Overview of KSTAR Results in 2013/2014 Campaign

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on behalf of

KSTAR Team and collaborators

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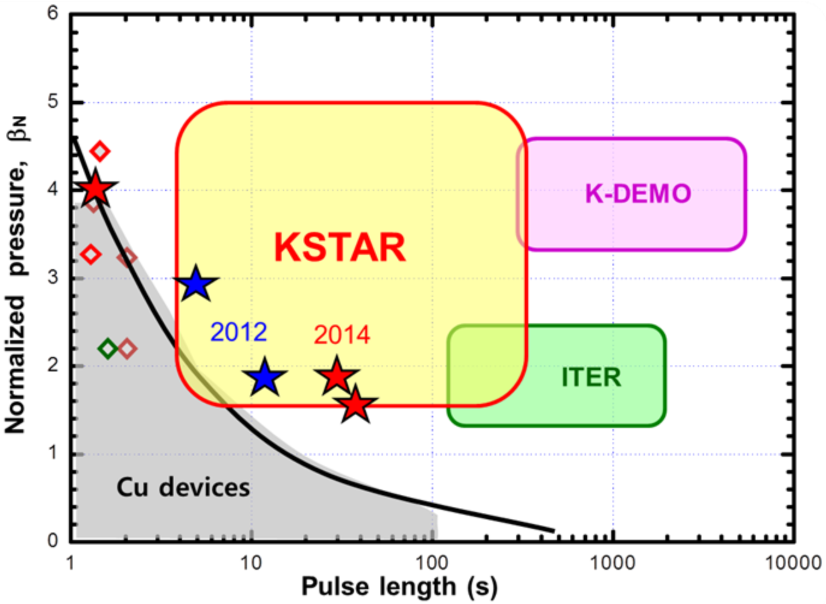
KSTAR

NFRI 국가핵융합연구소 National Fusion Research Institute

Contents

Original Mission and Key Parameters of KSTAR

- **KSTAR missions**
  - To achieve the **superconducting tokamak construction and operation experiences**
  - To explore the **physics and technologies of high performance steady-state operation** that are essential for ITER and fusion reactor



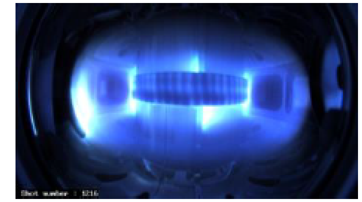
- **Achieved parameters**

Parameters	Designed	Achieved
Major radius, R_0	1.8 m	1.8 m
Minor radius, a	0.5 m	0.5 m
Elongation, κ	2.0	1.8
Triangularity, δ	0.8	0.8
Plasma shape	DN, SN	DN, SN
Plasma current, I_P	2.0 MA	1.0 MA
Toroidal field, B_0	3.5 T	3.5 T
H-mode length	300 s	40 s
Normalized beta, β_N	5.0	4.0
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD	~ 28 MW	~ 7 MW
PFC	C, CFC or W	C

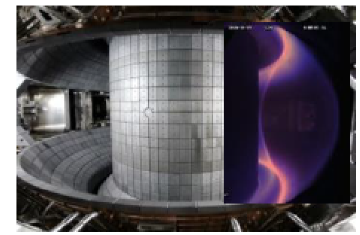
Machine design is optimized for advanced target operation
Strong shaping, Passive plates, low TF ripple, …

Recent Major Milestones of KSTAR

- 2008: First plasma at the first trial and successful X2 ECH pre-ionization. (contribute to ITER startup).
  (Ip >100 kA, B_T ~1.5 T, 84GHz ECH)



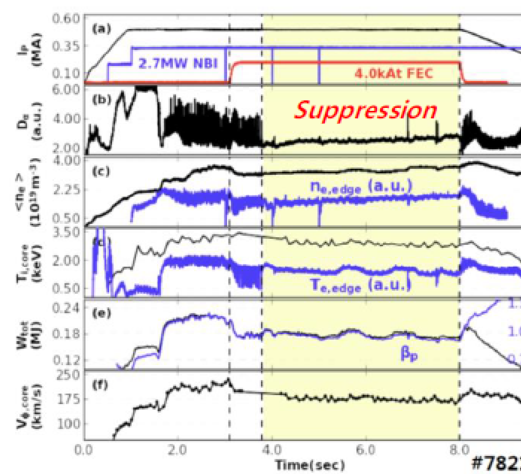
- 2010: Successful H-mode in superconducting tokamak. (start proposal-based experiments)
  (Ip_{Hmode} ~0.6 MA, P_{NBI}~1 MW)



- 2011: Successful ELM suppression at low toroidal mode. (contribute to ITER ELM control)
  (ELM suppression at n=1, 2 magnetic perturbation)

- 2012: Stationary H-mode and surpass n=1 ideal no-wall limit. (potential of advanced plasma)
  (t_{Hmode} > 16s @ 0.6 MA, β_N~2.9, β_N/ li > 4.1)

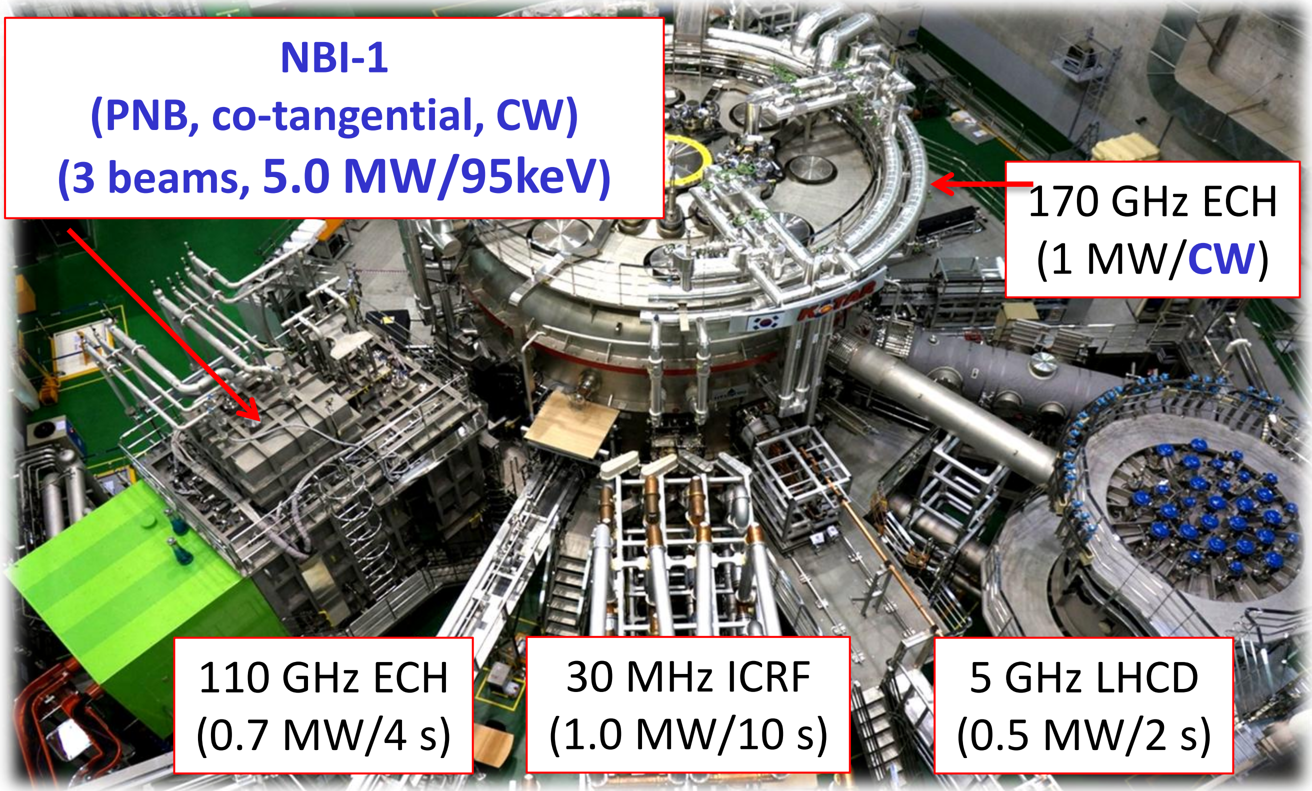
- 2013: Demonstrate very low intrinsic error field and TF ripple (KSTAR machine uniqueness) *($\delta B/B$ ~10^{-5})*

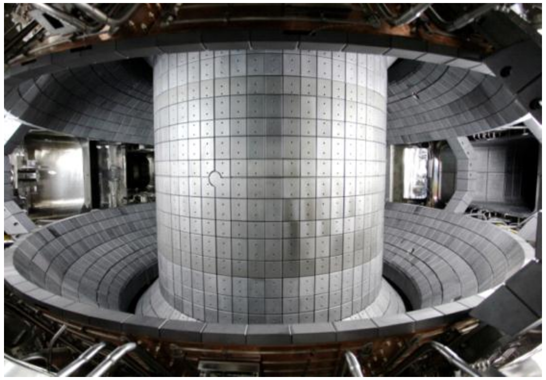


Contents

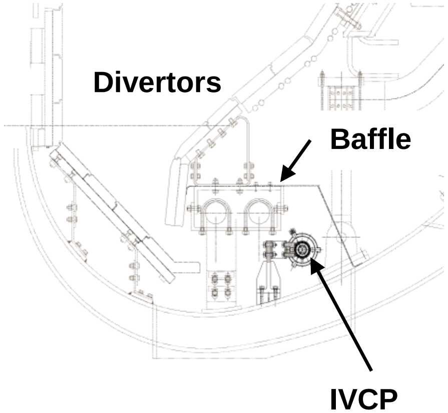
- **Extension of Operation Boundary**
  - Upgrade of KSTAR heating system
  - Long-pulse extension of H-mode duration
  - High Beta operation
- Advances of Tokamak Physics Research
  - Error field identification
  - Mitigation and Suppression of ELM
  - H-mode & rotation physics
- Future Plan

Current Machine Status (2014)
: long-pulse compatible NBCD and ECCD systems





Full Graphite PFCs
(with Water cooling pipe)

