Progress of KSTAR Operation and Upgrade

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On behalf of

KSTAR project participants and collaborators

Apr. 22nd, 2014

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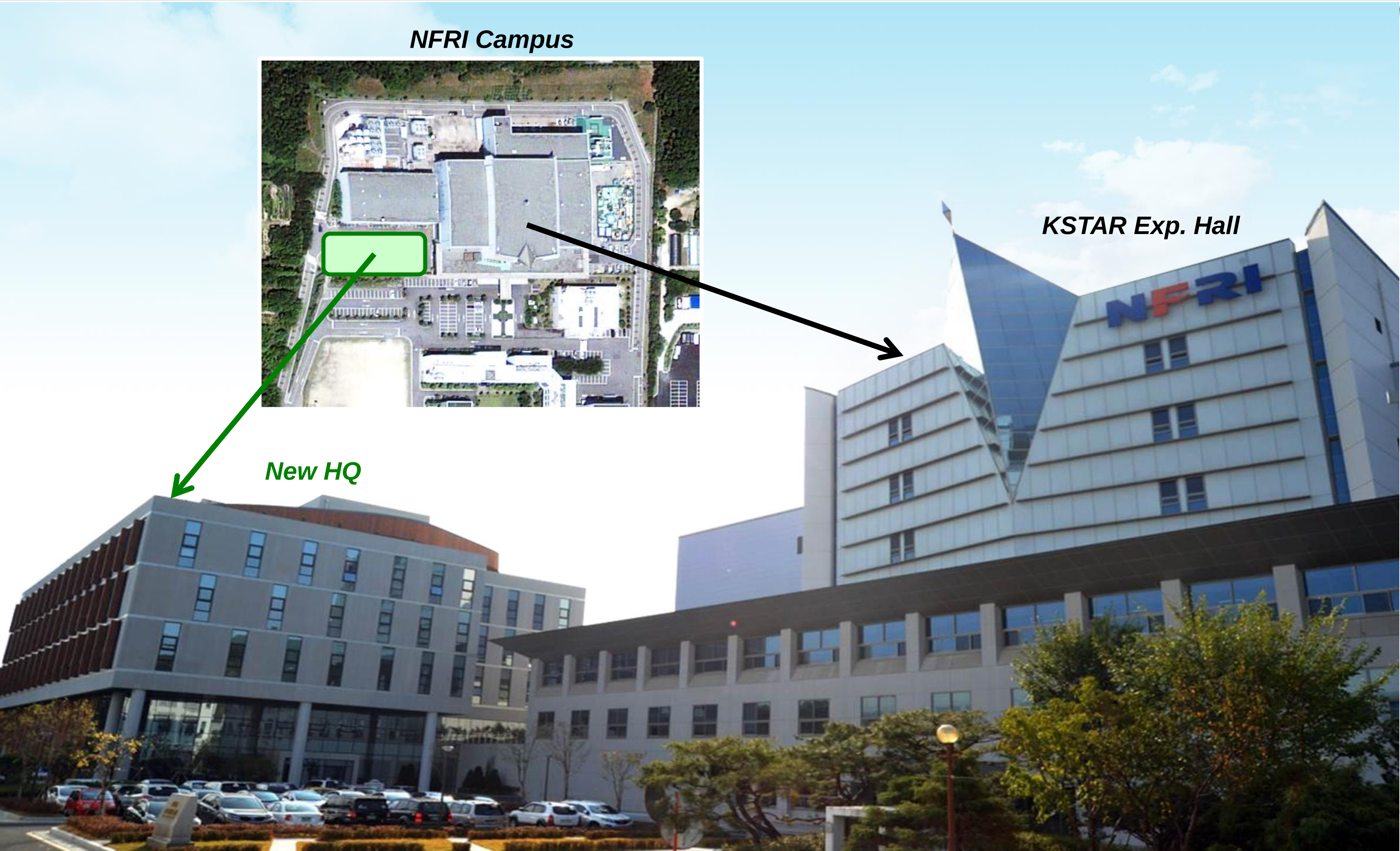
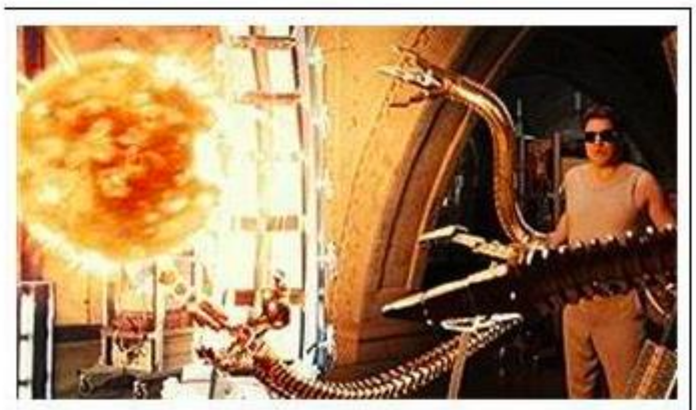
국가핵융합연구소
National Fusion Research Institute

New NFRI Head Quarter was ready for the KSTAR science, ITER-DA and DEMO research

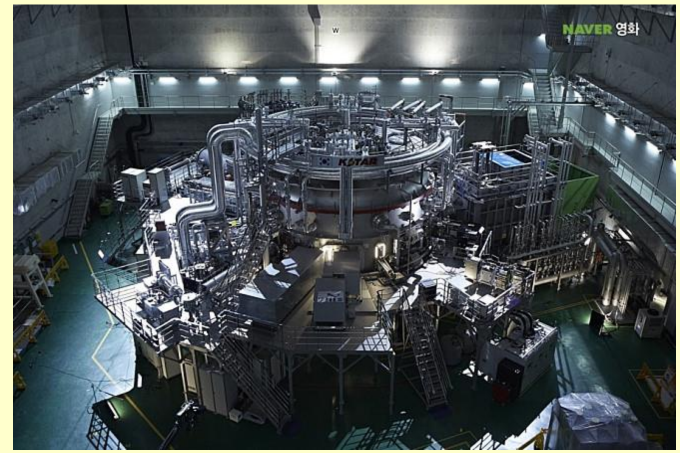


KSTAR program approached to public..

Hollywood Movie
Fusion energy for Aviation & Explosive



Korean Movie ("AM 11:00")
KSTAR for massive energy in Time Machine



Strong contributions from PPPL (including Columbia U. and ORNL) to KSTAR program

OAK RIDGE National Laboratory

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KSTAR

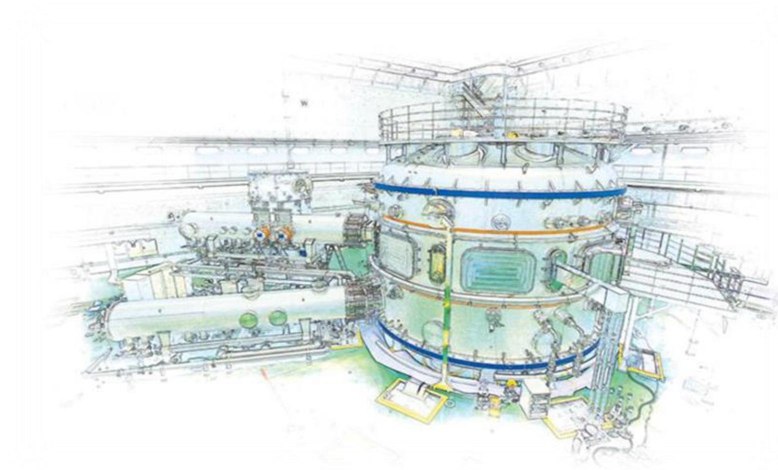
- **Design of fusion devices**
  - ✓Transfer TPX design documents
  - ✓KSTAR PVR, TSER design
  - ✓KSTAR PAC and review
  - ✓K-DEMO design validation
  - ✓Others

- **In-kind or experimental contribution**
  - ✓KSTAR heating (ECH launcher development, consult on NBI & ICRF)
  - ✓KSTAR diagnostic (XICS, TS, etc)
  - ✓KSTAR experiments (plasma control, H-mode, ELM control, rotation control, error field, MHD stability, etc.)

- **Human resource developments**
  - ✓PPPL staffs moved to Korea : H. Park, TS Hahm, KC Lee, etc.
  - ✓Participating the KSTAR experiments: D. Mueller, S. Sabbagh, J. Park, J. Ahn, Y. Park, CS Chang, R. Ellis, J. Hosea, L. Grisham, J. Menard, etc.
  - ✓Ph.D or post-doctorial courses : YS Hwang, W. Choe, W. Lee, JH. Kim, K. Kim, etc.
  - ✓Short or long-term visiting researchers (Sabbatical or short-term) : YK Oh, BH Park, etc.

