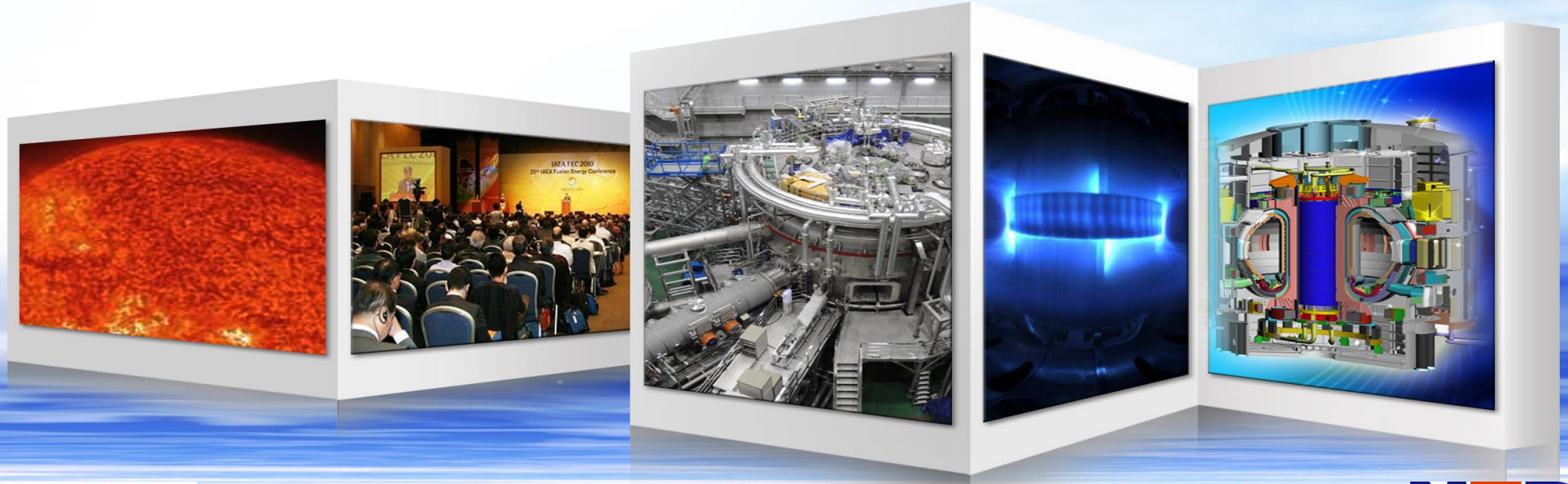
Overview of the KSTAR Research Progress and Future Plan toward ITER and K-DEMO



Hyeon K. Park
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UNIST Ulsan National Institute of Science and Technology

On behalf of
the co-authors and KSTAR Team

at 27th IAEA FEC,
Gandhinagar, India, 2018

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Topics to be addressed

- Mission and role of the KSTAR research for ITER and K-DEMO
- Advantages of tokamak plasma research on KSTAR
- Progress of the KSTAR research program
  - High performance and steady-state operation
  - Physics of MHD/Turbulence
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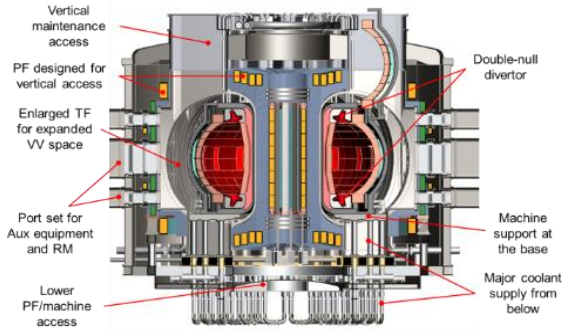
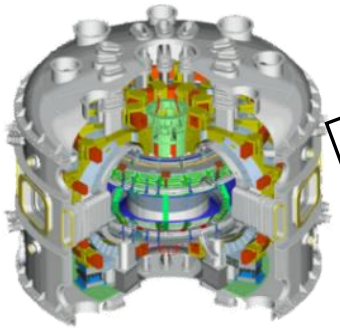
Mission and role of KSTAR for ITER and K-DEMO

- **KSTAR Mission is:**
  - to explore science and technology for high performance steady-state operation, that are essential for fusion reactors
- **Role of KSTAR for ITER & K-DEMO**
  - Expansion of operating regimes, validation of tokamak physics and advanced control for SC device like ITER using the KSTAR unique tools
    - to expand the KSTAR operation boundaries of the conventional modes of operation and new mode of operation for minimum harmful instabilities (avoid NTM and ELM-crash)
    - to explore physics and preemptive control of the harmful instabilities in high beta operation (ELM-crash, NTM, disruptions, etc.)
    - to assist optimum operation of ITER: H-mode threshold power control, rotation control via NTV, heat dispersion with RMP, etc.
  - Exploration of the limit of high beta steady state operation and R&D of key engineering and technology for K-DEMO
    - Exploration of higher beta operation with the KSTAR upgrade
    - Alternative current drive for steady-state operation
    - New start-up for high duty cycle with long pulse

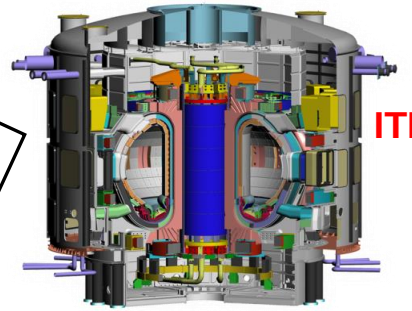


K-DEMO

- Stationary High beta (β_N ~4) with high bootstrap
- Optional new mode of operation including auto start-up with high duty cycle
- CD and divertor heat flux control



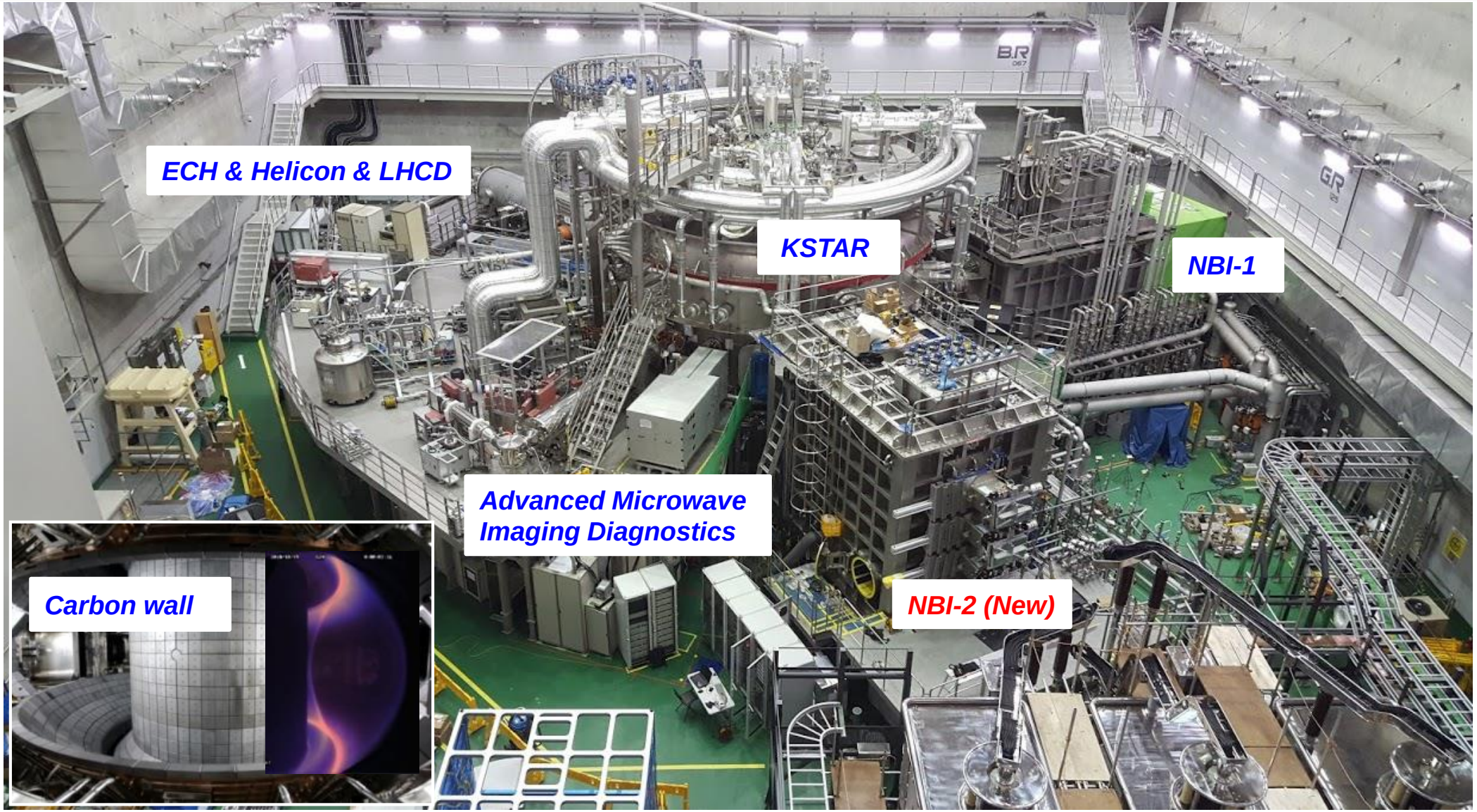
KSTAR



ITER

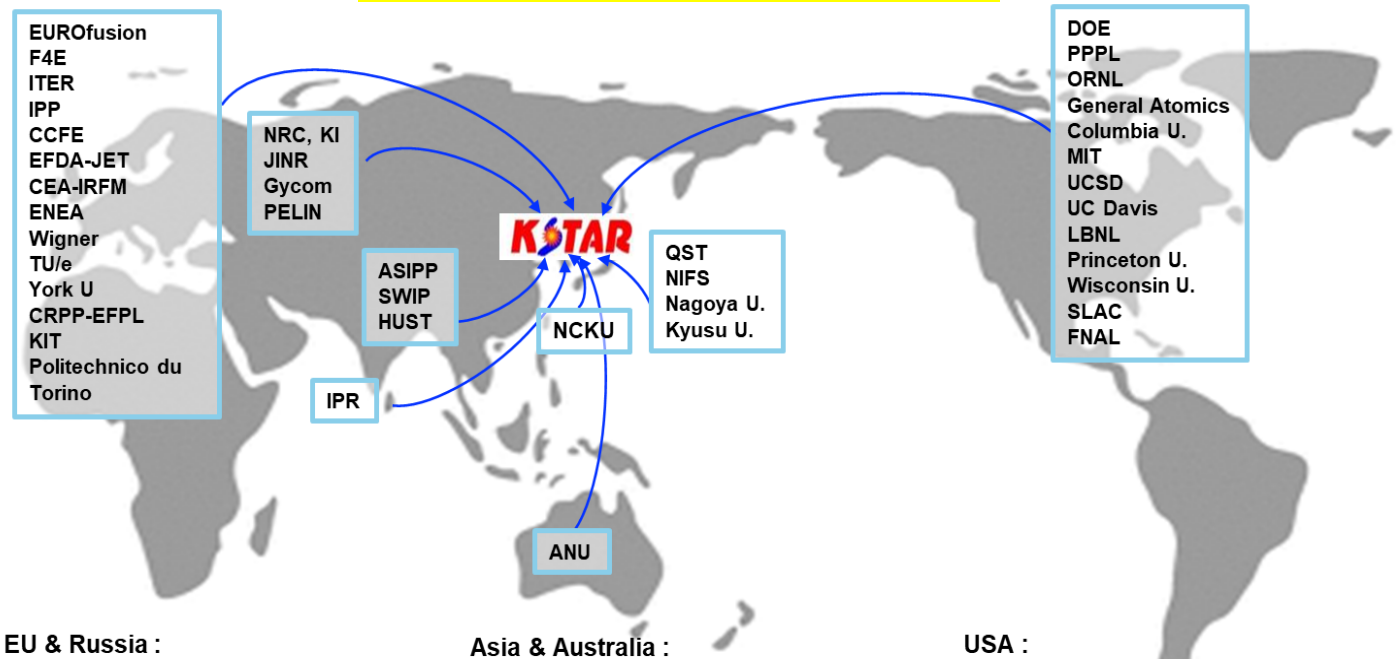
- Steady-state H-mode (β_N ~2)
- Rotation by NTV, and new start-up, H-mode access
- Suppression of ELM-crash, disruption