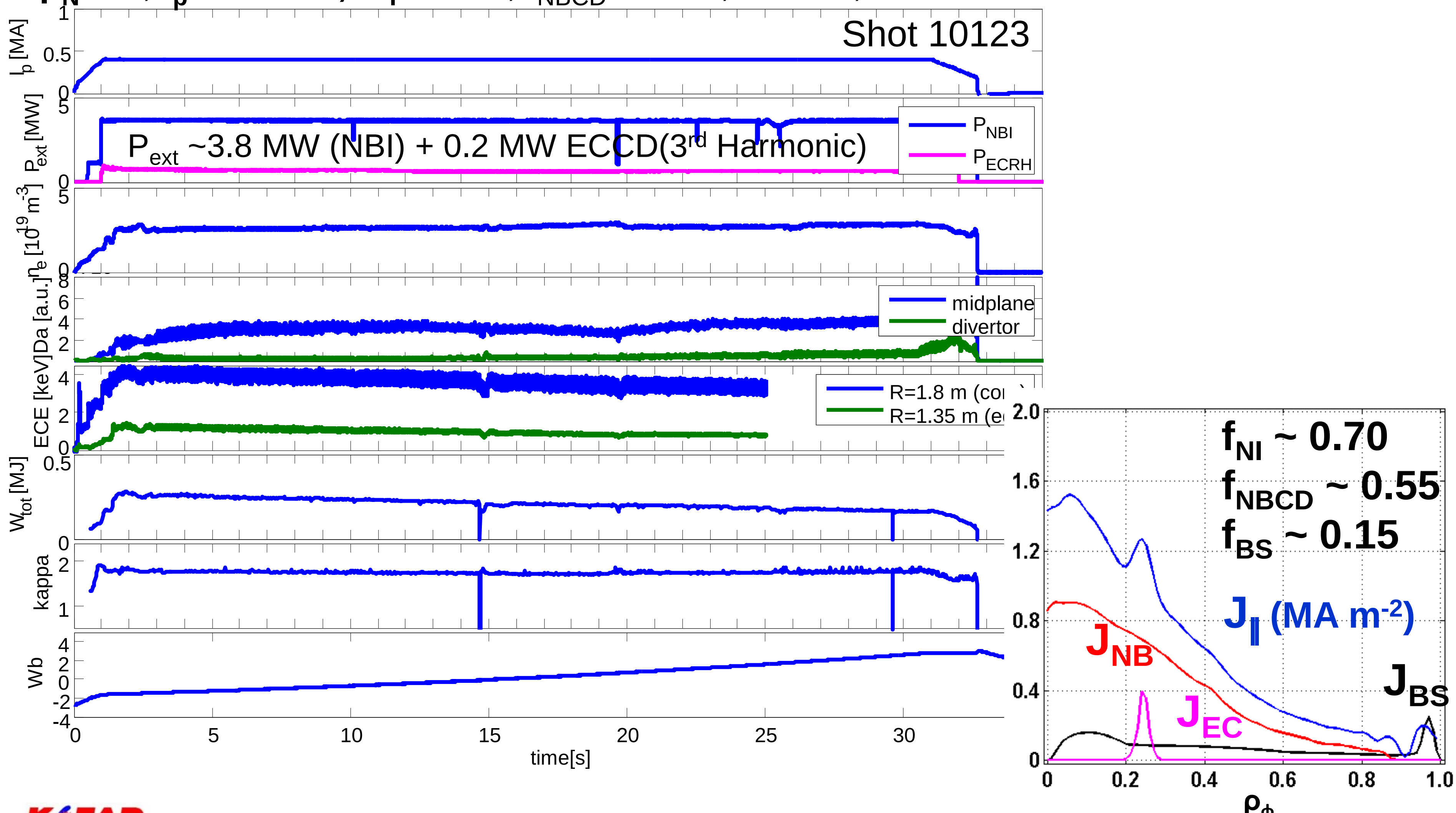


in-situ cryo-panel is ready

Long-pulse H-mode discharge (~ 30 s) achieved in 2014 campaign

Successful Extension of H-mode pulse-length upto 30 sec

β_N ~ 2, I_p =0.4 MA, B_T=2.0 T, f_{NBCD} ~ 0.55, κ ~ 1.8, δ ~ 0.6

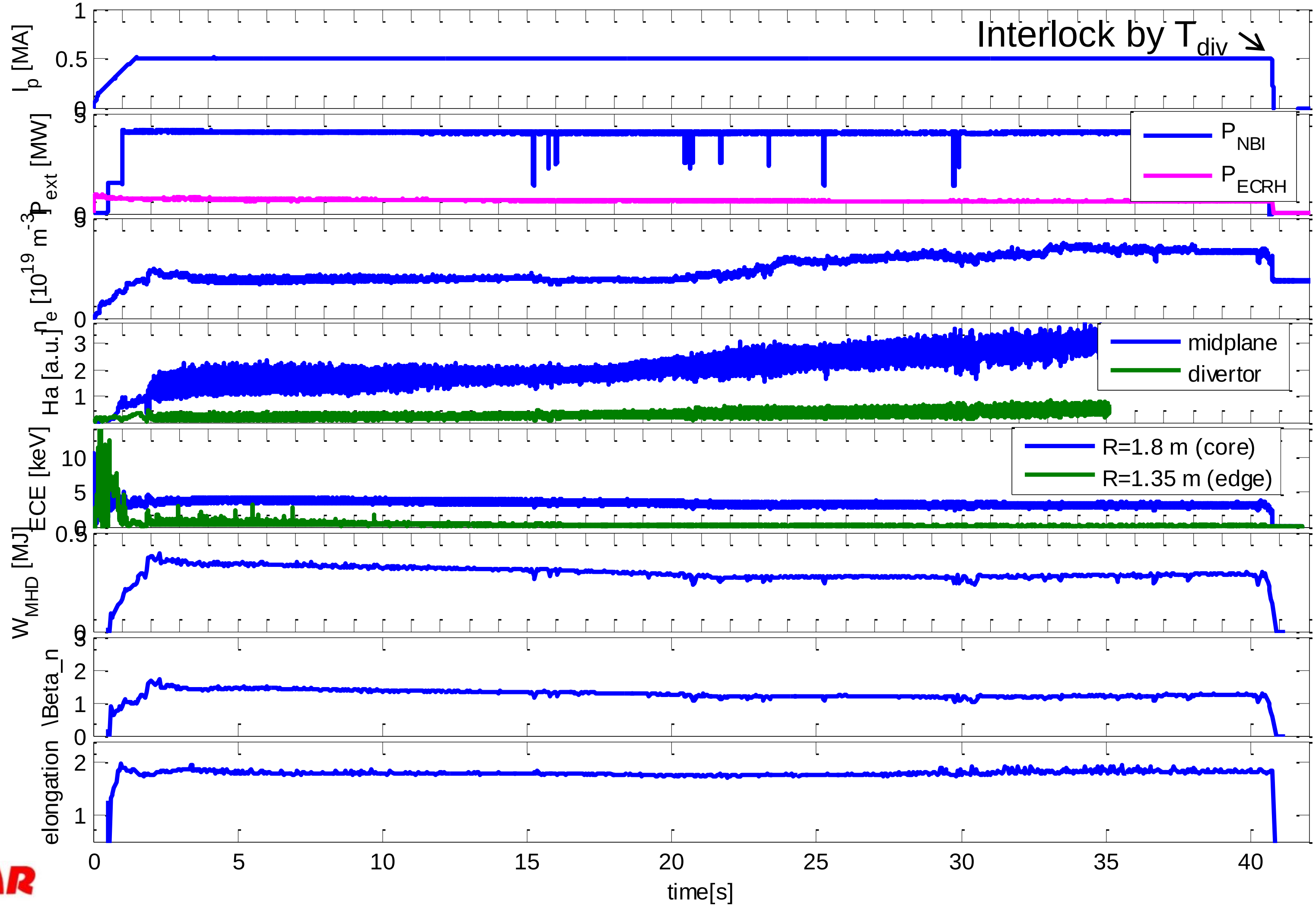


Pulse-length is further increased (~40 s) adding more ECCD and using in-vessel cryo-pump

Successful extension of H-mode pulse-length upto 40 sec

I_p =0.5 MA, B_T=3.0 T, **P_{ECCD}~ 0.8 MW**, P_{NBI}~ 3.8 MW, f_{NBCD} ~ 0.50, β_N ~ 1.4

Experiments for longer pulse is planned using Motor-Generator in this campaign



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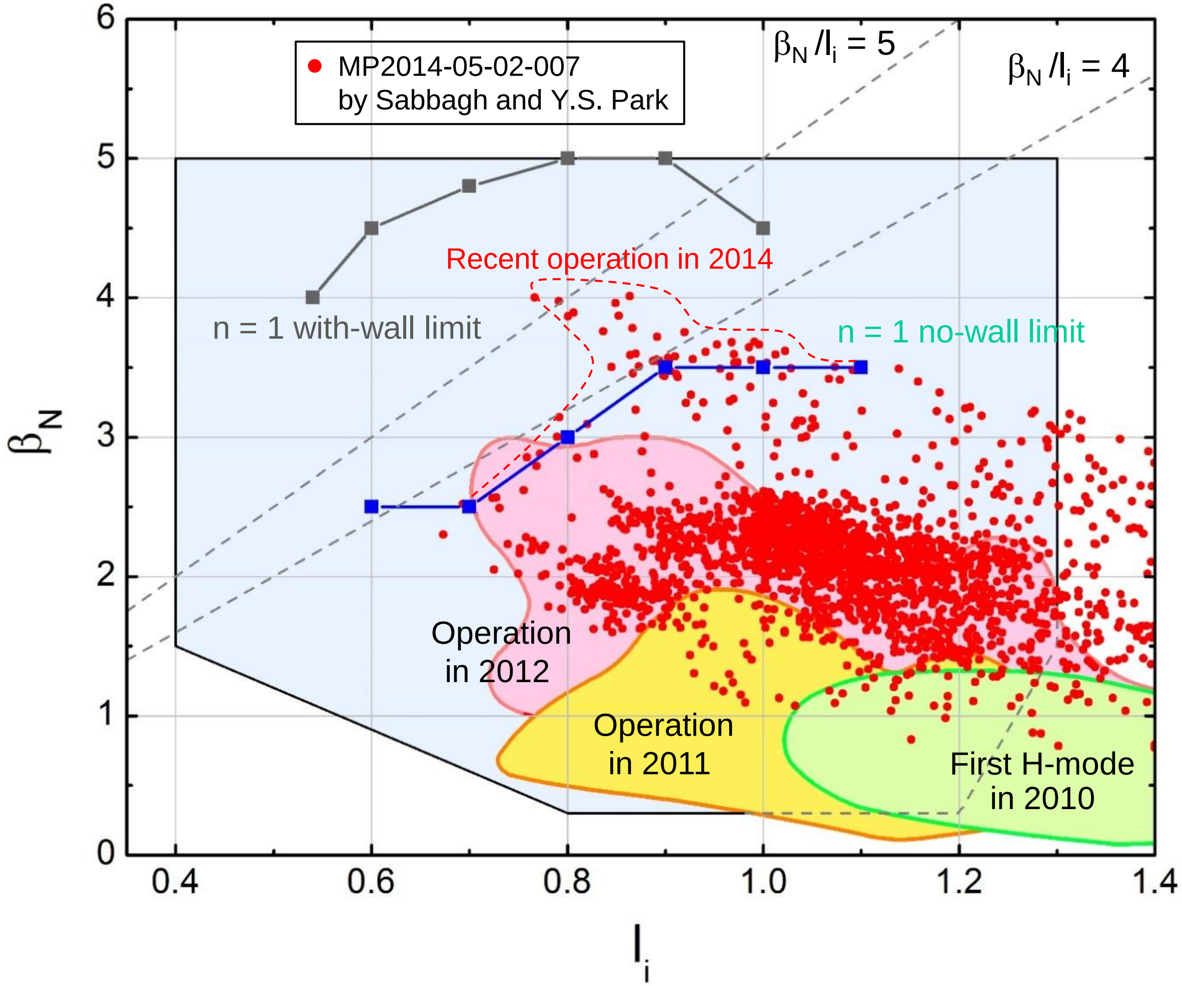
High Beta above no-wall limit is achieved transiently by optimal I_p/B_T and with P_{ext} ~ 3 MW

Sabbagh, EX/1-4



- **By Early heating for low l_i**

(Better Ip ramp-up scenario)

- **Optimizing B_T & I_p**
  B_T in range 0.9-1.5 T
  I_p in range 0.4-0.7 MA

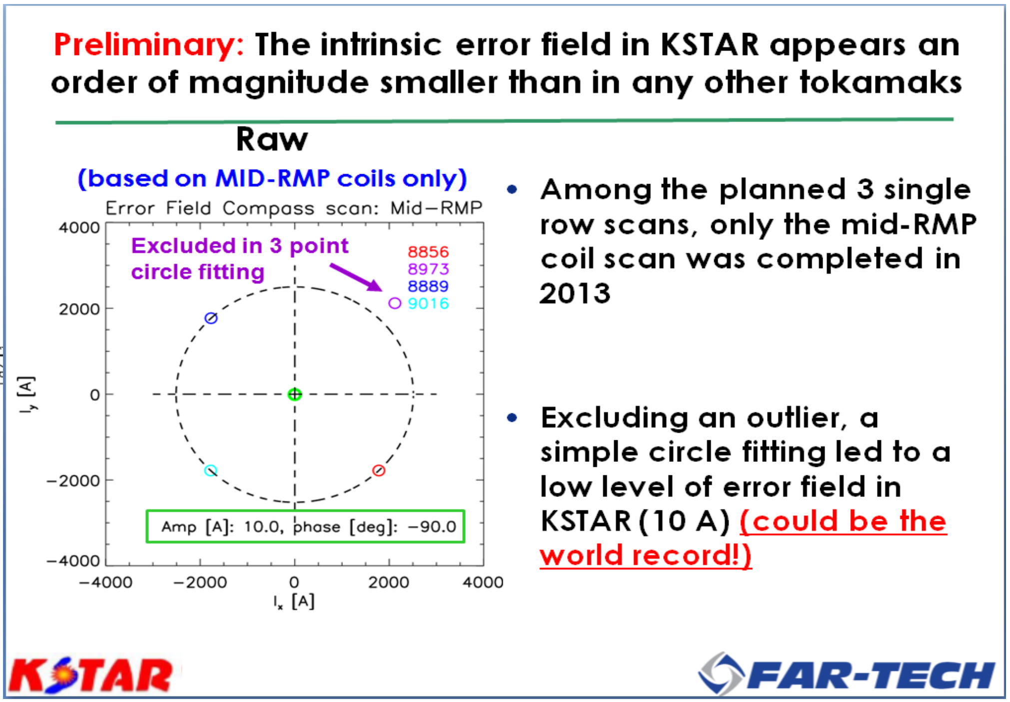
- **Prior published maximum was β_N=2.9**

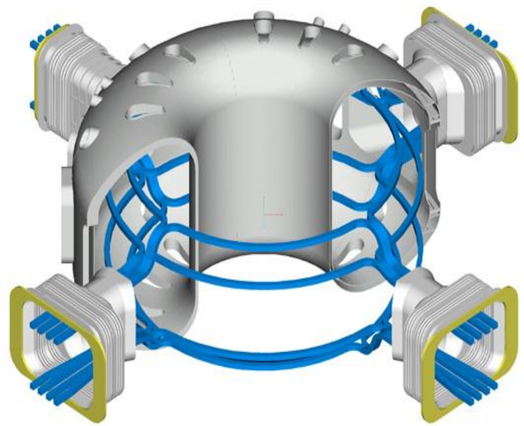
- **Present maximum β_N~4**

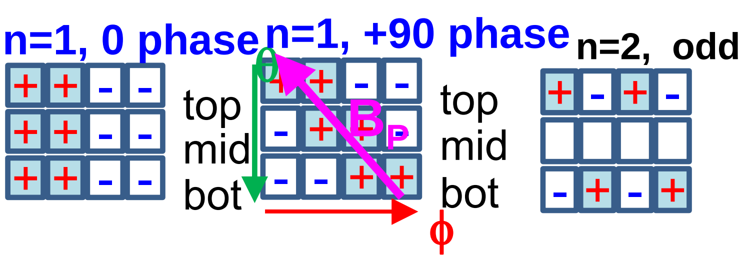
Contents

Unique features of KSTAR : Ideal machine for 3D & rotation physics

- **Intrinsically low toroidal ripple and low error field also**
  - Error field : very low value was detected (**$\delta B_{m,1}/B_0$~10^{-5}**)
- **Modular 3D field coils (3 polidal rows / 4 toroidal column of coils)**
  - Provide flexible poloidal spectra of low n magnetic perturbations



