Research Topics on Pedestal Physics at KSTAR

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Domestic & International Collaborators

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NFRI 국가핵융합연구소 National Fusion Research Institute

KSTAR

Contents

- **Characteristics of H-mode discharges**
  L-H transition, confinement, typical H-mode discharges, stimulated transition

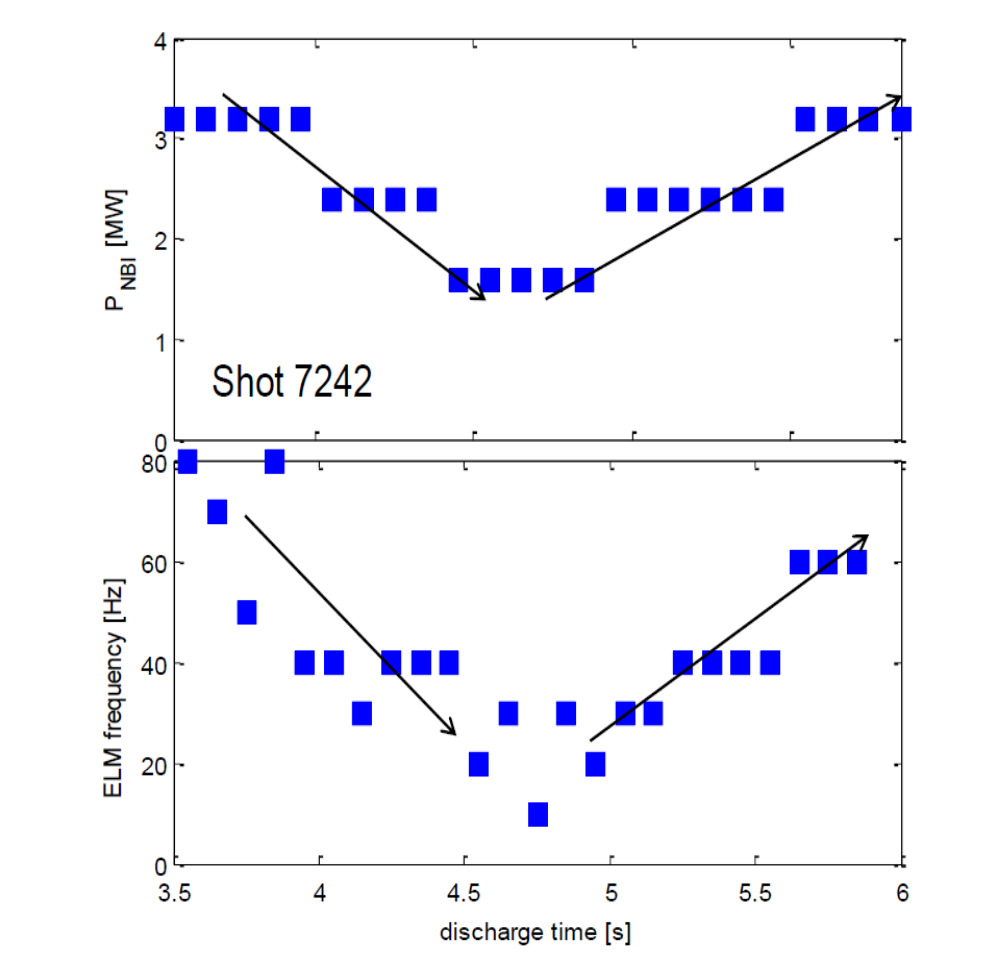
- **Status of pedestal diagnostics**
  Validation of profile & fluctuation
  profiles : Thomson Scattering, Charge Exchange Spectroscopy, Reflectometry,
  fluctuations :Beam emission spectroscopy, Imaging of Electron cyclotron emission

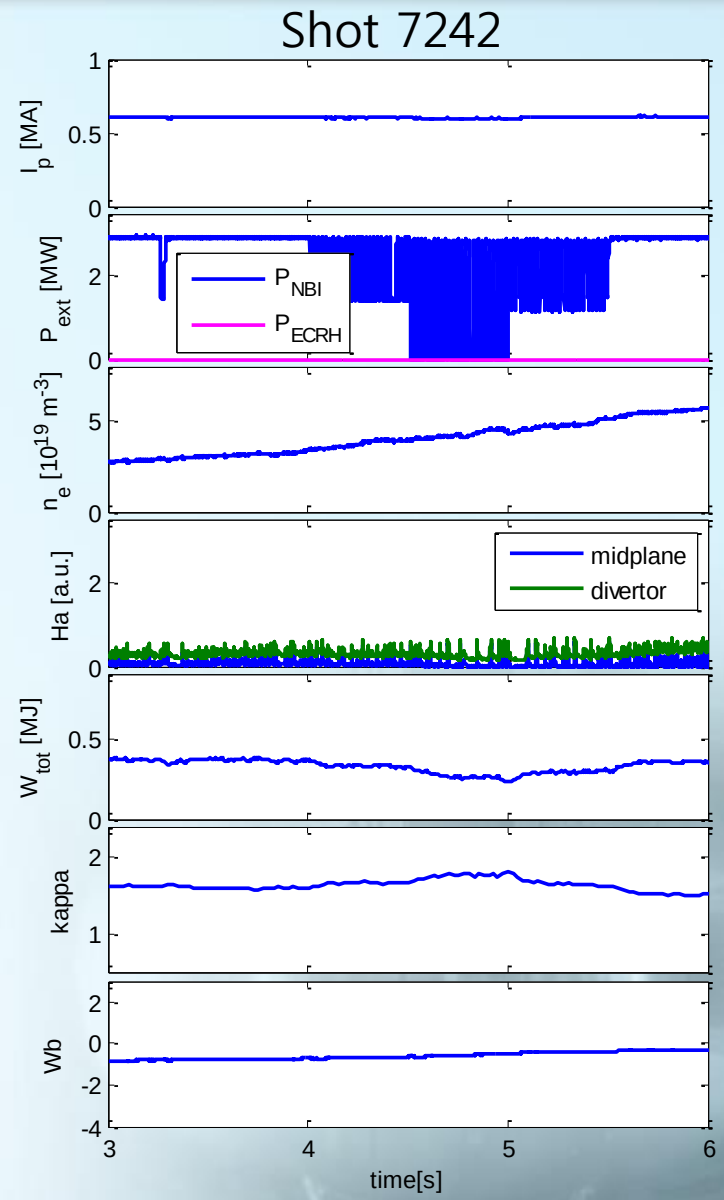
- **Research topics on pedestal physics**
  ELM mitigation / control
  (Resonant magnetic perturbation, edge ECRH, supersonic molecular beam injection)
  Pedestal evolution during ELM cycle
  (dynamics, mode structure)
  Searching for small ELM regimes

- **Near term research plan**
  Fast pedestal profile measurements including $j_{\parallel}$, E_r , & V_{pol} with cross-check
  (Li-Zeeman, poloidal CES, MSE, DBS)
  ELM physics/control in ITER relevant condition
  Transport in pedestal region (particle pinch, turbulence, ZF)

Characteristics of H-mode discharges

KSTAR Pedestal & ELM characteristics

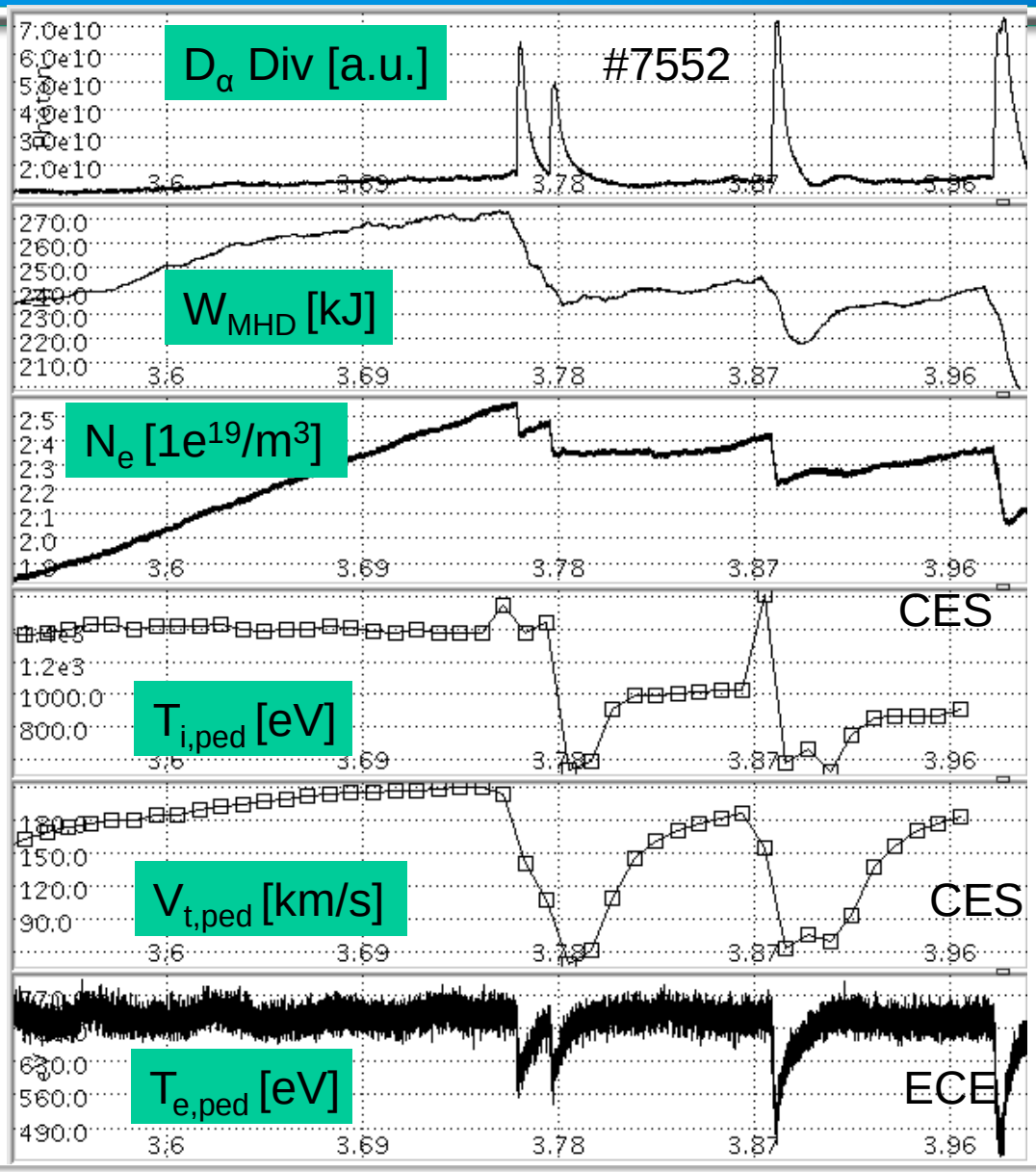




NBI power scan shows type-I character

2x PNBI -> ~2x f_{ELM}

Pedestal evolution in-between ELMs



Different time scales during ELM cycle
(For large infrequent ELMs)

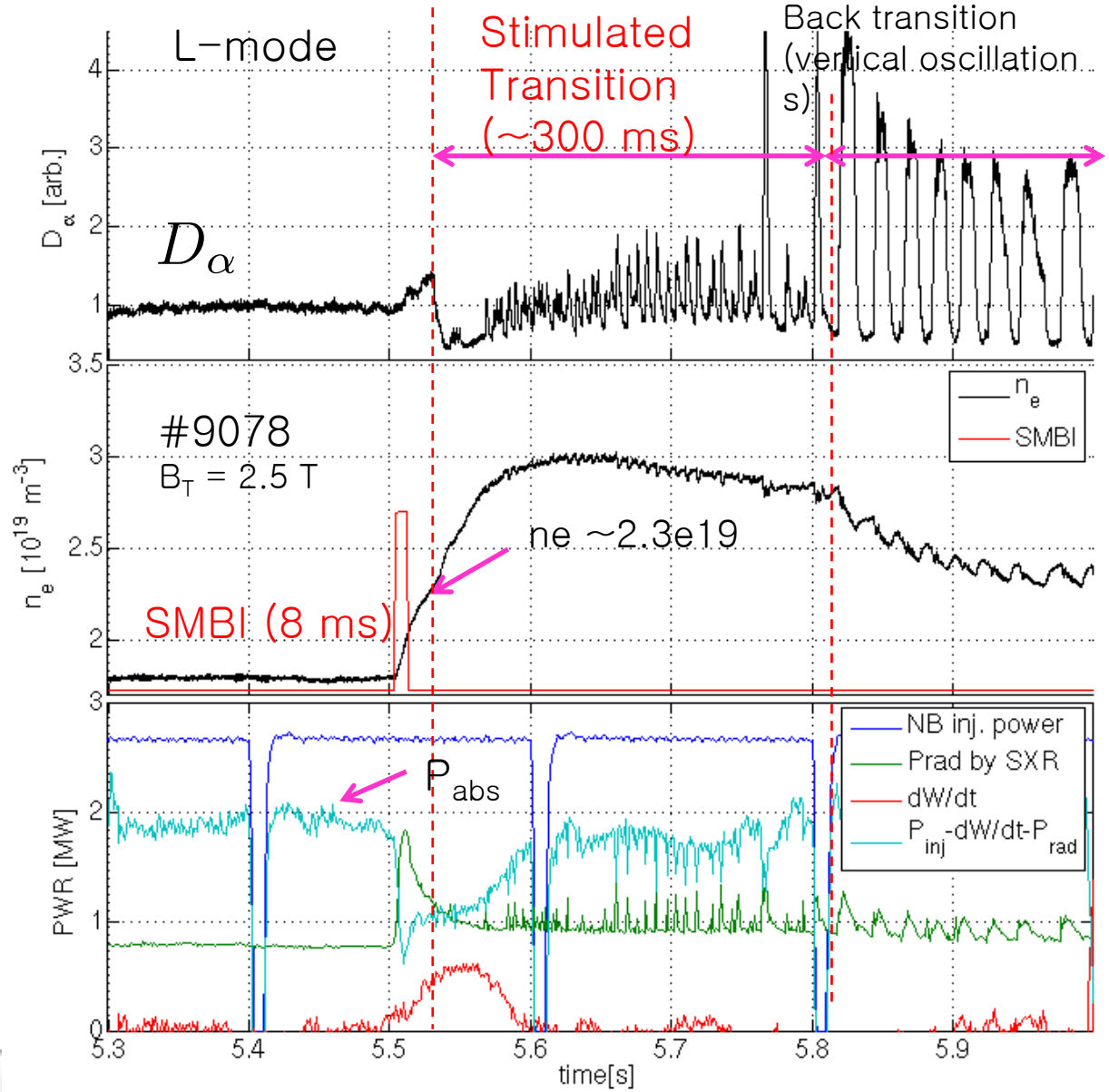
- Thermal ($T_{e,ped}$ & $T_{i,ped}$)
  Fast bulidup & saturation
  Faster saturation of Te

- Rotation
  steady increase in entire phase

Rotation (& shear) is the main driver?
(need pedestal density measurement)

Fluctuation analysis is on-going
(using Edge BES)