View of KSTAR with new NBI-2 system



Collaborating domestic and international Institutes and Universities on the KSTAR program

Domestic Collaborating Universities and Institutes



EU & Russia :

- Heating & CD (CEA)
- Diagnostics (ENEA, TU/e, Wigner)
- PWI, fueling (ITER, PELIN)
- Theory & analysis (York U)
- Experiments (JET, AUP, WEST)
- ELM, PSI, CODAC (ITER)
- ETC

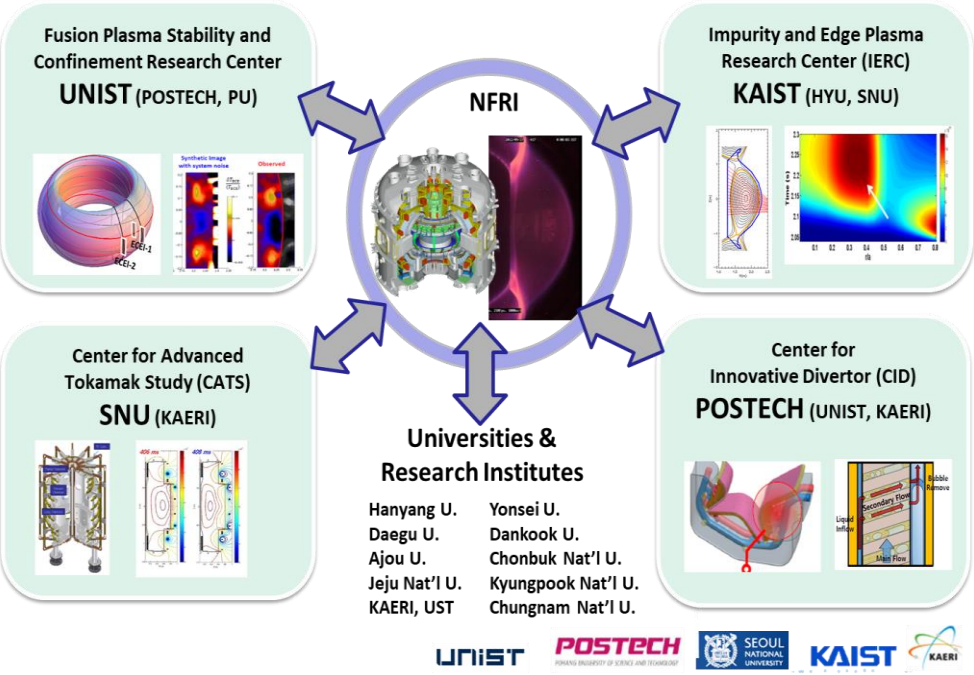
Asia & Australia :

- Heating & CD (QST)
- Diagnostics (NIFS, QST, Nagoya U, Kyushu U. ASIPP, HUST, ANU)
- PWI, fueling (ASIPP, SWIP)
- MHD physics & simulation (NCKU)
- Joint workshop (A3 project)
- ETC

USA :

- Heating & CD (PPPL, GA, SLAC)
- Diagnostics (ORNL, MIT)
- 3D physics (GA, PPPL, Columbia U)
- Plasma control & CODAC (GA, PPPL, ORNL, FNAL)
- ETC

Domestic Collaborating Universities and Institutes



Device parameters of KSTAR, ITER and K-DEMO

Parameters	KSTAR (achieved)	KSTAR (Goals)	ITER (Baseline/SS)	K-DEMO (Option II)
Major radius, R_0 [m]	1.8	1.8	6.2	6.8
Minor radius, a [m]	0.5	0.5	2.0	2.1
Elongation, κ	2.16*	2.0	1.7	1.8
Triangularity, δ	0.8	0.8	0.33	0.63
Plasma shape	DN, SN	DN, SN	SN	DN (SN)
Plasma current, I_P [MA]	1.0	2.0	15/ ~10	> 12
Toroidal field, B_0 [T]	3.5	3.5	5.3	7.4
H-mode duration [sec]	73	300	400 / 1000	SS
β_N	3.0 (4.3, transient)	5.0	~3.0	~ 4.2
Bootstrap current, f_{bs}	~0.5			~ 0.6
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD [MW]	~10	~ 28	~ 73	120
PFC / Divertor	C, W	C, W	W	W
Fusion power, P_{th} [GW]			~0.5	~ 3.0

* exceeded

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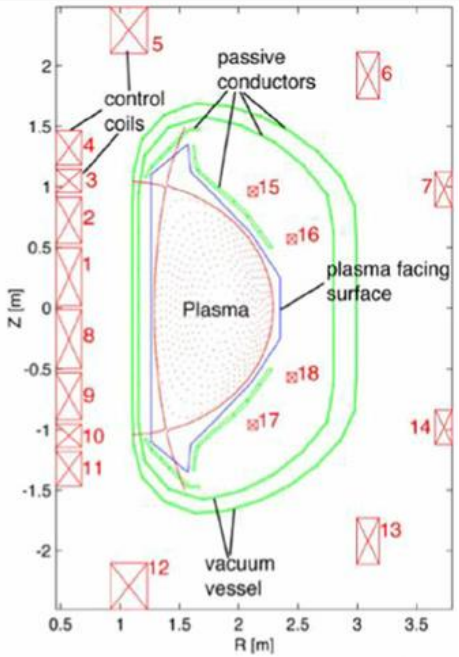
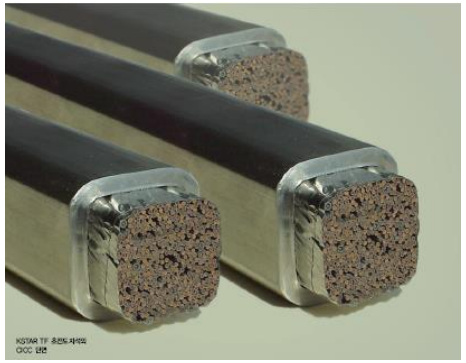
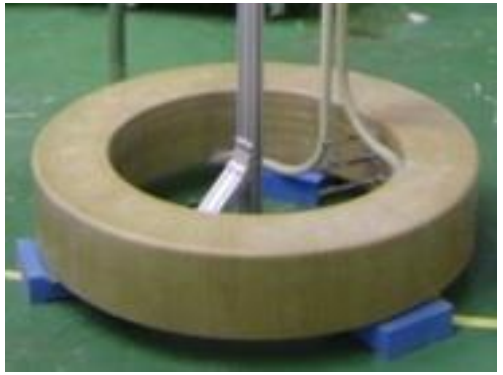
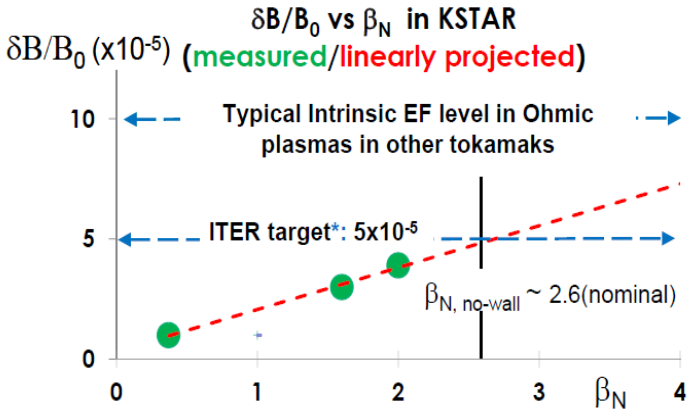
Uniqueness-1: nearly perfect symmetry of the tokamak plasmas

- **Extremely low magnetic ripple for minimum ripple loss.** ($\delta B/B$~0.05 %)
- **Extremely low error field configuration** ($\delta B/B_0$~1×10^{-5})
  - Manufacturing and assembly of the magnets with high accuracy
  - Robust structures to sustain the TF coil shape uniform
- **Designed with strong shaping capability for high beta operation stability**
  - Double & single null capable and passive stabilizer for stabilizing VDE & RWM
  - Control flexibility using four pairs of CS coils and high elongation (κ ~ 2.16) & triangularity (δ ~ 0.8)





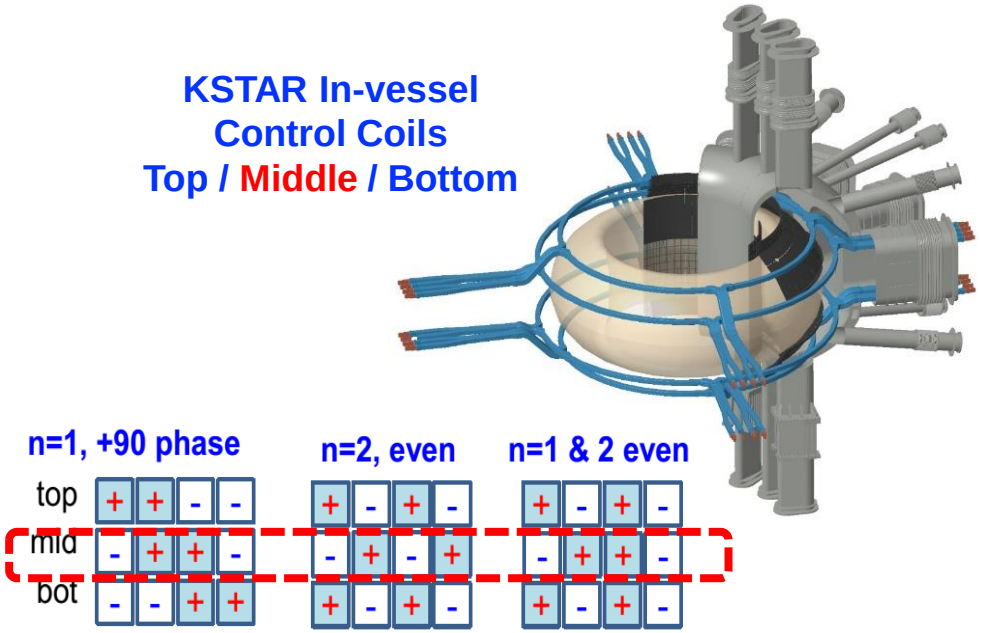




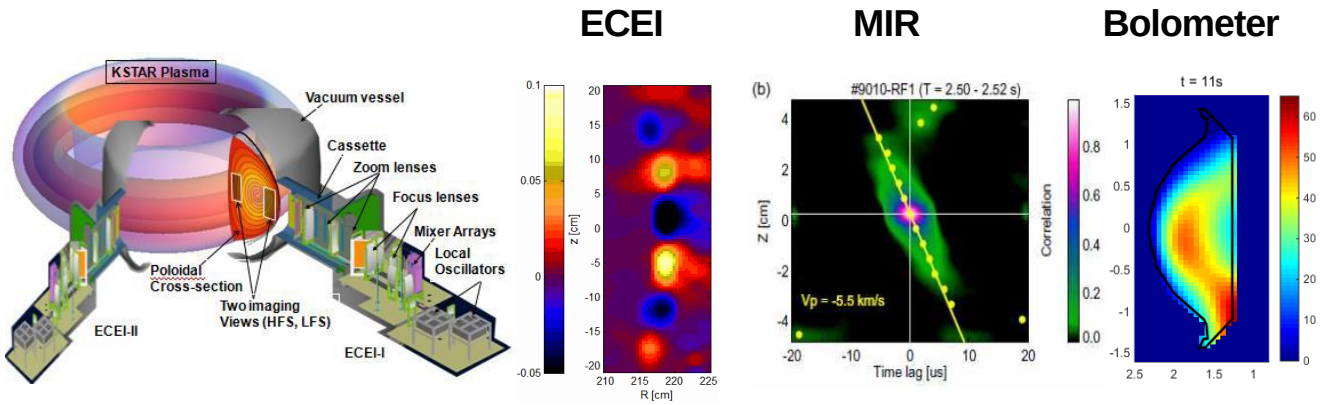
SC magnets manufactured without internal joints to minimize error field

