KSTAR to resolve critical issues for ITER and DEMO

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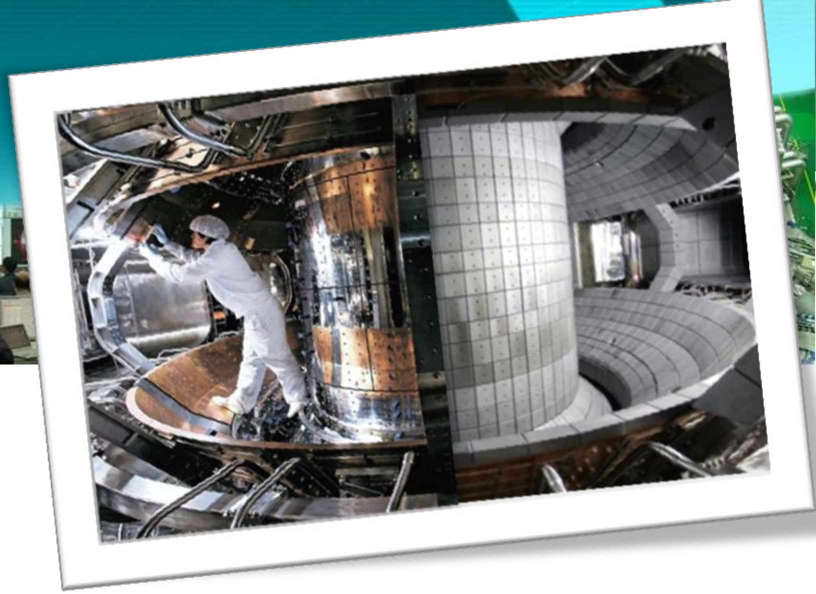
On behalf of the KSTAR Team and Research Collaborators

KSTAR

NFRI 국가핵융합연구소 National Fusion Research Institute

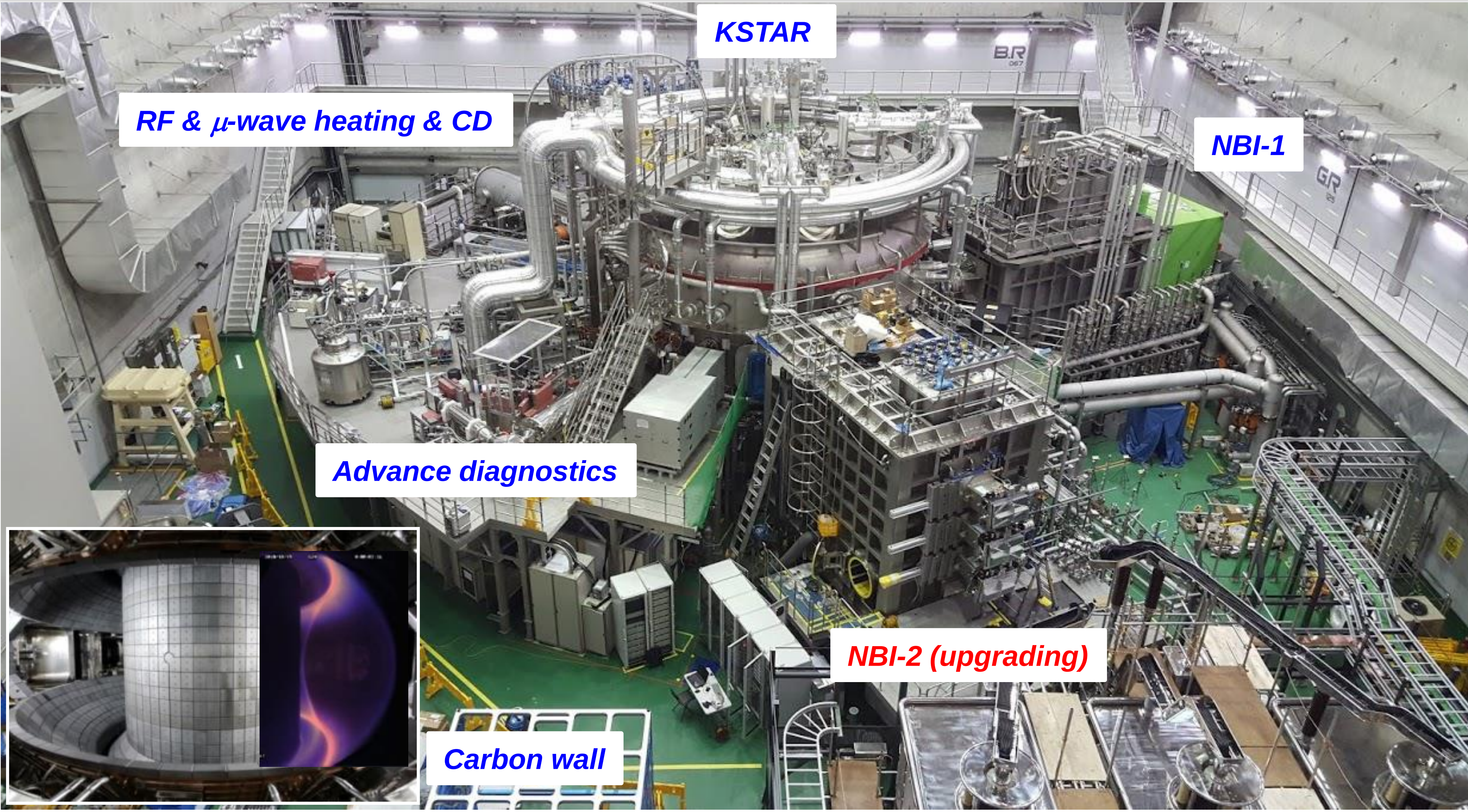
Ministry of Science and ICT



OUTLINE …….

- **Introduction**
  - **Role of KSTAR**
  - **KSTAR status and unique features**
- **Research Highlights of KSTAR campaign**
- **Future plan and upgrade**

Status of KSTAR device (Feb. 2018)

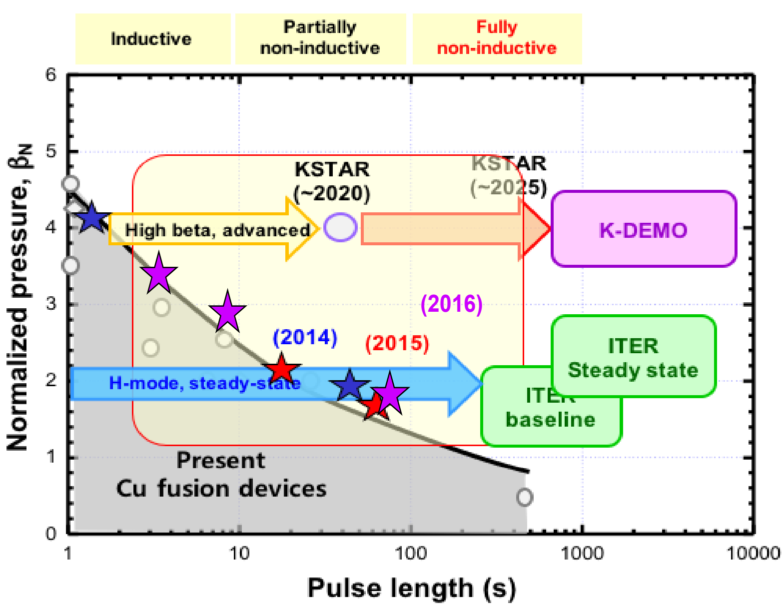


Construction (1995 ~ 2007) → First plasma (2008) → First H-mode (2010) → First ELM suppression (2011) → Long-pulse H-mode (> 70s) (2016) → Long ELM suppression (>34s) (2017) → on going NBI upgrade

KSTAR mission is
to explore the steady-state operation at high performance

▶ Mission of KSTAR:

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



➢ 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 (2.16)	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**
Bootstrap current, f_{bs}	**(~0.5)**		**~ 0.6**
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD [MW]	**~ 28 (10)**	~ 73	120
PFC	C, W	W	W
Fusion power, P_{th} [GW]		~0.5	~ 3.0

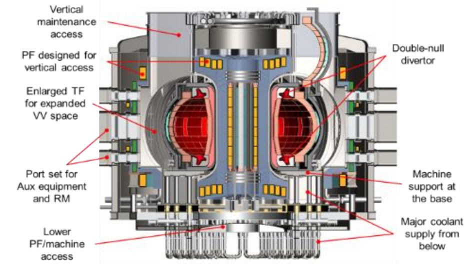
Mission and roles of KSTAR toward ITER and K-DEMO

➢ Operation goals:

- to achieve steady state H-mode with resolving engineering issues (ELM, disruption)
- to explore high performance operation modes with resolving harmful MHDs

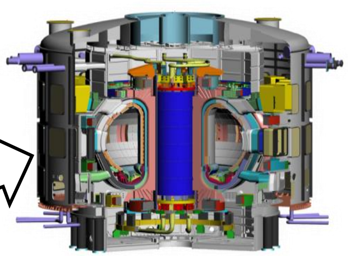
➢ Roles of KSTAR in ITER era

- To explore steady-state (~300s) and high beta (β_N > 4) operation regimes that are applicable to ITER and K-DEMO
- To resolve harmful instability issues in high beta operation (ELM-crash, NTM, disruptions, RWM, etc)
- To validate of not-yet proven fundamental physics using advanced diagnostics and modeling
- Innovative R&D on key engineering and technology (control of heat, recycle & current drive in steady state, etc)



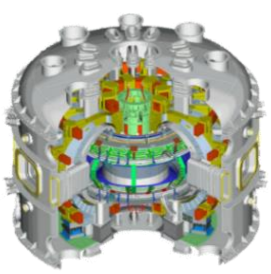
K-DEMO

- Stationary High beta (β_N ~4), high bootstrap
- Divertor heat flux control



ITER

- Steady-state H-mode(β_N ~2)
- Suppression of ELM, disruption

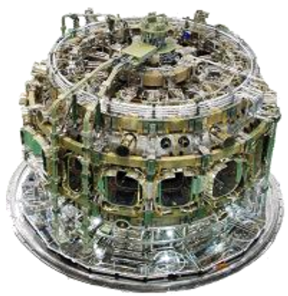


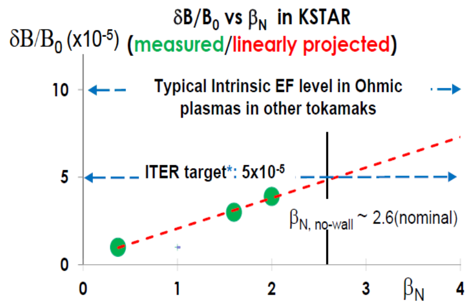
KSTAR

Uniqueness of KSTAR essential for β_N ~4.0 long-pulse demonstration

▶ Better plasma symmetry

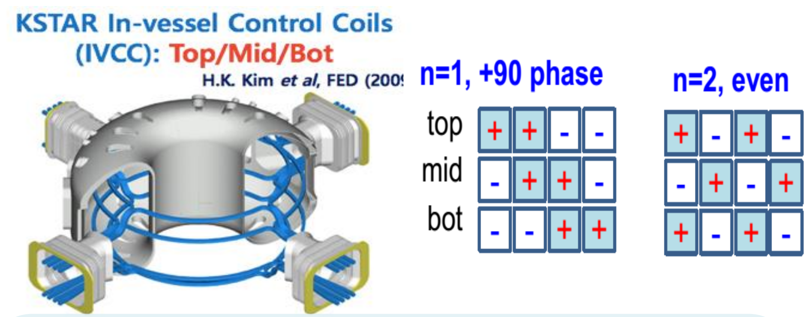
- Lowest error field ($\delta B/B_0$~1×10^{-5})
- Lowest toroidal ripple (~0.05 %)





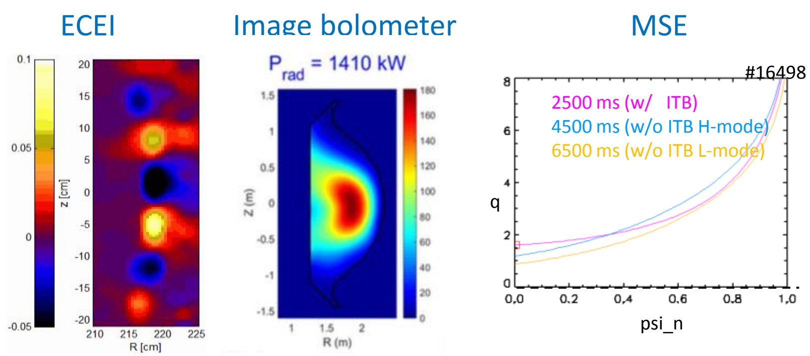
▶ Better instability control with IVCC

- Uniquely top/middle/bottom coils
- Reliable ELM-crash suppression (>30s)



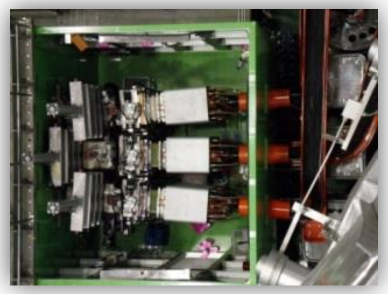
▶ Better understanding by Advanced diagnostic

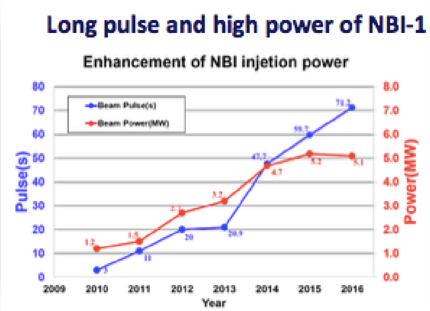
- Profile and 2D imaging diagnostics
- Physics validation of MHD & confinement



▶ Better efficiency in heating/CD & ready to upgrade

- Long pulse high beta op. using NBI (>70s)
- 2nd NBI system is under construction

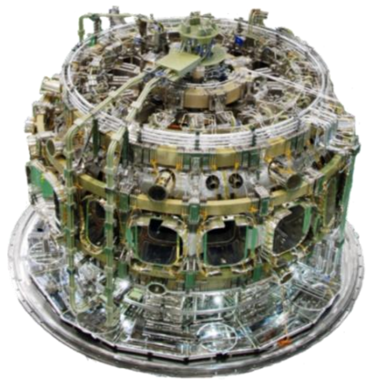


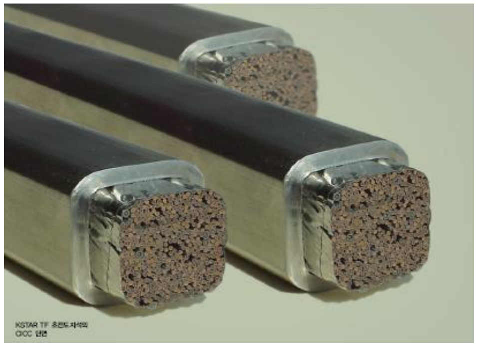


KSTAR unique features :
Engineering excellency in superconducting magnets

➢ **Challenges :**

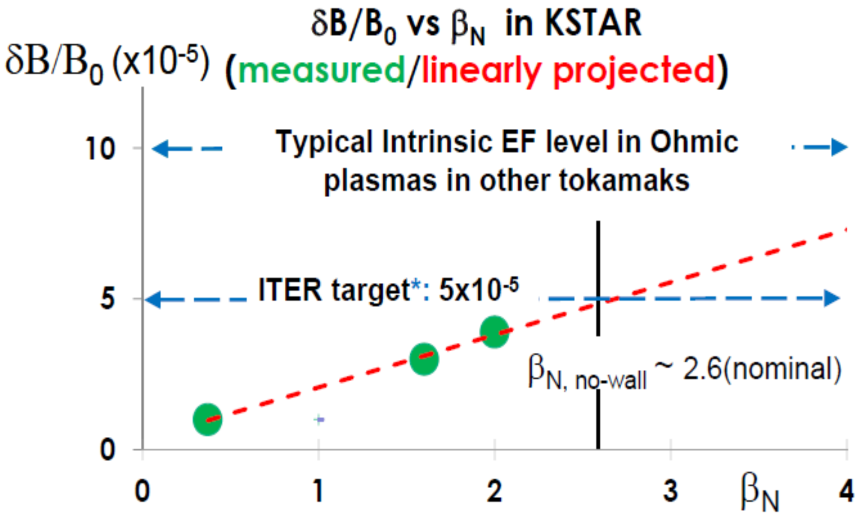
- The first Nb_3Sn CICC superconductor (same as ITER) and extremely high quality control of manufacturing and installation
- Extremely low error field ($|\overrightarrow{\delta B}/B_0|$ ~ 1×10^{-5}), it is about 1/10 than other major device.
- KSTAR could operated up to ITER operation conditions (betaN ~ 2.5) without external error field correction





Nb3Sn conductor & CICC

Accurate SC engineering

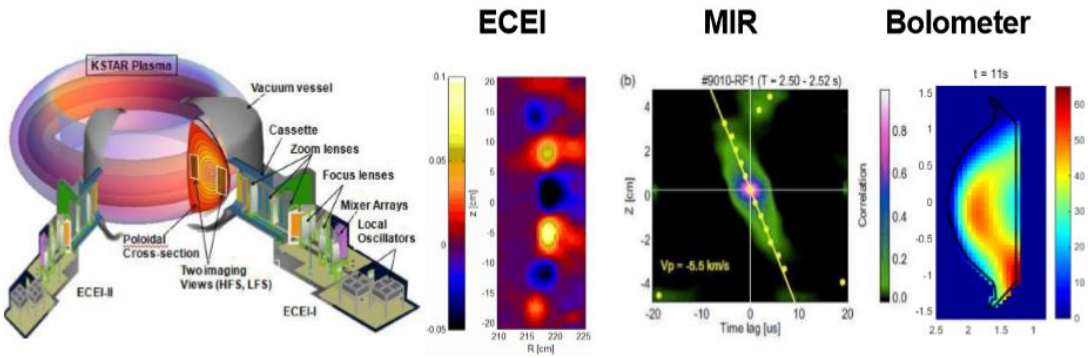


Y. In, NF2017

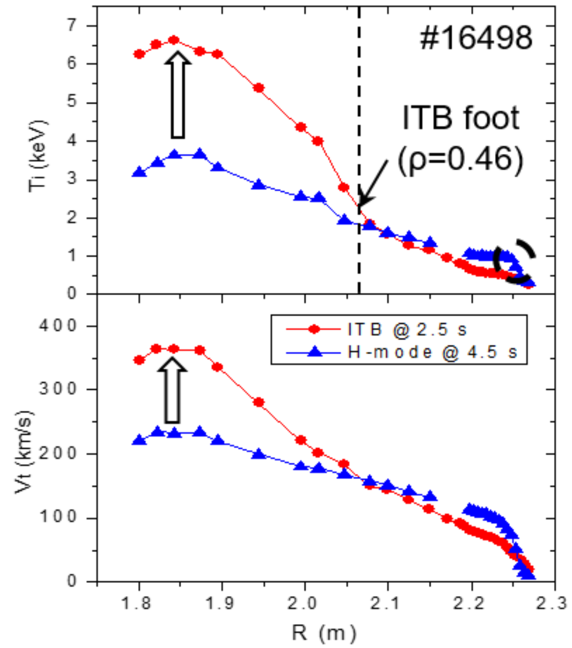
KSTAR uniqueness : Advanced diagnostics to validate fundamental physics and plasma control

