Overview of the KSTAR Research in Support of ITER and DEMO

October 17th, 2016

Yeong-Kook Oh[1]

On behalf of
KSTAR TEAM and Research Collaborators

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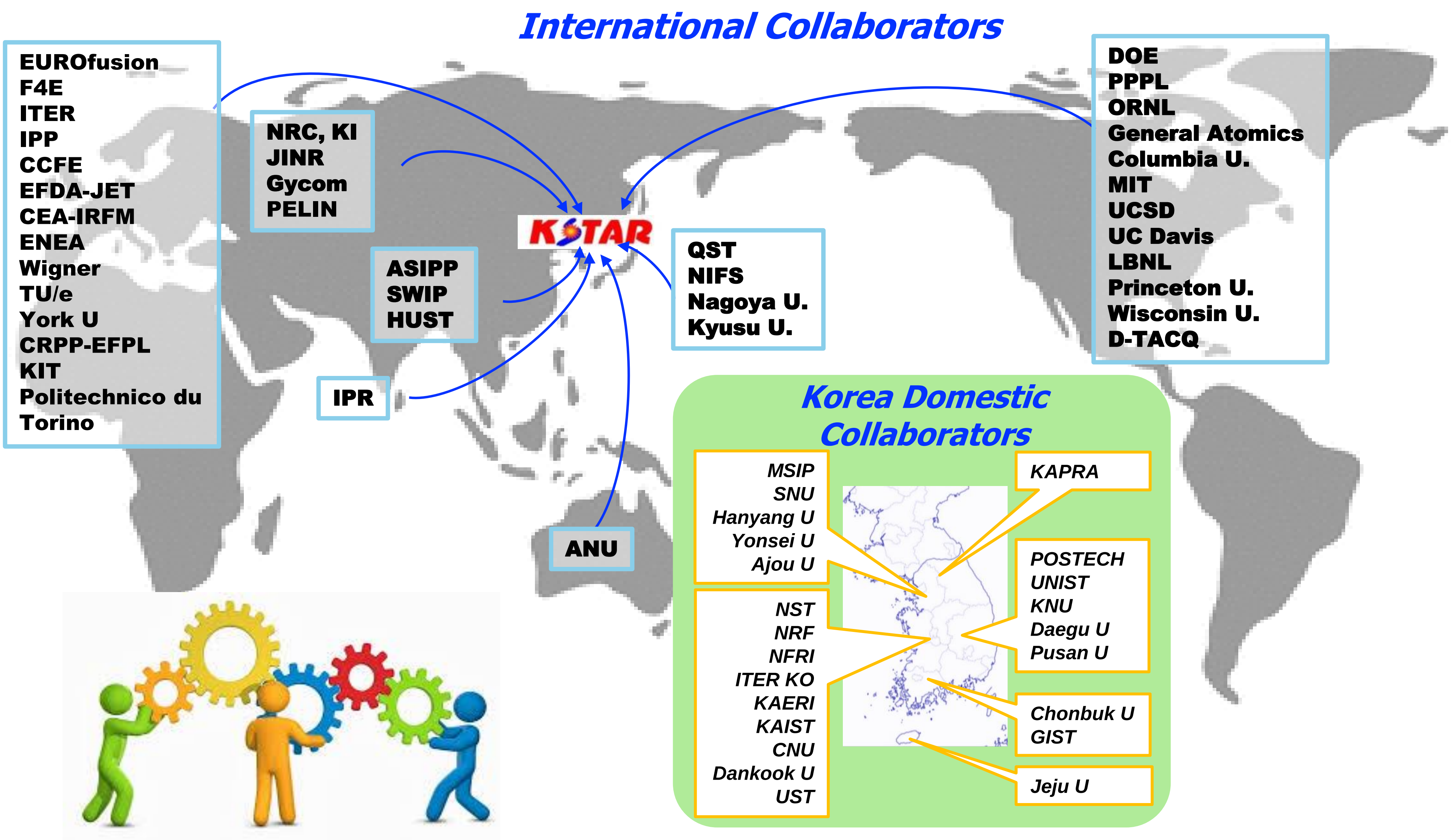
Ministry of Science, ICT and Future Planning

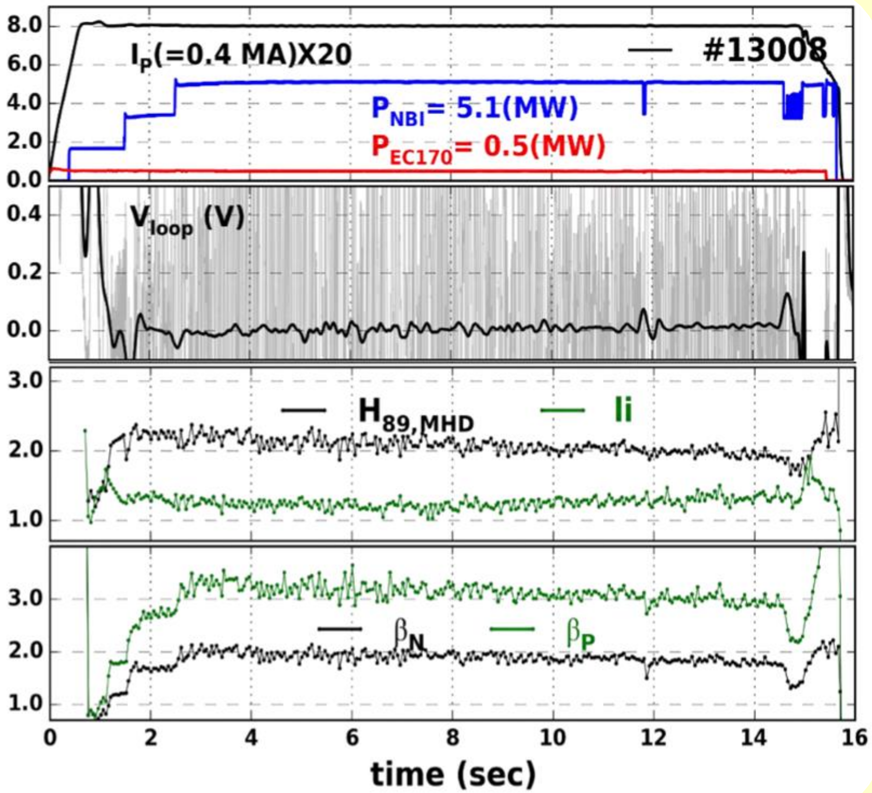
NFRI 국가핵융합연구소 National Fusion Research Institute

We appreciate all the research collaborators for their contribution to KSTAR program



Fully non inductive high beta (β_P > 3) discharge and physics validation of sawtooth and turbulence

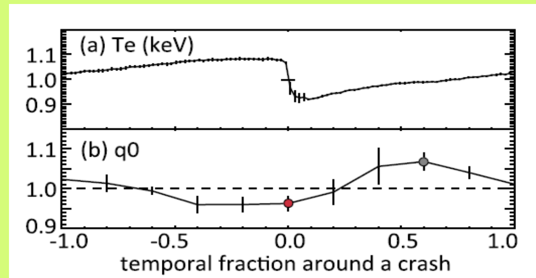
High β_P steady-state (fully non-inductive) discharge and extension to 70s



B_T=2.9 T, I_P=0.4 MA, P_{NBI}=5.0 MW, P_{ECH}~ 0.8 MW,
f_{NI} ~ 1, f_{bs} < 0.5, β_p > 3, β_N ~ 2, H_{89} ~ 2.0, li ~ 1.2

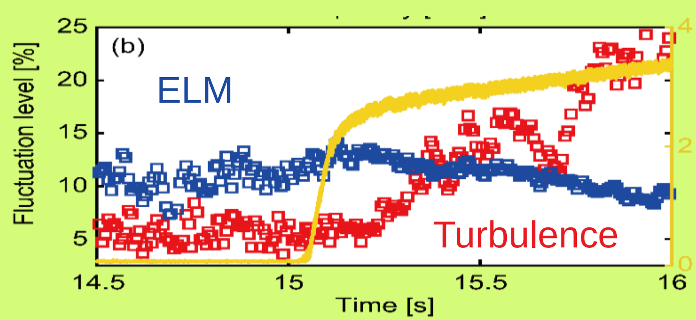
Physics validation of $q_0 \geq 1.0$ in MHD quiescent time after the sawtooth crash

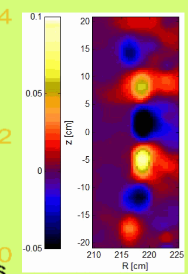
- 30 yrs ago, at Kyoto IAEA, it was reported that $q_0 \cong$ 0.75 ± 0.03 (TEXTOR and TFTR)
- In 2016, KSTAR validates $q_0 \geq 1.0$



MSE measured $q_0 \cong 1.0 \pm 0.03$ but uncertainty from E_r and κ makes q_0 value uncertain

Nonlinear interaction btw ELM & turbulent eddies induced by RMP





OUTLINE

- ***Introduction***
  - ***Research directions***
  - ***Unique research tools on KSTAR and role for the test bed for ITER and beyond***

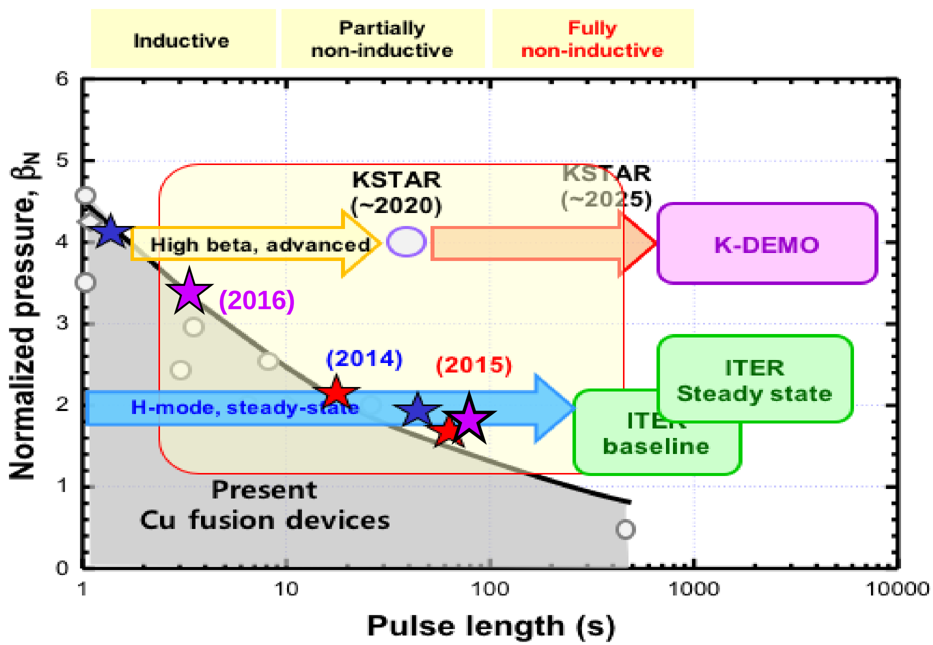
- ***Research highlights of KSTAR***
  - ***Extension of H-mode and high performance discharges into long pulse and steady-state***
  - ***Reliable ELM crash free operation and analysis***
  - ***Exploring confinement and stability issues using KSTAR unique research tools***

- ***Future plan & summary***

Research directions and key parameters in KSTAR

❑ Research directions of KSTAR

- Extend the reference H-mode and high performance discharge into long-pulse utilizing SC magnets
- Explore confinement and stability issues using the KSTAR uniqueness
- Exploit new stable high-beta and advanced plasma operation regime for K-DEMO



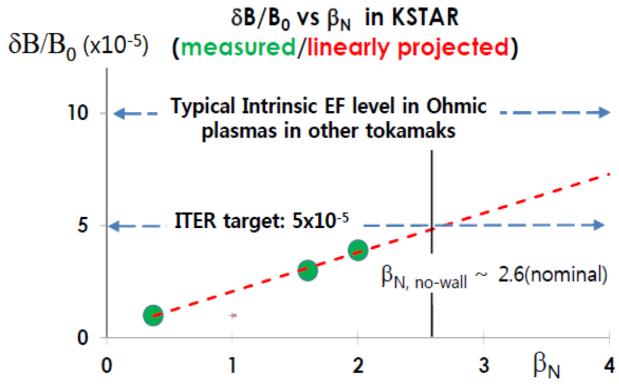
❑ Key parameters of KSTAR, ITER & K-DEMO

Parameters	KSTAR (achieved)	ITER (Baseline)	K-DEMO (Option II)
Major radius, R_0 [m]	1.8	6.2	6.8
Minor radius, a [m]	0.5	2.0	2.1
Elongation, κ	2.0 (1.8)	1.7	1.8
Triangularity, δ	0.8	0.33	0.63
Plasma shape	DN, SN	SN	DN (SN)
Plasma current, I_P [MA]	**2.0 (1.0)**	15	> 12
Toroidal field, B_0 [T]	**3.5**	5.3	7.4
H-mode duration [sec]	**300 (70)**	400	SS
β_N	**5.0 (4.3)**	~ 2.0	~ 4.2
f_{bs}			~ 0.6
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD [MW]	~ 28 (10)	~ 73	160
PFC	C, W	W	W
Fusion power, P_{th} [GW]		~0.5	~ 2.1

KSTAR has unique research tools as the test bed for ITER and K-DEMO

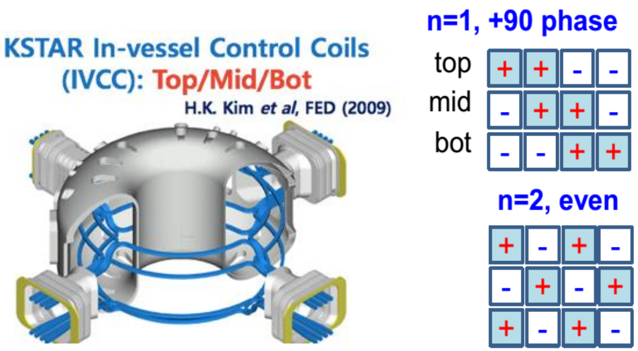
- **Lowest intrinsic error field ($\delta B/B0 \sim 1x10^{-5}$) and low magnetic ripple (~0.05%)**
  - Lower L-H transition threshold power
  - High beta operation accessible without error field correction