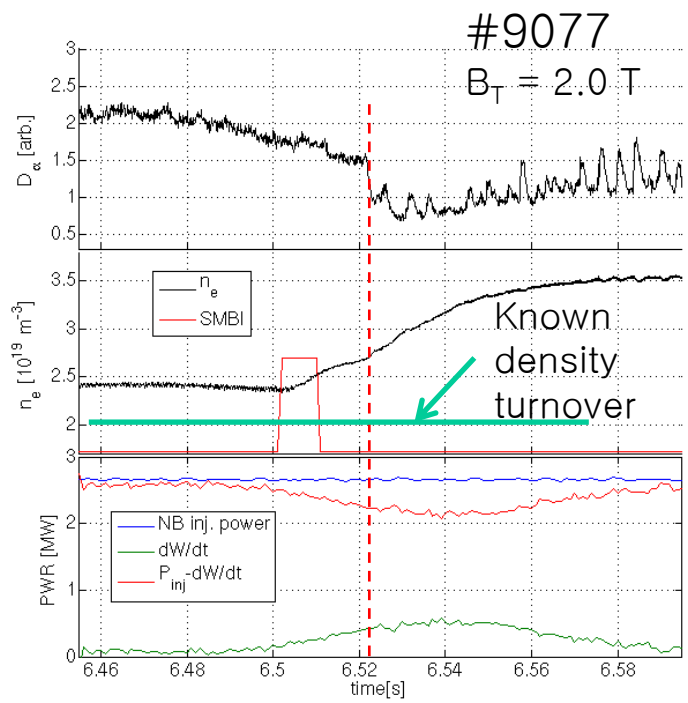
With SMBI, Stimulated transitions found with 30% reduced absorbed power



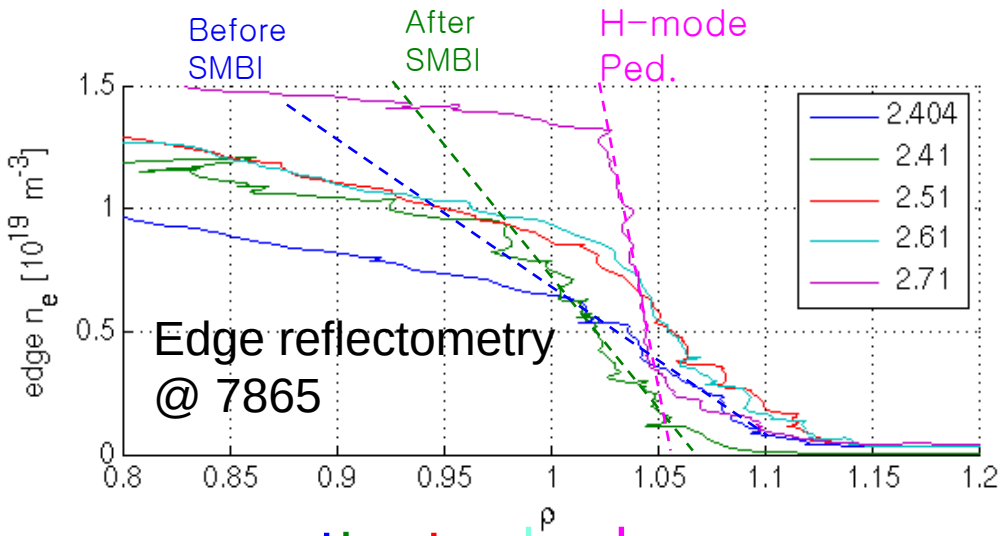
Triggering of L-H & small ELM is observed by 8 ms of SMBI

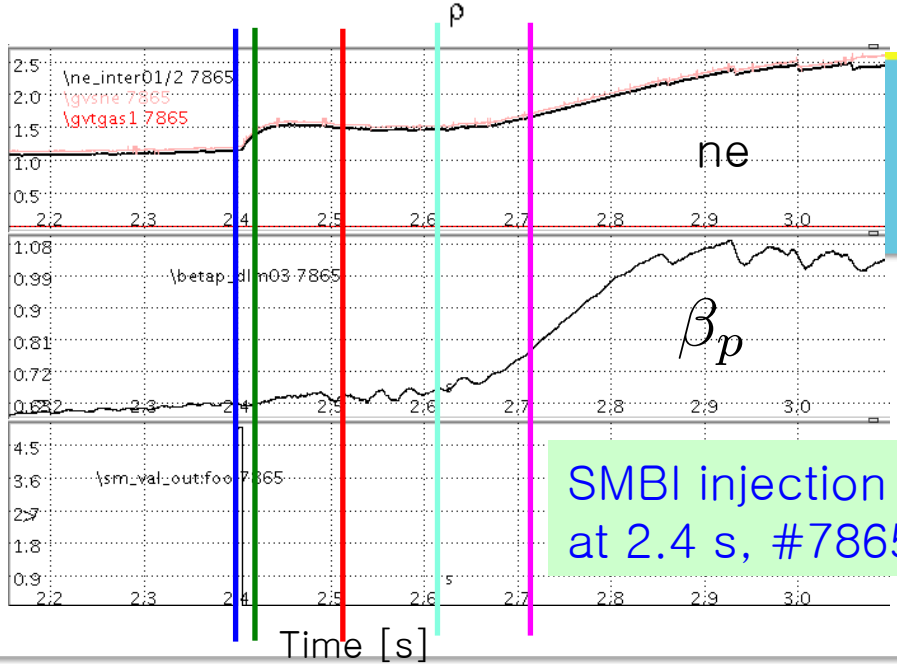
- Transition occurred for less absorbed power

$P_{abs} = P_{inj} - dW/dt - P_{rad}$ (cyan line)



Edge profile changes are accompanied for the stimulated dynamics





SMBI injection at 2.4 s, #7865

- Lower n_e branch case (#7865)
- **The induced density profile steepening is maintained** more than ~200 ms until the H-mode onset at 2.65s
  - Longer than particle confinement time
- Possible mechanism:

SMBI deposit on pedestal → local profile changes → changes on $\langle V_E \rangle'$

$$V'_{E\times B} = \frac{1}{eB}\left[-\frac{1}{n^2}n'p' + \frac{1}{n}p''\right] + \left(\left[\frac{r}{qR}u_{\parallel}\right]' - u'_{\theta}\right)$$

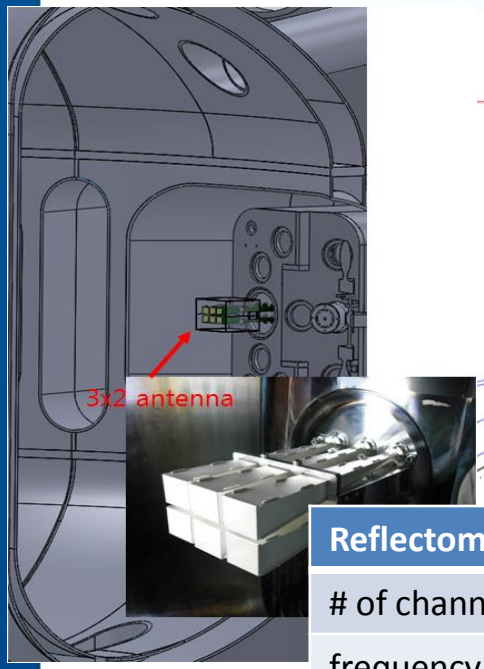
Density gradient; Pressure curvature; Diamagnetic drift; Toroidal flow (not considered here); Poloidal flow

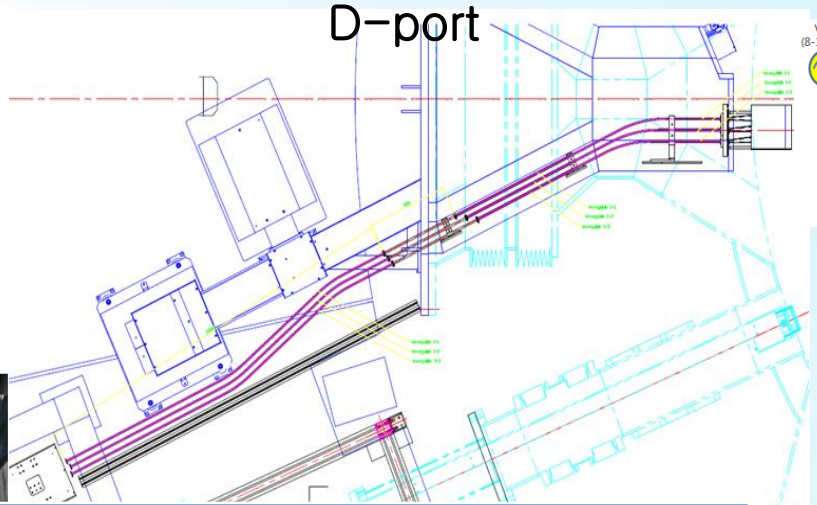
K. Miki, PRL 2013

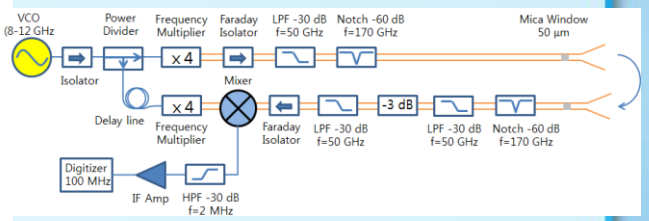
cf. DIII-D 1.3 mm smaller pellet scan did not report any stimulated transition with no change on pedestal (2013)

- **Status of pedestal diagnostics**

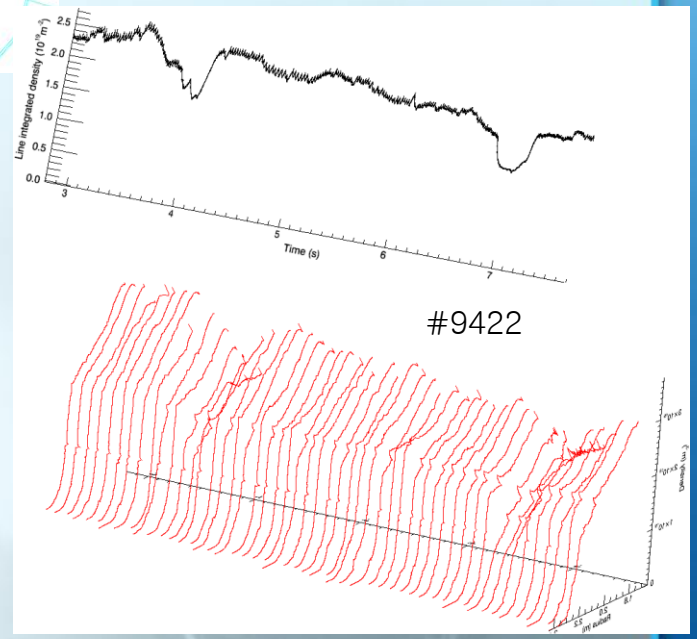
Profile Reflectometry which covers full radial range







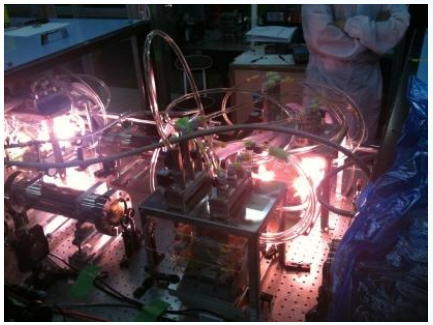
Reflectometry Specifications	
# of channel	3 bands (Q, V, and W)
frequency	33.6-54 GHz (Q band) 48-72 GHz (V band) 72-108 GHz (W band)
time resolution	25 μs
spatial resolution	0.5 mm
maximum storage	160 ms (32 Mbytes memory)
antenna	pyramidal long horn antenna (40 mm x 32 mm x 300 mm)
antenna position	antenna entrance @ R = 2.624 m



Specification of KSTAR Thomson scattering system

KSTAR Thomson scattering system(2013)

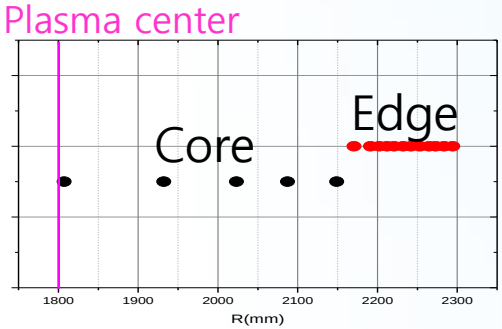
- Te : 10eV~1.5keV (edge), 500eV~20keV (core)
- ne : $3X10^{12}$~$2\ X10^{14}$ cm^{-3}
- 17spatial points (core 5, edge 12 points)
- Spatial Resolution : <10cm (core), <10mm (edge)
- Polychromator 17ea (core 5ea by NFRI, edge 12ea by NIFS)
- Laser : ~5J, 100Hz Nd:YAG Laser, 1064nm



5J, 100Hz, 1064nm Double laser line

λ=1064nm, pulse width ~20nsec

* LASER system rented from JAEA

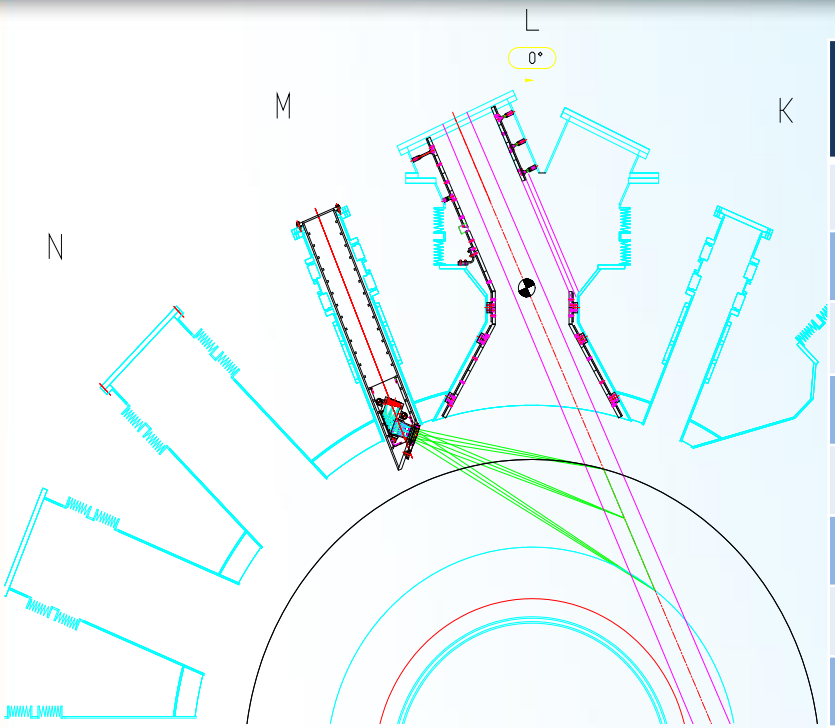


Measuring Position

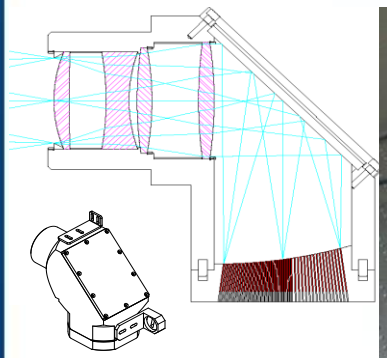
Calibrated by

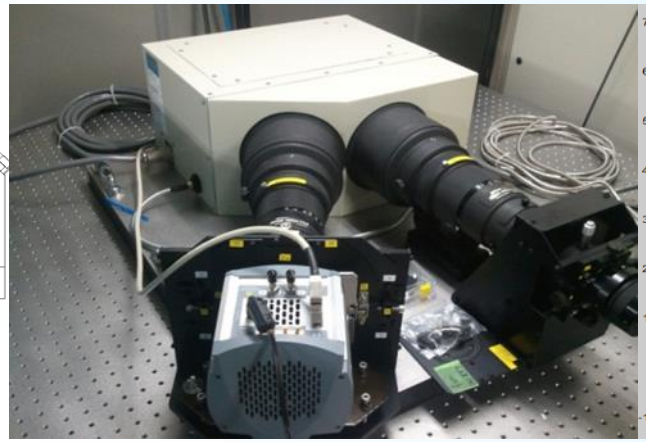
- Rayleigh scattering with N_2
- Spectral calibration with W (tungsten) light

