KSTAR
Current Status and Future Plan

Jong-Gu Kwak
National Fusion Research Institute (NFRI), Daejeon, Korea

PPPL GENERAL ATOMICS OAK RIDGE National Laboratory COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK JAEA
KAERI KAIST SEOUL NATIONAL UNIVERSITY PDS²O POSTECH WCI Center for Fusion Theory

KSTAR NFRI 국가핵융합연구소 National Fusion Research Institute

Research opportunity with KSTAR

- **Before and after the first plasma of KSTAR at 2007**
  There were collaboration meetings(with seminar) between NFRI and PPPL about KSTAR.

- **Since then, via KSTAR PAC and FEC satellite meeting,**
  The formal reporting was given to USA colleagues

- **KSTAR completed its first phase of experiments and now steps into the next five year plan**
  so it is necessary to call for collaboration meeting

- **After this talk, I expect**
  PPPL colleagues are familiar with the recent KSTAR achievements
  and to figure out the new collaboration opportunity

Contents

- **Introduction to KSTAR**

  Original Mission/ History

- **What we achieved during last five years**

  Machine performance

  New findings

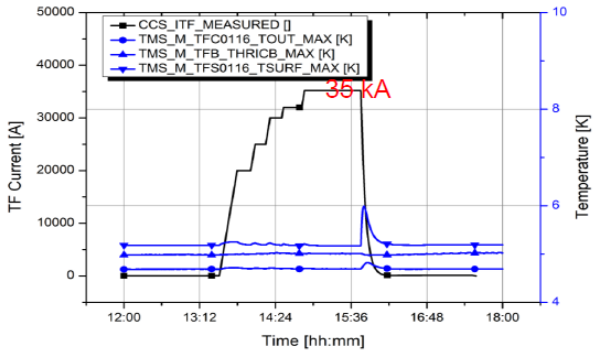
- **The next five year plan(What do we do)**

- **summary**

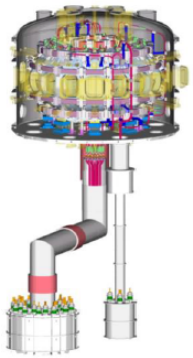
Mission of KSTAR

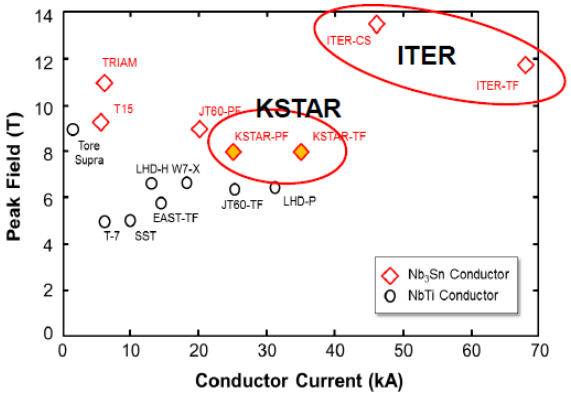
- **To achieve the SC tokamak construction and operation experience**
- **To explore long pulse capability and the physics and technology of high performance Steady state operation**

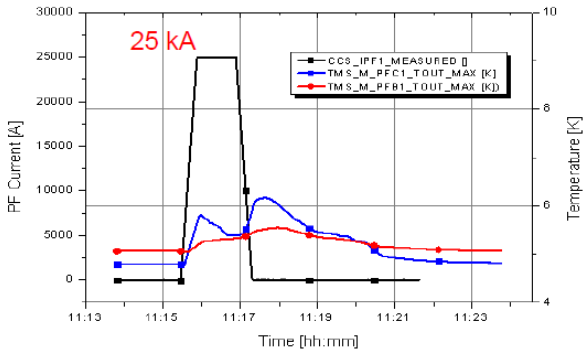
- **Stable operation of SC magnets in cryogenic and mechanical aspects.**
  - Superconductor : Nb3Sn, NbTi
  - TF magnets : 35 kA (Bpeak ~ 7.2 T),
  - PF magnets : 25 kA
  - ac loss in PF coils shows a gradual decrease.
  - Operational experience will be basis for future superconducting tokamak operation.



TF magnet operation current and temperature





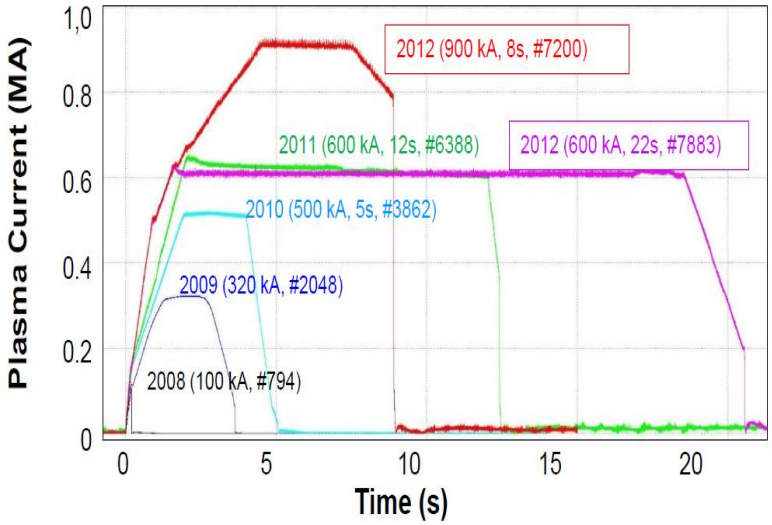


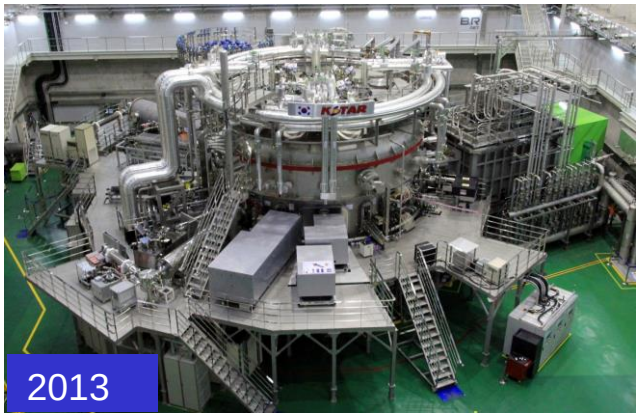
PF1 magnet operation current and temperature

Progress of tokamak

❖ **Brief History of KSTAR**

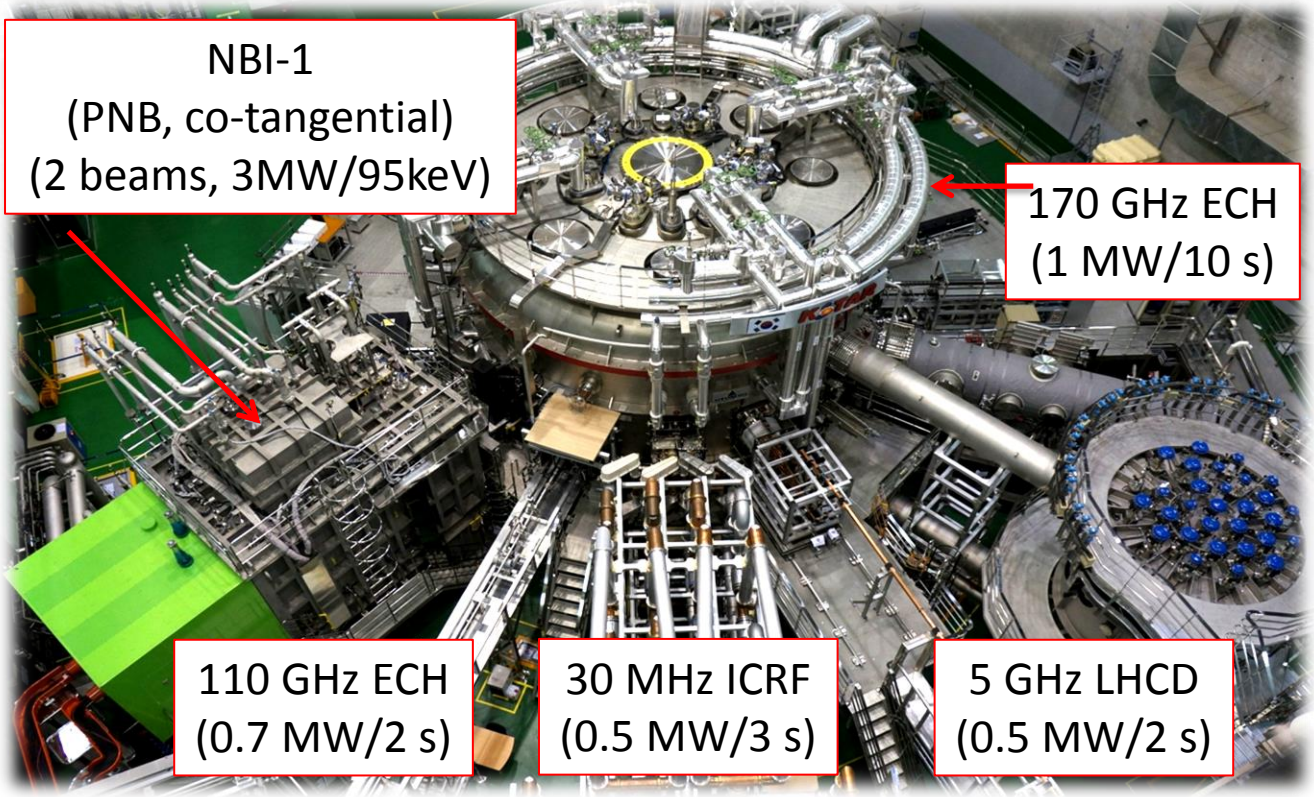
- 2007. 9 Device construction completion ceremony
- 2008. 6 First plasma (Ip = 107 kA, ECH 84 GHz, 1.5 T)
- 2009. 10 Plasma current control up to 320 kA (ECH 110 GHz, 2 T)
- 2009. 11 TF magnet operation up to 35 kA (3.5 T @ R=1.8 m)
- 2010. 10 First H-mode (500 kA, 2.0 T)
- 2011. 8 Successful ELM suppression by using n=1 RMP
- 2012.11 H-mode flattop extension (>15 sec at 600 kA)

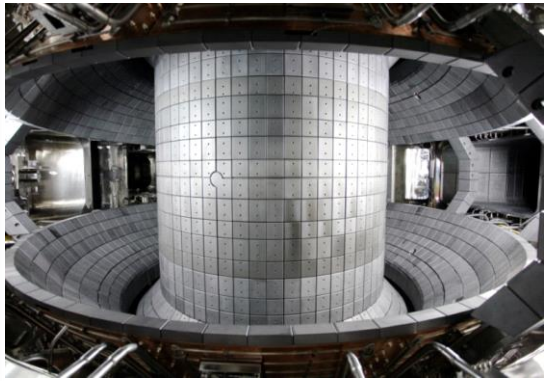




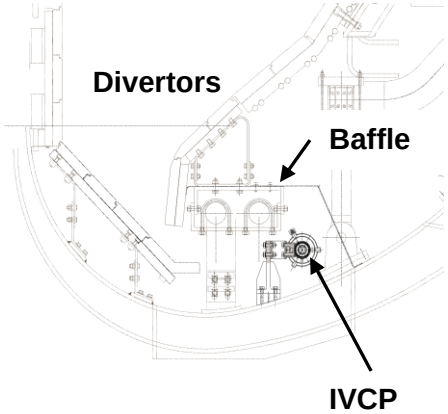
2013. 8. H-mode flattop was extended to 20s

Present machine status of KSTAR (2013)





Full Graphite PFCs
(Water cooling pipe is installed, however, pump is not installed)



invessel Cryopump
(etc. cryo cooling tube was installed, But cryoplant(1kW) is not installed)

What we achieved during last five years in tokamak performance

- Unique feature of machine
- H-mode
- Long pulse capability under SC coils
- Exceeding no wall limits
- Toward advanced inductive mode

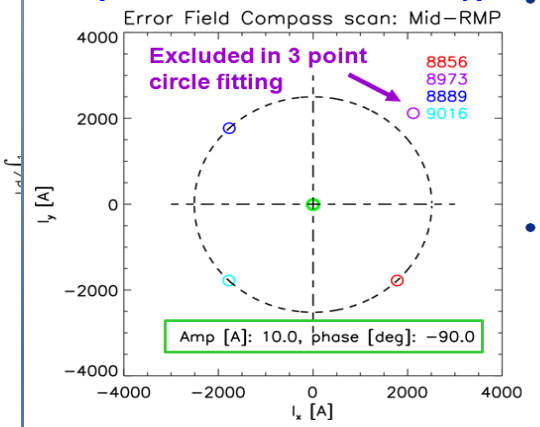
Unique features

- **Intrinsically low toroidal ripple and perhaps low error field**
  - Error field : very low value was detected (**δB/B~10^{-5}**)
- **Modular 3D field coils (3 rows/4column of coils)**
  - Provide flexible poloidal spectra of low n magnetic perturbations

Preliminary: The intrinsic error field in KSTAR appears an order of magnitude smaller than in any other tokamaks

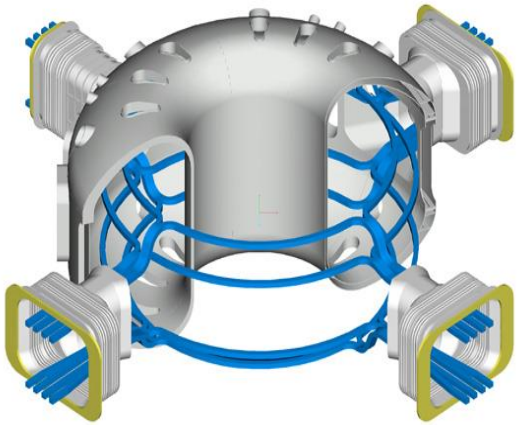
Raw

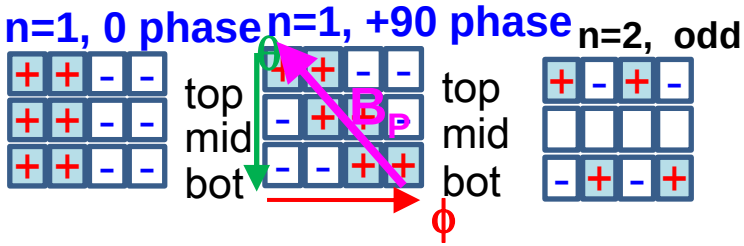
(based on MID-RMP coils only)



- Among the planned 3 single row scans, only the mid-RMP coil scan was completed in 2013
- Excluding an outlier, a simple circle fitting led to a low level of error field in KSTAR (10 A) (could be the world record!)