Y. In (NFRI) NF2015



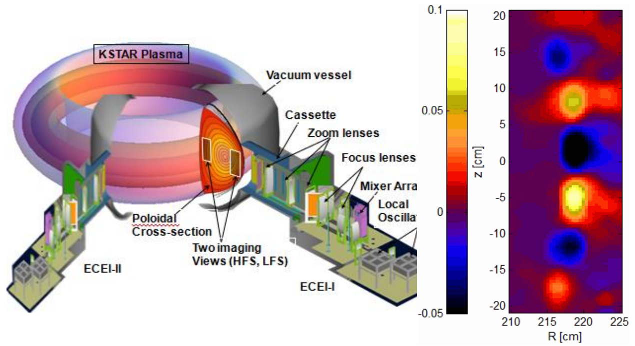
- **ITER relevant In-vessel control coils (IVCC) for ELM control**
  - Three poloidal rows (top / middle / bottom) same as ITER
  - Stable ELM crash suppression/mitigation at n=1, 2 and mixed

Y.M. Jeon (NFRI) PRL2012



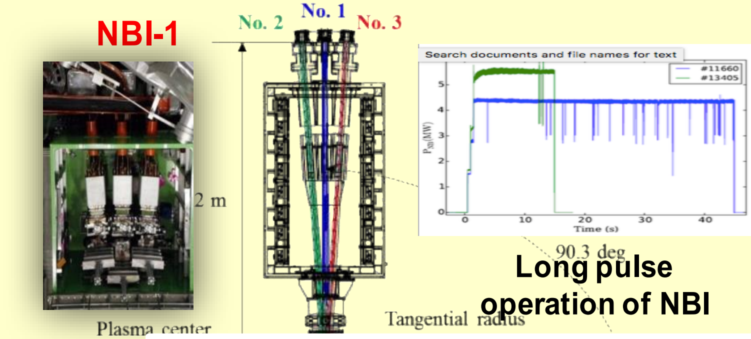
- **Advanced 2D/3D imaging diagnostics**
  - 2D/3D ECEI, MIR, BES, etc
  - New physics from the measurement of turbulence and MHD instabilities

G.S. Yun (POSTECH) PRL2011



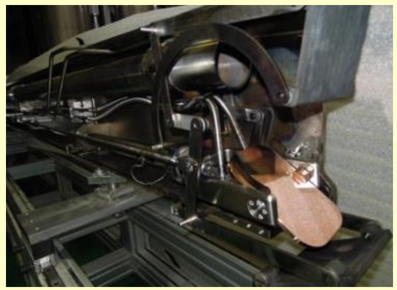
Status of heating & current driving systems in KSTAR

Heating &CD in 2016 ~10 MW
NBI 5.5 MW, 100 keV (on-axis, ~70s)
ECH/CD 1 MW, 105/140 GHz 1 MW, 170 GHz
LHCD 0.5 MW, 5 GHz
ICRF 2 MW, 30-60 MHz
Helicon CD 0.3 MW, 0.5 GHz



Long pulse operation of NBI

KAERI



Water-cooled steering mirror (collab. with PPPL)

Prototype Helicon CD & fully active LHCD antenna

POSTECH PPPL GENERAL ATOMICS AND AFFILIATED COMPANIES Alcator C-Mod IRFM SLAC

Goal of H&CD ~ 28 MW, 300s
NBI (~'18) 6 MW, 100 keV, on-axis 6 MW, 100 keV, on/off-axis
ECH/CD 2 MW, 105/140 GHz 4 MW, 170/140 GHz
LHCD 5 GHz, 4 MW
ICRF/ICWC 30-60 MHz, 2 MW
Helicon CD 0.5 GHz, 4 MW

- Fueling (SMBI, pellet, divertor puffing)
- In-vessel cryo-pump
- Wall conditioning under TF field
- Active water cooling on PFC
- Castellated PFC/Divertor tile

Diagnostics systems developed through collaboration

❑ Profile Diagnostics

- Thomson Scattering — NIFS, QST
- ECE Radiometer — NIFS, KYUSHU UNIVERSITY, KAERI
- CES / XICS — NIFS
- MSE / iMSE — TU/e, Australian National University
- Reflectometer — PPPL, ASIPP
- Reciprocating Probe

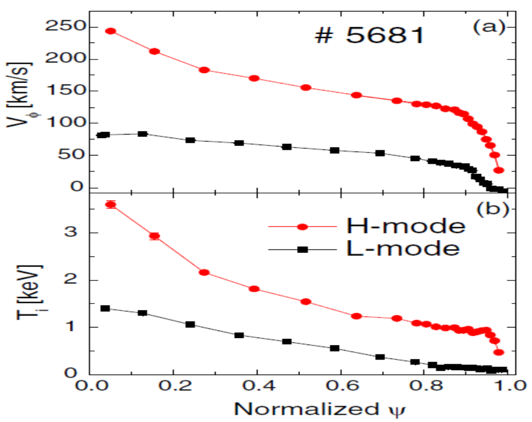
❑ Imaging Diagnostics

- ECEI — UNIST, POSTECH
- MIR — KNU, UCDAVIS
- BES — Wigner
- Visible TV
- Tangential & Div IRTV
- Soft X-ray Imaging — KAIST, ENEA
- Imaging Bolometer — NIFS, KAIST

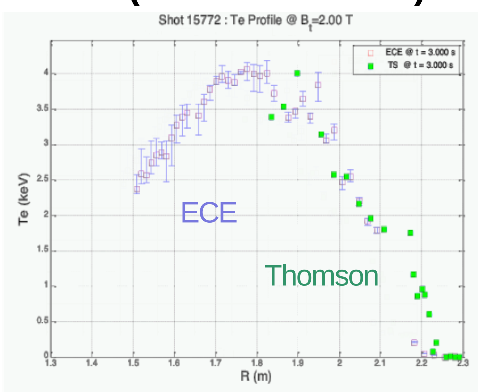
❑ Survey Diagnostics

- Magnetic Diagnostics — ASIPP
- Edge Probe — HYU
- Interferometers — SEOUL NATIONAL UNIVERSITY, NIFS, QST
- FILD
- VUV Spectrometer — KAIST, iter KOREA
- Deposition Probe
- Visible Filterscope — OAK RIDGE National Laboratory
- Neutron Spectrom. — JINR

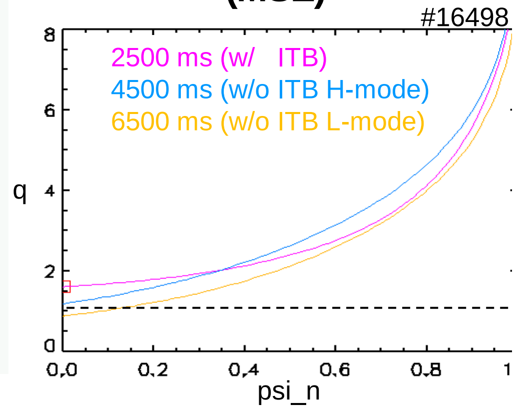
Ti & rotation profile
(CES / XICS)



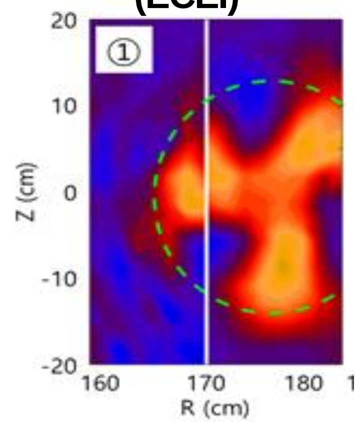
Te profile
(ECE & Thomson)



q profile
(MSE)



Turbulence
(ECEI)



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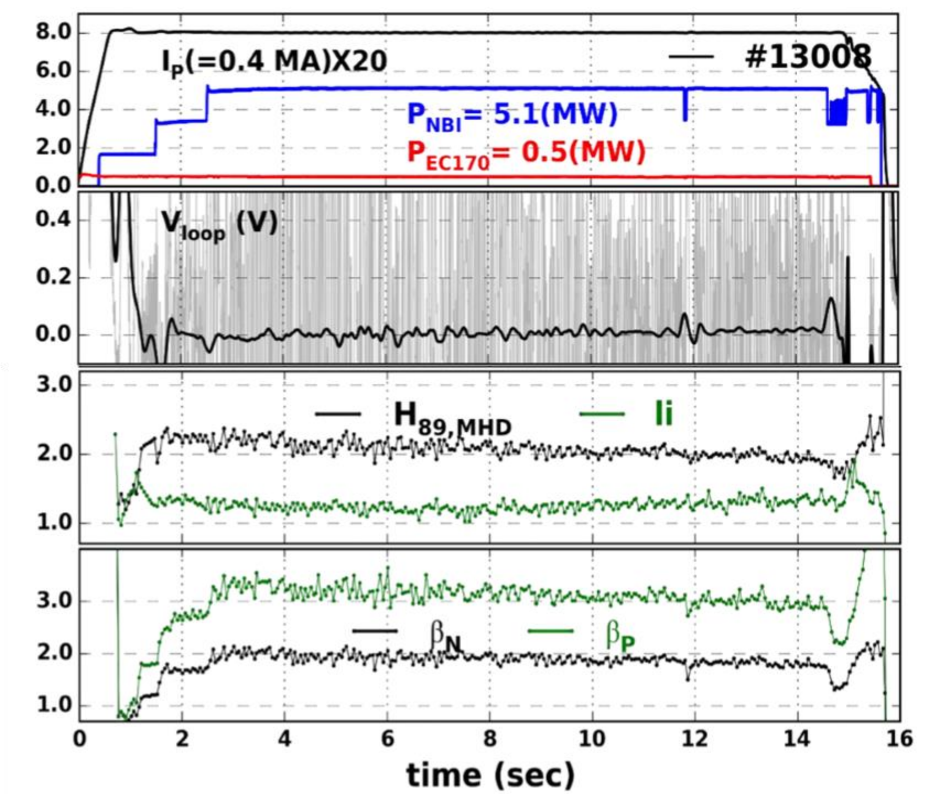
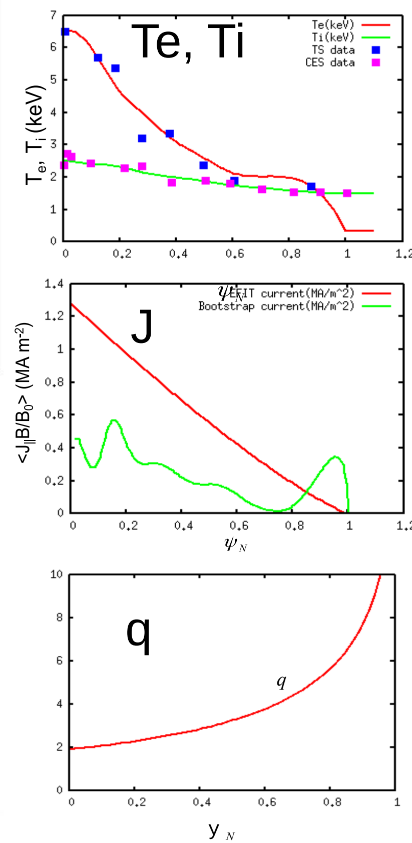
Fully non-inductive current drive discharge has been achieved with high poloidal beta ($\beta_p > 3$)

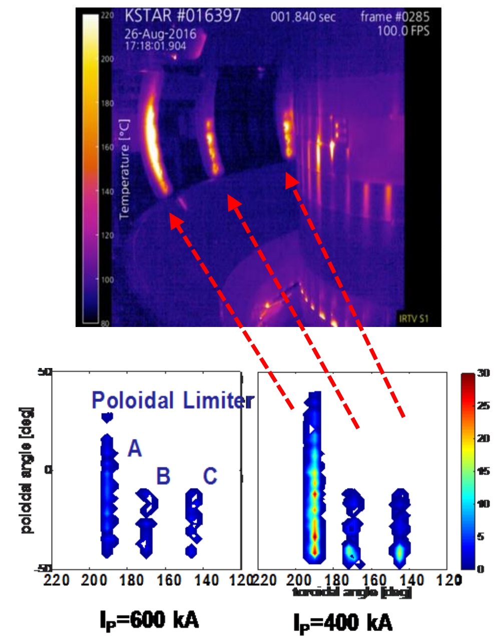
- Fully non-inductive discharge without limits in flux and MVA
  - $f_{NI} \sim 1$, $f_{BS} < 0.5$, $\beta_p > 3$, $\beta_N \sim 2$, $H_{89} \sim 2.0$, $li \sim 1.2$,
  - B_T=2.9 T, I_P=0.4 MA, P_{NBI}=5.0 MW, P_{ECH}~ 0.8 MW
- Early termination due to safety interlock (heat load on poloidal limiter)
  - Increases fast ion loss from neutral beam at lower plasma current



(EX/P4-1) S.W. Yoon (NFRI), et al



Temperature rise in poloidal limiter at long pulse operation (IRTV)

