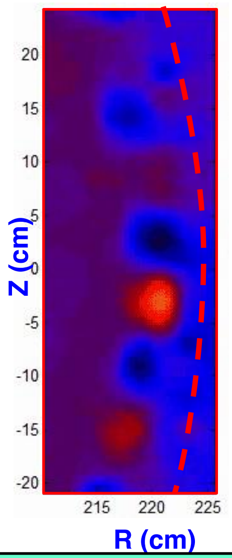
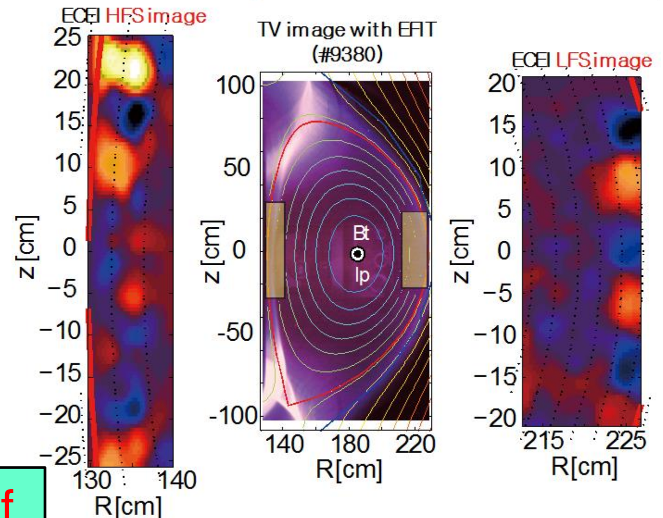
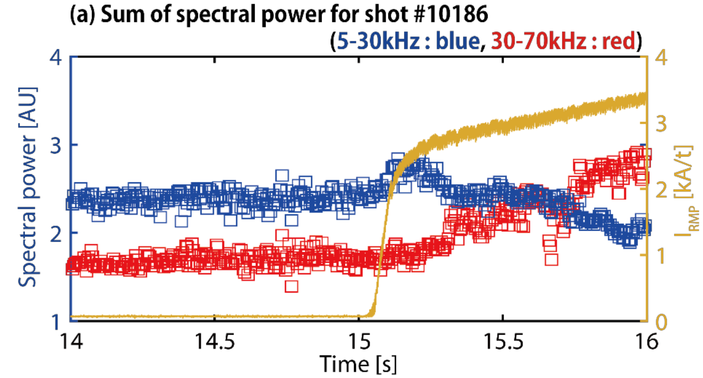
# Dynamics of the ELMs in the pre-crash and crash suppressed period in KSTAR




Real time 2D images of the ELM and ELM-crash




ELMs at LFS and HFS




Decrease of the ELM amp. and increase of the turbulence under RMP

**Hyeon K. Park, NFRI/UNIST**

*at*

*Theory Seminar at PPPL*

*July 28, 2016*

NFRI 국가핵융합연구소 National Fusion Research Institute

POSTECH

미래창조과학부 Ministry of Science, ICT and Future Planning

UNIST Ulsan National Institute of Science and Technology

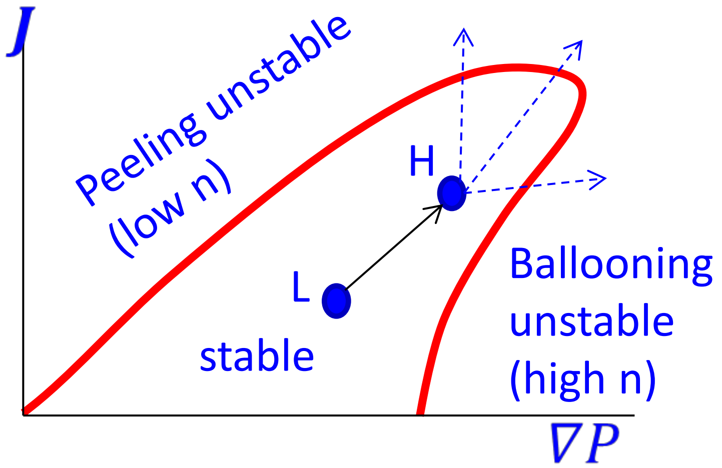
# Talk

- Edge Localized Modes in KSTAR
  - New findings in pre-ELM crash period with advanced diagnostic systems (ECEI and RF emission)
  - Validation of the observed ELMs through global simulation (MHD vs. full kinetic)

- Challenge for the physics of suppression of the ELM-crash
  - ELM dynamics and ELM-crash suppression under the resonant magnetic perturbation (RMP)
  - Interaction between the ELMs and turbulence induced by the RMP

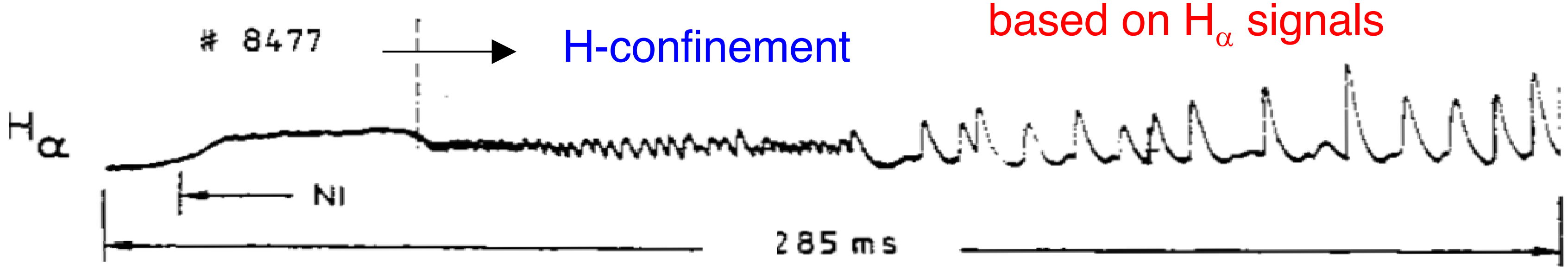
# The edge localized mode and suppression

- Edge Localized Mode (ELM)
  - ASDEX [Keilhacker 1984] for **semi-periodic edge-localized relaxation phenomena** (cf. PDX, Kaye 1984),
  - Nonlinear theory and modelling (Connors, Wilson, Snyder, Hegna, Becoulet) identified as the relaxation event of the growth of **Peeling and Ballooning modes**



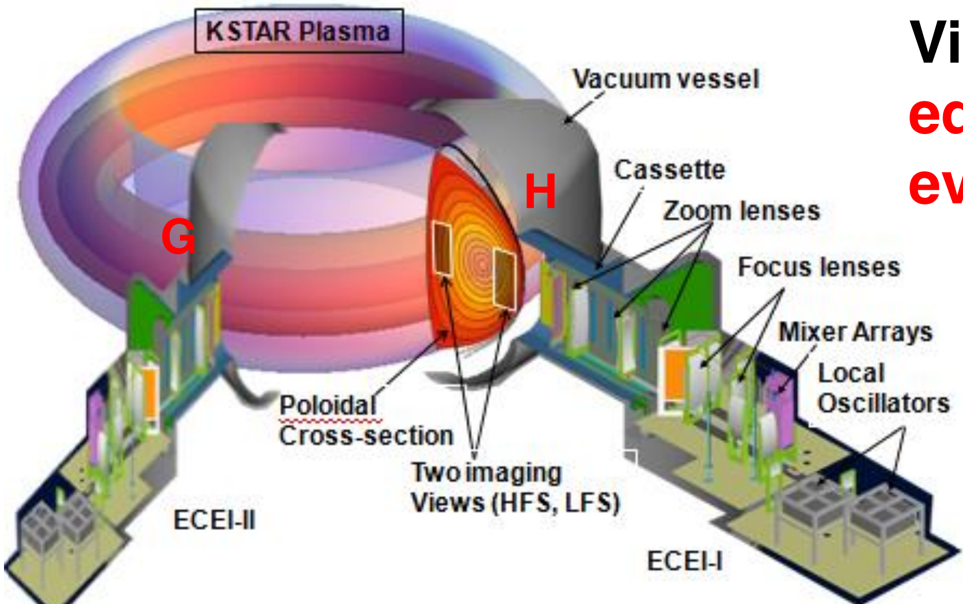

- Suppression/mitigation of the ELM crash
  - Stochasticity induced by Magnetic Perturbation (Evans, etc.)