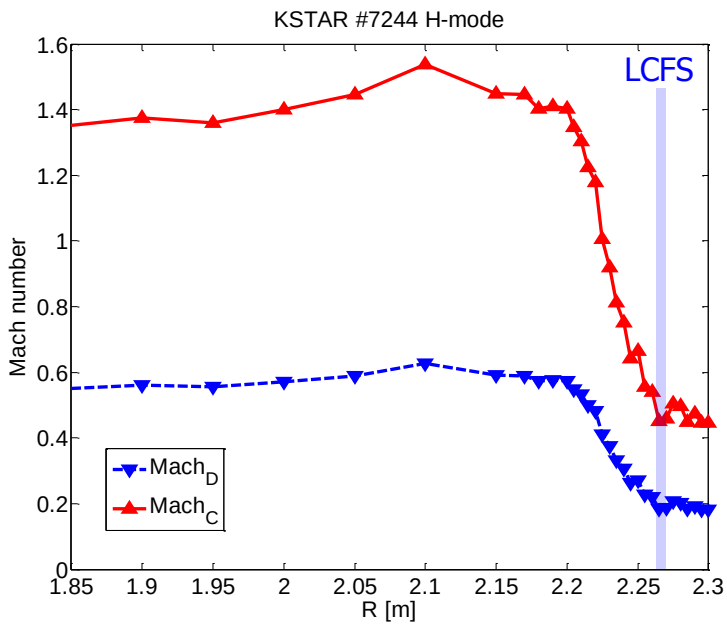
KSTAR FAR-TECH

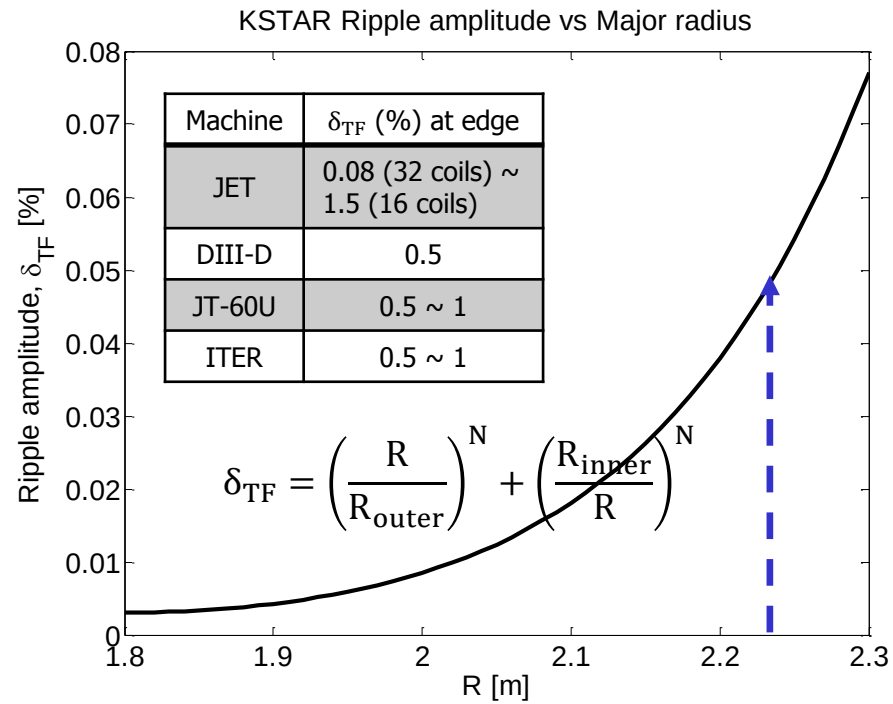




Full angle scan shows that the error field would be lower than sub Gauss (resonant field at q=2/1 based on IPEC calculations)

Pedestal in toroidal rotation velocity profile

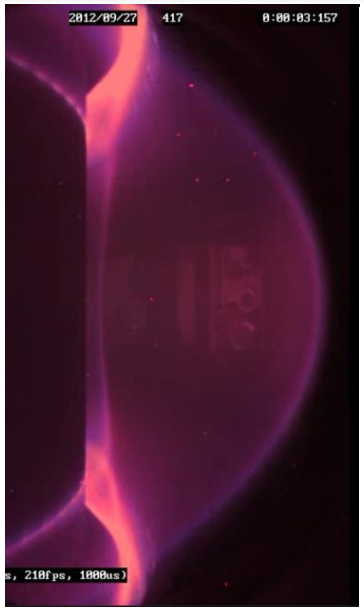


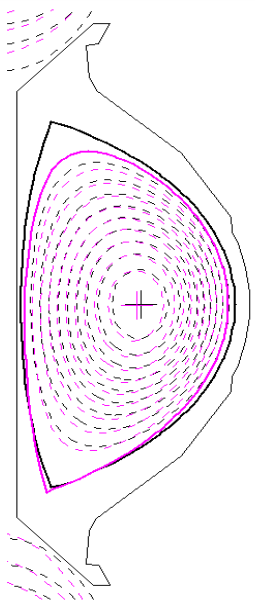


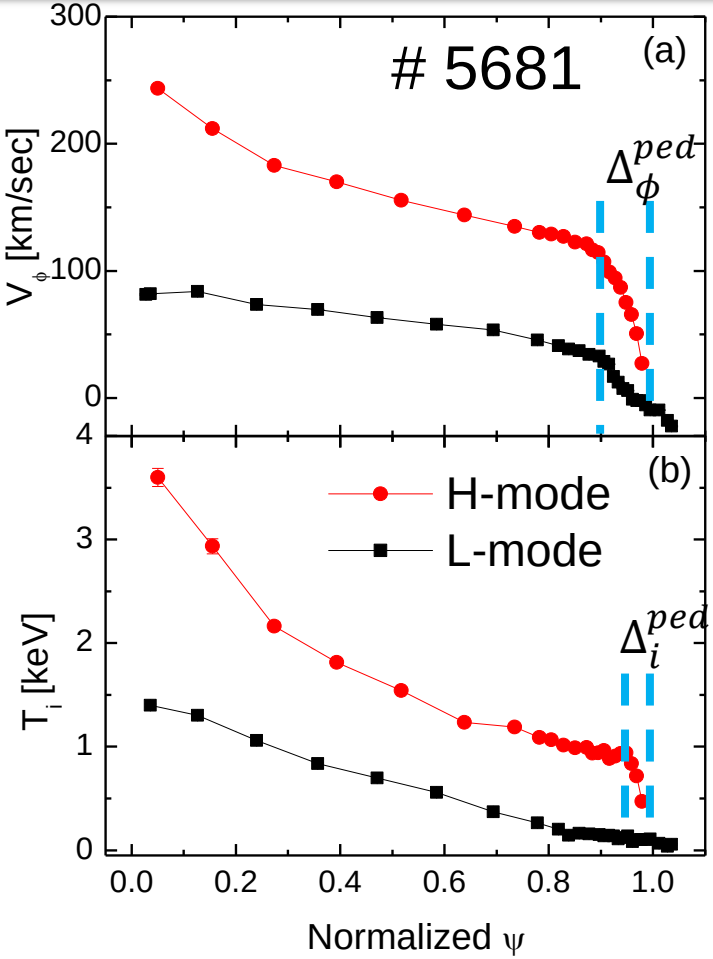
Machine	δ_{TF} (%) at edge
JET	0.08 (32 coils) ~ 1.5 (16 coils)
DIII-D	0.5
JT-60U	0.5 ~ 1
ITER	0.5 ~ 1

- **Mach number ($\equiv v_\phi / v_{thermal}$) is also found to be very 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** of the KSTAR tokamak (~ 0.05%)
- NB : It has been observed that the toroidal rotation velocity at the pedestal is significantly changed by the toroidal field ripple whereas the plasma pressure is not changed [P. C. de Vries NF (2008), H. Urano NF (2011), M. F. F. Nave PRL (2010)], 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)

H-modes (Firstly success in 2010 in KSTAR)







- Central deuterium co-NBI heated
  $P_{NBI} \geq 3$ MW , $P_{ECRH} \sim 1$ MW
- Balanced double null, lower & upper single nulls
  (Kappa ~ 1.8, Delta ~ 0.6)
- Stored energy ~ 0.4 MJ
- **Strong rotation ~ 300 km/s ($n_e \sim 3\times10^{19}/m^3$)**

- All Graphite PFCs (Boron & overnight GDC)
- Typically Type-I ELMs
  (Type-III & mixed at low power, high density)

- Vϕ pedestal broader than T_i ($\Delta_\phi^{ped} > \Delta_i^{ped}$) in contrast to usual profiles ($\Delta_i^{ped} > \Delta_\phi^{ped}$) in which turbulence suppressed and neoclassical physics is dominant so $\chi_i^{neo} > \chi_\phi^{neo}$

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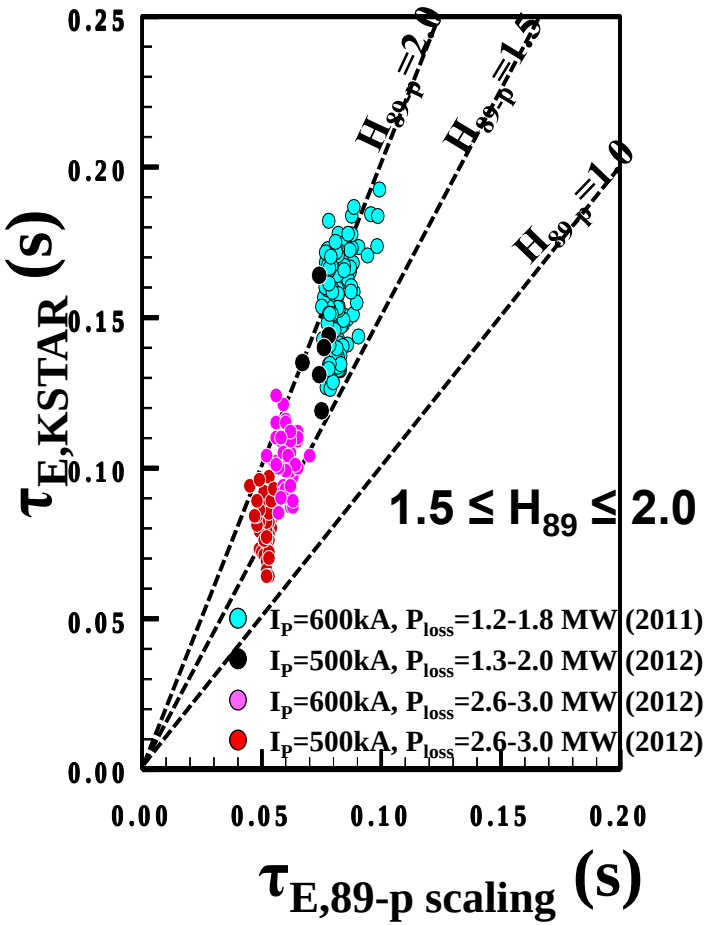
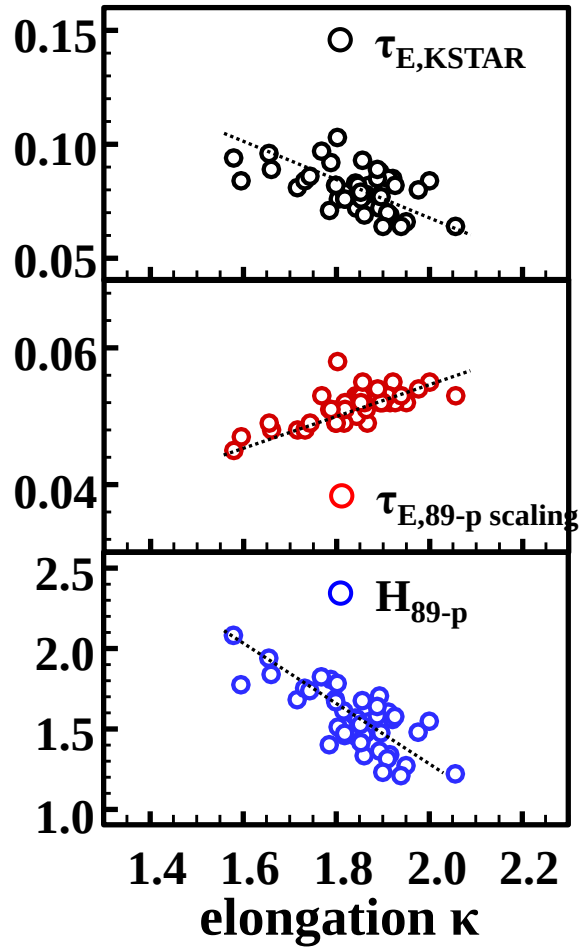
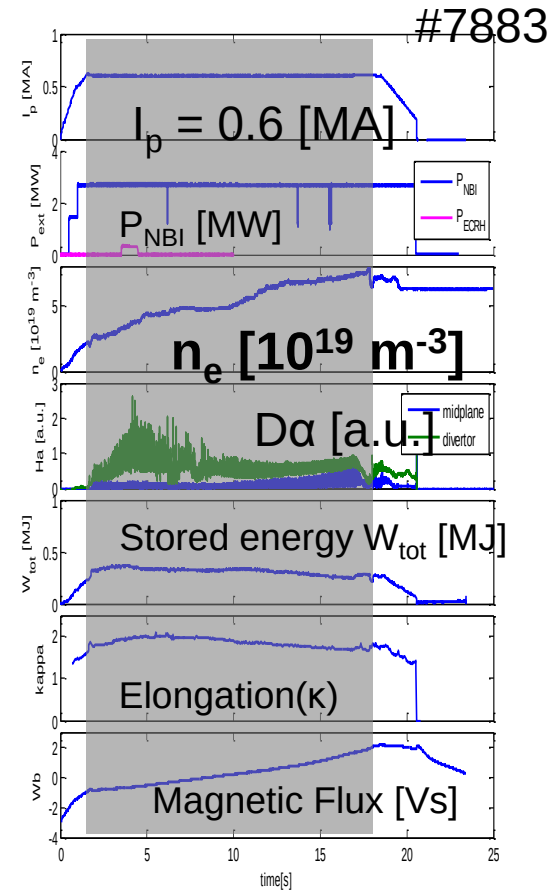
H-mode confinement is in accordance with ITER89 scaling (except for negative trend with elongation)