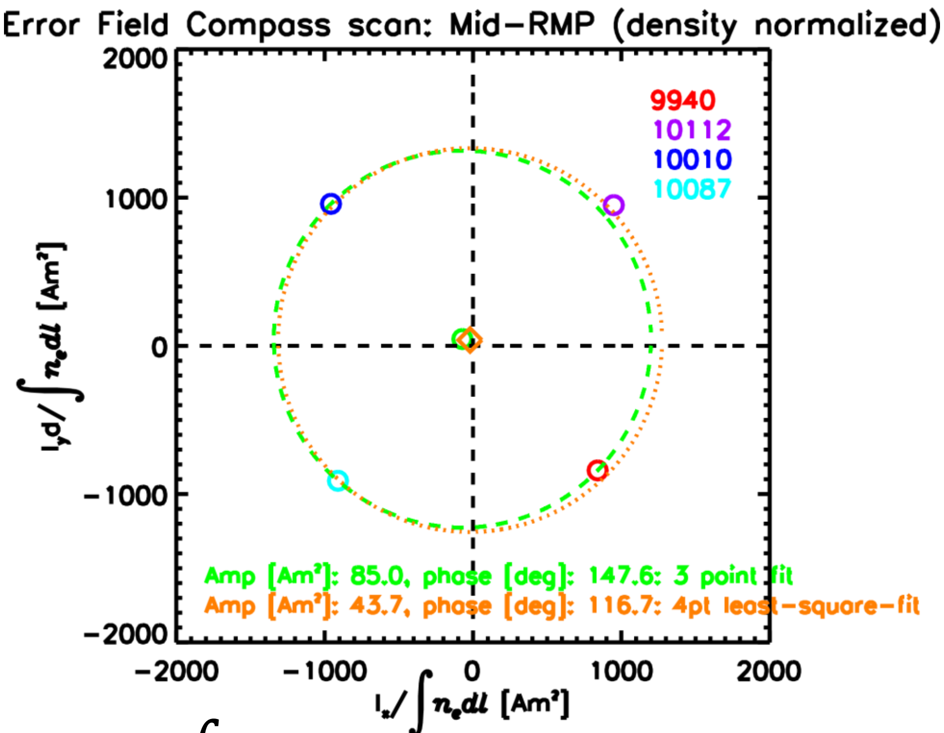




Full angle scan shows that the error field would be lower than sub Gauss (resonant field at q=2/1 based on IPEC calculations)

A complete set of compass scan using mid-RMP coils in 2014 again confirms the record-low intrinsic EF in KSTAR

KSTAR: $\langle \delta B_{m/n=2/1} \rangle / B_0 \leq 10^{-5}$ (typically 10^{-4} in other devices)



$$\int n_e dl [E19 m^{-2}] = 1.5$$

Device [References]	Error Field*
COMPASS-C [Hender92NF, LaHaye92PFB]	$B_{r21}/B_T\|_a \approx 1\times10^{-5}$
DIII-D [Scoville91NF, LaHaye92PFB]	$B_{r21}/B_T\|_a \approx 1.7\times10^{-4}$
JET [Fishpool94NF]	$B_{m=2,n=+/-1}/B_T \leq 1.7\times10^{-4}$
COMPASS-D [Buttery99NF]	$B_{pen}/B_T \approx 1\times10^{-4}$ (Estimated from Figure 5 of [Buttery99NF])
Alcator C-Mod [Wolfe05PoP]	$B_{21}^{intrinsic}/B \approx 6\times10^{-5}$ (Estimated from Figure 4 of [Wolfe05PoP])
MAST [Howell07NF]	$B_{21}/B_T \sim 1.3\times10^{-4}$
NSTX [Menard10NF]	$\tilde{B}/B_T \sim 2\times10^{-4}$ (Estimated from Figure 6 of [Menard10NF])

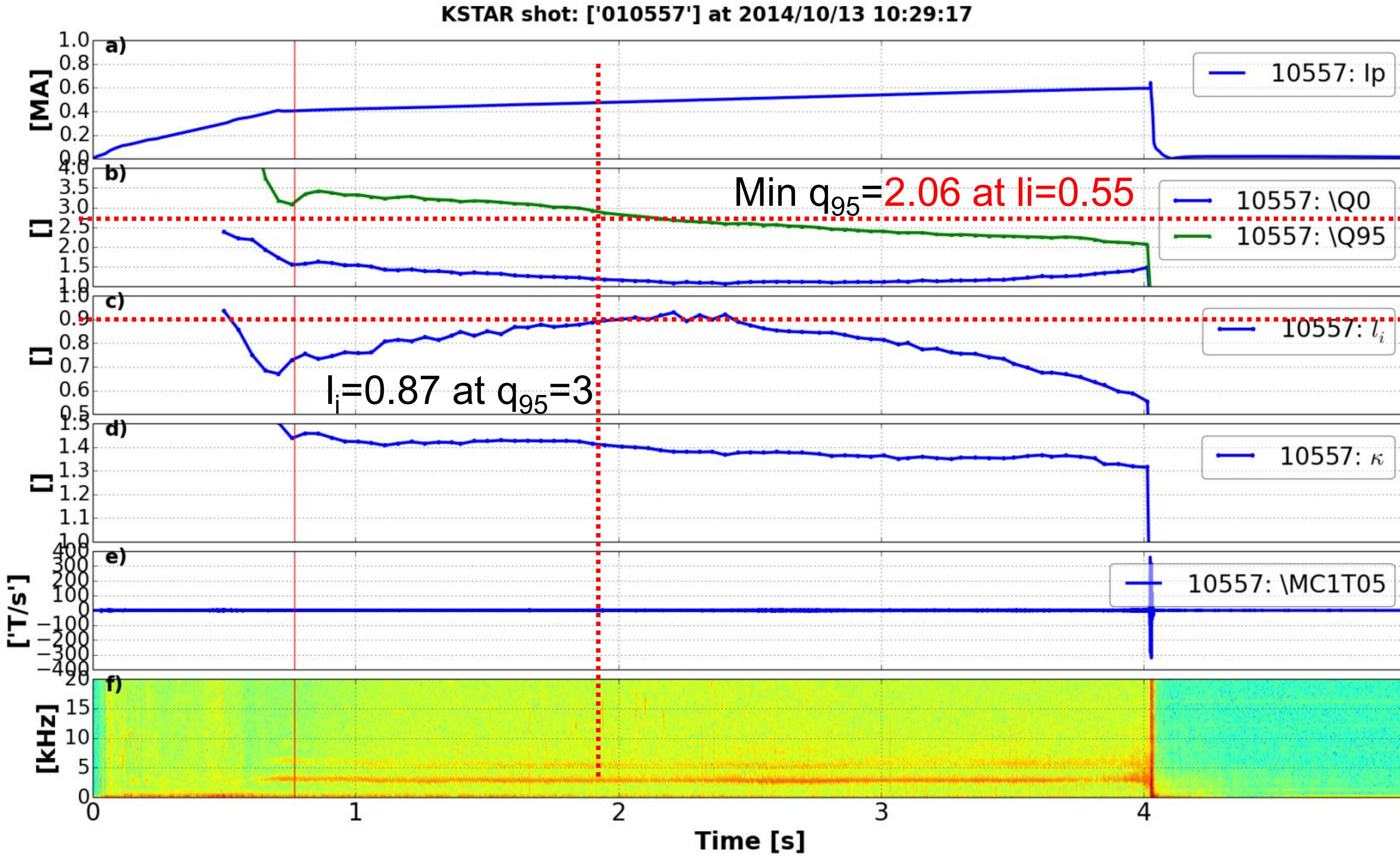
*The exact definitions slightly differ, as referenced

Purest plasma response against externally applied non-axisymmetric fields in KSTAR

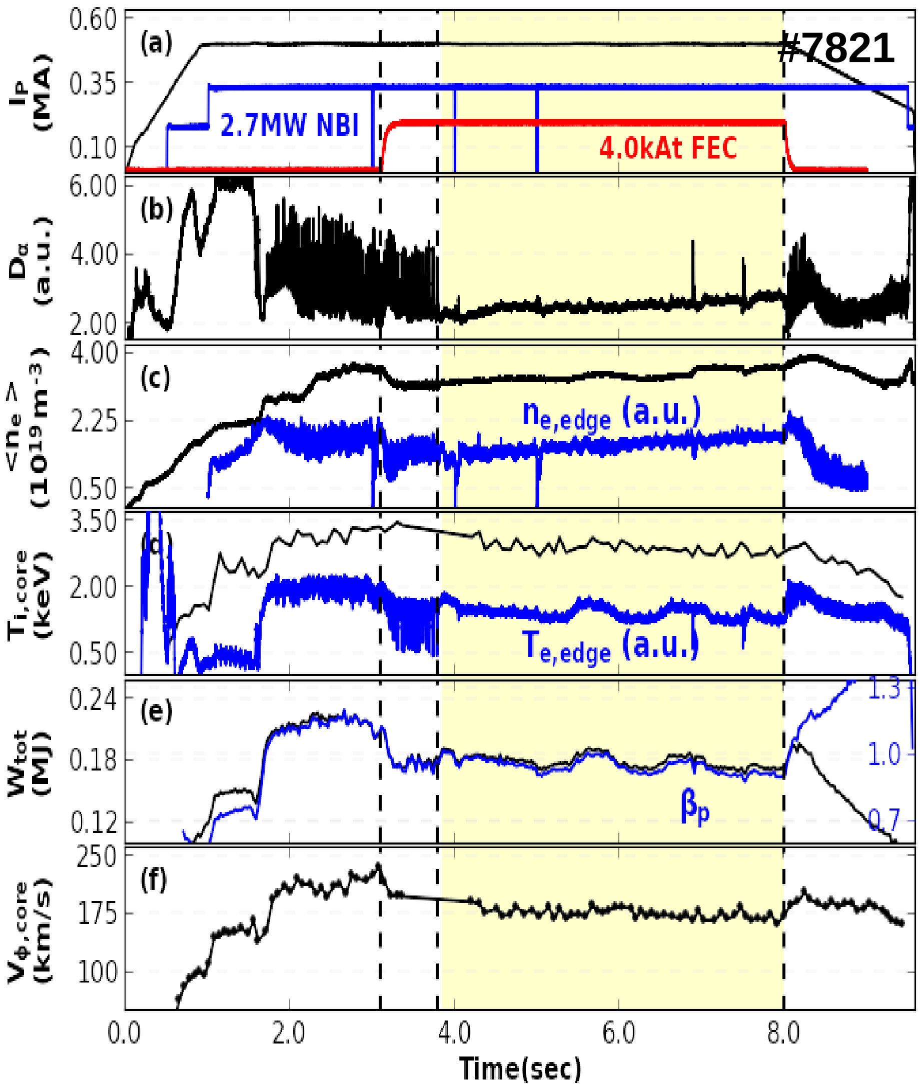
KSTAR

The presence of low EF is also supported by accessing low q_{95} Ohmic discharges without any external means