Uniqueness-2: Versatile in-vessel control coils for perturbation study and advanced imaging diagnostics

- **Unique in-vessel control coils with 3 poloidal rows (top, middle and bottom; e.g., ITER)**
  - Flexible 3D field perturbation with n=1, 2 and mixed
  - Broad band power supply (~10 kHz) and patch panel for fast control for position, ELM-crash, rotation control & RWM control



- **Advanced 2D/3D imaging diagnostics**
  - ECEI, MIR, BES, imaging bolometer, FILD, SXR, etc.
  - Enable us to access the dynamics of fundamental physics of MHD/ turbulence that were not available



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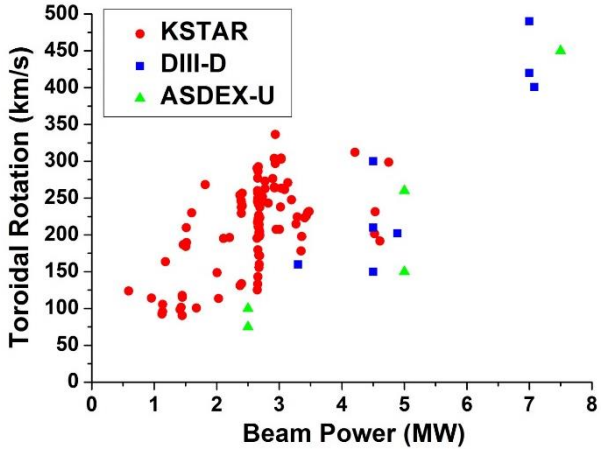
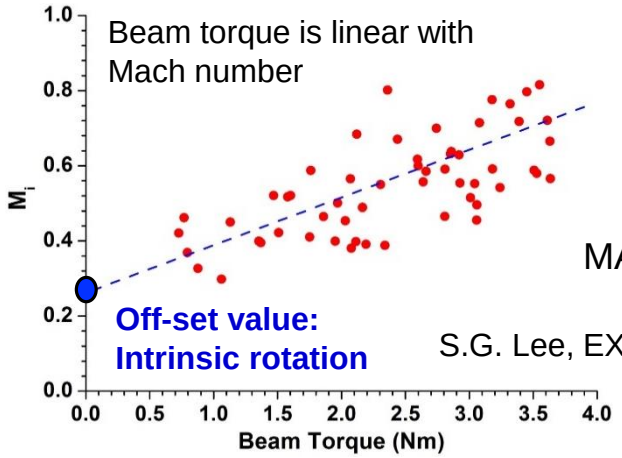
Effect of high toroidal rotation (or high edge rotation shear) on energy confinement in KSTAR

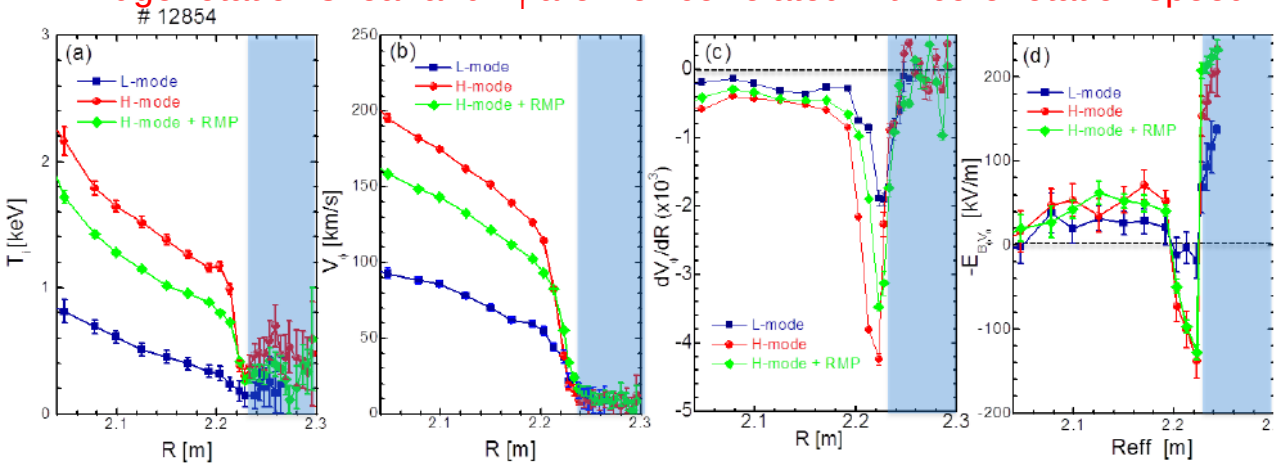




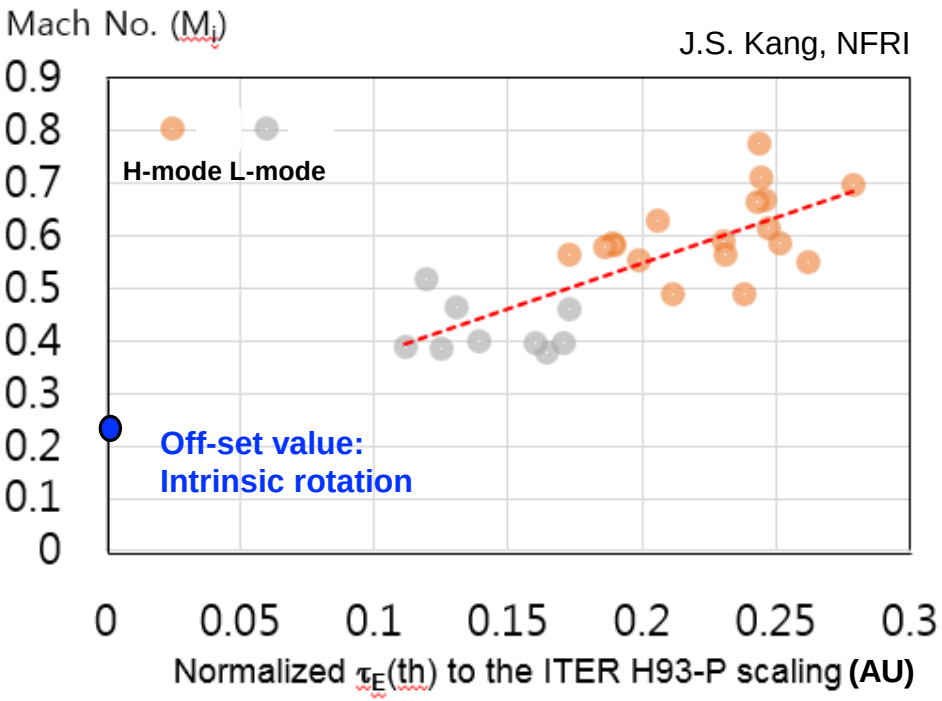
MAST, M_i ~1.

S.G. Lee, EX/P7-4

- High toroidal rotation speed in KSTAR may be due to nearly perfect tokamak plasma symmetry (low error field)
- Beam torque is linear with the Mach number (record high Mi~0.8)
- Edge rotation shear and E_r are well correlated with core rotation speed



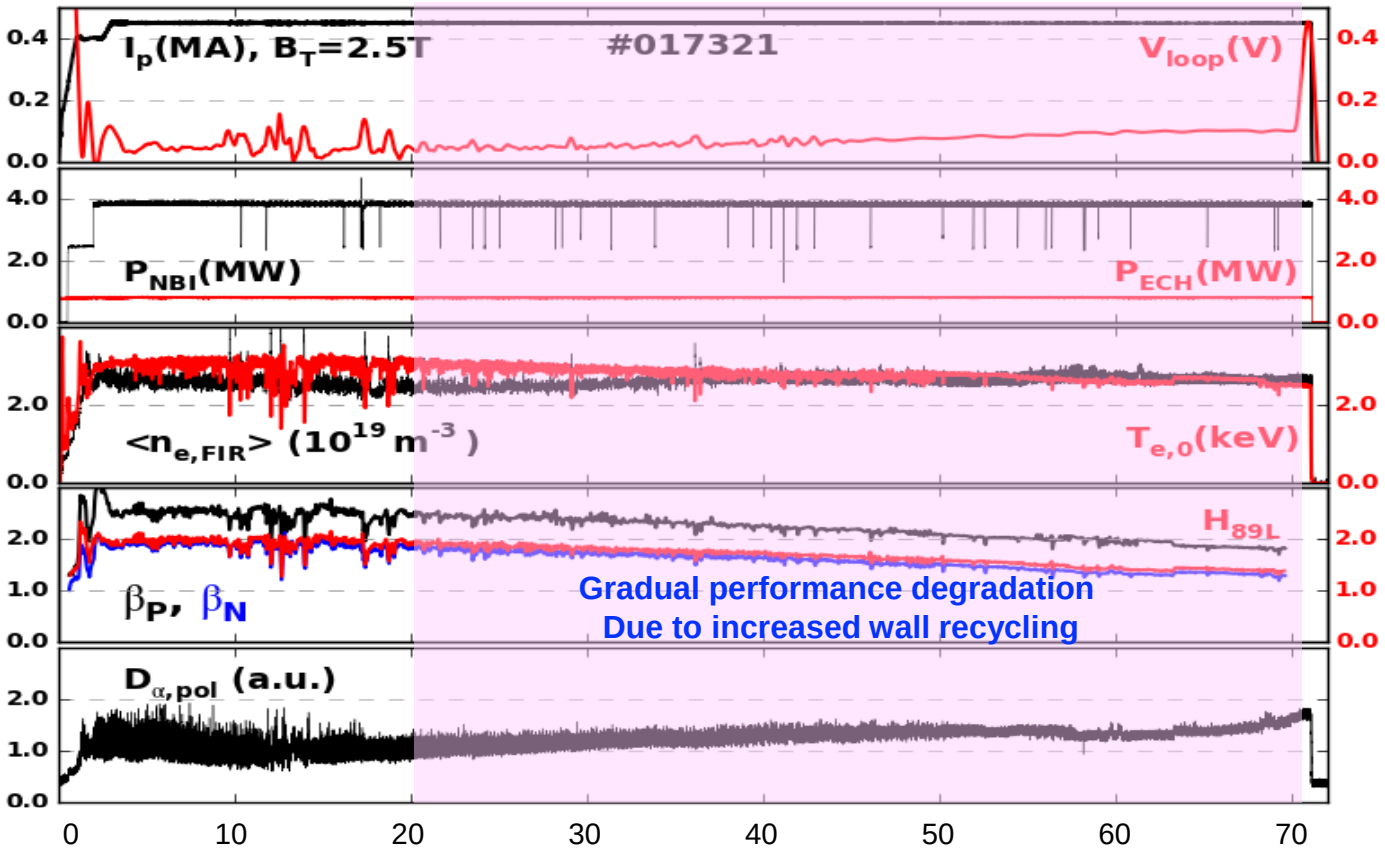
- Toroidal rotation (M_i or torque) is a hidden parameter in energy confinement scaling??
  - Excellent correlation between the energy confinement time (τ_{th}) and Mach number (M_i) or torque
  - L-mode and H-mode data can be combined with the rotation related parameter (turbulence physics basis?)
  - Further study on edge shear, counter rotation, role of intrinsic rotation, etc. is in progress