Interpretation and classification of the ELM-crash are vastly based on $H_\alpha$ signals




In this talk, “ELM” and “ELM-crash” refer to coherent mode and burst event, respectively

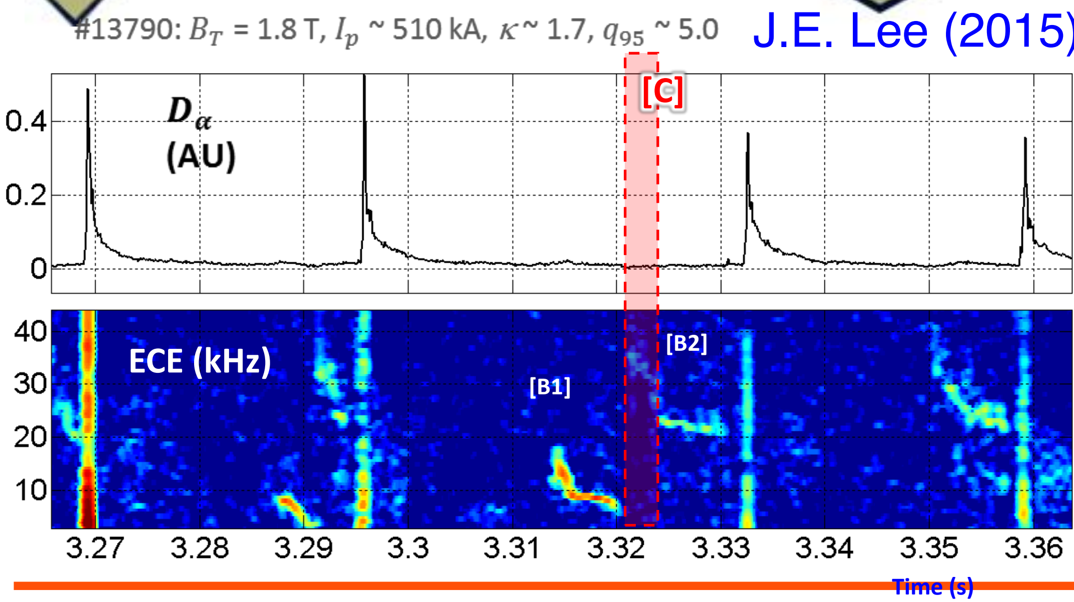
# Advanced diagnostic capabilities of KSTAR

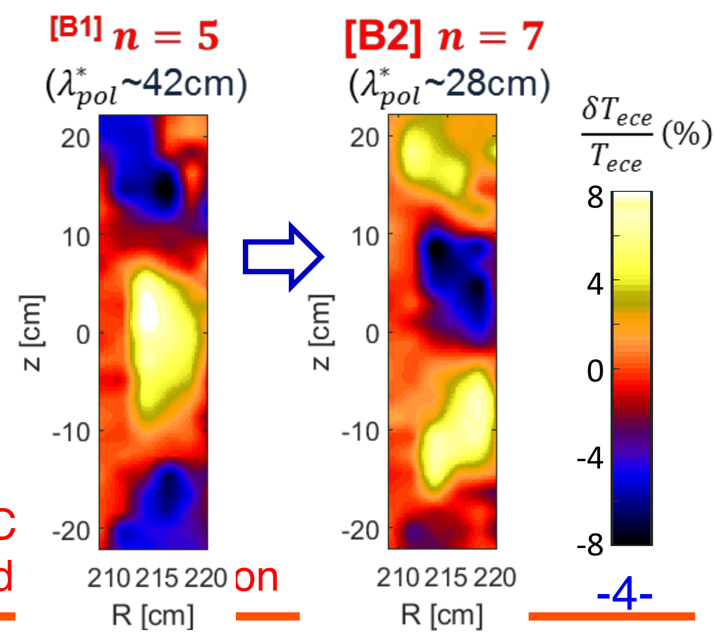



**Visualization revealed that the edge-localized mode (ELM) evolves through multiple stages.**

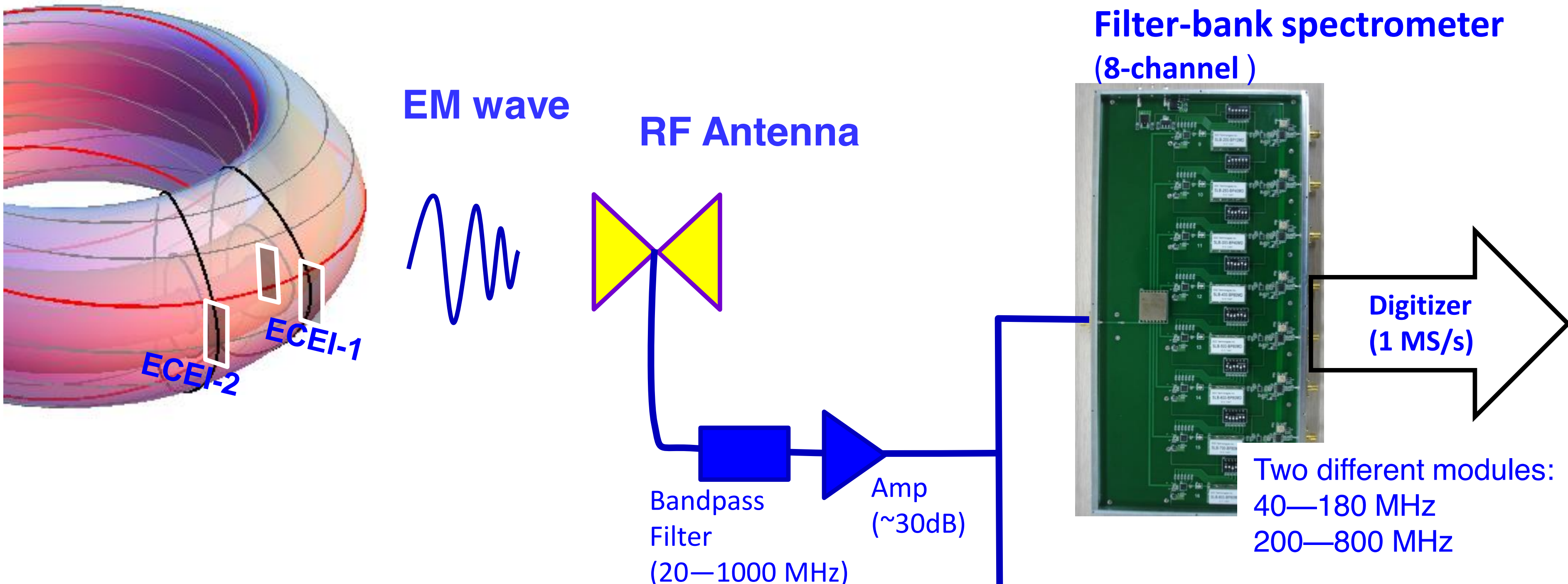
***Semi-periodic evolution characterized by***
- **[B]** ***Quasi-steady saturated state***
- **[C]** ***Phase transition***
- **[D]** ***Rapid collapse***

J.E. Lee (2015)



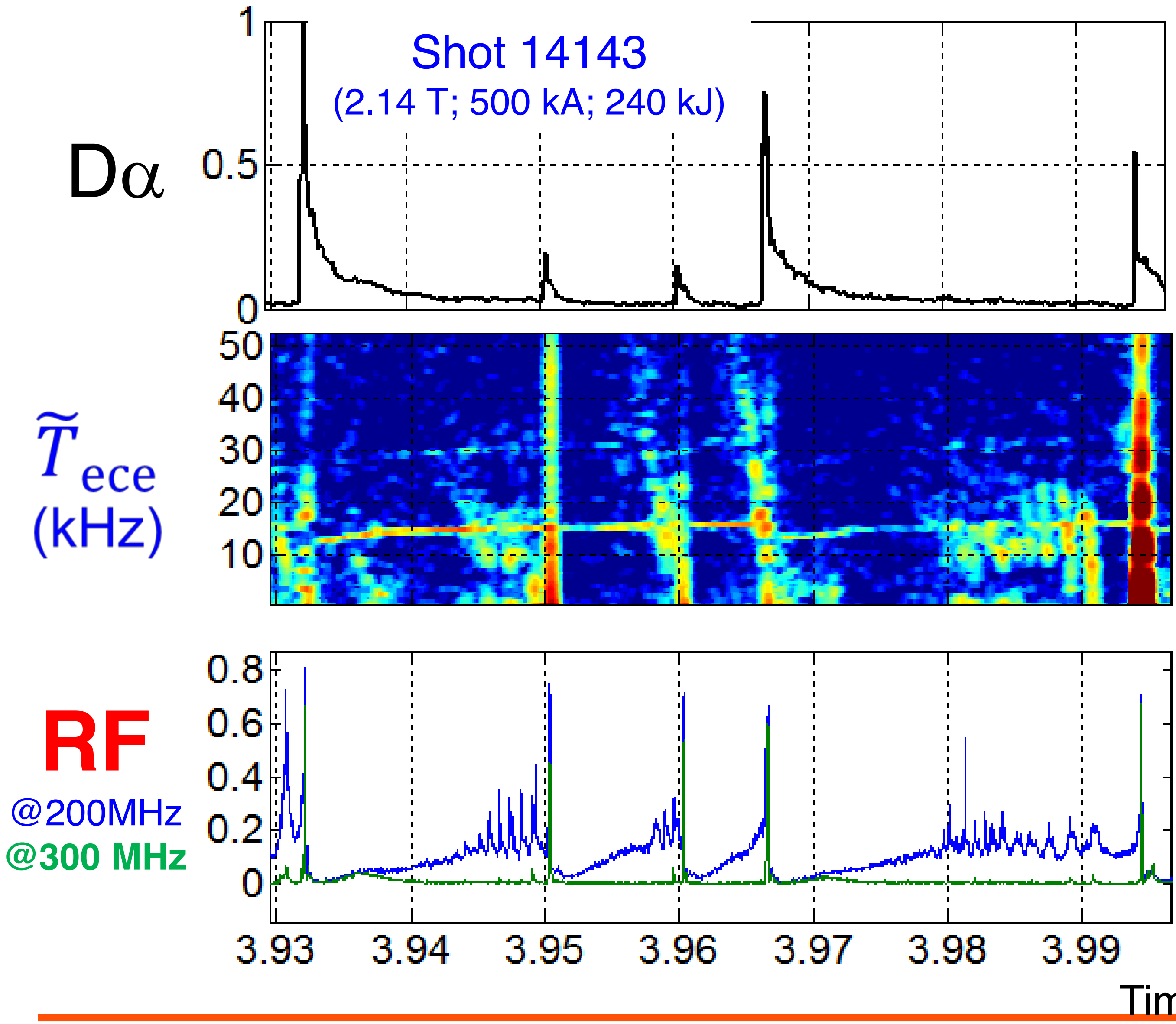
# ELM dynamics from“RF” emission†.