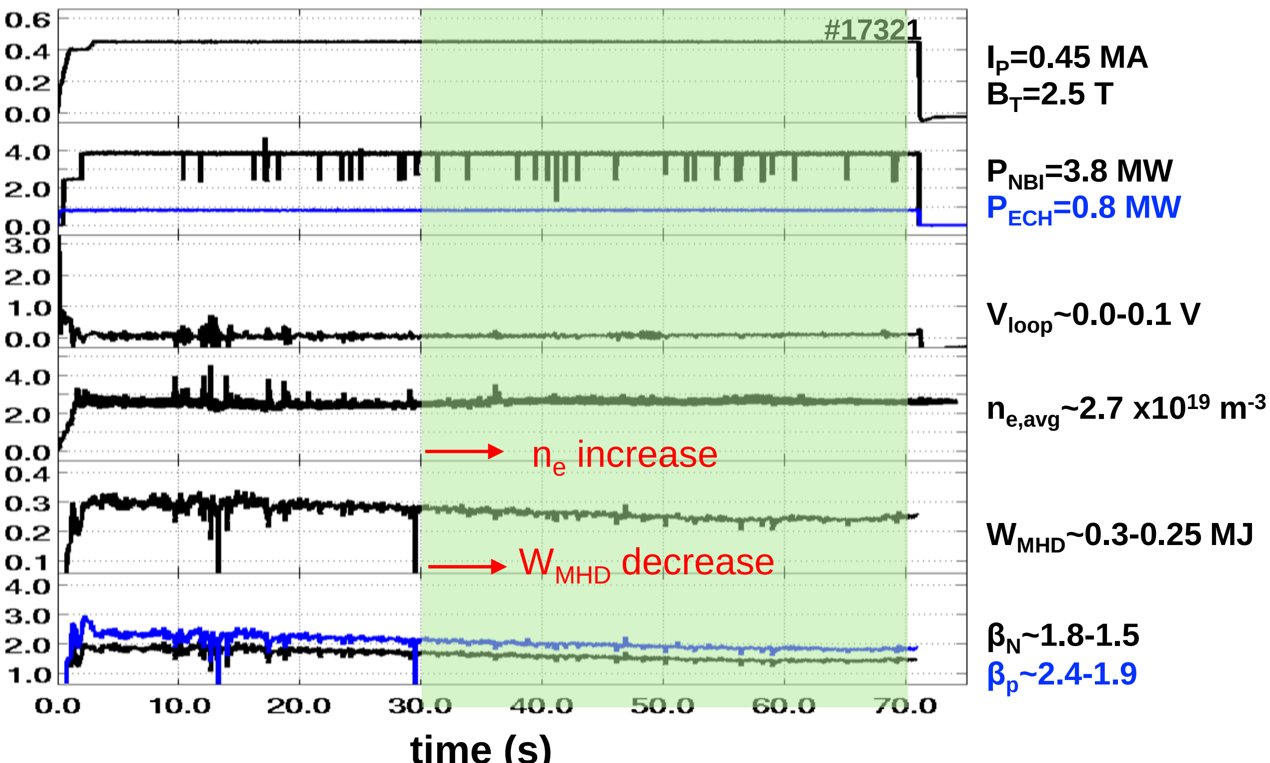


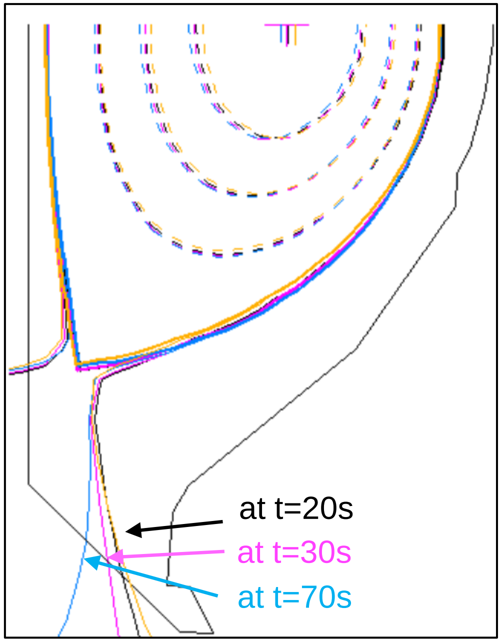
Good agreement with prompt loss calculation

Courtesy of K. Shinohara (QST)

H-mode discharge with highly non inductive current drive has been extended over 1 min (~ 70s)

- Problem of heatload on poloidal limiter was resolved by reduced NBI power (5.1 → 3.8 MW) and increased gap between plasma and PFC
  - $f_{NI} \leq 1$, β_p : 2.4 ~ 1.9, β_N ~ 1.8 ~ 1.5, W_{MHD} ~ 0.3 – 0.25 MJ
  - B_T=2.5 T, I_P=0.45 MA, P_{NBI}=3.8 MW, P_{ECH}~ 0.8 MW
- However density and loop voltage increased slowly from 30s due to un-controlled striking point → need density control and striking point control



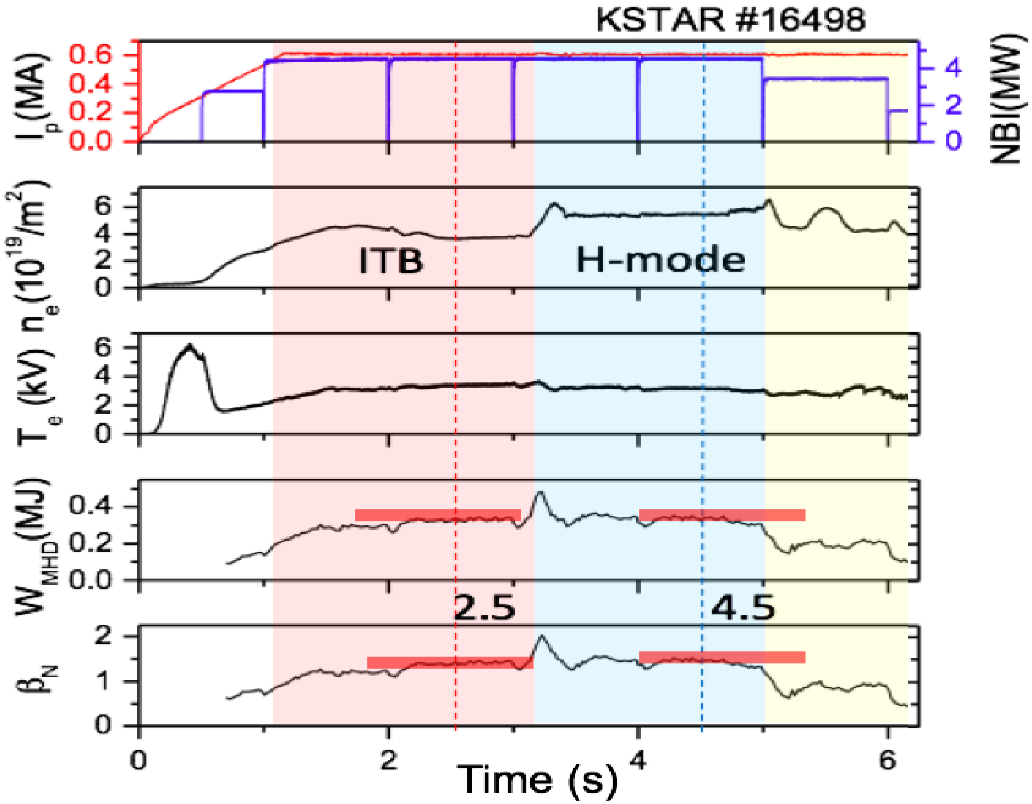


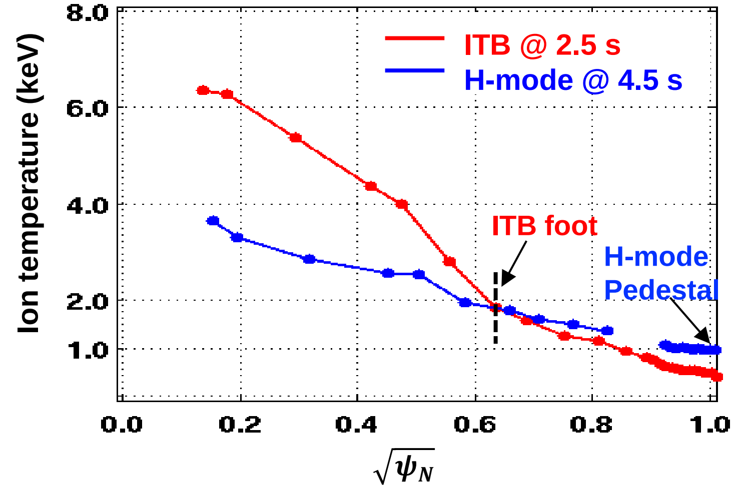
Degradation may comes from shift of outer strike point

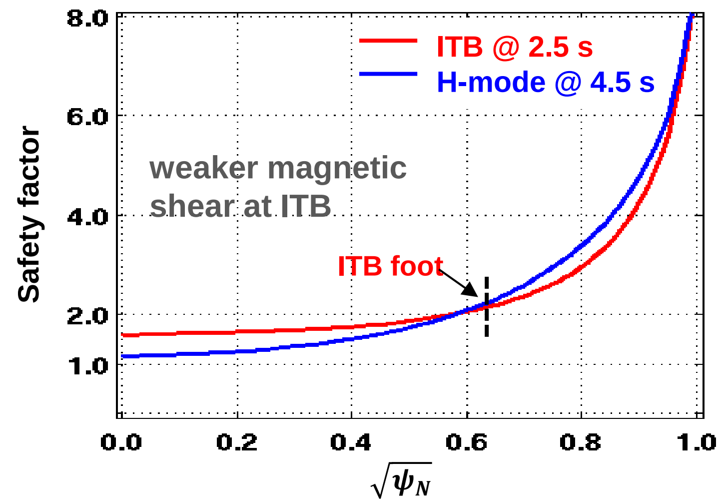
EX/P4-1, S.-W. Yoon (NFRI), et al

KSTAR observed ITB formation in L-mode discharge with the confinement comparable to that of H-mode

- ❑ ITB (internal transport barrier) formed at electron and ion temperature profiles
  - ITB could last up to 10s (> 40 τ_E).
- ❑ Significant improvement in confinement (stored energy and β_N) with comparable to that of H-mode discharge



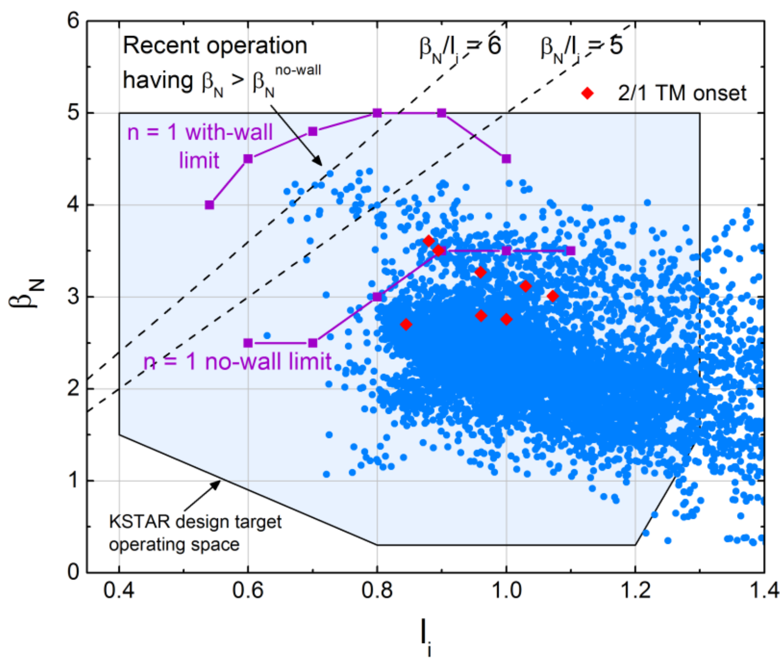




Courtesy of J. Chung, H.S. Kim (NFRI)

Higher β_N and lower q95 discharges are under development for the stability limit research

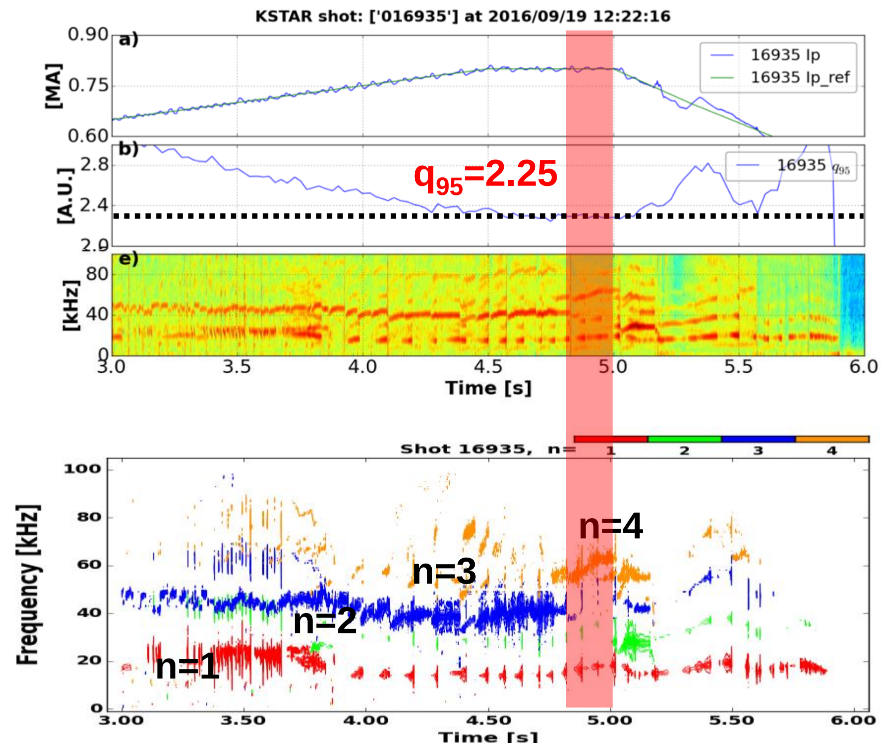
- **KSTAR H-mode equilibria have reached and exceeded the computed n = 1 ideal no-wall stability limit**
  - Highest β_N = 4.3, β_N/l_i =6.3
  - High $\beta_N > \beta_N^{no\text{-}wall}$ operation mostly limited by 2/1 mode (β_N =3.3 sustained 3 s)



Y.S. Park, S. Sabbagh (Columbia U), et al, NF 2013

(EX/P4-2), Y.S. Park (Columbia U), et al

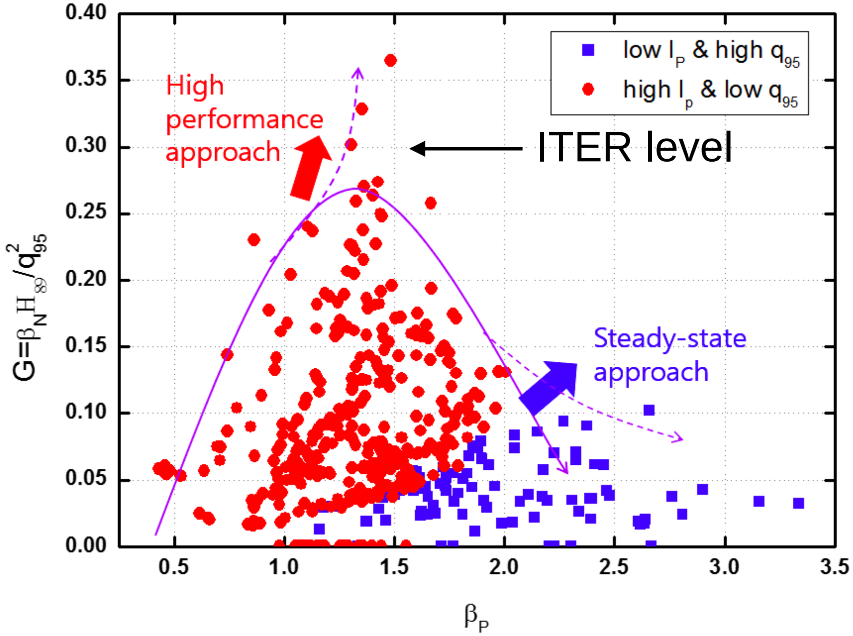
- **Attempt lower q_{95} (< 2.3) discharge to minimize harmful MHDs (low m/n)**
  - Low m/n rational surfaces are pushed out
  - Removal of strong n=3 mode brought the confinement recovery (red shade).