J.S. Kang, NFRI

NBI-heated long pulse H-mode operation (> 1 min)

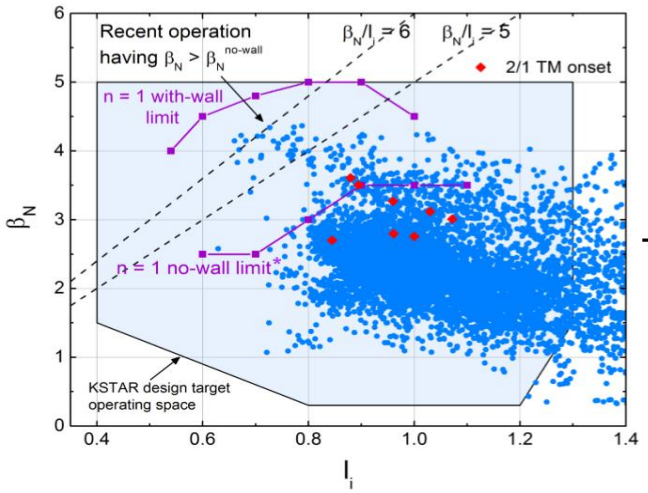
- **Long pulse H-mode discharge with NBI & ECH**
  - Fully non-inductive advanced operation with high beta (β_N ~2.0, β_P ~2.5) was up to 20s.
  - H-mode was sustained over 70 s, BUT gradual performance degradation due to the heated limiter

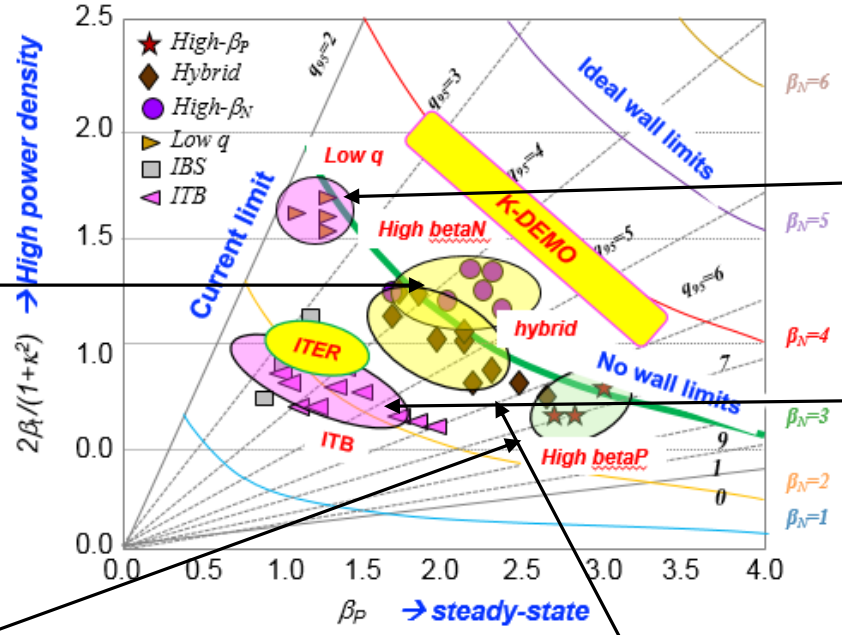


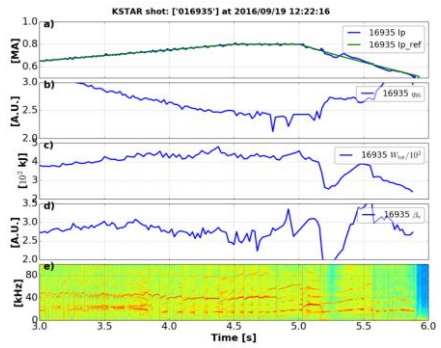
In 2018 campaign, longer steady-state, fully non-inductive operation over ~100s will be attempted with upgraded

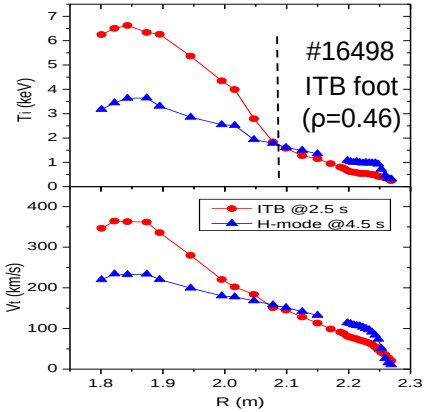
- Active water cooling into PFC/Divertor
- Boron powder dropper (PPPL / ORNL collaboration)
- Additional heating (NBI, ECCD)

Exploring conventional and new operation modes for optimal scenarios applicable to ITER and K-DEMO

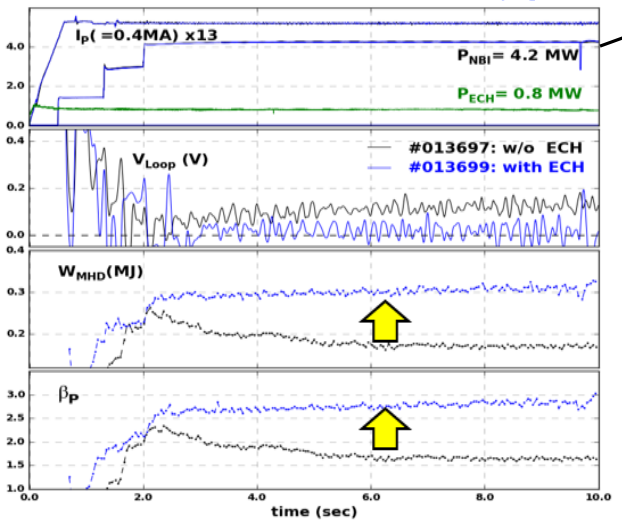


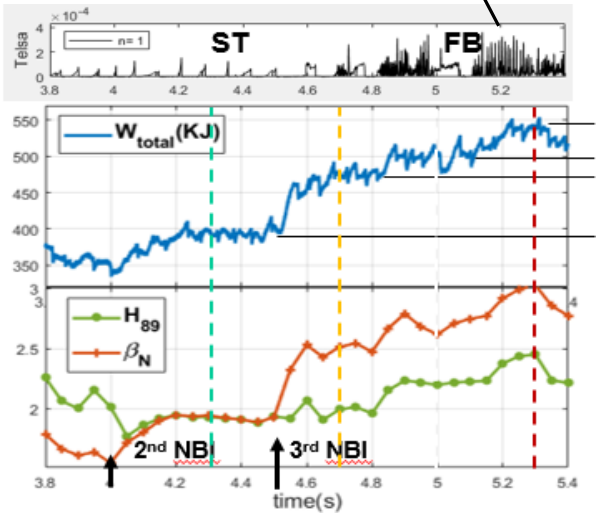






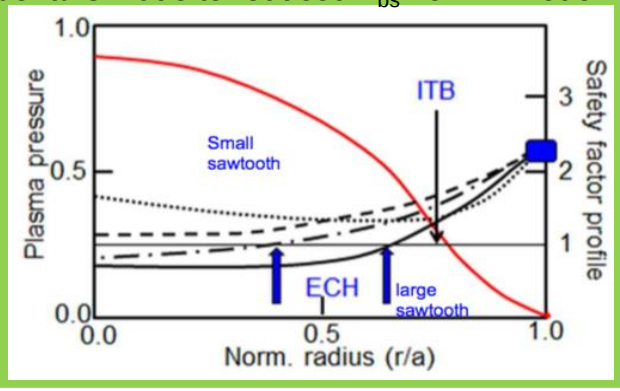
In 2017 Campaign





Search of alternative new mode of Operation (combine ITB and low q_{95})

- Broad ITB provides good confinement in the core
- Low q_{95} avoids harmful MHDs (e.g. NTM and ELMs)
- Sawtooth can be used for particle control and q~1 surface can be controlled with CD.
- Expense for MHD control (ELM and NTM) can be used for additional CD due to reduced F_{bs} from H-mode



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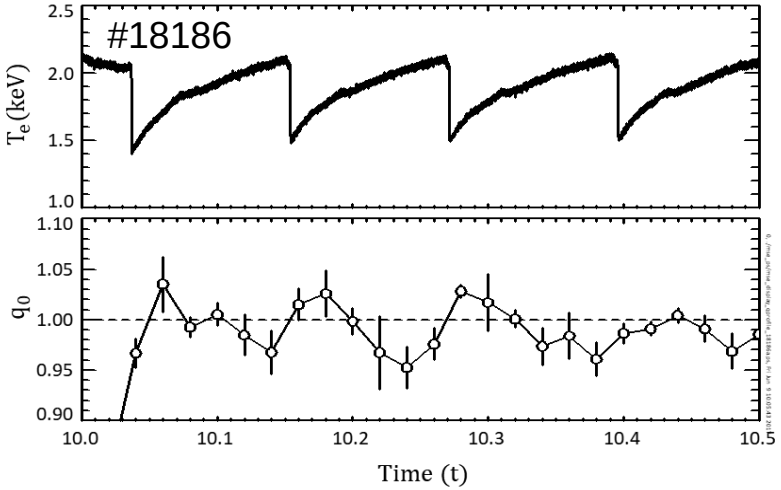
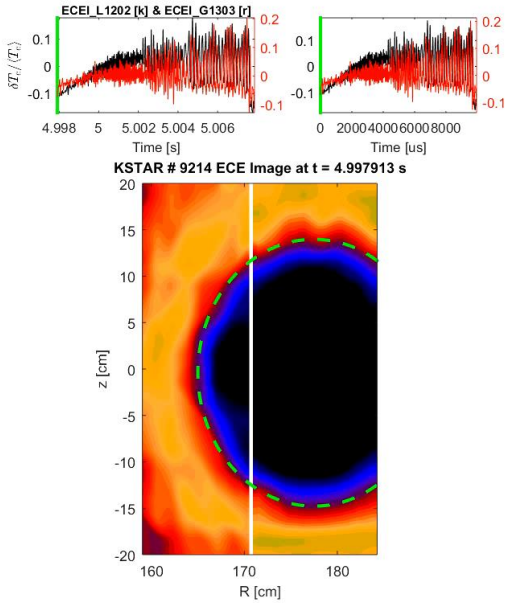
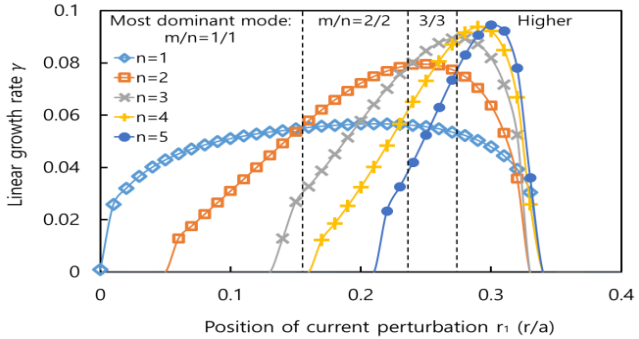
Theoretical model for Sawtooth instability (Full or Partial)?