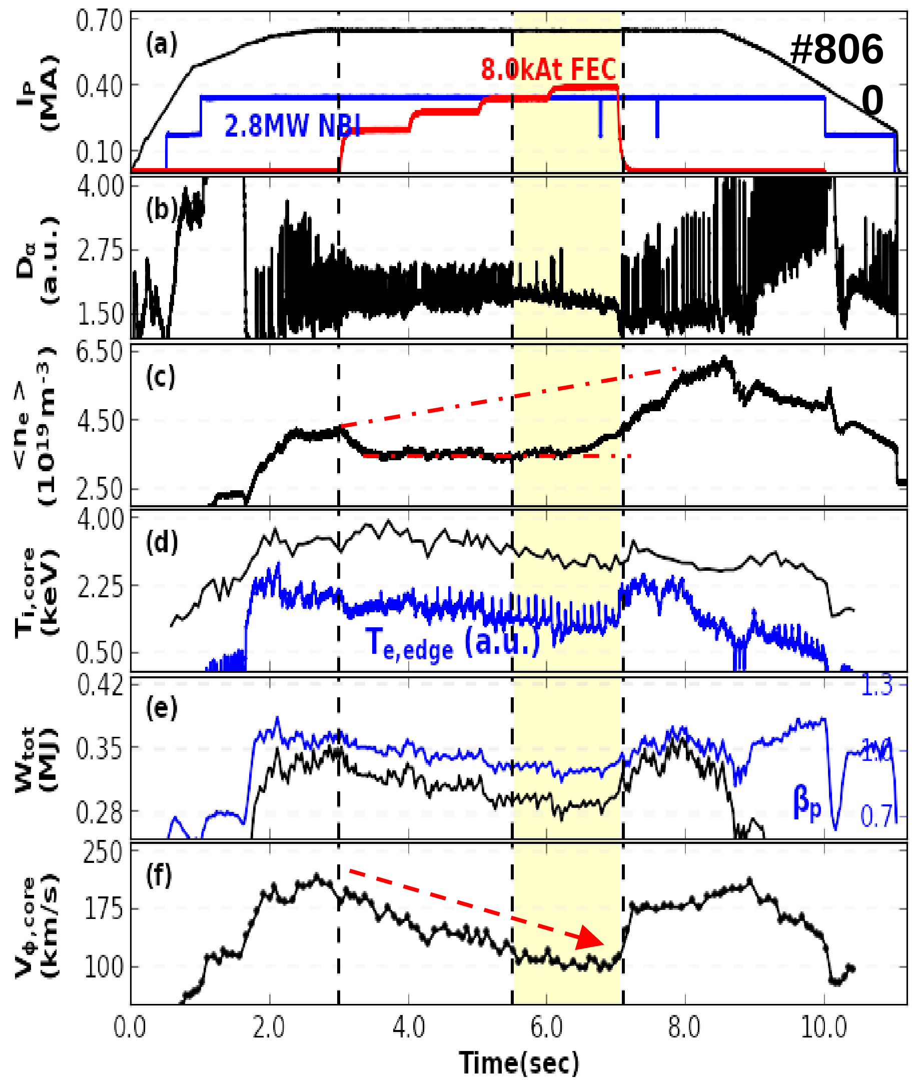
Passing q_{95}=3 (li=1.0) without (violent)MHD



ELM-suppressions have been demonstrated using both n=1 or n=2 RMP with specific q_{95} windows



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

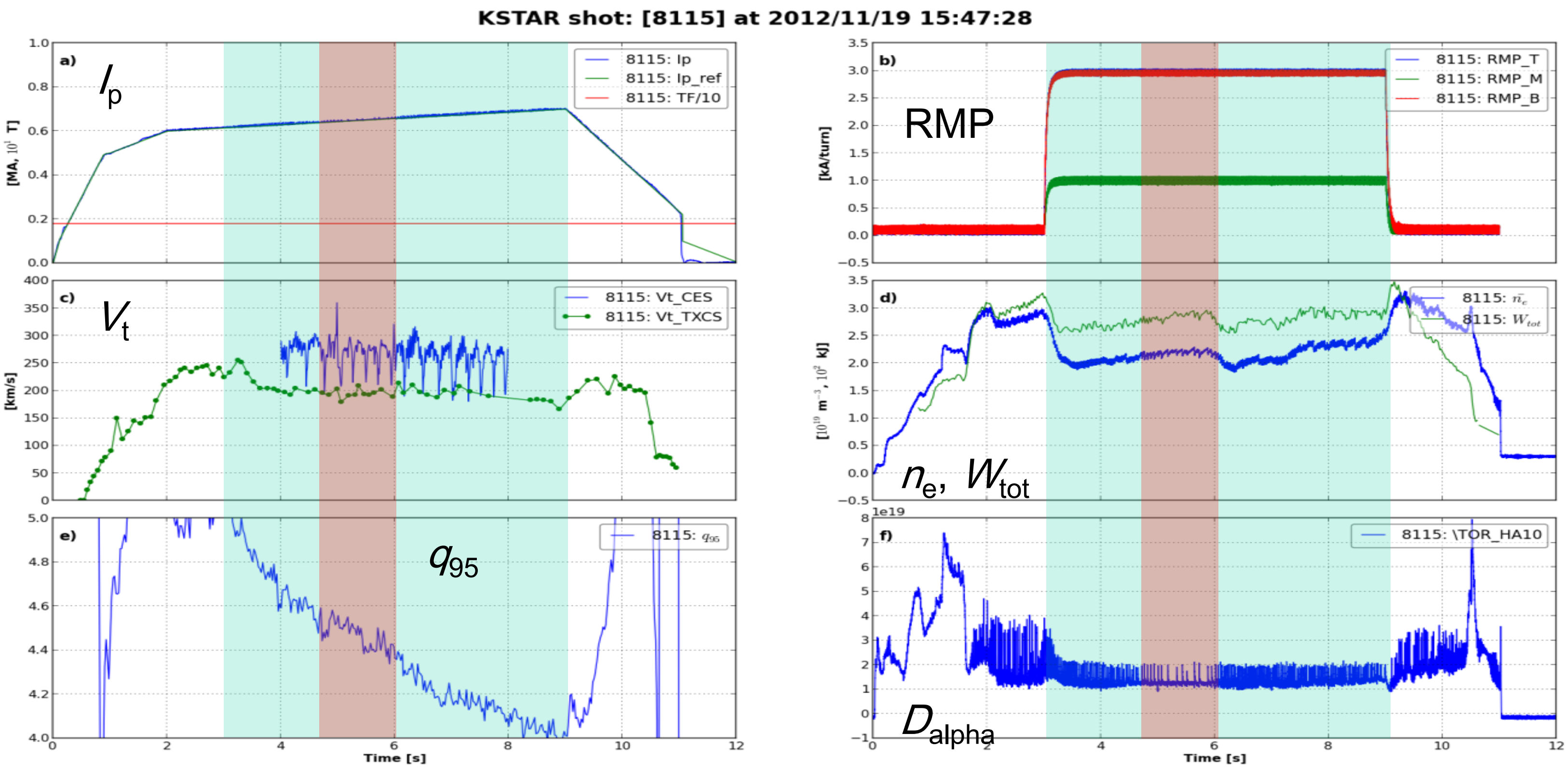


n=2 RMP (mid-FEC only) at q_{95}~4.1

KSTAR

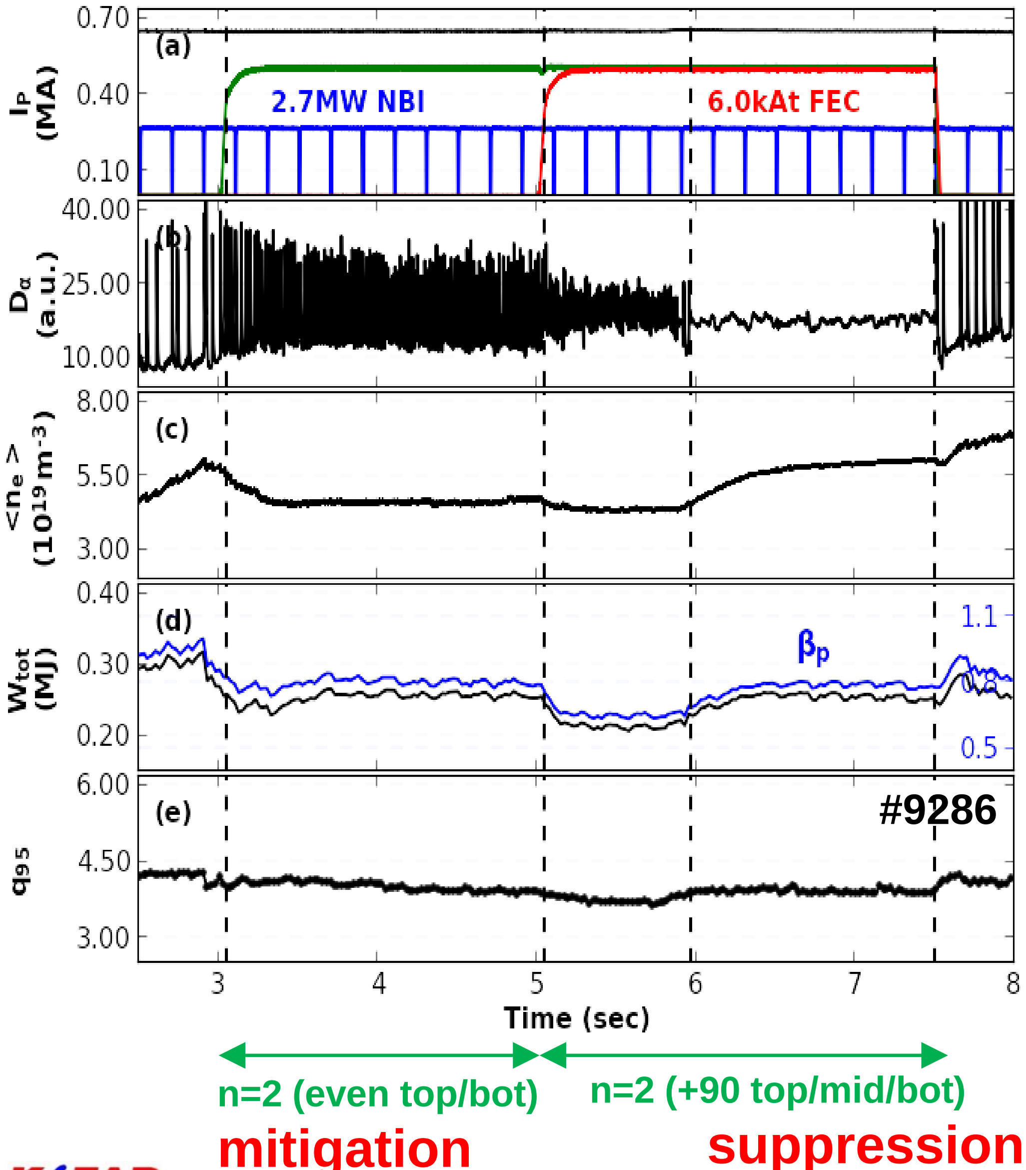
ELM suppression is transiently achieved also at intermediate q_{95} ~ 4.5 combining of n=1 & 2 RMPs

- n=1 (middle) and n=2 (top/bottom)
- The q-window (4.3~4.5) in ELM suppression is observed during I_p scan (q-scan).
- **NB : q~6 at n=1, q~3.7 at n=2, q~4.5 at n=1+2 (wide q_{95} window)**



Extending q_{95} window space at ELM suppression

Depending on the n=2 RMP configuration, either suppression or mitigation of ELMs could be selected