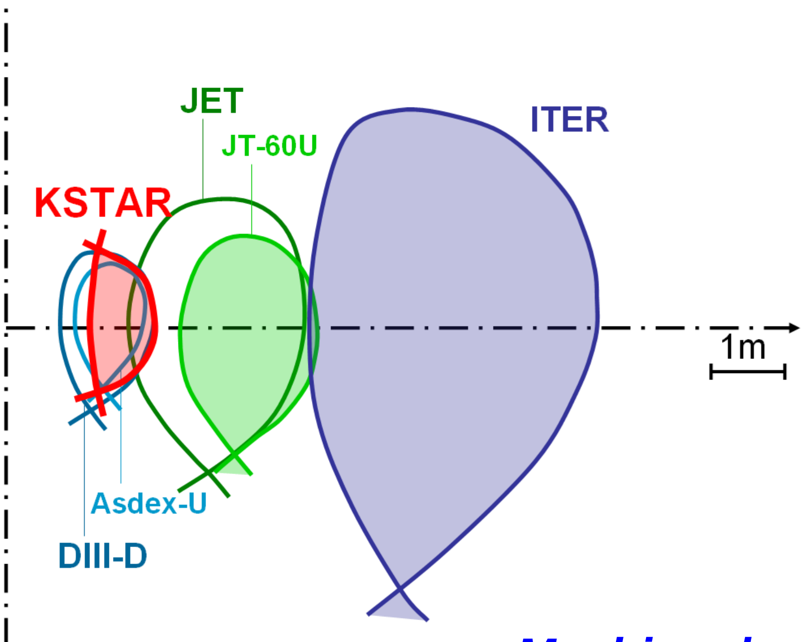
OUTLINE

- ***KSTAR Overview***
- ***Key Achievements***
- ***Research Plans and Upgrade***
- ***Remarks***



KSTAR Mission and Design Parameters

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



- **KSTAR parameters**

Parameters	Designed	Achieved
Major radius, R_0	1.8 m	1.8 m
Minor radius, a	0.5 m	0.5 m
Elongation, κ	2.0	1.8
Triangularity, δ	0.8	0.8
Plasma shape	DN, SN	DN, SN
Plasma current, I_P	2.0 MA	1.0 MA
Toroidal field, B_0	3.5 T	3.5 T
Pulse length	300 s	22 s
β_N	5.0	2.9
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD	~ 28 MW	~ 5 MW
PFC	C, CFC or W	C

- *Machine design is optimized for advanced target operation with strong shaping, passive plates, low TF ripple, …*

Brief history of KSTAR operation

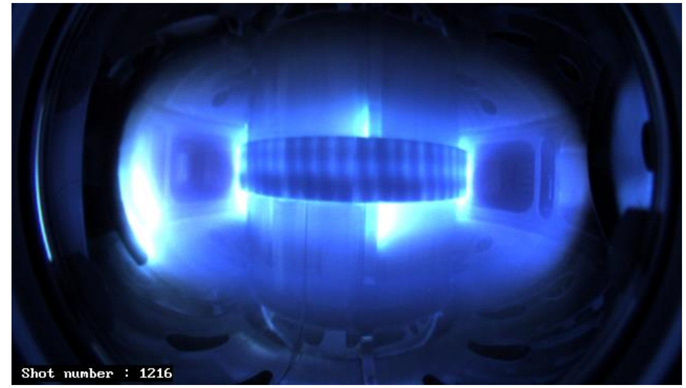
- **2008 : First plasma achievement**
  Ip >100 kA, B_T ~1.5 T, 84GHz ECH

- **2010 : First H-mode achievement**
  Ip ~0.6 MA, P_{NBI}~1 MW

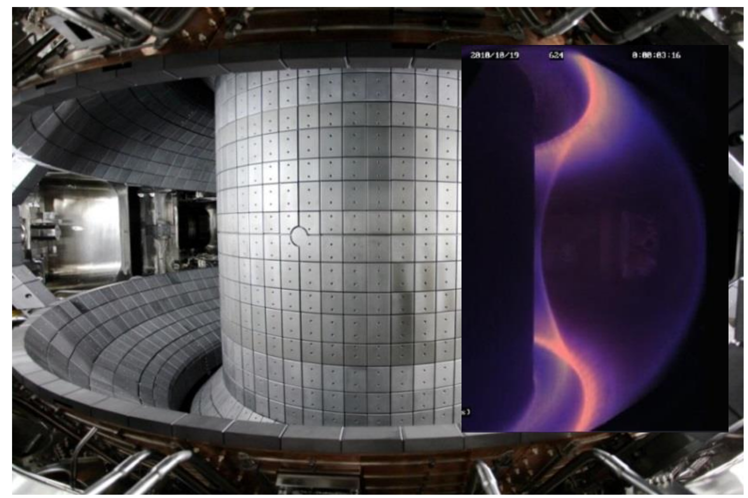
- **2011 : Successful ELM suppression @ *n=1***
  1 MA discharge (L-mode)

- **2012 : Stationary H-mode** ***(~16s @ 0.6 MA)***
  Surpass n=1 ideal no-wall limit
  (β_N~2.9, β_N/ li ~ 4.1)

- **2013 : Error field measurement** ***(~10^{-5})***
  Stationary H-mode ***(~20s @ 0.5 MA)***



First Plasma (2008)

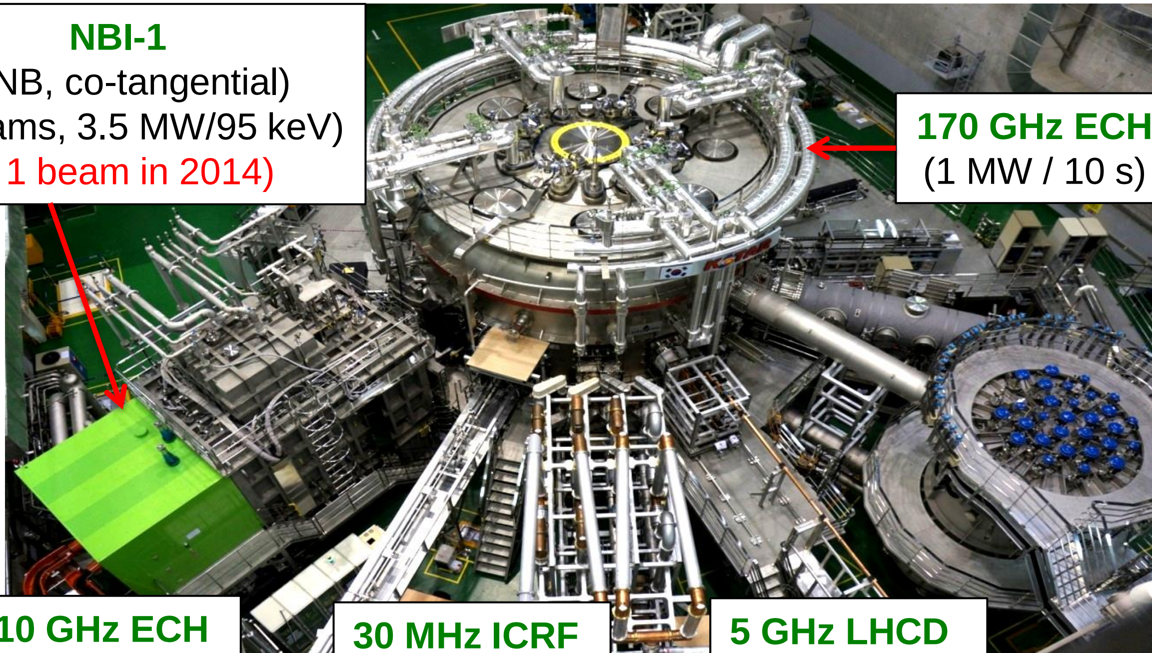

H-mode Plasma

- ***Long-pulse discharges & ITER urgent issues were main thrusts in the KSTAR 2013 campaign.***

Machine status of KSTAR (2013)

NBI-1
(PNB, co-tangential)
(2 beams, 3.5 MW/95 keV)
(+ 1 beam in 2014)

170 GHz ECH
(1 MW / 10 s)

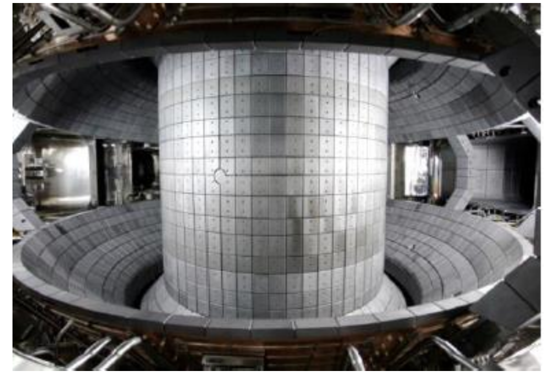


110 GHz ECH
(0.7 MW / 2 s)

30 MHz ICRF
(0.5 MW / 3 s)

5 GHz LHCD
(0.5 MW / 2 s)

In-vessel Control Coils (Vertical stabilization & ELM control are ready. Broadband power supply is planned from 2015.)



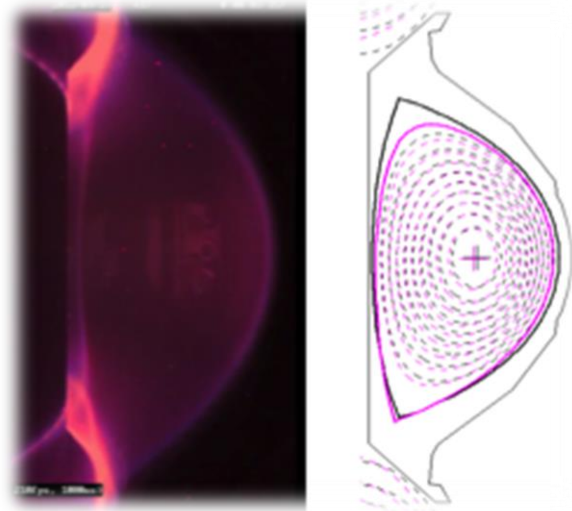
Full Graphite PFCs (Water cooling pipe was installed. Active cooling is planned from 2016.)

Ad-hoc In-vessel Cryopump (Cryo-cooling tube was installed. Liquid Helium circulation is planned from 2016.)