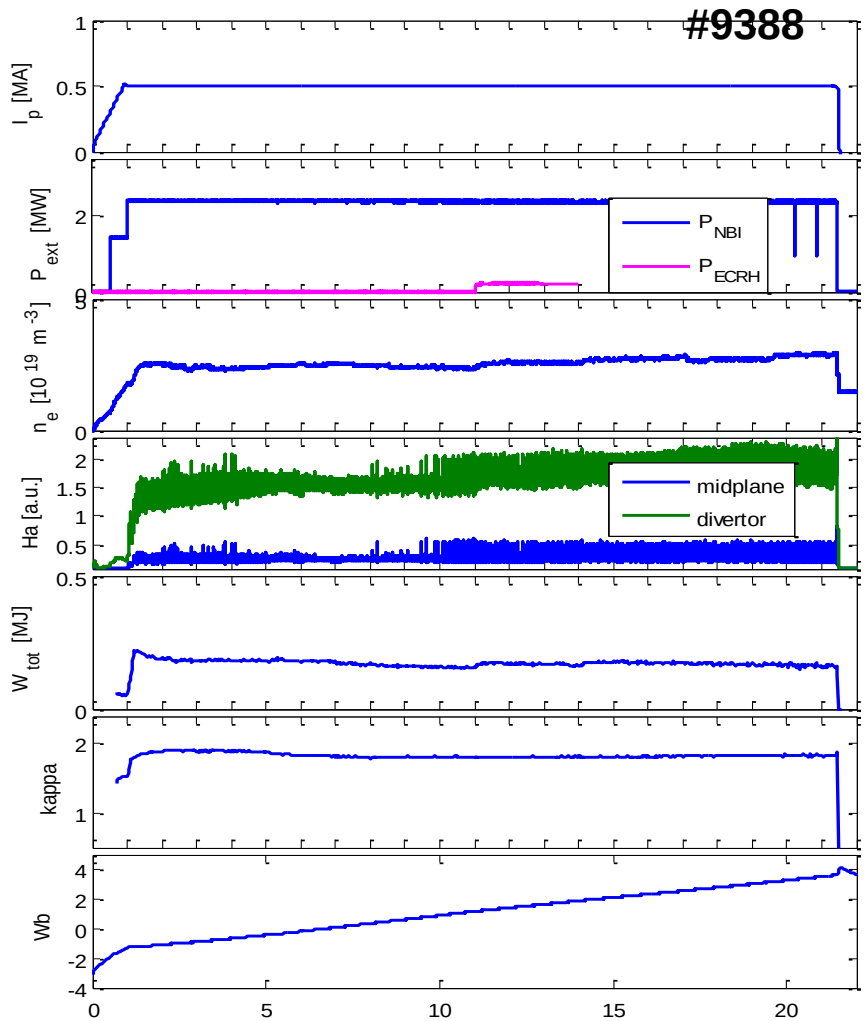




Larger impurity build-up at high κ in 2012

H/D ratio at 2011 : ~20 % vs ~40 % at 2012 (less than 10% variation in H_{89-p})

Longer phase of H-mode flattop ($t_{H\text{-}mode}$~20s) in 2013



Better shape control in 2013
Stationary line density
(better X-point control)

Disruption at t=21.4 s
due to limit of electricity of grid
(VAr limit) **not due to flux limit**

With better PF control logics and motor-generator(2 GJ), longer pulse will be available in next campaign

- **Based on experiments, Ohmic flux available more than 50 second operation in Ip= 1 MA even with P_{NBI} ~ 3 MW**

3.8 Wb (up to 1 MA ramp-up) + 0.15 Wb/s*50 s
= **11.3 Wb < 12 Wb limit**

Good shaping control warrants long pulse as well as good confinement

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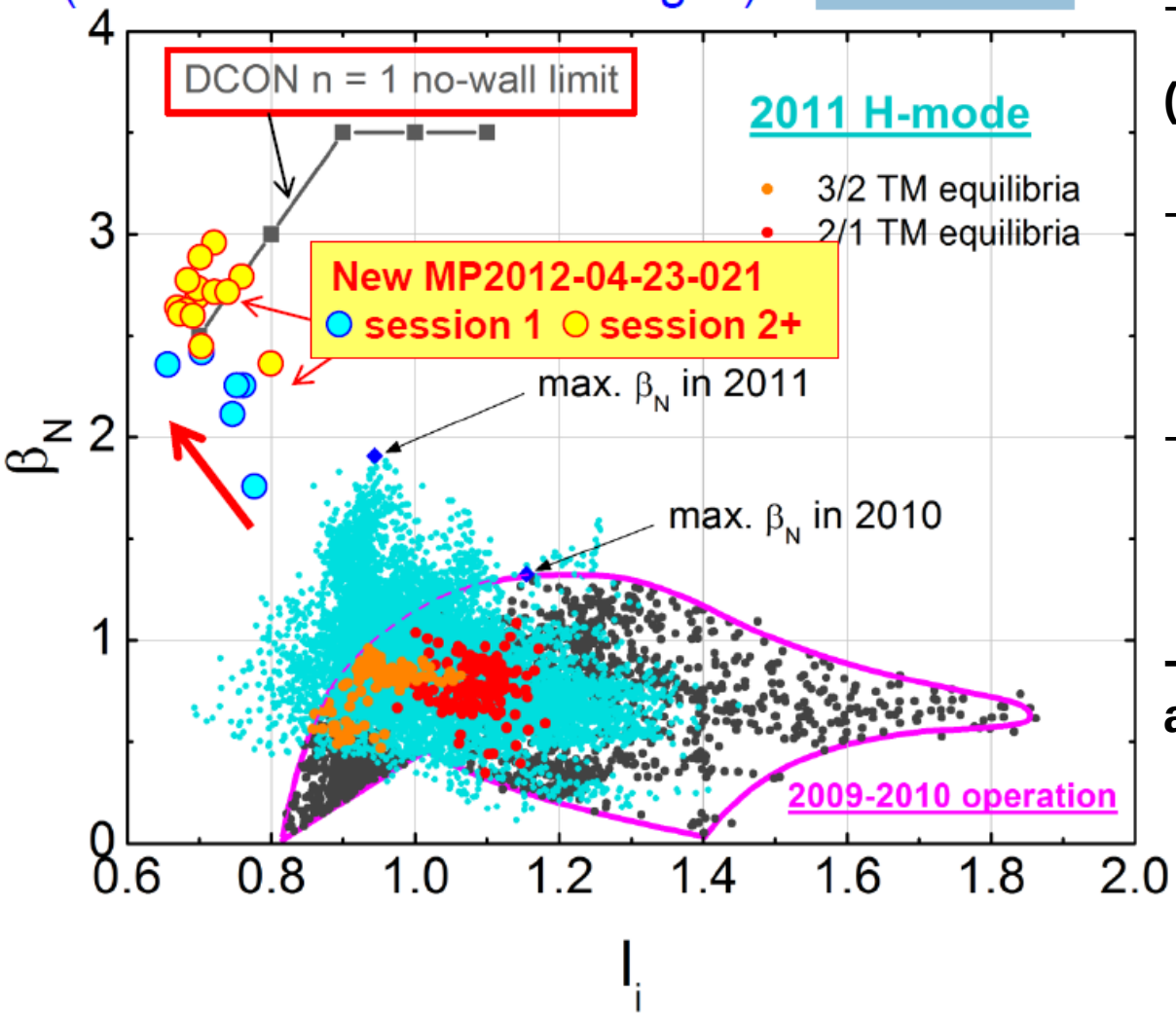
KSTAR is approaching and exceeding no-wall MHD stability limit

KSTAR equilibrium operating space 2009 – 2011

(evolution of > 130 discharges) + new results



- By Early heating for low l_i

(Better Ip ramp-up scenario)

- Optimizing B_T & I_p
  B_T in range 1.3-1.5 T
  I_p in range 0.5-0.7 MA

- Max β_N/l_i ~ 4.1
  β_N~ 2.5, l_i~ 0.7
  100% increase from 2011

- Rotating n=1, 2 mode activities observed in core

S. Sabbagh & Y. Park
(Columbia Univ)

Operation regime extended to lower l_i & higher κ w/o sawtooth suitable for advanced scenario

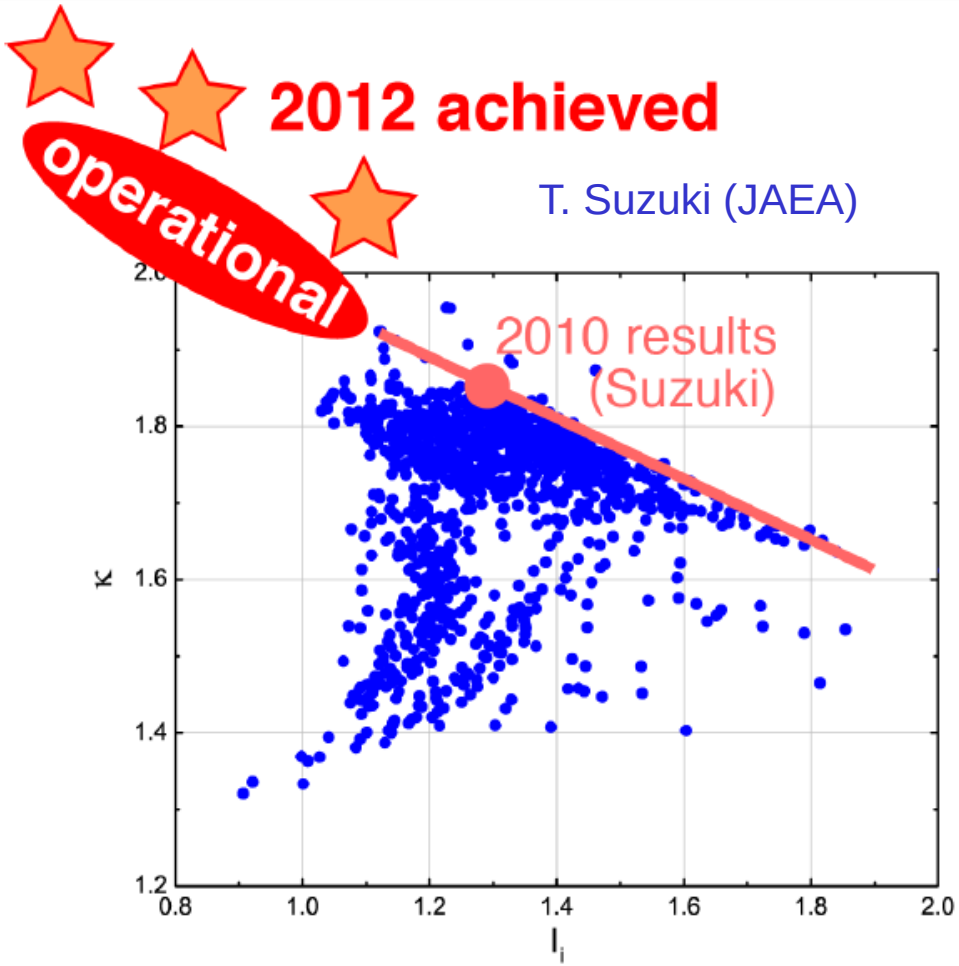


Figure 7. Plasma elongation versus internal inductance of elongated equilibria in 2010. Equilibria are from full discharge evolutions during current flattop for 27 shots.

Y.S. Park et al., NF51(2011) 053001

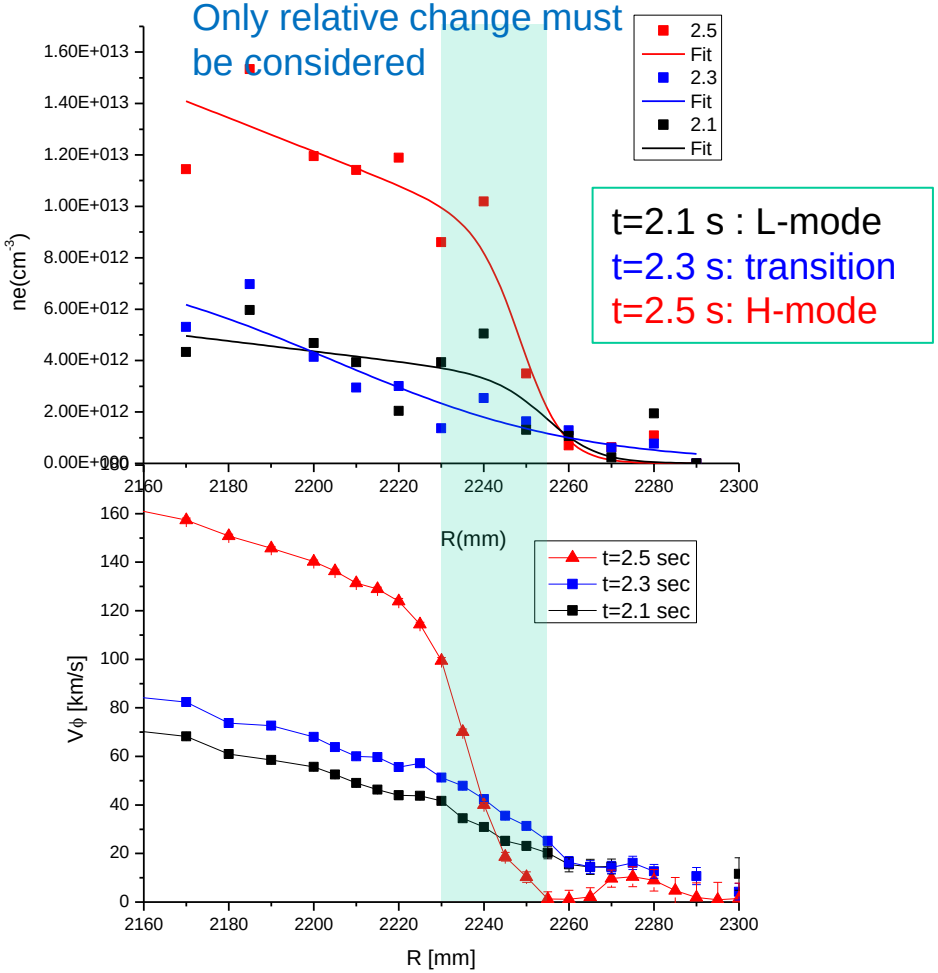
- ✓ Operation regime largely extended to lower li and higher κ
- ✓ Stability boundary of vertical instability is newly identified for li<1, and increases with decrease in li, as expected.
- ✓ Raised limit in κ at lower li enables higher I_p operation.