Jeon, EX/1-5

#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

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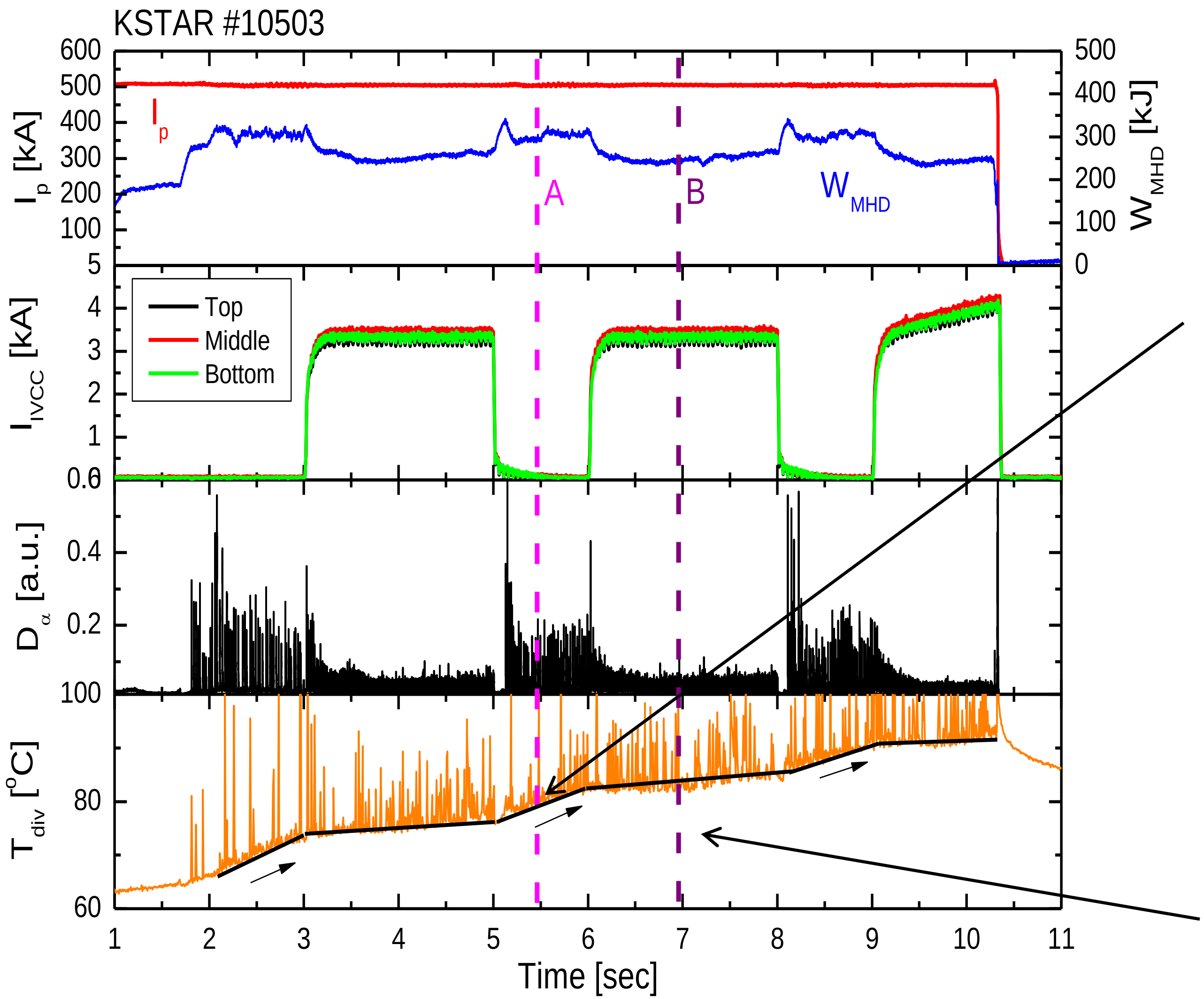
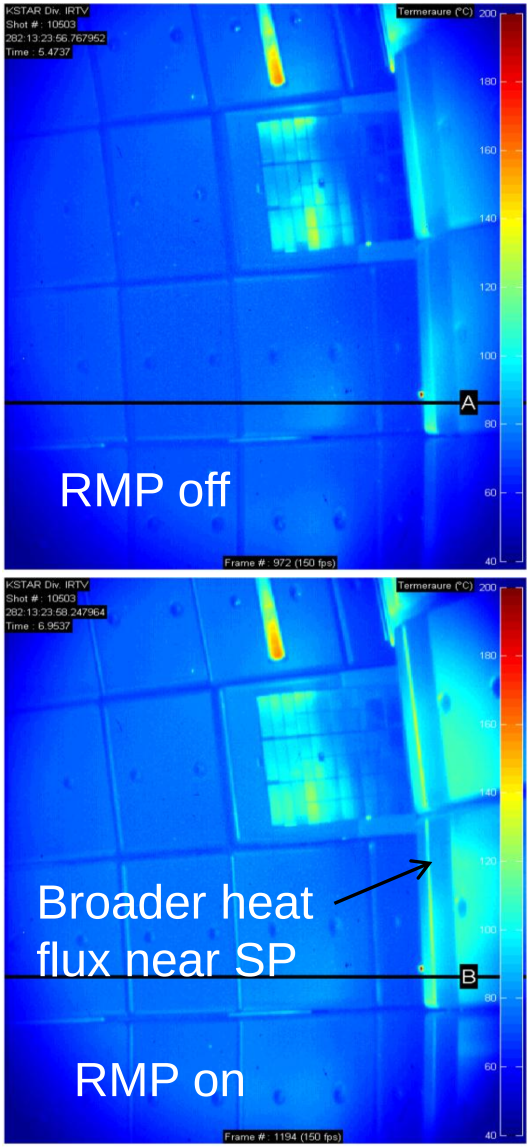
Reduced Heat flux at outer divertor is confirmed for RMP (n=1) ELM mitigation with newly installed IRTV



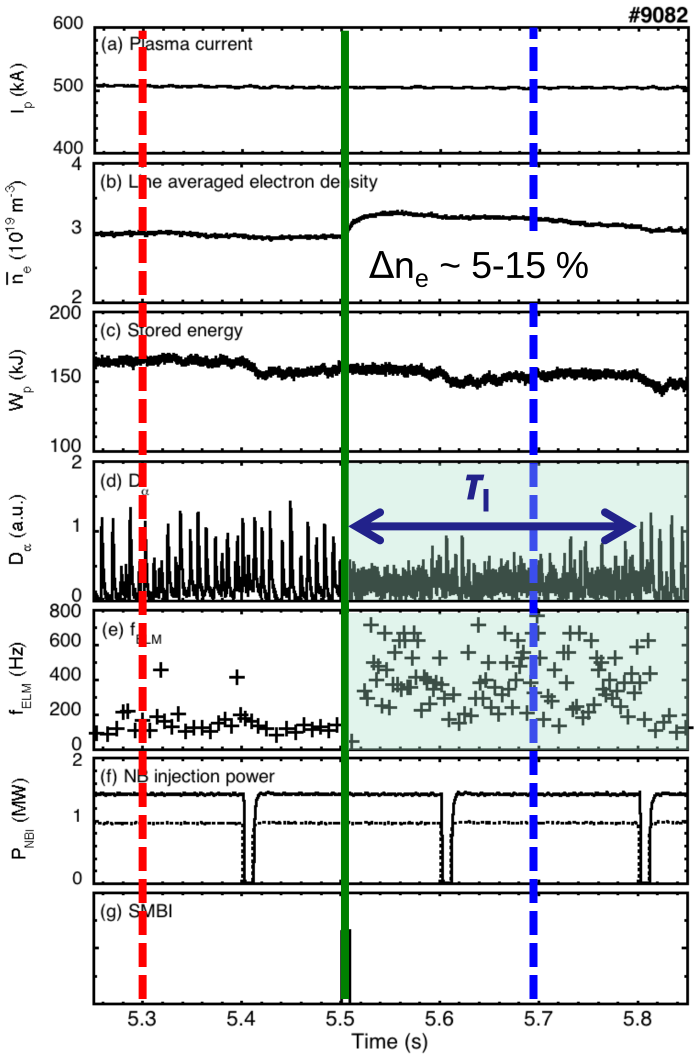
IRTV on outer divertor

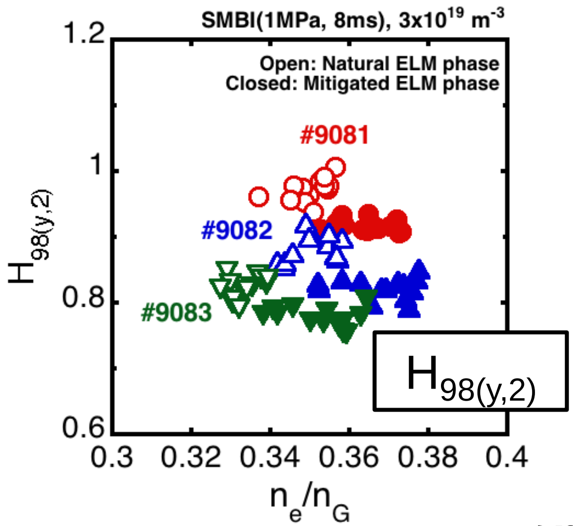


ELM mitigation by Supersonic Molecular Beam injection with small confinement degradation

- **Typical features of ELM mitigation by SMBI**

H. Lee, EX/P8-9





- **Characteristics of ELM mitigation by SMBI**
  - Δn_e ~ 5-15 % after SMBI
  - τ_I ~ 200-400 ms
  - $f_{ELM}^{SMBI}/f_{ELM}^{0}$ ~ 2.0-3.1

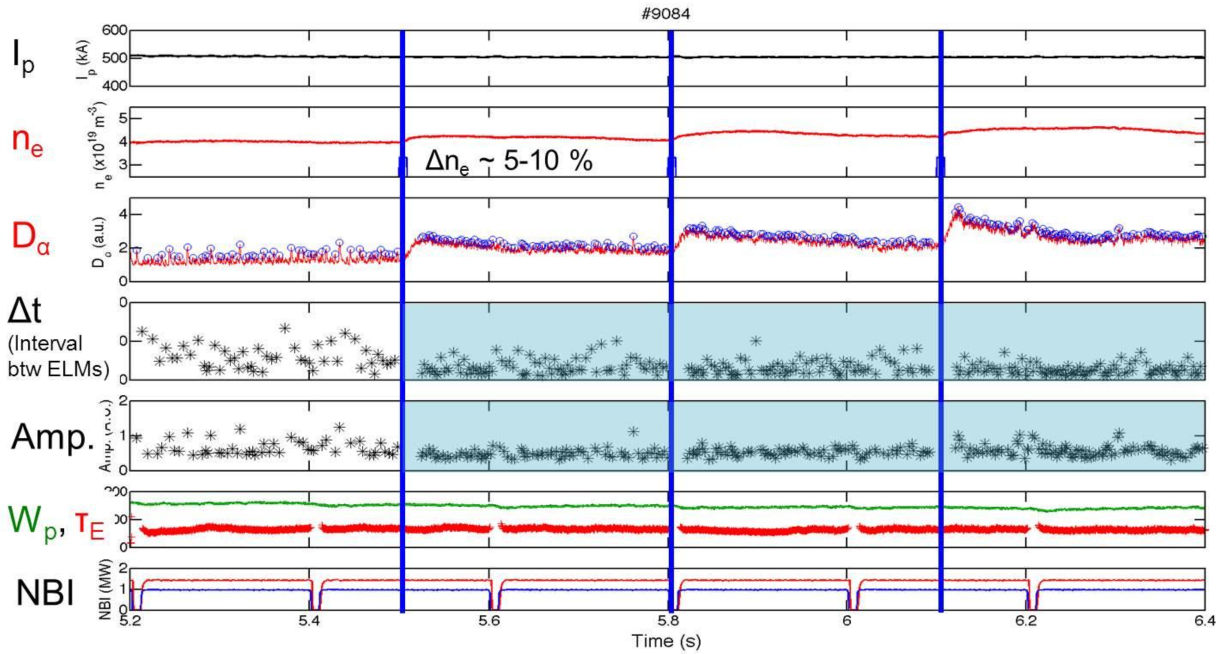
- **Degradation of global confinement is insignificant**
  - $H_{98(y,2)}$: 0.9-1.0 → 0.8-1.0

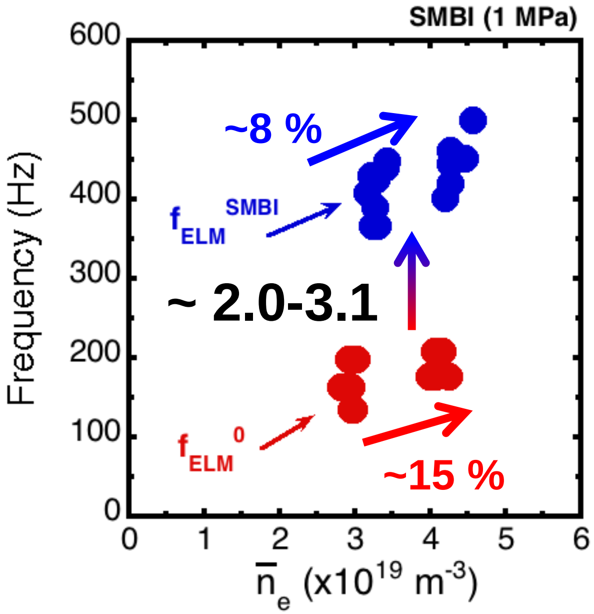
(Too small for ELM type transition)

KSTAR

ELM mitigation sustained by multiple SMB injection

H. Lee, EX/P8-9





- f_{ELM}^0 ~ 180 Hz , f_{ELM}^{SMBI} ~ 430 Hz
  → f_{ELM}^{SMBI}/f_{ELM}^0 ~ 2.4