- KSTAR Overview
- **Key Achievements**
  - Long-pulse H-mode operation
  - Extension of operation boundary
  - ELM control & H-mode physics
  - MHD/Transport Physics
- Research Plan and Upgrade
- Remarks

Research focus in 2013 campaign

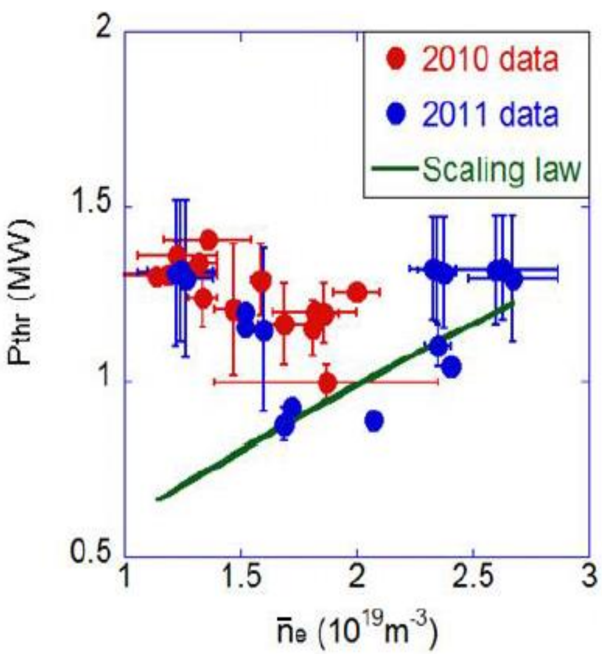
- **Extension of long-pulse capability and operation boundary**
  - Pulse-length (>20 s) /plasma current (~ 1 MA)
  - Stability diagram (higher betaN, lower li)
- **ELM control in wider operational range**
  - n=1 & n=2 magnetic perturbation (wider q95 window)
  - Update of ECH/SMBI induced ELM control
- **H-mode physics**
  - L-H transition
  - ELM filament imaging (LFS-HFS)
- **MHD / transport related physics**
  - Rotation damping by ECH
  - Soft-landing scheme for Disruption/Lock-mode
  - Control of NTM / Sawtooth
  - Fast ion transport during ELM suppression

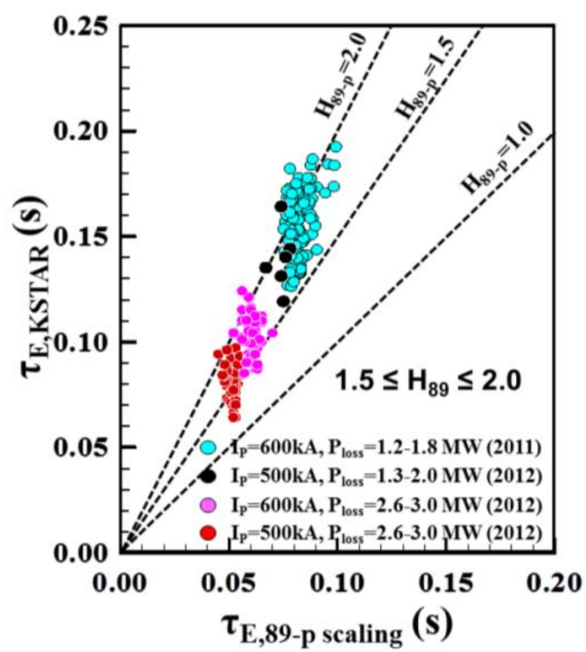


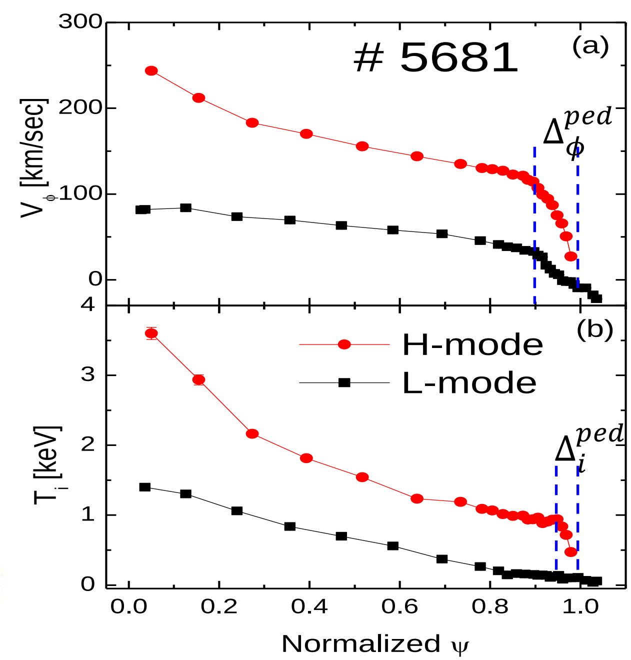
Typical H-mode plasma discharge in KSTAR

- ***Control of plasma discharge :***
  - Balanced DN, USN, LSN
  - Shaping : κ~ 1.8, δ ~ 0.6
  - Heating : P_{NBI} ≥ 3 MW, P_{ECH} ~ 1 MW
  - PFC : graphite tiles (no active cooling)
  - WC : Boronization and overnight GDC

- ***H-mode plasma***
  - LH transition threshold ~ 1 MW
  - Density roll over : ~ 2 x10^{19}/m^3
  - H89 : 1.5 ~ 2.0
  - Strong rotation ~ 300 km/s
  - Stored energy : 0.4 ~ 0.6 MJ
  - ELM types : Type-I (f_{ELM} ∝ P_{ext}),Type-III