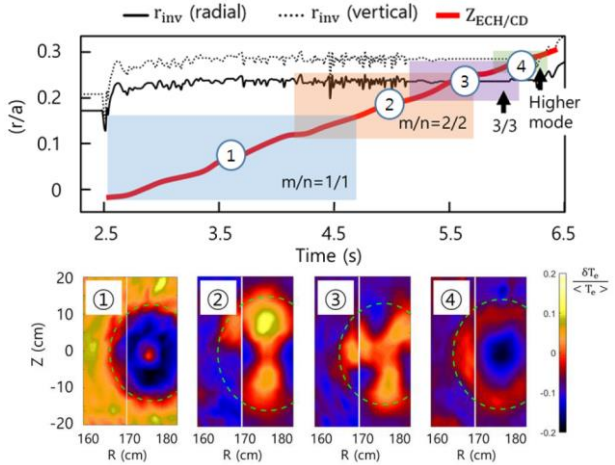
- **Direct q_0 measurements (2015, 2016) alone cannot validate the model**
  - During nearly four decades, there are two groups of measurement; $<q_0>$~1.0 and $<q_0>$~0.8 with δq_0 ~0.07
- **Supplementary experiment is essential**
  - Excitation of double tearing modes inside the q~1 surface is consistent with the growth rates calculated by M3DC1 with q_0>1.0 in MHD quiescent time right after the crash
  - Time evolution of 3/3 → 2/2 →1/1 further supports q_0>1.0
- **"Full reconnection model" by Kadomtsev is supported by the validation experiments**



Measurement of q_0 for two years (2015, 2016) confirms $<q_0>$~1.0 with δq_0~0.07 (J. Ko)





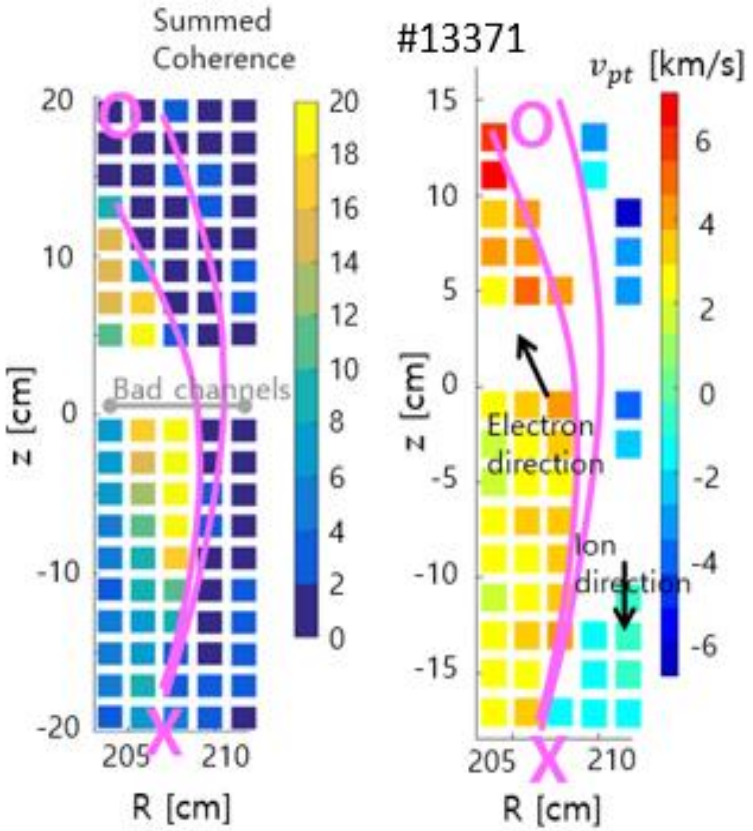


Growth rates of double tearing modes with the position of current blip (M3DC1)

Y. Nam, NF 2018

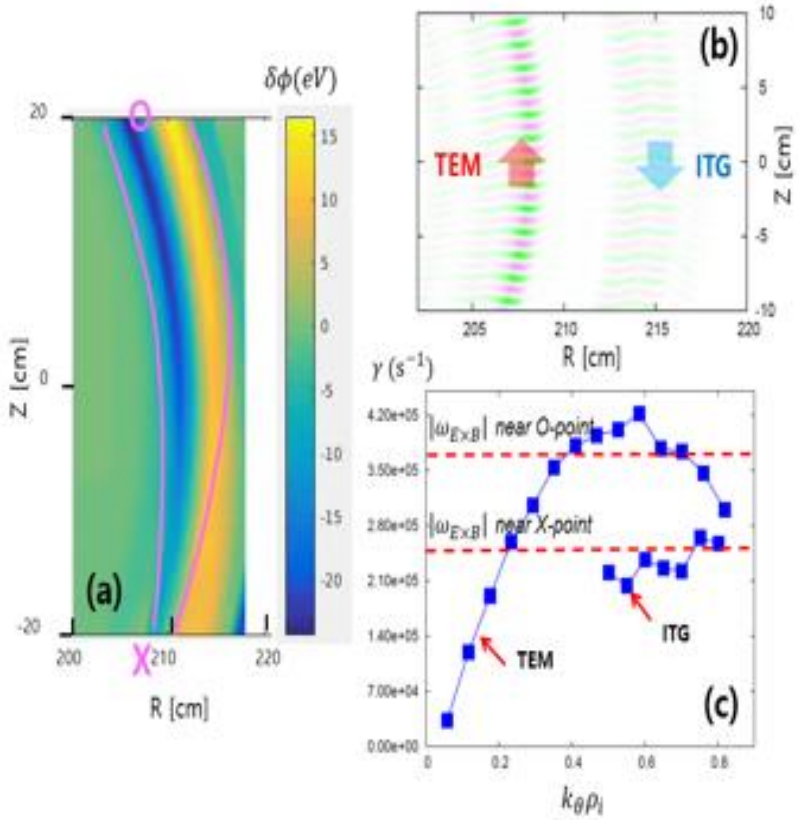
Magnetic island (2/1) can alter the electron heat transport by the flow and turbulence

- **Measured T_e turbulence and apparent rotation around the 2/1 island**
  - Merging of turbulence near X-point and penetration to the island can cause "minor and major" disruption



M.J. Choi, NF (2017), EX/11-2 (oral)

- **Magnetic island modifies the poloidal flow and the T_e turbulence around itself**

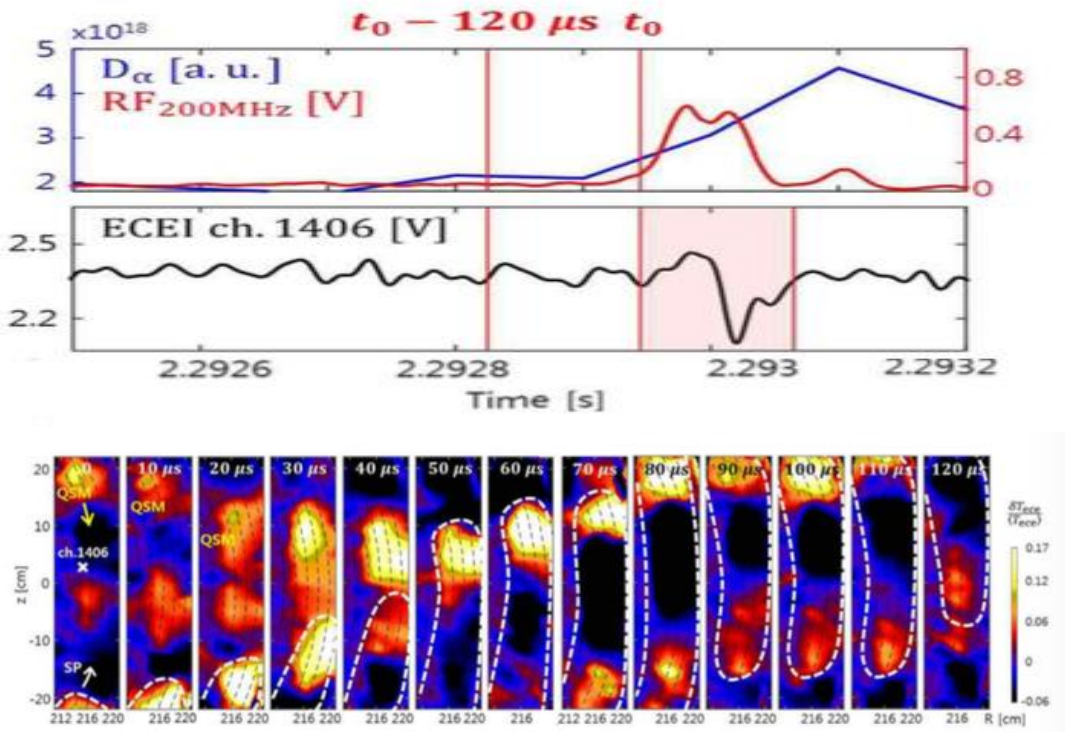


- Global XGC1 simulation shows that magnetic island makes an 2/1 electrostatic potential structure → non-axisymmetric $E \times B$ flow perturbation (a)
- gKPSP Micro-stability analysis shows that the $E \times B$ shear flow at near O-point is strong enough to suppress a significant portion of micro-instabilities (c)

J.M. Kwon, Phys. Plasmas (2018)
TH/8-1 (oral)

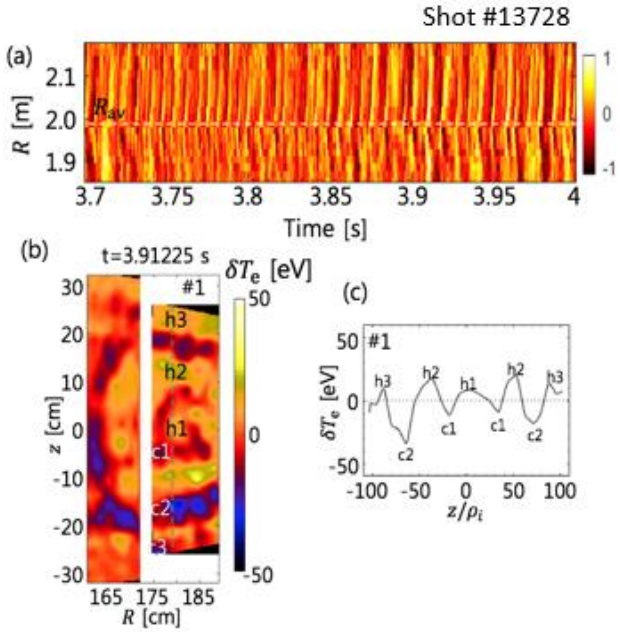
Exploring the physics of transport and transient instability using ECEI and MIR systems

- **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 drift



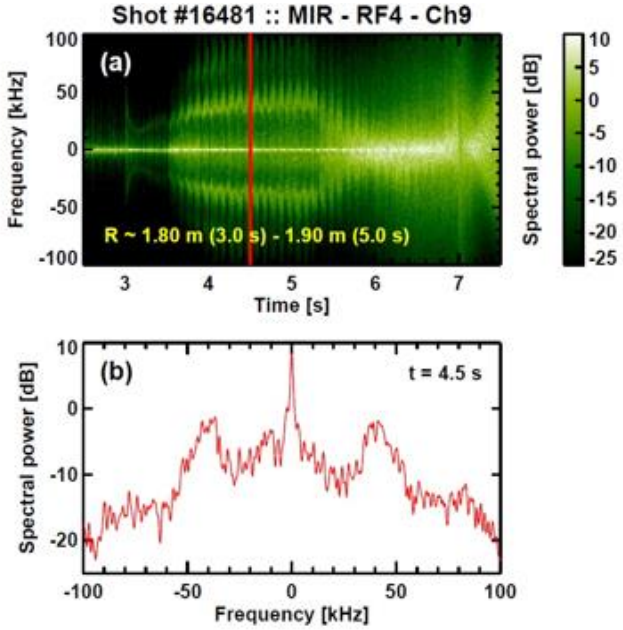
JE Lee, Scientific Report 2017

- **Observation of long range non-diffusive "avalanche" event**
  - Voids and bumps in spatial T_e fluctuations is shown in (a)
  - Symmetric corrugations in T_e profile are shown in (b) and (c)



M. Choi, 4th UNIST-Kyoto Workshop (2018)

- **Quasi-coherent modes (QCMs) were observed in low-collisionality regime of KSTAR ECH and ohmic discharges.**
  - In ECH discharge, the increased Te/Ti by ECH injection seems to drive the QCM.