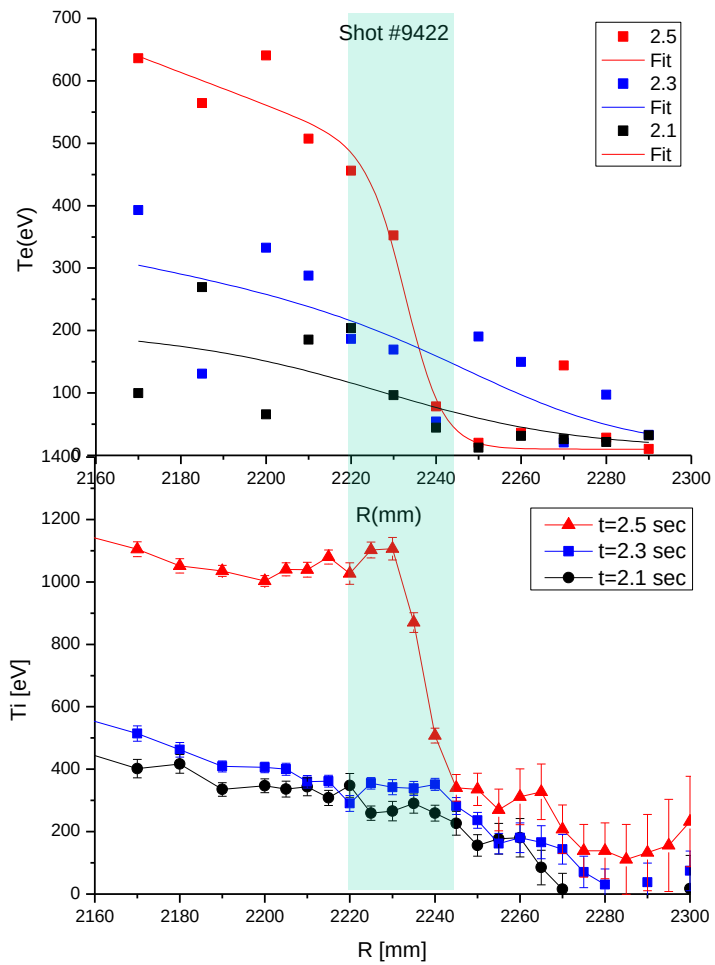
Better TS profiles with similar pedestal position (TS provide the data not routine, but at specific shot)

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

Issue of TS calibration

Only relative change must be considered



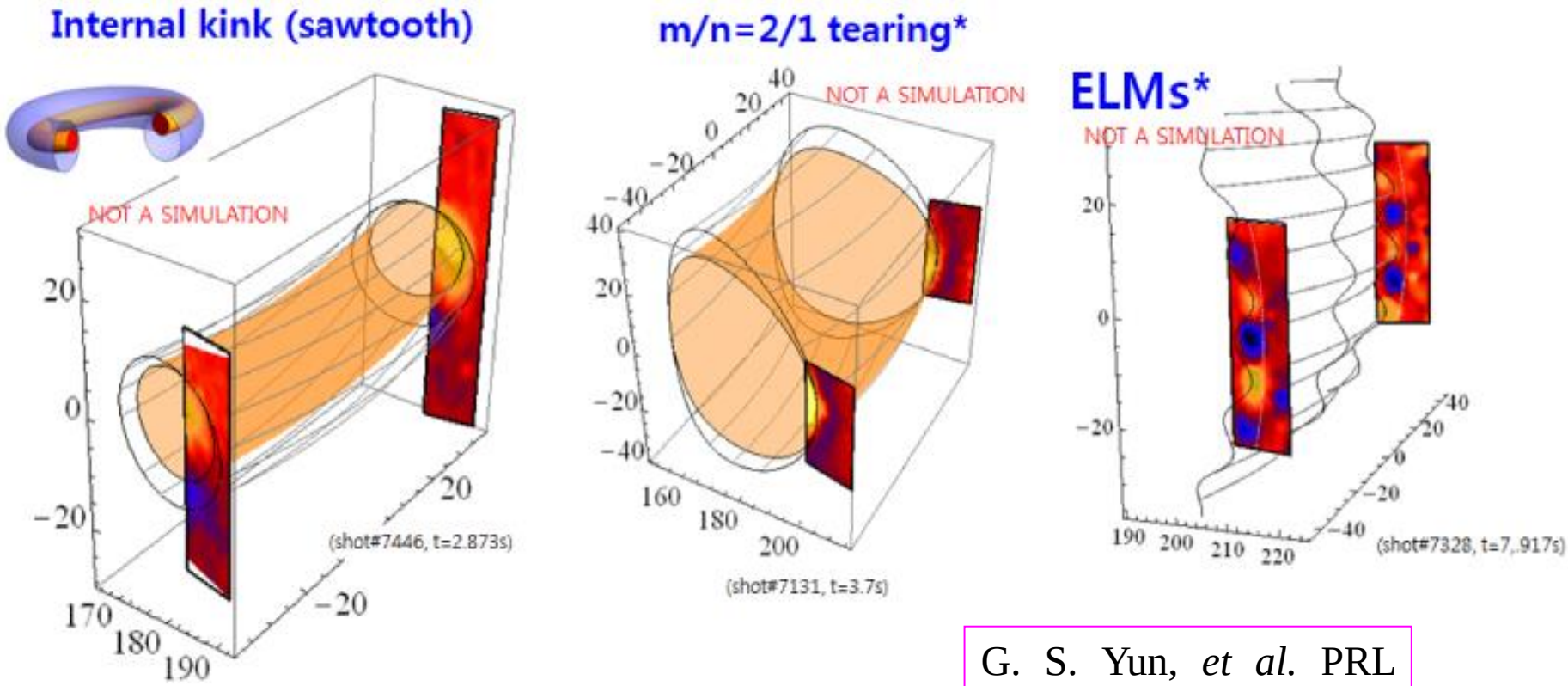


What we found and are investigating in detail

- TM and ELM behavior using ECE-i
- ELM control using RMP and ECCD
- Pedestal width of rotation
- Fast ion loss associated with 3D field
- Validation of theoritical prediction
  (Rotation breaking, NTV offset)

2D & 3-D visualization of fluctuations using ECEI

- Two ECEI systems installed with 22.5 degree space in toroidal angle
  - $\boldsymbol{pitch\ angle \approx 6^\circ}$ (A useful constraint for equilibrium reconstruction)
  - Toroidal asymmetry of ELM dynamics under investigation.



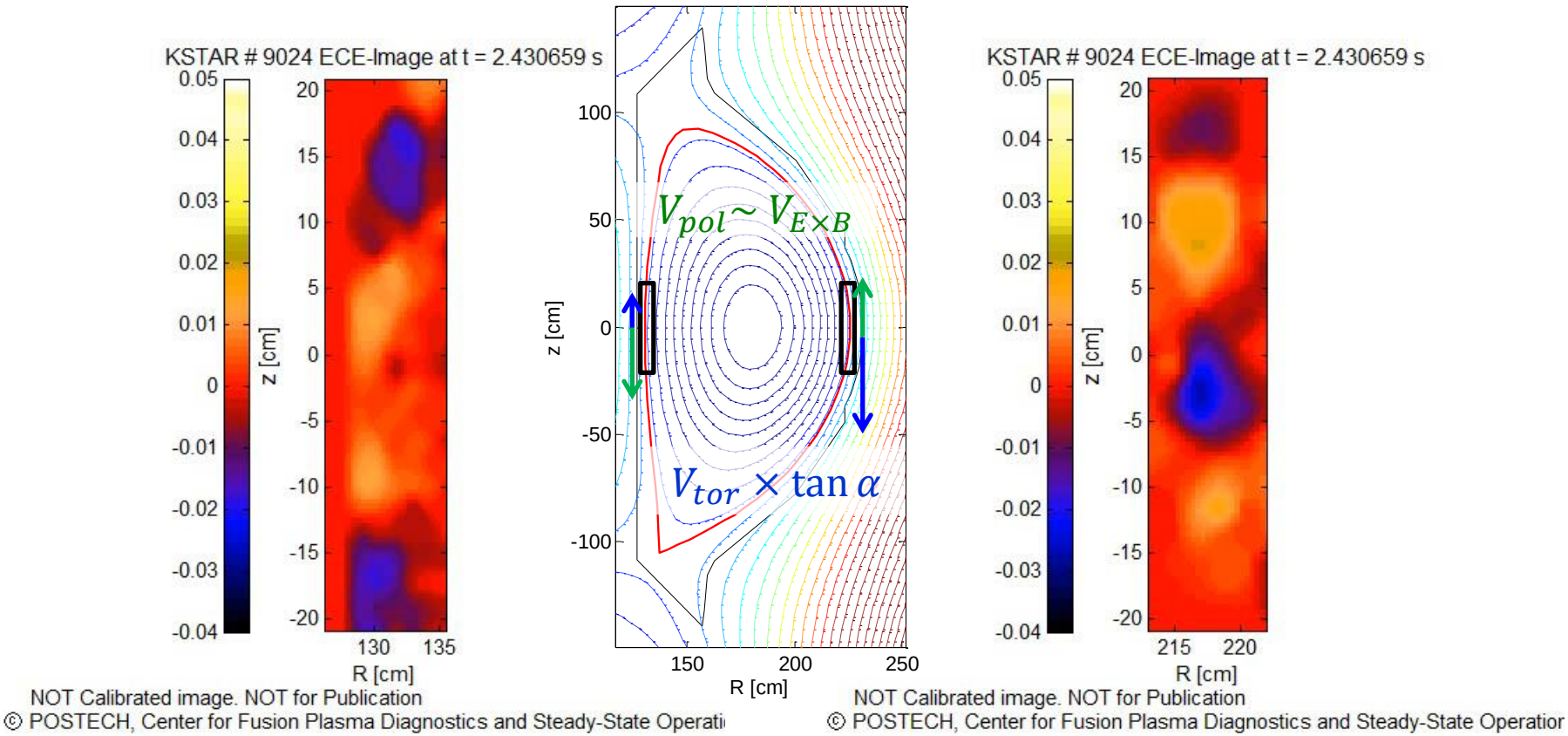
G. S. Yun, *et al.* PRL (2011) & (2012)

High-field size imaging of ELM structure

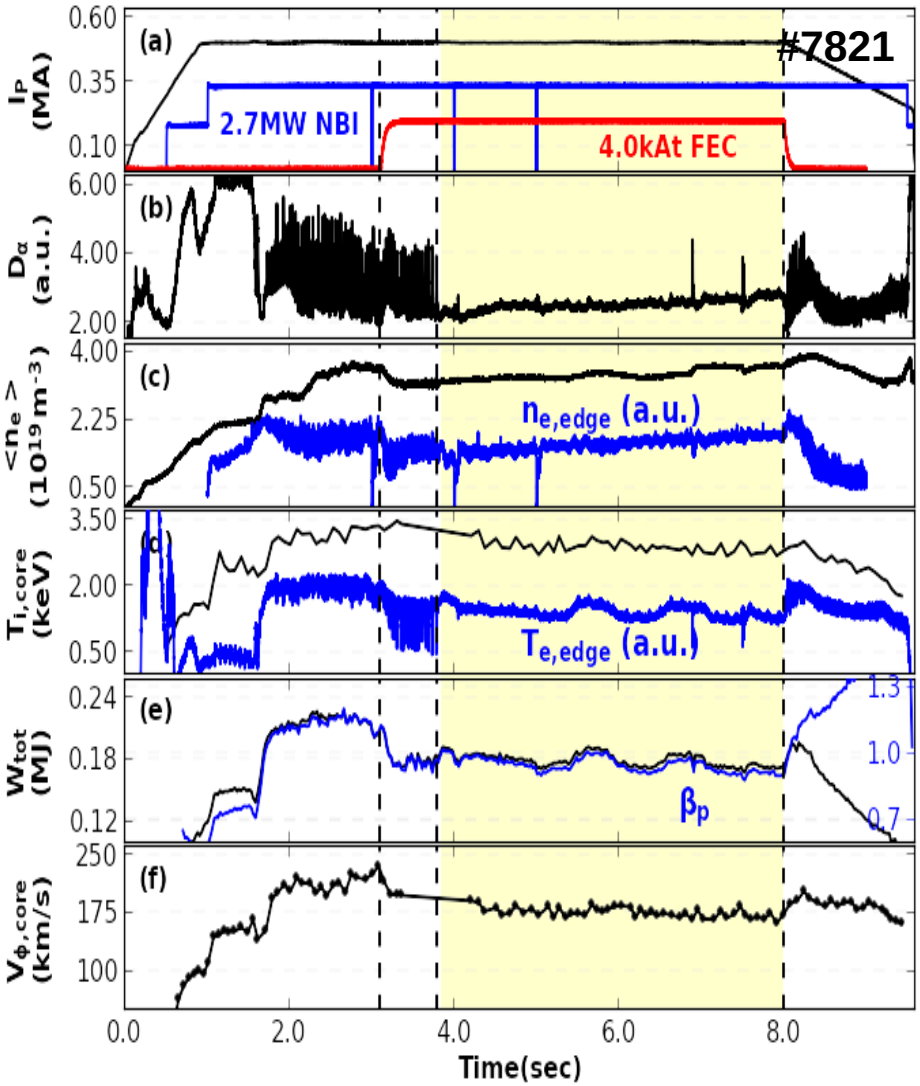
Jaehyun Lee, G.S Yun, M. Kim, M.J. Choi, H.K. Park (POSTECH)