➢ Δn_e ~ 5-15 %

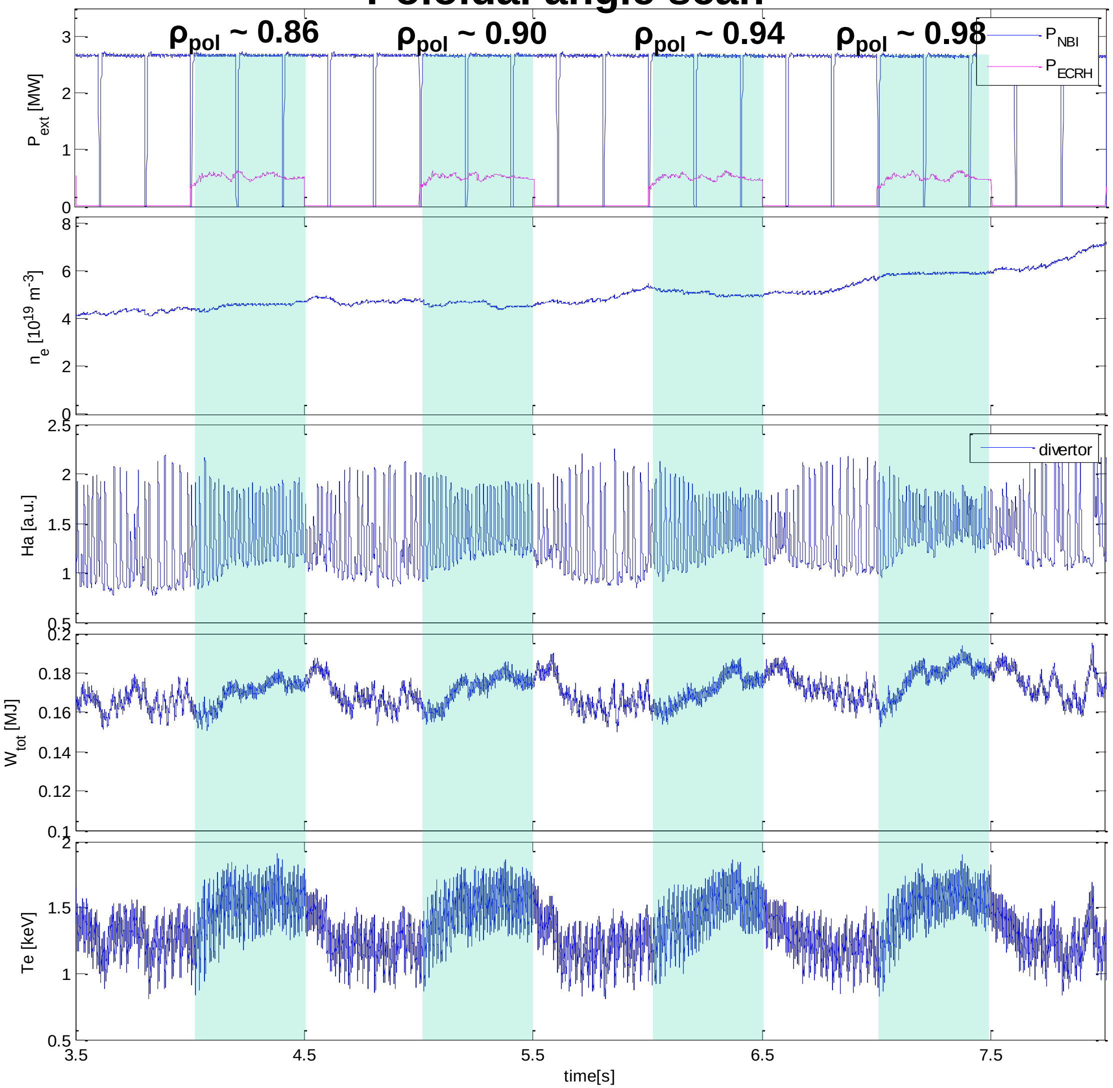
➢ Change of f_{ELM}^0 with 30% of n_e increase ~ 15 %

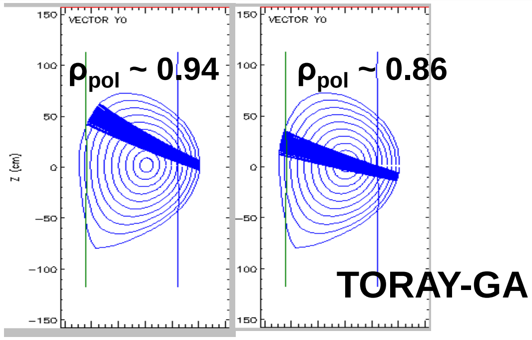
➢ f_{ELM}^{SMBI} ~ 2.0-3.0xf_{ELM}^0

➢ **Change in f_{ELM} owing to SMBI is much larger than that due to increase in n_e**

Strong ELM mitigation (~ x10) observed also by injecting ECH at pedestal

Poloidal angle scan





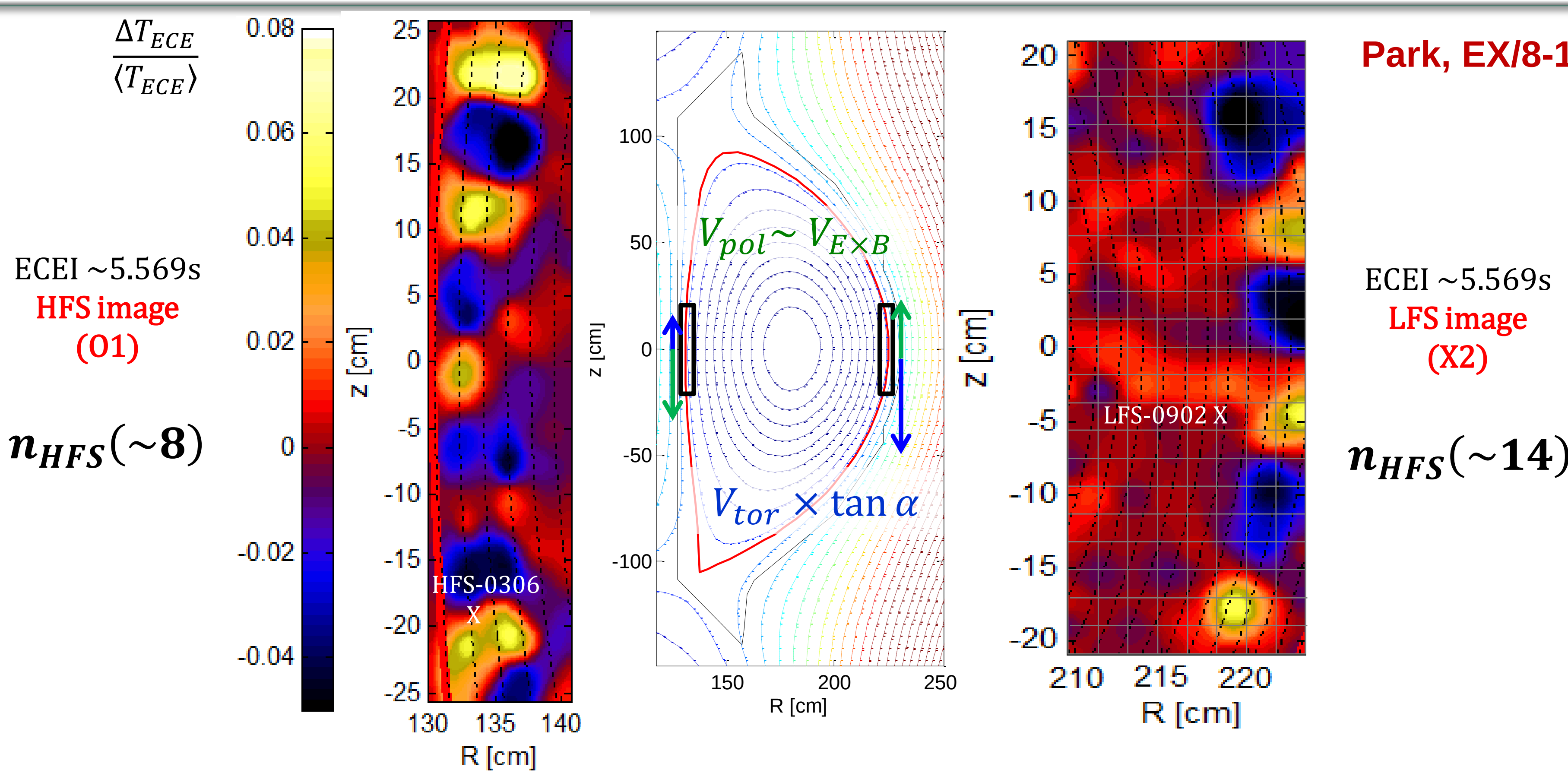
2^{nd} Harmonics deposition at LFS

Mitigation stronger at larger ρ_{pol}

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

Strong coherent oscillation (~10 kHz) exists during ECH injection

High-field side ECE imaging of ELM filaments

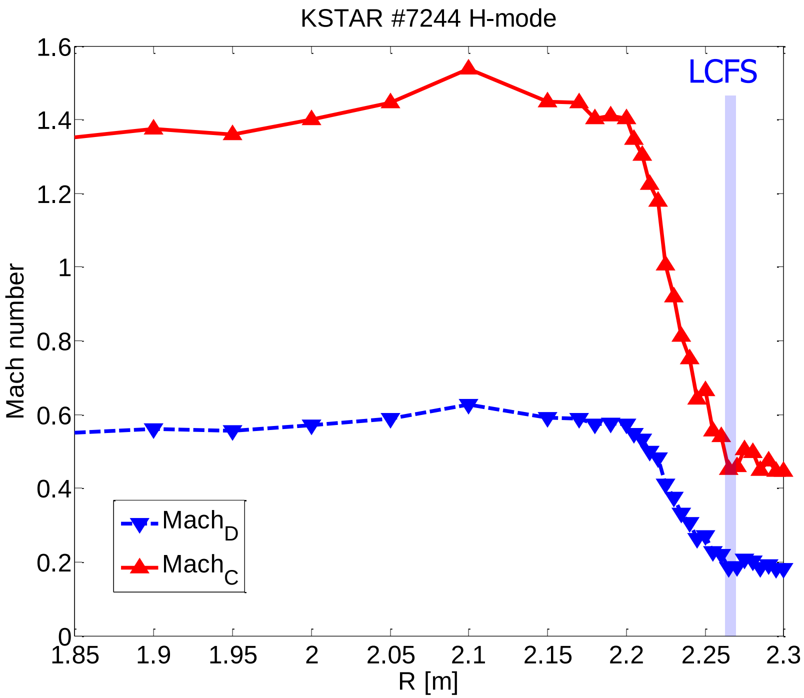


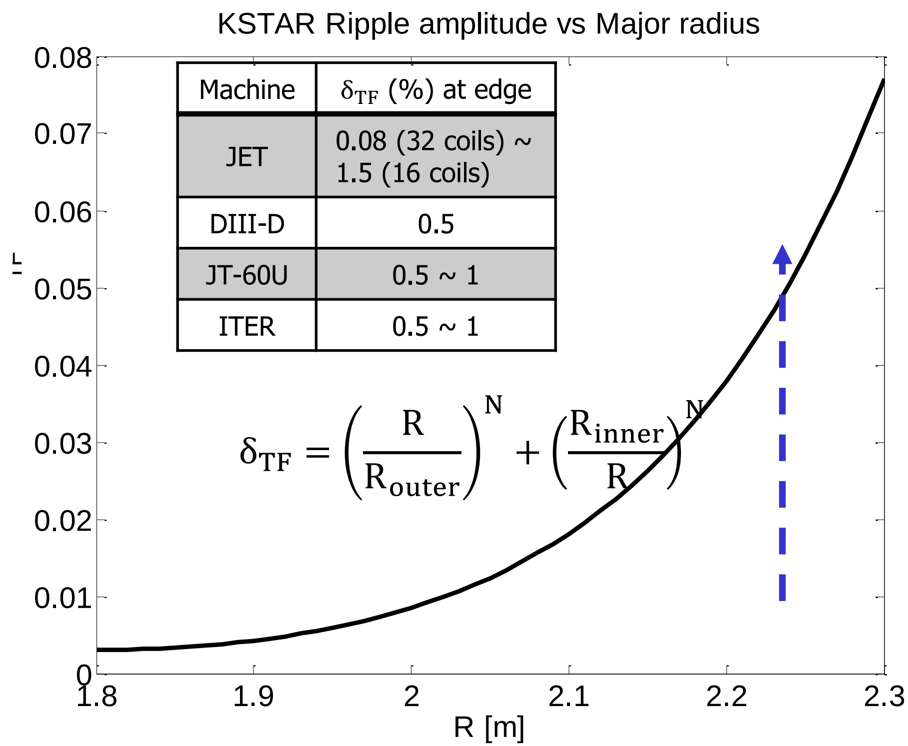
→ The HFS mode does not fit into the conventional ballooning mode picture

→ Investigating the possibility of simultaneous existence of two modes of the same helicity

- **Opposite poloidal rotations between HFS and LFS**
- **A strong Pfirch-Schlüter flow** (~25km/s) **at the edge** is suggested, which makes a poloidal asymmetry in the toroidal flow

High toroidal rotation at pedestal top is likely due to both low EF & TF ripple in KSTAR