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

# ELM dynamics before the crash

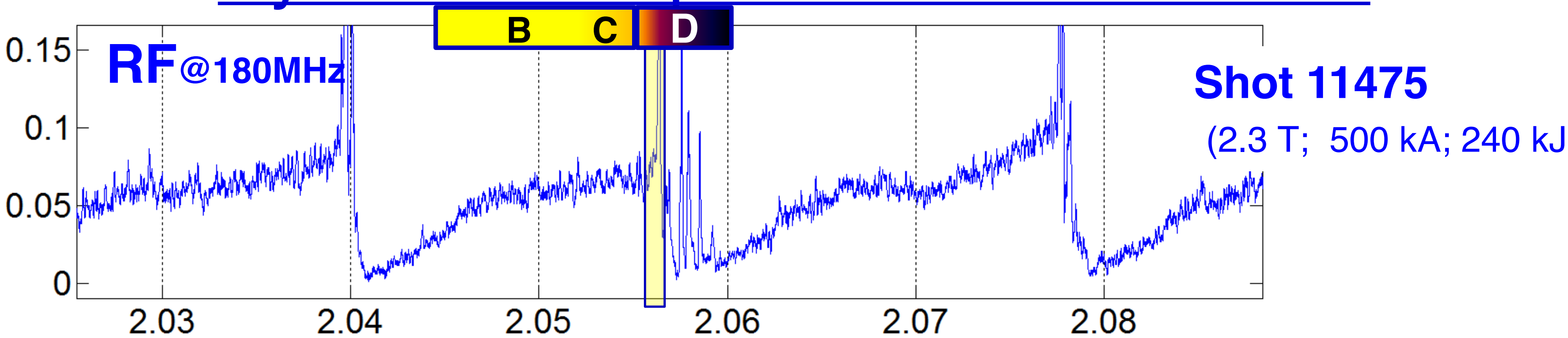


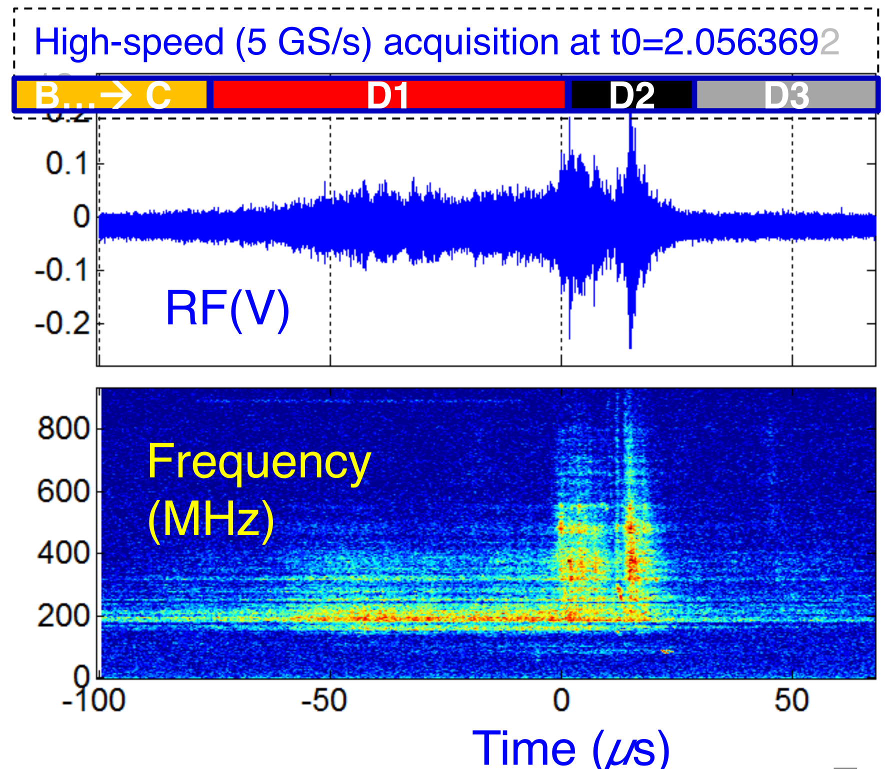

$H_\alpha$ signal is only an aftermath of crash

ECE signal spectrogram provides information on the mode activities.

RF signals capture the mode activities and the exact moment of crash.

# Dynamic RF spectrum at ELM crash



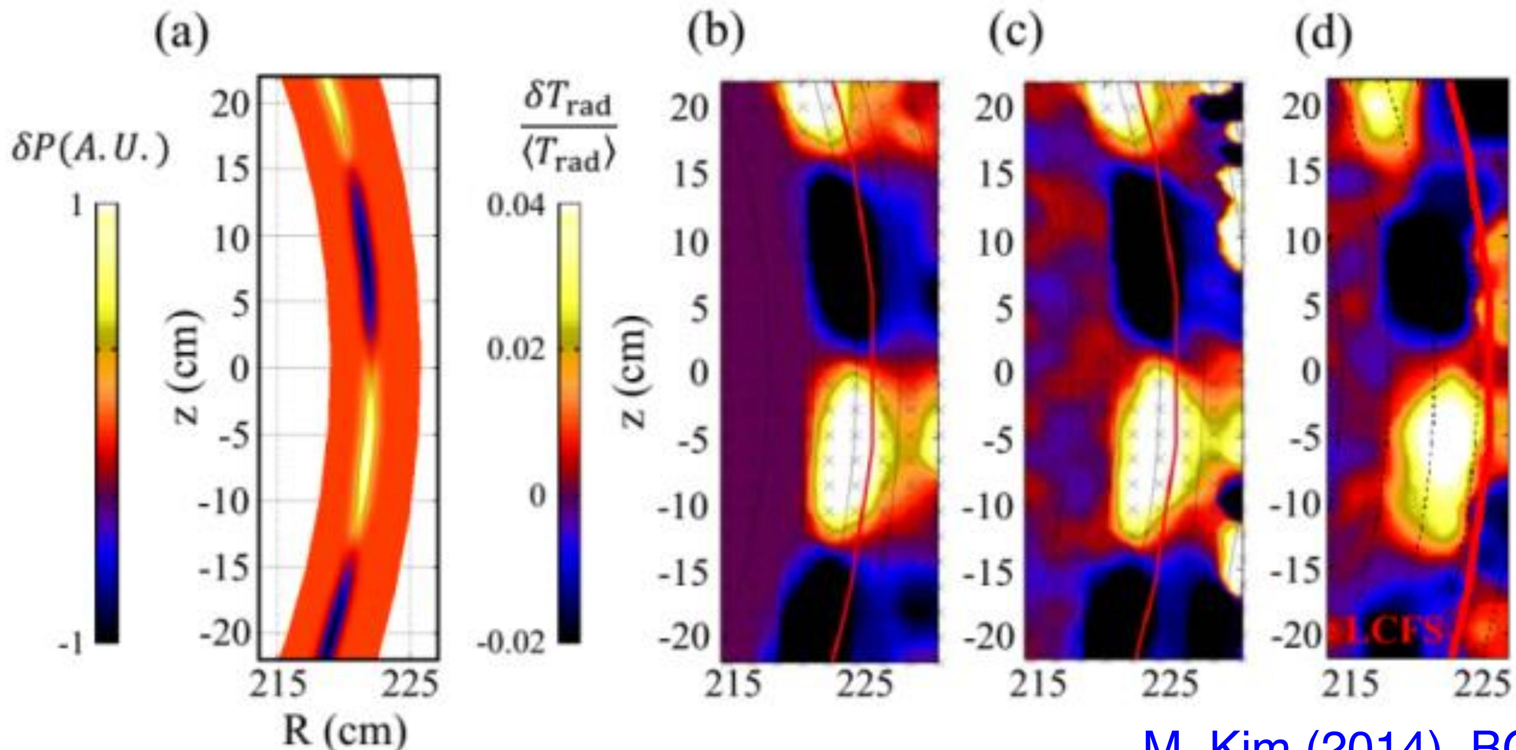

[B-C] Persistent emission ~200 MHz ($\sim f_{LH}$) in the inter-crash period

[D1] Harmonic lines spaced by $\sim f_{c,H}$ or $\sim f_{c,D}$

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

# Validation of the ELM structure

- Modeling of the ELMs is in progress via collaboration with the simulation groups: BOUT++, M3D, M3Dc1, JOREK