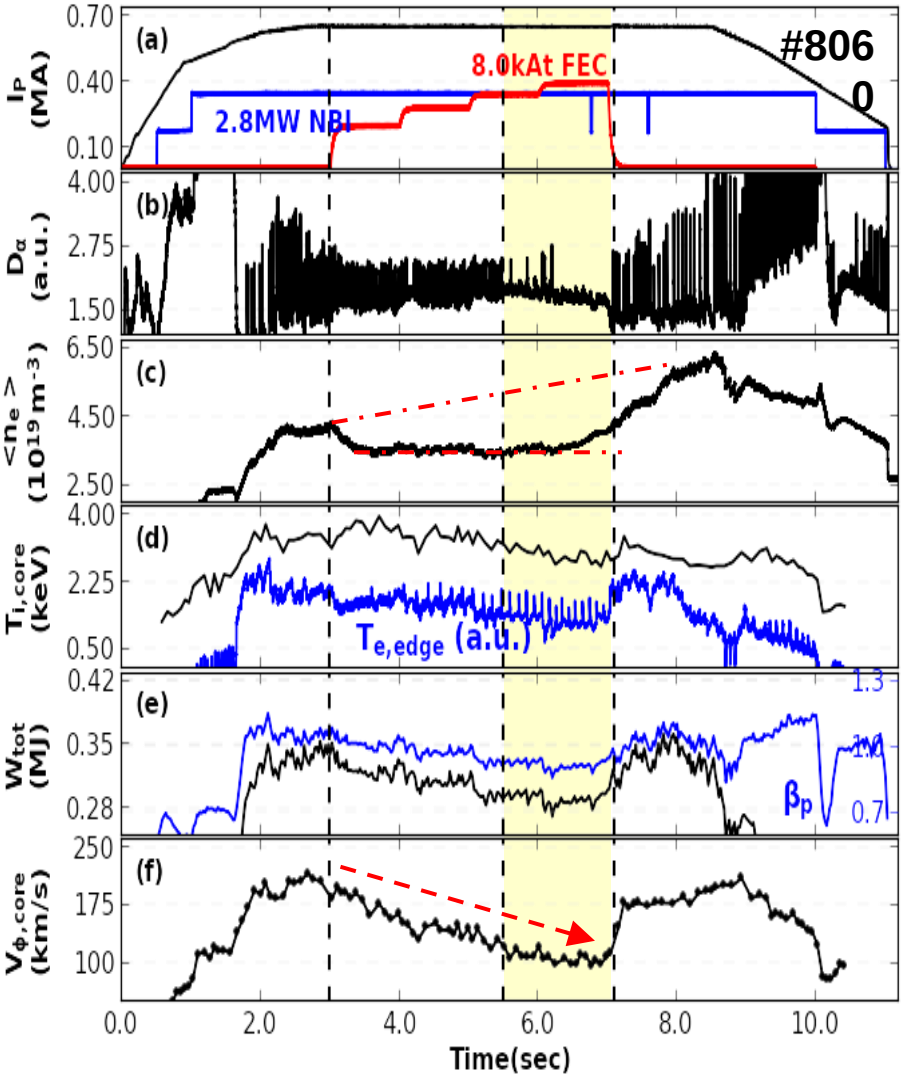
C.W. Domier, N.C. Luhmann, Jr. (UC Davis)

Understand the global geometry and flow of the *ELM filaments*



ELM-suppressions have been demonstrated using both n=1 or n=2 RMP with specific q window





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

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

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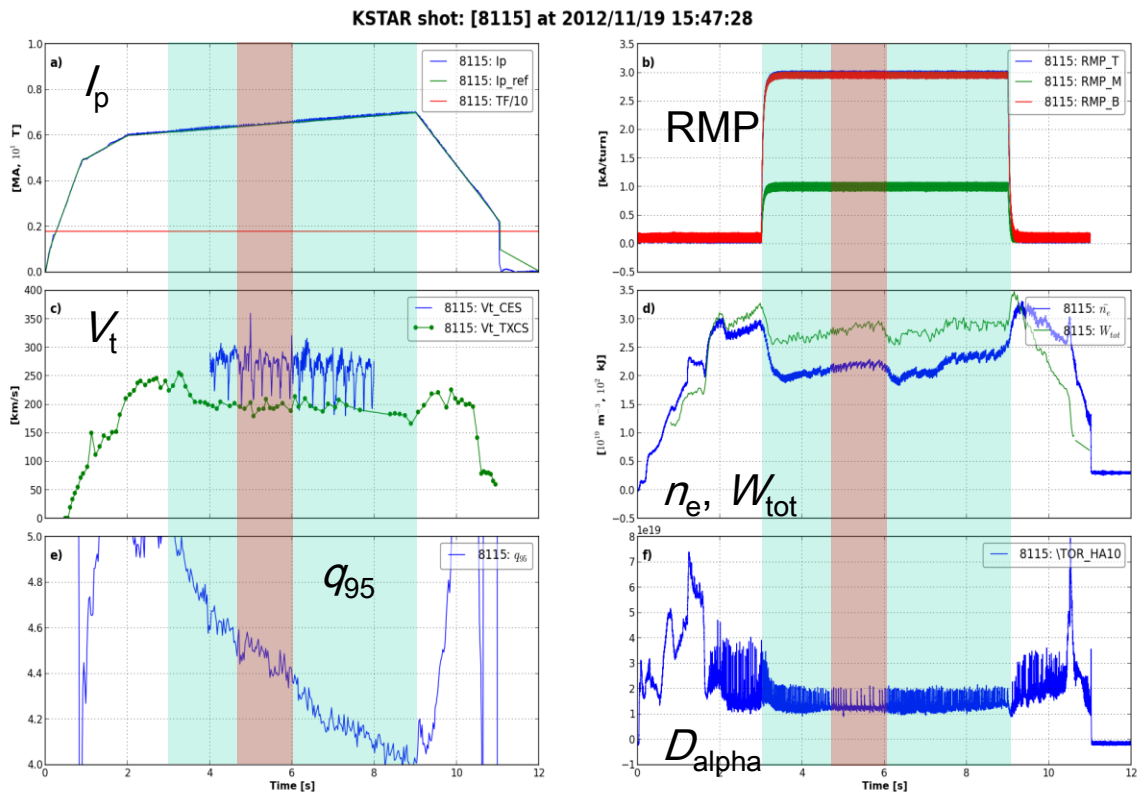
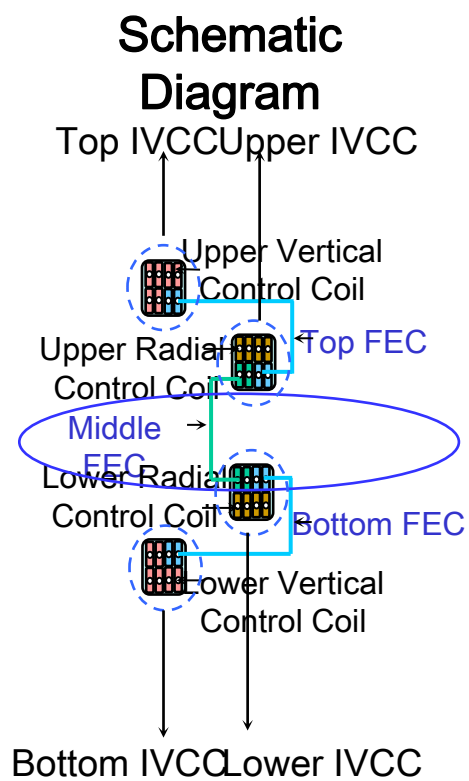
ELM suppression is achieved with using the combination of n=1 and 2

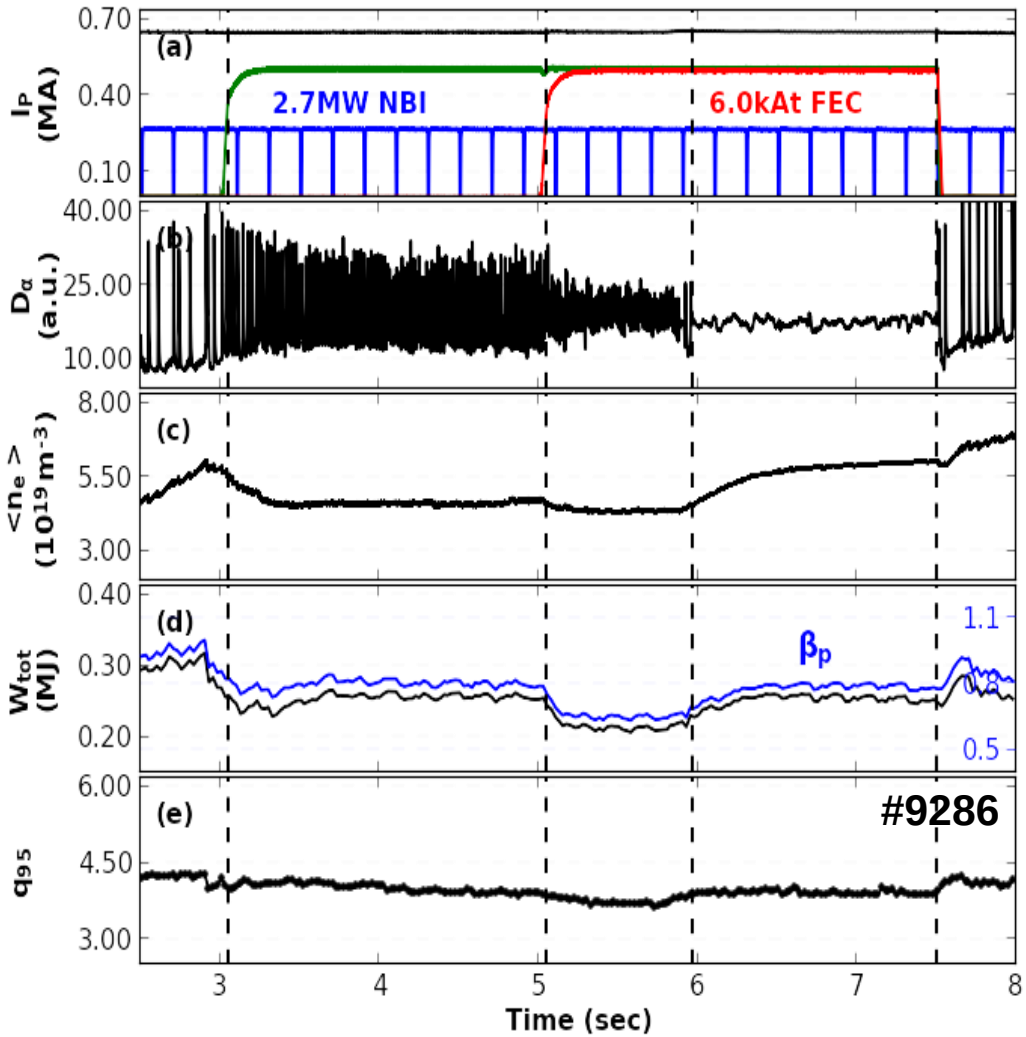
- n=1 (middle) NOR n=2 (top/bottom) NA field ALONE has not shown the ELM suppression yet.
- The q-window (4.3~4.5) in ELM suppression is observed during I_p scan (q-scan).
- **NB : q~6 at n=1, q~3.7 at n=2, q~4.5 at n=1+2 (wide q window)**





Extending q window space at ELM suppression

By varying selective RMP setup(top/bot, or top/mid/bot), ELMs was suppressed or mitigated in n=2 (+90) RMP



n=2 even (top/bot) — n=2 (+90, top/mid/bot)

mitigation — **suppresion**

#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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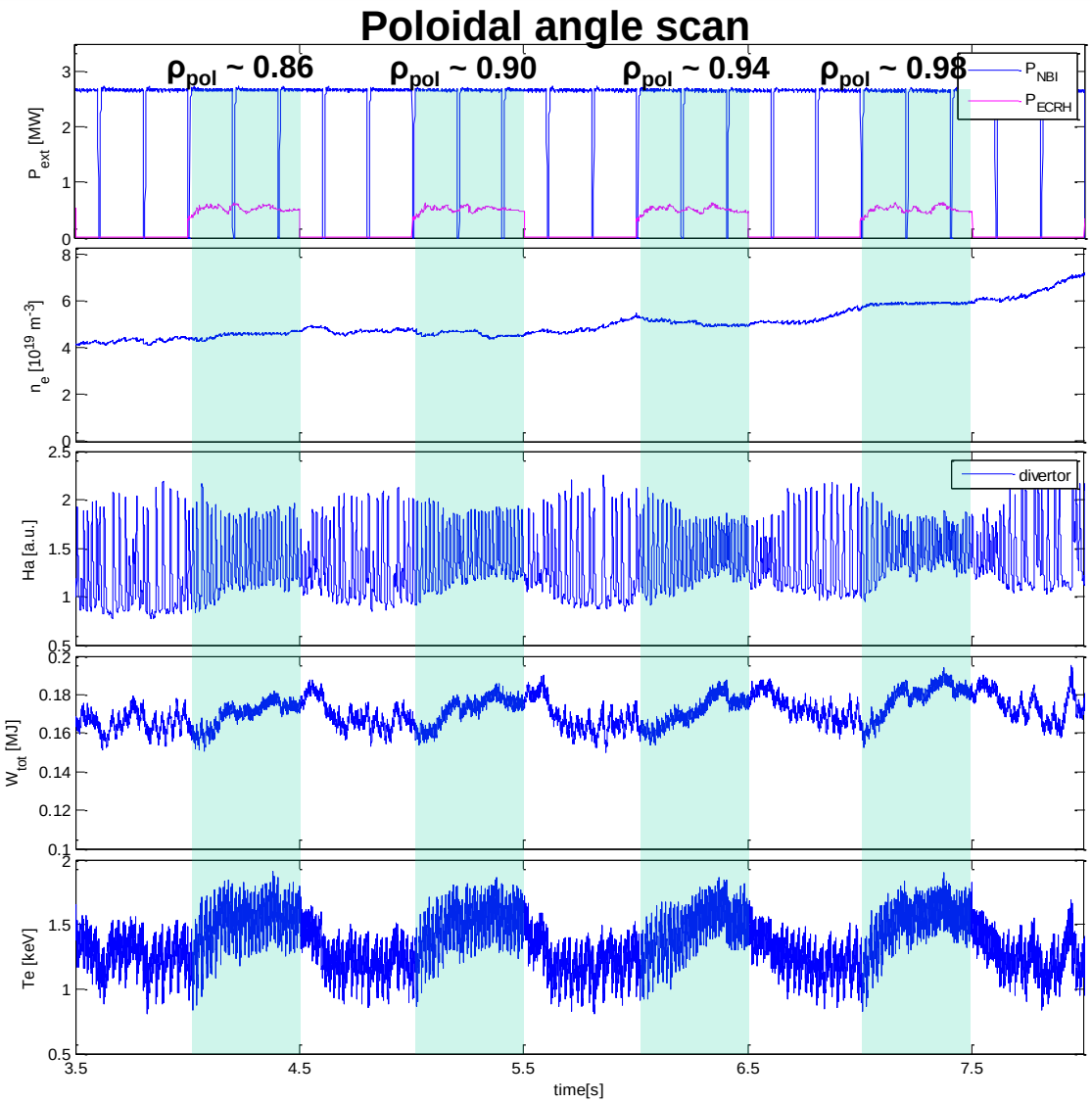
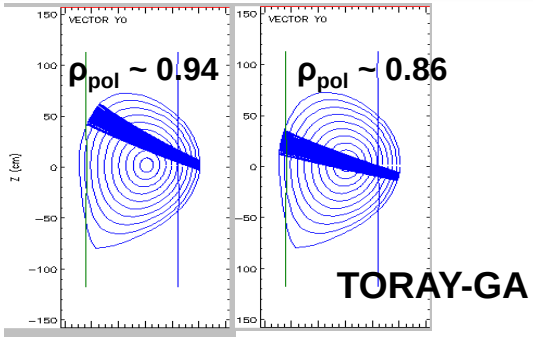
ELM mitigation effect observed by injecting ECCD at pedestal