J.H. Lee, POP (2018)

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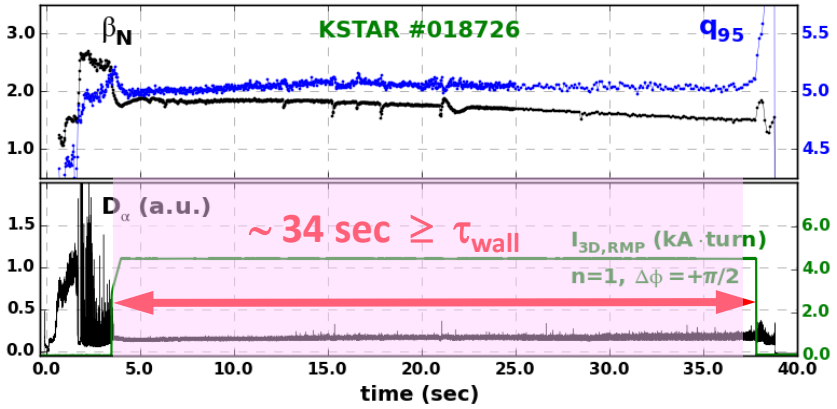
  - **Progress and understanding of the ELM-crash control with RMP**
  - Research efforts for ITER and K-DEMO
- Future upgrade plan
- Summary

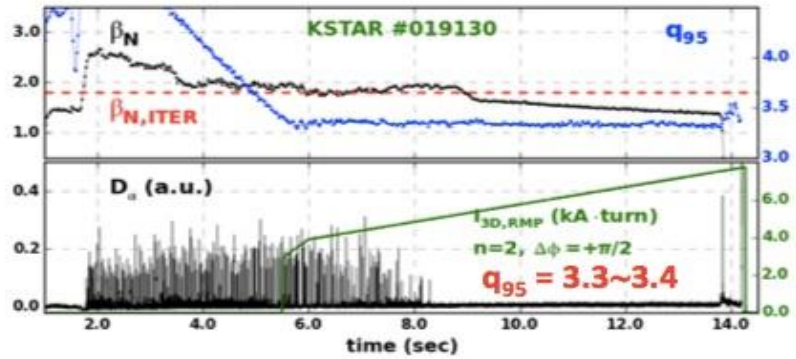
Stable and robust ELM-crash control at ITER baseline operation conditions

- **ELM-crash suppression state sustained with n=1, and RMPs (record ~34 s with n=1)**



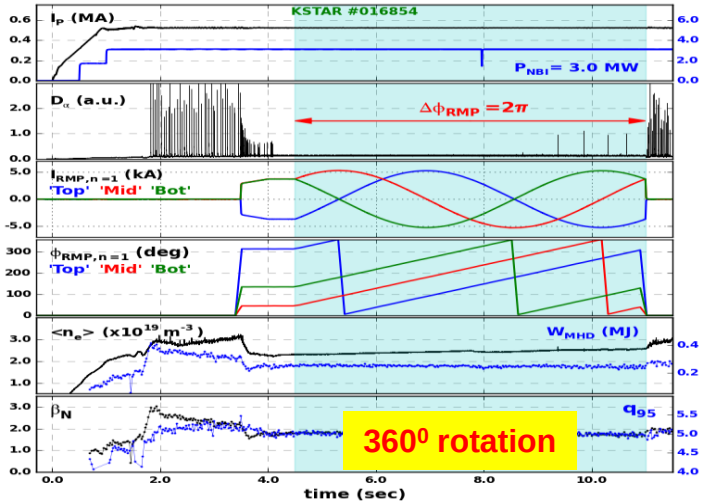
- **ELM-crash suppression is close to the ITER baseline conditions** (q_{95}~3.4, and β_N~1.8)

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

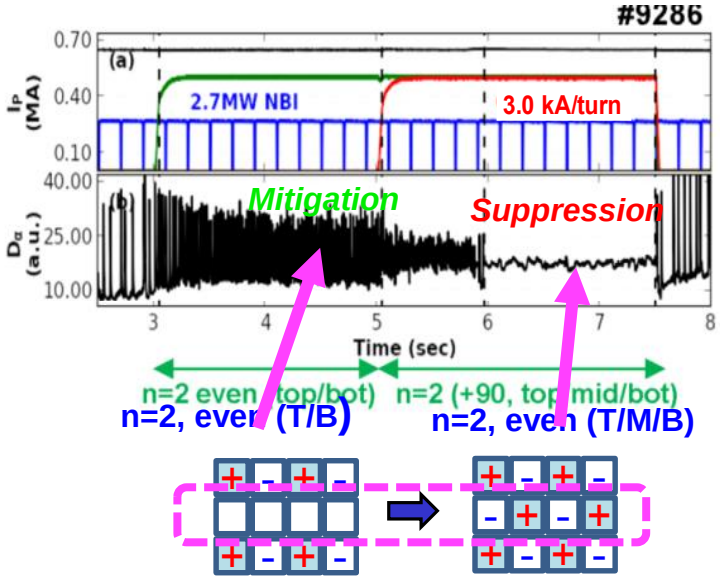


- **ELM-crash suppressed condition is sustained under 360⁰ rotation at n=1 RMP: owing to the low error fields in KSTAR?**

n=1 full RMP under 360 degree rotation



- **Middle coils are very important to get better and reliable ELM-crash suppression in KSTAR**
  - **Additional mid-RMP coil could provide more flexibility in control of the ELMs and rotation in ITER**

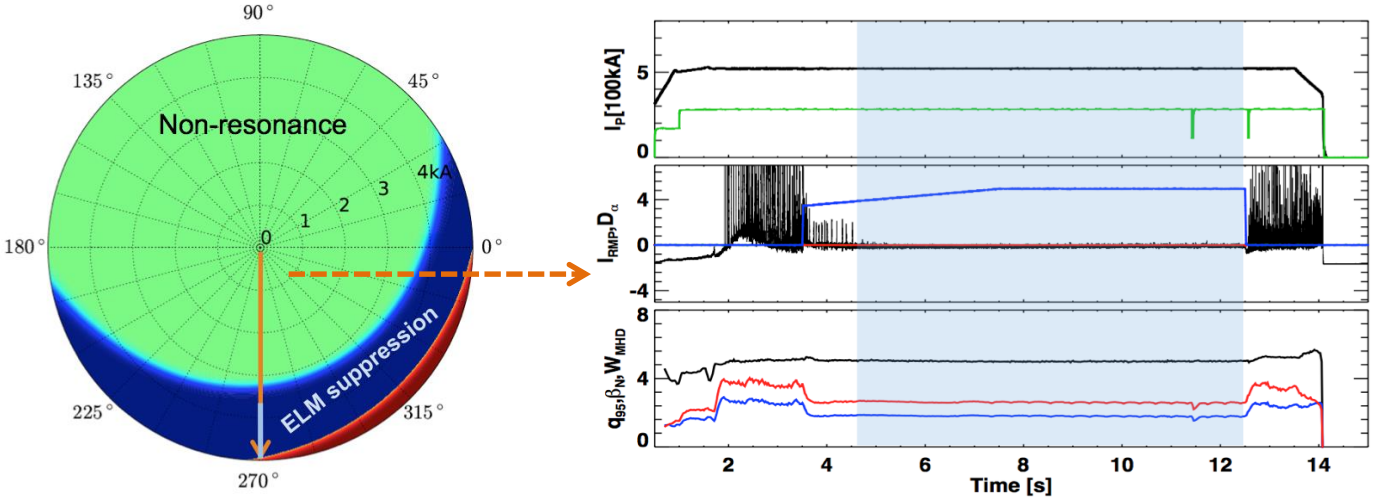


Prediction and validation of the n=1 RMP operating window for the ELM-crash suppression in complex KSTAR coil configuration space

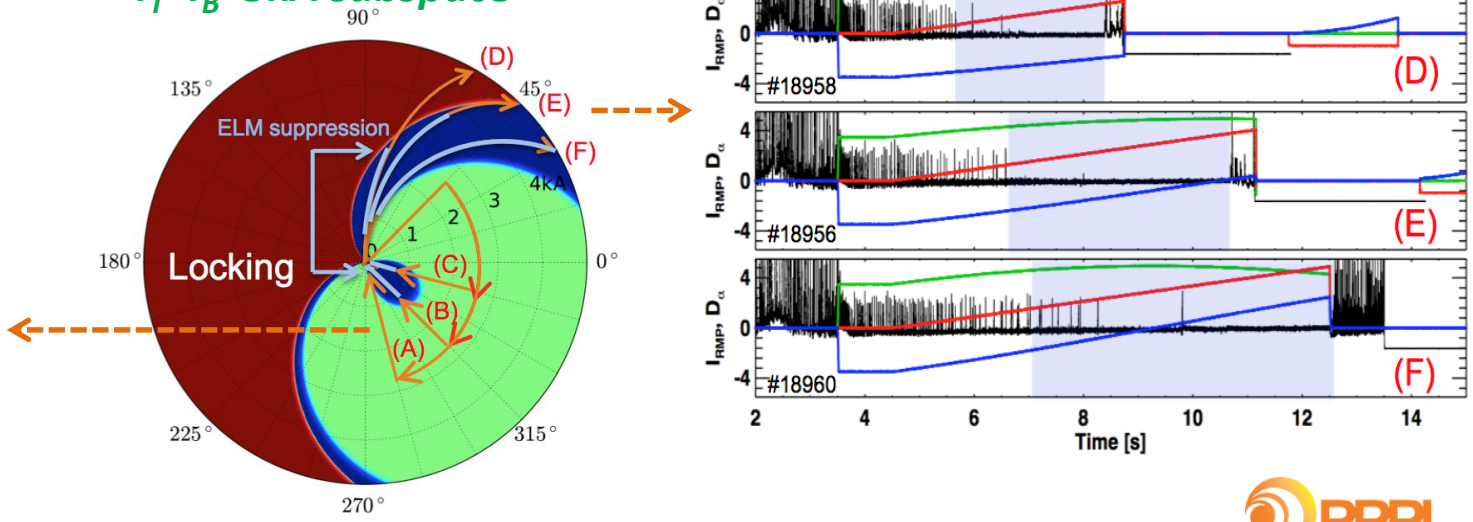
- Offering excellent guidance to optimize new RMPs – such as "off-mid-plane" only n=1 RMP ELM suppression in KSTAR
- Various ELM suppression windows were successfully validated with dynamic RMPs

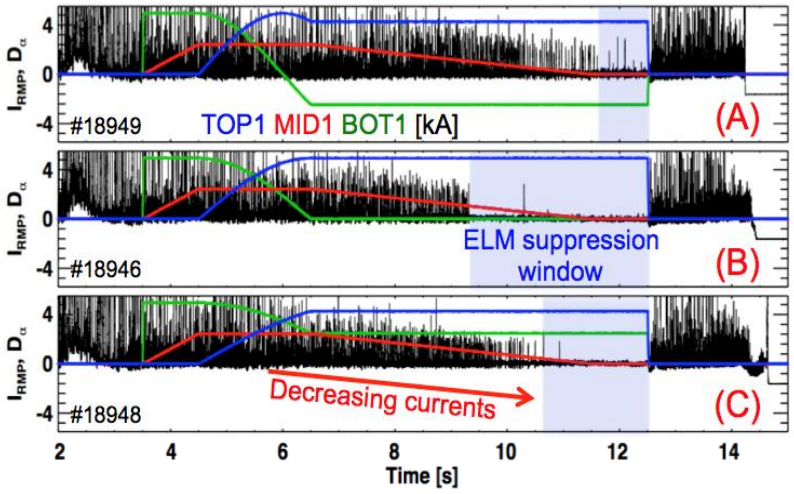
I_M=0kA subspace (off-mid-plane only)