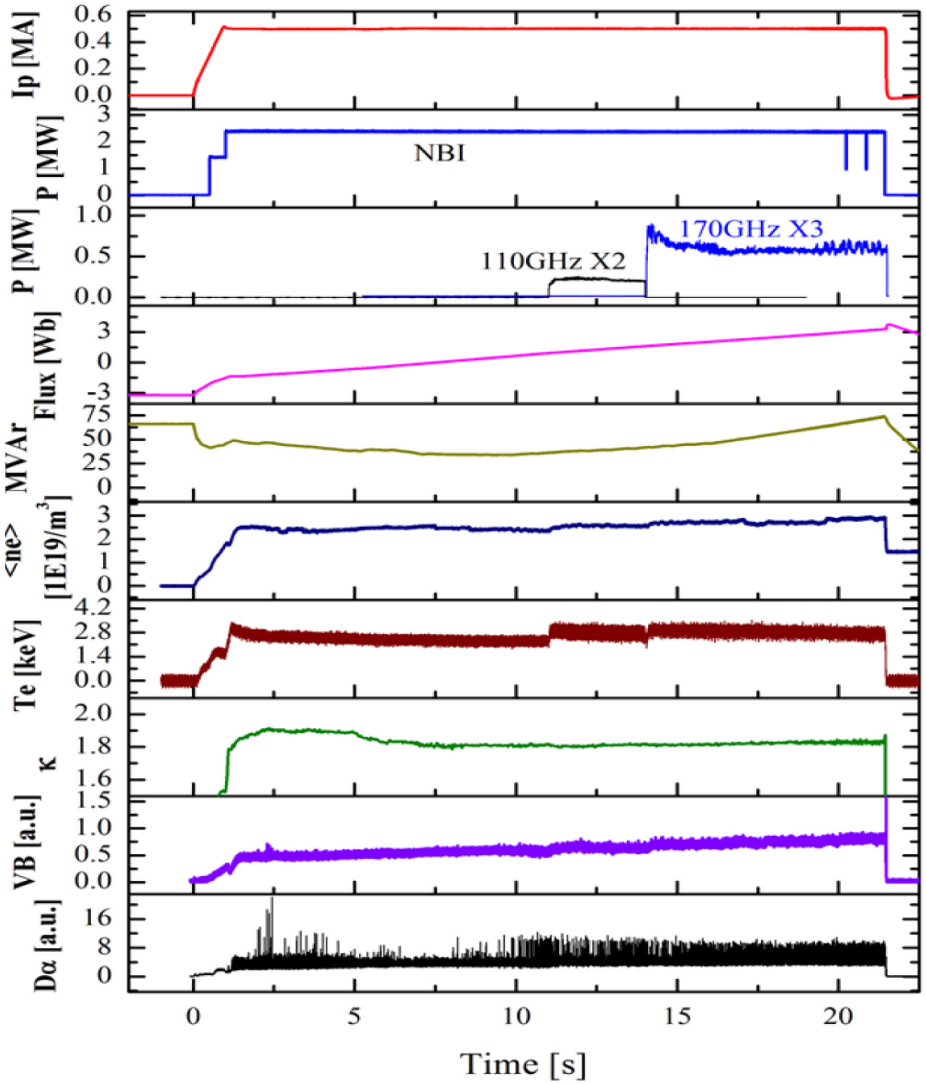






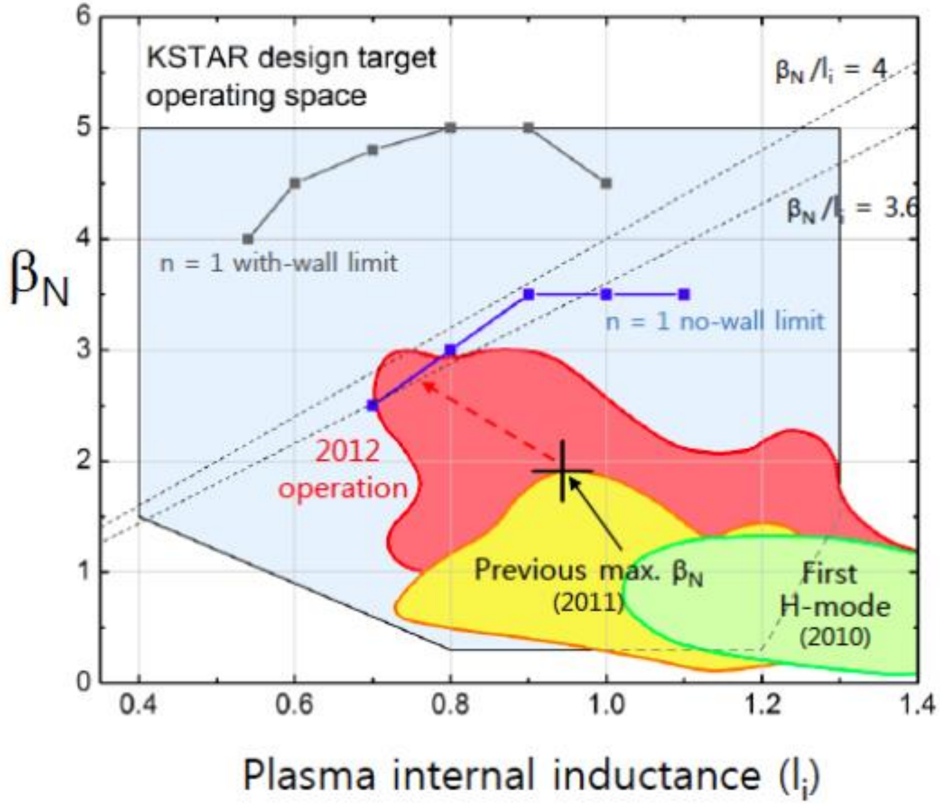
Effort for long-pulse operation : Longer phase of H-mode flattop ($t_{H\text{-}mode}$~20s)

Early shaping & L-H transition **#9388**



- ***Operation parameters***
  - Ip = 0.5 MA (B_T = 2 T, q95 ~ 6.4)
  - P_{NBI} ~ 2.5 MW
  - P_{ECH} @ 110 GHz, X2 ~ 250 kW,
  - P_{ECCD} @170 GHz, X2 ~ 700 kW
- ***Extended H-mode flattop up to 20s***
  - Better shape control without strong n_e rise (due to better X-point control)
  - Shut-down at t=21.4s due to limit of electricity of grid (< 73 MVar limit), not due to Vs limit.
- ***Plan for longer pulse***
  - Ohmic flux (~ 12 Wb) is available for more than 50s flattop at Ip=1 MA, even with P_{NBI} ~ 3 MW, if motor-generator(1.6 GJ, 200 MVA) is in operation.

KSTAR is approaching and exceeding no-wall MHD stability limit by optimizing scenario



S. Sabbagh & Y. Park

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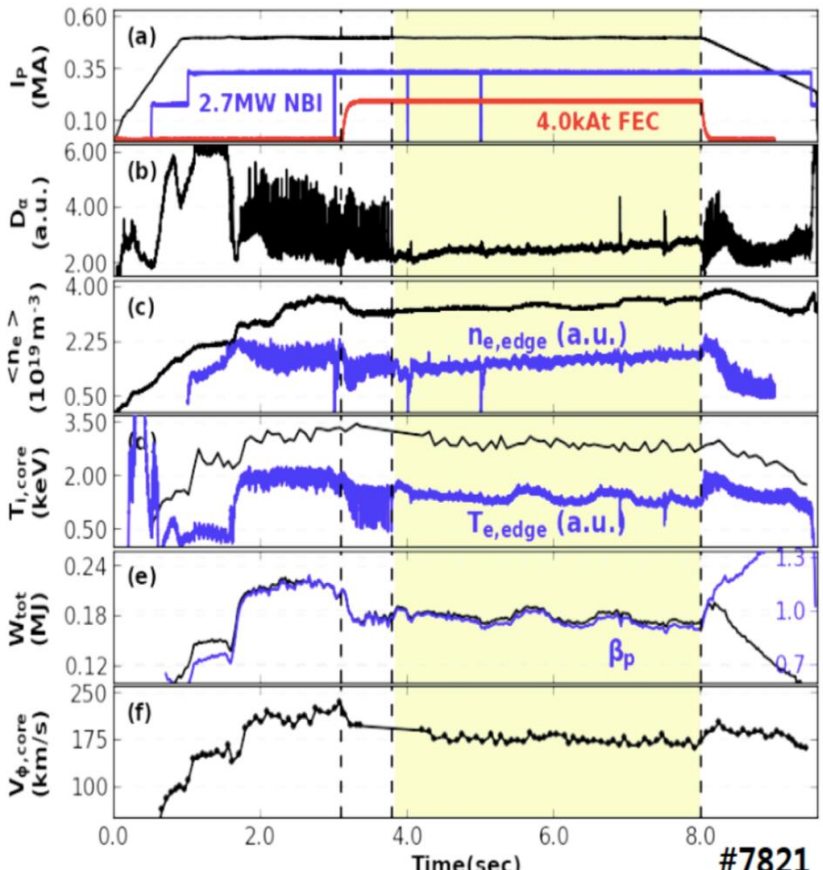
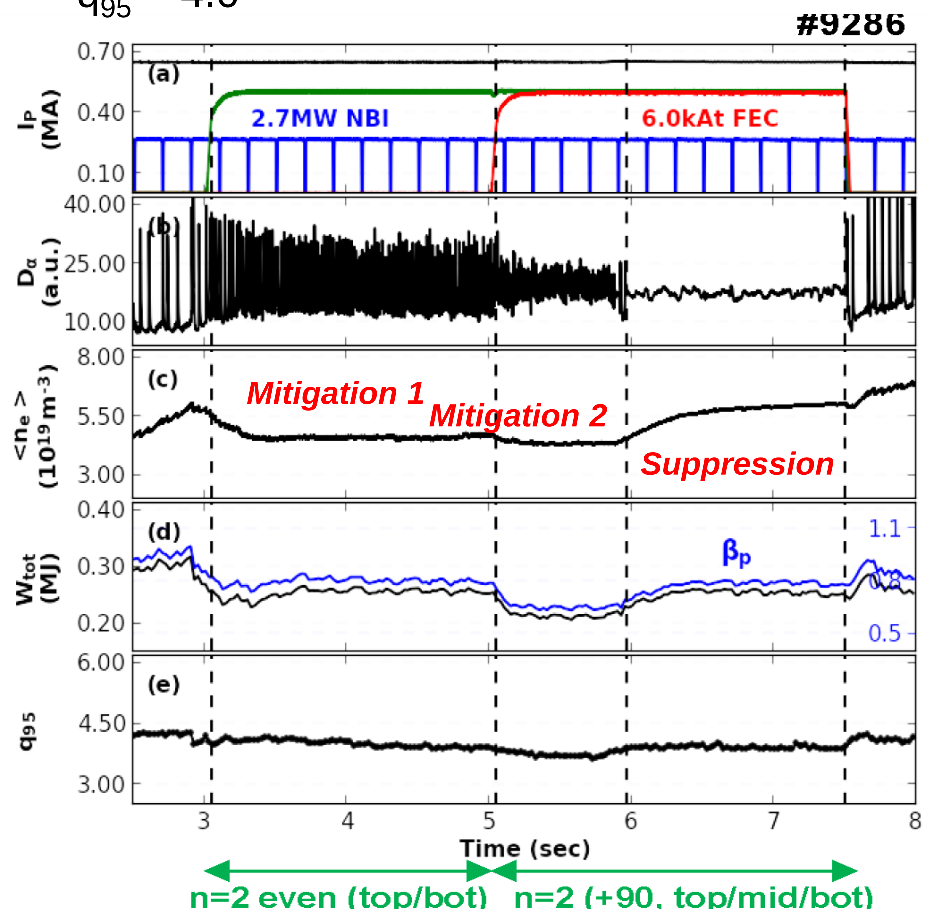
- ***KSTAR equilibrium operating space has been extended to advanced operation range***
  - By early heating for low li (better Ip ramp-up scenario)
  - Optimizing B_T & Ip
    - B_T in range 1.3 - 1.5T
    - Ip : 0.5 ~ 0.7 MA
    - $\beta_N / l_i \sim 4.1$
    - $\beta_N \sim 2.9$, $l_i \sim 0.7$
  - We expect more advanced results from 2014.
    - NBI heating increased in 2014
    - broadband IVCC power supplies from 2015.