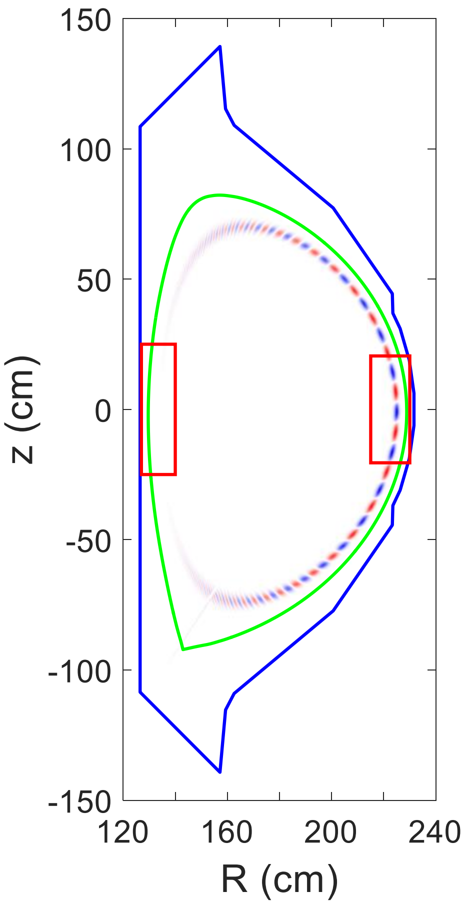



M. Kim (2014), BOUT++

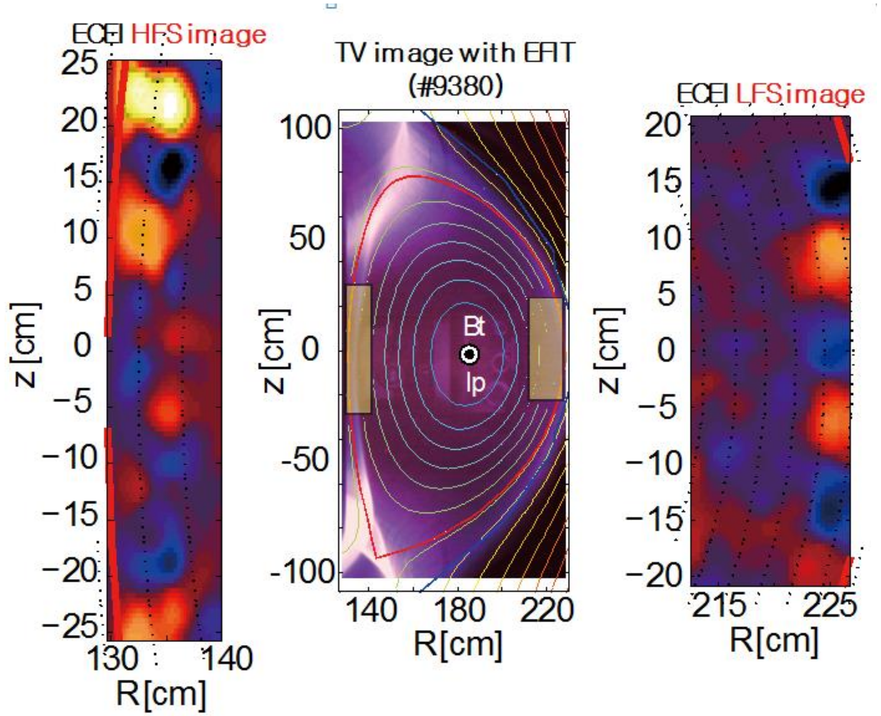
(a) Linear simulation of ELM with n=10
(b) 2D image with emission broadening and antenna responses
(c) 2D image with background noise
(d) Measured 2D image by ECEI system

# Global simulation of the ELM (MHD vs. Kinetic)

*n* = 12 simulation (BOUT++) - MHD



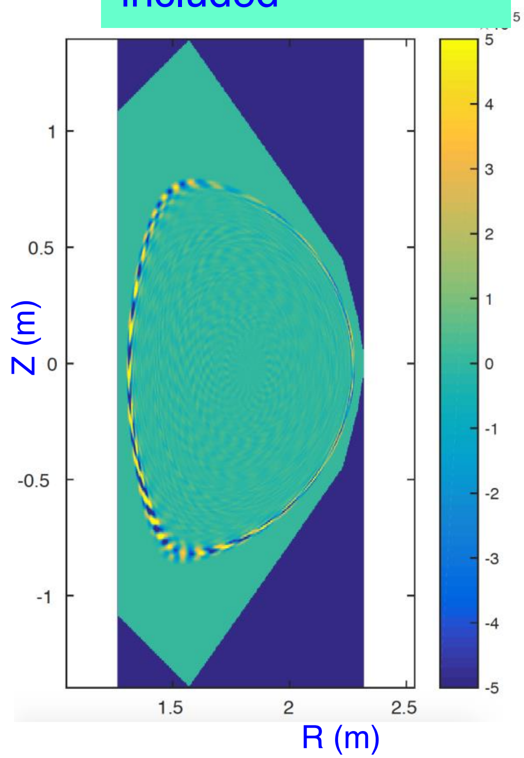

- KSTAR #9380




Controversies in 1) Mode intensity 2) Mode number 3) Rotation direction cast a doubt in PB modeling

Kinetic (XGC1) results are closer to the measurement

*n* = 12 simulation (XGC1)- kinetic Collision is not included




C.S. Chang, S. Ku, M. Kim

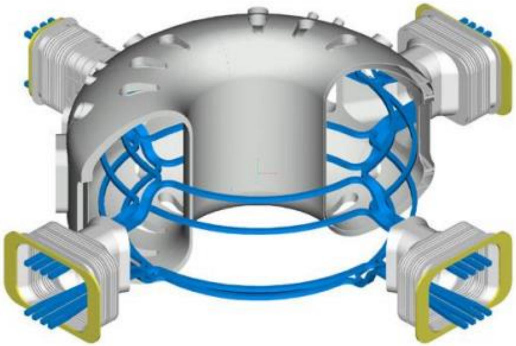
M. Kim, and Xu

# Magnetic perturbation system in KSTAR

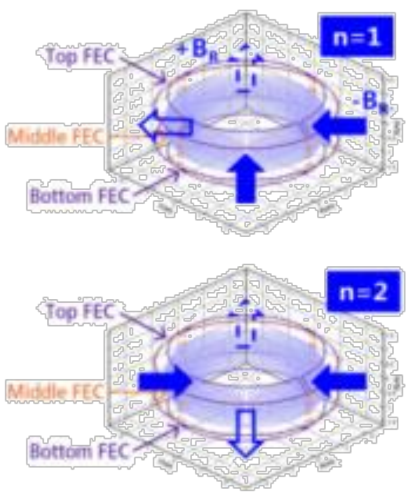
- Magnetic perturbation (n=1,2) with variety of phase and amplitude by IVCC

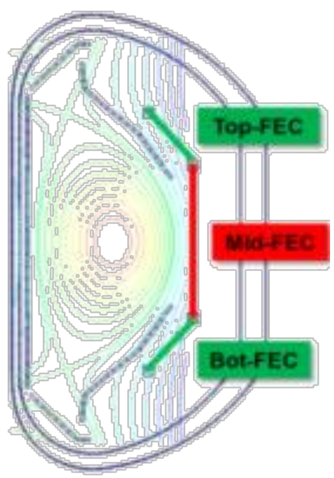
**Flexible modular 3x4 coils for low *n* magnetic perturbation‡**

| | n=1, +90 phase | | | | n=2, even | | | | n=1 & 2 even | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| top | + | + | - | - | + | - | + | - | + | - | + | - |
| mid | - | + | + | - | - | + | - | + | - | + | + | - |
| bot | - | - | + | + | + | - | + | - | + | - | + | - |



‡H.K. Kim, Fusion Eng. Design 2009



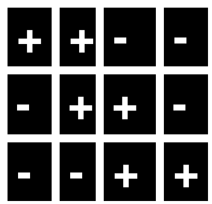




- In KSTAR, ELM-crash suppression has been demonstrated with MP induced by IVCC (n=1,2) with variety of phase and amplitude

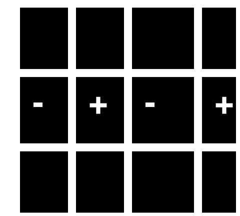
# ELM-crash suppression w/ n=1 and n=2 (KSTAR)

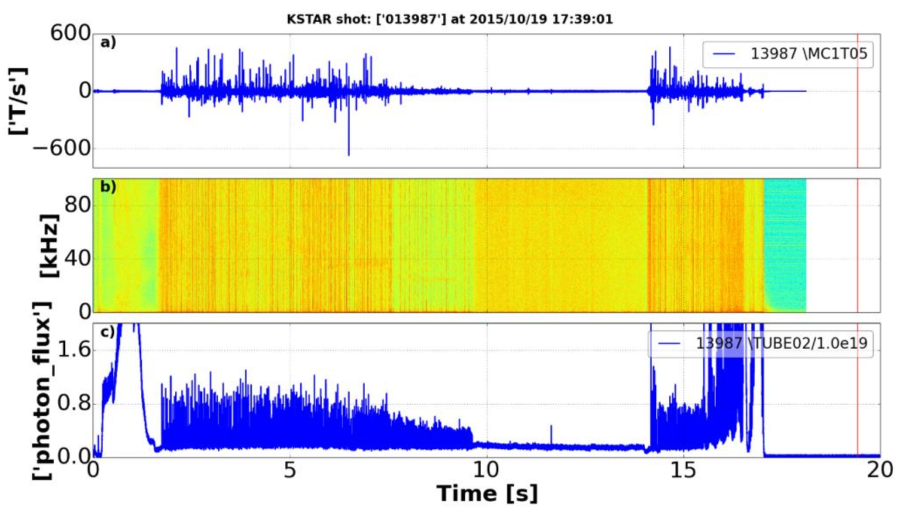
- Positioning plasmas is critical (optimum coupling of MP?)
- Effective in both n=1 and n=2 attempts, but needs more robust control

n=1 (+90 phasing) full RMP at $q_{95}$~6.0 [2.7 kA/turn]

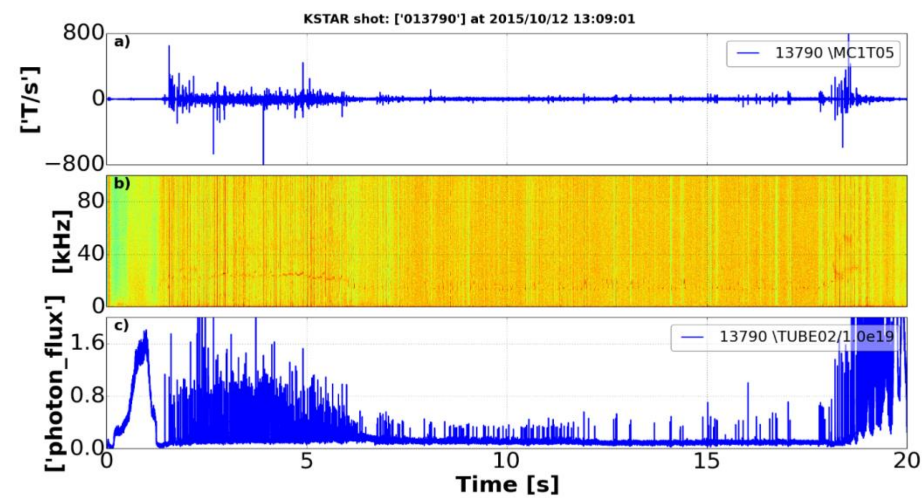



n=2 mid-frame MP at $q_{95}$~4.0 [4.8 kA/turn]