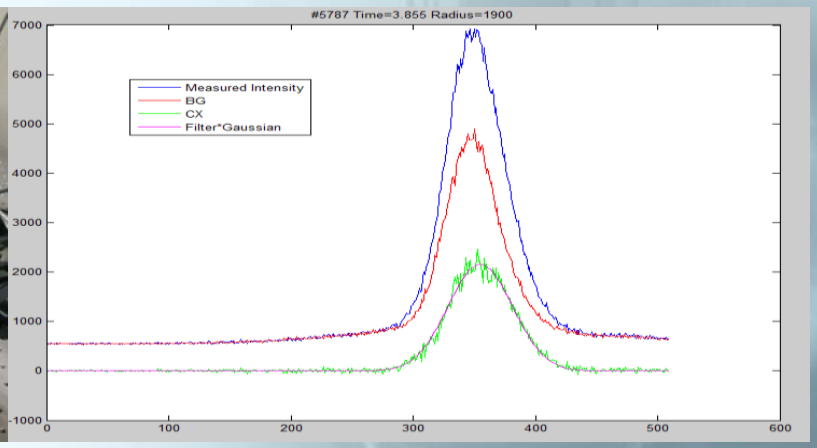
Charge Exchange Spectroscopy on KSTAR



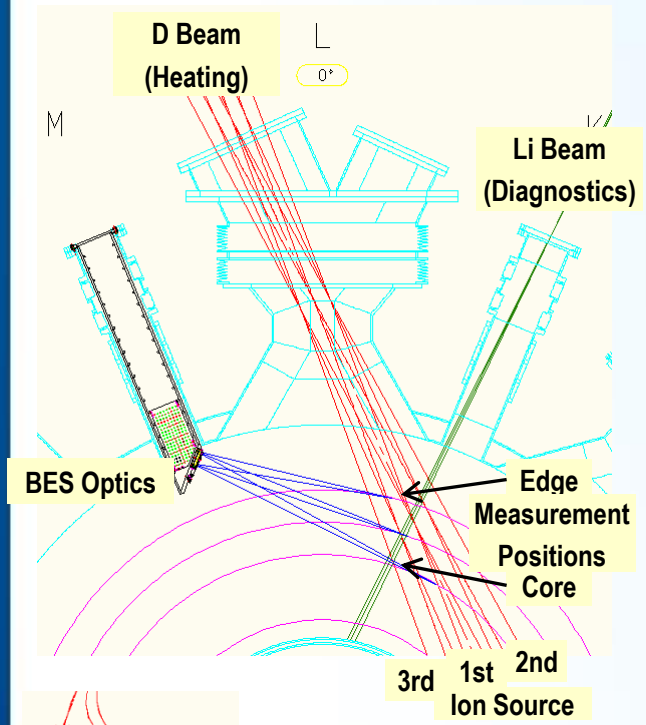
Name	CES specification in 2013
Time resolution	10 msec (100 Hz)
Spatial resolution	20 ~ 50 mm (Core), 5 mm (Edge)
Ti & V_ϕ range	> 100 eV & > ~ km/sec
System location	Active CES – M port
No. of Channels	32 points (Max.51points available)
NBI modulation	5Hz 95% duty rate (requirement)
Impurity	C_{VI} (529.05 nm)
Spectrometer	DS-spectrometer (DU897), K-spe.

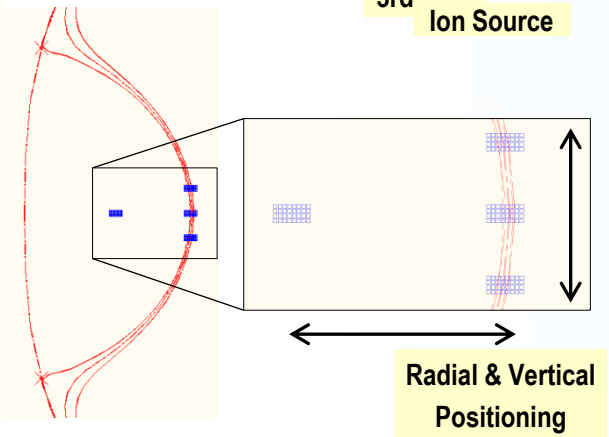






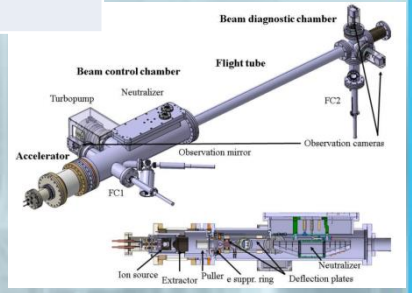
Li/D Beam Emission Spectroscopy System





BES Specifications	
Local (Resolution)	1 cm
2D (Pixel)	4x8 (will be upgraded to 4x16)
Fast (Sampling)	2 MHz
Fluctuation (SNR)	~ 150 (~ 3% background)
Meas. Position	Radial & Vertical Scan (shot by shot)
Filter	Heatable (for fine tuning) Rotatable (for background cal.) Changeable (for Li/D)
Cameras	APD (fast) / CMOS (high res.)
Time Range	up to 100 sec

Li Beam Parameter	
Diameter	2 cm (in the plasma) 10 cm (defocused)
Current	~ 2 mA
Energy	< 60 keV
Pulse Length	20 s
Species	Lithium (neutralized by Sodium)

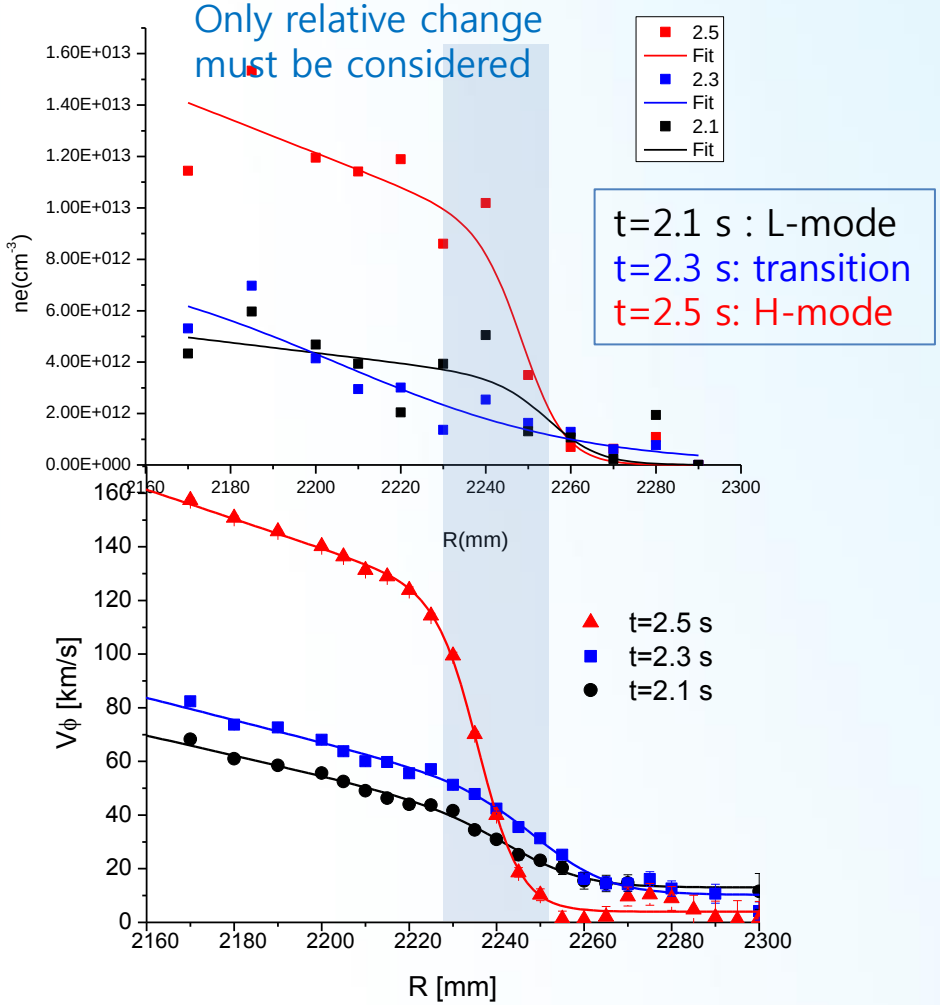


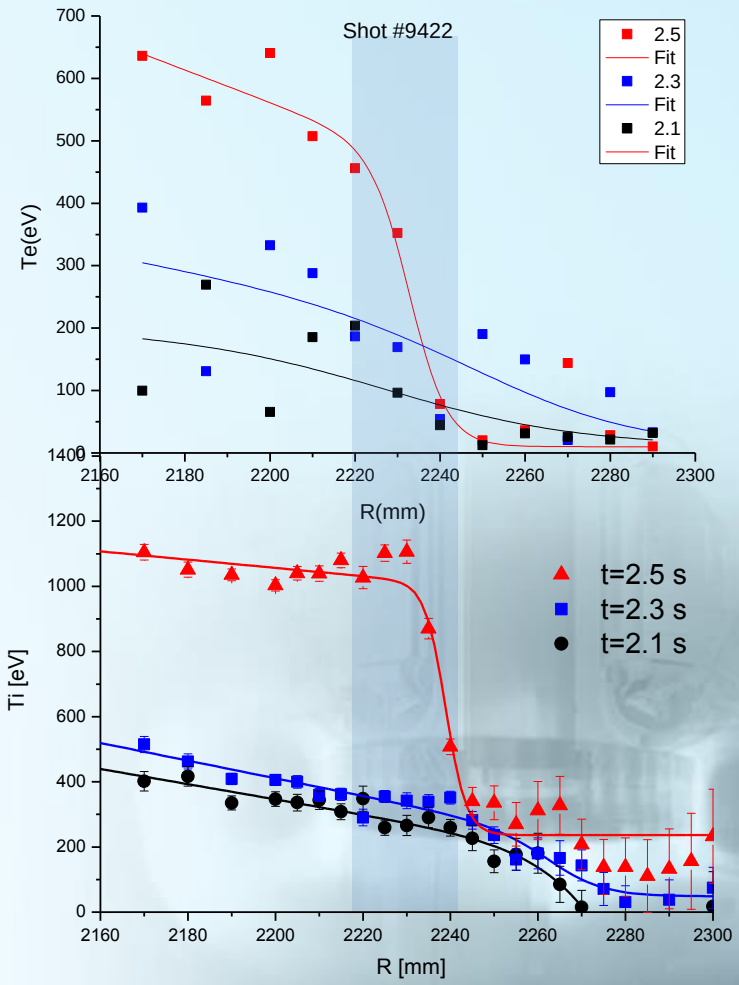
Typical KSTAR Pedestal profiles

Pedestal structure both in Thomson & CES for H-mode (further comparison is on-going)

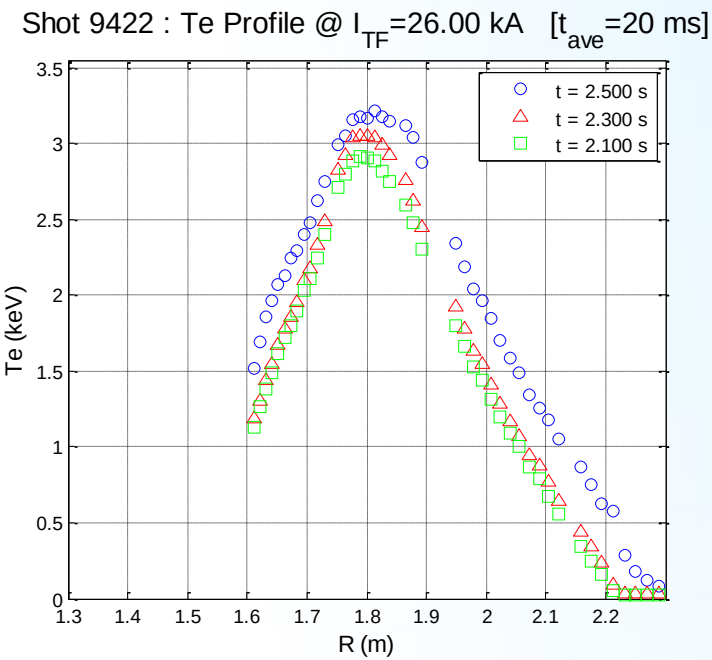
Issue of TS calibration

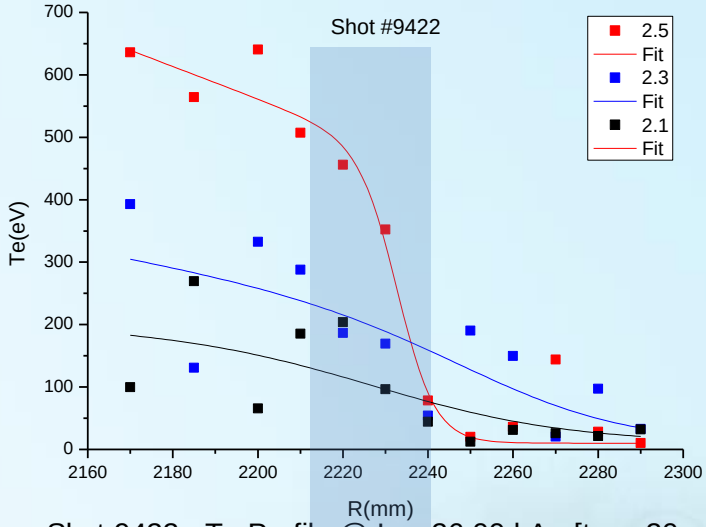
Only relative change must be considered

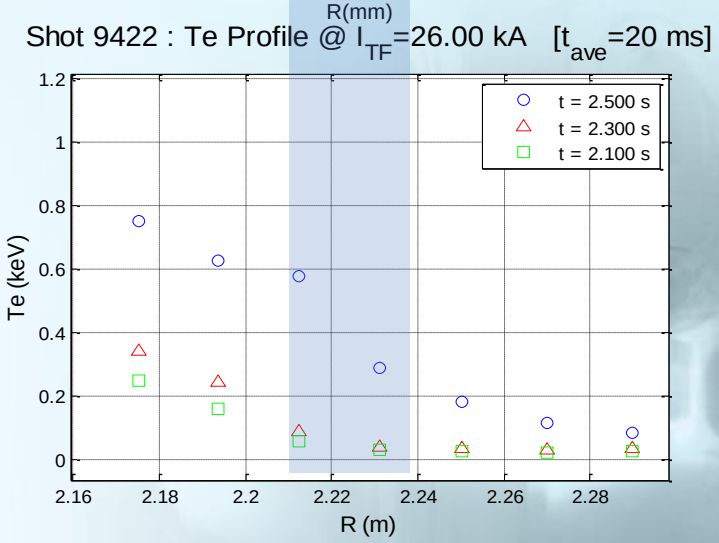




Initial comparison showa good correlation between ECE & TS







Value of $T_{e,ped}$ are in good agreement
Position of separatices < ~ 1 cm

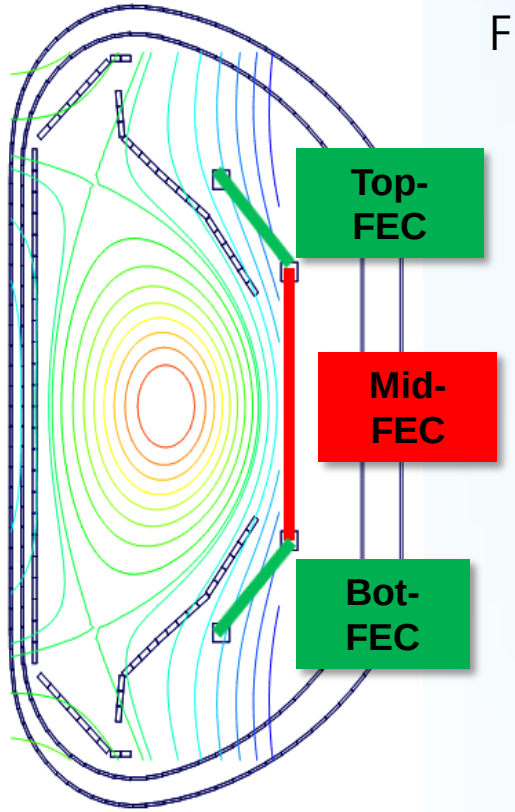
ECE could be used for fast pedestal Te measurements with B_T>2.6 T