ITER high priority research ; ELM suppression by n=1 and n=2 perturbation

- ELM suppression over 4s by n=1 RMP
- **Unique result in KSTAR and it could be related to low intrinsic error field.**
- q_{95} = 6.0 ~ 6.5

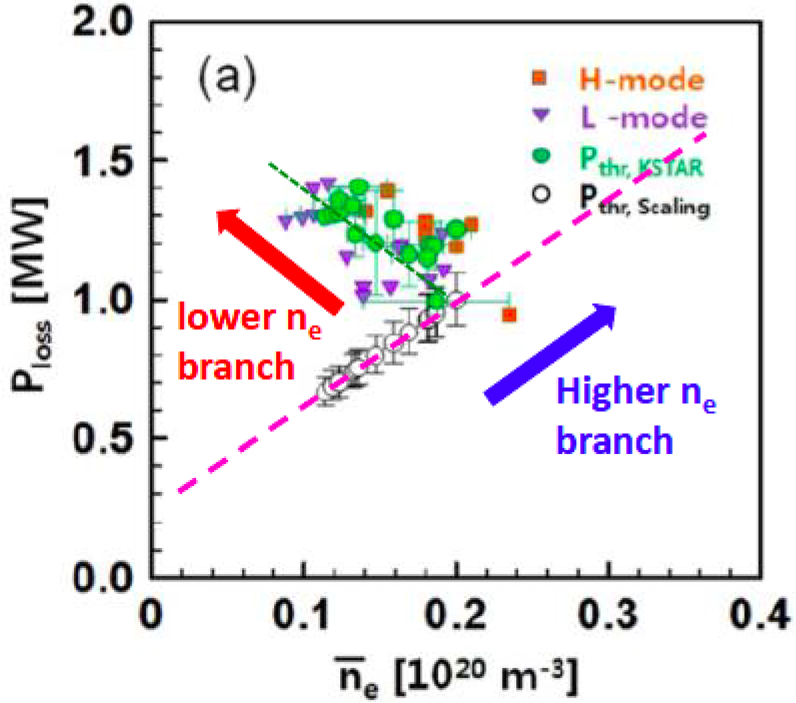


- ELM mitigation / suppression by n=2 RMP.
- **It depends on selective setup (top/bottom or top/mid/bot)**
- q_{95} ~ 4.0



- **Approach to get wider operation in q95 and collisionality and to keep longer suppression period (> 10s).**

ITER high priority research ; Stimulated L/H transition using SMBI



Lower n_e branch (ne < 2.e19) + small SMBI (4 ms): various dynamics are triggered as

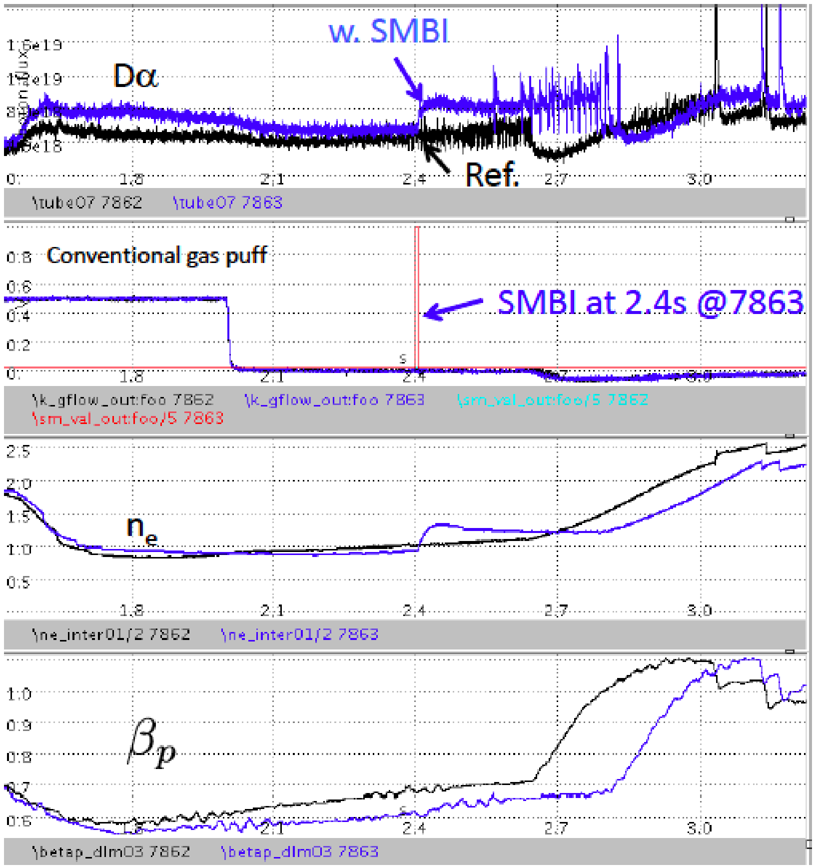
- Extension of LCO
- Enhancement of density pedestal
- Transition is often delayed in time
- Steepening of edge density found

Higher n_e branch + stronger SMBI (8 ms):

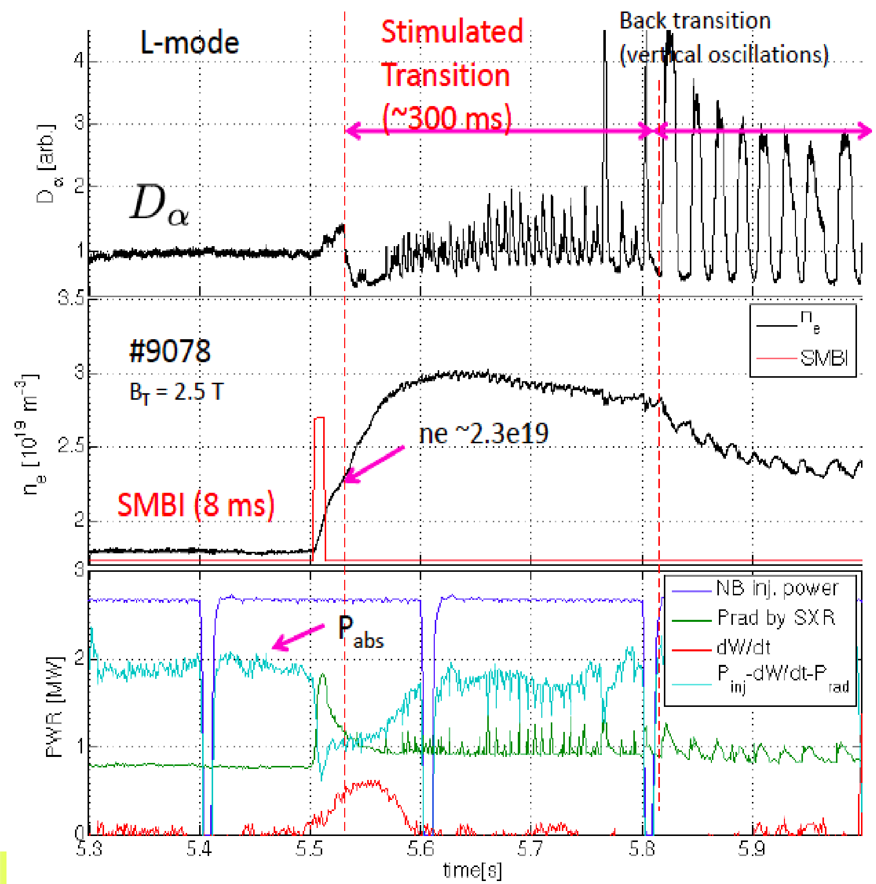
- **Stimulated L-H occurs with increase of density toward which the transition is more unlikely to occur**
- Reduction of required absorbed power = Pinj – dW/dt – Prad has been reported, up to 30% less than baseline
- The profile change seems to be localized in space, according to spatial BES profile

ITER high priority research ; Stimulated L/H transition using SMBI

- Lower n_e branch :
- Injection of 4 ms SMBI at 2.4s makes larger oscillations at Dα, extends the I-phase and causing L-H at 2.8s

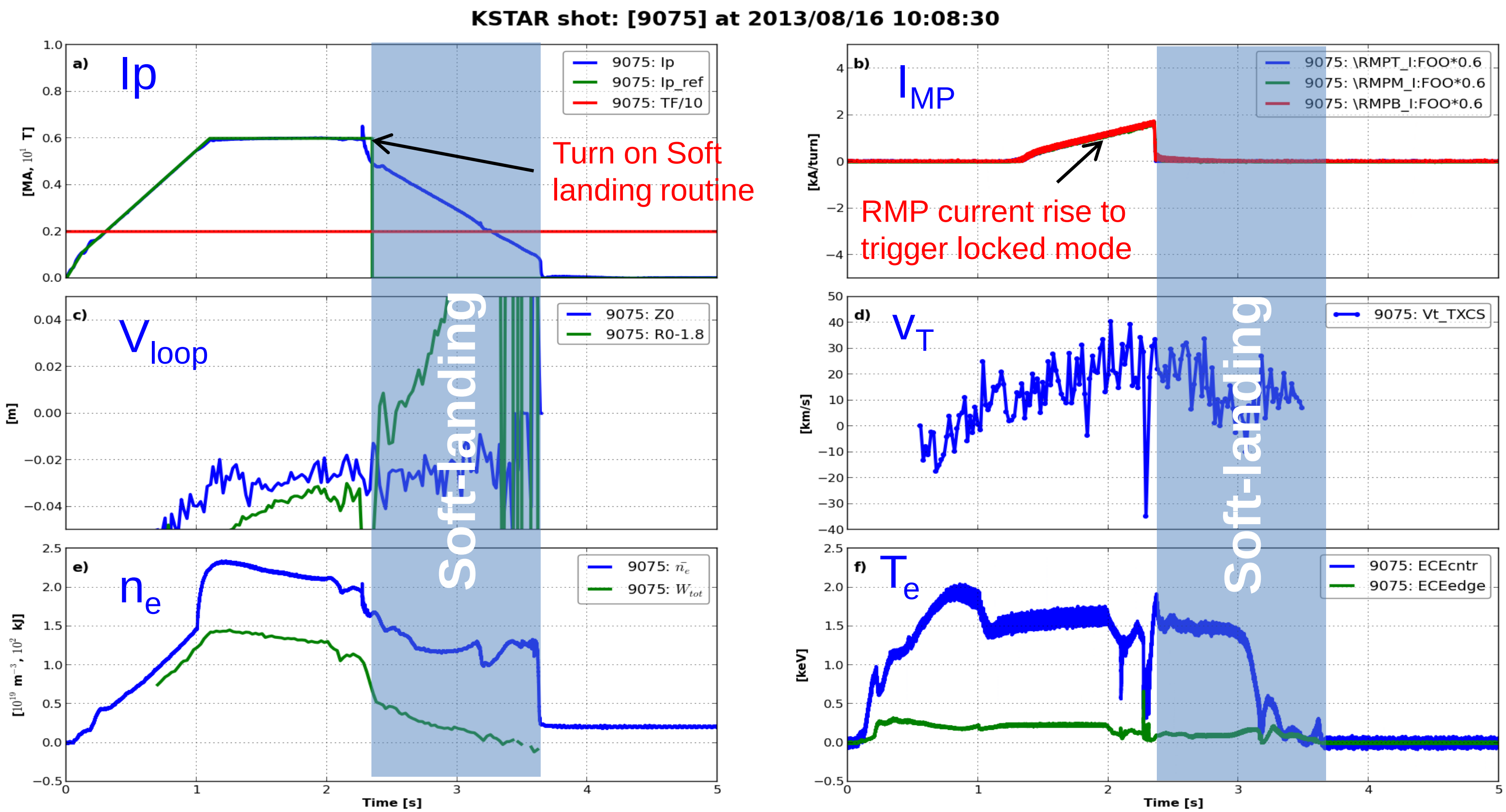


- Higher n_e branch :
- stimulated transition found with 30% reduced absorbed power