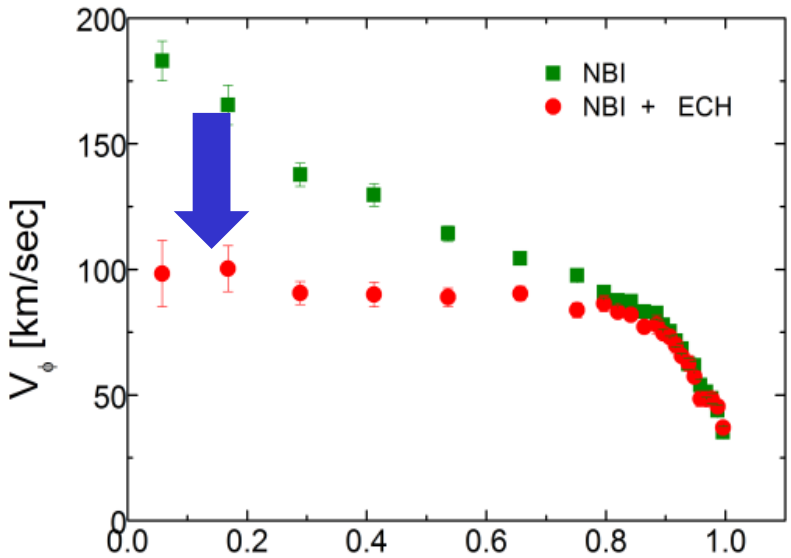
2nd Harmonics deposition at LFS

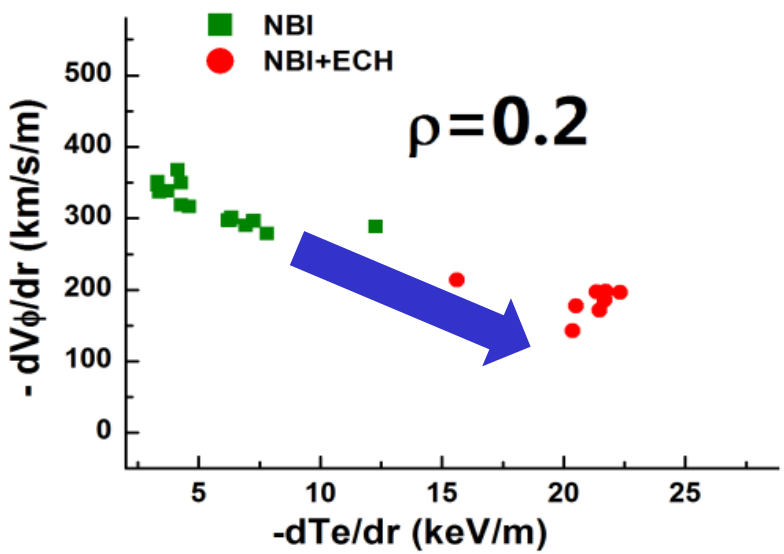
Mitigation stronger at larger ρ_{pol}

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

Profiles & fluctuations are under investigation

Significant rotation control also by core ECH (Te decrease was also measured by XICS)





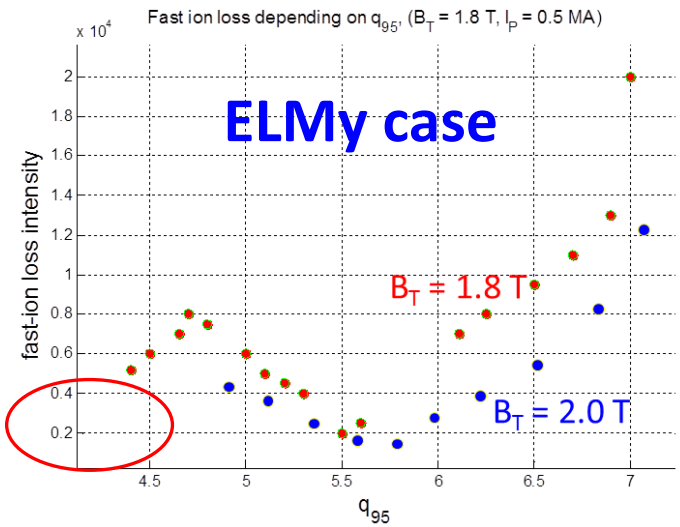
- **On-axis ECH (400kW) to co-NBI plasmas**
  - Counter-current torque in core: $-\Delta V_\phi/V_\phi \sim 30\%$
  - Strong correlation: $-\Delta(\nabla V_\phi) \sim +\Delta(\nabla T_e)$
- **Core intrinsic torque reversal upon ITG→TEM by T_e steepening**
  - Linear gyrokinetic analysis: ITG→TEM occurs for ρ=0.2 ~0.5 depending on density profile ➔ density profile is important!
  - Momentum and particle transport are strongly coupled
  - More data analysis (density and fluctuation) ongoing

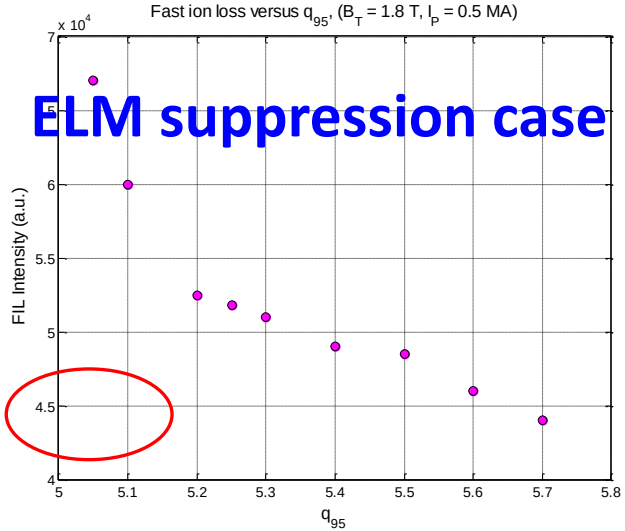
Y. Shi et al., IAEA FEC 2012

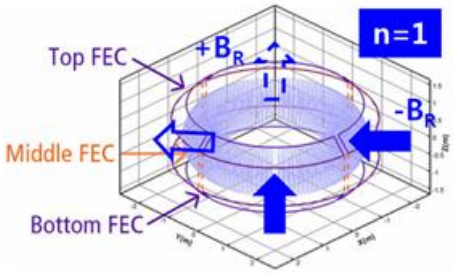
- **Possibly MHD plays a role in rotation change**
  - The internal kink mode generally appears when ECRH is injected inside q=1 surface
  - The NTV enhanced by ECRH-induced internal kink mode damps rotation

J. Seol et al., Phys. Rev. lett. (2012)

Fast ion loss associated with 3-D *magnetic perturbation* (resonant, n=1, +90°, I_p scan)







Scintillator-based fast-ion loss detector

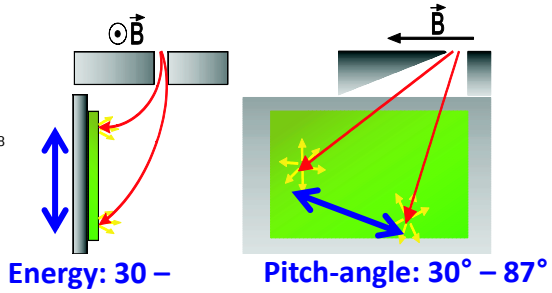
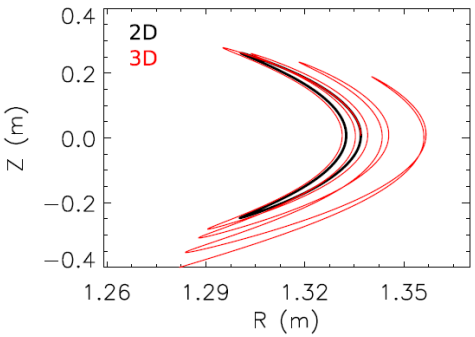


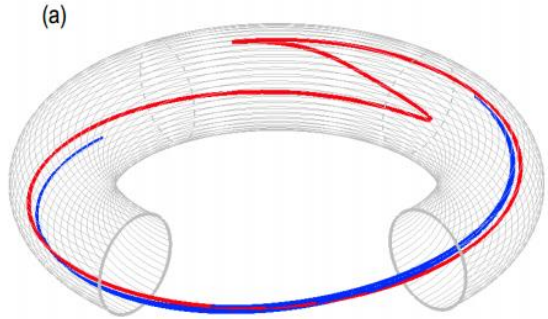
Figure courtesy of M. Garcia-Munoz

I_p scan with various conditions:

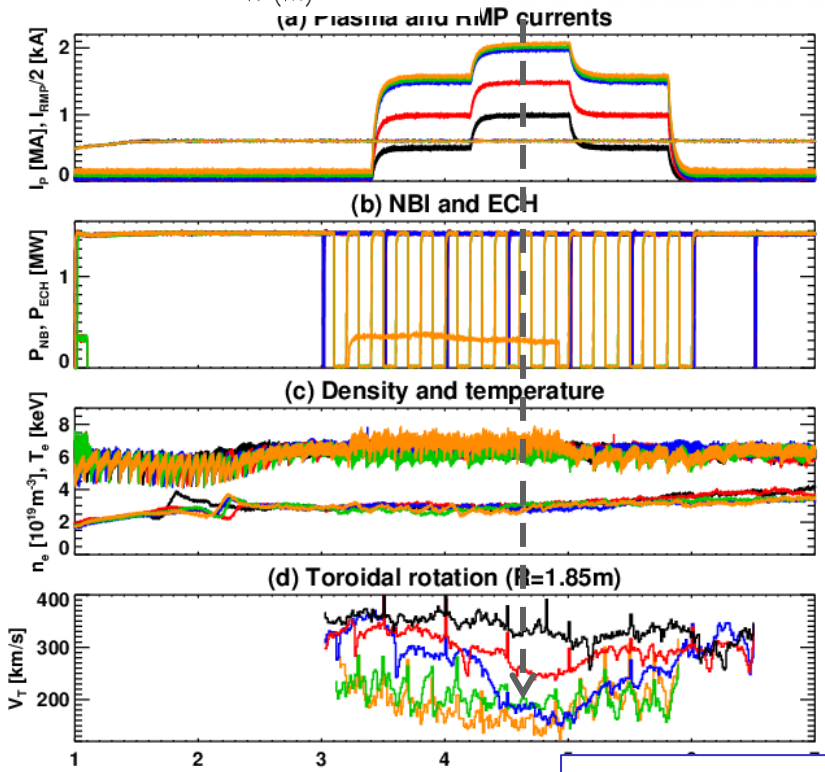
- *Seems to be existing edge helicity (q_{95}) window to increase or decrease fast-ion loss during RMP*
- *Maybe fast-ions exploring at the edge/SOL are mainly affected.*
- ***Fast-ion loss at ELM suppression is much larger than at ELMy case.***

Bounce harmonic resonance in rotation braking





- RMP causes NTV transport
- Braking increases when orbits are nearly closed
- Rotation itself reduces rotation braking by phase-mixing



RMP n=1 pulse is used for rotation braking (damping)

Rotation braking becomes stronger in a particular rotation level

- Braking becomes stronger when rotation decreases, but becomes weak when rotation further decreases

Braking peak observed is consistent with the 2nd BH, but actual analysis should be done (1st BH is suspected)

Jong-kyu Park, *et al.* PRL (2013) accepted

$V_{T,BH} \approx 110 km/s, 220k$

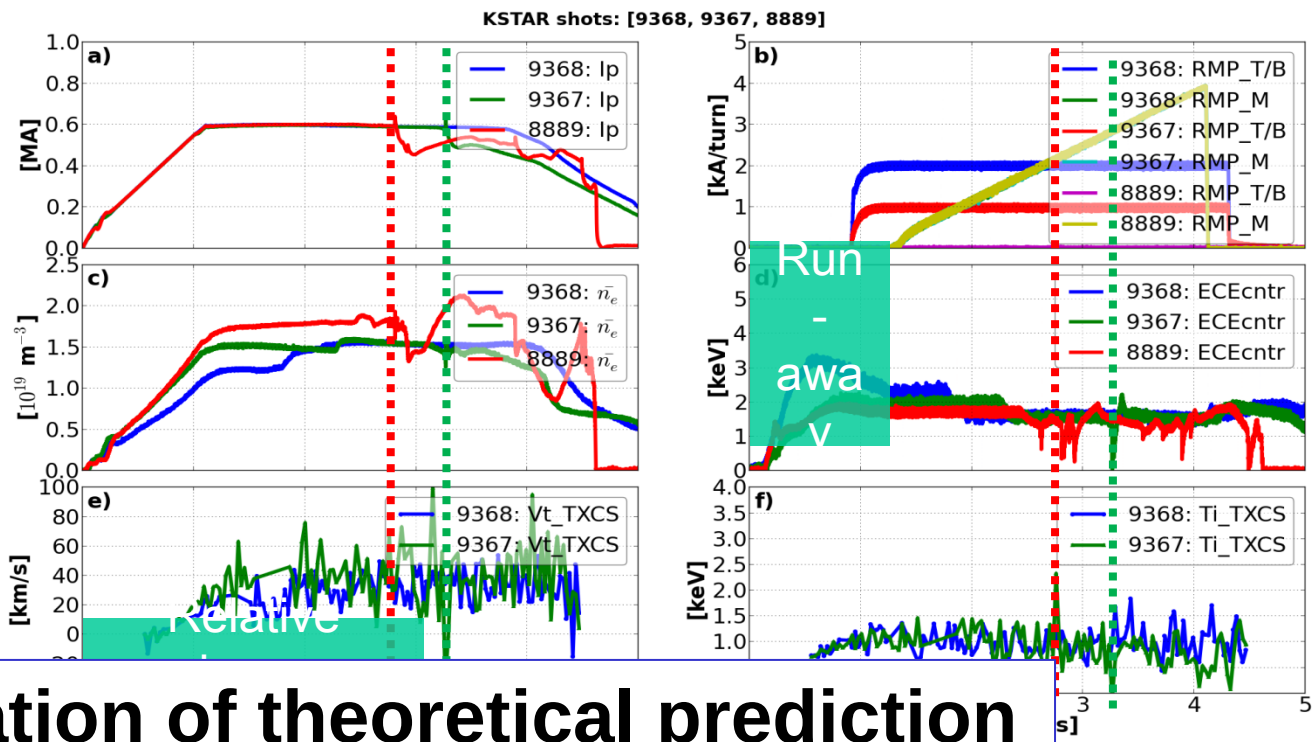
Validation of theoretical prediction

Higher n=2 even field(NRMF) discharge is less susceptible to final locking by n=1 field.