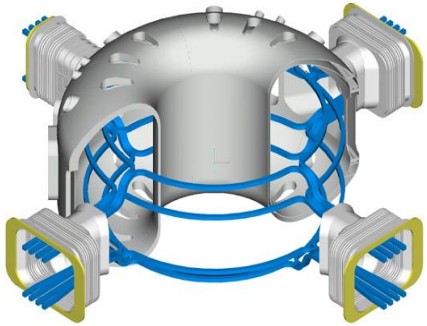
Density need better laser calibration (also with Li-BES)

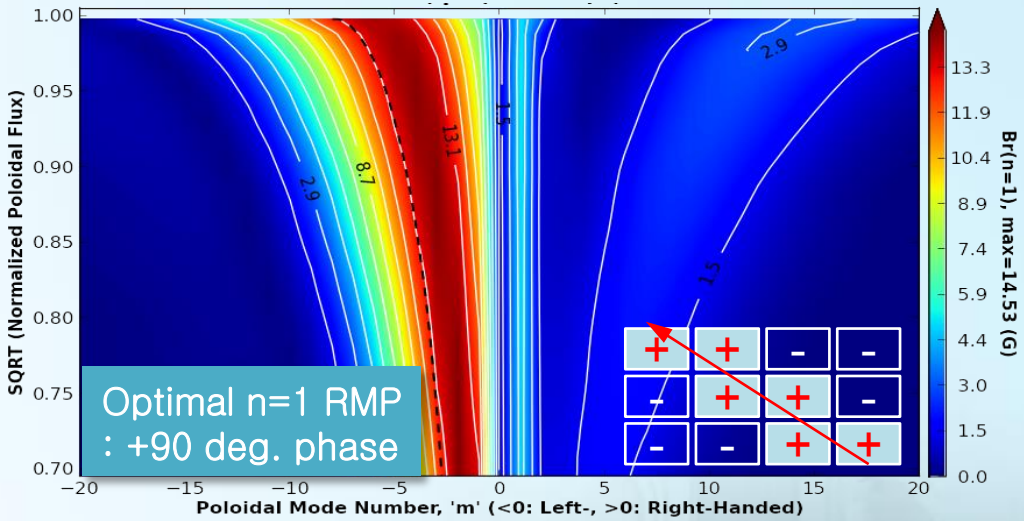
Research topics on pedestal physics

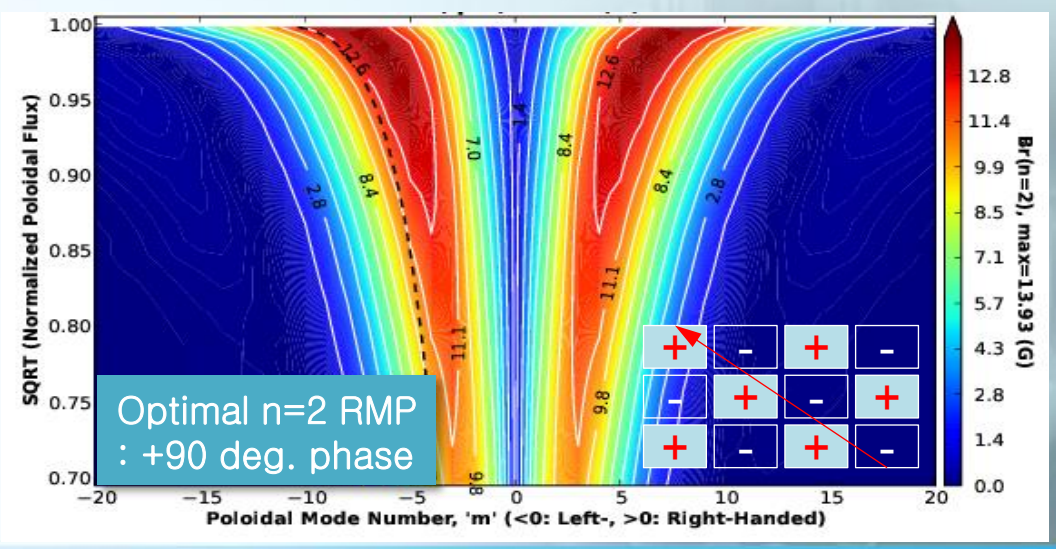
Optimal RMP configurations for KSTAR

FEC coils used for RMP = 3 (poloidal) x 4 (toroidal)

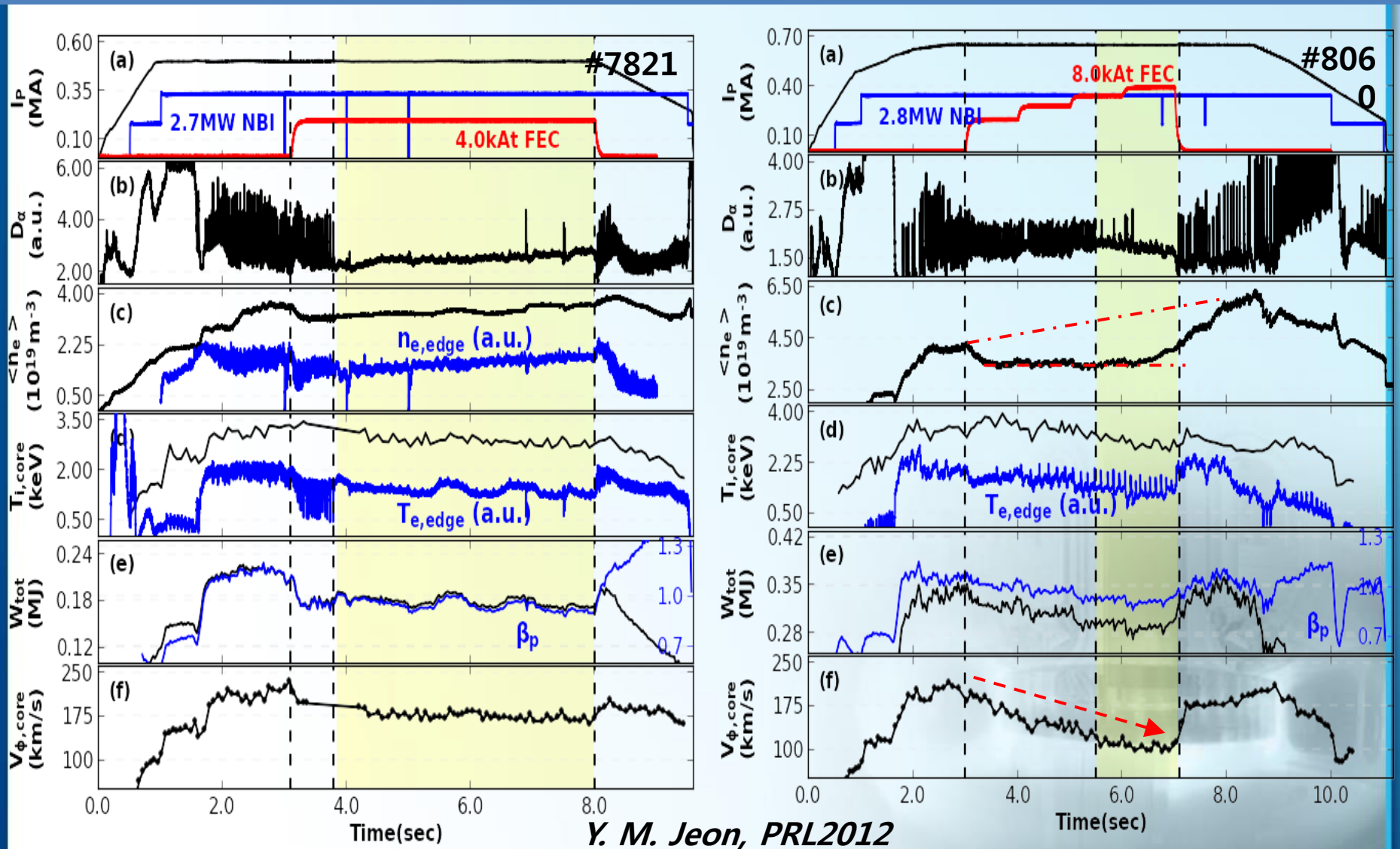








In 2012, ELM-suppressions have been successfully demonstrated using both n=1 or n=2 RMP

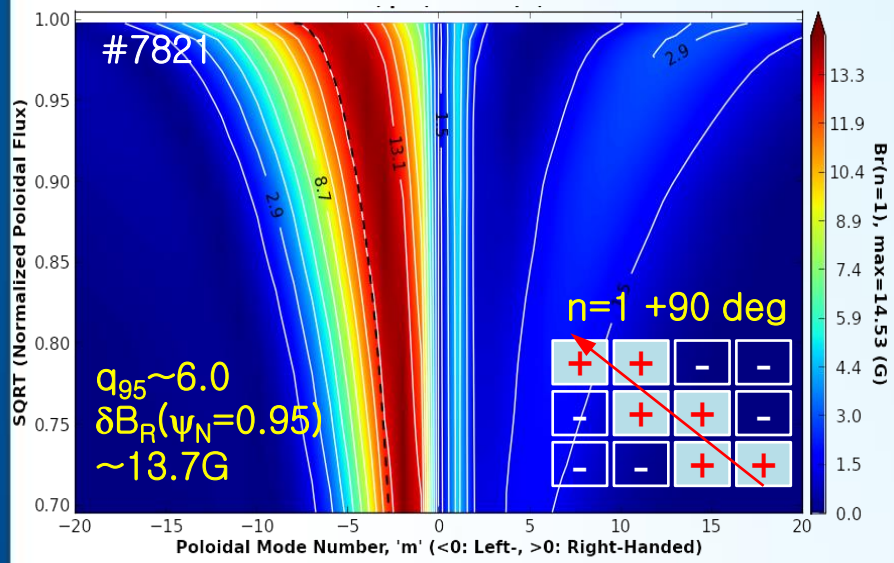


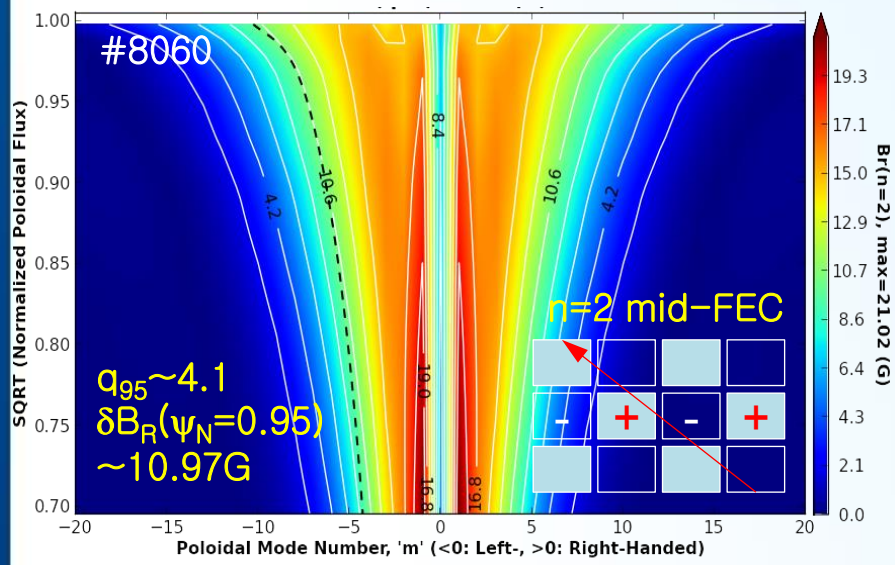
Y. M. Jeon, PRL2012

n=1 (+90 phase) RMP at q_{95}~6.0

n=2 RMP (mid-FEC only) at q_{95}~4.1

A generalized criterion suggested for ELM-suppression





#7821 (n=1, +90 deg)

$\delta B_R(\psi_N=0.95)/B_T = 13.7\times10^{-4}/1.8$

$\sim 7.71\times10^{-4}$

#8060 (n=2, mid-FEC only)