Demonstration of successful soft-landing at the Locked-mode with slow SC coils

- Lock-mode trigger : n=1 magnetic perturbation
- Detection : PCS catches drop of Ip (despite of its control effort)
- Action : PCS invokes async. ramp-down procedure for safe discharge termination

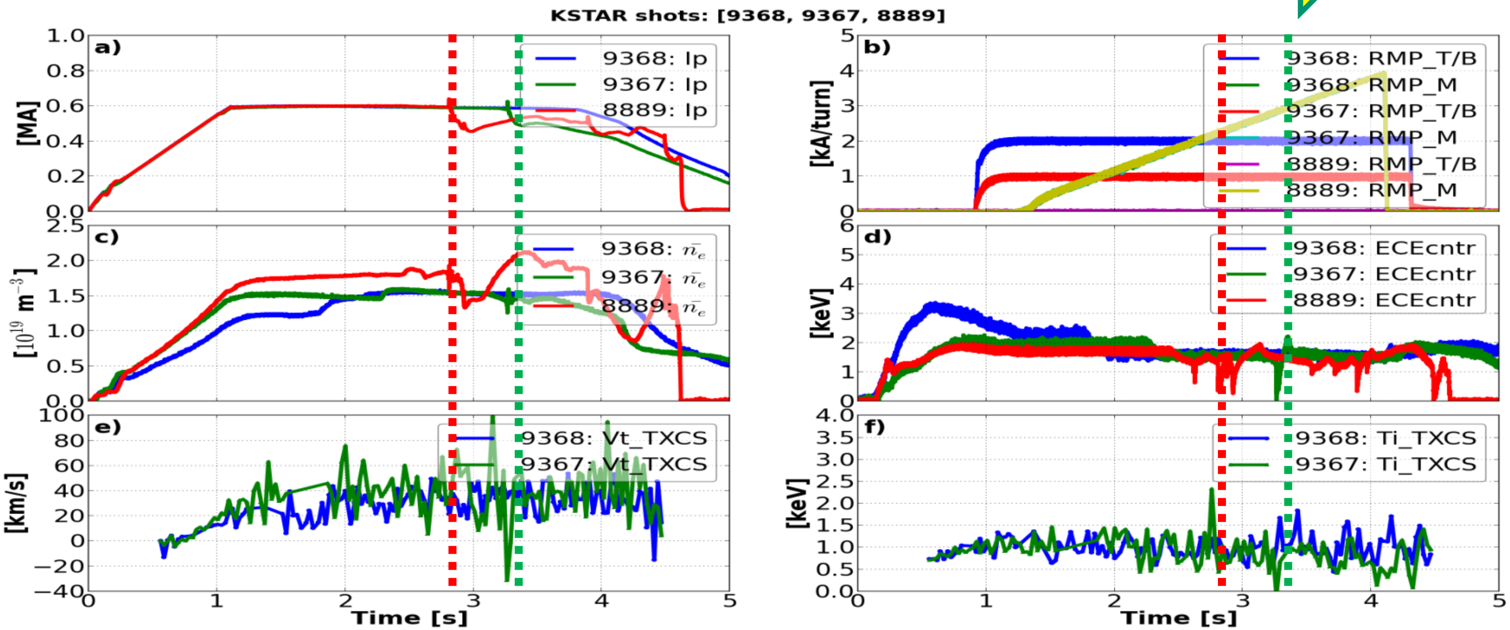


Effective tools for mixed error field perturbation experiments

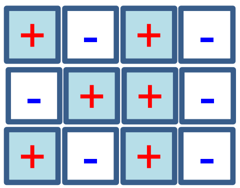
- ***In-vessel control coils are powerful tools for studying the effect of overlapped non-axisymmetric field with difference modes.***
  - n=1 field is gradually increased to cause the final locking.
  - n=2 even field is constantly applied during n=1 field increase.

  - **The early trigger of Mode-lock as the current In=2 increases.**
  - **However, final disruption is delayed as In=2 increased.**

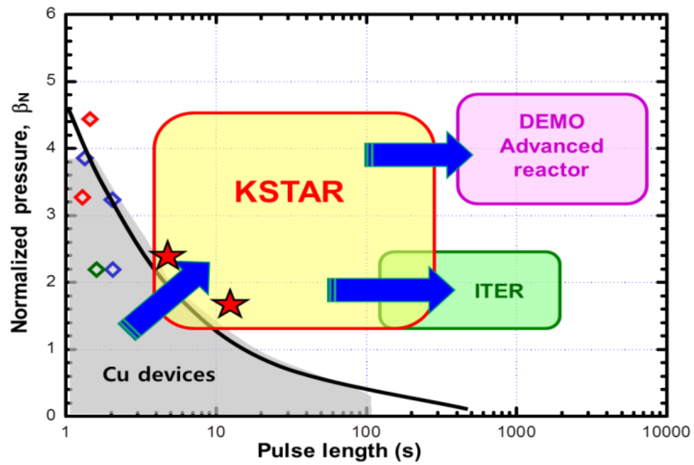
Early locking | #8889 (n=2, 0 kAt) → #9367 (n=2, 2 kAt) → #9368 (n=2, 4 kAt) | No locking



n=1 & 2 even



- KSTAR Overview
- Key Achievements
- **Research Plans**
  - Long-term plan of operation and upgrade
  - Research directions in Phase 2
  - Hardware upgrade in 2014
  - Research plan in 2013
- Remarks



Long-term plan of operational and hardware upgrade

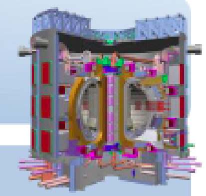
Operation Phase I 2008 ~ 2012	Operation Phase II 2013 ~ 2017	Operation Phase III 2018 ~ 2022	Operation Phase IV 2023 ~
Superconducting Tokamak Operation	**Long-pulse H-mode and ITER pilot**	**High-performance Scenario related to DEMO**	**DEMO Advanced Technology**
• Integrated control of SC tokamak • First plasma • H-mode discharge • Experimental collaboration	• ITER priority research (ELM, Disruption, NTM) • High performance plasma study using KSTAR intrinsic tools (intermediate heating power, low density)	• Demonstrate advanced operation scenario (high power, high density) • Integrated control of profile and stability • DEMO compatible scenario development	• Stabilization and optimization of advanced scenario • Components test under extreme environments
Upgrade Plan	• Heating : upgrade to 13MW - NBI ~ 6MW - ECH ~ 3MW • PFC : graphite & strengthen • Density control: cryopump & PFC active cooling • 3D field : IVCC PS upgrade • Electric : MG • Control & diagnostics	• Heating : upgrade to 28 MW - NBI ~ 12 MW - ECH ~ 4 MW - LHCD ~ 4 MW - ICRF or Helicon CD ~ 8 MW • PFC : Metal PFC & advanced divertor • Density control : pellet • Electric : 5 T capability	

Black : already featured
Blue : under upgrade
Red : planned upgrade

Major research topics in 2nd operation phase

1. Exploration of ITER operational range based on long-pulse H-mode in MA level
2. Optimization of heat-load on plasma facing components
3. Realization of real-time plasma control in long-pulse discharges
4. Extension of advanced operation modes to reactor relevant conditions

	2014	2015	2016	2017
Long-pulse ITER Operation	Experiments on long-pulse ITER baseline scenario; β_N ~2 for 30s	optimal operation with limitations of SC PF coils; β_N ~2 for 50s	β_N > 2.5 for 50s	
Heatloads on Dirvetor/Firstwall	Control of ELMs(RMP) > 10s; Pre-cursor detection for disruptions	Radiative divertor in long-pulse; High-Z impurity transport	Experiments on optimal divertor shapes	W firstwall(?)
Realtime Control & Diagnostics	Integrated ELM control; Control of n_e/T_e profiles	NTM control; Integration of plasma current profile	Fully integrated PCS in long-pulse operation	RWM control
Advanced operation modes	Quiescent H-mode	Hybrid-mode in long-pulse and SS mode; Te~Ti experiments		vT~0 experiments