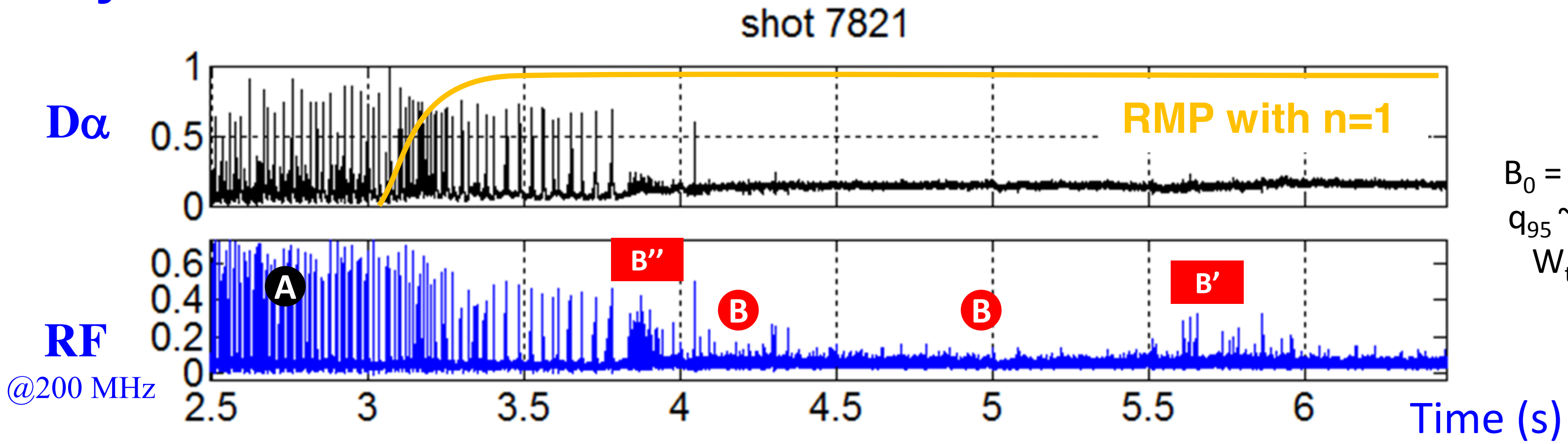




(4.4 sec; > 40 $\tau_E$)




(> 10 sec; marginal)

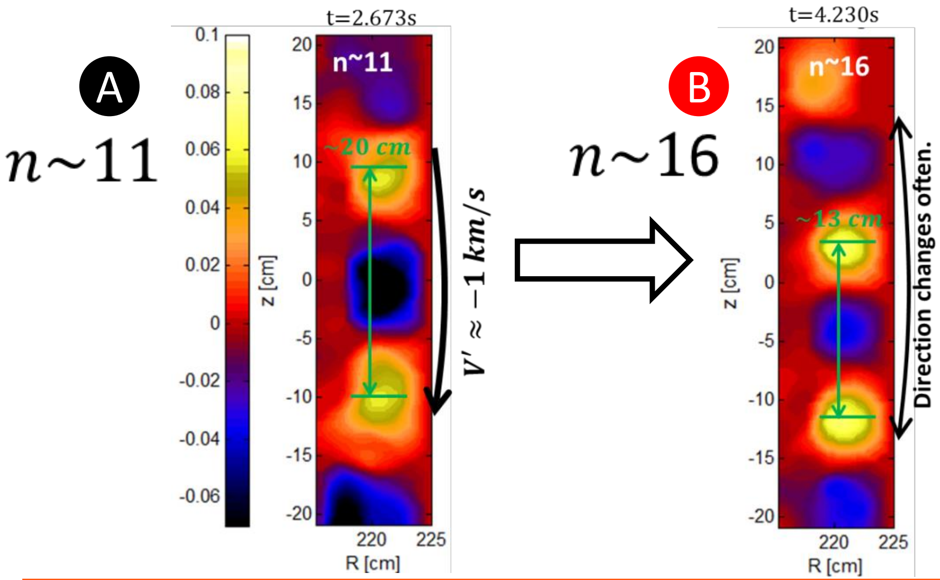
# Dynamics of the ELMs and ELM-crash under RMP




$B_0$ = 1.8 T, $I_p$ = 510 kA,
$q_{95}$ ~ 6, $P_{NBI}$ = 2.7 MW
$W_{tot}$: 220→180 kJ

**Physics of ELM-crash has been mainly based on $H_\alpha$ signal !!**

**In Peeling-Ballooning model, mode is unstable (A) → is it stable (B) ?**




**(A) ELM crash period: mode leads to large burst/crash**

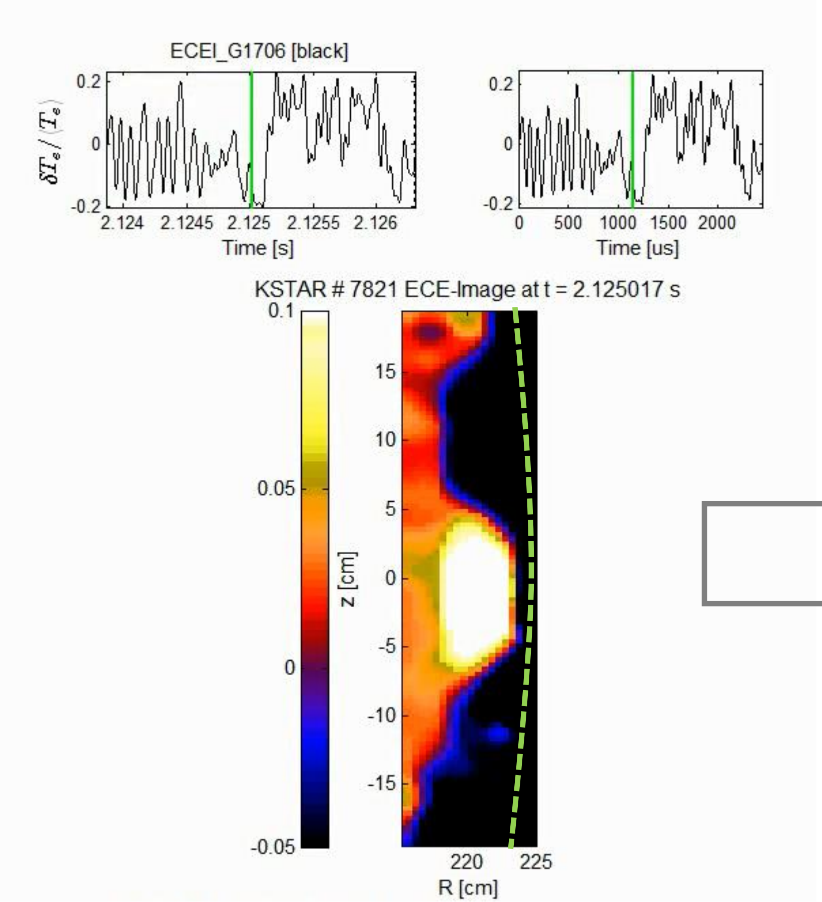
**(B) Crash-suppressed period: Often higher or same coherent modes (marginally stable)** - No stochastic island visible up to resolution limit and various different phases of burst/crash

# Variety of ELM burst/crash processes (large, small, tiny)

Pedestal collapse

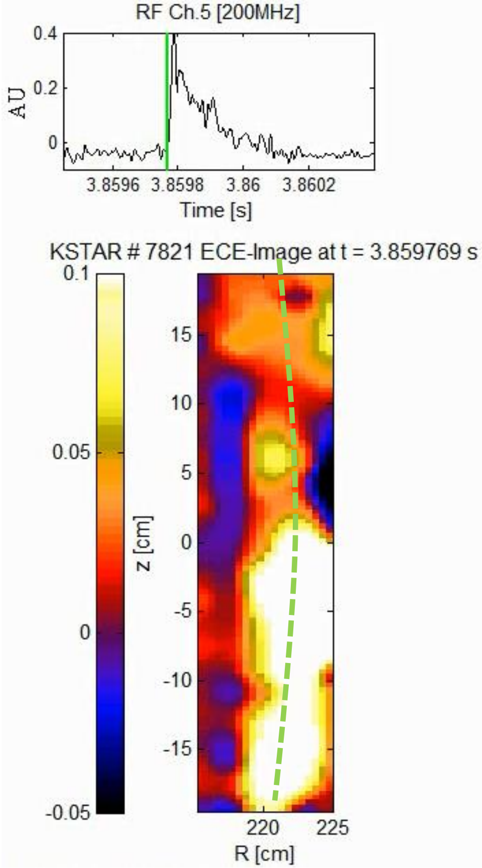
Small-scale burst localized to very thin edge layer

Ⓐ Normal ELM crash ("ELM")