$\delta B_R(\psi_N=0.95)/B_T = 10.97\times10^{-4}/1.5$

$\sim 7.31\times10^{-4}$

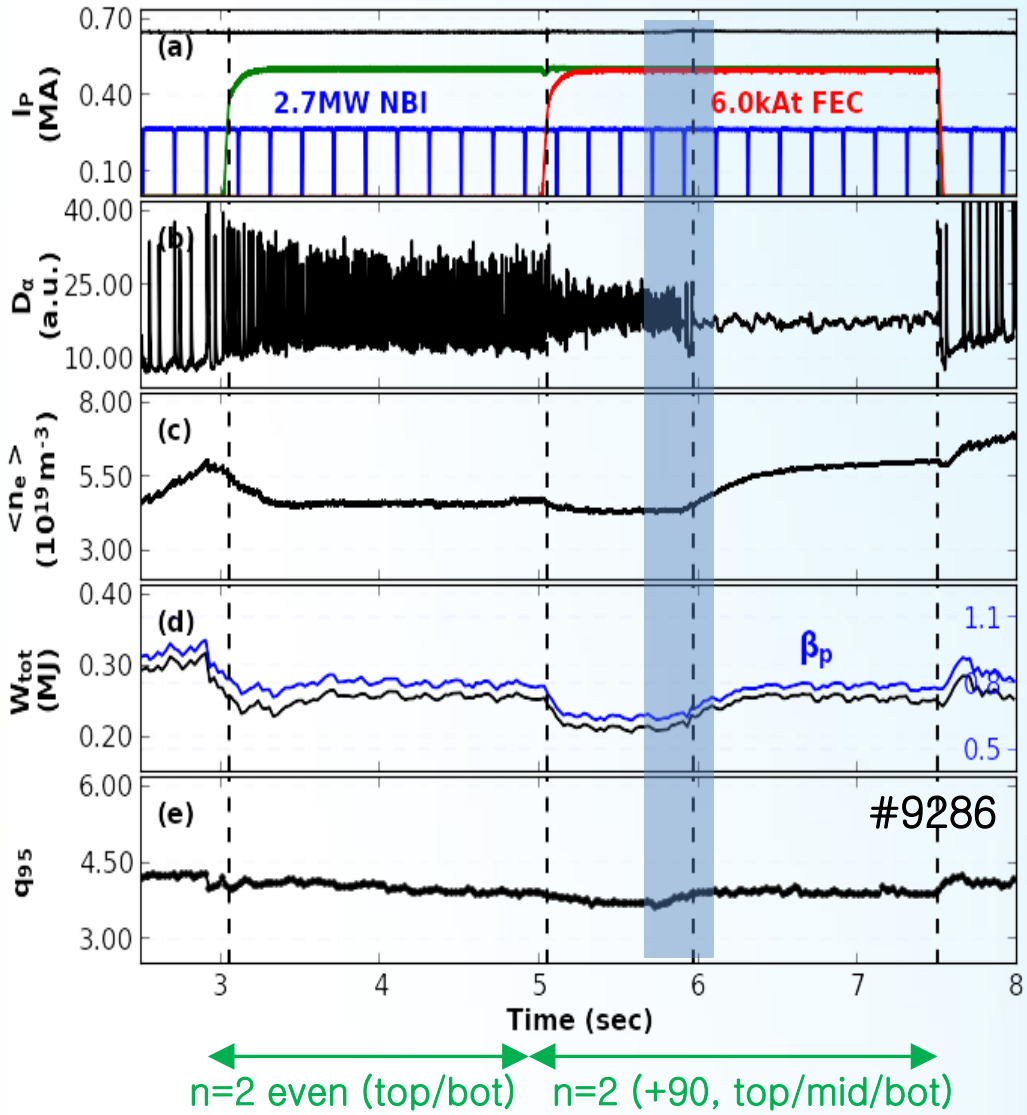
ELM-suppression requires

$\delta B^*_{R95} \equiv \delta B_R(\psi_N=0.95)/B_T$

$\delta B^*_{R95} > 6\times10^{-4}$

Similar ELM-suppression by '+90 phased n=2 RMP' is expected with less FEC currents if the generalized criterion is valid, since '+90 phased RMP' is more resonant by a factor of 1.7.

ELMs suppressed using +90 phased n=2 RMP



#9286: I_p=0.65MA, B_T=1.8T ➔ **q_{95}~4.0**

➔ ELM suppression under 6.0kAt n=2 RMP at q_{95}~4.0

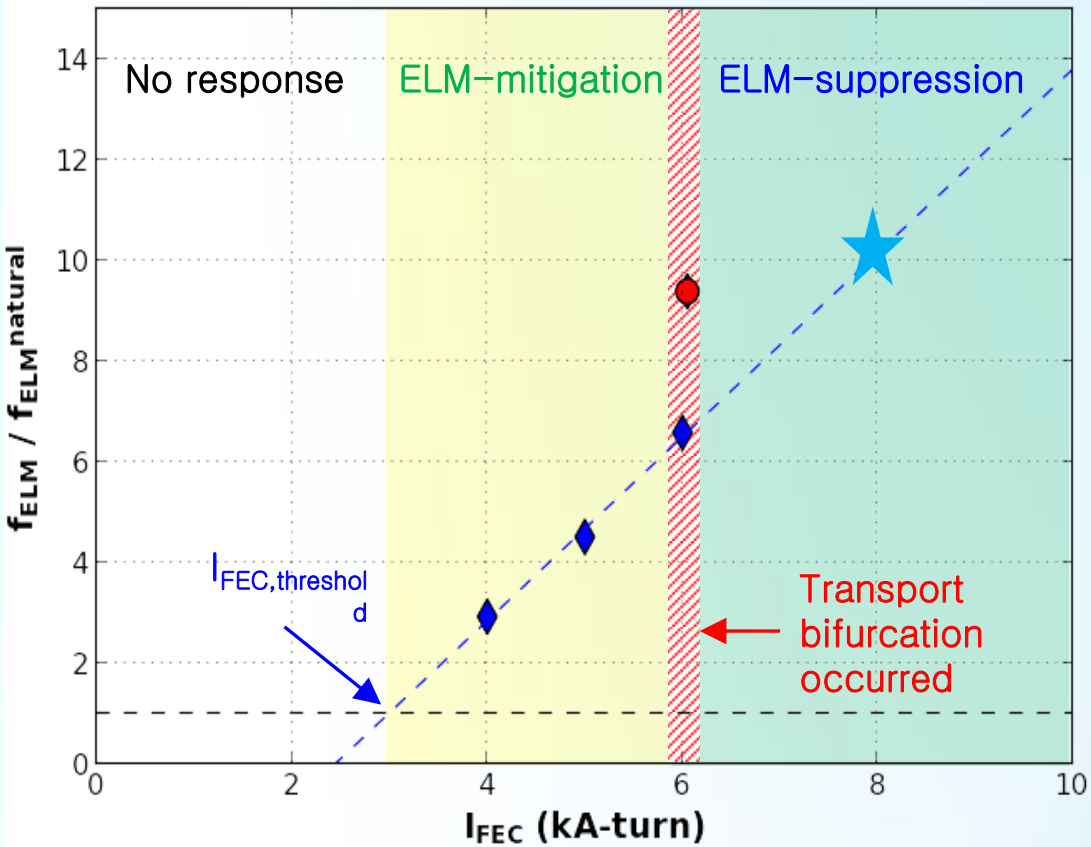
Initially ELMs mitigated by n=2 even (top/bot) RMP

As mid-FEC currents added (n=2,+90 RMP), **ELMs further mitigated and then suppressed**

Note that **ELM-suppressed phase showed better confinements** than that in ELM-mitigated phase

- See changes on $<n_e>$, W_{tot}, and β_p

ELM responses to n=2 RMP field strength



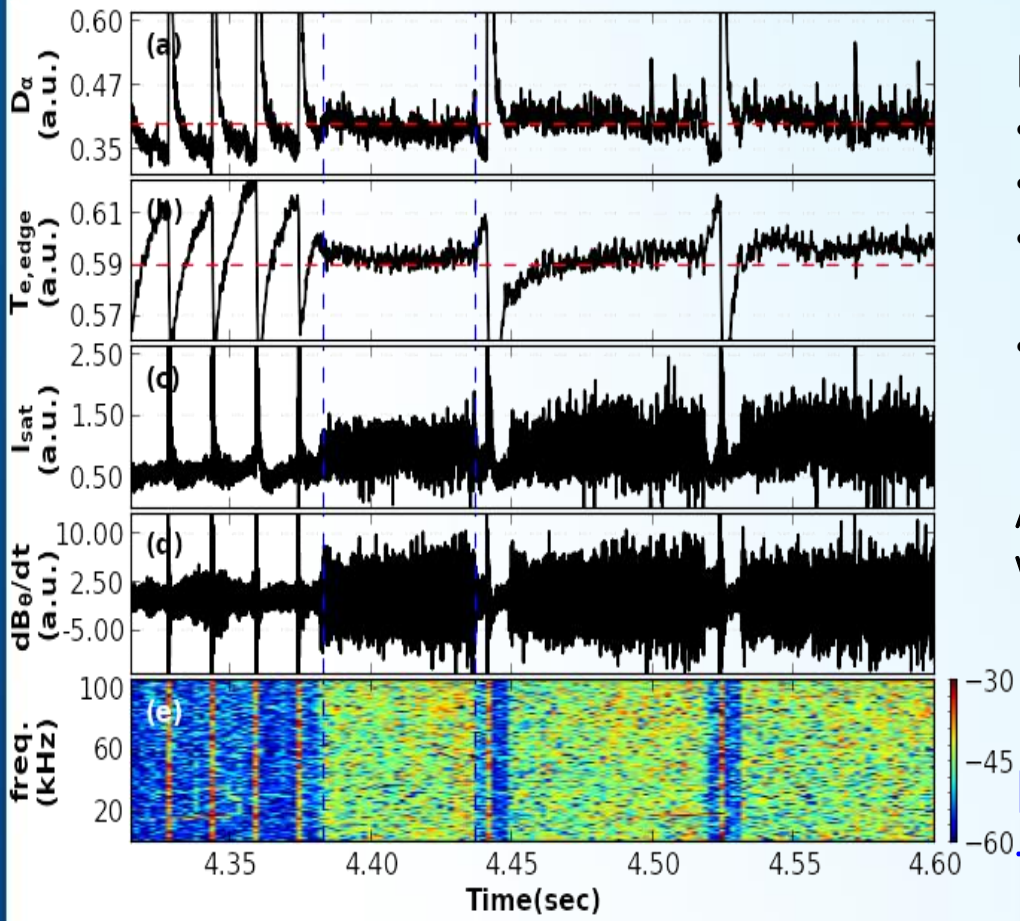
Blue points: ELM mitigation by different n=2 FEC currents in identical discharges (**q_{95}~4.0**)
- **Strong linear correlation** between ELM freq. change and FEC currents

Red point: mitigated ELM at just outside ELM-suppression window of q_{95} (during q_{95} scan)
- f_{ELM} change reached up to a **factor of ~10**

((Bifurcation))
With 6.0kA n=2 RMP fields, ELM-mitigation was **bifurcated to ELM-suppression** state

(Q) Can we get to the point marked ★ with , by applying I_{FEC}=8.0kAt at q_{95} outside suppression window ?

Distinctive fast time scale phenomena that are directly linked to the transition to ELM-suppressed



At the moment of transition to ELM-suppression in KSTAR #7820. RMP was applied in whole period here

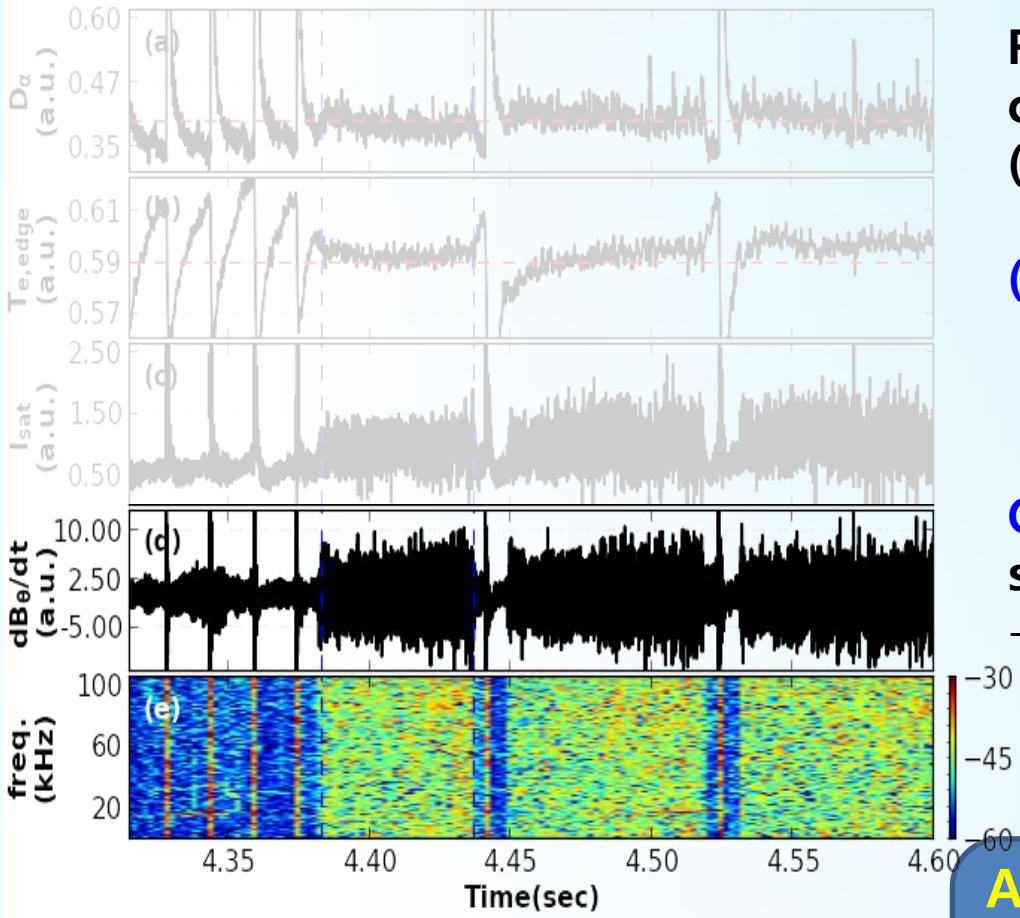
Distinctive features observed …

- Increased base-level of D_α
- Saturated growth of $T_{e,edge}$
- Increased fluctuation of I_{sat} on divertor
- Broadband increase of EM fluctuations

All of these "fast time-scale phenomena" were "precisely synchronized"

How we can understand all of these consistently ?

How the uniform broadband increase of EM fluctuations can be produced ?