Courtesy of J. Kim (NFRI) et al

Development of hybrid and reverse shear scenarios for high confinement regime

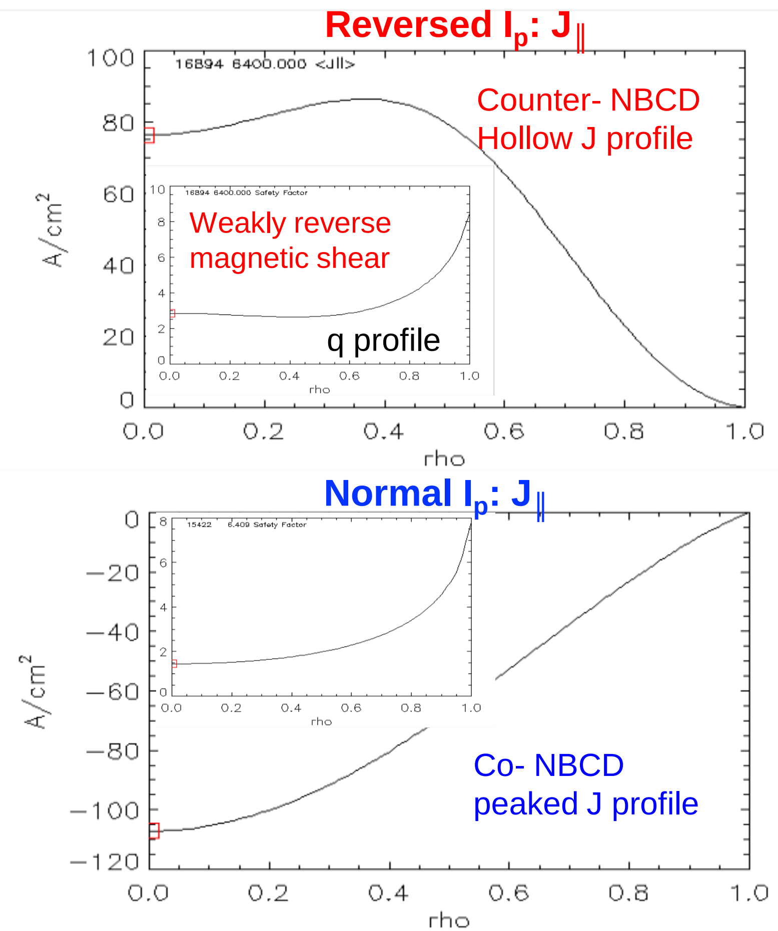
- **In KSTAR, hybrid mode was achieved by beam timing control in H-mode, and sustained for 5-8 s without any harmful MHD activities**
  - $G\ (= \beta_N H_{89}/q_{95}^2) \sim 0.38$,
  - $H_{89} < 2.3$, $\beta_N < 2.7$ at $q_{95} = 3.8$-4.5
  - It was close to ITER baseline (G = 0.4) and above ITER steady state (G = 0.3)



Courtesy of Y.S. Na (SNU), et al

SEOUL NATIONAL UNIVERSITY

- **Weak reverse shear profile achieved by revered I_p operation due to strong counter tangential NBCD**



Courtesy of J. Kim (NFRI) et al

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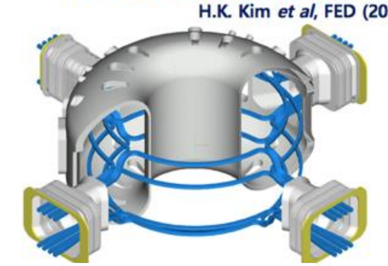
Demonstration of extremely reliable ELM crash suppression (~ 10 s) under static and rotating RMP

- ❑ Robust ELM crash suppression is one of the high priority issues in ITER with W wall.
- ❑ Recently, KSTAR has demonstrated very stable ELM crash suppression under static and rotation of the RMP (resonance magnetic perturbation).
  - Wider q_{95} = 5±0.25 (relaxed constraint), Rx or triangularity dependance (Delta_lower ~ 0.74 ± 0.04)

KSTAR In-vessel Control Coils (IVCC): Top/Mid/Bot

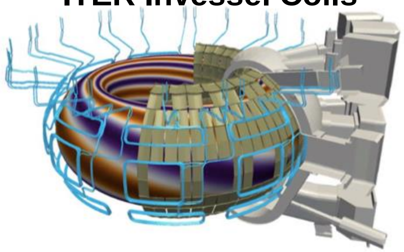
H.K. Kim *et al*, FED (2009)



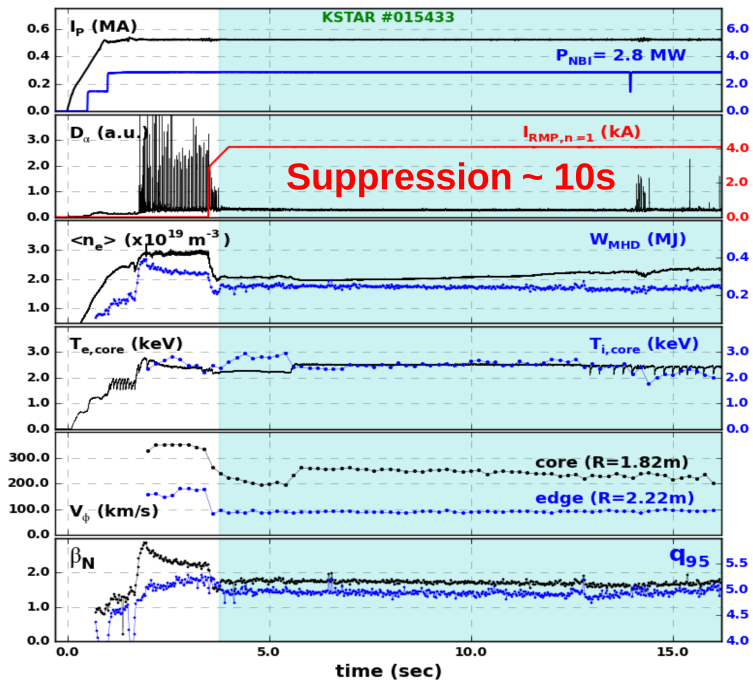
n=1, +90 phase

top	+	+	-	-
mid	-	+	+	-
bot	-	-	+	+

ITER Invessel Coils

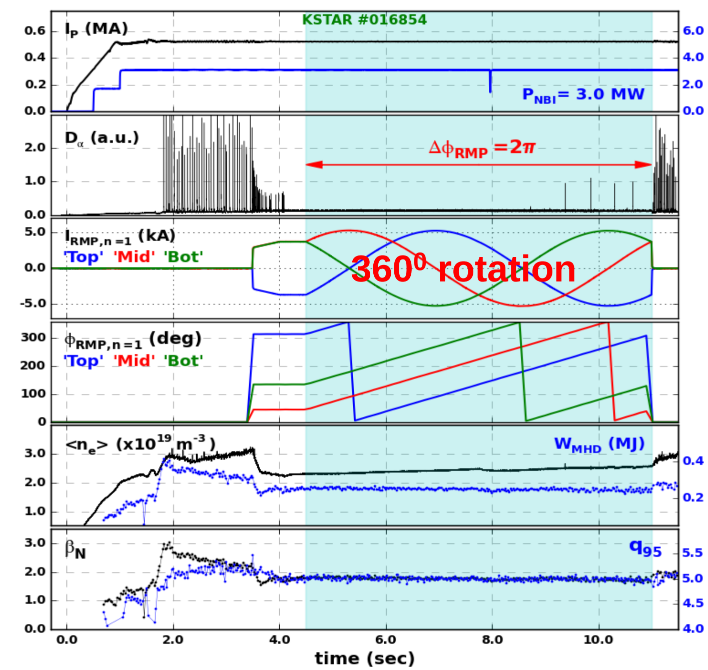


n=1 (+90 phasing) full RMP at q_{95}~5.0 [~2



Y.M Jeon (NFRI), PRL 2012

n=1 full RMP under 360 degree rotation

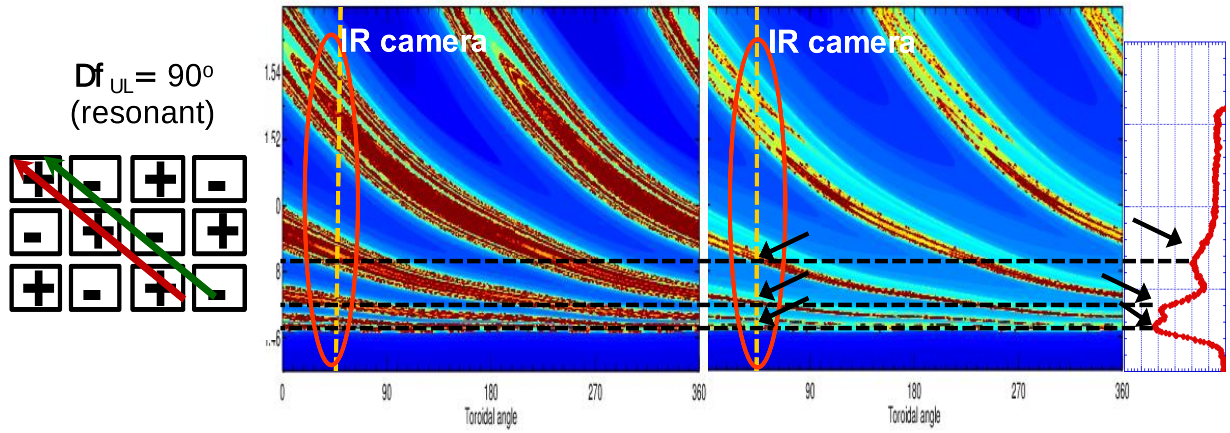


(Post-Deadline) Y.M. Jeon (NFRI), et al

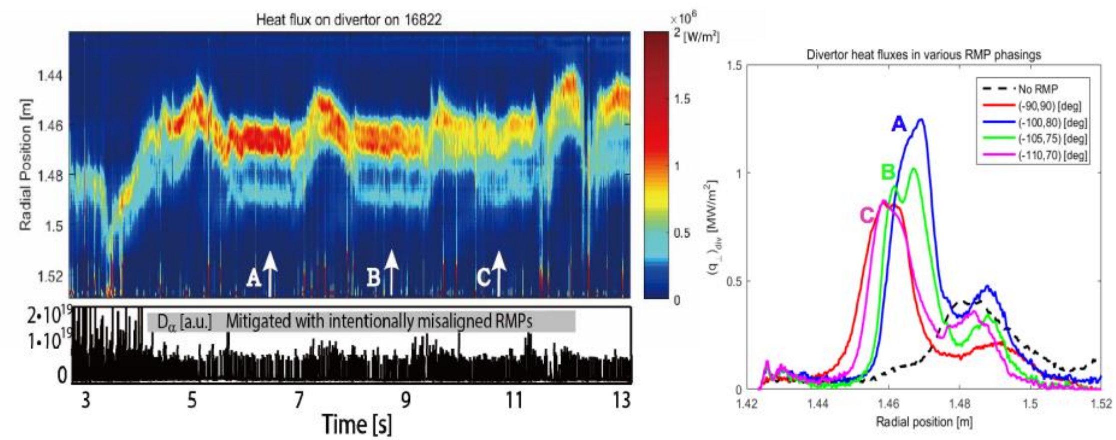
Profile of divertor heat flux has ben measured during ELM-crash suppression at static and rotating RMP

- **Heat flux profile shows very different splitting pattern, depending on phasing and coil configuration**

- **Intentionally misaligned RMP configurations would spread the divertor heat fluxes in a wider area (in support of ITER)**



Heat flux splitting by misaligned RMP configuration



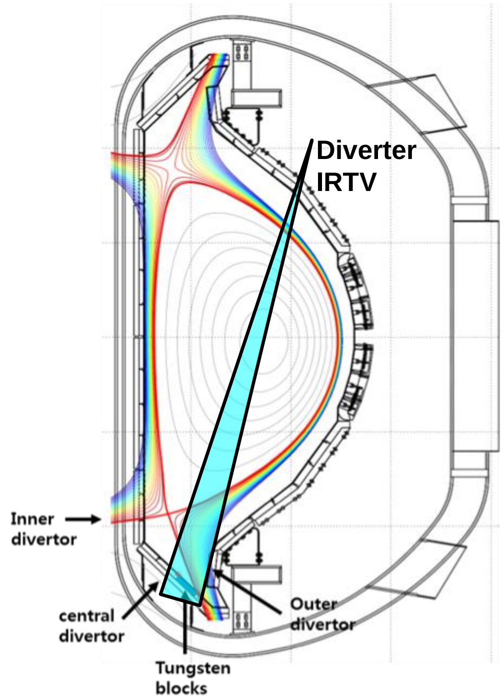
(EX/P4-24) H.H. Lee (NFRI), et al

(EX/P4-30) J. Ahn (ORNL), et al

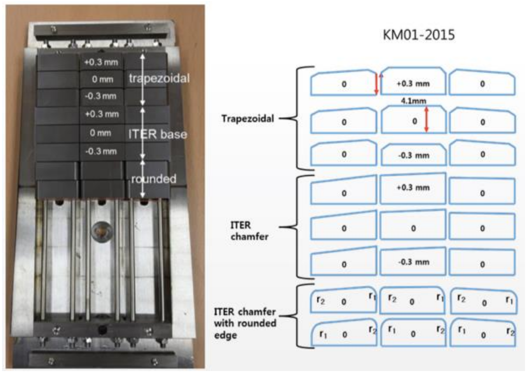
Courtesy of A. Loarte (ITER) , et al

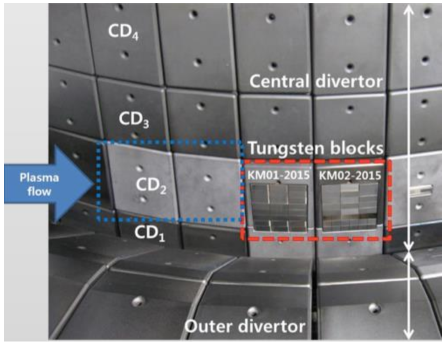
Plasma surface interaction of metal divertor using castellated Tungsten block