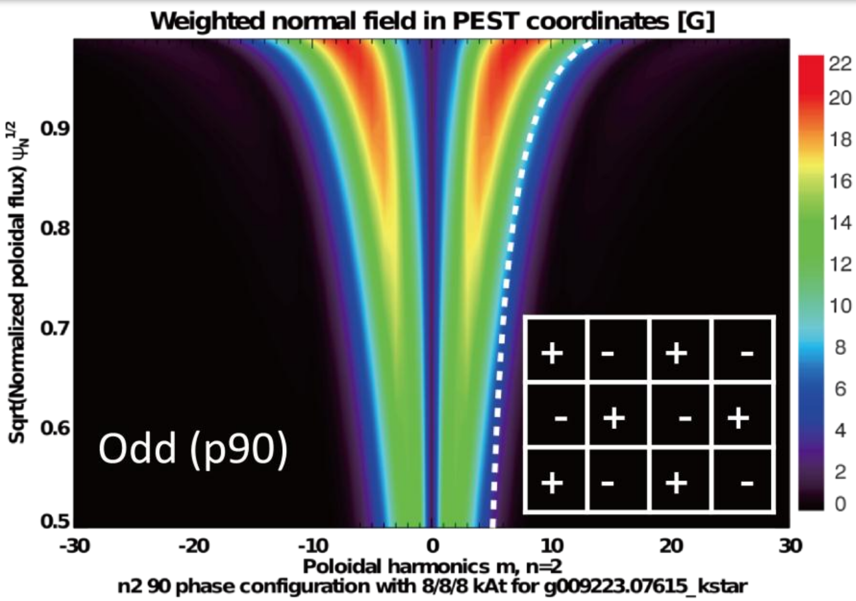


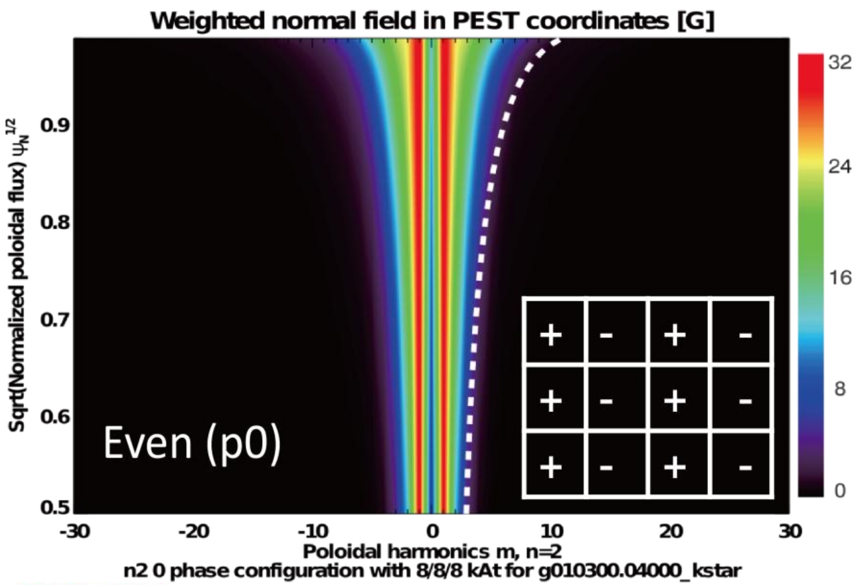
Machine	δ_{TF} (%) at edge
JET	0.08 (32 coils) ~ 1.5 (16 coils)
DIII-D	0.5
JT-60U	0.5 ~ 1
ITER	0.5 ~ 1

$$\delta_{TF} = \left(\frac{R}{R_{outer}}\right)^N + \left(\frac{R_{inner}}{R}\right)^N$$

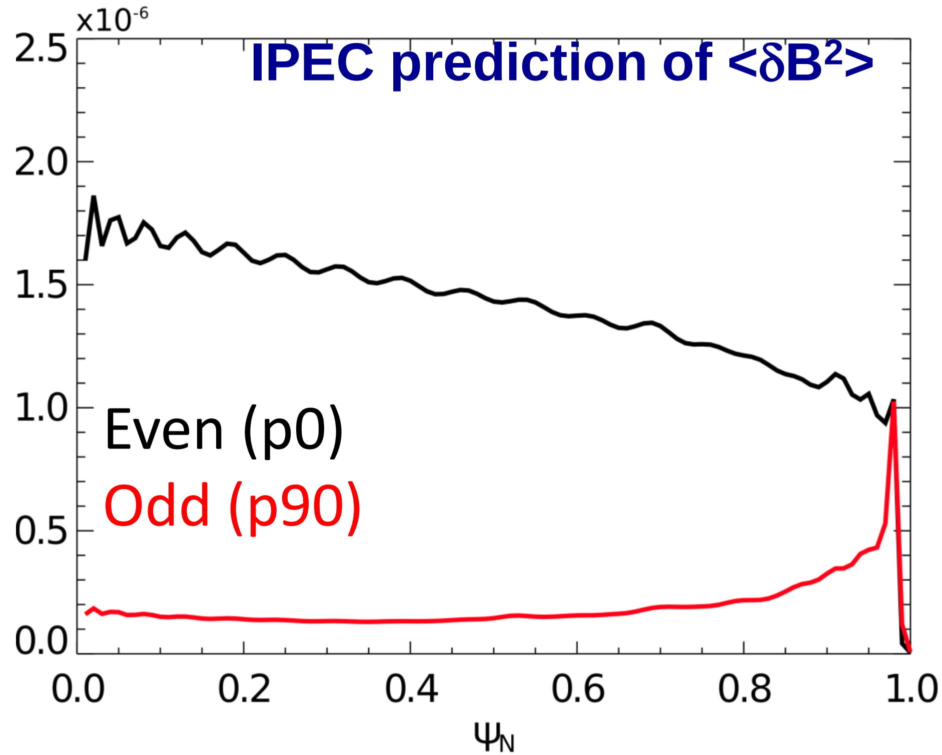
- **Mach number ($\equiv v_\phi / v_{thermal}$) is also found to be high** ($Mach_D$ ~ 0.6, when $V_{\phi,D} = V_{\phi,C}$)
- The clear observation of the toroidal rotation velocity pedestal seems **to come from a low toroidal field ripple** (~ 0.05%) **and error field** of the KSTAR tokamak
- In JET, Mach number is 0.5 for $\delta_{TF} \sim 0.08$ % whereas 0.2 for $\delta_{TF} \sim 1$ % (Mach number in KSTAR is ~ 0.6)

Configurations of n=2 magnetic braking are expected to alter rotation profiles selectively



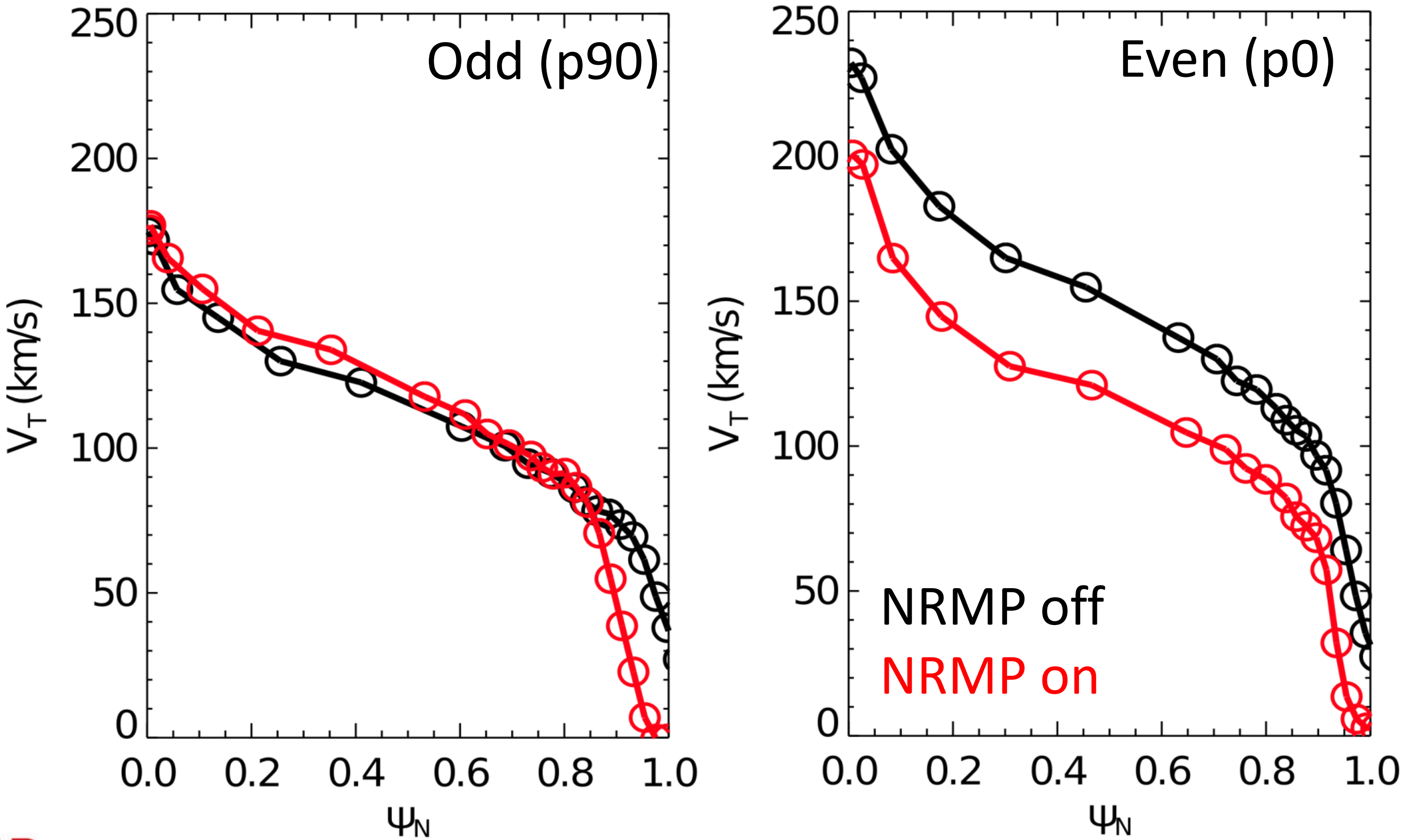


- Vacuum spectrum indicates n=2 non-resonant field can be drive at q_{95}~5 for both configurations
- Ideal plasma response(IPEC) predicts deeper penetration & amplification of applied field in **Even** parity, but strong shielding in **Odd** parity



Measured rotation profiles are in agreement with plasma response modeling

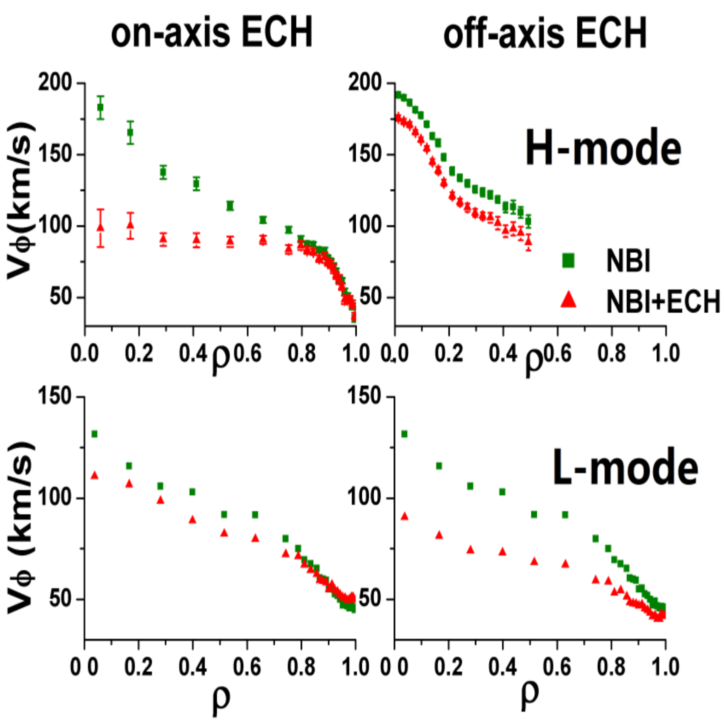
- CES measurement indicates edge-localized magnetic braking by n=2 Odd parity, but global rotation damping by Even parity
- **n=2 IVCC parity provides another channel of selective core/edge/global momentum transport for control of rotation and rotational shear**



KSTAR

Effect of ECH on rotation profiles is different for L- and H-modes : consistent with linear G-K modeling

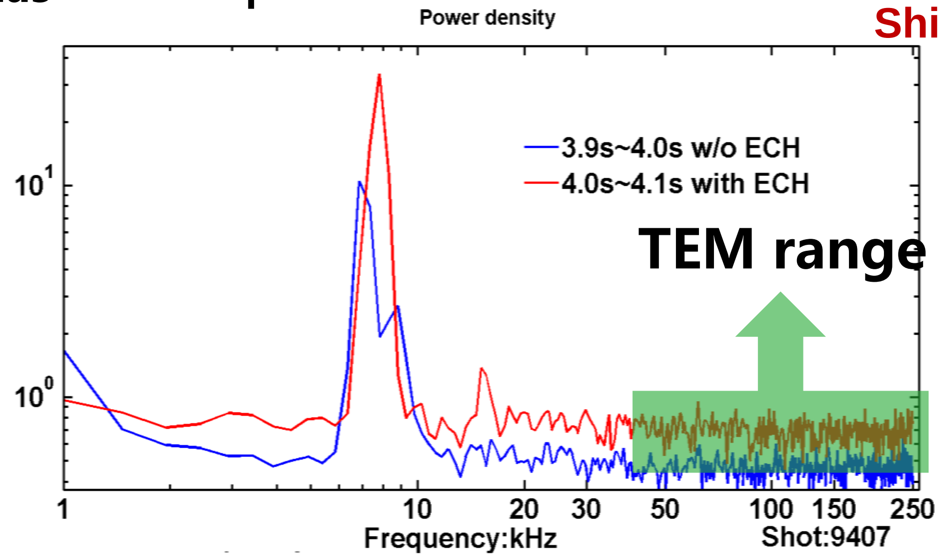
Rotation Profiles for ECH+NBI plasmas



•ITG→TEM transition occurs
inner region for on –axis ECH
outer region for off –axis ECH