- **Very reliable operation of advanced 2D/3D imaging diagnostics**
  - ECEI, MIR, Collective Sc., BES, imaging bolometer, FILD, SXR,, etc
  - Enable understanding of fundamental physics including MHD mechanisms (ST, ELM, Tearing Modes,)

- **Reliable profile diagnostics benefits of low ripple and error field**
  - CES, MSE, ECE, TS, refectometer
  - Clear profile information at core and pedestal also
  - to be applied for real-time profile control

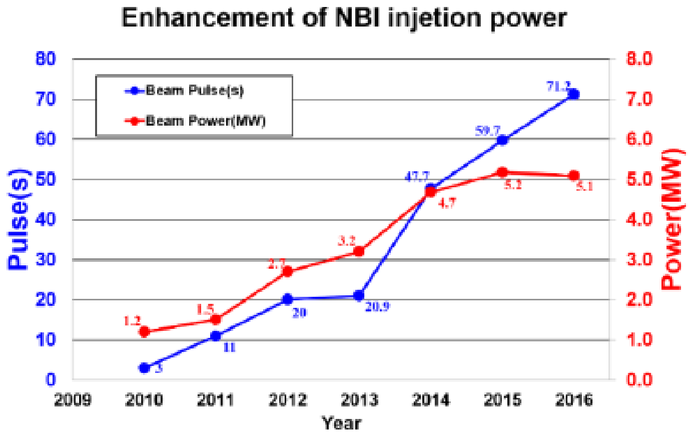


ECEI, MIR, and imaging bolometer diagnostics

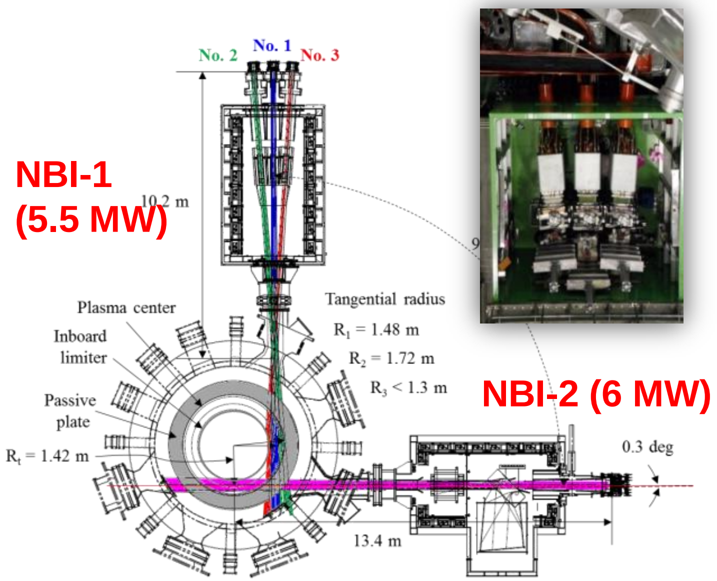


KSTAR uniqueness : High efficient long-pulse capable NBI & EC heating system

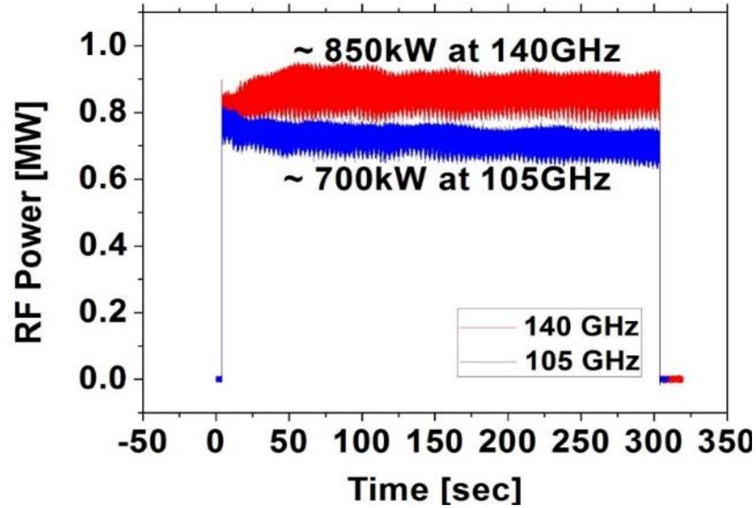
- **achievements :**
  - NBI : 100 keV positive D^+ beam, lonest operation (>70s) – efficient NBCD
  - ECH : dual frequency gyrotron (105/140 GHz, 1 MW) operation up to 300s
  - Fast steering high power EC heating launcher



Long pulse NBI operation (>70s)



NBI system layout



Long pulse ECH operation (300s)

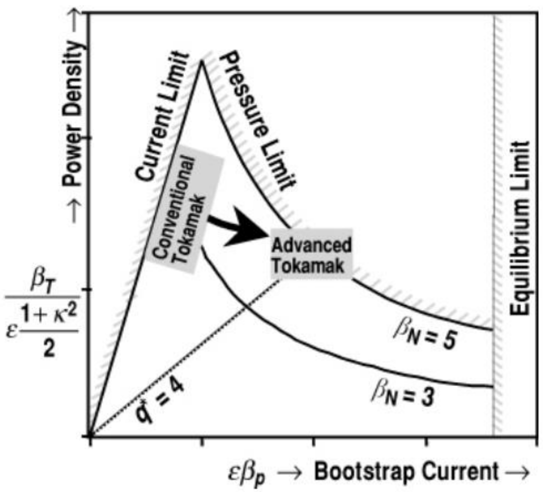
OUTLINE …….

- Introduction
- Research Highlights of KSTAR campaign
  - High performance steady-state scenarios
  - ELM suppression & 3D field research
  - Exploring the fundamental physics
- Future plan and upgrade

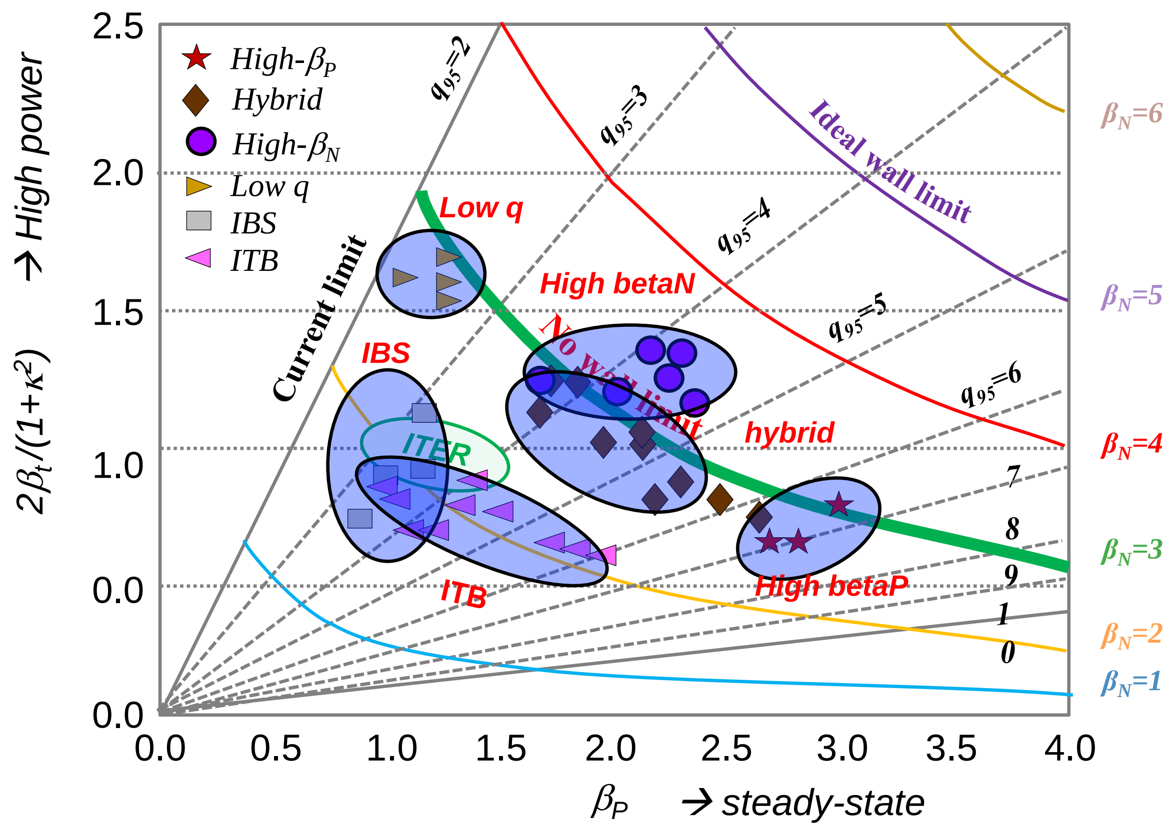
Progress in the high performance discharges in 2017 surpassing the no-wall limits with broad q95 operations

- Reliable startup using TPC (ECH-assisted)
- High elongation discharge (k~2.16)
- High Ip discharge (Stable 1 MA)
- Long pulse H-mode discharge (~73 s)
- ITB (ITER Baseline) scenario

- High β_P mode : β_N <2.7 β_P <3, f_{NI} ~ 1, f_{BS}~0.5, q_{95}>6
- High β_N mode : β_N < 3.2, 4.3 (transient), 2/1 NTM
- Hybrid mode : fusion gain G ~ 0.45, q_{95} >4
- ITB formation : β_N <2.0 β_P <1.5 with L-mode edge
- lowq95 mode : stable up to q95 ~ 2.3 (H-mode)

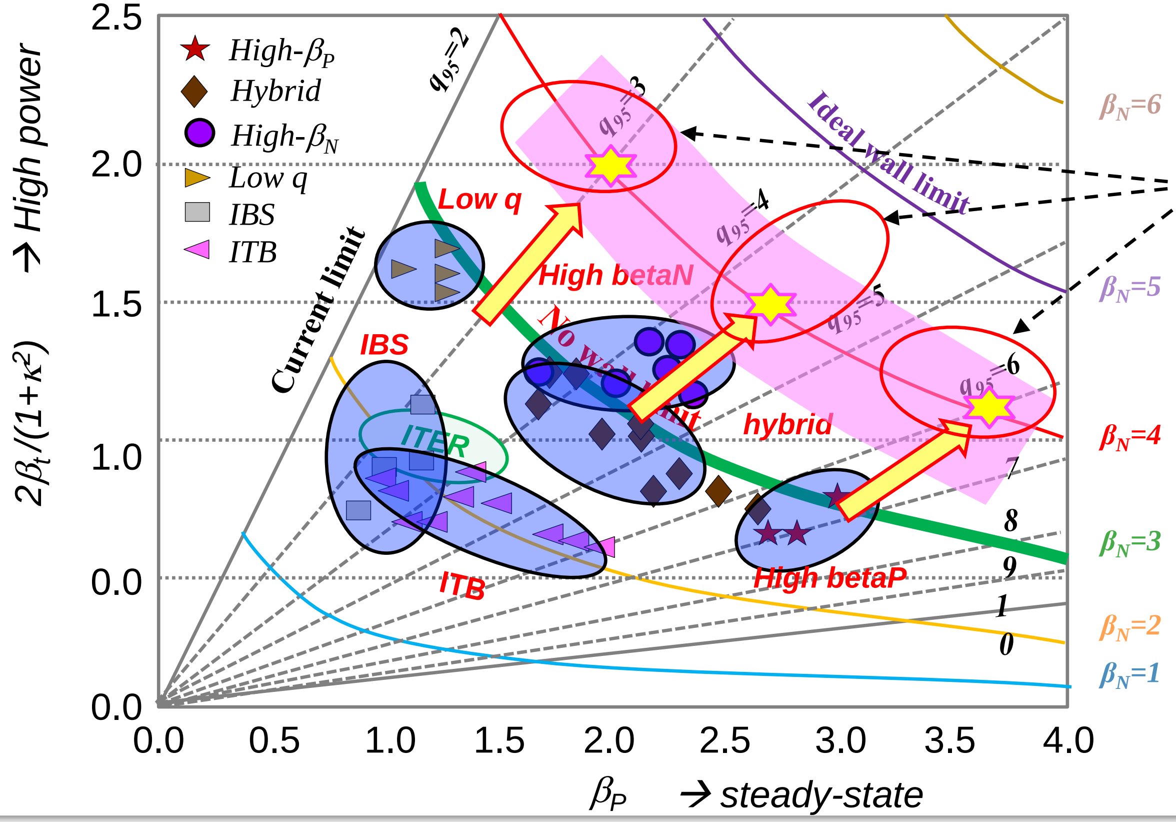


$$f_{BS} = I_{BS}/I_p \propto \beta_p \propto q\beta_N$$



Future research goals are exploring the high beta (β_N ~ 4) after the heating system upgrade (NBI & ECH)

- **Upgrade in heating system : NBI (5.5 MW → 12 MW) & ECCD (1 MW → 6 MW)**
- **Exploring the higher β_N operation (β_N ~ 4.0) with MHD instability control**



Extrapolation to high beta operation after heating upgrade based on 2017 experiments

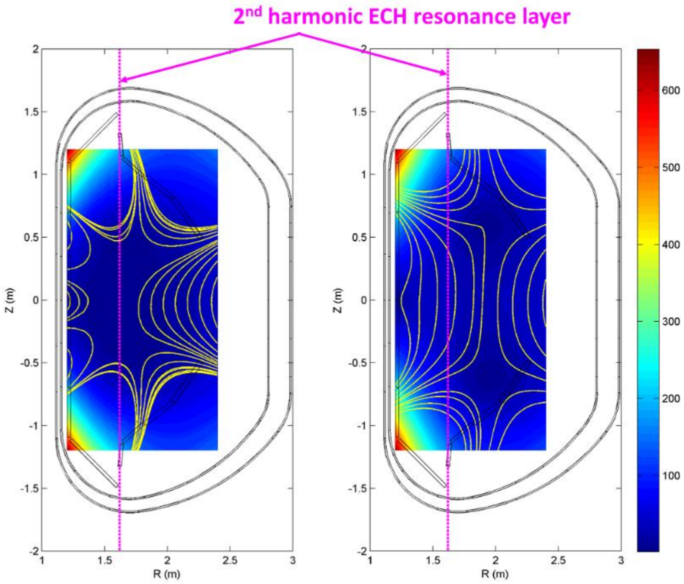
- Calculation with CRONOS without stability consideration

- PNBI = 11.7 MW
- PEC = 4 MW
- IP = 0.6 ~ 1.2 MA
- BT = 1.9 ~ 2.4 T
- neL = 5.22E19 m-3
- H98y2=1.1

Improved plasma control : startup (TPC), and enhanced vertical stabilization

- **Validation of Trapped Particle Configuration (TPC) startup as the most promising technique for ITER**
- **Improvement of vertical stabilization beyond design point**
  - Elongation up to ~2.16 with less sensitivity to I_P & β_P

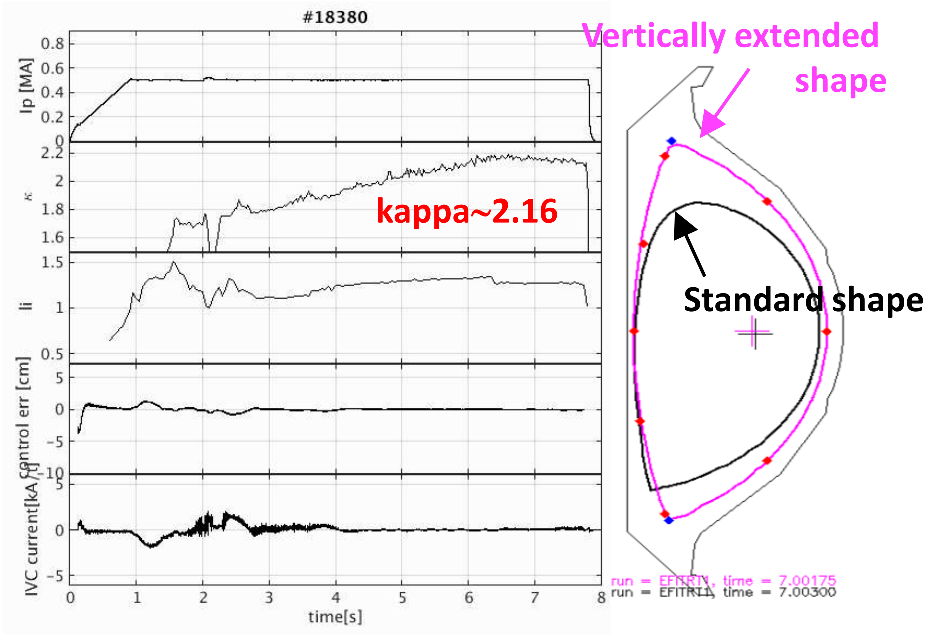
Trapped Particle Configuration (TPC)



Reference field null **Reference TPC**

Courtesy of J.W. Lee (NFRI)

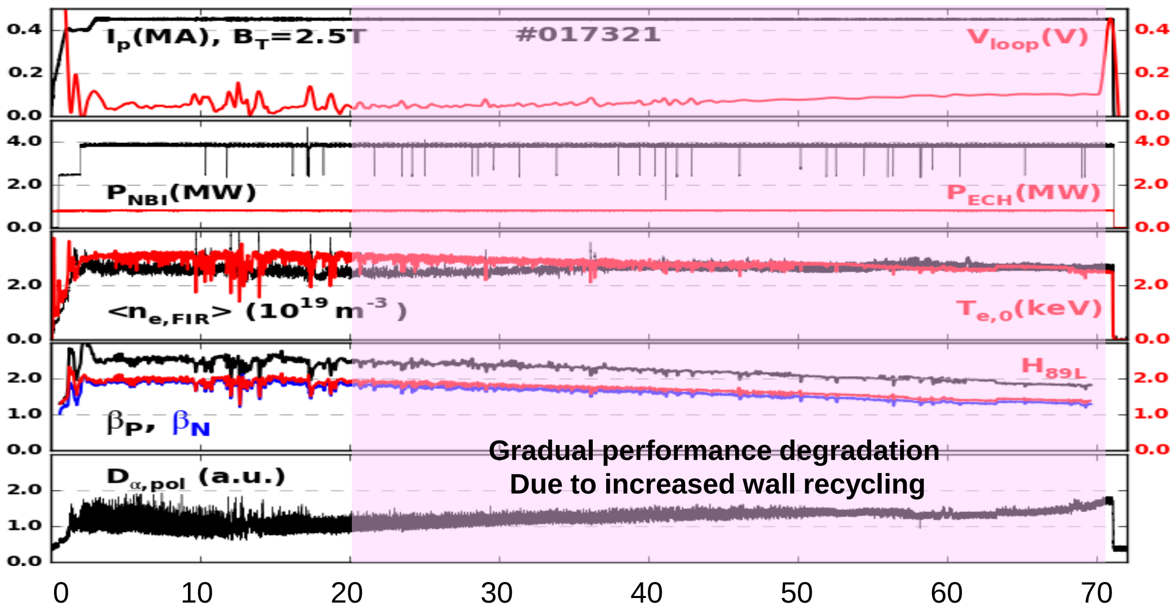
High elongation (k ~ 2.16)