- **Install and exposure of castellated tungsten block**
  - Castellated W tile with different leading edge and shape installed on divertor
  - Heat flux and temperature are monitored using IRTV (3x optical zoom)



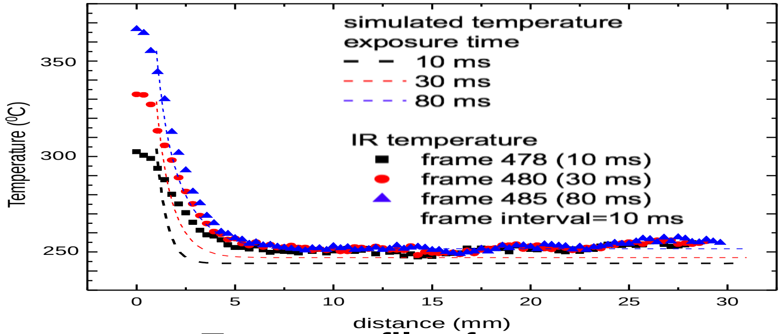
Divertor IRTV (w/ optical zoom)



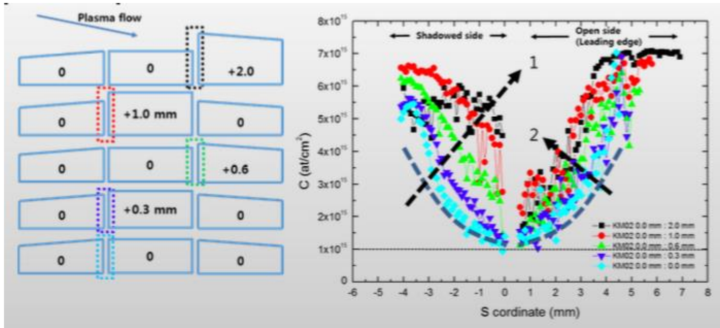


Castellated W tile

- The heat load on divertor is evaluated using IRTV (tangential & vertical)
- A complete set of deposition profiles inside the gap of castellated blocks were analyzed.



Temp. profile after exposure



Deposition depending on the height of leading edge

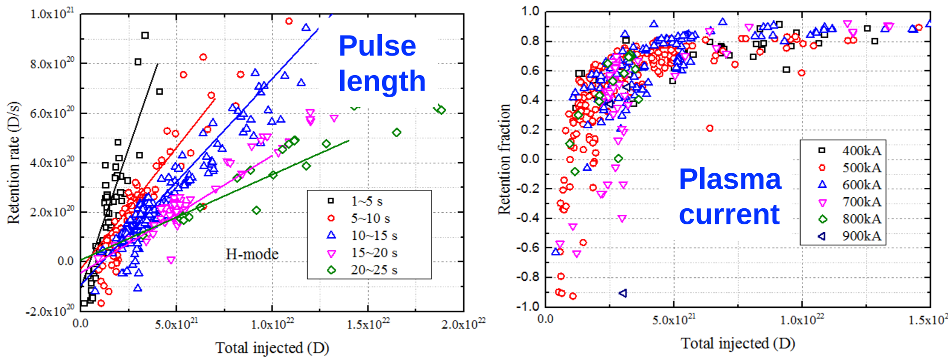
(EX/P4-21) S.H. Hong (NFRI), et al

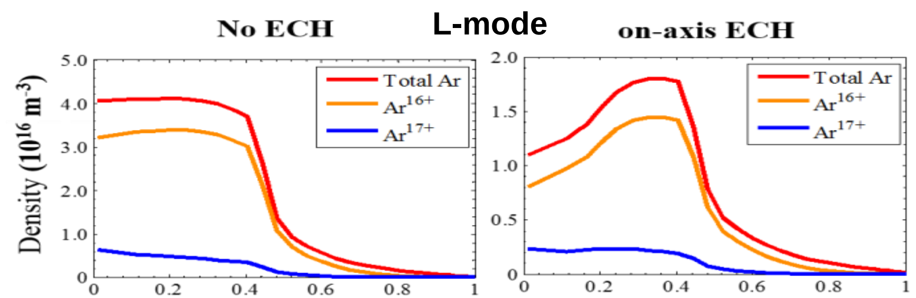
Research on the retention and high-Z impurity transport in KSTAR

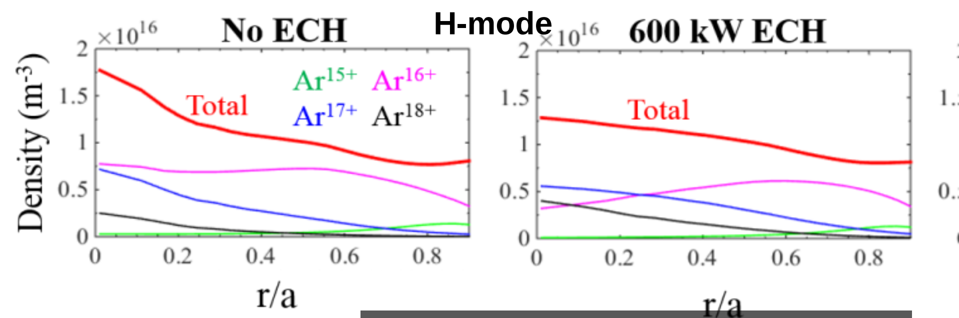
- Hydrogen retention on carbon wall depends on plasma current and pulse length.
  - Retention is proportional to pulse length and issues in long pulse discharge.
  - Wall conditioning between shot

- Ar impurity accumulation control using ECCD and RMP
  - On-axis ECCD suppressed core accumulation of Ar
  - Hollowed profile in L-mode and flat profile in H-mode
  - Kr injection changed ELM features (mitigation and suppression)

Fuel retention on carbon tile according to plasma current and pulse length







(EX/P4-18) J. Hong (KAIST), et al

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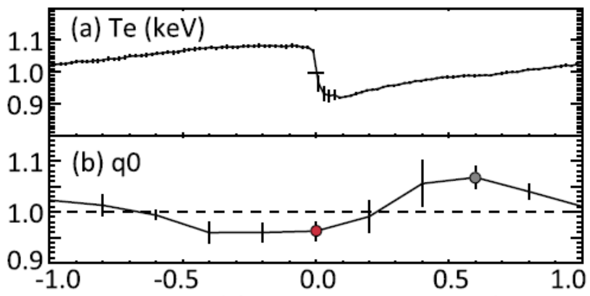
  - *Reliable ELM crash free operation and analysis*
  - ***Exploring confinement and stability issues using KSTAR unique research tools***

- ***Future plan & summary***

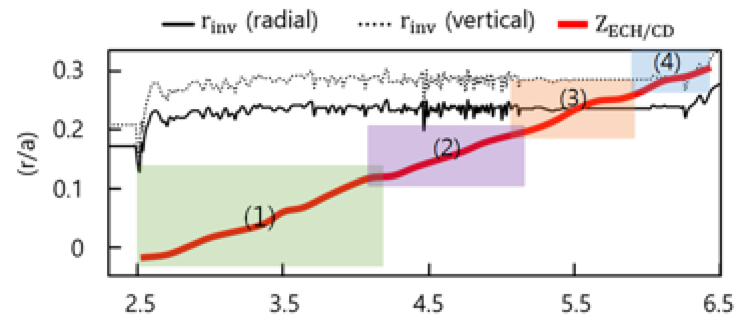
Validation of $q_0 \geq 1.0$ in MHD quiescent time after the sawtooth crash

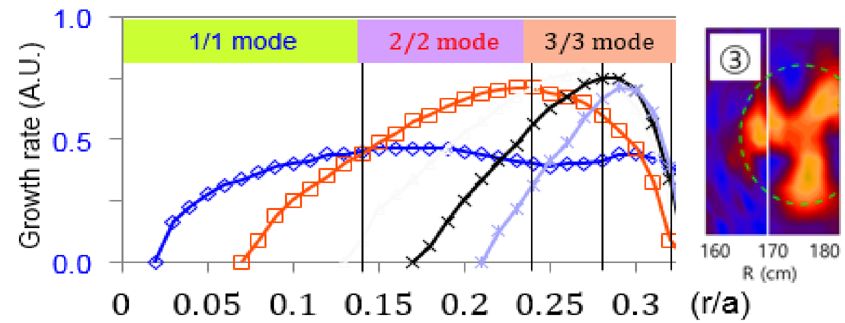
- 30 yrs ago, at Kyoto IAEA, it was reported that $q_0 \cong 0.75 \pm 0.03$ (TEXTOR and TFTR)
- 20 yrs ago, $q_0 \cong 1.0 \pm 0.03$ was reported (DIII-D) and later raised issue of E_r effect
- 2016, KSTAR validates $q_0 \geq 1.0$
  - MSE measured $q_0 \cong 1.0 \pm 0.03$ but uncertainty from E_r and κ makes q_0 value uncertain



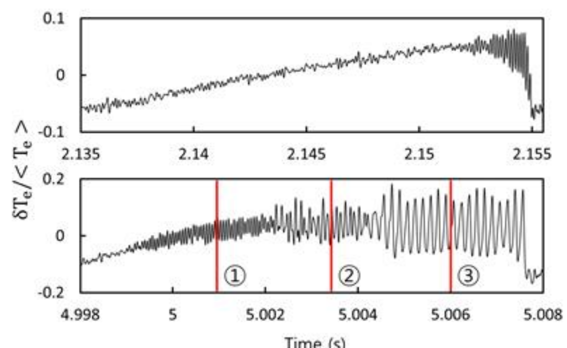
Required absolute accuracy is ± 0.01 for $q_0 \geq 1.0$ after the crash (challenging !!)

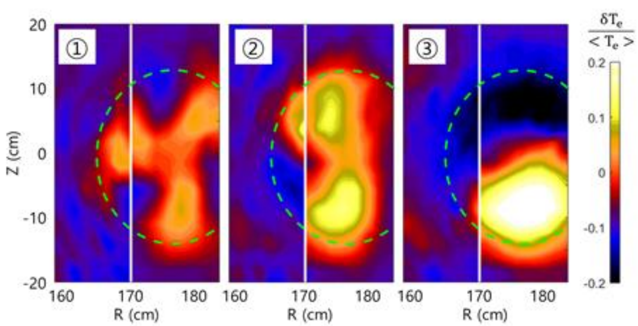
(EX/P4-27) J. Ko (NFRI), et al





- Growth and decay of the tearing mode Exp. within q=1 surface
  - Sawtoothing discharge : tearing mode evolve (e.g. 3/3 to 2/2, 1/1)
  - Non-sawtoothing discharge : no change



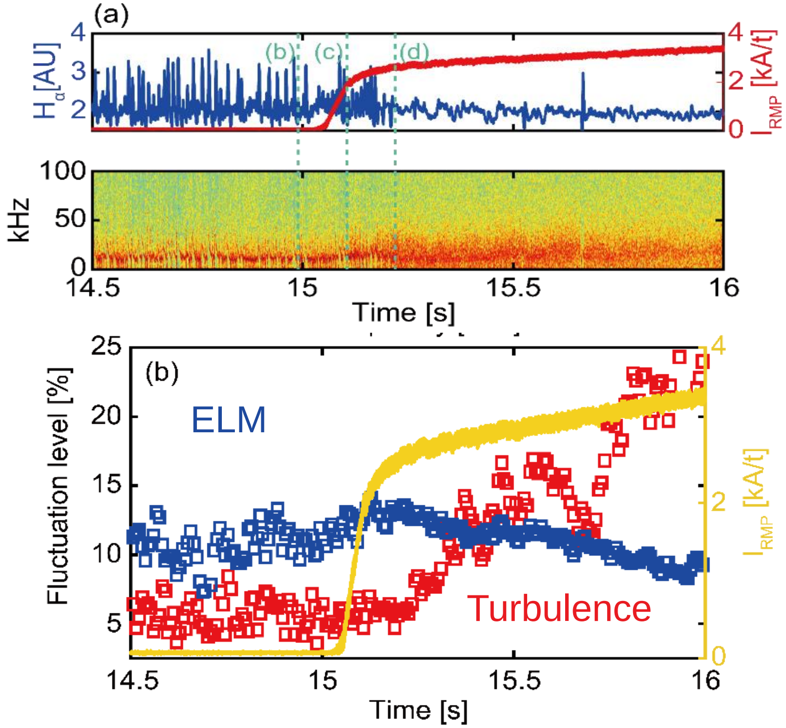


(EX/P4-3) H. Park (UNIST), et al

UNIST Ulsan National Institute of Science and Technology
POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY
NFRI

Theoretical and experimental validation of the ELM crash suppression mechanism

- **Nonlinear interaction btw ELM & turbulent eddies induced by RMP**
  - Broadband turbulence induced by RMP damps the ELM amplitude

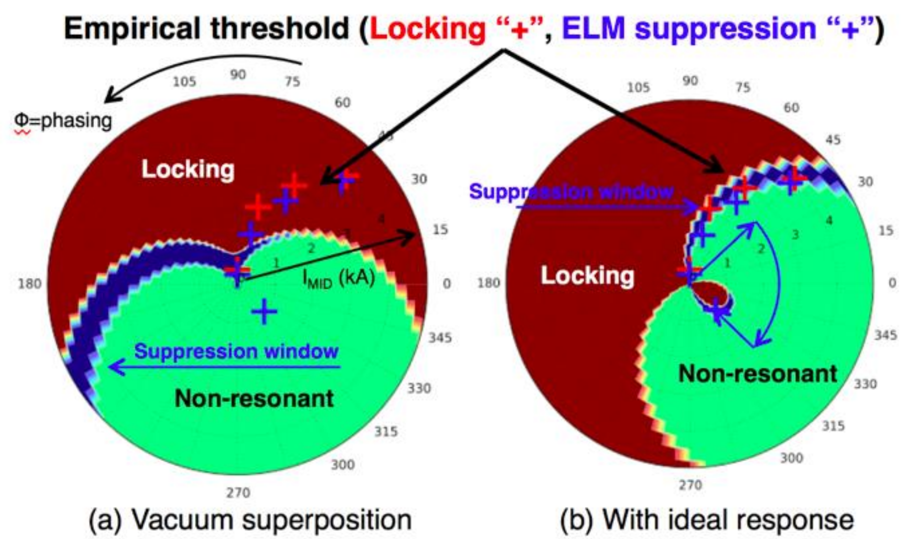


J. Lee (UNIST), PRL 2016

(EX/P4-15) J. Lee (UNIST), et al

UNIST UCDAVIS POSTECH NFRI

- **Exploring optimum phasing angle and amplitude for reliable ELM crash suppression**
  - Fixed top/bottom at 5kA/turn
  - Phasing and amplitude of middle coil
  - Experiments well match with modeling
  - Plasma response calculation is necessary over vacuum calculation