J.K. Park, Nature Physics 2018



I_T=I_B=5kA subspace

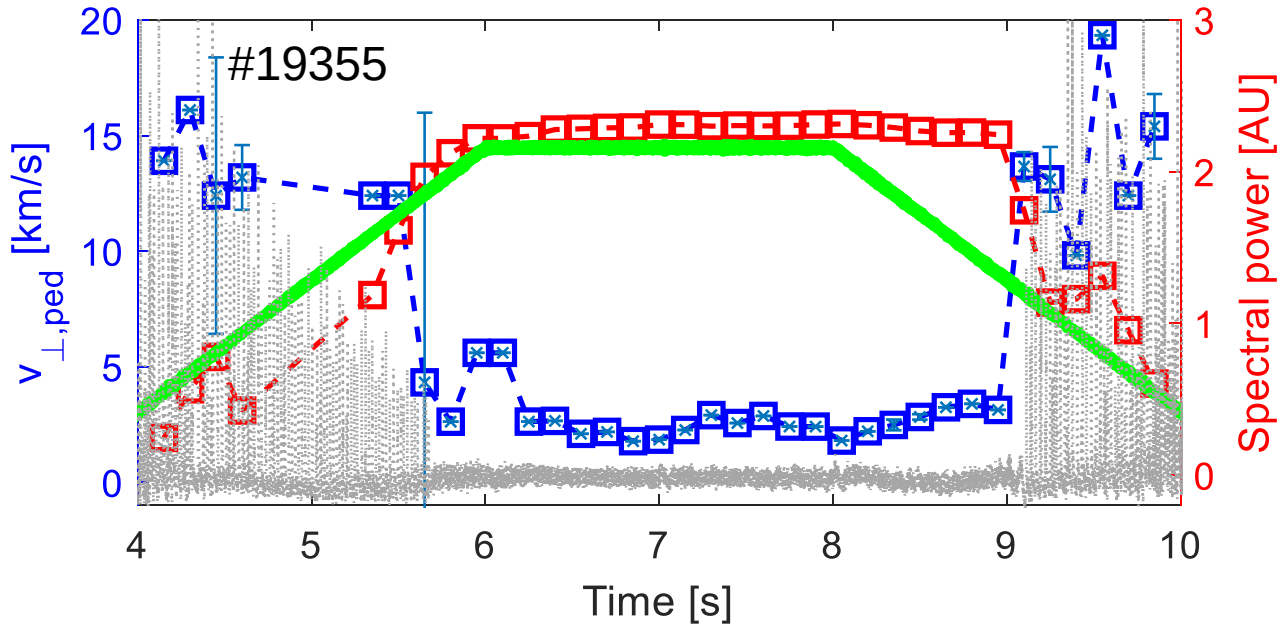


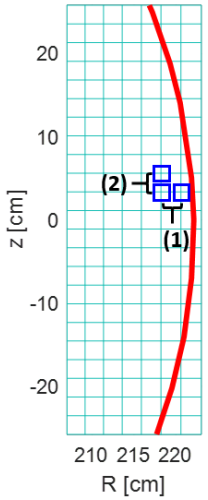


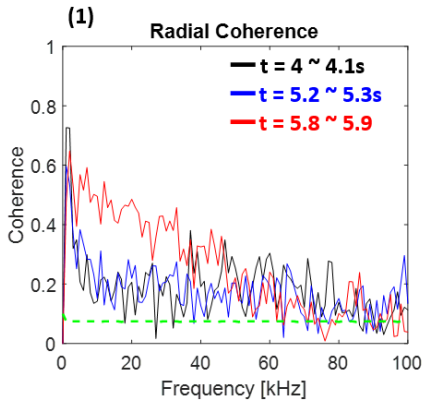
Role of turbulence induced by RMP and rotation ($v_{\perp,ped}$) in the ELM-crash suppression experiment

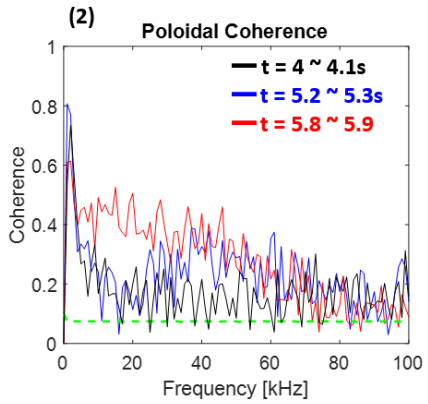
- Change of the turbulence amplitude (red box) and $v_{\perp,ped}$ (blue box) as the RMP current ramp up and down (green) during ELM-crash suppression experiment:
  - Turbulence amplitude: Gradual increase and gradual decrease with a clear time delay with the RMP current ramp up and down – slow magnetic diffusion?
  - Rotation ($v_{\perp,ped}$): Bifurcation?

J.H. Lee, EX/P7-13





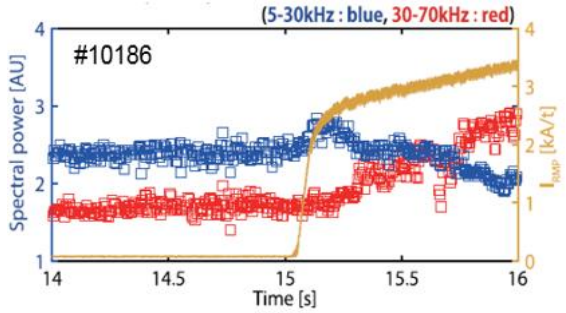




- Poloidal coherence : Gradual increase in turbulence level along the field line through the ELM-crash phase, -mitigation, and -suppression phases
- Radial coherence : only at ELM-crash suppression phase – turbulence spread ?

J.H. Lee, PRL, 2016

- In early study, amplitude of the ELM (blue) during ELM-crash suppressed period is decreasing as the amplitude of turbulence (red) induced by the ramping RMP current (gold)



Topics to be addressed

- Mission and role of KSTAR research
- Advantages of tokamak plasma research on KSTAR
- **Progress of the KSTAR research program**
  - High performance and steady-state operation
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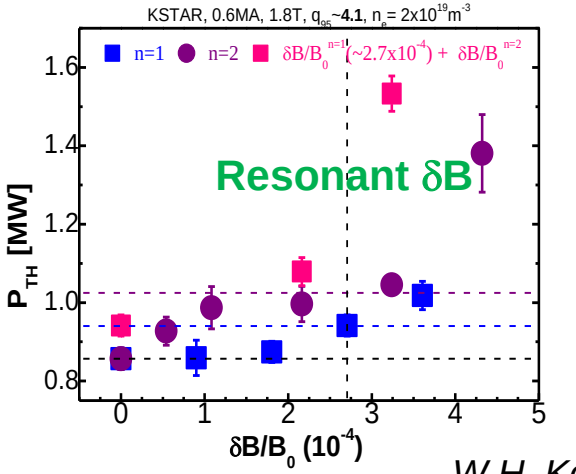
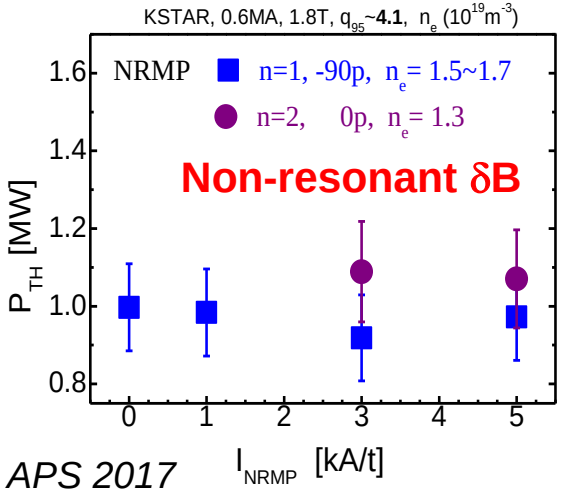
Study of L/H transition P_{th}, NTV controlled rotation and divertor heat dispersion using RMPs

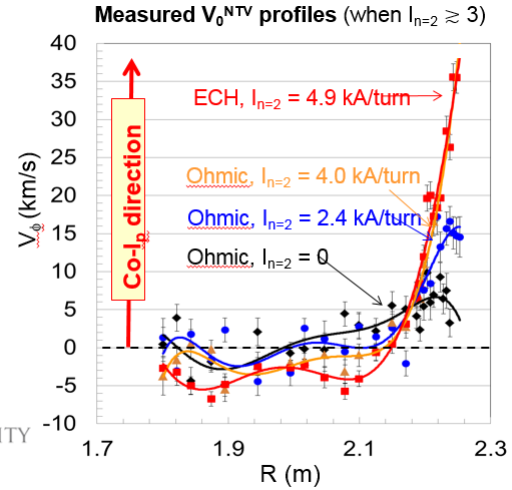
- **The effect of error fields on L-H transition threshold (Resonant δB is more critical)**





W.H. Ko, APS 2017

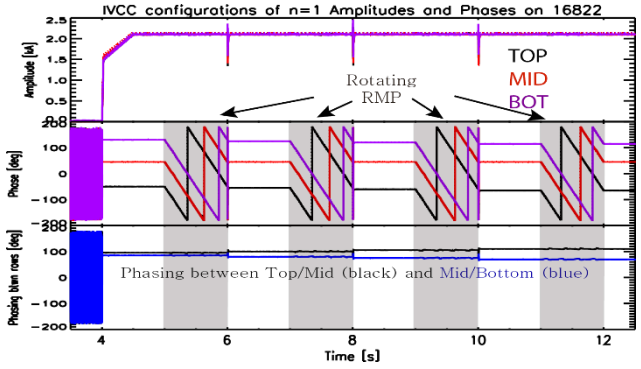
- **Rotation control with NTV**
  - Strong n = 2 field + ECH heating yields counter-Ip rotation in core, co-Ip rotation in outer region (first direct measurement of NTV)
  - Application to the ITER initial H-modes (5 MA / 1.8 T) with ECH heating to increase edge rotation

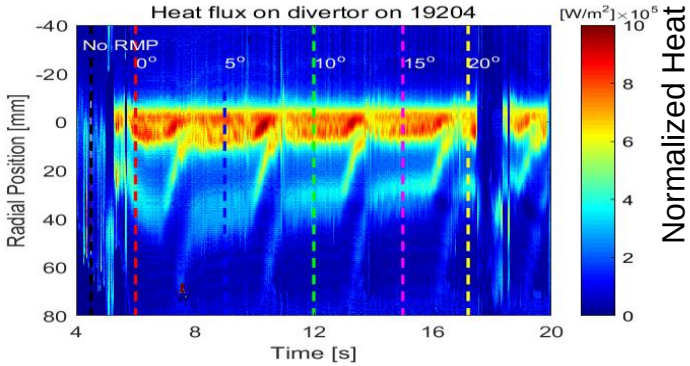


S. Sabbagh (Columbia U)

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

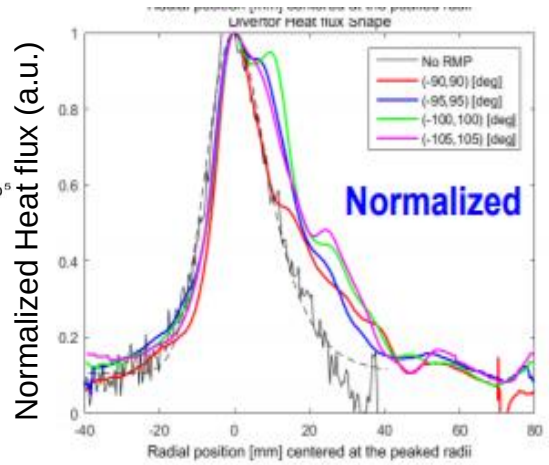
- **Misaligned RMP configurations could be an alternative way to disperse the localized divertor heat flux**
  - No electromagnetic cycling of the coils for misaligned RMPs.





