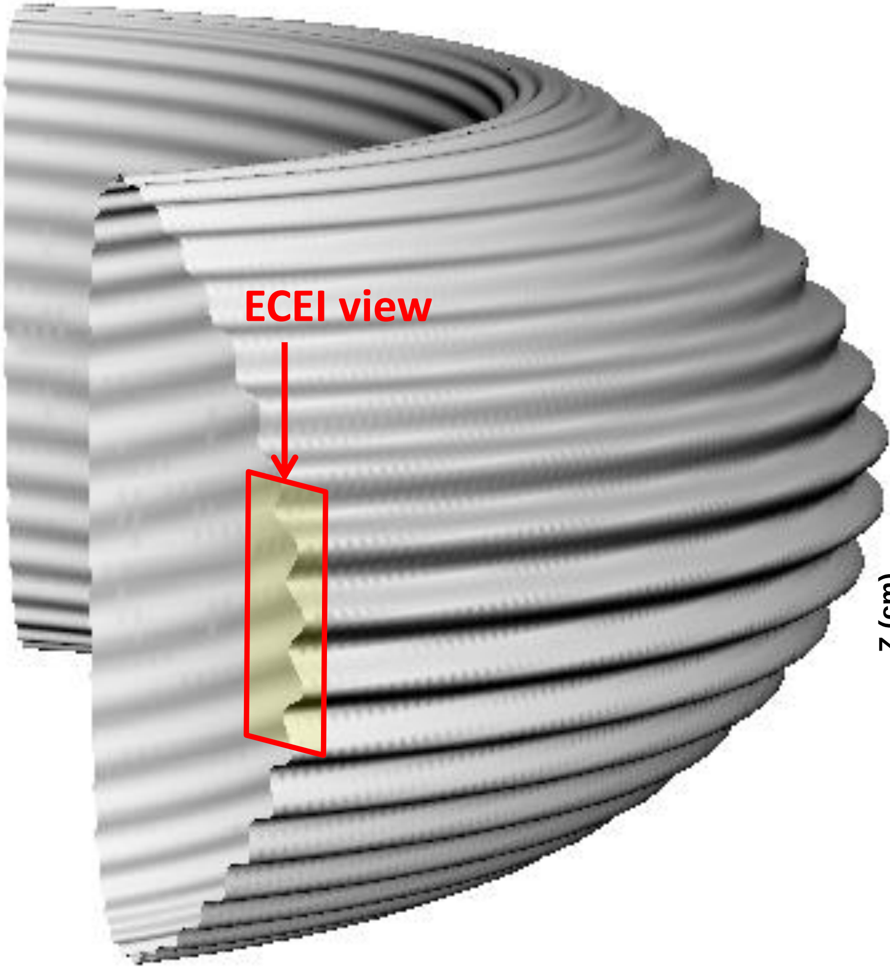
The intense RF peaks may be compared with the intense bursts of microwave emission (BMEs) in the electron cyclotron (EC) frequency range at MAST [Freethy 2016].

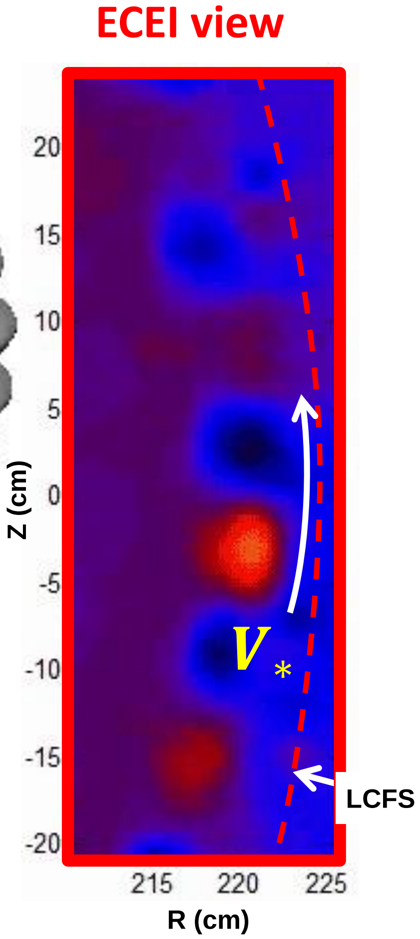
A phenomenological model for the ELMs



Flux surface with filamentary perturbations of m=37 and n=6

$(R = 1.8\text{m}; a = 0.5\text{m};$
$\kappa = 1.8; \delta = 0.7)$





Toroidal mode number estimated by ECEI

- At the mid plane $n = \frac{2\pi R^*}{\lambda_{tor}}$, $\tan(a^*) = \frac{\lambda_{pol}}{\lambda_{tor}}$ ➡ $n = \frac{2\pi R^*}{\lambda_{pol}}\tan(a^*)$

$$\boldsymbol{n = \frac{2\pi R^*}{\lambda_{pol}} tan(a^*)}$$

λ_{pol} : Poloidal wavelength at the midplane

n : Toloidal mode number

a^* : Pitch angle at the midplane

R^* : Major radius at ELMs position

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1) λ_{pol} from ECE image

2) $\tan(a^*)$ by EFIT or from 3D ECE images

3) R* from ECE image