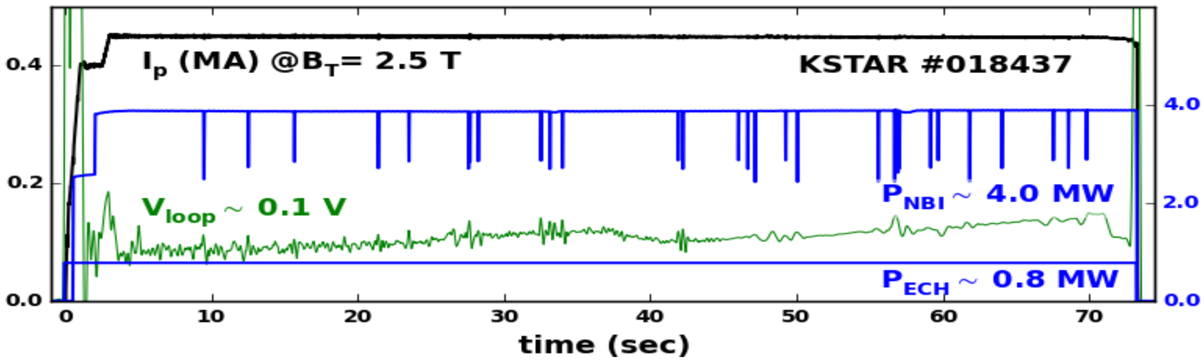
Courtesy of D. Mueller(PPPL)

Trial to steady-state long pulse discharges: Reproducing 2016 discharges (~ 73 s) but need additional efforts

- In 2016, long pulse limited by interlock (temperature of IVCC surface)



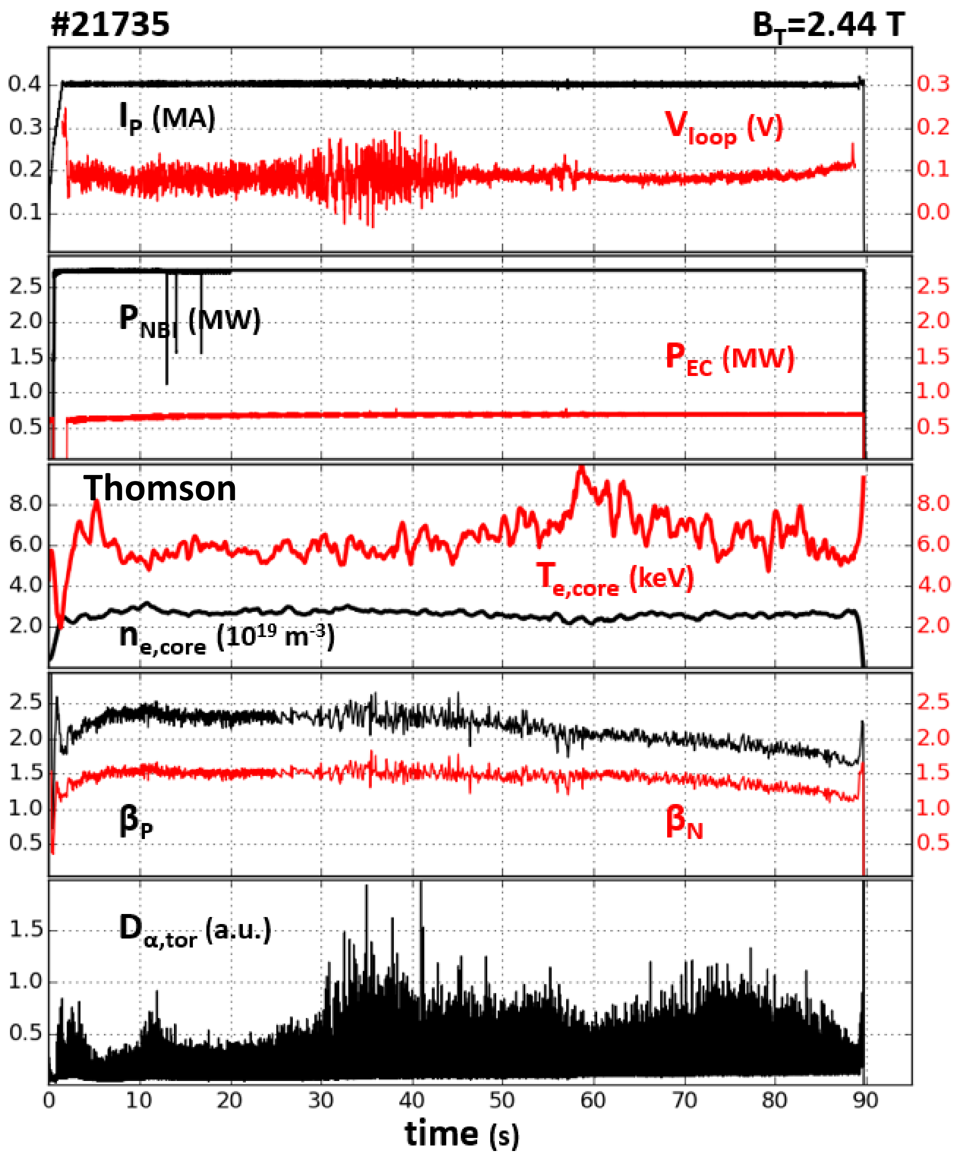
- In 2017, long pulse limited by trip in NBI or ECH system



- **Fully non-inductive advanced operation with high beta (β_N ~2.0, β_P ~2.5) up to 20s.**
  - Comparable to ITER baseline operation
- **Long pulse H-mode discharge (>70s)**
  - Gradual performance degradation due to increased wall recycling
  - In 2017, Loop voltage increasing at long pulse is similar to 2016 in spite of hot PFC operation

→ **Performance improvement in 2018 by adopting active water cooling into PFC and increased heating power**

#21735, new record of pulse length achieved in 2018



- I_P = 400 kA, B_T=2.44 T, P_{NBI}=2.8 MW, P_{EC}=0.7 MW
- He-IVCP and Water-Cooled PFC conditions

- V_{loop} ~ 0.1 V is kept during entire discharge.
- Relatively low density in the core at #21735 compared with the past.
- High temperature is shown as $T_{e,core}$ > 6.0 keV.
- β_P is sustained to almost constant until ~45-50 sec.
- β_P degradation for 50-60 sec comes from X-point changes to reduce a burden of PF3 and PF4.
- After 70 sec, β_P degradation is accelerated.
- Density is almost constant and temperature is even increased in some time-region, … β_P is degraded??

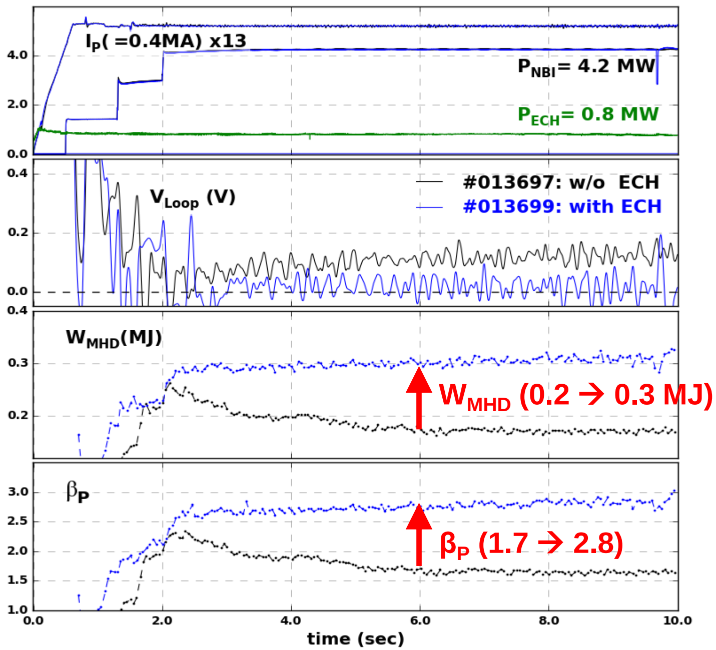
- D_α baseline is slightly increased.
- For 10-30 sec, EHO-like activity is observed.

Progress in High β_P discharges : performance improved by adding central ECH

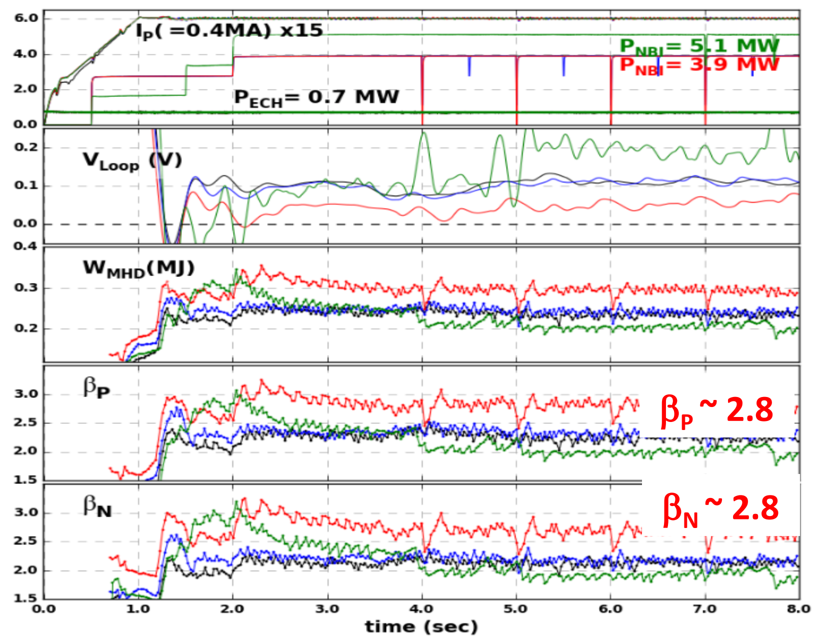
- **Enhanced High poloidal beta (β_P) discharges**
  - Improved performance by adding central ECH/CD
  - β_P and β_N ~2.8 (ITER SS comparable)
- **Narrow windows for high β_P**
  - 1.696m < $R_{ECH,Res}$ < 1.744m(Δ $R_{ECH,Res}$ = 5.0 cm)

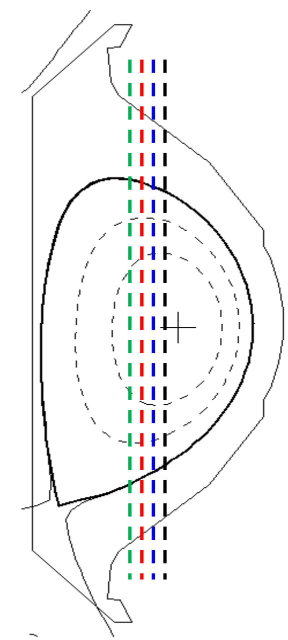
#18597 (1.90T) : normal H-mode
#18600 (1.85T) : normal H-mode
#18602 (1.80T) : high β_P mode
#18691 (1.75T) : normal H-mode

Improved β_P by adding central ECCD

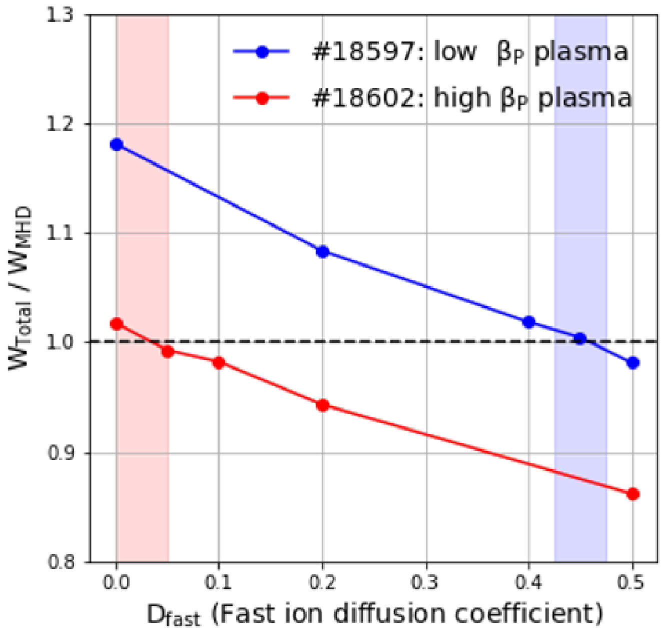


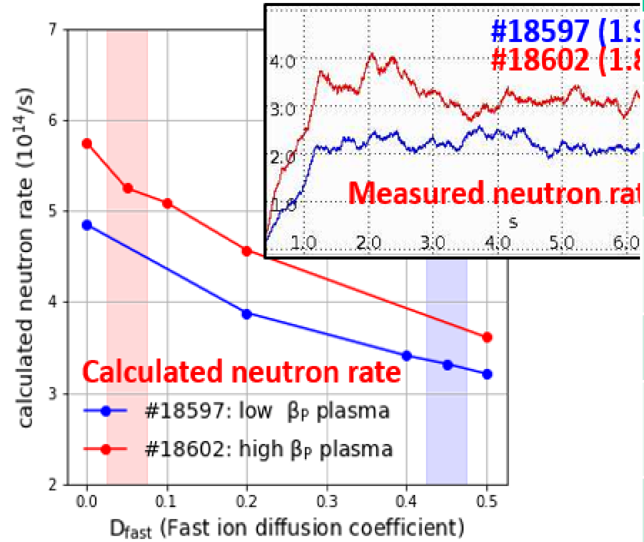
Stationary high beta discharge (β_N ~ β_N ~ 2.8) at 0.4 MA, 3.9 MW NBI and 0.7 MW ECH





High β_p mode : TRANSP analysis reveals fast ion transport (D_{fast}) is reduced with localized ECH





	High β_p mode	H-mode
W_{tot} [kJ]	300	235
W_{th} [kJ]	220	175
W_{fast} [kJ]	80	60
D_{fast} [m²/s]	0.4	1.2
H98/H89	1.1/2.1	1.0/1.7
$P_{th,NBI}$ [MW]	2.7	1.7
$P_{loss,NBI}$[MW]	0.8	1.8

$$W_{total} \equiv W_{thermal} + W_{fast}$$

- $W_{thermal}$: from kinetic profiles
- W_{fast} : from NUBEAM with D_{fast} variations
- D_{fast} : flat profile assumed

- D_{fast} can be determined by "W_{total} = W_{MHD}"
  → ~0.0 for high β_p and ~0.45 for low β_p

- Ratio of neutron rates in two discharges
  - Measured: 2.1/3.2 = 66%
  - Calculated: 3.3/5.2 = 64%

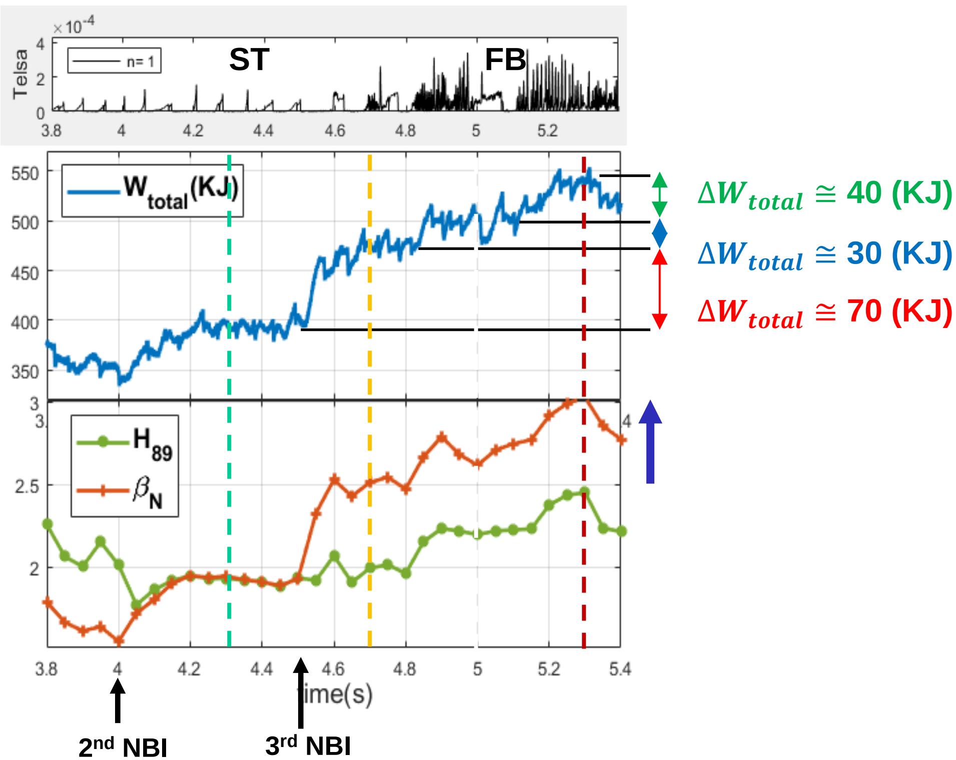
  → Good agreement

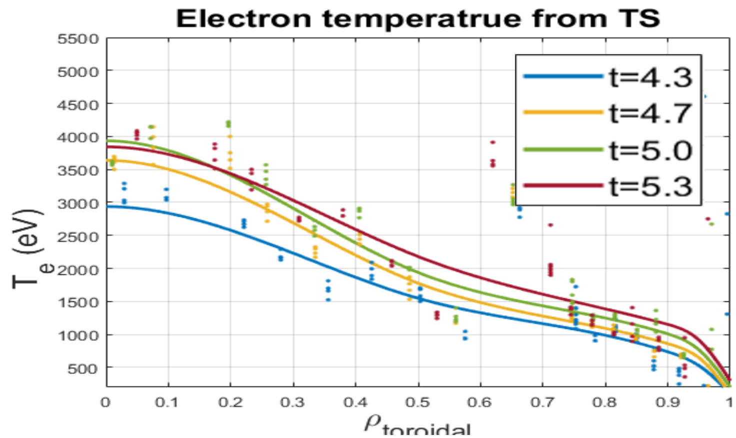
  → Good cross-check for D_{fast}

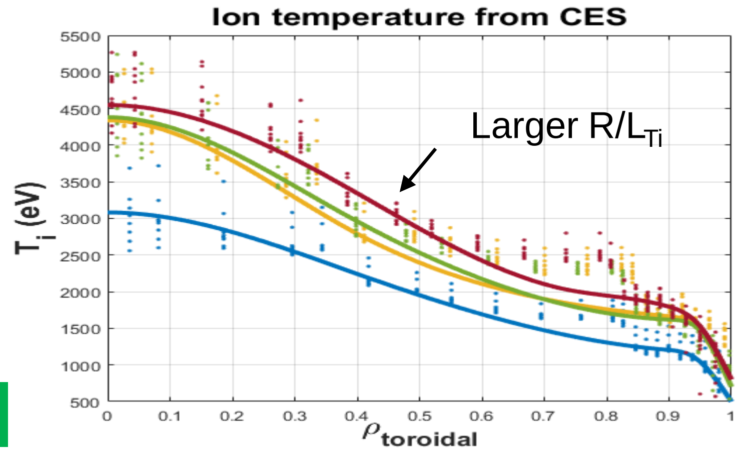
- Based on this, high β_p discharges show
  H98 ≥ 1.1, f_{NI} ≥ 90%, f_{BS} ~ 40%
  (cf: H98 ~ 1.0 in the low β_p discharges)

Hybrid mode : accessed by additional NBI timing and also related with fast ion confinement and pedestal increases

- **Exploring the Hybrid (advanced inductive) operations by adjusting heating time, and current overshoot**
  - Define hybrid : $\beta_N > 2.4$ & $H_{89} > 2.0$ in $q_{95} < 6.5$ w/o sawtooth
  - Increased H98, H89 by improved H-mode pedestal