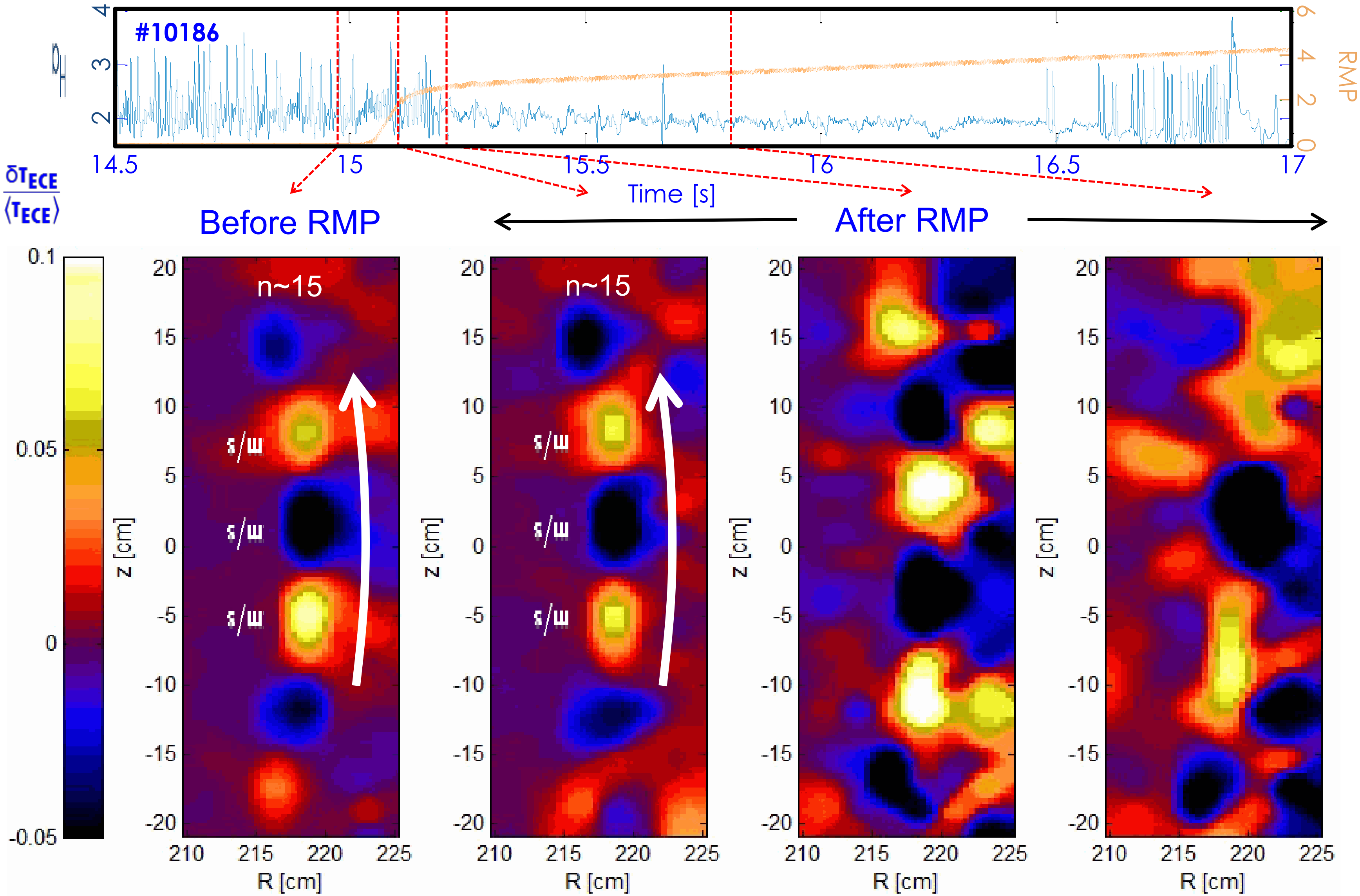



B' (initial phase of suppression)

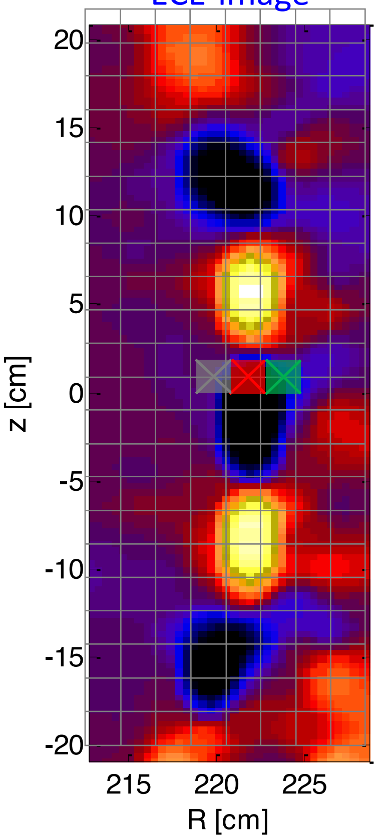
Frequent RF bursts = Grassy (small) crash

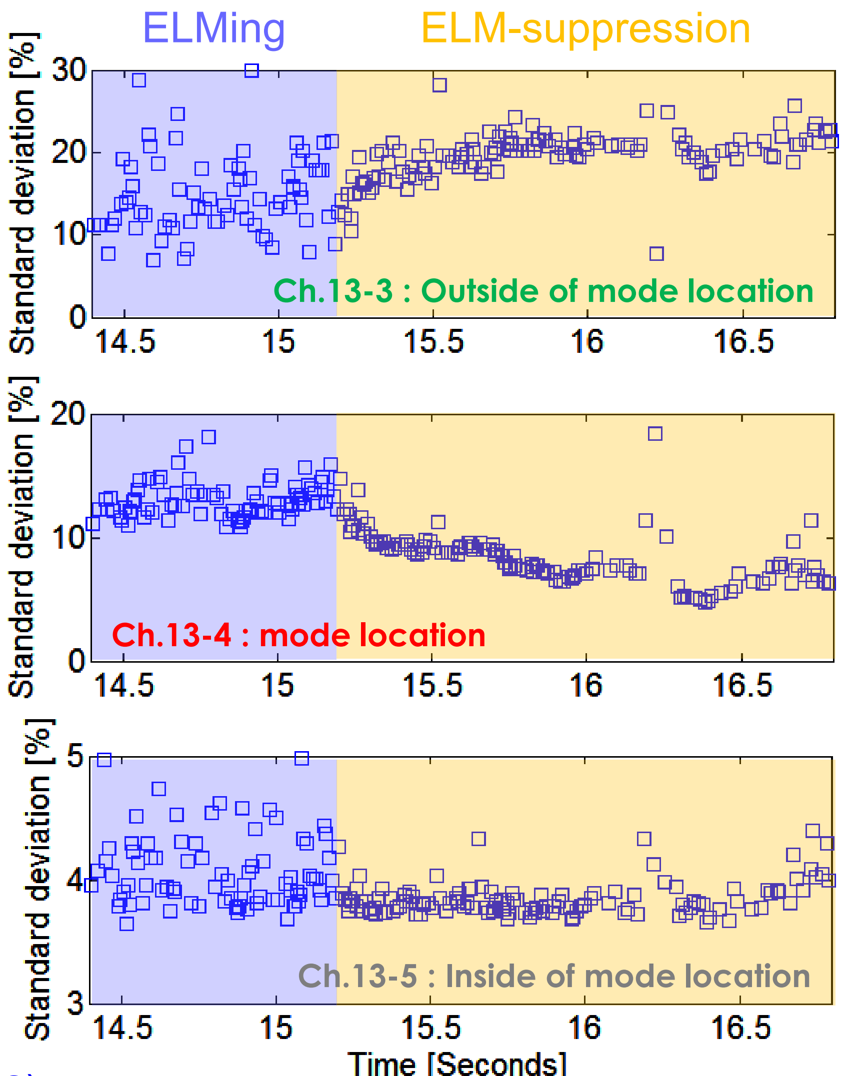


# Suppression dynamics under n=1 RMP



# Change of fluctuation amplitude




J.H. Lee (2016)

$$\sigma^* = \frac{\sqrt{\delta T_{ECE}^2 - \delta T_{ECE,0}^2}}{(T_{ECE} - T_{ECE,0})}$$

where,
$\delta T_{ECE}$ is a standard deviation of ECE signal
$\delta T_{ECE,0}$ is a standard deviation of base level signal
$T_{ECE}$ is a ECE signal and $T_{ECE,0}$ is a base level signal

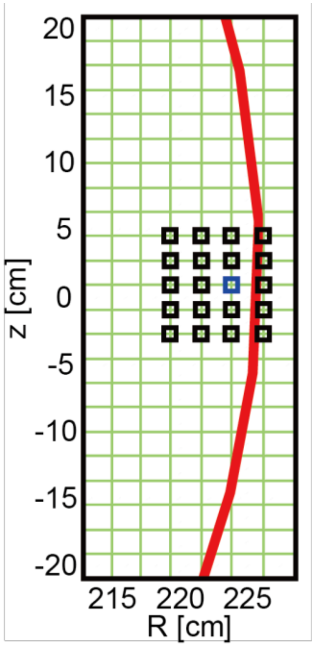
- Large fluctuation outside of ELM position means frequent transport event at the edge?

- What caused the radial transport at the edge?