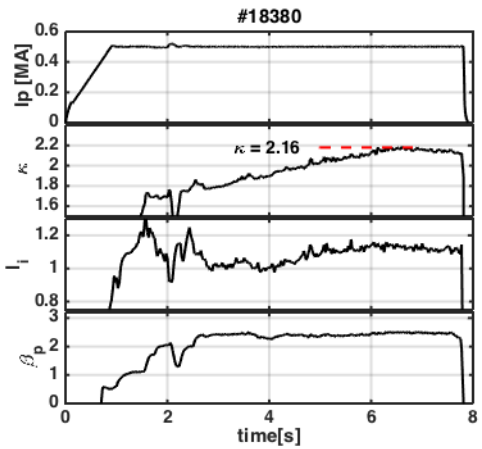
Y. In (oral) EX-7-1

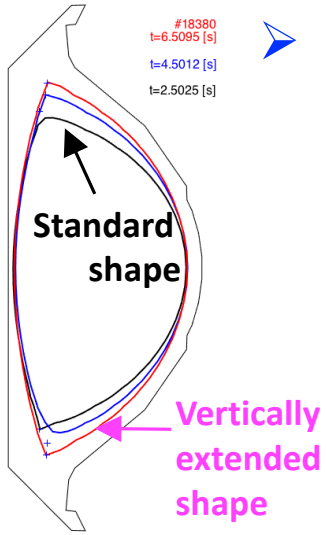
broadening of wetted area during RMP suppression



Advanced shaping control and new start-up method for superconducting tokamak plasmas

- **Improved stability - high elongation up to κ~2.16 (design ~ 2.0) for high β operation**

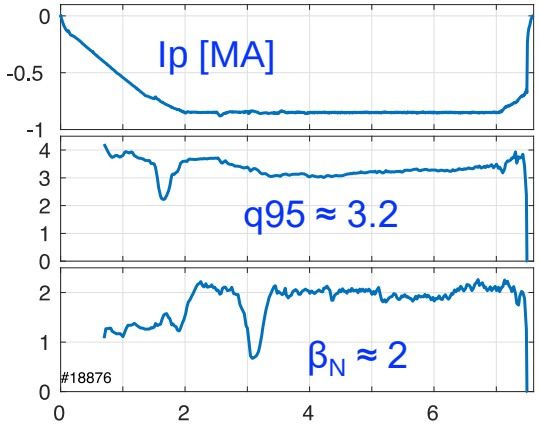


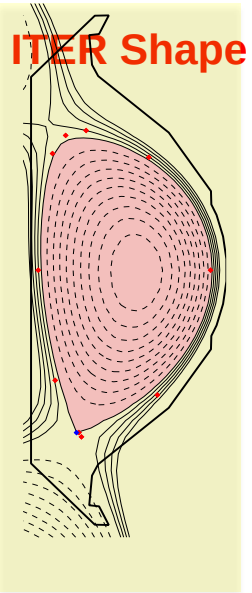


D. Mueller et al. APS 2017

PPPL

- **ITER baseline scenario with ITER similar shape (ISS)**



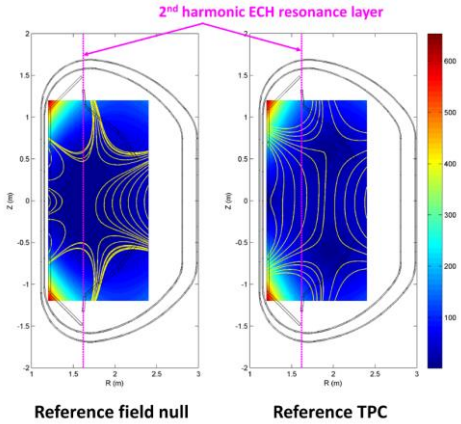


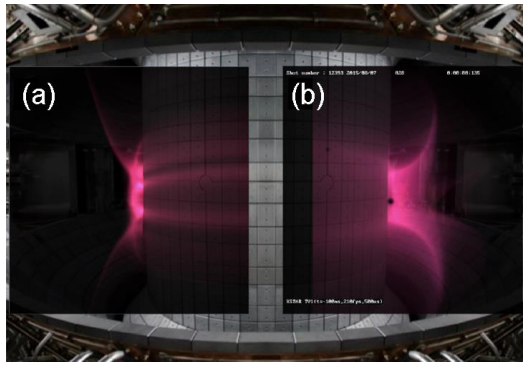
N. Eidietis, APS 2017

GENERAL ATOMICS

- **Validation of Trapped Particle Configuration (TPC) for reliable ECH-assisted startup**
  - Robust startup method than the conventional field null method
  - Possible new automated start-up

J.W. Lee, NF 2017





Comparison of a synthetic diagnostic of the Balmer-α line emission in the BREAK code simulation considering the self-generated electric fields (a) with an experimental visible camera image (b)

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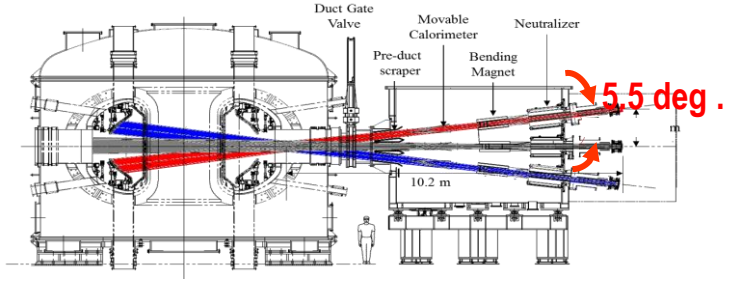
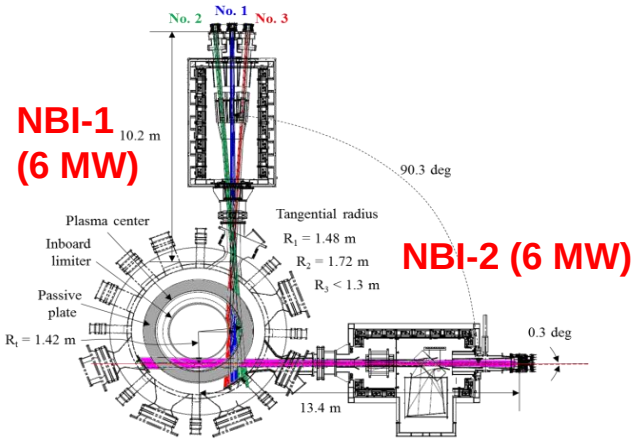
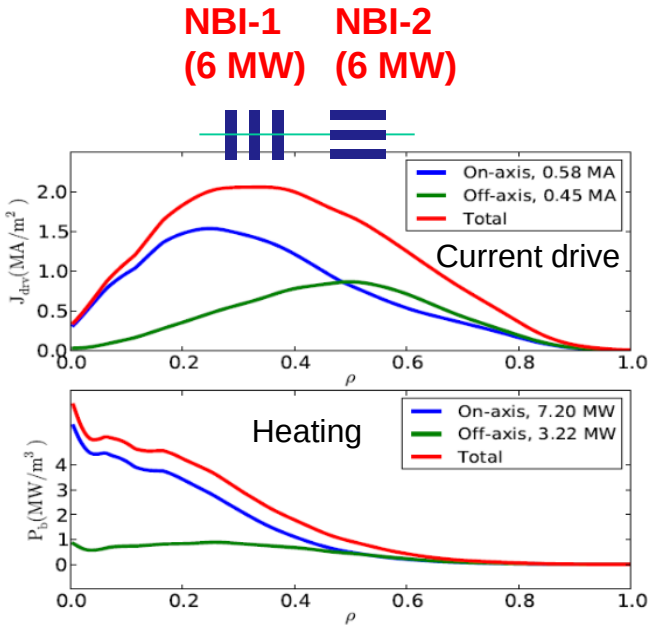
New NBI-2 and Helicon CD systems for KSTAR

➢ NBI systems (6 MW NBI-1 + 6 MW NBI-2)

- On-and Off-axis heating to get stable high beta operation
- Co-current direction in both NBI-1 & 2 (for CD & high rotation)
- NBI-2: 6 MW, 100keV, 300 s (4MW off-axis + 2MW on-axis)
- Schedule : 1 ion source (in 2018), 3 ion sources (in 2019)



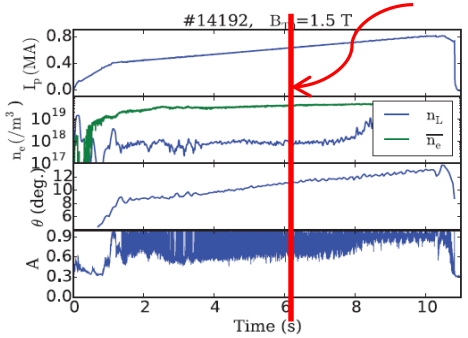




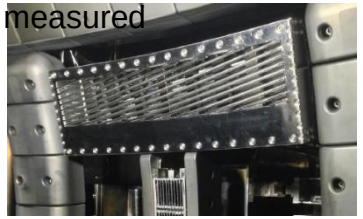
➢ Helicon CD experiment and modeling

- Prototype 500 MHz : 0.1 MW ('16 ~'18)
- High power HCD (2 ~ 4 MW)
  - Klystron : 1 MW CW tube (5 units from SLAC) ('19)
  - Power supply : 2 MW ready ('19)
  - Launcher : 2 MW ('19)

Perfect alignment

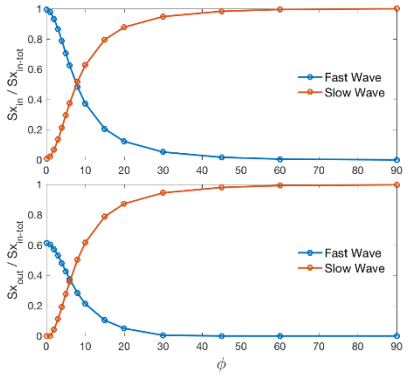


No dependency of coupling (A) on misalignment +/-3 degrees measured



Prototype Helicon Antenna

1-D full wave modeling



Slow wave coupling can be ignored if polarization misalignment phi<5 degrees ($k_{\parallel}/k_{\perp}$)

E.H Kim, PPPL

Time line of research and upgrade plan of KSTAR

2008 → **2017**

First plasma
(ECH 84 GHz)

Long-pulse Heating
(NBI~5.5 MW)
(ECH~1 MW)

Long-pulse H-mode research

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

2018 → **2020**

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

Advanced scenario & MHD research

- *Stable high beta operation*
  (β_N > 3.0, f_{BS} > 0.5, T_{ion} ~ 10 keV)
- *Advanced mode develop. (hybrid, ITB, low q)*
- *MHD & disruption control*

2021 ~ → **2023 ~** →

Divertor upgrade
(Tungsten divertor)
(Detached divertor)

CD upgrade
(LHCD~4 MW)
(Helicon CD~4 MW)

Steady-state & reactor mode research

- *Tungsten divertor & active cooling*
- *Advanced current drive*
  (HFS LHCD, Helicon CD, etc.)
- *Steady-state operation (~300s)*

Summary

- KSTAR is well engineered superconducting tokamak with unique tools for advanced research
  - Nearly perfect tokamak symmetry, intricate IVCC (top/middle/bottom) like ITER IVCC and advanced 2D/3D microwave imaging diagnostics
- Significant progress in expansion of operation regimes, validation of fundamental physics and ITER/DEMO relevant research
  - Long pulse H-mode (with ELM-crash) over 70s and ELM-crash suppressed H-mode over 30s
  - Expansion of conventional operating regimes (hybrid, high beta-P, ISS, High poloidal beta, ITB, low edge q_{95}, etc.) and exploration of new alternative mode for minimum harmful instabilities
  - Validation of fundamental physics: “full reconnection model” in sawtooth (1/1), Transport modification by turbulence and MHD in TM (2/1), design of optimum window for RMP field penetration, role of turbulence induced by RMP in ELM-crash suppression and turbulence physics (Avalanche and QCM)
  - ITER relevant research results: H-mode threshold power influenced by error fields, Rotation by NTV, Divertor heat dispersion by rotating RMPs, New start-up method, etc.
- Future upgrade plan with new ancillary systems
  - NBI-2 installation (2018~) and Helicon CD installation (2019~)
  - Upgrade plan (2021~) will be followed for actively cooled divertor and in-vessel components

Thank you for your attention !

감사합니다