At the moment of transition to ELM-suppression in KSTAR #7820. RMP was applied in whole period here

Features of observed EM fluctuation change

(1) Broadband (actually **full range** up to ~250kHz) frequency

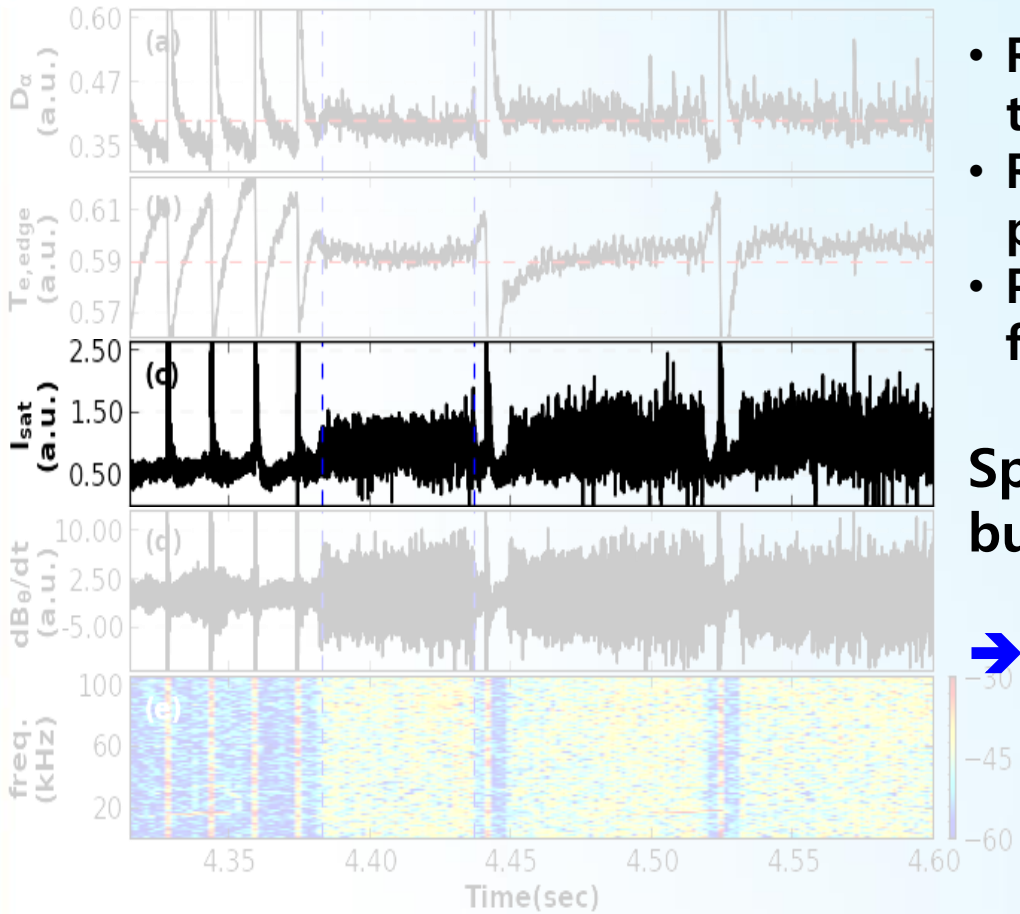
(2) **Uniform spectrum power**

Only possible with a bursty event such as shown in ELM-crashes

- cannot be explained with coherent MHD activities

A persistent bursty event may be activated **in the plasma edge,** which produces broadband EM fluctuations

Rapidly increased, steady fluctuations on Ion saturation current suggests a persistent bursty event



At the moment of transition to ELM-suppression in KSTAR #7820. RMP was applied in whole period here

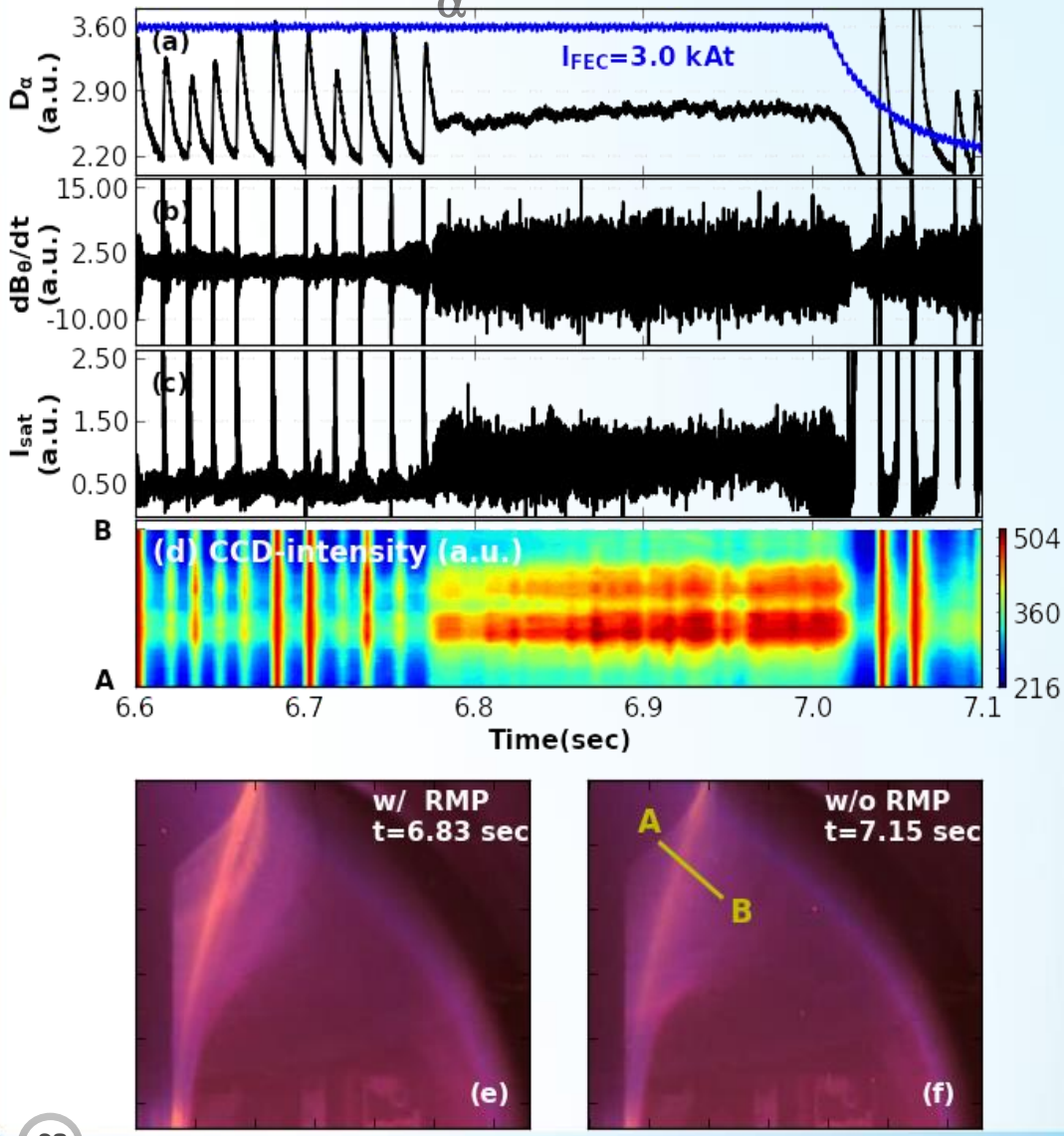
- Rapid increase of I_{sat} fluctuation in the inter-ELM period
- Rapid decrease of I_{sat} fluctuation prior to the next ELM crash
- Precise synchronization with EM fluctuation

Spiky fluctuation on I_{sat} → bursting event

➔ A persistent, rapidly repeating bursting event produces a steady spiky fluctuations on I_{sat}

The persistent bursty event occurred in the plasma edge

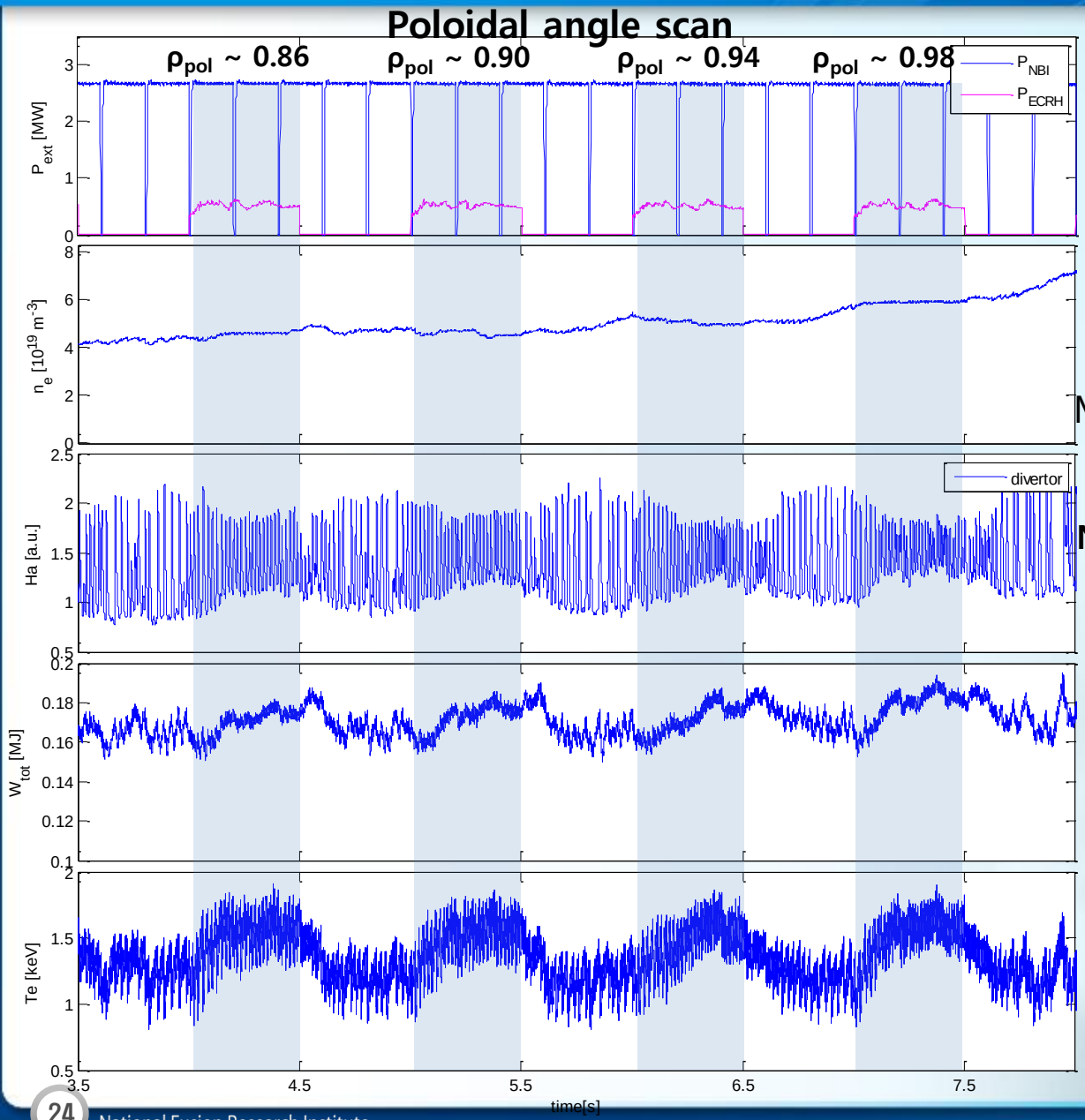
Increased D_α emission near the plasma boundary

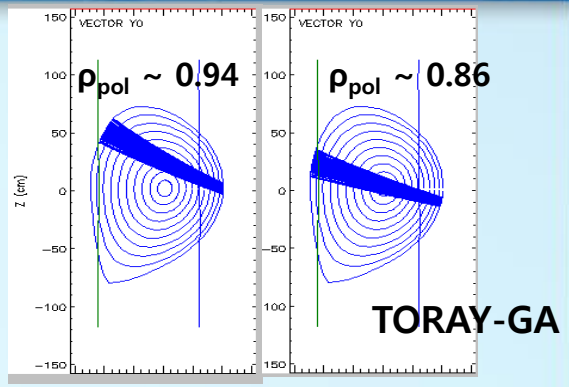


- Emission from CCD ∝ D_α
- No clear change on topology at the transition
- Only emission intensity was increased strongly

➔ The persistent bursting event in the plasma edge leads increased neutral recycling near the plasma boundary, thus increasing D_α emission

Scan of position of ECH deposition





2nd Harmonics deposition at LFS

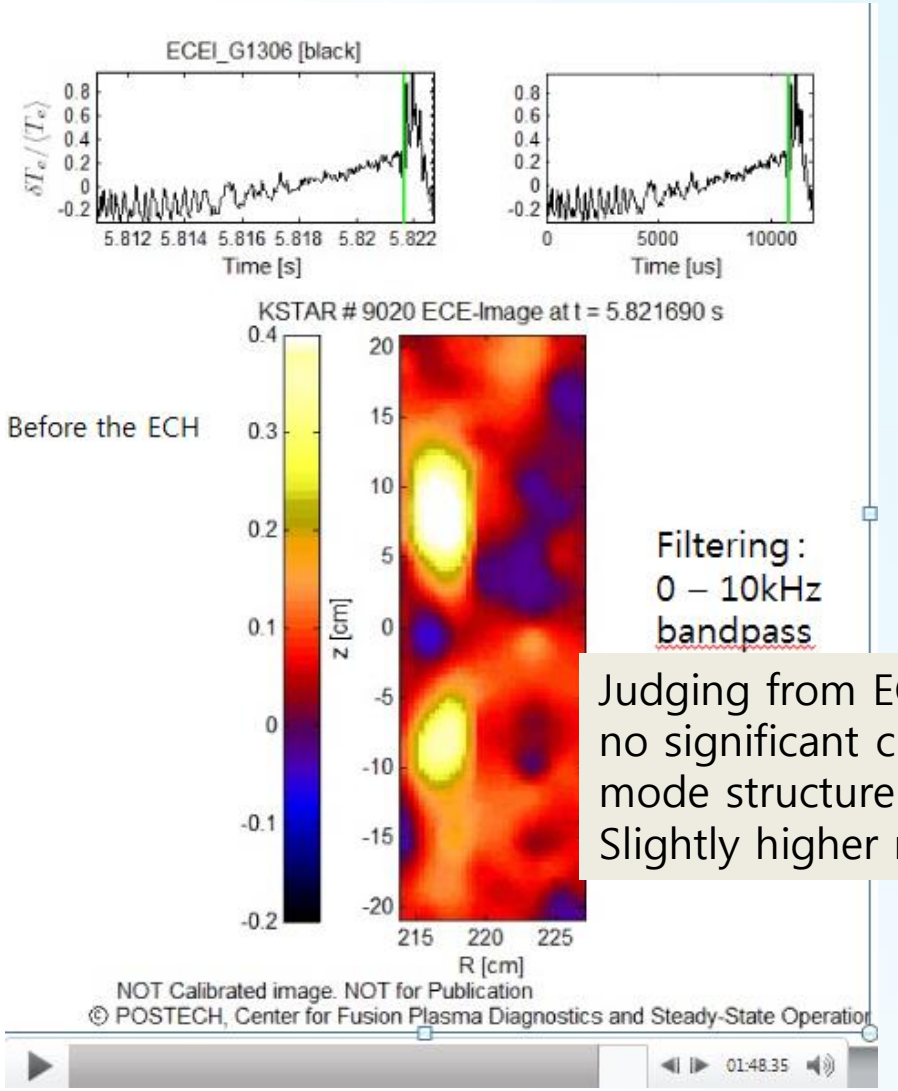
Mitigation stronger at larger ρ_{pol}

No ECH	f_{ELM}	~30 [Hz]
	ΔW_{ELM}	~20 [kJ]
	Δn_{eL}	~0.16 [10^{19}/m3]
	$\Delta T_{e,ped}$	~0.4 [keV]
ρ_{pol} ~ 0.86	f_{ELM}	~60 [Hz]
	ΔW_{ELM}	~ 4 [kJ]
	Δn_{eL}	0.05 [10^{19}/m3]
	$\Delta T_{e,ped}$	0.3 [keV]
ρ_{pol} ~ 0.98	f_{ELM}	~90 [Hz]
	ΔW_{ELM}	~2 [kJ]
	Δn_{eL}	0.06 [10^{19}/m3]
	$\Delta T_{e,ped}$	0.15 [keV]