(a) Vacuum superposition (b) With ideal response

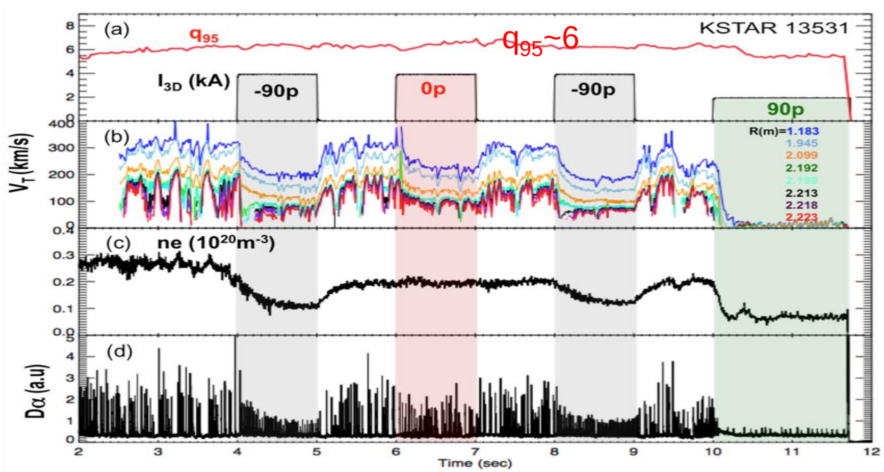
Courtesy of J.K. Park (PPPL) et al

PPPL NFRI

KSTAR has an excellent environment for Neoclassical Toroidal Viscosity (NTV) physics research using reliable rotation profiles

- Plasma rotation highly important for tokamak stability and confinement
  - If sufficiently strong, this rotation could provide stabilization and improved performance in ITER and future devices
  - Effect of localized NTV on toroidal rotation profile : *(TH/P3-11) J. Seol (NFRI) et al*
  - Code verification and validation in most quiescent plasmas : *(TH/P1-6) J.K. Park (PPPL) et al*

Phase dependence on NTV magnetic braking

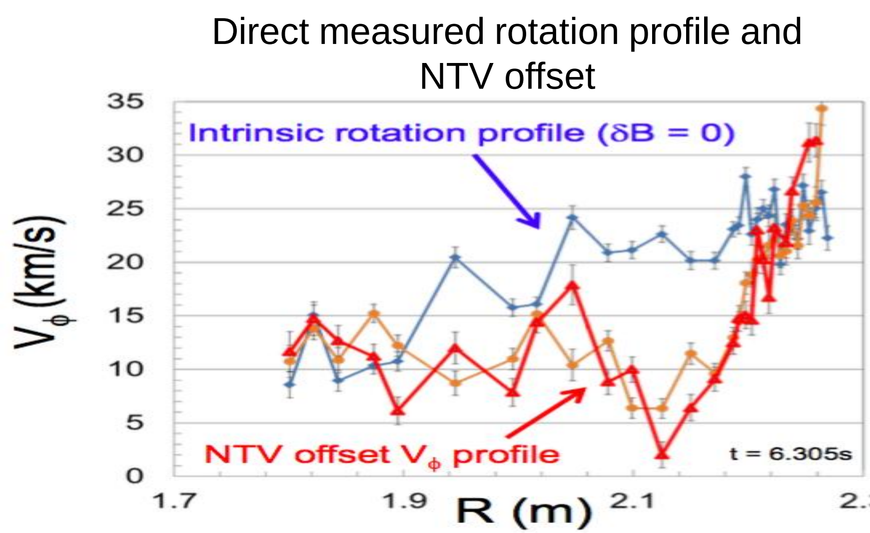


- 0-phasing : quiescent, No density pump-out
- -90 phasing : resonant configuration
- 90 phasing : transition

(EX/P4-9) K. Kim (KAIST), et al

KAIST

Direct measured rotation profile and NTV offset



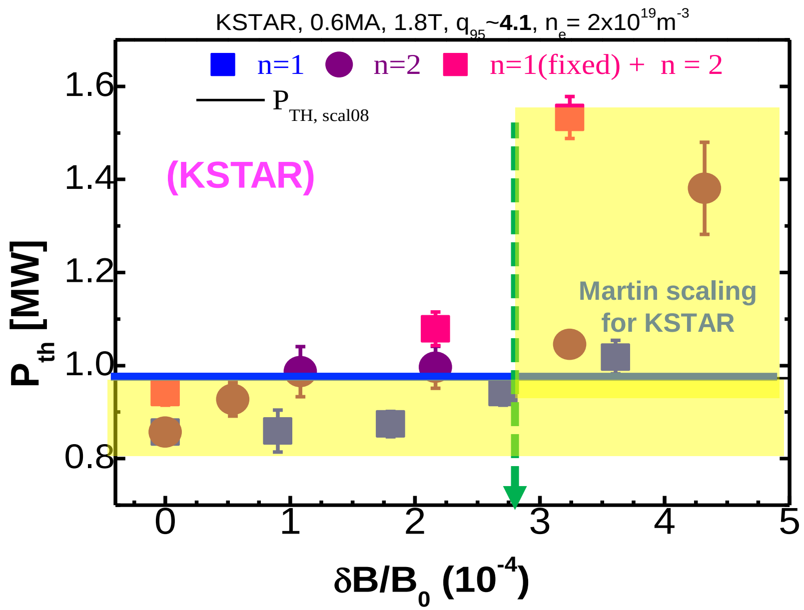
- Final saturated rotation profile at n=2 lead to strong rotation shear at edge

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK
NIFS
PPPL

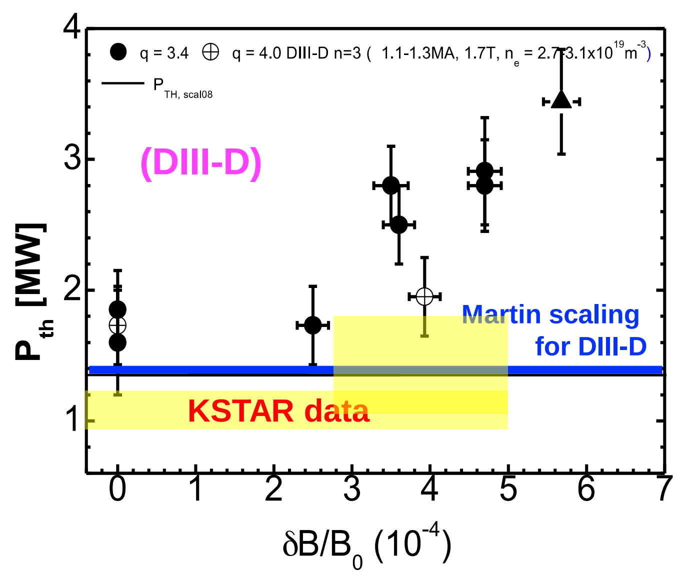
(EX/P4-33) S. Sabbagh (Columbia U.) , et al

L-H transition threshold power (P_{th}) depends on the level of error field in fusion devices

- The dependence of P_{th} on the applied error field ($\delta B/B_0$) was reported by DIII-D team (2011).
- P_{th} dependence on n=1, 2 error field has been measured In KSTAR,
  - P_{th} in KSTAR is much less than the *Martin scaling* *(Journal of Physics, 2008) at single mode error field* ($\delta B/B_0 < 2.7 \times 10^{-4}$), which is level of intrinsic error field in conventional devices.
  - However, in mixed mode error field case, strong dependence of Pth on $\delta B/B_0$
- It showed that the n=2 error field is not negligible compared to n=1 error field to get H-mode within limited heating power such as in early state of ITER operation.
  - For ITER, the test blanket module is one of the sources of error field and need a clear mapping of δB.



(EX/P4-4) W.H. Ko (NFRI), et al



P. Gohil (GA), et. al, NF 51 103020 (2011)

OUTLINE

- ***Introduction***
  - *Research directions*
  - *Unique research tools on KSTAR and role for the test bed for ITER and beyond*
- ***Research highlights of KSTAR***
  - *Extension of H-mode and high performance discharges into long pulse and steady-state*
  - *Reliable ELM crash free operation and analysis*
  - *Exploring confinement and stability issues using KSTAR unique research tools*
- ***Future plan & summary***

Major system upgrade toward high beta long pulse operation (~2021)

- Up to 2020, research campaigns to explore the optimum operation regime for steady-state and high beta using NBI-2 : Confinement, Stability, Bootstrap current, etc.
- From 2021, In-vessel components upgrade for the optimized plasma volume and shape
- Optimized divertor configuration with new first wall material (compatible for k-DEMO)
- Optimum current drive configuration: high field side LHCD, Helicon CD, top launching ECCD

2008 — **First plasma**

- *Research on long pulse & steady-state H-mode operation*
- *Stable ELM–crash free operation*
- *Study of MHD dynamics*

2016

2018 — **NBI-II**

- *Stable high beta regimes explored using NBI-II (Ti ~ 10 keV)*
- *In-depth physics using advanced diagnostics*
- *Prepare major upgrade*

2021 — **Major upgrade**

- *Advanced operation scenarios (k-DEMO relevant)*
- *Advanced divertor research*
- *Advanced current drive*

Contribution to IAEA FEC from KSTAR collaborators

[Overview & scenarios]

OV/2-3	Y.K. Oh	KSTAR Overview
EX/P4-1	S.W. Yoon	High beta operation
EX/P4-12	S.H. Hahn	Vertical stabilization control
EX/P4-13	H.S. Kim	Physics based profile control
EX/P4-14	J.W. Lee	Trap Particle Confinement
EX/P4-53	H. Lee	EBW assisted startup, VEST

[3D field, ELM & NTV]

EX/1-3	Y. In	Nonaxissymetric
EX/10-3	G.S. Yun	ELM & global structure
TH/P3-11	J. Seol	NTV & rotation
EX/P4-33	S. Sabbagh	NTV profile & 3D
TH/P1-28	J. Kim	Magnetic perturbation
EX/P4-4	W.H. Ko	L-H treshold under 3D field
EX/P4-7	M. Kim	ECEI ELM observation
EX/P4-9	K. Kim	Magnetic braking
EX/P4-15	J.H Lee	Edge turbulence interaction

[Divertor & PSI]

EX/P4-21	S.H. Hong	Deposition inside gaps
EX/P4-24	H.H. Lee	Divertor target heat load
EX/P4-25	M.K. Bae	Heat flux to first wall
EX/P4-30	J.W. Ahn	Diverter heat flux & 3D
TH/P6-5	W. Choe	Divertor heat flux & 3D

[Fusion engineering]

FIP/3-3	J. Kang	Algorithm for K-DEMO
FIP/P7-15	J. Park	Structure analysis for K-DEMO

[MHD, EP & disruption]

EX/P4-3	H. Park	Sawtooth crash
TH/P1-17	A. Aydemir	Disruption
EX/P3-19	D. Orlov	Perturbation & MHD
EX/P4-2	Y.S. Park	MHD stability at high betaN
EX/P4-5	J.Kim	Destabilizing Edge instability
EX/P4-6	Y. In	Locked mode dissipation
EX/P4-8	J.G. Bak	Halo current
EX/P4-10	S.G. Lee	Long-lived mode
EX/P4-20	W. Lee	Ion-scale turbulence
EX/P4-26	J.H. Kim	Alfven Eigenmode
EX/P4-28	M. Cheon	Runaway Runaway electron
EX/P4-29	C.M. Ryu	TAE
EX/P4-22	J.G. Kwak	Neutron yield

[Confinement & transport]

TH/P2-25	J.Y. Kim	Energy confinement
EX/P4-16	S. Ko	Toroidal rotation & ELM
EX/P4-23	K.C. Lee	Poloidal asymetry on ELMs
EX/P4-17	Y. Shi	Rotation reversal & transport
TH/P2-24	Y.S. Na	Particle transport
EX/P4-19	D.H. Na	Intrinsic rotation reversal
EX/P4-27	J. Ko	Current profile evolution
EX/P4-18	JH. Hong	Ar transport
TH/8-3	H.G. Jhang	Zonal flow and edge collapse
TH/P3-13	H.H. Kaang	Momentum transport
TH/P3-25	T.S. Hahm	ExB shear
TH/P3-27	M. Leconte	Zonal flow & RMP
TH/P3-29	S.S. Kim	Turbulence BOUT++
TH/P3-32	C.Y. An	Energy non-trapping

Summary

KSTAR, as an international collaboration device, has directions to resolve the scientific and technical issues in developing steady-state high beta and advanced plasma operation regime for ITER and K-DEMO.

KSTAR is well engineered superconducting tokamak with several unique research tools as a test bed for ITER and K-DEMO ;

- lowest intrinsic error field and ITER relevant in-vessel control coils (top/middle/bottom)
- Advanced 2D/3D imaging diagnostics and long pulse heating/CD systems

Remarkable progress in plasma operation and physics research has been conducted according to strong contribution from domestic and international collaborators.

- extension of H-mode discharge into large Ip (1 MA) and long pulsed (up to 70s)
- developing stationary high performance discharge (high beta and ITB operation)
- robust ELM-crash suppression (~10sec) at n=1 under static and rotational RMP.
- theoretical and experimental validation of MHD instabilities (sawtooth and ELMs)

Improved research long pulse & high performance operation (Ti ~ 10 keV) and in-depth r esearch are planned using NBI-II installation (2018) and in-vessel components upgrade i n divertor and current drive (2021).