# Turbulent fluctuations in ELM-crash-supp.

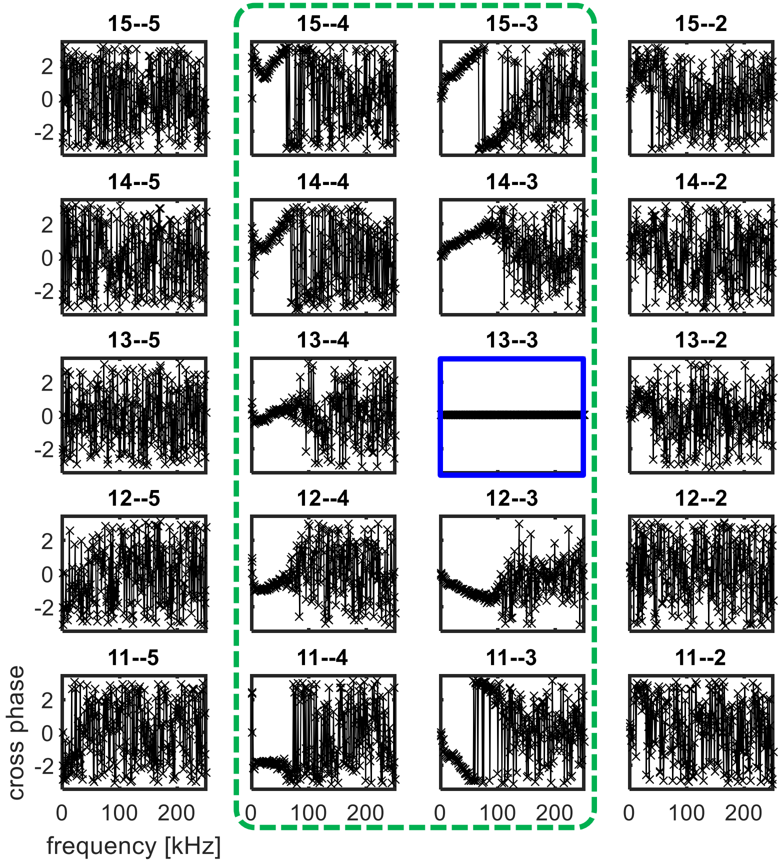
- The correlation analysis clearly shows the existence of broadband and low frequency coherent modes (f<70kHz) along the vertical direction in narrow radial zone.

Channel positions

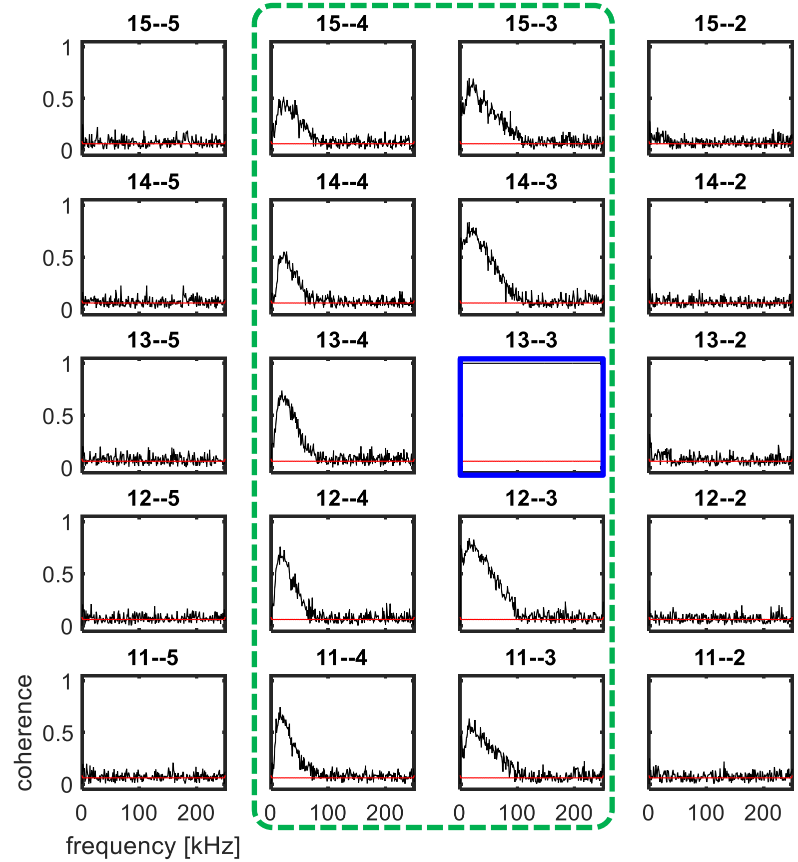



Shot #10186
Time : 15.7-15.85s

Cross-phase

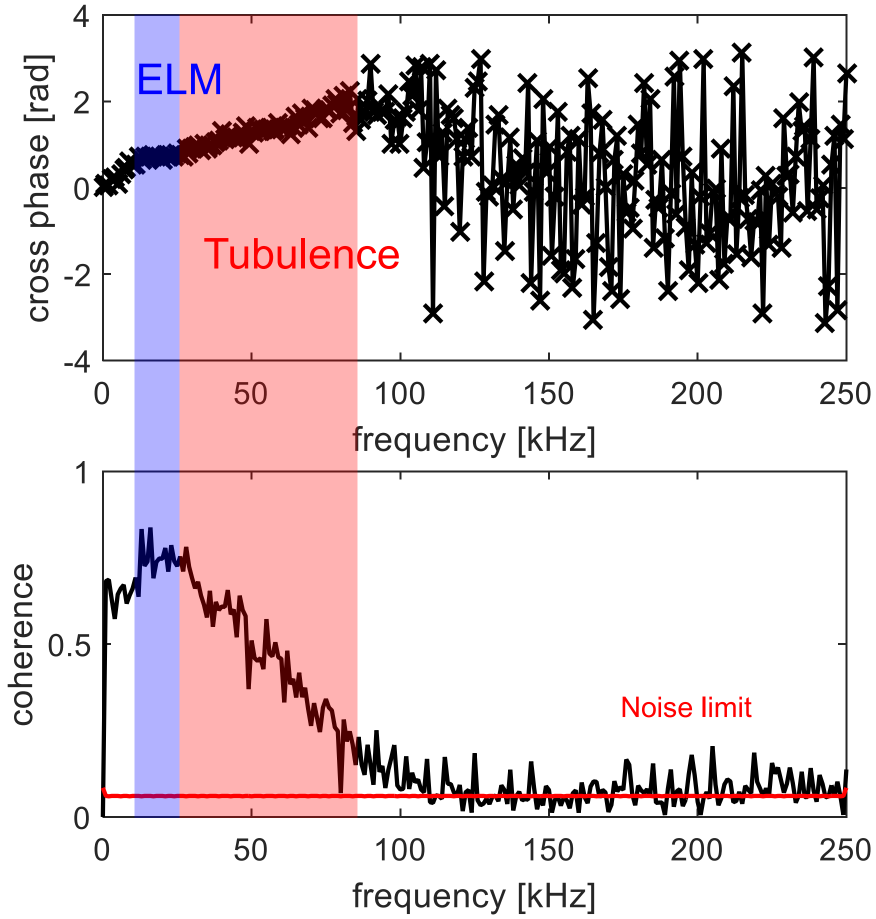



Coherence

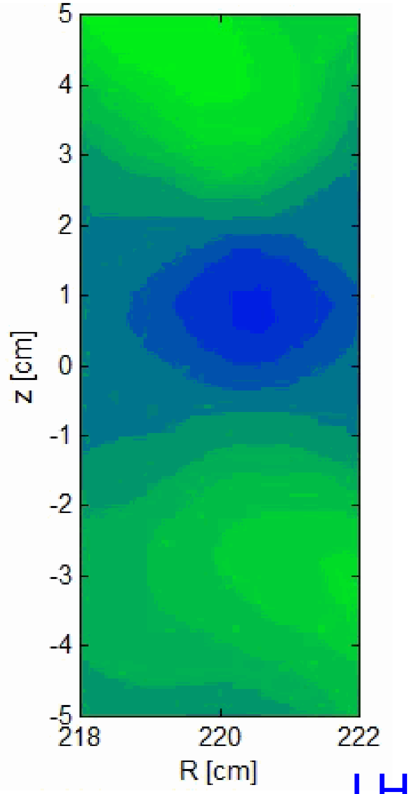


# 2D turbulence under the RMP.

- There are two components; (1) ELM at ~20 kHz, (2) turbulent eddies
- The turbulence movie was made using high frequency components only (40-80 kHz), excluding the ELM (~20 kHz).




**Turbulence movie for KSTAR #10186 at ~16.410 s. (2 us time step, FFTpass 40-80kHz)**

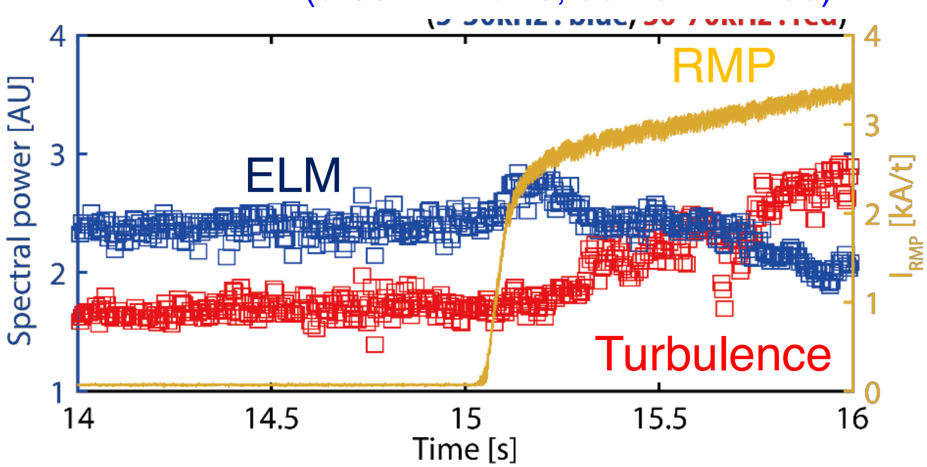



J.H Lee (2016)