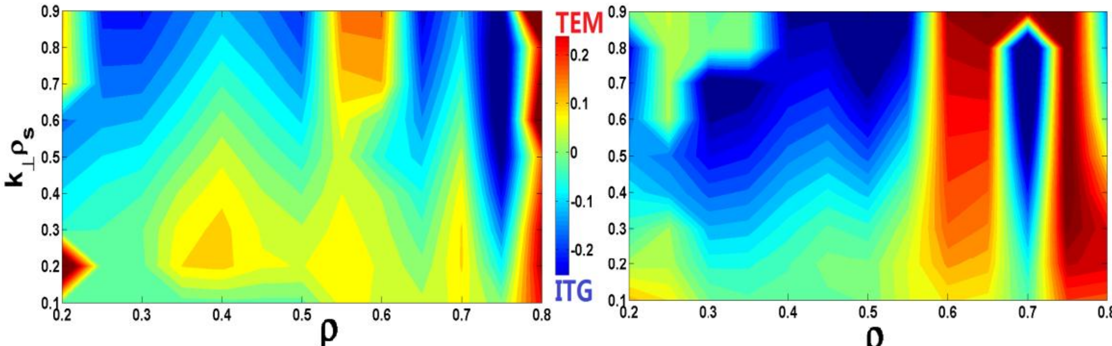
Power spectra of fluctuated Te for L-mode

Shi, EX/6-3



Power spectra of fluctuated Te from ECEI strongly indicated the excitation of TEM during ECH

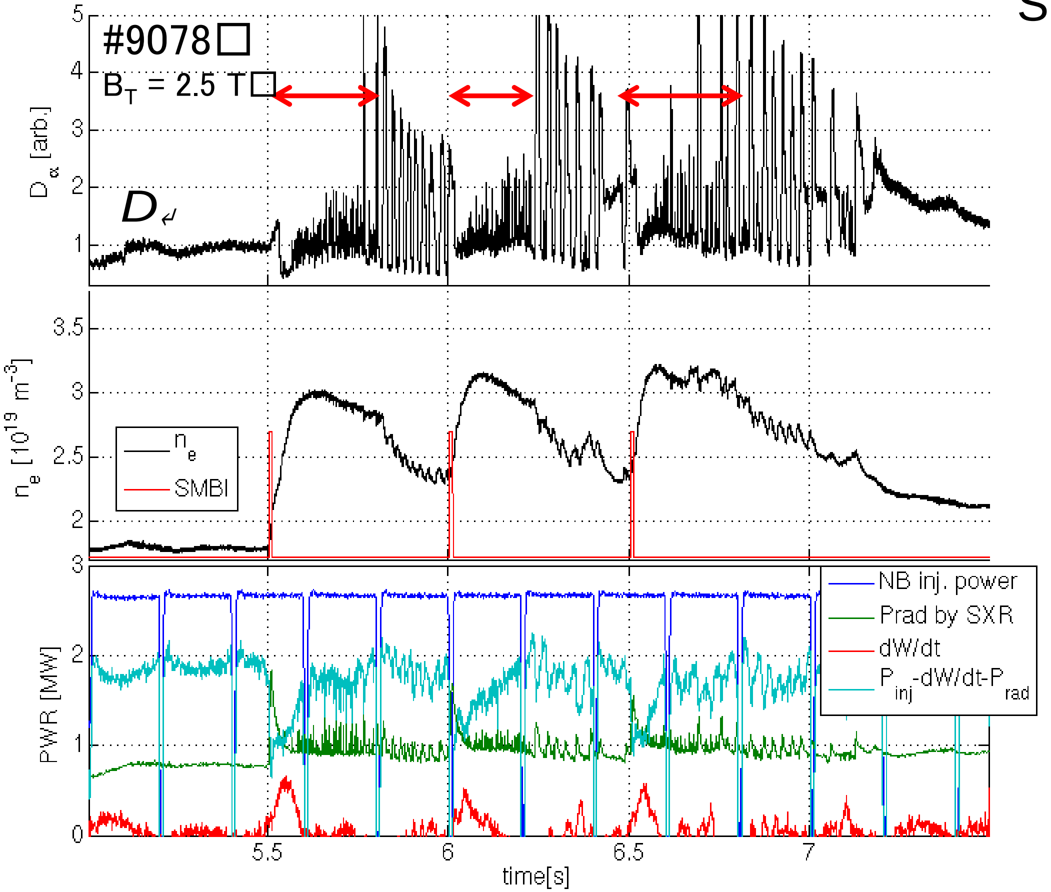
Linear gyro-kinetic analysis of ECH+NBI L-mode plasmas



on-axis L-mode ECH   off-axis L-mode ECH

SMBI-Stimulated L-H transitions enable us to explore the H-mode accessibility issue in both experiment and modeling

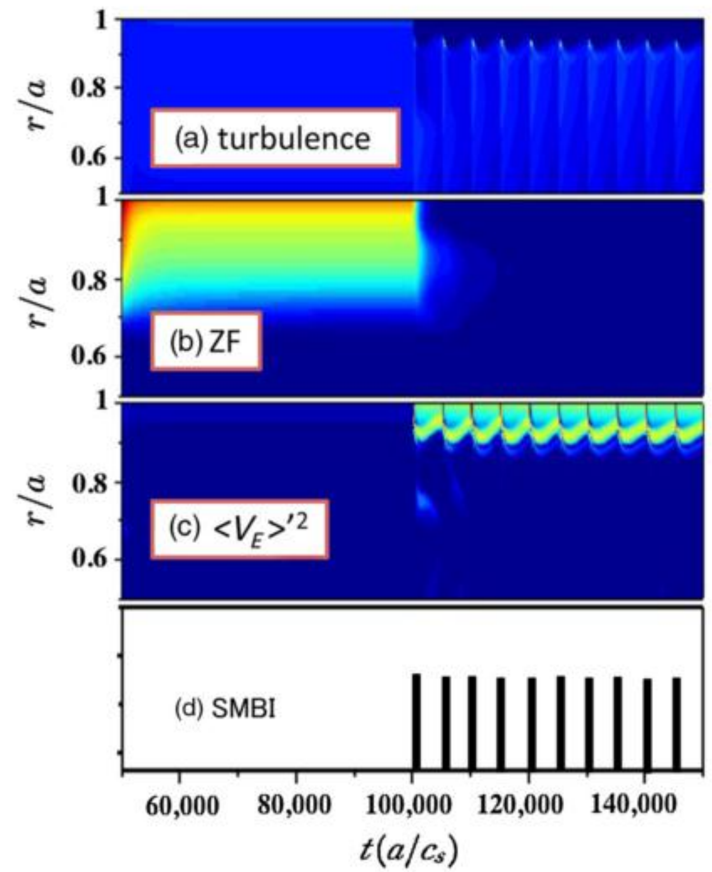
Reproducible & transient "Stimulated ETB states", triggered by deuterium SMBI, are found experimentally under subcritical heating condition



Hahn, EX/P8-11

Reduced 1D Model study demonstrated that repetitive SMBIs can allow sustainment of the "Stimulated ETB State"

K. Miki, PRL 2013



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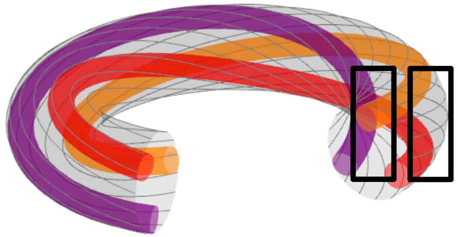
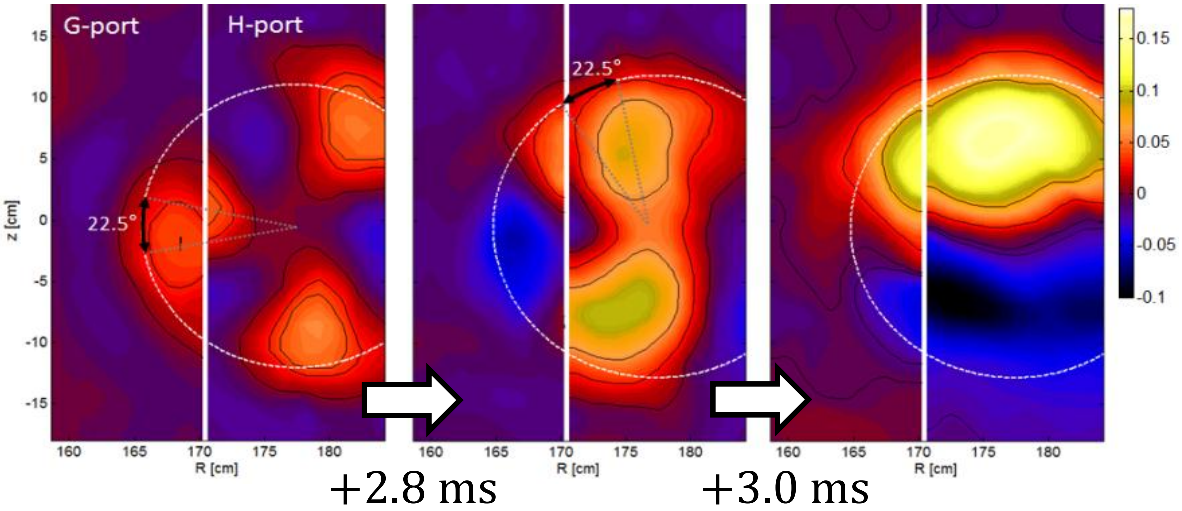
Multiple flux tubes (MFTs) common in KSTAR plasmas with localized ECH at q=1 surface

Yun, EX/P8-12



Example (#9214, t=5.00s)

Triple → Dual → Single tube



Observation

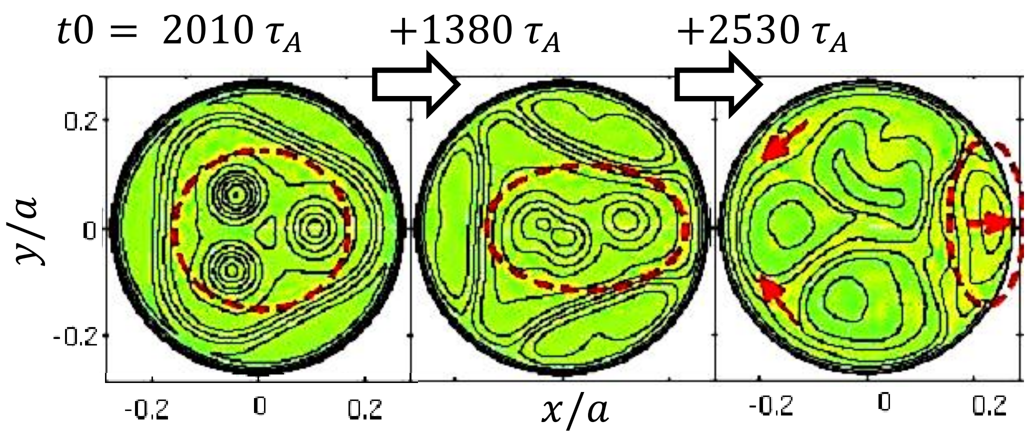
Yun, PRL 2012

Choe, NF (submitted)

Reduced MHD with an empirical source model

Nearly flat q=1 profile is necessary for MFTs

Bierwage, NF (submitted)



Summary

- KSTAR has successfully extended the operation boundary toward high-performance, long-pulse H-mode (~ 40 Sec), transiently accessing to high beta (β_N ~ 4) beyond no-wall limit

- Low n=1 intrinsic error field ($\delta B_{m/n=2,1}/B_0 \sim 10^{-5}$) has been identified in KSTAR

- Advances in rotation physics : localized/global plasma response by n=2 NRMP and Damping mechanism of ECH in L- and H-mode rotation profiles

- In support of ITER, ELM suppression/mitigation physics study has been prioritized, expanding the operation range of q95 (4 – 6)
  - Other ELM mitigation techniques : SMBI, ECH/ECCD

- 2-D ECE imaging provides the new insight : Simultaneous LFS/HFS measurements of ELM filaments and Formation of multiple flux tubes at q=1 surface

Future Plan (focusing on next three year)

- **Toward fully high beta non-inductive discharges**
  - **Upgrade of heating/CD by 2017**
  - **Central co-P_{NBI} ~ 6 MW, off-axis co-P_{NBI} ~ 4 MW, P_{ECCD} ~ 3 MW**
  - **f_{NI}~1, I_p=1 MA, B_T~ 2 T, q_{95}~ 3, β_N ~2-3, t_{pulse} ~ 100 s**

- **Providing solutions for ITER urgent issues**
  - **Extension of RMP ELM suppression at ITER relevant conditions**
  - **Development of baseline scenario**
  - **Disruption mitigation (MGI, pellet, …)**

- **Advanced physics research**
  - **3-D Rotation physics utilizing low EF and control knobs**
  - **Pedestal and ELM physics using novel diagnostics**
  - **Real-time profile/stability control**

- **Hardware upgrade for extending operational boundary**
  - **Active cooling of PFC, 2 GJ motor-generator, in-vessel cryo-pump**
  - **Broadband power supply for in-vessel 3-D coils**