Many strong points of KSTAR for advanced research capabilities

- Robust machine integrity and reliability of long-pulse SC magnet operation is demonstrated
- Low error field, TF ripple and hence strong rotation : ideal for rotation study and low q95 operation
- Low intrinsic error field : ideal for magnetic perturbation study and MHD stability
- Versatile in-vessel coils and power supplies for multi-purpose : flexible system for ELM/RWM/EF control
- Similar magnetic/vessel system as ITER
- Optimized for advanced operation scenario : equipped with passive plates, in-vessel coils and capable of strong shaping
- Advanced diagnostics : ECEI, MIR, BES, Li-Zeeman and TS
- Mix of various heating technologies: tangential NBI, ECH/ECCD, LHCD, ICRF

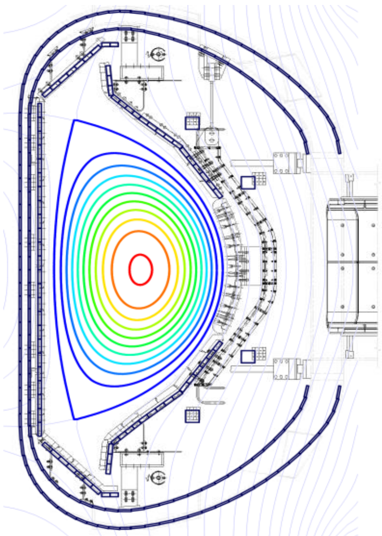
Very low toroidal ripple as an effective environment for the pedestal study

- **KSTAR features :**
  - Very low TF ripple at edge (~0.05%) by locating the plasma at inboard
    - JET (~ 0.08 %, at 32 coils)
    - DIII-D (~ 0.5 %), ITER (0.5 ~ 1 %)
    - KSTAR (~0.05 %)
  - Clear detection of pedestal rotation profile

- **Research capability :**
  - Accurate inspection and control capability of pedestal profile
  - Research at higher rotation
  - MHD research at extreme operation (ex, min. q95 operation, high rotation)

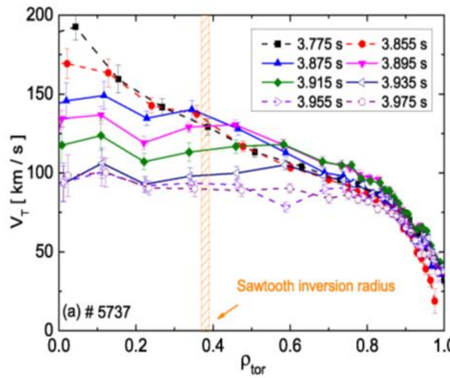
- **Upgrade :**
  - Diagnostics upgrade: MSE, Li-Zeeman splitting, p-CES, TS

KSTAR plasma position and low TF ripple

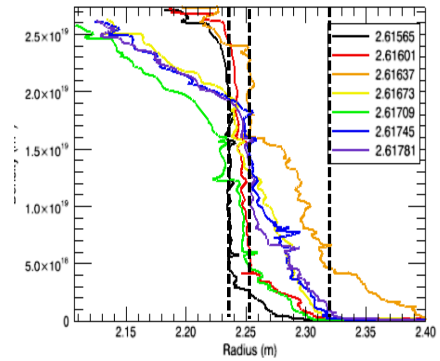


Machine	(%) at edge
JET	0.08 (32 coils) ~ 1.5 (16 coils)
DIII-D	0.5
JT-60U	0.5 ~ 1
ITER	0.5 ~ 1
KSTAR	**0.05**

Rotation pedestal



Density pedestal



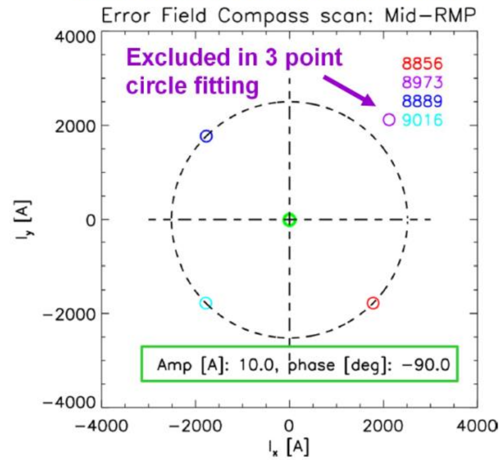
Very low intrinsic error field and effective stability research

- **KSTAR features :**
  - Low intrinsic error field ($\delta B/B \sim 10^{-5}$) was measured, it is about one order of magnitude lower than others

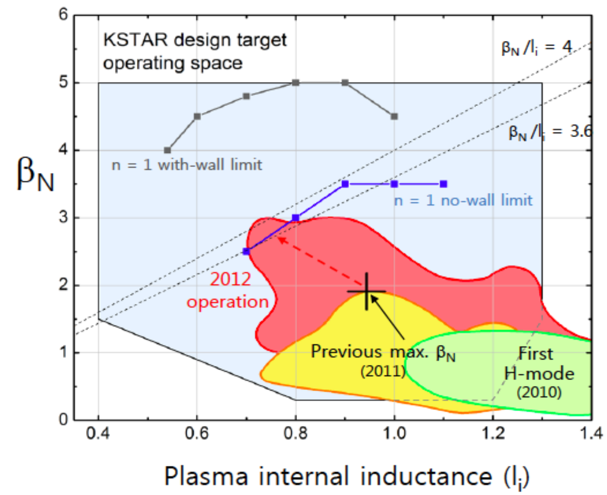
- **Research capability:**
  - Explore the relation of ELM suppression at n=1 with low n=1 intrinsic error field.
  - Compare the confinement database according to error field variation by using in-vessel control coils for error field source
  - MHD research according to error field at high beta or high beta/low li region.

KSTAR error field measurement

(based on MID-RMP coils only)



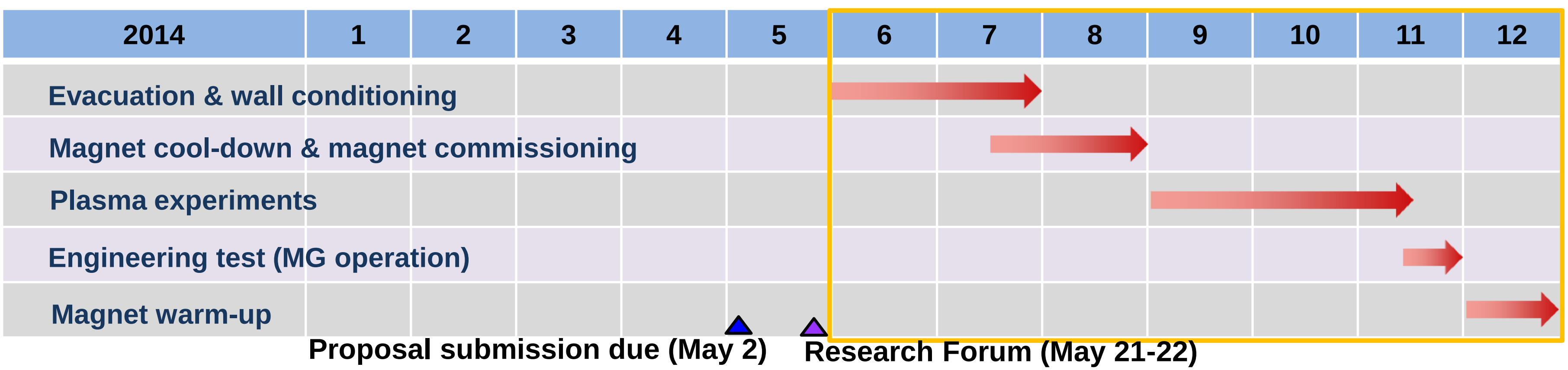
High betaN operation



Plan of 2014 campaign

- **Goals of experiments in 2014(tentative)**
  - Schedule for plasma experiments : 10 Sep – 15 Nov
  - Extended H-mode plasma : Longer (30s at 0.5 MA) and higher current (~1 MA)
  - P_{NBI}~5 MW, co-/cntr- ECCD (1MW) with β_p & better gap control
  - Long-pulse sustainment/scenario for RMP ELM suppression (~10 sec)
  - Commissioning of 200 MVA Motor Generator
  - Identification of intrinsic error field & its impact on machine performance (lower q95, extended operation in Hugill diagram at low ne & q95)