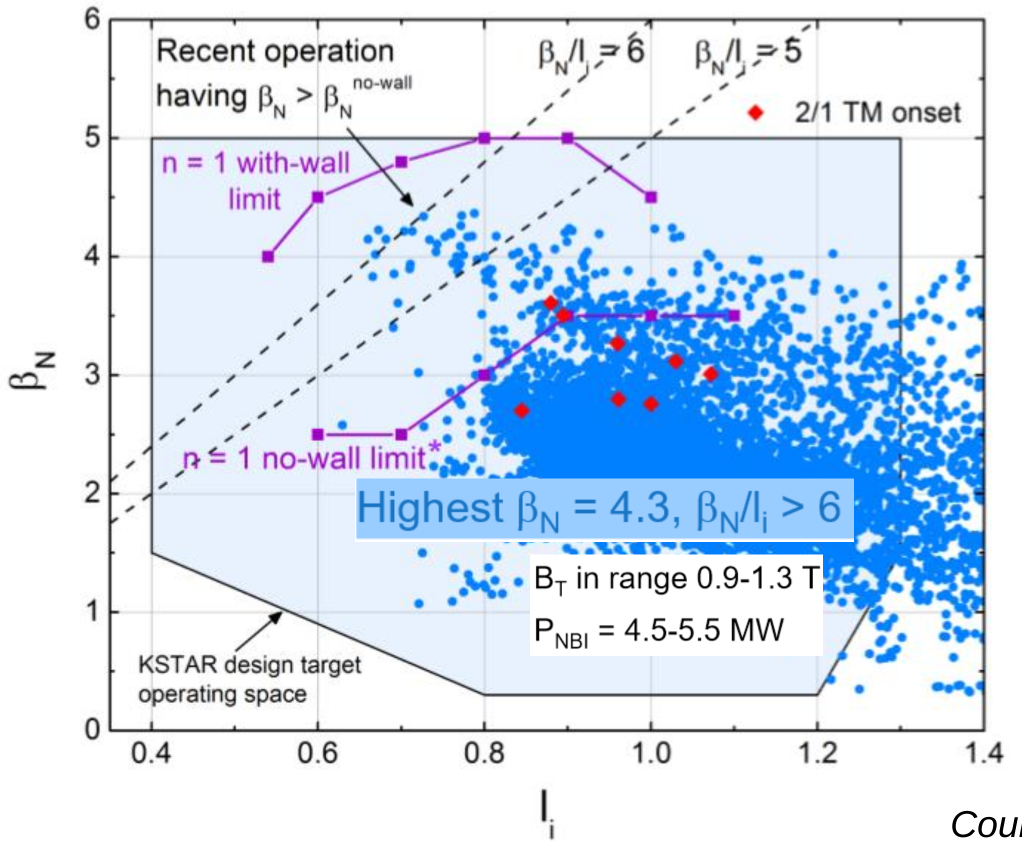


Y.S. Na (SNU), Oral 1A (Feb.21)

High β_N discharges : 'Stationary' high β_N > 3 discharge is achieved above no-wall limit

- **KSTAR H-mode equilibria have reached and exceeded the computed n = 1 ideal no-wall stability limit**

Normalized beta vs. internal inductance



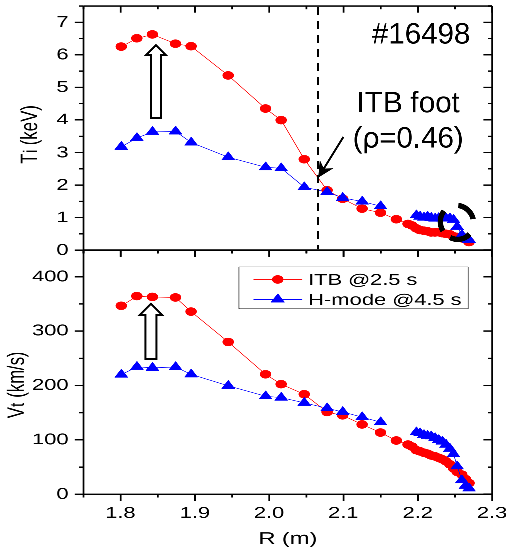
- Transient and highest β_N
  - β_N ~ 4.3
  - β_N / li ~ 6
  - (close to with wall limit)

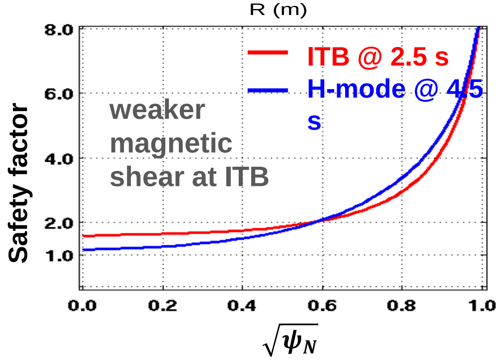
- Stationary high β_N
  - Sustained β_N = 3.3 (for 3 s)
  - High β_N plasmas were significantly extended to longer pulse by utilizing improved plasma control
  - Surpassing ideal no-wall limits

Courtesy of S. Sabbagh, Y. Park (Columbia U.)

Exploring low q95 operation to resolve low n MHD

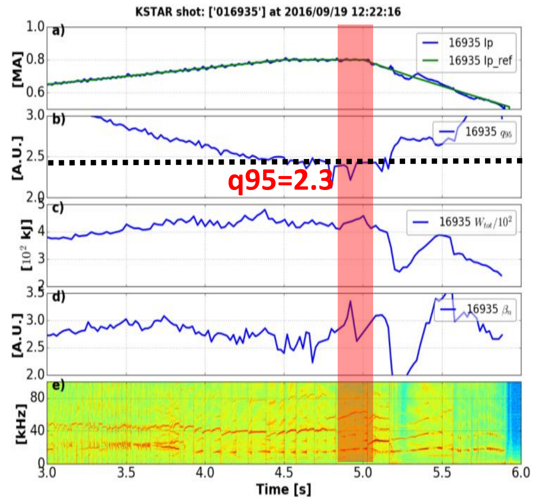
Internal Transport Barrier (ITB)



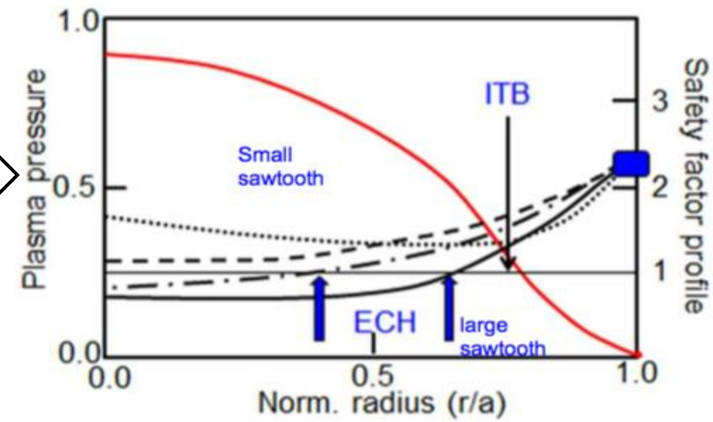


J. Chung, NF 2017

Low edge q operation



New operation window ? (ITB + Low edge q)

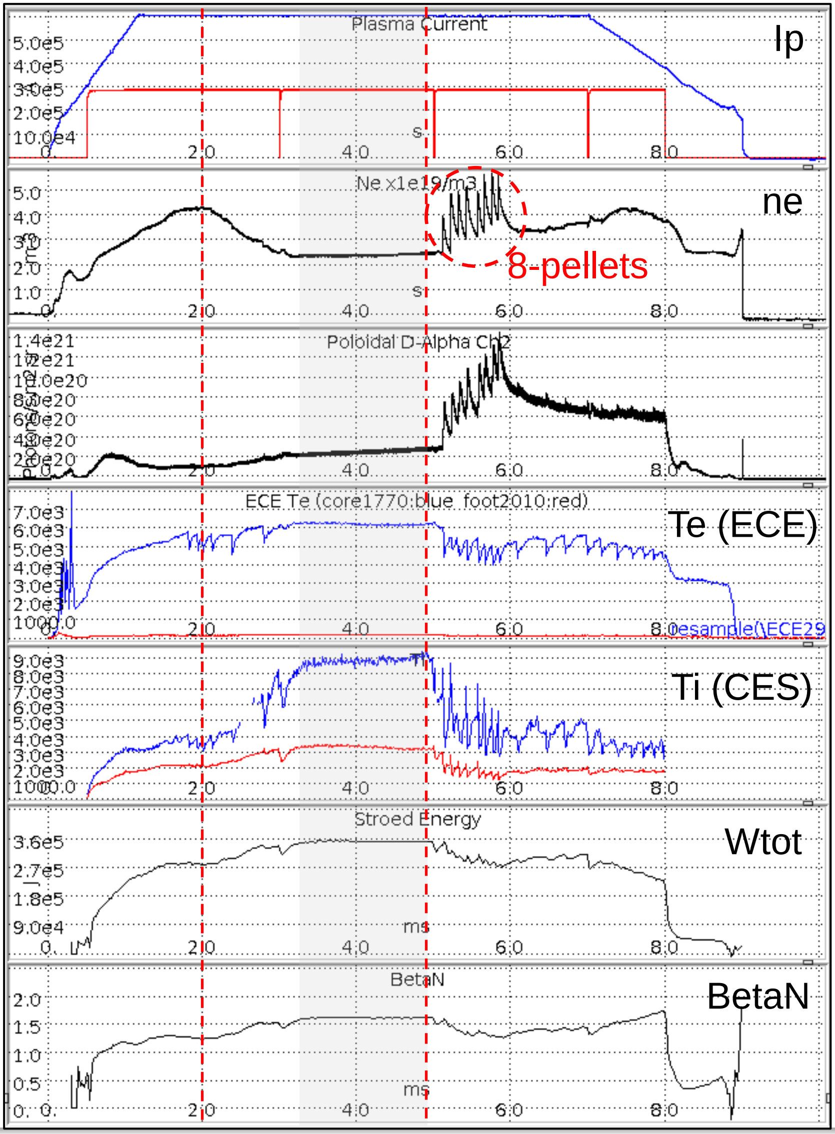


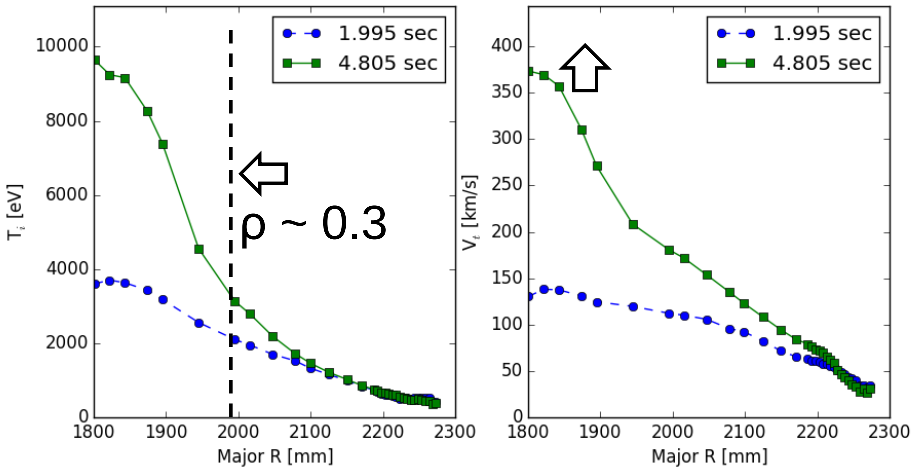
- **KSTAR could access to low q95 (<3.0) without any error field correction due to low intrinsic error field**
  - low q (<3) low m/n rational surfaces were pushed out
  - stable low q95 discharge with benign MHD activities
  - Exploring to combine with internal transport barrier (ITB) discharge

Courtesy of J. Kim, J. Chung (NFRI), H. Park (UNIST)

Internal transport barrier : Stable high Ti for ~ 1.6 s

#21631





#21631

Ti~9kev "for ~1.6s"

Wtot >350MJ, BetaN>1.6

25% lowered the 2nd gas puff.

Pellet injection @5s

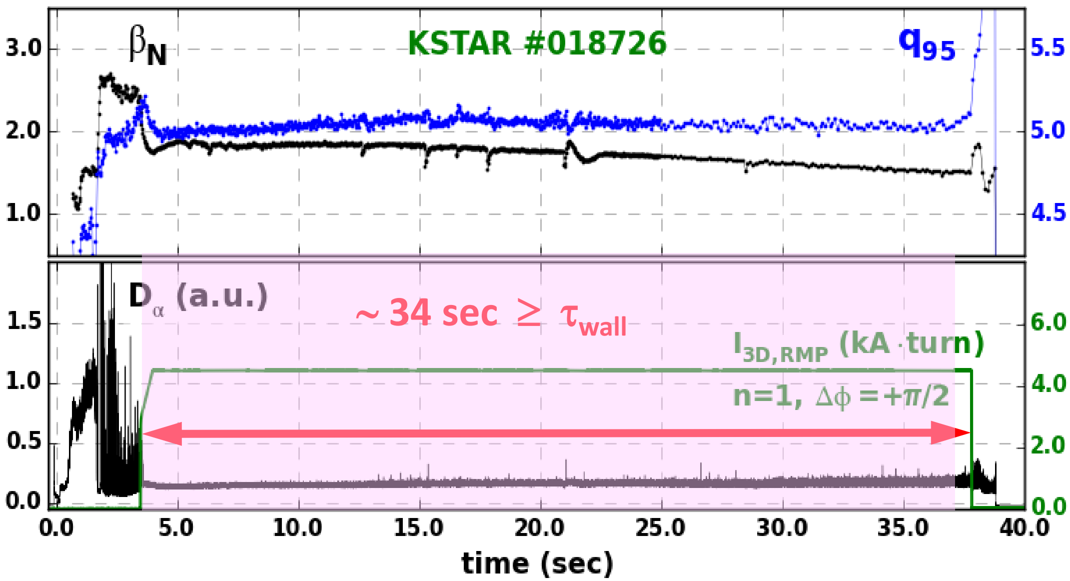
#21710

Ti~6keV "for ~18s"

OUTLINE …….

- Introduction
- Research Highlights of KSTAR 2017 campaign
  - High performance steady-state scenarios
  - ELM suppression & 3D field research
  - Exploring the fundamental physics
- Future plan and upgrade

Newly identified shape provides more stable and robust, even universal ELM-control with RMP

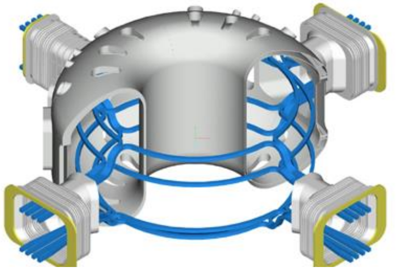


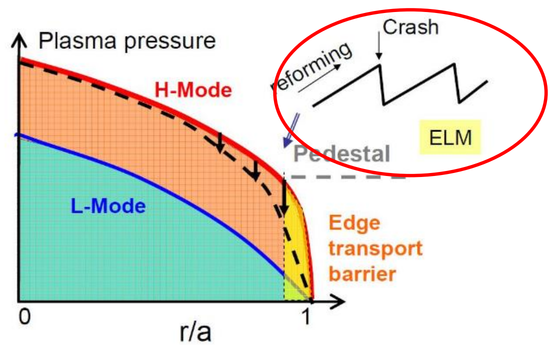
Record breaking long ELM-crash suppression (~34s)

- **Much longer pulse ELM-crash suppression enabled : ~10s in 2016 → 34s in 2017 (stable / robust)**
- ELM-crash suppression were expanded to operation at ITER baseline conditions : q_{95} ~ 3.4, β_N ~ 1.8
- ELM-crash suppression achieved for both n=1 and n=2 RMPs with same shape (universality)

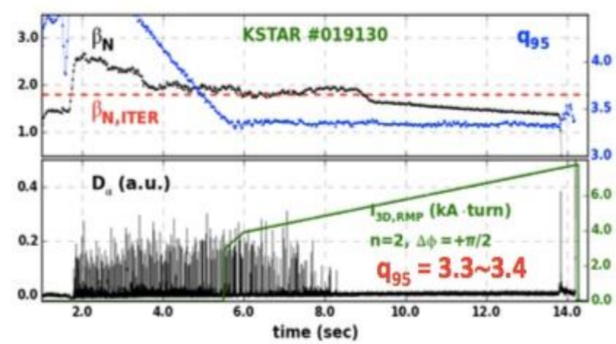
KSTAR In-vessel Control Coils (IVCC): Top/Mid/Bot

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



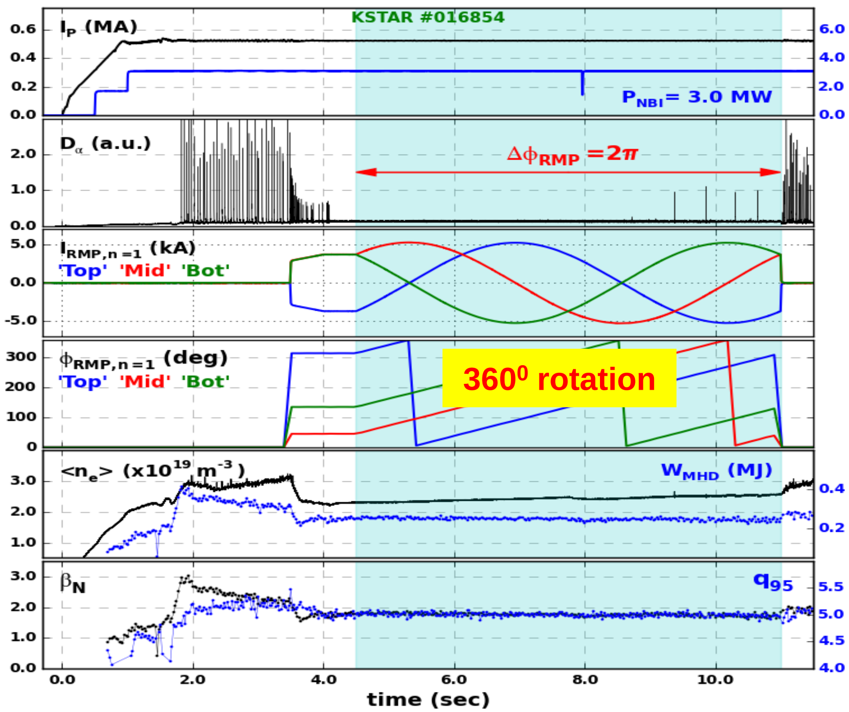


Lowest q_{95} ELM-suppression by n=2 RMP



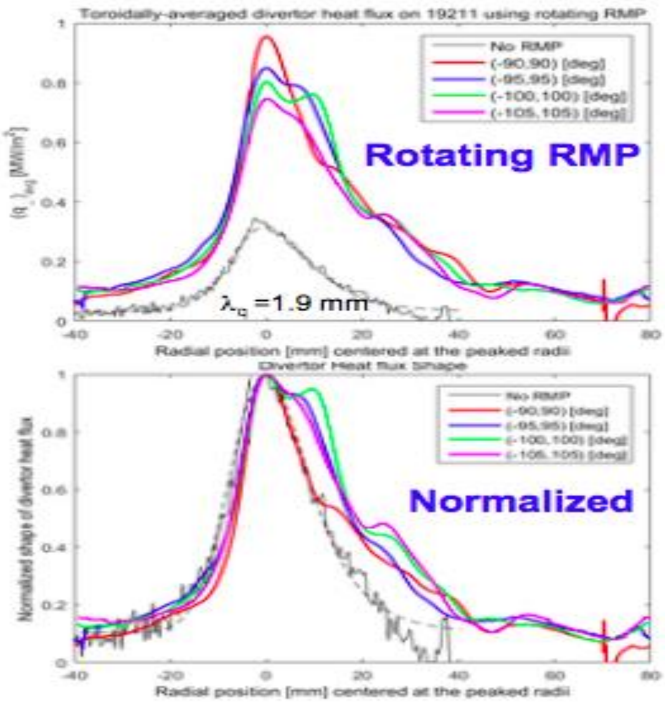
Taming the RMP and non-RMP field to control the divertor heat flux