Theoritical background (A.J. Cole et al., 2007 Phys. Rev. Letters): *The plasma is **less susceptible** to error-field penetration and locking, by a factor that depends on the non-resonant error-field amplitude.*

- n=1 field is gradually increased to cause the final locking.
- n=2 even field is constantly applied during n=1 field increase.

Early locking → #8889 (no n=2) > #9367 (n=2, 1 kA/t) > #9368 (n=2, 2 kA/t) → No locking



Validation of theoretical prediction

Future

- Original aim of SC machine
- Research plan and roadmap

Toward the original aim of KSTAR and future

- **Final goal : Steady state operation with active profile controls**
  (to the time scales that wall processes were in equilibrium with the plasma)

- **In the next five years, focus would be long-pulse operation with high beta**
- Demonstrating current tokamak performance for long pulse on time scales much longer than the resistive current relaxation time
- Intrinsically stationary state with minimum profile control(ne, Ip, shaping, beta)

- **In addition, exploring ITER urgent issues** will be an important mission such as divertor heat-load control.

- **To do that, understanding of control physics parameters and securing various control knobs of particle, heat and rotation are essential**
- this effort should be done with **highly concentrating and optimizing methods considering limited our resources.**

- **There also remains many engineering issues** such as the sustainment of heating power, heat removal(diverter), magnetic senor issues in long-pulse operation

Research highlight in 2nd phase (2013-2017)

Investigation of ITER operation scenario in long-pulse high beta plasma

Sustainment of long-pulse ITER reference scenario in H-mode (β_N>2, t_{pulse}>50s)
Extension of KSTAR dimensionless parameters close to ITER class (ν^*, ρ^*, n/n_{GW})

Optimization of heat loads on the first wall and divertor (ITER hot issues)

Reliable control of ELMs and disruptions in long-pulse discharges
Control of divertor heat loads and core impurity accumulations
Effect of metal PFCs on the plasma performance

Realization of active plasma control in long-pulse discharges

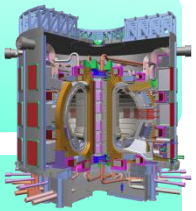
Development of realtime diagnostics and control of plasma current profiles
Active MHD control including NTMs, ELMs, and RWMs

Extension of advanced operation modes to reactor relevant conditions

Development of long-pulse Hybrid-mode (β_N>2.5)
Investigation of Advanced inductive-mode characteristics at V_T~0 and T_e~T_i

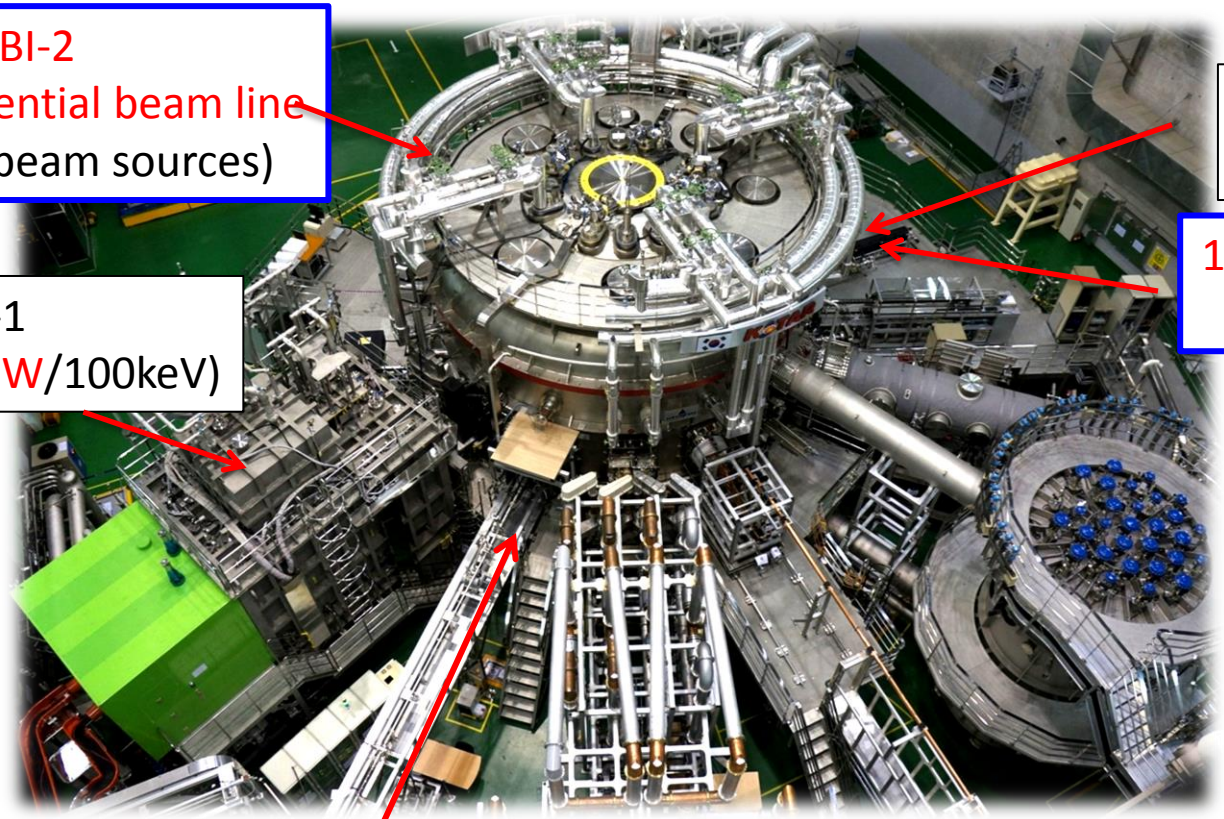
Research roadmap in 2nd phase

	2013	2014	2015	2016	2017
Long-pulse ITER Operation	Experiments on long-pulse ITER reference scenario β_N ~2 for 30s	optimal operation with limitations of SC PF coils	β_N ~2 for 50s		β_N ~2.5 for 50s
Heatloads on Dirvetor/Firstwall	Control of ELMs(RMP) 10s >	Pre-cursor detection for disruptions	Radiative divertor in long-pulse	Experiments on optimal divertor shapes	Tungsten firstwall
		High-Z impurity transport			
Realtime Control & Diagnostics	Integrated ELM control		NTM control		RWM control
	Control of n_e/T_e profiles		Integration of plasma current profile		Fully integrated PCS in long-pulse operaion
Advanced operation modes		Quiescent H-mode	Extension of Hybrid-mode in long-pulse		
			Te~Ti experiments		vT~0 experiments
Upgrade of Major Hardwares		NB: 5.5MW Thomson IVCP	NB: 6MW ECH: 1MW MSE/IRC PFC(water)	NB: 6MW ECH: 2MW RWM PS	NB: 6MW ECH: 3MW W-divertor



Next 5-yr upgrade plan of KSTAR heating systems

- Upgrade plan considering limited budget



NBI-2
Off-axis tangential beam line
(2 MW x 2 beam sources)

170 GHz ECH
(1 MW/300 s)

105/140 GHz ECH
(2 MW/300 s)

NBI-1
(3 beams, 6MW/100keV)

105/140 GHz ECH
(1 MW/300 s)

30 MHz ICRF
(2 MW/300 s)

5 GHz LHCD
(1 MW/300 s)

More than double of present heating power

Ready for future

- **Control knob**

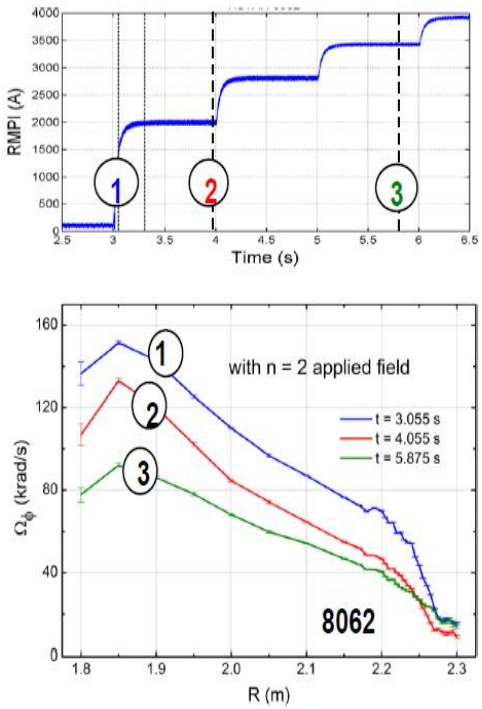
  Momentum, NTM(Sawtooth), Disruption, density
- **Diagnostic capability**
- **RWM**

Non-Resonant Magnetic Perturbation and ECH provides effective tools for rotation control

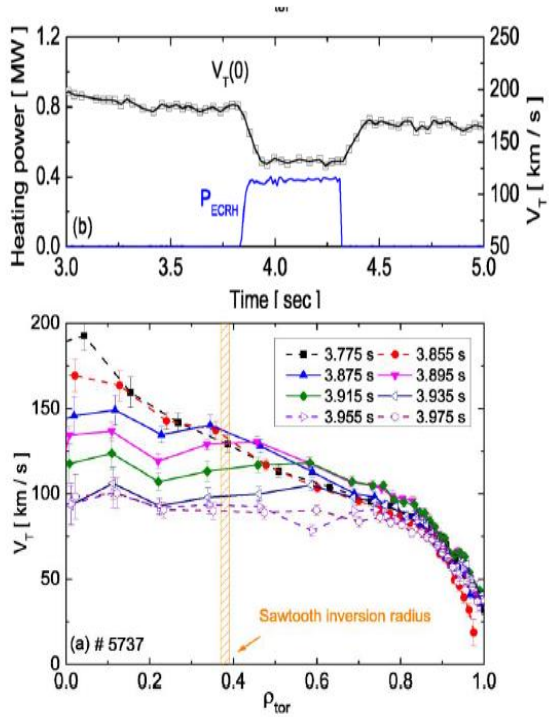
- Rotation control using IVCC
  - Toroidal rotation decrease depends on the level of IVCC current.
  - IVCC could be applicable for the low rotation experiments.

- Rotation control using ECH
  - Core toroidal rotation speed was reduced during on-axis ECH injection

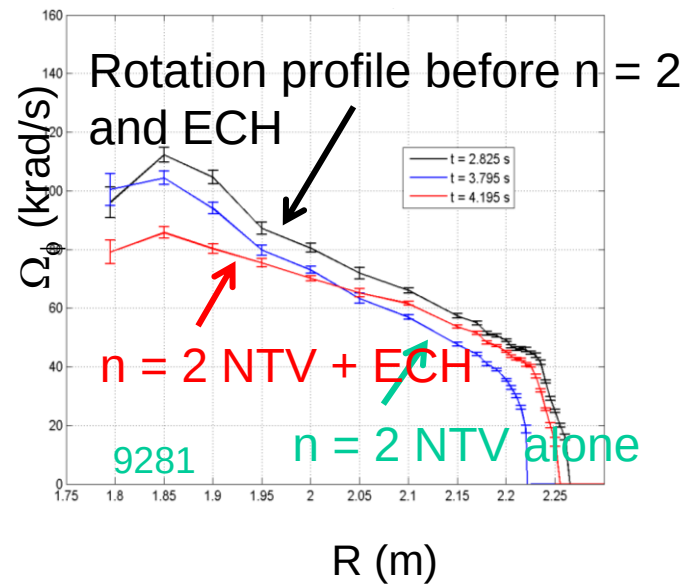
Rotation profile alteration with combined IVCC n = 2 NTV + ECH (110 + 170G)Hz)



Rotation change according to n=2, non-RMP



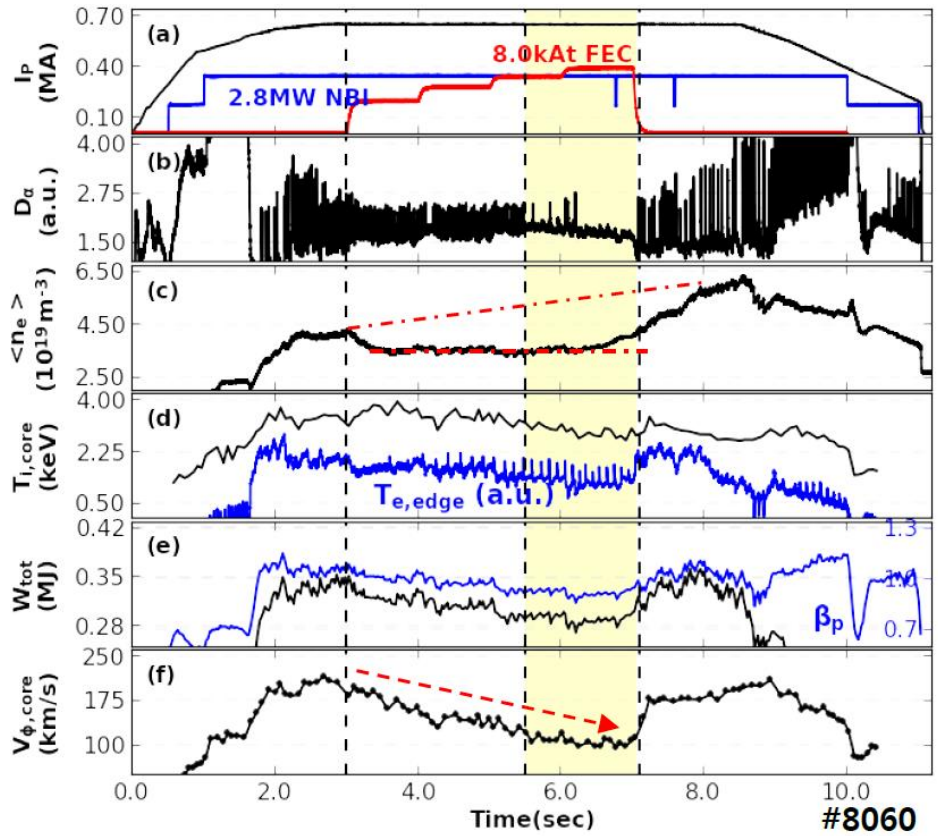
Rotation change due to ECH



Not optimized

RMP could be a good option for density control (pump-out), in addition to ELM control

w/o in-vessel cryopump, line density is kept stationary in ELMy H-mode discharges
Effect of Non-resonant component is weak for density pump-out