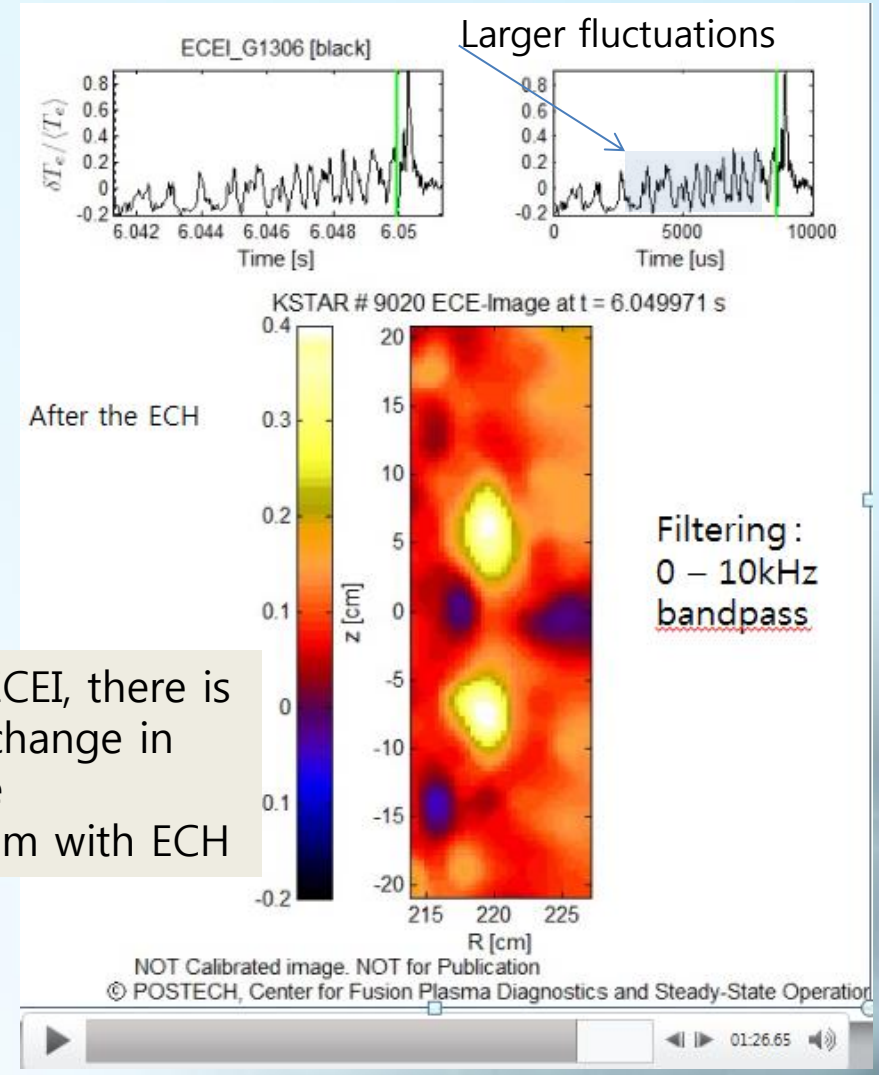
Profiles & fluctuations are under investigation

Similar ELM crash but more fluctuation during ELM cycle (J. H. Lee, POSTECH)

w/o ECH

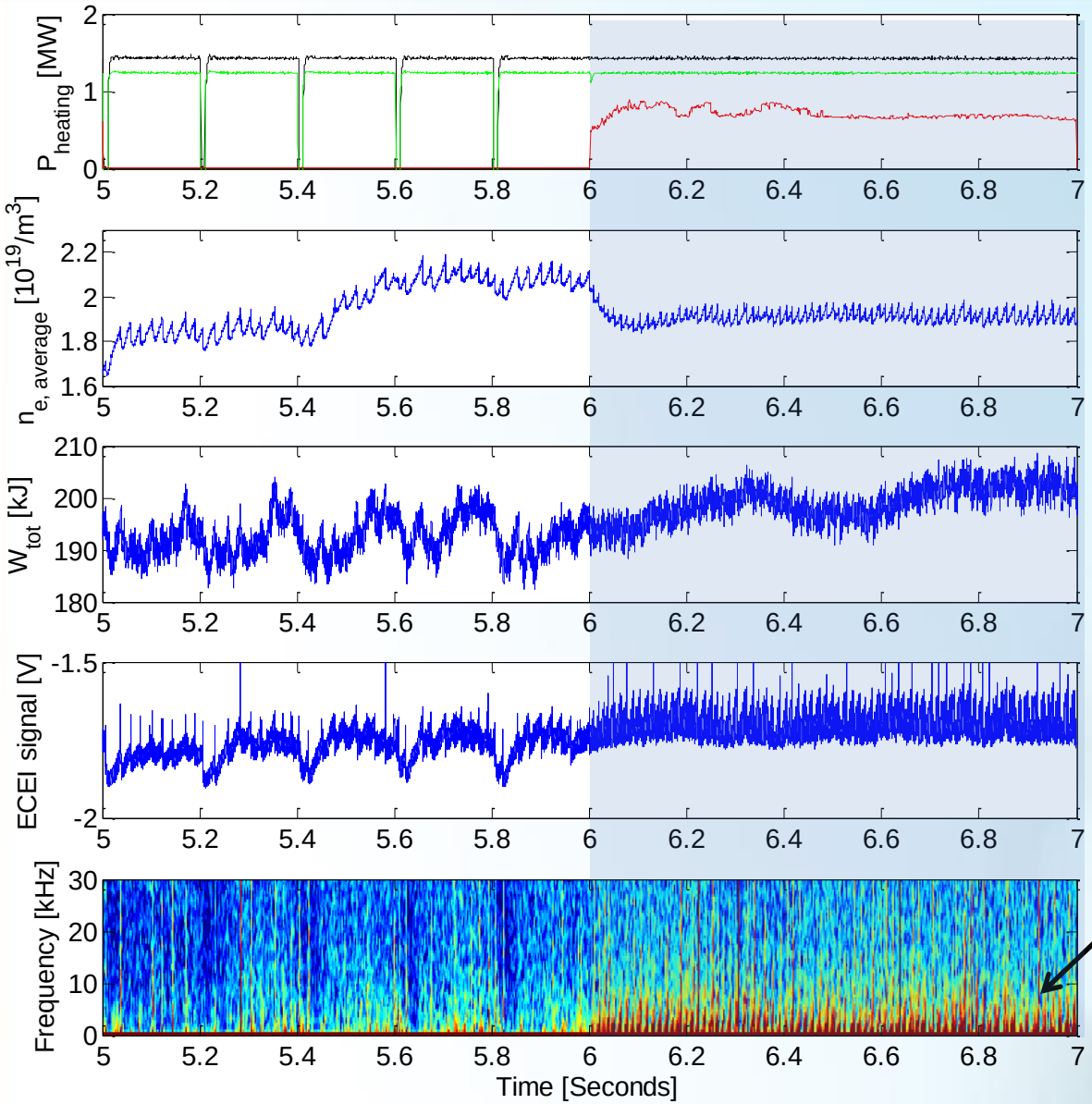


w ECH



Judging from ECEI, there is no significant change in mode structure
Slightly higher m with ECH

Similar ELM crash but more fluctuation during ELM cycle (J. H. Lee, POSTECH)



10% drop of density

Strong pump-out at midplane injection

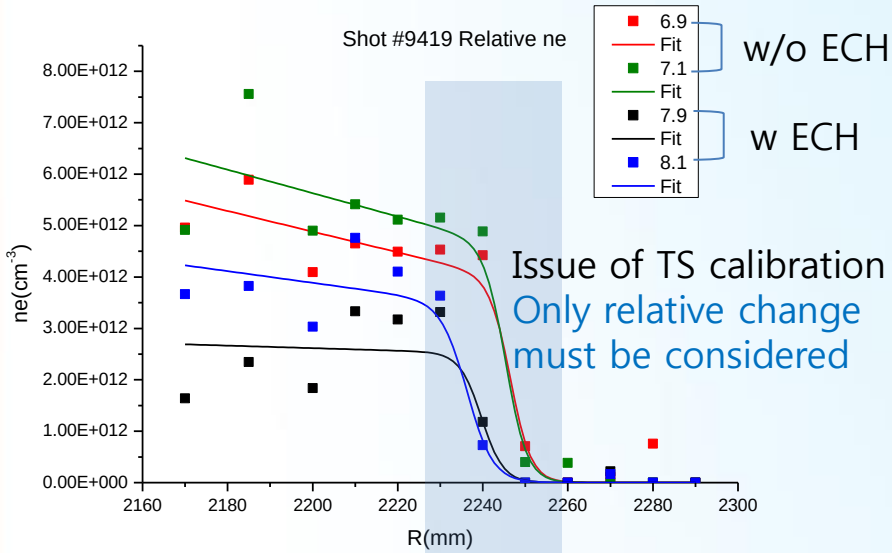
Low freq fluctuations (10 kHz)

Localized in pedestal

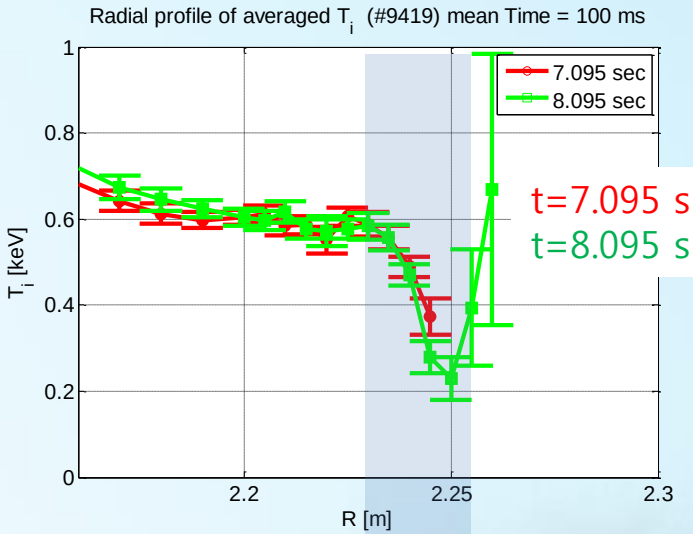
Similar modes also in density fluctuation (by D-BES)

Change of pedestal profile during ECH injection

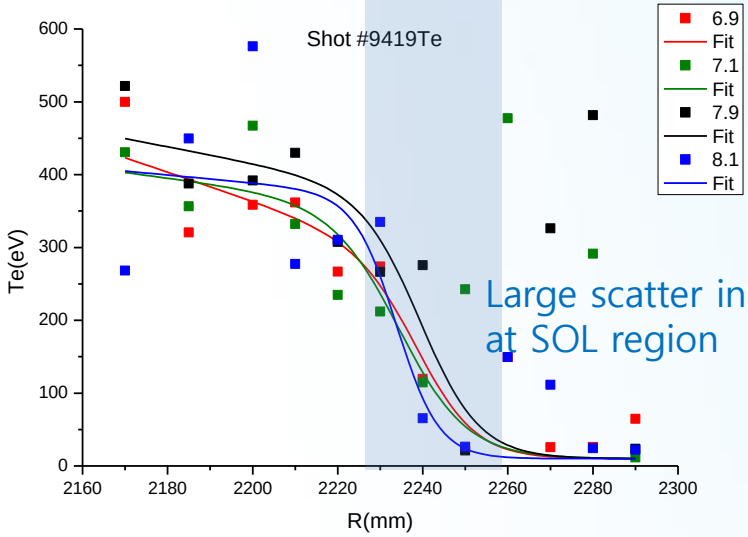
ELM averaged difference of pedestal profiles



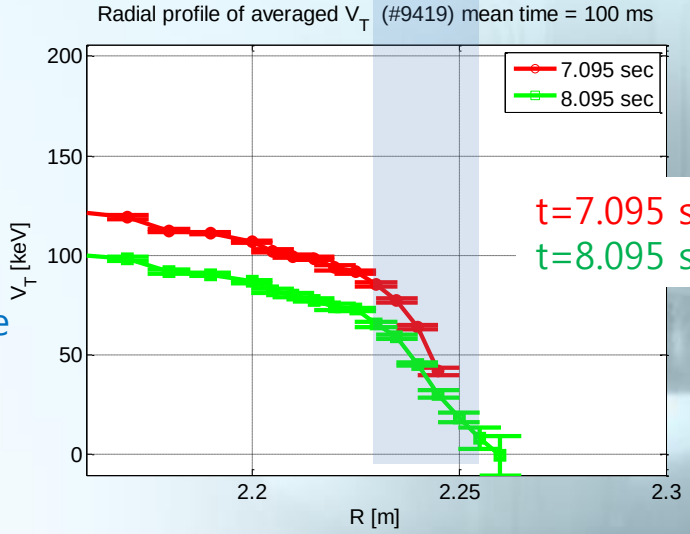
Issue of TS calibration
Only relative change must be considered



t=7.095 s (w/o ECH)
t=8.095 s (w ECH)