- **Sustaining ELM-crash suppression under 360^0 rotated at n=1 RMP**
  - Rotation RMP could smooth the non-symmetric heat flux at divertor



n=1 full RMP under 360 degree rotation

- **De-phased RMP field lead to broader wetted area of heat flux on divertor during ELM-crash suppression**
- Reduced peak of heat flux, along with broadened shape, during RMP-ELM suppression is quite favorable to ITER

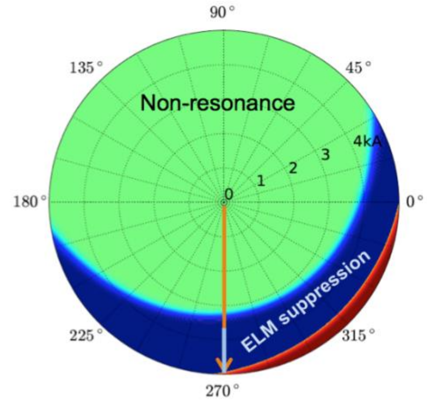


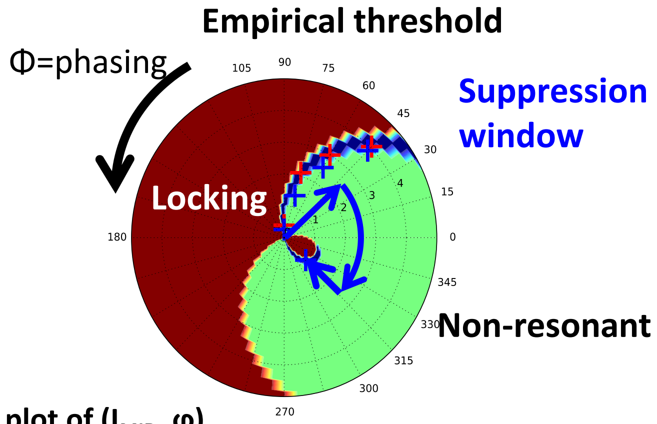
Courtesy of A. Loarte (ITER)

Confirmed excellent predictability of ideal response modeling for ELM suppression (phasing and shaping)

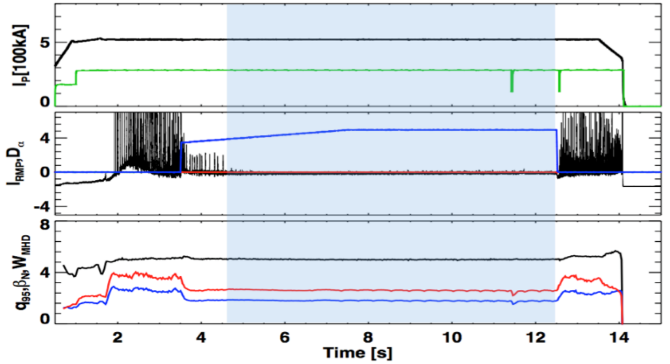
- **Prediction and validation of full n=1 RMP operation window for ELM suppression in complex KSTAR coil configuration space**

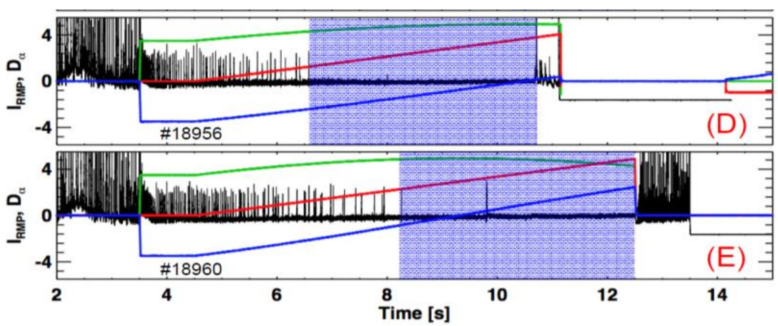
I_M=0kA subspace (off-midplane only)





Polar plot of (I_{MID}, φ)
with I_U=I_L=5kA and φ=$φ_{UM}$=$φ_{ML}$
(Locking "+", ELM suppression "+")



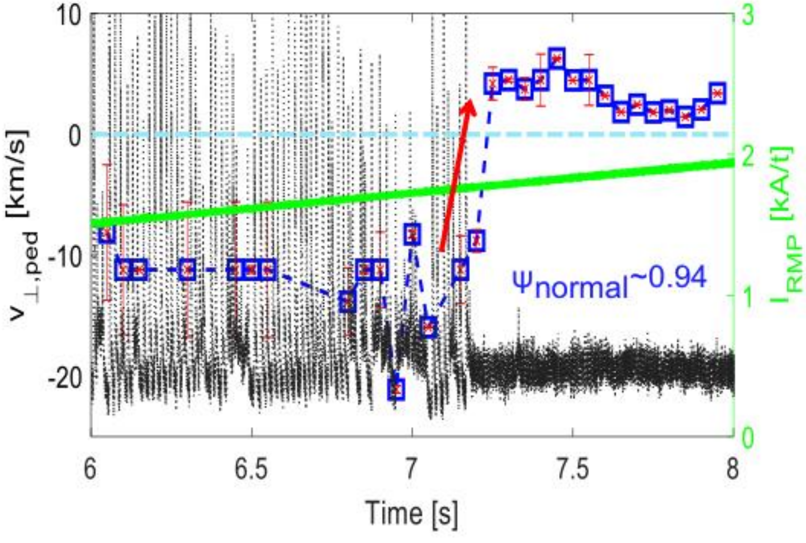


J. -K. Park, Nature Physics

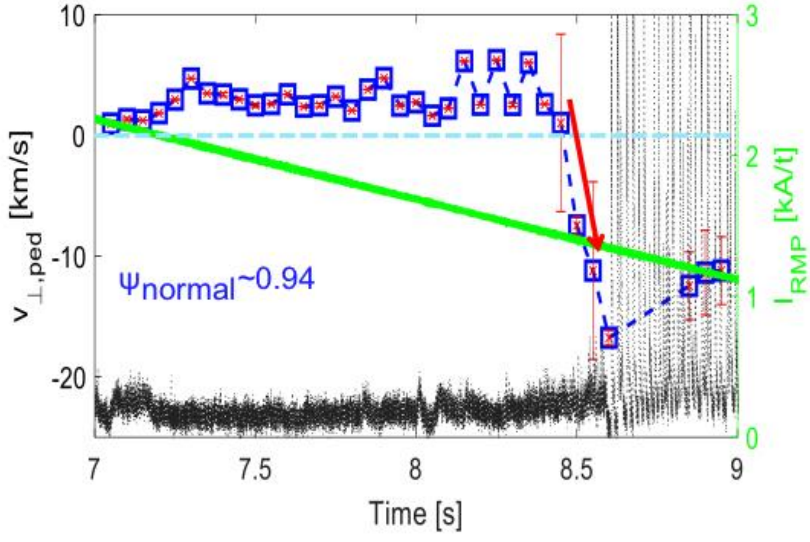
Rapid bifurcation of $v_{\perp,ped}$ has been observed using ECEI in KSTAR at the onset of RMP-driven ELM-crash suppression

- **Perpendicular flow ($v_{\perp}$) can be measured using ECEI by tracking the movement of turbulent eddies.**
- The rapid changes in $v_{\perp,ped}$ are synchronized with the transition into and out of ELM-crash suppression, which may be associated with the RMP field penetration into the plasma.

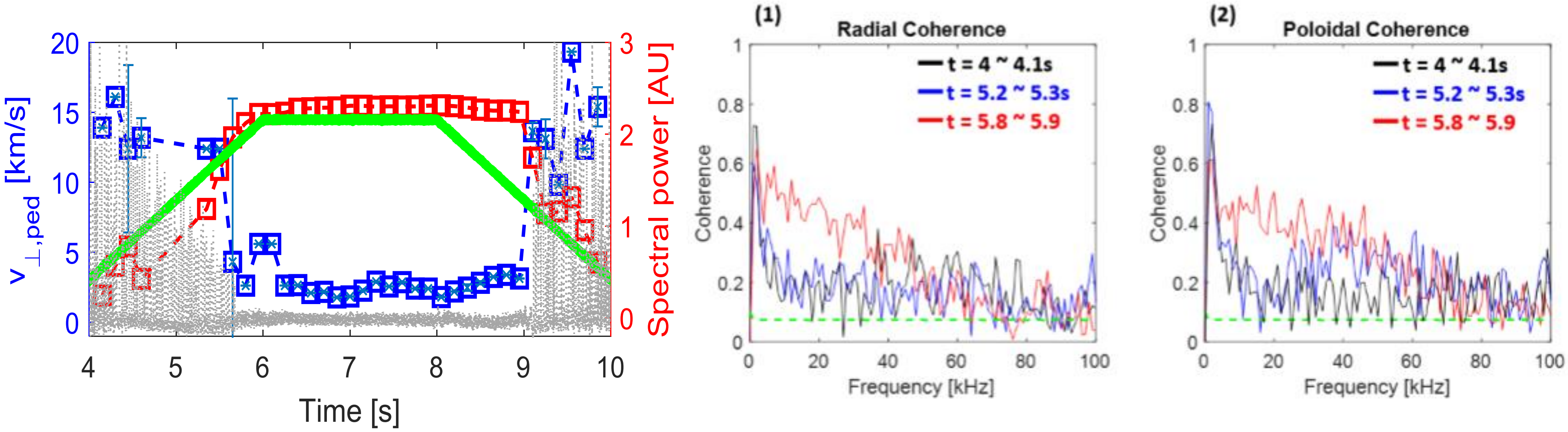
Time trace of $v_{\perp}$ near the pedestal with slowly increasing RMP strength (ref. shot #19347, n=1 RMP)



Time history of $v_{\perp}$ near the pedestal with slowly decreasing RMP strength (ref. shot #19348, n=1 RMP)



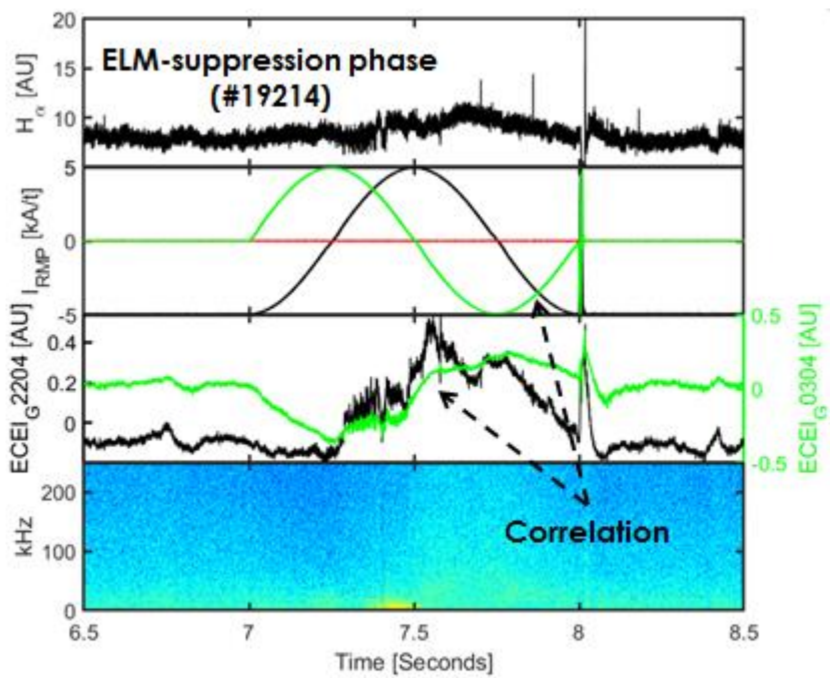
Changes of turbulent fluctuations and perpendicular flow at the transition into and out of ELM-crash suppression



- **The RMP enhances the turbulent fluctuations in the edge toward the ELM-crash suppression.**

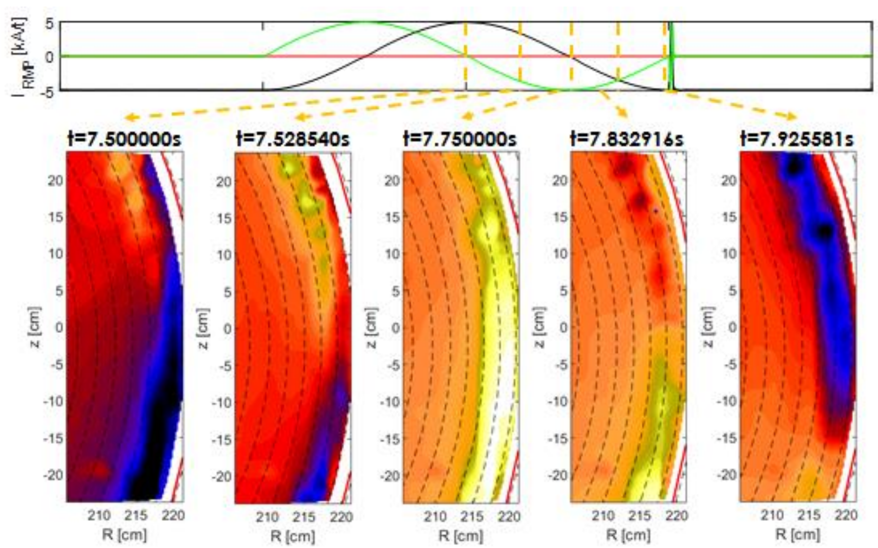
- **The rapid changes in perpendicular flow is synchronized with the onset of transition into and out of ELM-crash suppression, which may be associated with the RMP field penetration into the plasma.**

RMP-plasma response can be quantified by measuring the radial displacement with rotating RMP



The kink response of plasma can be measured using rotating RMP

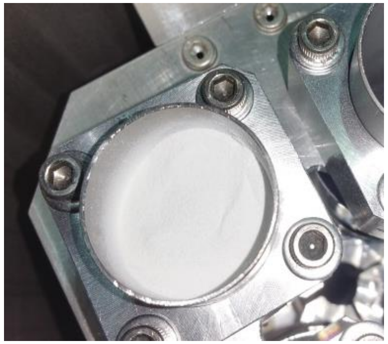
During RMP rotation, 2D radial displacement of Te measured

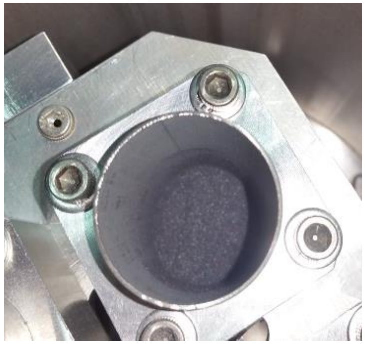


Impurity powder dropper has been installed on KSTAR under the collaboration between NFRI and PPPL/DIII-D

✓ Now, it is available to drop Boron or Boron Nitride into the plasma

Boron Nitride

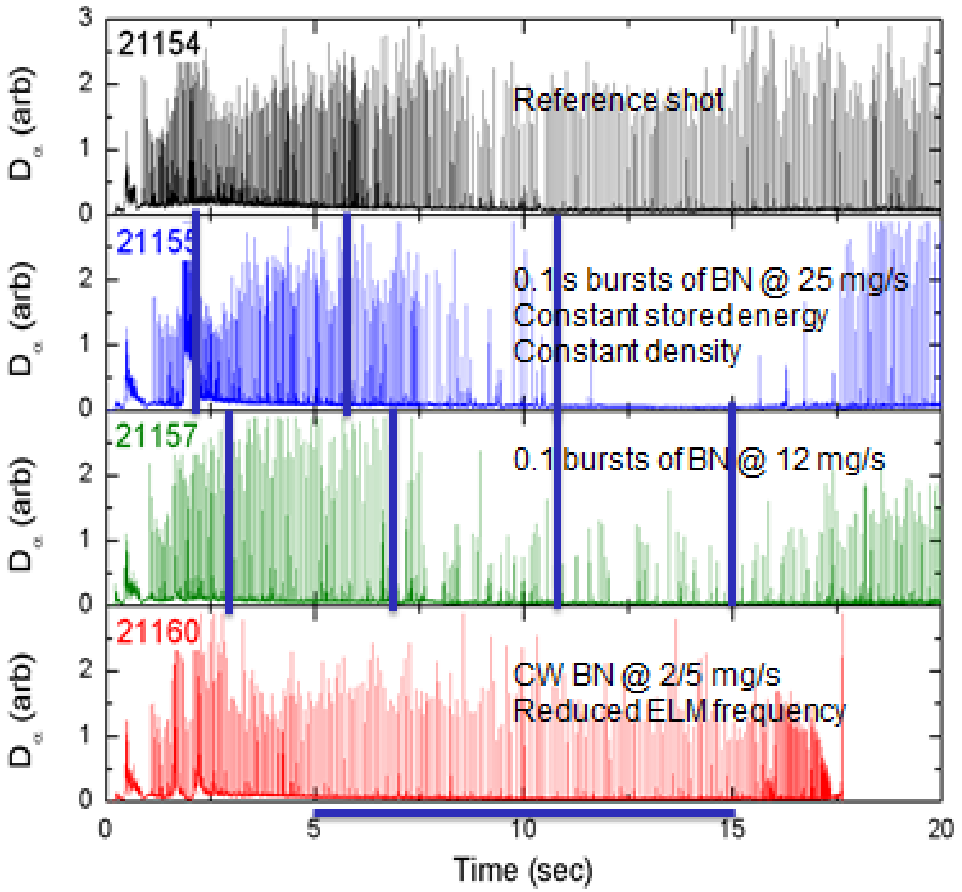




Boron

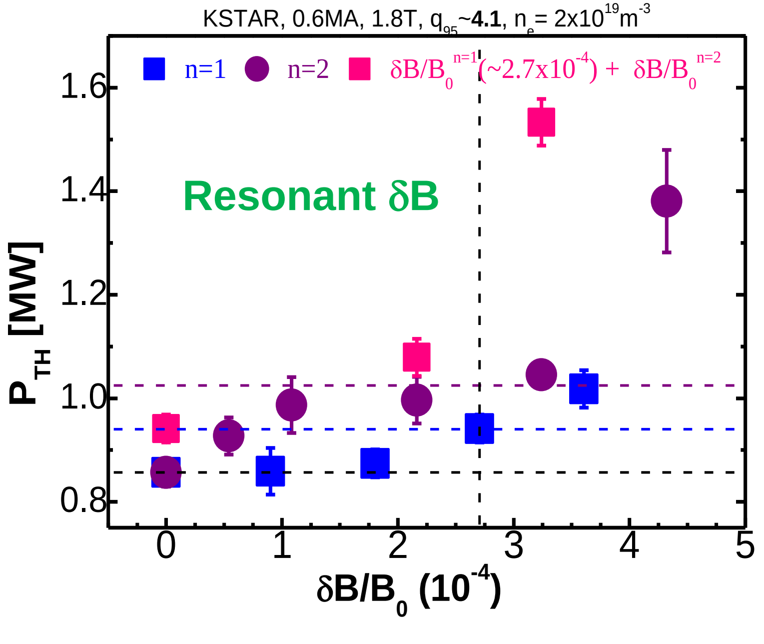
E. Gilson, PPPL

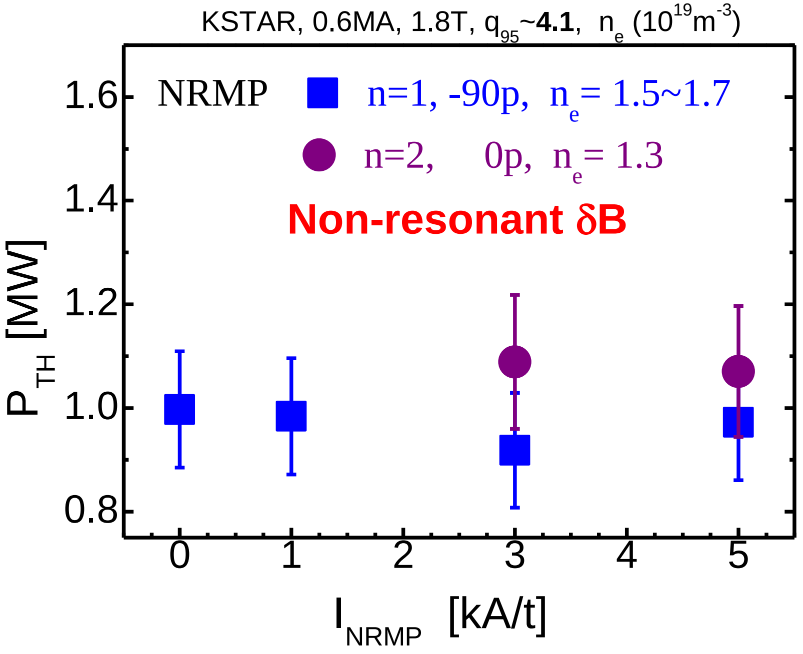
BN ELM suppression in KSTAR (preliminary)