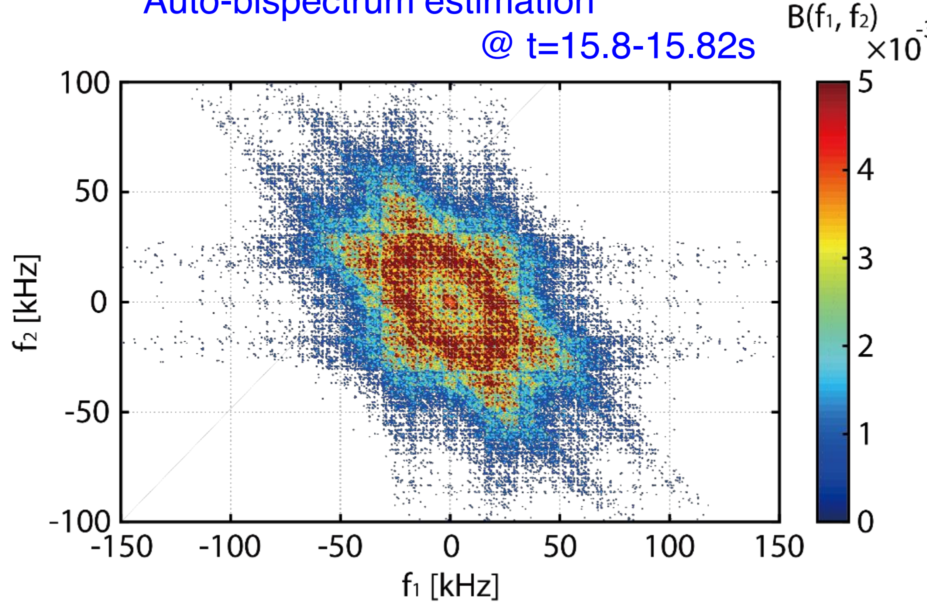
# Interaction between the ELM and turbulence

J.H Lee (2016)

Sum of spectral power
(5-30kHz : blue, 30-70kHz : red)




Auto-bispectrum estimation
@ t=15.8-15.82s

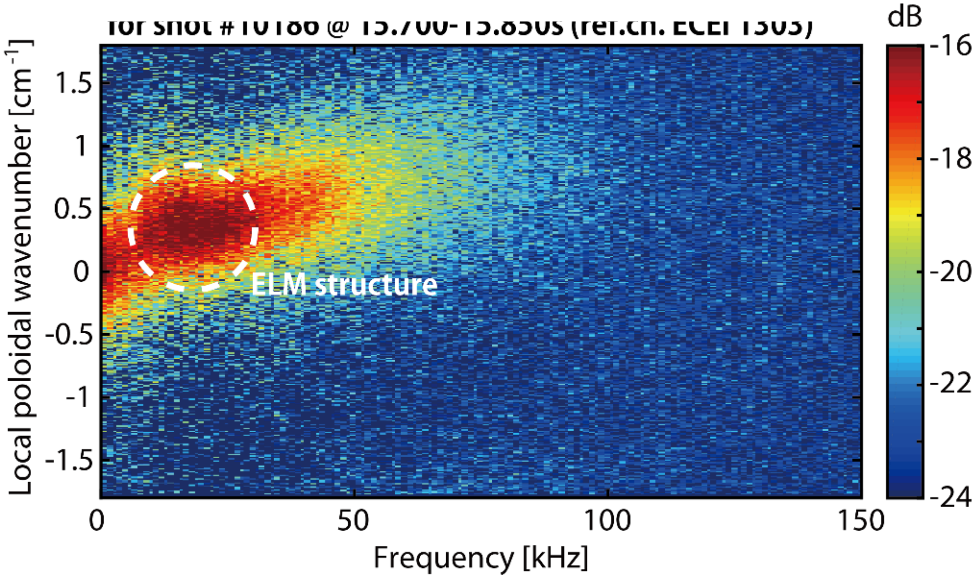



- The spectral power of the turbulence (30-70kHz) increases with IRMP while the spectral power of the ELM (5-30kHz) decreases.
- Bispectrum is defined by $B(f_1, f_2) = F(f_1)F(f_2)F^*(f_1 + f_2)$, where $F$ denotes the Fourier transform.
- As expected from nonlinear interaction between a narrow-band coherent wave (i.e. ELM) and broad-band waves (i.e. turbulence), the auto-bispectrum shows line features which suggest that the turbulence dissipates the free energy for the ELM growth.

# Characteristics of turbulence

- Clear linear dispersion of spectral power distribution
- Wide range of wavenumber ($k_\theta < 1\ \mathrm{cm}^{-1}$) and frequency ($f < 70\ \mathrm{kHz}$)
- **Average group velocity** of turbulence $v_{g,avg} \sim 3\ \mathrm{km/s}$ (electron diamagnetic drift direction in the lab-frame)
- The characteristic size of turbulence is calculated $k_\theta \rho_s < 0.1$ ($\rho_s \sim 1$ mm).
- The dispersion curve is observed near the pedestal region only.

Spectral power distribution $S_L(k_\theta, \omega)$
for shot #10186 @ 15.7-15.85s



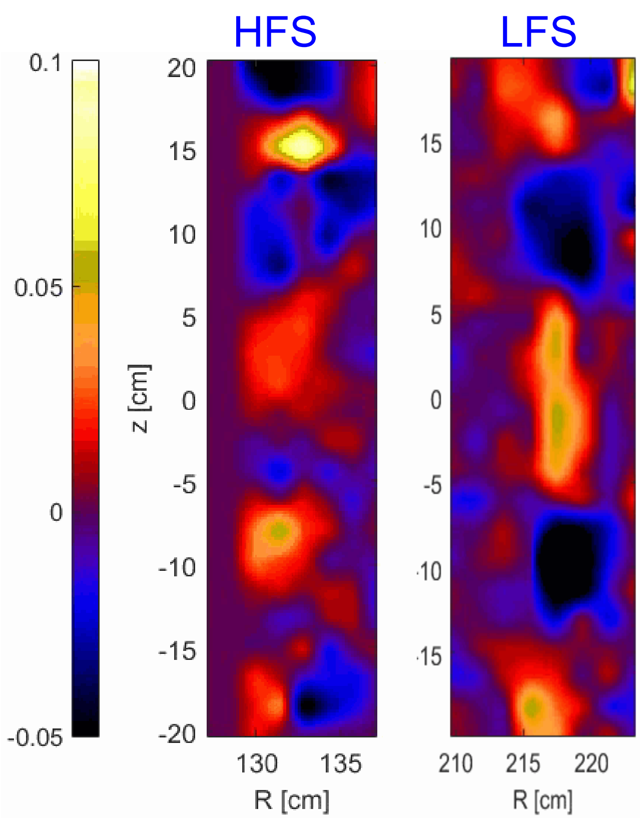

| Instability | Drive | Prop. | Scale | Parity |
|---|---|---|---|---|
| KBM | $\nabla T_{e,i}$ | i dia. | $k_\theta \rho_s \sim 0.1$ | Ball. |
| RBM | $\nabla p$ | n.p. | $k_\theta \rho_s \sim 0.1$ | Ball. |
| MTM | $\nabla T_e$ | e dia. | $k_\theta \rho_s \sim 0.1$ | Tear. |

# Responses of global ELM behaviors by RMP (2015)

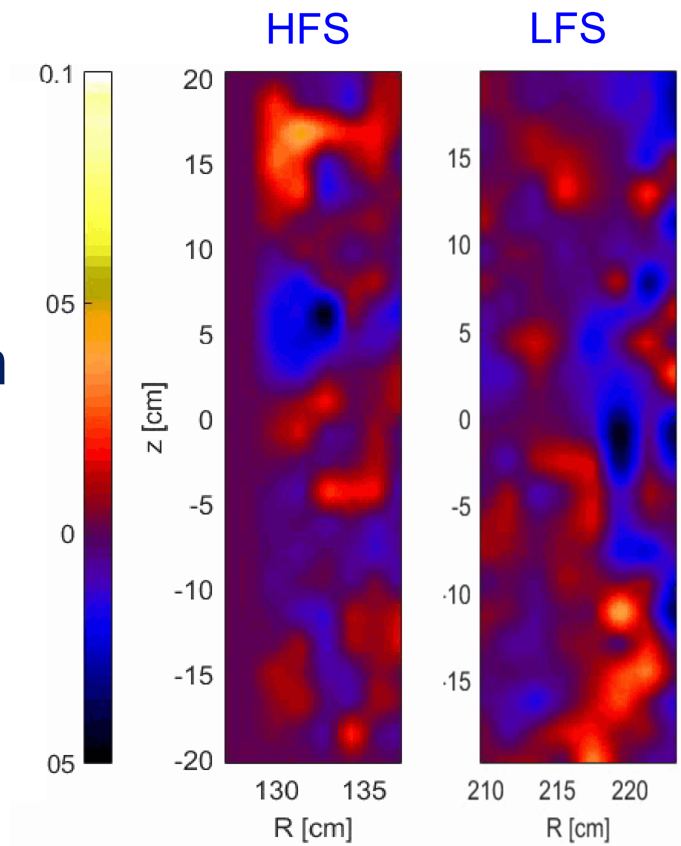
**ELM-crash active phase No RMP**

**# 14058**

**ELM-crash suppressed phase under RMP**




Real time images of the ELM behaviors before/during n=1 RMP suppression experiment have been simultaneously captured in both inboard and outboard sides.



# Summary

- New ELM physics in KSTAR
  - ECEI and RF emission data revealed new findings of the ELM and ELM-crash physics
  - Theoretical modeling validated the observed ELM structure in the saturated linear regime
  - ELMs at HFS and LFS require more than PB model
  - Simulation results from full kinetic and MHD model

- Turbuelnce measurement under the RMP
  - Successful ELM-crash suppression with n=1, 2 RMP (IVCC)
  - Role of the turbulence induced by magnetic perturbation in reduction of the ELM strength

# Thank you for your attention !
# Future is in your dream !