Your recommendation and collaboration on KSTAR are very welcome everytime.

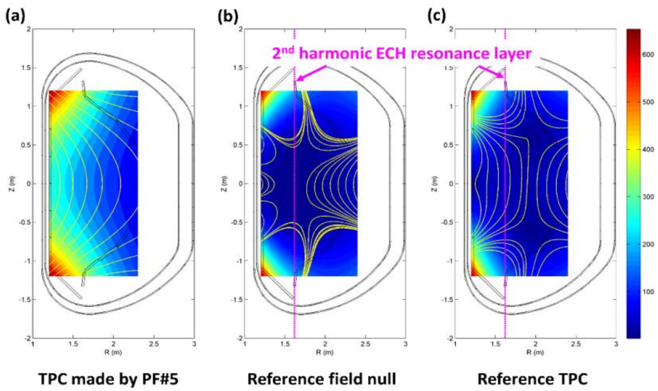
Thank you for your attention !

감사합니다

Back Up Slides

Plasma control improvement for Mega-ampere discharge and ITER baseline scenario

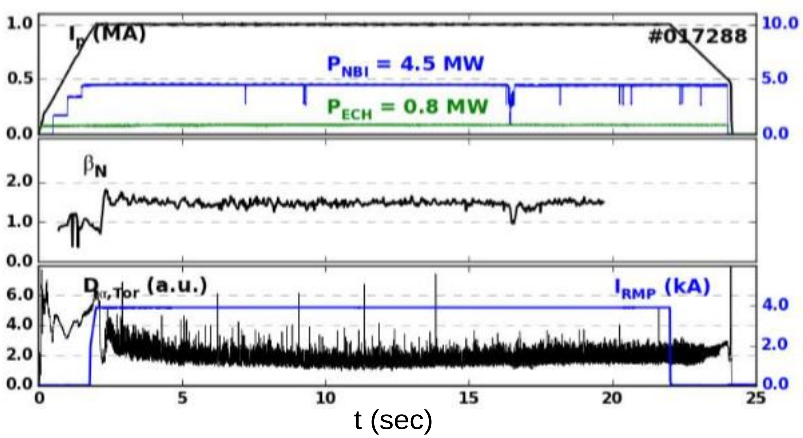
- **Improved ECH-assisted startup using Trapped Particle Confinement**



SEOUL NATIONAL UNIVERSITY

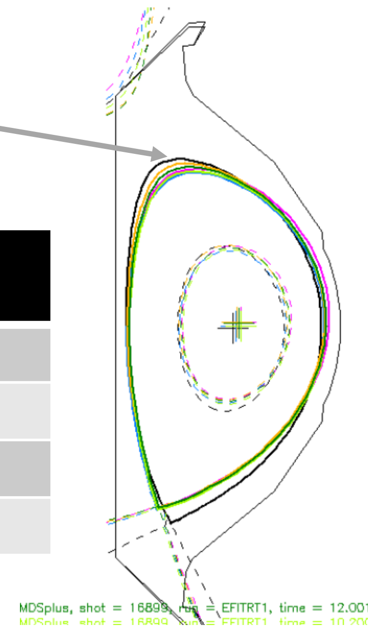
(EX/P4-14) J. Lee (SNU), et al

- **Plasma control improvement to access Mega-ampere current (1 MA) H-mode**



- **Advanced control technique integrations developed for ITER baseline scenario research in KSTAR**
  - "Decoupled" Z control in the frequency responses
  - Real-time PF feedforward calculation w/ plasma resistance tracking
  - MIMO X-point controller

ITER-similar shape (scaled for KSTAR)



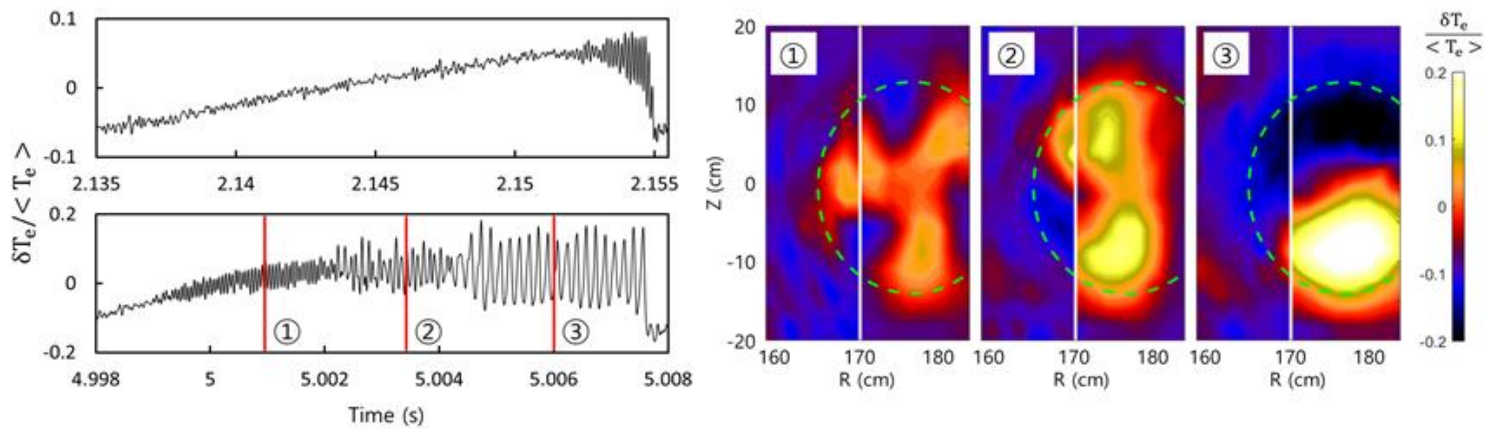
parameter	#16380 t=6.4s	Scaled ITER BS
β_N	2.0	1.8
q_{95}	3.2	3.2
κ	1.8	1.9
I_p/aB_T	1.0	1.4

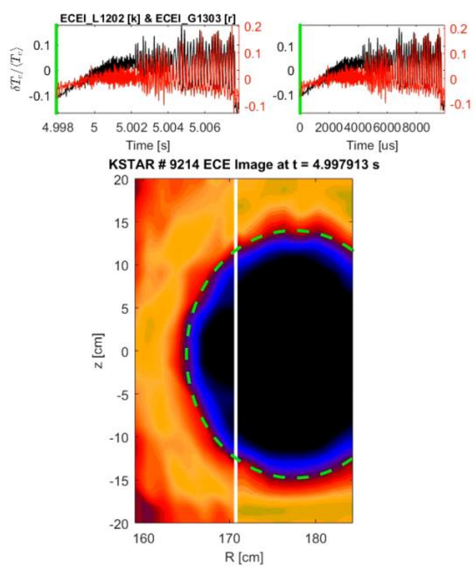
Courtesy of M. Lanctot (GA), et al

(EX/P4-12) S.-H. Hahn (NFRI), et al

PPPL GENERAL ATOMICS

Validation of complete reconnection model





- Time evolution of the 3/3 mode in one sawtooth cycle suggests q_0 >1.0 up to 2/2 mode.
- q_0 drops below ~1.0 as the 1/1 kink mode appears
- The strength of 1/1 mode may suggests the depth of the drop.
- No mode number change in non-sawtoothing discharge
- Kadomtsev model is valid model !!!

Complete or incomplete reconnection ? (q_0?)

- Measurement of q_0 at the center has been intrinsically difficult !! MSE:E_r and kappa. Polarimeter;uncertainties in double inversion
  - $q_0 = 0.75 \pm 0.5$ [TEXTOR;Soltwisch(1988)], [TFTR; Levinton (1989)]
  - q_0 ~ 0.95 to 1.1 [DIII-D; Wroblewski (1992,1993), Rice (1997)]
  - q_0 ~ 0.8 to 1.1 [JET; N. Hawkes (1996?)]

- If the measurement is ~1.0, then it is difficult to conclude the sawtooth instability is complete or incomplete

H. Soltwitsch (TEXTOR)

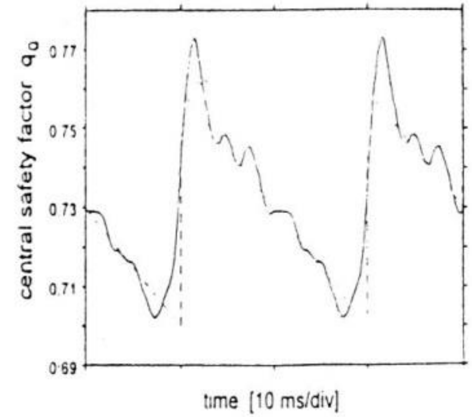
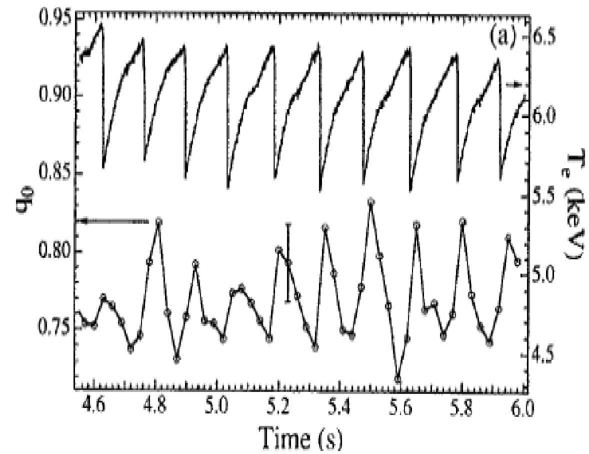
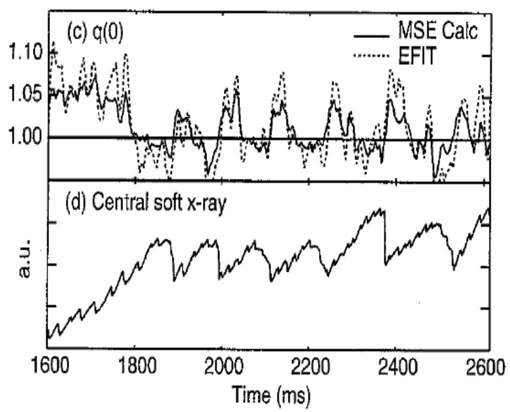


Figure 9. Behaviour of $q(0)$, during a Sawtooth on TEXTOR. The axial value of q never rises above 0.8. Box-car averaging techniques were used to sum the signals from many similar Sawteeth, and enable the ~ 5% sudden changes in q_0 to be monitored.

F. M. Levinton (TFTR)

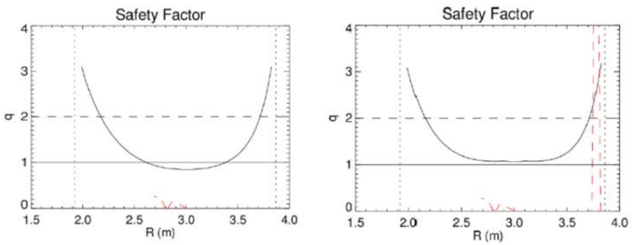


D. Wroblewski, B. Rice (DIII-D)



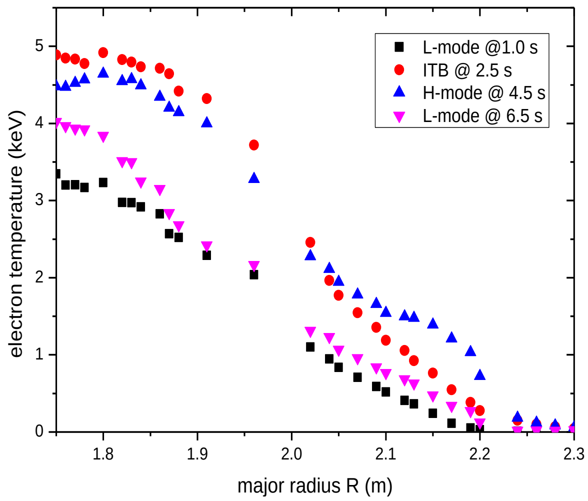
N. Hawkes (JET)

Shot 65252, Sawtooth crash. MSE/Pini 7 data

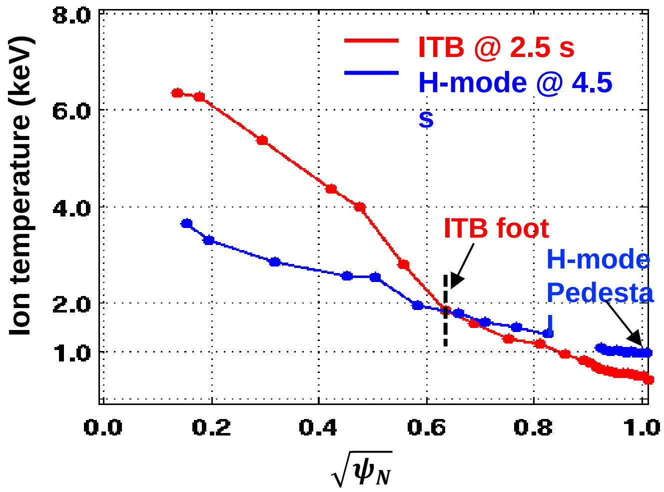


56.69s pre-crash   56.78s post-crash

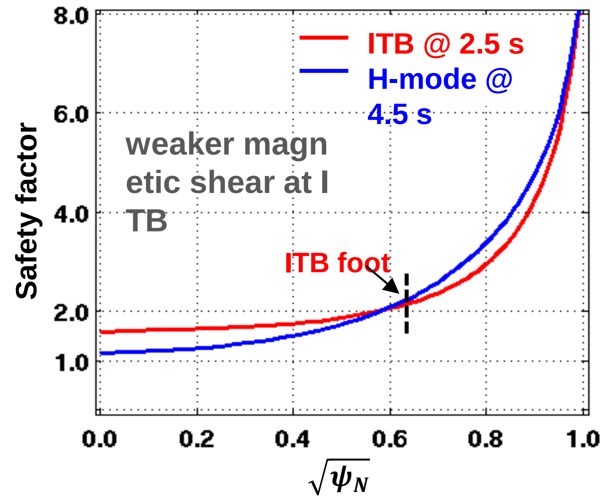
ITB



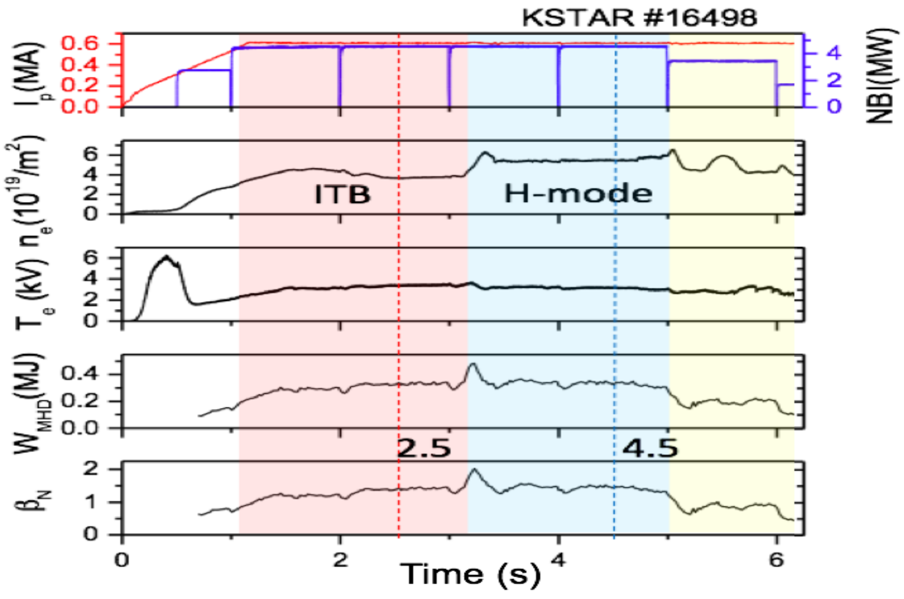
L-mode @1.0 s
ITB @ 2.5 s
H-mode @ 4.5 s
L-mode @ 6.5 s
electron temperature (keV)
major radius R (m)