Contrasting 3D field dependences of Resonant vs Non-Resonant components on P_{TH} observed in KSTAR

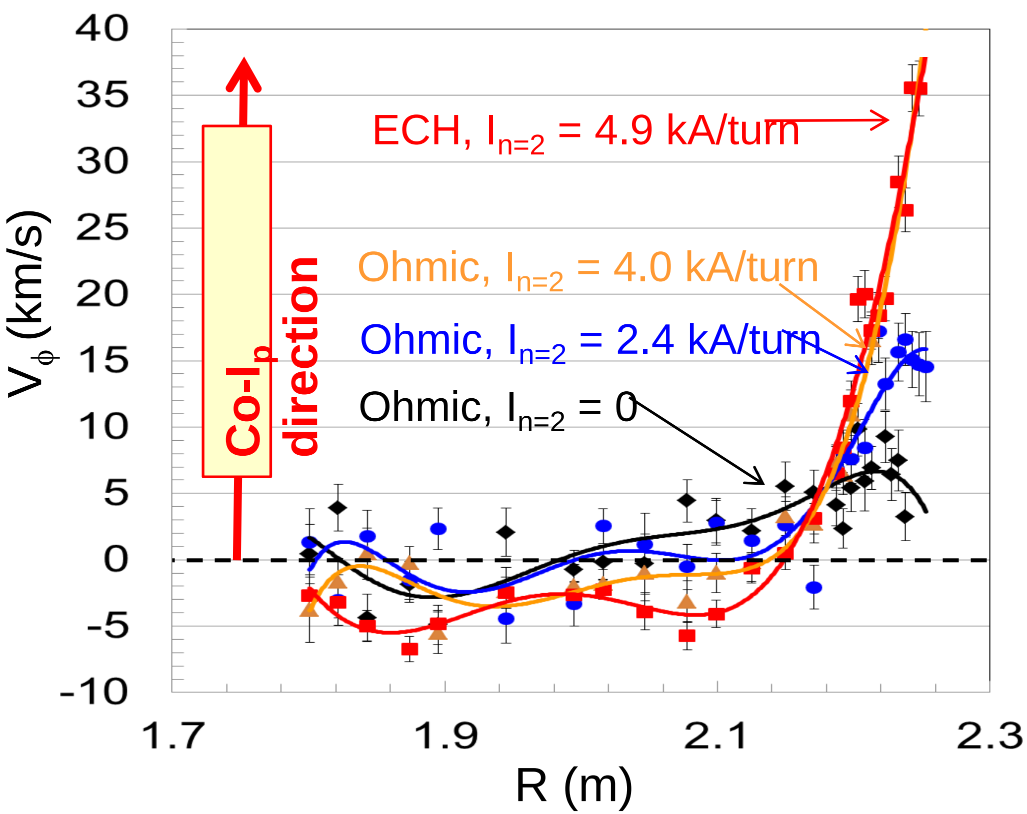
- **P_{TH} in KSTAR [$dB^{n=1}/B_0 \sim O(10^{-5})$] shows quite a sensitive dependence on both n=1 and n=2 resonant components, unlike in conventional devices [$dB^{n=1}/B_0 \sim O(10^{-4})$],**
- **BUT, P_{TH} in KSTAR did show no dependence of non-resonant components, even when toroidal rotation got lowered by about 25 %**
- **There is no consideration of non-resonant components of 3D field for ITER and future machine.**





Generalized Neoclassical Toroidal Viscosity (NTV) Offset rotation profile V_0^{NTV} measured in KSTAR

Measured V_0^{NTV} profiles (when $I_{n=2} \gtrsim 3$)



- **Co-I_p rotation generated**
  - Stronger n = 2 field + ECH heating clearly yields counter-Ip rotation in core, co-Ip rotation in outer region
  - Direct measuring the NTV is the first time
  - Co-I_p rotation is only possible by V_0^{NTV} effect
- **Potential aid for ITER**
  - ITER simulations: Ω_φ ~ 2 krad/s in outer region
  - KSTAR result shows very strong rotation (Ω_φ > 12 krad/s) and rotation shear in outer region by RMP

Courtesy of S. Sabbagh (Columbia U)

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

OUTLINE …….

- Introduction
- Research Highlights of KSTAR
  - High performance steady-state scenarios
  - ELM suppression & 3D field research
  - Exploring the fundamental physics
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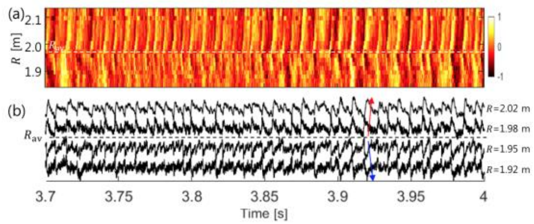
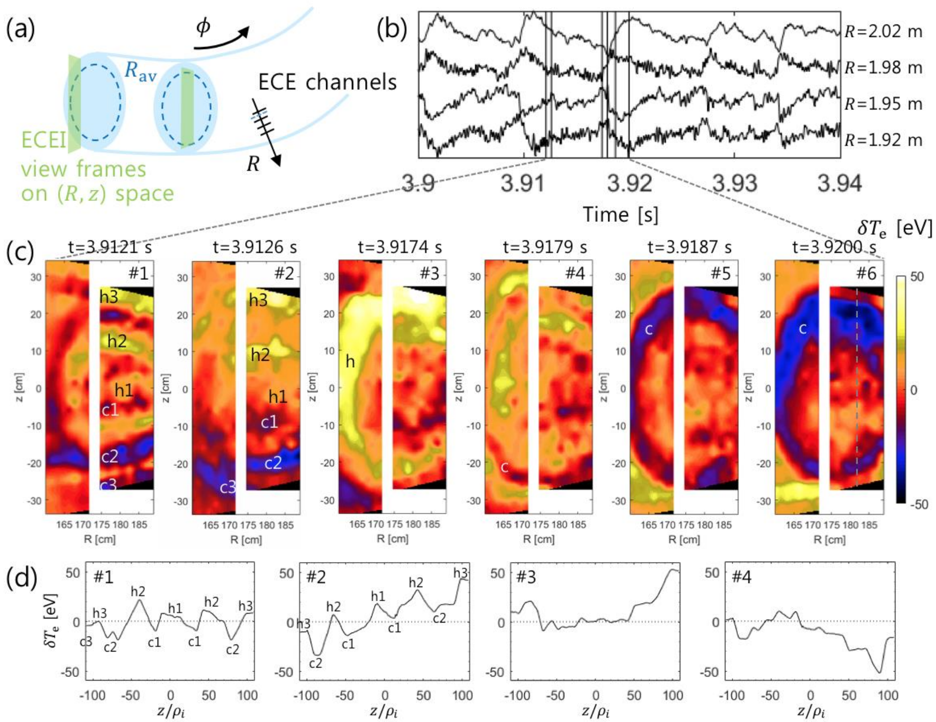
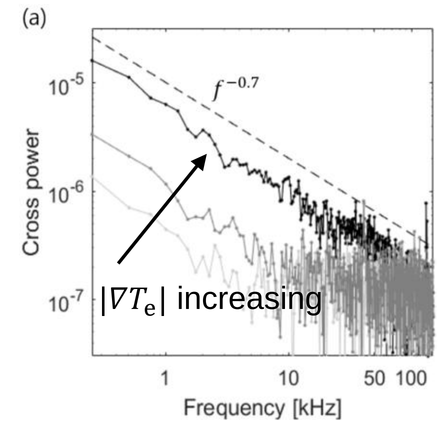
Long range avalanche-like electron heat transport events driven by ∇T_e-correlated-fluctuation in L-mode

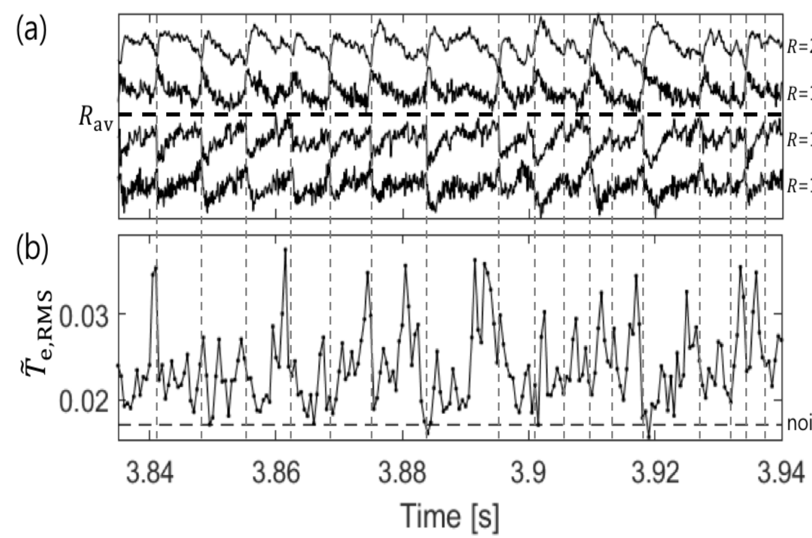
Dynamics of avalanche-like electron heat transport events in the MHD-quiet L-mode plasma





∇T_e-correlated-fluctuation with the power law is identified, play a role in onset of the avalanche (indicating non-diffusive radial transport)

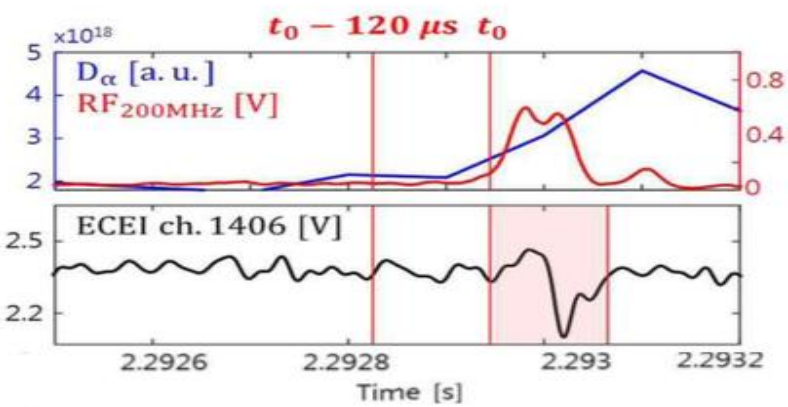


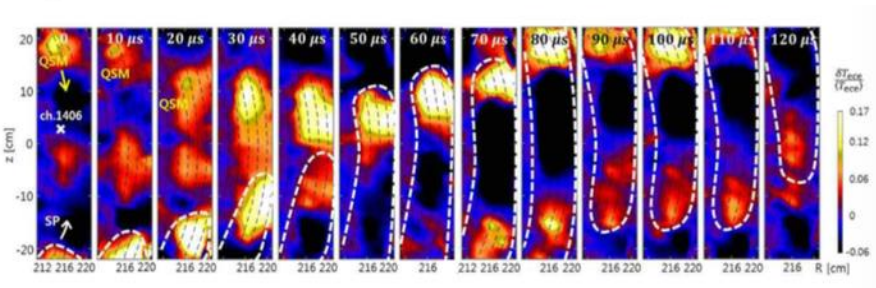


Understanding basic and underlying physics : Interaction of ELM with solitary perturbation and q0 after sawetooth crash

➢ Interaction of the ELMs and Solitary perturbation (SP: partial n=1 mode)

- SP appears ~ 100 μs prior to crash
- Opposite rotation due to E_r x B drif

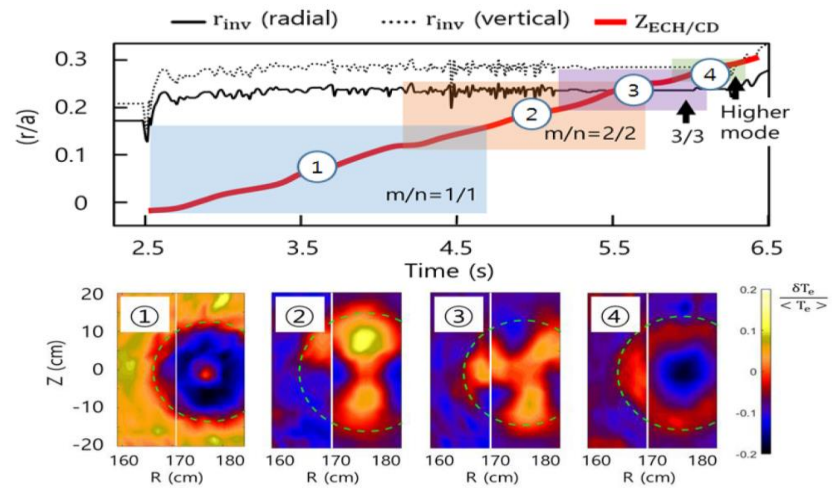




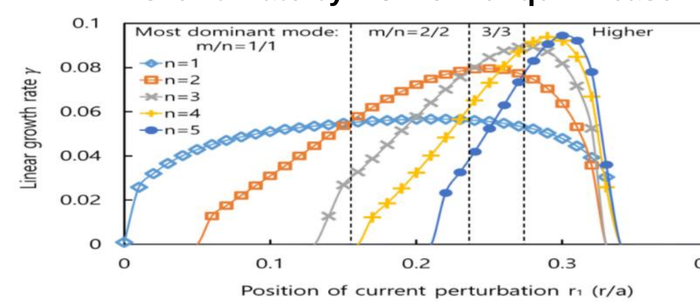
Solitary perturbation prior to ELM crash

➢ Validation of q0 > 1 in the MHD quiescent period of after crash of sawtooth in KSTAR

- MHD mode excitation by ECCD within q < 1 is performed with M3D-C1 stability analysis.



Growth rate by M3D-C1 for q0 > 1 case



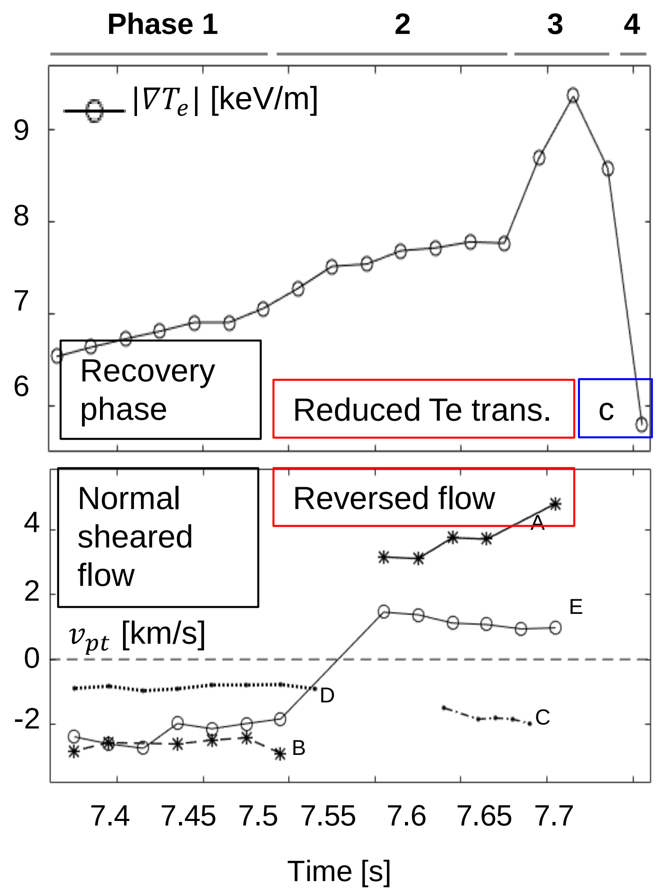
JE Lee (UNIST), Scientific Report 7, 2017

H. Park (UNIST), IAEA FEC 2016

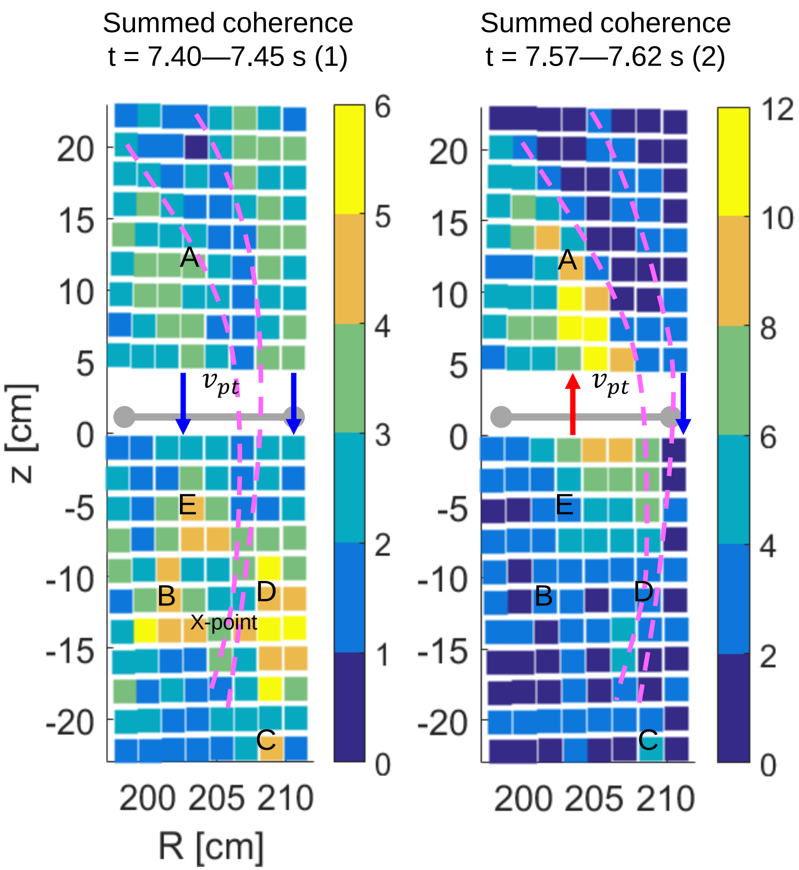
Effects of magnetic island on electron heat and momentum transport