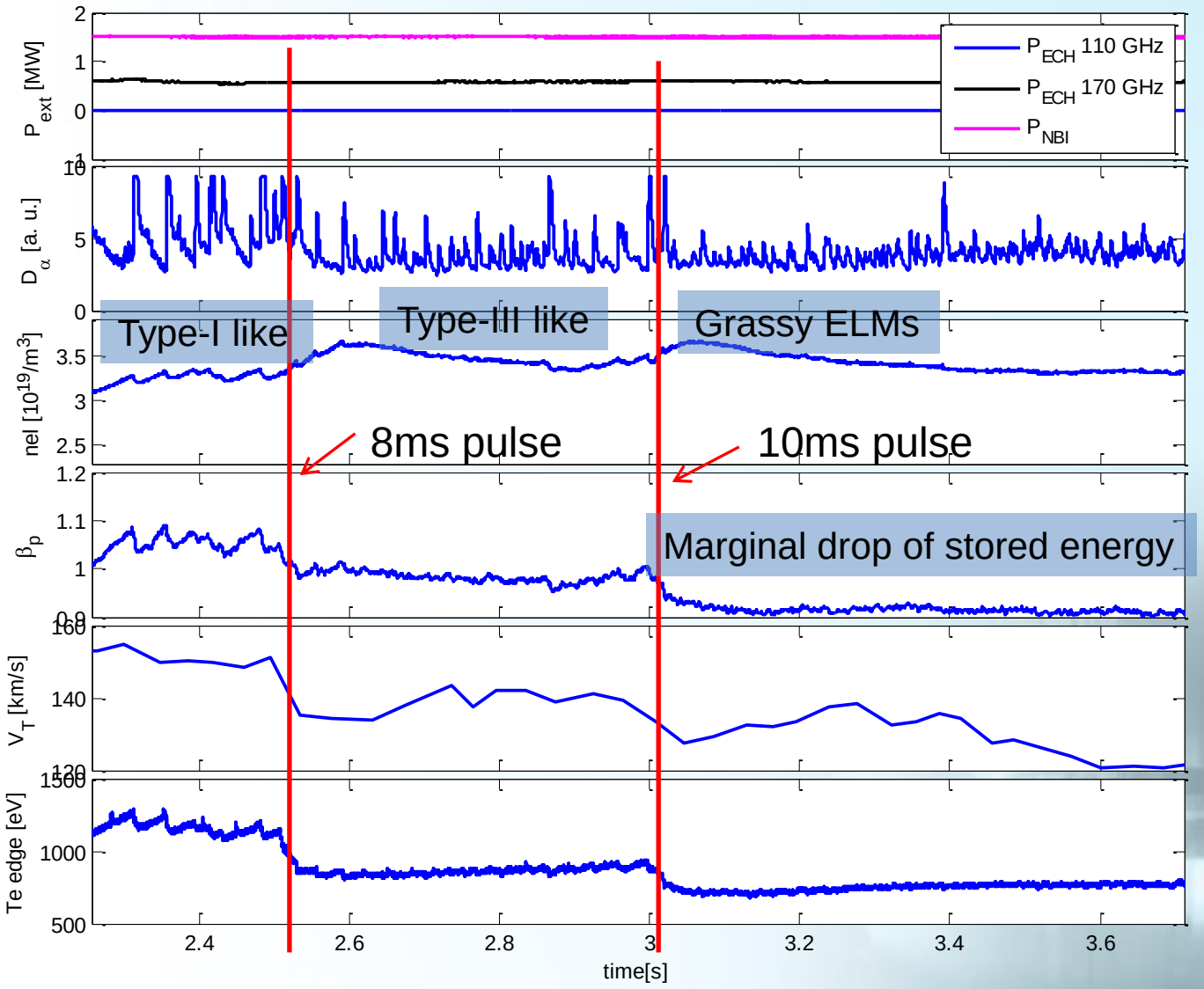


Large scatter in TS Te at SOL region



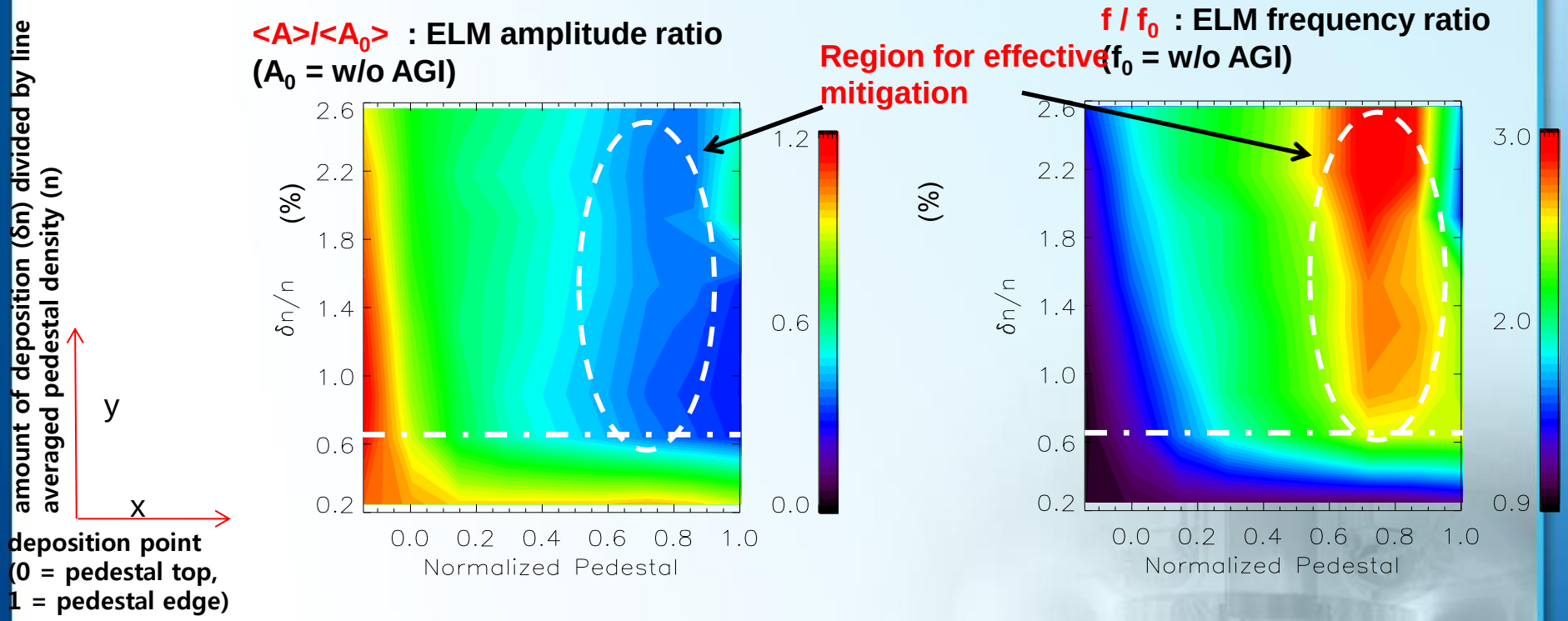
t=7.095 s (w/o ECH)
t=8.095 s (w ECH)

Temporary transition to grassy ELMs by Supersonic Molecular Beam Injection



A simple cellular automata model predicts best mitigation case with shallow deposition of SMBI

- Scanning SMBI deposition size and injection location



- Pedestal base injection effectively mitigates ELM with deposition size greater than a critical level.
- Critical deposition size is minimum number of grains which can drive a pedestal cell over hard limit.

Near term research plan in pedestal physics

- **Fast pedestal profile measurements**
  ELM-resolved full sets of pedestal profiles for detailed stability analysis
  Detailed cross-validation of all the dynamic parameters
  p_{ped} : TS(2012), profile reflectometry(2013), r-ECE(2010), Li-BES (2013), t-CES(2010)
  $j_{||}$ + E_r + $V_{p,t}$: **MSE**(2015), Li-Zeeman(2015), **p-CES** (2015), ECEI (2010)

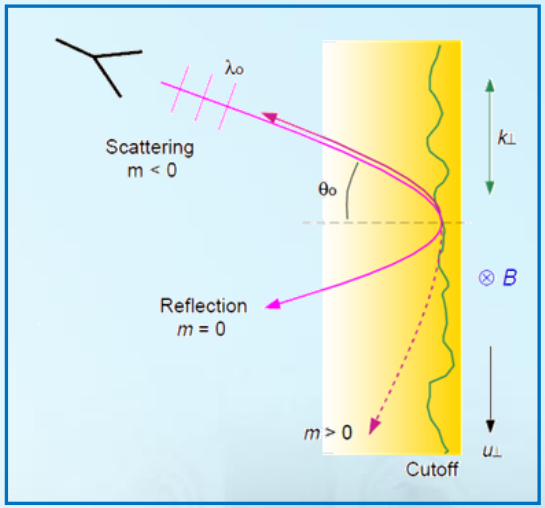
- **ELM physics/control in ITER relevant condition**
  Extension of ELM control technique to ITER based on physics understanding
  Validation of long-pulse RMP suppression in ITER Similar Shape
  Detailed measurements of profile & fluctuation change during ELM control
  Searching for small/no ELM regimes (drsep, I-mode, QH-mode, …)

- **Transport in pedestal region**
  ELM dynamics and identification of background turbulence in the pedestal region
  Validated local measurements of $k_{||}$, $k_{\perp}$ & $v_{\perp}$: DBS, MIR and D-BES
  Identification of background transport (Micro-tearing, Flow-shear ITG, k-Ballooning, …)
  Relation between fluctuations and transport : radial particle & thermal pinches

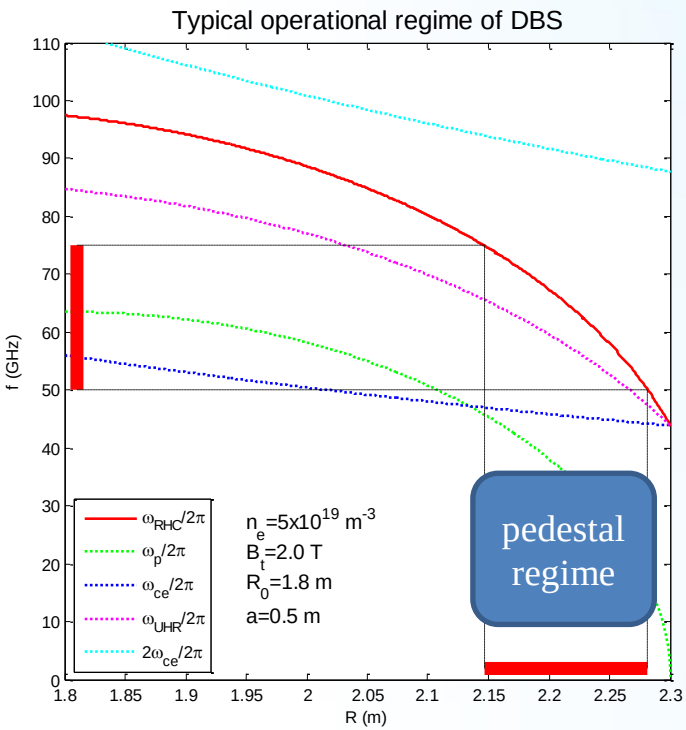
- **L-H transition Physics**
  Mechanism for L-H & H-L transition
  Effect on L-H transition by SMBI & RMP : minimizing power threshold in ITER
  I-phase during H-L back transition : slow back-transition

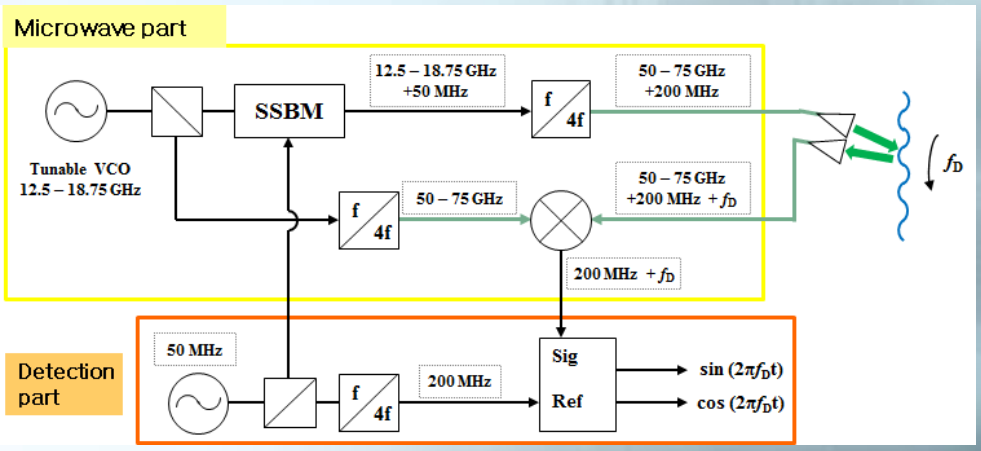
KSTAR Doppler Reflectometry (2014)

- **V-band X-mode Doppler Back-Scattering (DBS) System**
  - **Heterodyne system using a single side band modulator (SSBM)**
  - **Frequency regime in the plasma edge : V-band (50-75 GHz)**
  - **Antenna tilt angle Θ_o : 10°-12°**
  - **max. $k_\perp$ = 5.5-6.5 cm^{-1} @ 75 GHz**
  - **f_D ~ 1.7-2.6 MHz @ $u_\perp$ ~20-30 km/s (H-mode)**



- $k_\perp \approx 2k_o \sin\Theta_o$
- $\omega_D \approx u_\perp k_\perp$
- $u_\perp = v_{E\times B} + v_{ph}$
- $E_r \approx -v_{E\times B} B$



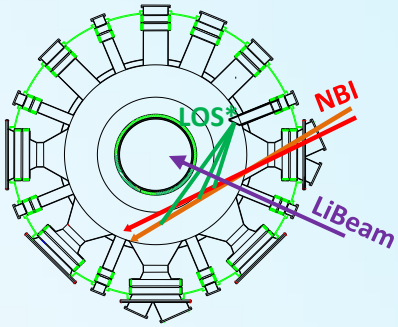


Lithium-beam Zeeman polarimetry (2015)

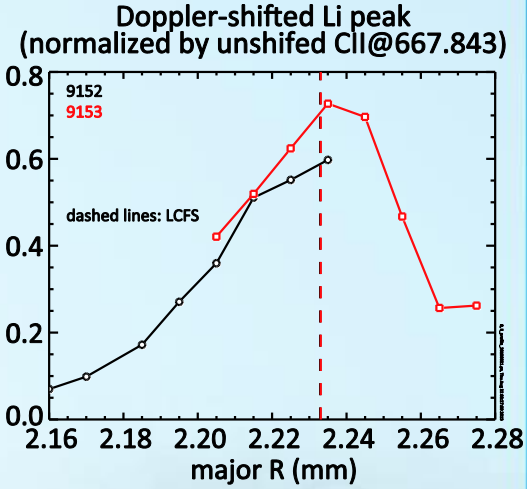
- KSTAR Li-beam system was successfully commissioned in 2013.

Parameter	
Diameter	2 cm (FWHM / fully focused in the plasma), 10 cm (defocused)
Current	2-4 mA
Energy	60 keV
Pulse Length	20 s
Species	Lithium (possible upgrade to Sodium)

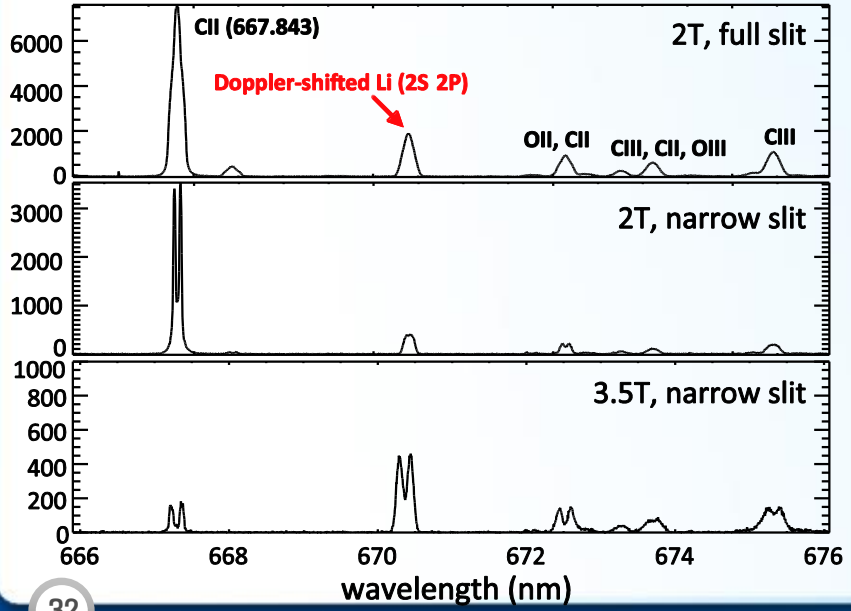
- The Li-Zeeman emission is at its maximum around the pedestal region (R=2.22–2.25 m).

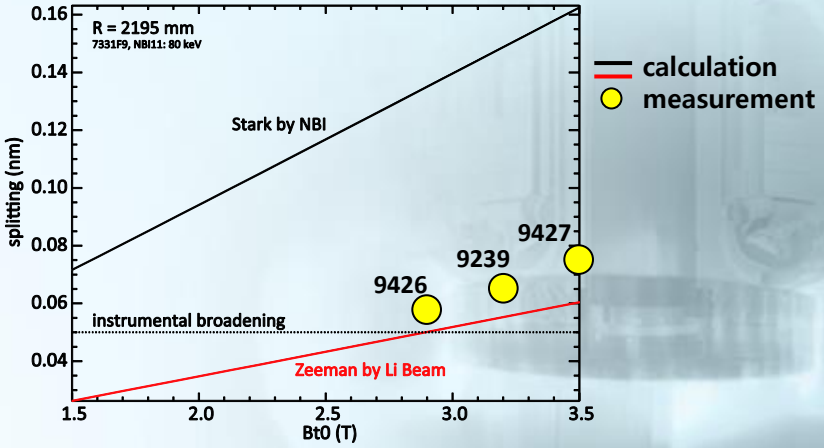


*Lines of sight in 2013 are horizontal at the midplane.



- The Zeeman split greater than the instrumental broadening was observed with Bt > 2.8T. Li-beam emission.





- For the Zeeman polarimetry to measure the edge J(r), vertical views are more preferred.