ITB @ 2.5 s
H-mode @ 4.5 s
ITB foot
H-mode Pedestal
Ion temperature (keV)
$\sqrt{\psi_N}$

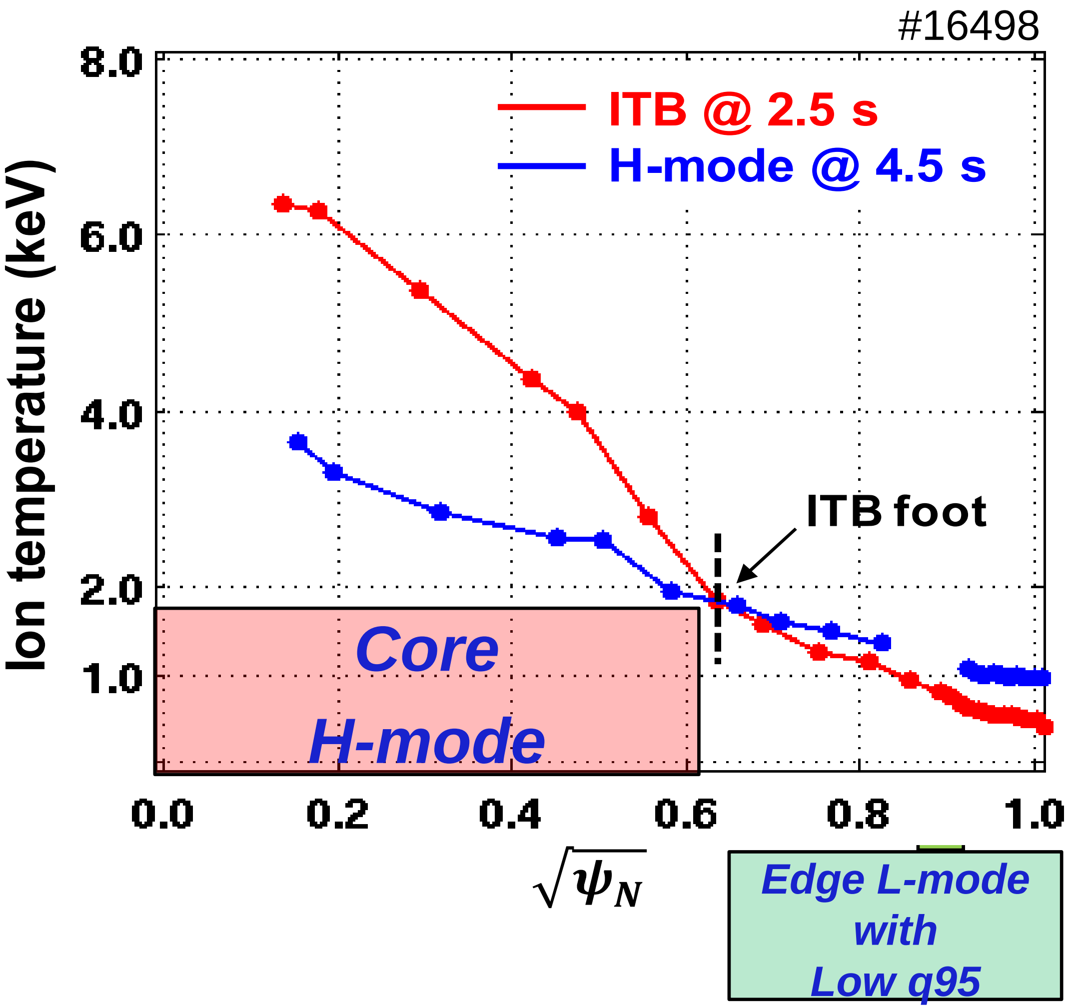


ITB @ 2.5 s
H-mode @ 4.5 s
weaker magnetic shear at ITB
ITB foot
Safety factor
$\sqrt{\psi_N}$



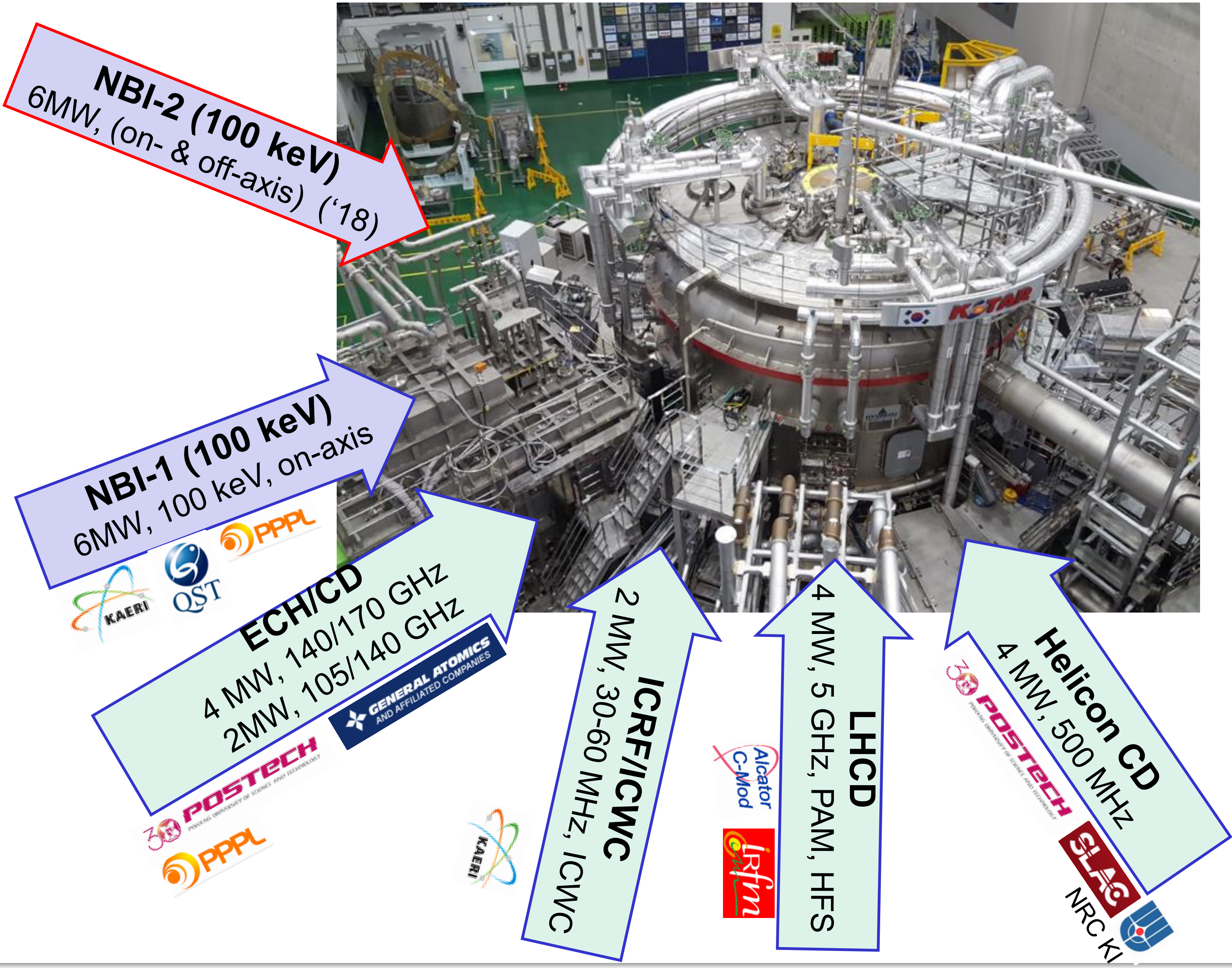
KSTAR #16498
I_p(MA)
NBI(MW)
$n_e(10^{19}/m^2)$
ITB
H-mode
T_e(kV)
W_{MHD}(MJ)
2.5
4.5
β_N
Time (s)

Model discharge for high beta steady state operation for K-DEMO



- ❑ Eliminate ELM-crash
  - ➢ Core H-mode + edge L-mode
- ❑ Eliminate harmful MHDs such as 2/1 mode
  - ➢ Edge q95 ~2.1 - 2.3
- ❑ Easy control of sawtooth for particle exhaust
  - ➢ ECH for crash time
  - ➢ Off-axis CD for on/off switch for sawtooth
- ❑ 3/2 mode is relatively easy to control

Upgrade plan of the heating and CD for high performance steady-state operation

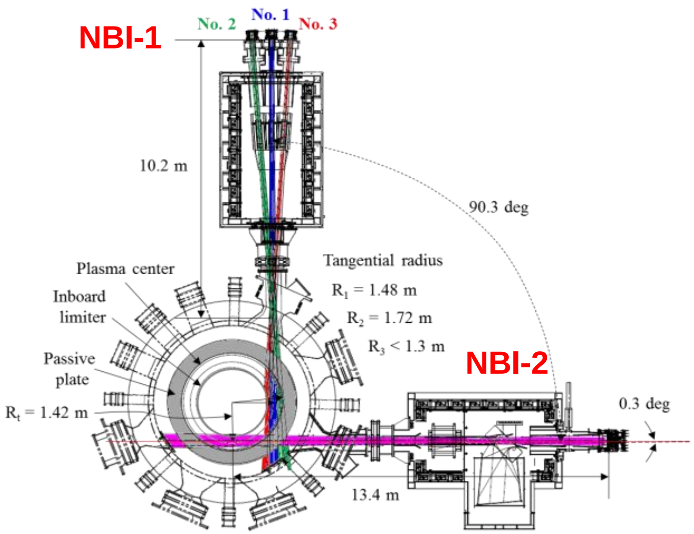


- 12 MW NBI systems
  - 8 MW on-axis and 4MW off-axis
  - Broader j(r) & p(r) for higher β_N limits
- 6 MW ECH/CD
  - 4MW 105/140 & 2 MW 140/170 GHz
  - Higher Te/Ti, q(r) tailoring, Rotation control, MHD control
- 4 MW LHCD and 4MW Helicon
  - off-axis CD & β_N ~ 5 (RS with q_{min} > 2)
- Expected high performance discharge
  - ***$G = \beta_N H_{89}/q_{95}^2 = 0.92$***

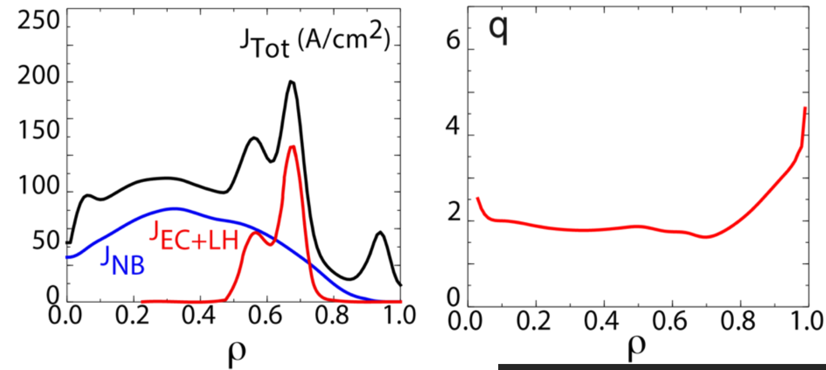
Upgrade plan of heating system for high performance steady-state operation

❑ Heating system upgrade to ~28 MW

- NBI : 5.5 MW → total 12 MW ('18) : on & off-axis, *collab. KAERI, QST, PPPL*
- ECH/CD : 105/140 GHz (2 MW) & 140/170 GHz (4 MW) *collab. QST, PPPL, KAERI*
- LHCD : 5 GHz (4 MW, PAM or HFS launch) *collab. CEA, MIT, POSTECH*
- Helicon CD : 0.5 MHz (4MW) *collab. KI, SLAC, POSTECH*
- ICRF : 30-60 MHz, optimize for IC wall condition



Fusion performance, G
$G = \beta_N H_{89}/q_{95}^2 = 0.92$
(cf: G~0.5 for ITER)



Courtesy : J.M Park (ORNL)

	Near Term	Long Term
P_{NB} On/Off	4/4 MW	6/4 MW
P_{EC} (X2)	2.4 MW	4.8 MW
P_{LH}	-	3 MW (n//=2.0 from off-mid)
I_p/B_T	0.6 MA/1.8 T	1 MA/1.8T
q_{95}	5.2	3.1
Shape	SN	DN
β_N	3.45	4.2
f_{NI}/f_{BS}	1.0/0.5	1.1/0.47
H_{89}	2.2	2.1
q_{min}	1.54	1.63
$G=H_{89}\beta_N/q_{95}^2$	0.3	0.92
T_e/T_i	1.31	1.1