- Magnetic island can reduce or enhance the electron heat transport by changing the flow and turbulence around the rational surface

Flow is reversed when phase 1→2

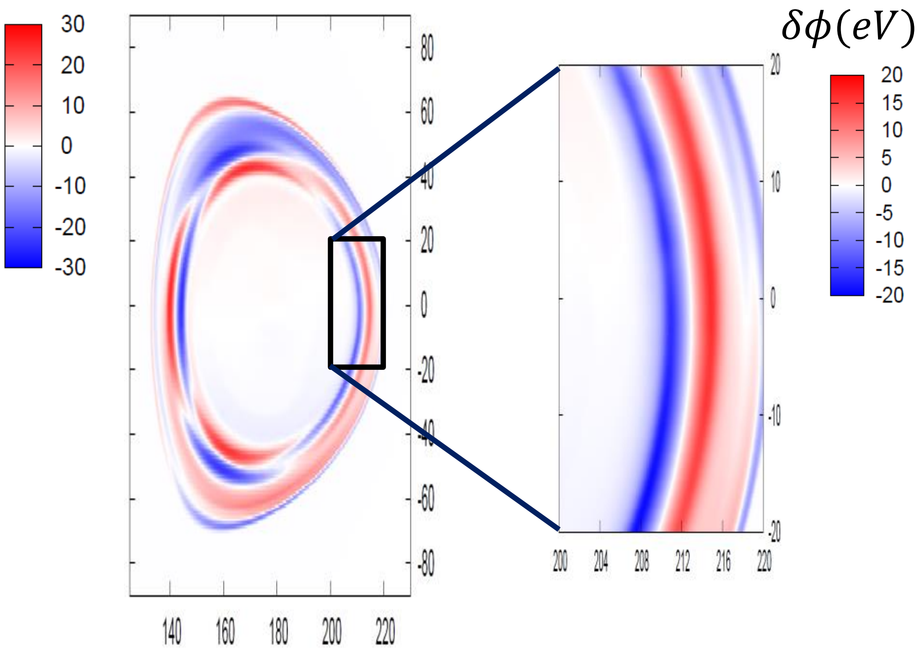


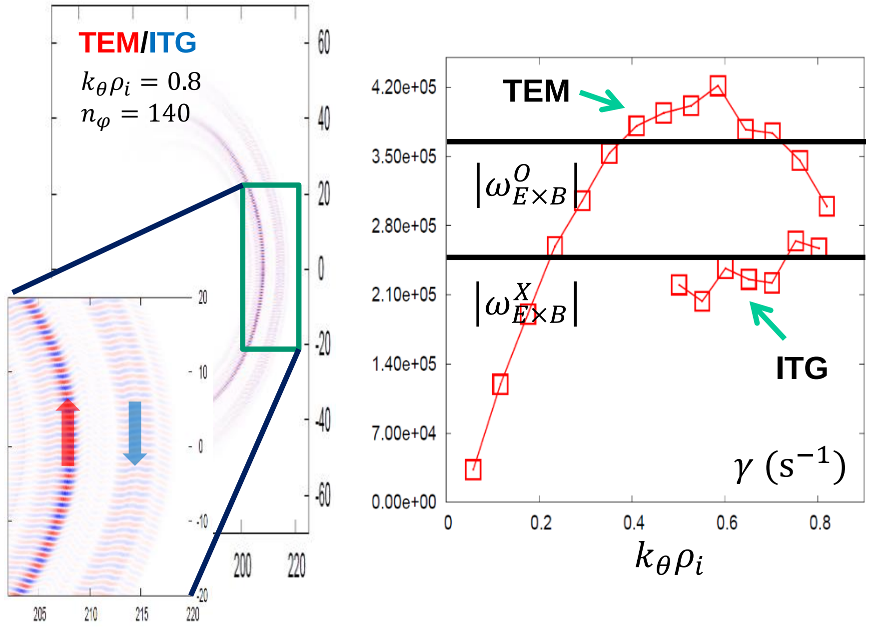
2D turbulence changes when phase 1→ 2



M.J. Choi et al, Nucl. Fusion Lett. 57, 126058 (2017)

Gyrokinetic Study of Flow Shear on Microinstability around Magnetic Island in KSTAR L-mode Plasma





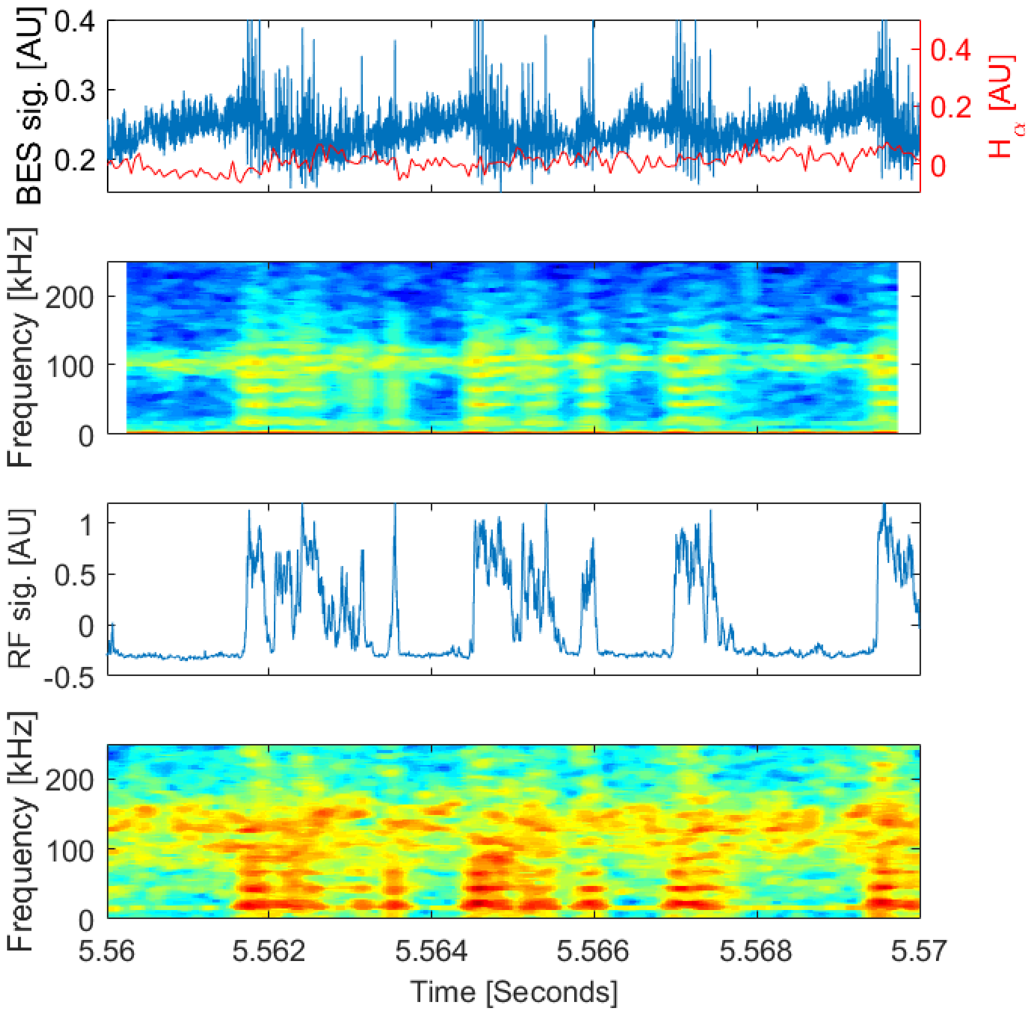
- Global XGC1 neoclassical simulation of perturbed equilibrium potential by (2,1) magnetic island
  - (2,1) mode structure of perturbed potential
  - Poloidally and toroidally inhomogeneous ExB shearing structures by perturbed potential
  - ➔ Impact on ambient micro-instabilities e.g. TEM, ITG

Jae-Min Kwon et al, Phys. Plasmas 25, 052506 (2018)

- Global gKPSP micro-instability analysis of profiles modified by (2,1) magnetic island
  - Excitation of TEM and ITG in inner and outer region neighboring the island
  - Flow shear by island-driven perturbed potential can suppress ambient TEM and ITG

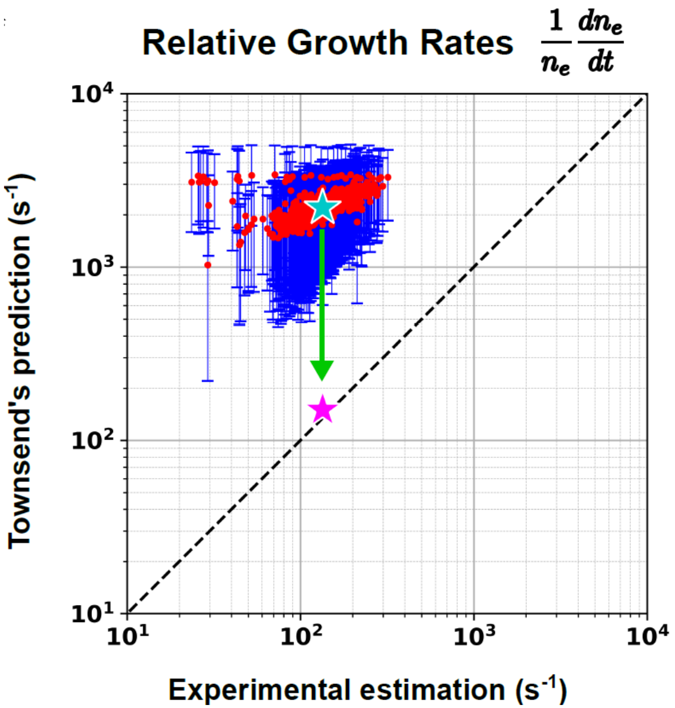
➔ Flow and fluctuation patterns are consistent with ECEI observations

Edge Harmonic Oscillation (EHO) is regulating pedestal density in Quiescent H-mode phase



- **The EHO in QH phase (in co-Ip plasma) is synchronized with density collapse measured by BES**
- The EHO in QH phase is discontinuous and also synchronized with the RF burst (f_{RF}~500-600MHz)
- The RF bursts are related to the transport because the BES signal level decreases when the RF bursts
- However, ELM filaments observed in ECEI do not collapse although the RF bursts, suggesting that the RF bursts are related to edge harmonic oscillation dynamics
- Identifying the correlation between the RF burst and the harmonic oscillation will be important in future studies of the ELM-free plasma

Fundamental physical mechanism of Ohmic breakdown is identified



M. G. Yoo, Nature communication 2018

❑ **KSTAR experiments reveal that Townsend avalanche theory is not valid for the ohmic breakdown mechanism**

- Experimental avalanche growth rates are 10-100 times slower than Townsend theory
- Homogeneous density profile along B in experiments cannot be explained by Townsend theory that must have exponential profile along B

❑ **A new breakdown theory by considering plasma response discovers crucial roles of self-electric fields**

- $E_{self,\parallel}$ cancels out $E_{ext,\parallel}$ and decrease ohmic heating power (parallel dynamics)
- $E_{self,\perp}$ induces dominant turbulent ExB transports and diffusion (perp. dynamics)

❑ **The theory is demonstrated by successful reproduction of KSTAR experiments using particle simulation code BREAK**

- Drastic decrease of avalanche growth rate due to decreasing heating power and increasing convection loss
- Homogeneous plasma structure along B by fast turbulent diffusion along B

KSTAR

OUTLINE …….

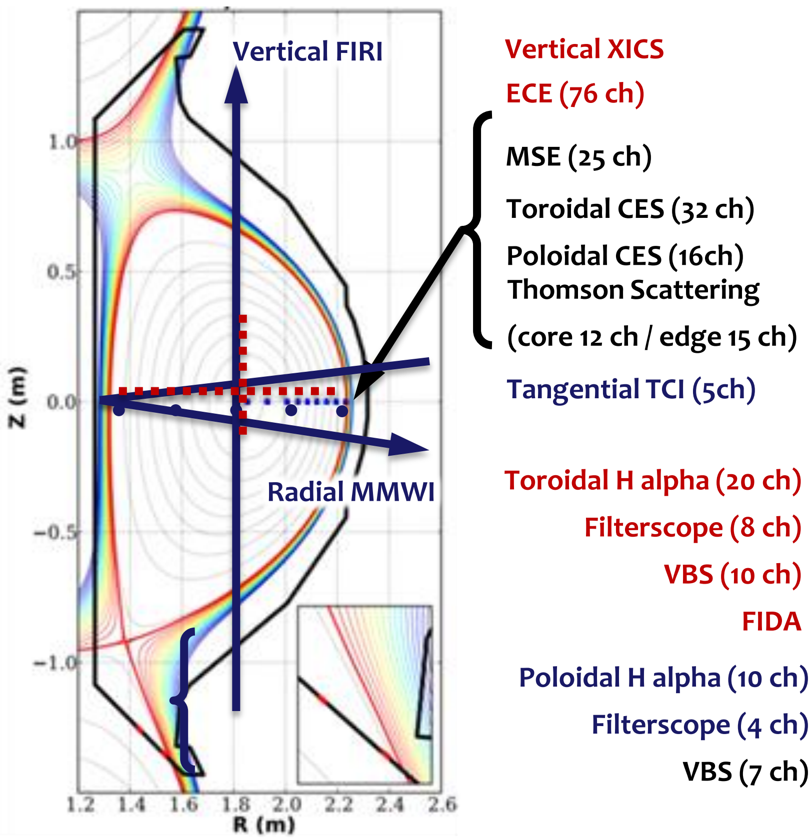
- Introduction
- Research Highlights of KSTAR 2017 campaign
- Future plan and upgrade
  - Plan for 2018 campaign
  - Long-term research plan & upgrade

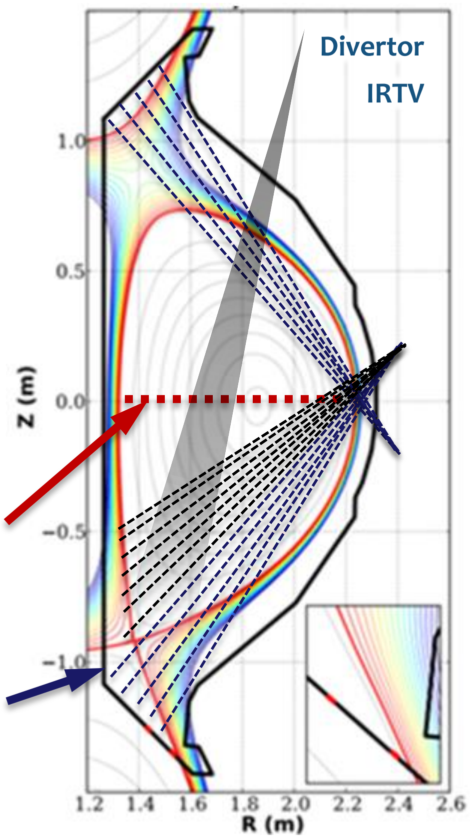
Diagnostics systems development under domestic & international collaboration

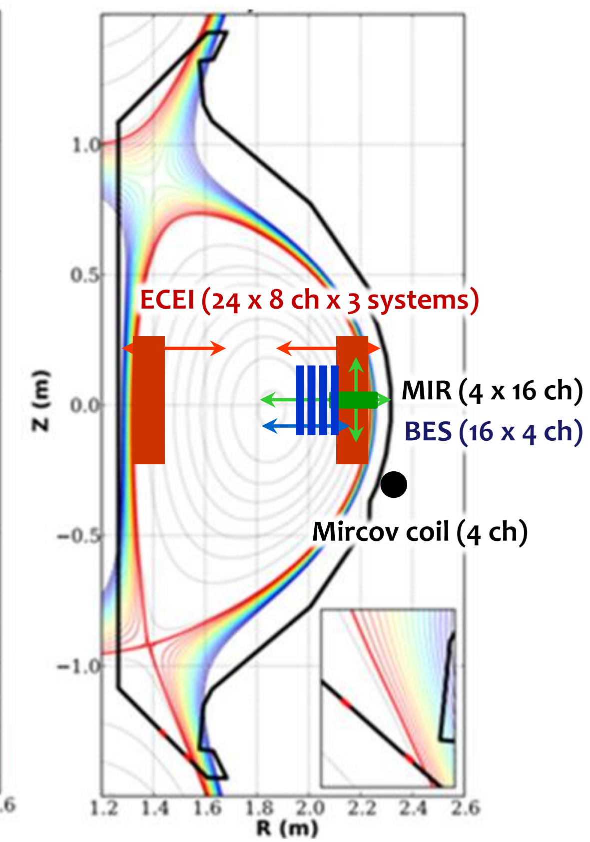
Profile Diagnostics

Visible/IR Diagnostics

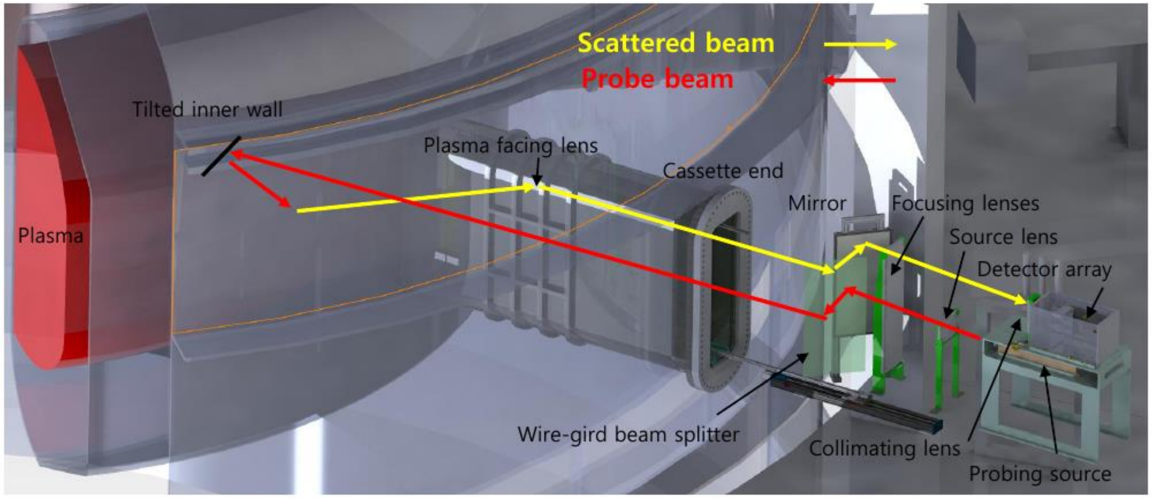
Fluctuation Diagnostics

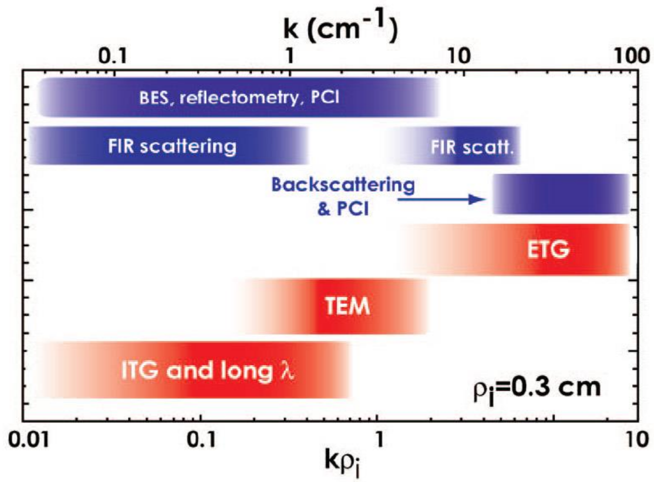






Collective scattering system for short-scale ETG turbulence





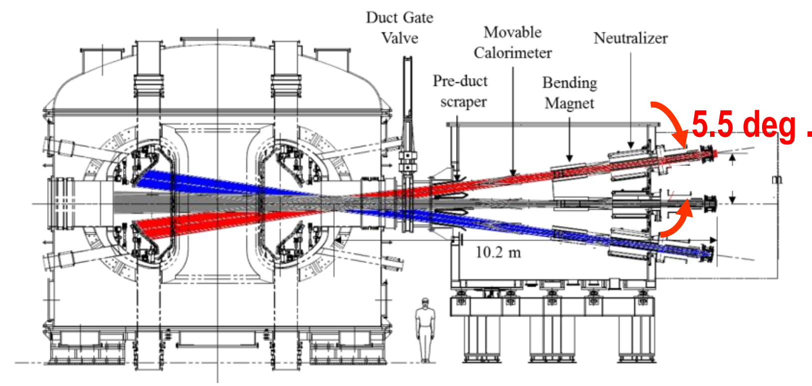
- **The 300 GHz collective scattering system (CSS) can measure the electron density fluctuations with four discrete poloidal wavenumbers.**

–Typical scattering angles are 13.0, 16.3, 18.6, and 23.9 degrees, which correspond to the poloidal wavenumbers 14.2, 17.8, 20.3 and 25.4 cm^{-1} covering the ETG mode range.