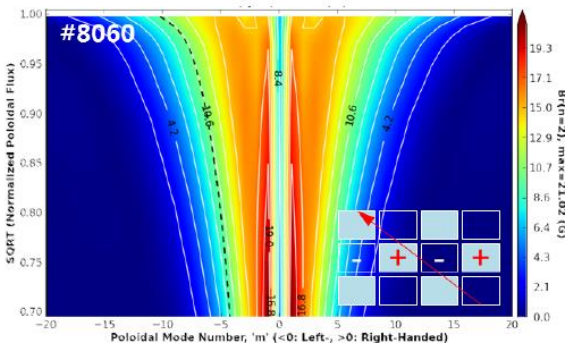


Dependent on q_{95}

- B_T=1.5T, I_P=0.65MA➔ q_{95}~3.7
- **Use n=2 mid-plane coil alone**

- **Δn_e ~ I_{FEC}**

- **Significant V_ϕ drop (~50%)**
  : Due to strong magnetic damping via JxB and NTV



Invessel cryo pump is routinely operated in 2015
Pellet would be available around 2016

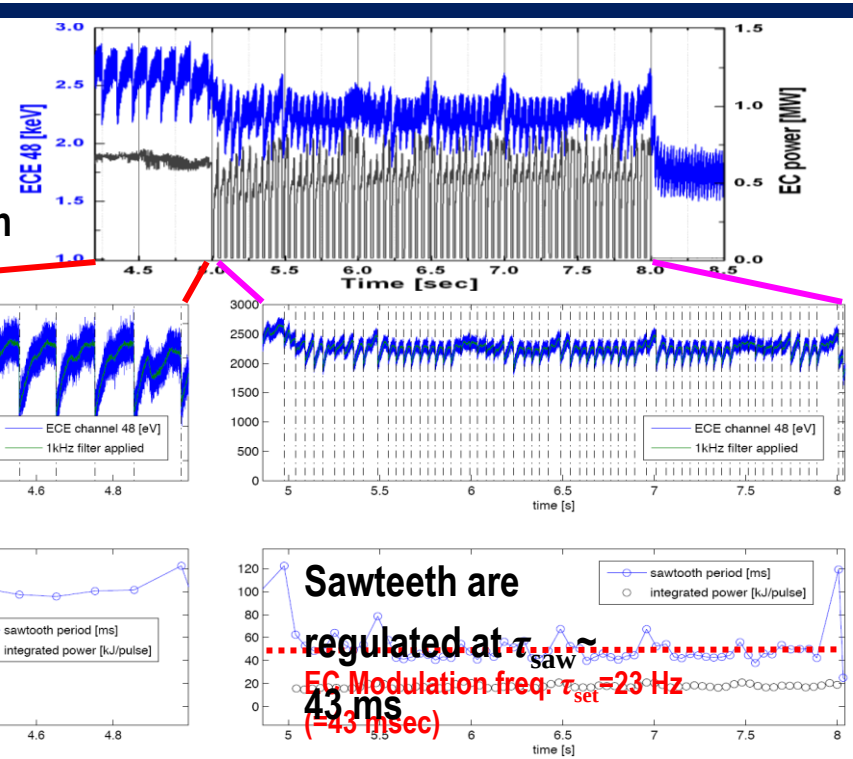
Sawtooth / NTM control (Sawtooth locking)

- ECH/CD is very efficient to modify the sawtooth period [1]

1. By **tailoring the profiles** of j_{CD} which is associated by the magnetic shear **on the q=1 surface (= s_1)**
   - Experimental results are well corresponded with the other tokamaks
2. **Possible of injection locking** by the **modulated EC beam** [2,3]

❖**EC injection**

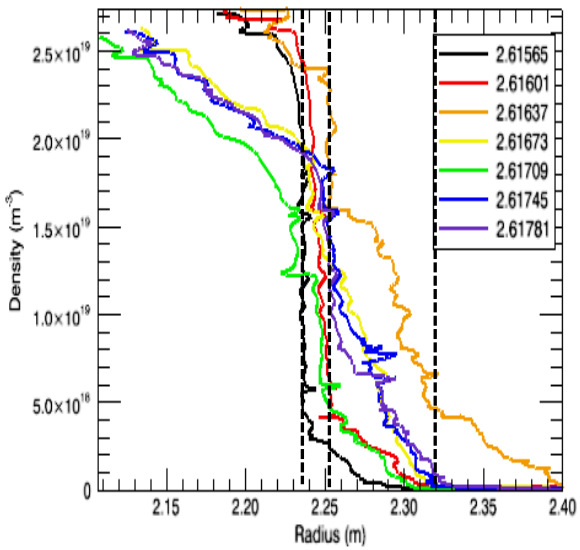
- **z=26 cm from mid-plane**
- **τ_{set}=43 msec (=23 Hz with 70 % duty)**



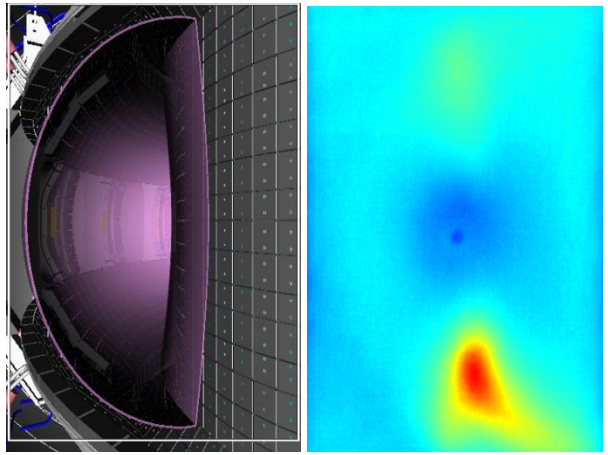
[1] C. Angioni, T.P. Goodman, M.A. Henderson and O. Sauter, Nucl. Fus. **43** 455 (2003)
[2] T. P. Goodman *et al.*, Phys. Rev. Lett. **106** 245002 (2011)
[3] G. Witvoet *et al.*, Nucl. Fusion **51** 103043 (2011).

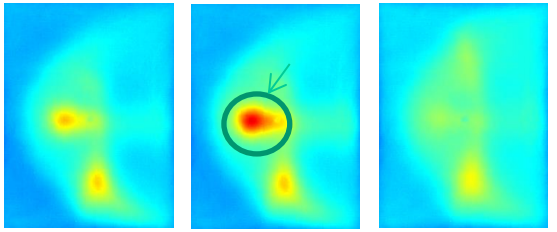
Upgrade plan for profile diagnostics

High resolution Thomson/ECE : n_e/T_e profile control – RMP/SMBI(2014)
Poloidal/Toroidal CES : rotation profile control (2015) – NRMF/ECH
MSE/Li-beam (both polarimetric+spectral) : current profile control (2015)
2D/3D ECE imaging : sawtooth/NTM/AEs control (2016)
Reflectometry : mid-plane gap control (2014)



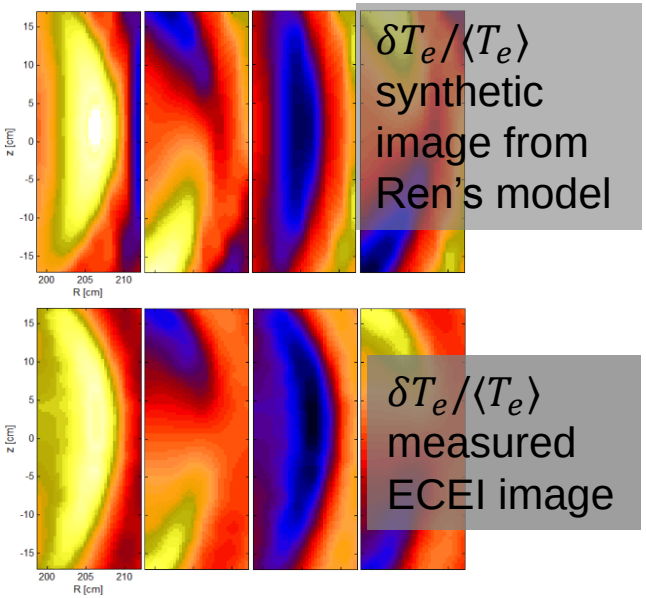
Potentials for real-time determination of LCFS by X-mode reflectometry





1200 1320 2250

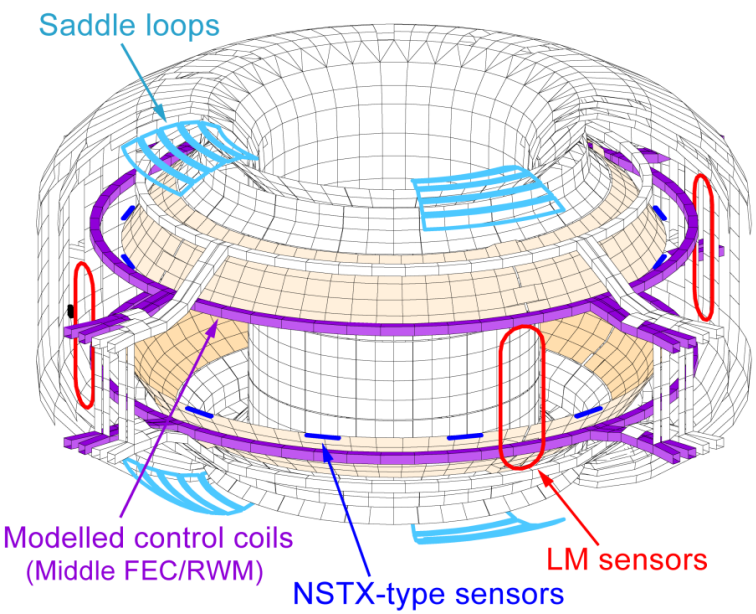
Imaging bolometer

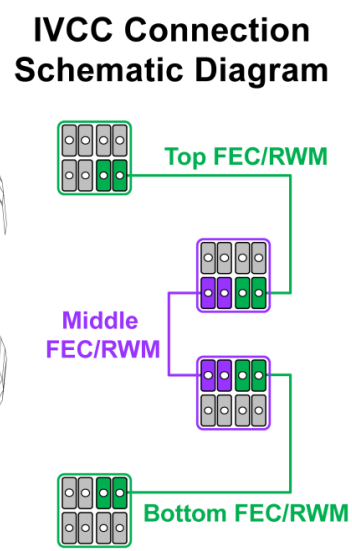


Potentials for real-time pattern matching of positions of by X/O - points of tearing modes by 2D ECE imaging (M. J. Choi, POSTECH)

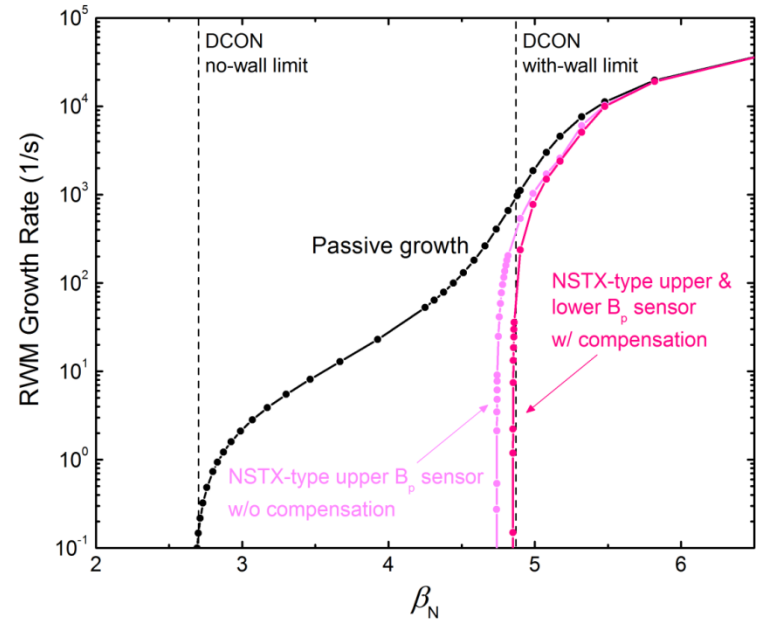
Upgrade plan for In-vessel Control Coils

- In addition to the fast vertical control and static RMP operation, various control research using in-vessel coils and broadband power supplies
  - 5 sets of broadband power supplies (+/- 4kA, +/- 1 kV, dc to a few kHz)
  - ELM mitigation / triggering / suppression using RMP or NRMP (n=1, 2)
  - Fast or slow Error Field Correction
  - NTV rotation profile alternation / control
  - **Feedback stabilization of Resistive Wall Modes**





S. Sabbagh & Y. Park
(Columbia Univ)



Effective control of RWM with given power supplies & optimized SLs

Summary

- **KSTAR is ready for long-pulse operation and pulse length is successfully extended to more than 10 seconds**

  With heating & CD capability(~10 MW)

  With decent level of plasma current up to 1 MA (B_T=2.5 T)

  With efficient isoflux shape control

- **KSTAR is ready for the high beta and MHD study above no-wall limit**

  starts to develop advanced scenario target without sawteeth using early diverting & heating

- **KSTAR is equipped with efficient techniques for rotation & density control in long-pulse operation** (n=1 & n=2 external coils, ECH heating) and improving diagnostic systems.

- **KSTAR is focusing the long-pulse advanced target with ITER urgent issues during the next five years and this efforts should be done with highly concentrating and optimizing methods considering limited our resources and collaboration is essential.**

Thanks,

Welcome to KSTAR researches.

KSTAR conference, Feb. 2014

KSTAR 2014 campaign, Sep.(plasma experiment)

From KSTAR delegation

Pedestal(Siwoo),

MHD(Byongho)

Transport(Chunho)

Theory/Modelling(Jinyong)

From PPPL

MHD(Steve), H-mode(Joon Wook), NTV(Jongkyu), ECH(Ellis)