- **The CSS together with MIR/ECEI provides measurements of turbulence in a wide scale range from ITG to ETG.**
- **Available from 2018 campaign**

W. Lee et al., JINST 8, C10018 (2013)

New KSTAR NBI (NBI2) having off-axis CD capability

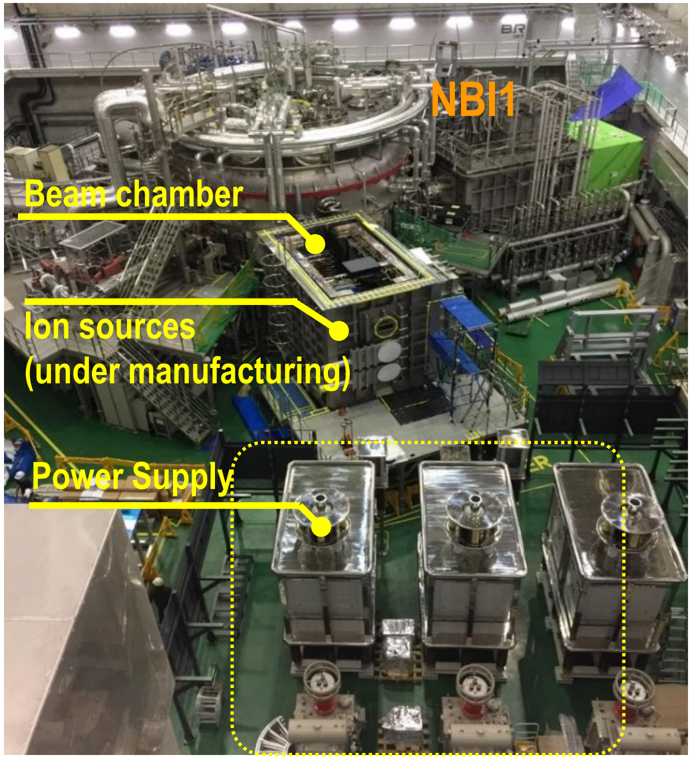


Goals

- Additional ion heating for the higher plasma temperature (Ti ~ 10 keV)
- Off-axis heating (4 MW) to get stable high beta operation

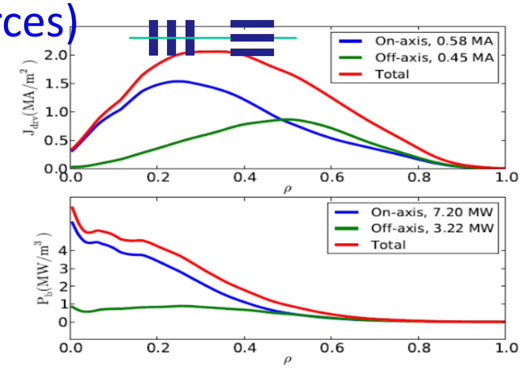
Specifications and feature

- 6 MW, 100keV with CW operation (up to 300 s)
- 6MW with vertically arranged three IS (4MW off-axis + 2MW on-axis)



Schedules

- 2 MW in 2018 (1 ion source, off-axis)
- 6 MW in 2019 (3 ion sources)



Research and upgrade plan for higher beta and steady-state operation

2008 → **2017**

First plasma
(ECH 84 GHz)

Long-pulse H-mode
(NBI~5.5 MW)
(ECH~1 MW)

Long-pulse H-mode research
- *Long pulse H-mode (>70s)*
- *ELM research & control (>30s)*
- *Alternative operation modes (ITB, low q, ..)*

2017 → **2021**

Heating upgrade
(NBI~12 MW)
(ECH~6 MW)

Advanced scenario & MHD research
- *Stable high beta operation*
  (β_N>3.0, T_{ion} ~ 10 keV)
- *Advanced mode develop.*
  (hybrid, ITB, low q)
- *MHD & disruption control*

2021 → **2025 ~**

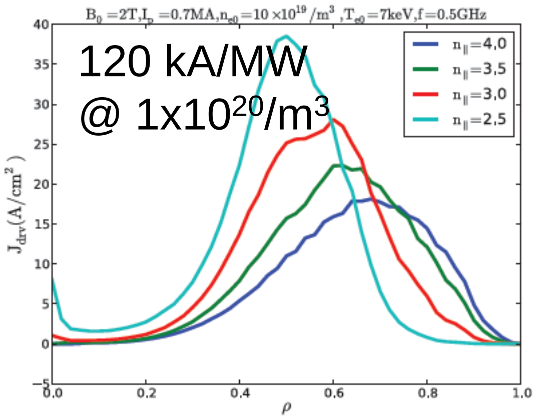
Divertor upgrade
(Tungsten divertor)
(Detached divertor)
(Diagnostics)

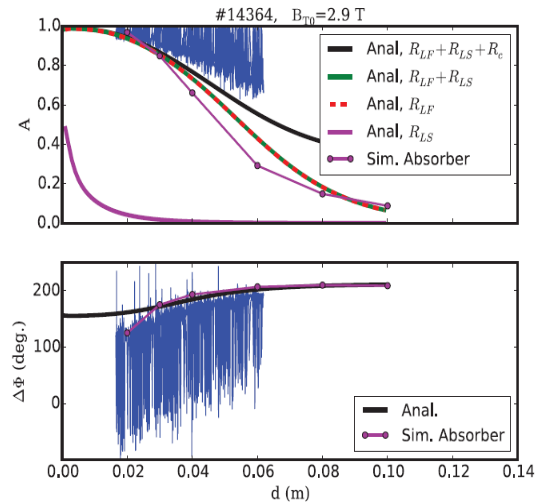
Advanced current drive
(LHCD~4 MW)
(Helicon CD~4 MW)

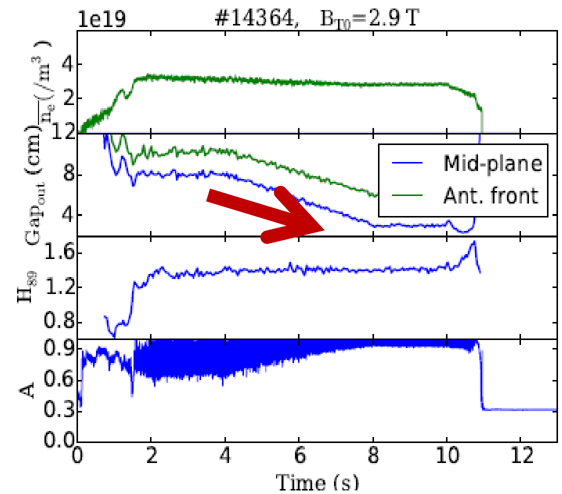
Steady-state & reactor mode research
- *Tungsten divertor & active cooling*
- *Advanced current drive under test*
  (HFS LHCD & Helicon CD)
- *Steady-state operation (~300s)*

Helicon CD for high electron beta discharges

- **Low power test revealed highly controllable wave couplings and is in good agreement with modeling**
- **Medium power test, to demonstrate CD capability and to identify nonlinear channels(PDI), is expected in year 2018.**



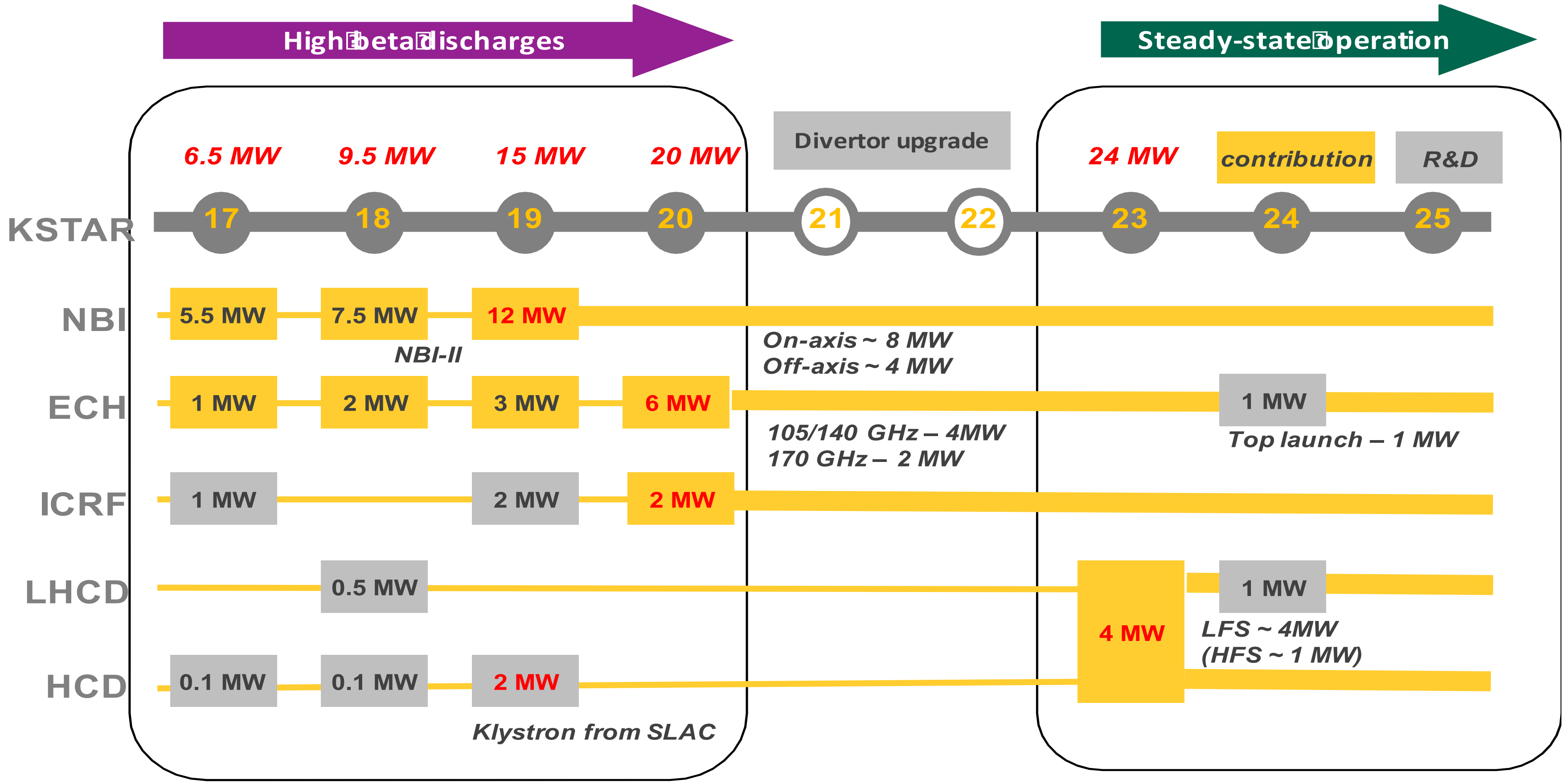




- **Demonstration of full CD performance should be followed**
  - **MW level of power is required – collaboration with SLAC PEP-II**
  - **Collaboration in full wave modeling with AORSA**
- **HCD 4 MW in KSTAR will contribute significant advances in fusion plasma technology**
  - **achieving flexible q-profile controllability – developing advanced plasma scenario**
  - **developing effective reactor relevant CD scheme**

Timeline of heating & CD upgrade in KSTAR

- 28 MW heating & CD with steady-state operation capability

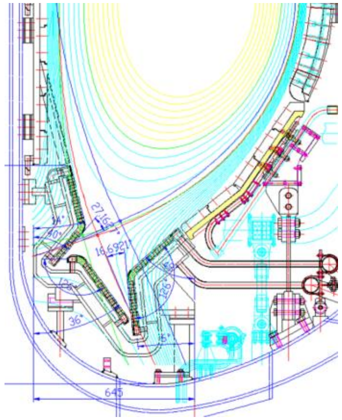


S.J. Wang (NFRI), Oral 1A (Feb.21)

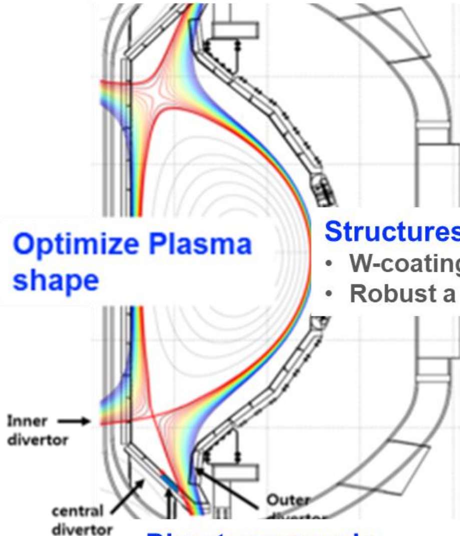
Upgrade plan of divertor & in-vessel components for steady-state operation in preparing for K-DEMO R&D

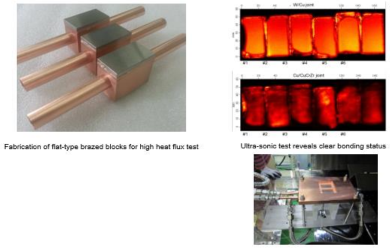
Major considerations for upgrades

- **Upgrade period : FY 2021 ~ 2022 *(planned)***
- **Divertor upgrade**
  - **Material : W-based (monoblock for divertor)**
  - **Optimum shape and baffles for heat flux and detachment control**
  - **Integrated diagnostics for divertor**
- **Advanced current drive**
  - **Current drive for higher density**
  - **HFS & LHS LHCD launcher**
  - **Helicon CD**

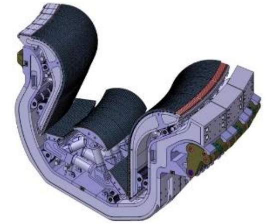


Current drive
- HFS slot & LHS PAM LHCD
- Helicon CD / Top launching ECCD

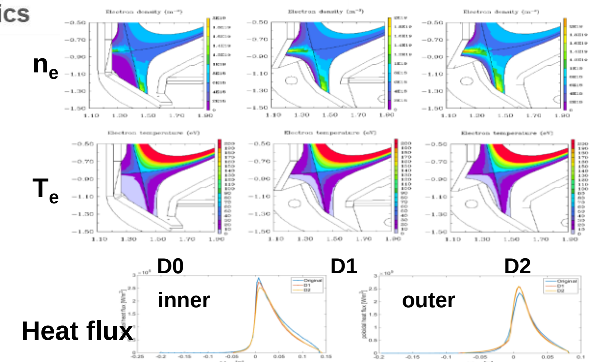




Structures
- W-coating
- Robust a ginst disruption



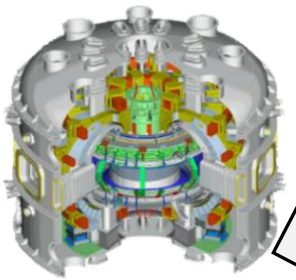
Divertor upgrade
- W-based material (monoblock)
- Optimum shape and baffles
- Gas feeding and cryopump
- Diagnostics



KSTAR has strong capability to contribute to SC technology and advanced plasma operation toward ITER and DEMO

Preparation K-DEMO beyond ITER

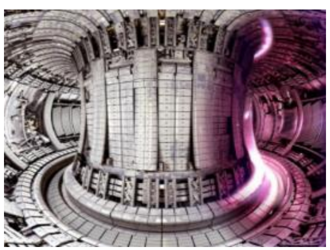
Advanced operation
high β_N (~4) & high bootstrap current



KSTAR
(β_N ~2, steady-state)
(β_N ~4, stationary)
($f_{bootstrap}$ > 50%)

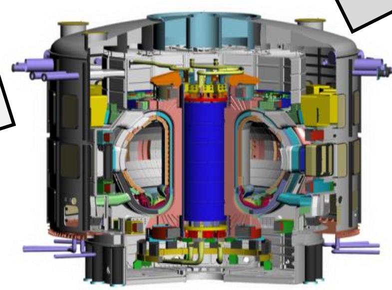
Contribution to ITER

SC tokamak
(Steady-state at β_N ~2)



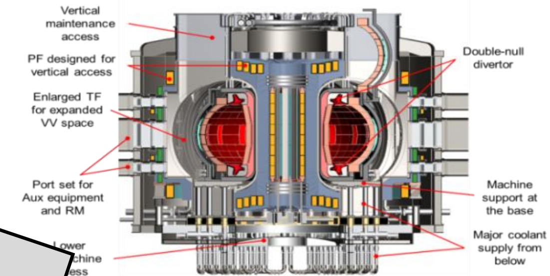
TFTR, JET, JT60U
(Large plasma volume)
(β_N ~ 2 & D-T fusion)

Large tokamak
DT operation (β_N ~2)



ITER
(Reactor-scale plasma volume)
(β_N ~ 2 & D-T fusion)
(steady-state, external CD)
(alpha heating)

(α-heating)
(TBM)



K-DEMO
(Reactor-scale plasma volume)
(β_N ~ 4 & D-T fusion)
(steady-state, by bootstrap)
(alpha heating)
(Blanket, T-breeding)

Fusion Technology R&D / others
- Material R&D
- System Eng. (Tritium, remote)
- Engineering optimization
- License & Codes
- Human resource
- Etc