- **2014 Experimental campaign**

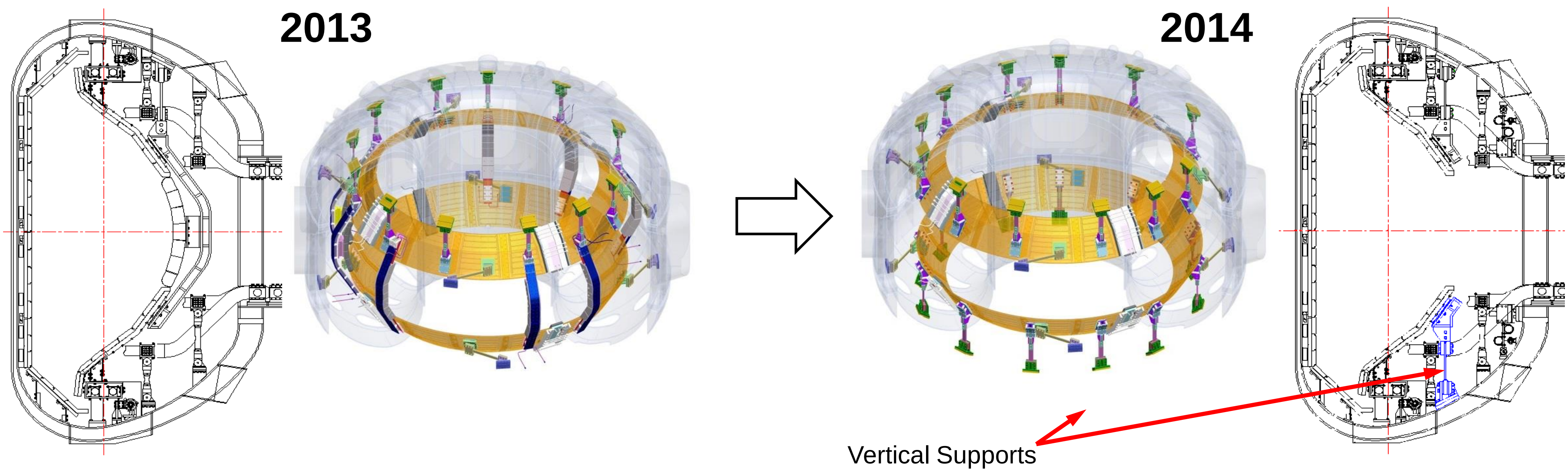


On-going KSTAR upgrades

- **In-vessel Components**
  - Passive stabilizer modification (2014)
  - Preparing the active cooling of PFC (2016)
  - Preparing the in-vessel cryopump operation (2016)
  - Preparing the pellet injector
- **Magnetics**
  - TF magnet slow/fast discharge dump resisters (2014)
  - Motor-generator (2014)
  - IVCC power supply (2015)
- **Control**
  - Network connection (full tunneling VPN) (2014)
  - Additional control room (2015)
- **Heating & CD**
  - Additional ion source for NB (~ 6 MW max) (2014) & NBI-2 design
  - Coupling of ICRF, LHCD (2014)
  - New 105/140 GHz ECH/CD (2015)
- **Diagnostics**
  - Thomson (channel increase),
  - W impurity transport (2014)
  - MSE (2015)
  - P-CES, Li-Zeeman (2015)

Modification of Passive Stabilizer to enhance the structural rigidity

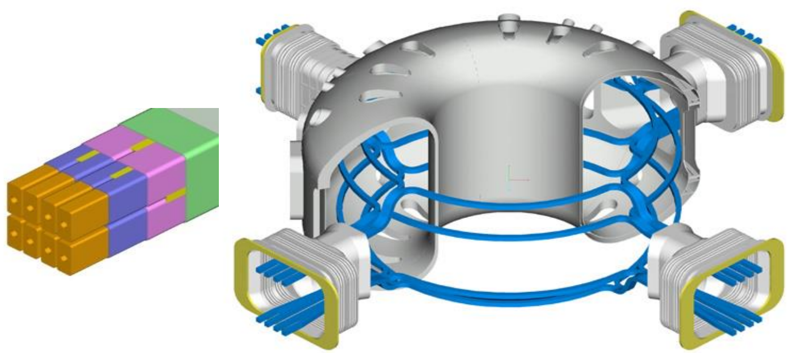
- **Modification in passive stabilizer in 2014**
  - In the previous design, bottom passive stabilizer is weak against lateral force due to asymmetric forces due to VDE or halo current.
  - There were some damages in PFC tiles and mechanical connectors in bottom passive stabilizer.
  - Modification : Separate supporting of bottom PS using additional supporters and removal of mechanical bridges.
- **Major upgrade of in-vessel structures are also considering.**
  - Advanced divertor for high heat flux handling.



Versatile in-vessel control coil and effective for the magnetic field perturbation study

- **Extended operation of IVCC**
  - Research on the error field effects under n=1, 2, with 3 poloidal layers of control coils.
  - Dynamic ELM control, rotation control, error field effect, RWM control, ..
- **Power supplies**
  - 5 sets of Broadband SPAs (500 V, dual 2.5 kA or single 5 kA, dc ~ 10 kHz switching)
  - Switching panel for convenient mode change between shots
  - Operation from 2015 campaign.

Complex in-vessel control coils



n=1, +90 phase

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

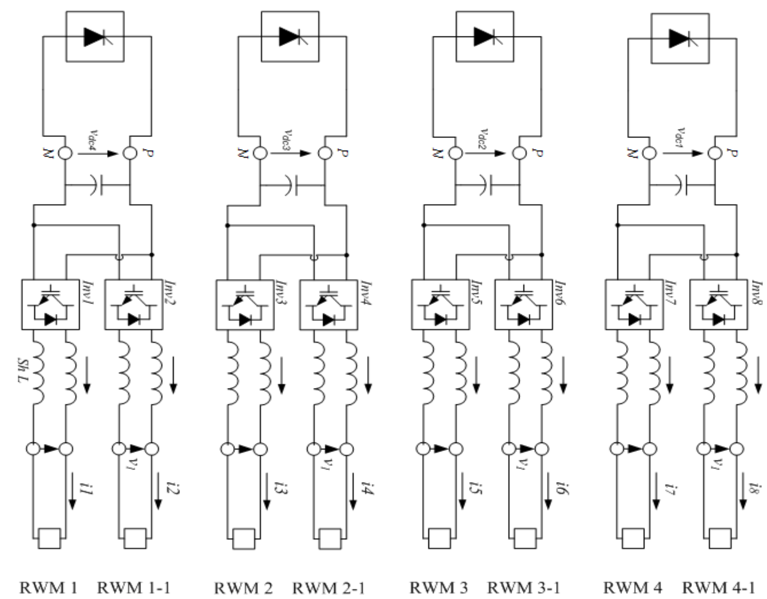
n=2, even

+	-	+	-
-	+	-	+
+	-	+	-

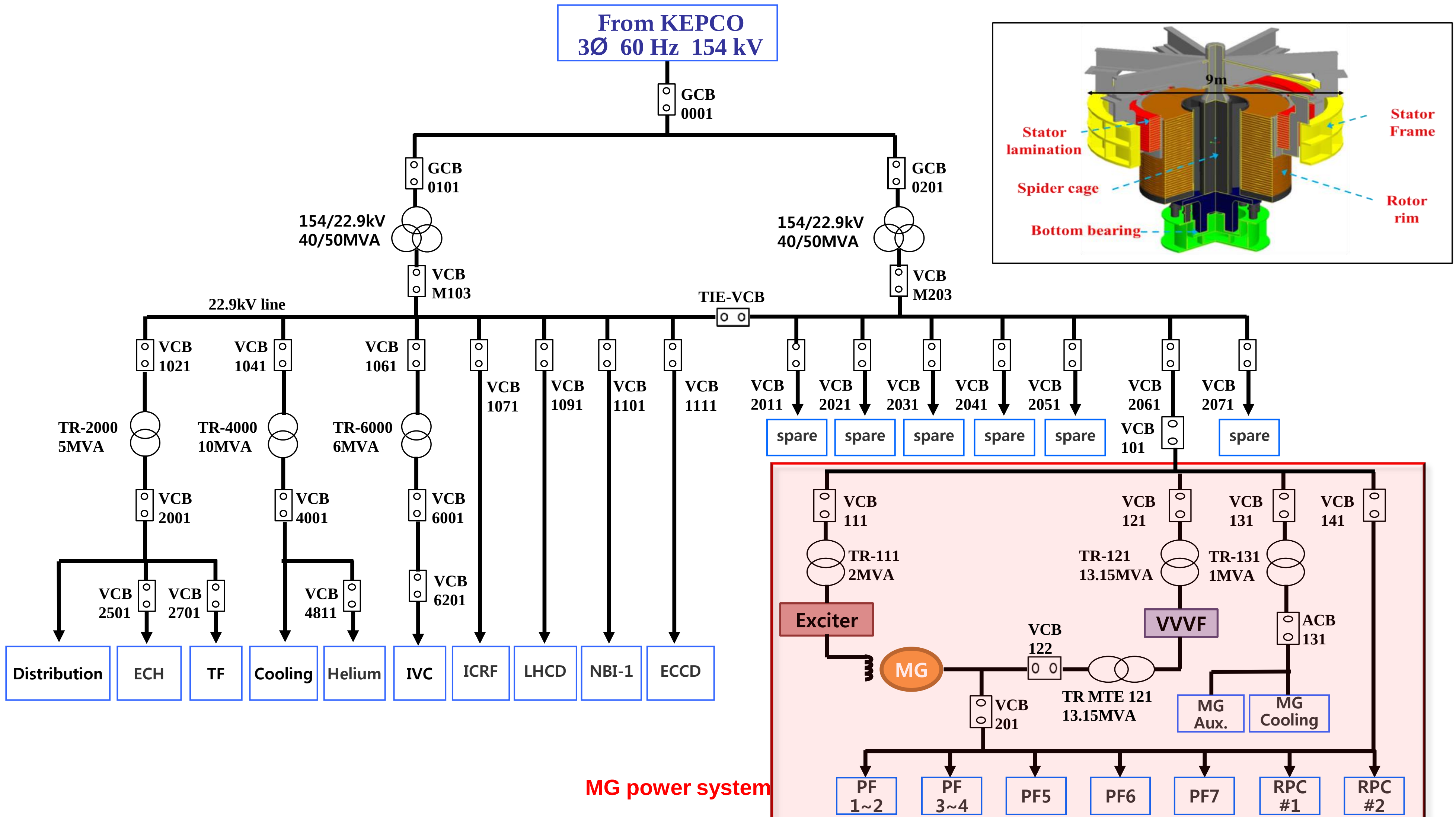
n=1 & 2 even

+	-	+	-
-	+	+	-
+	-	+	-

RWM Power Supply : 2.5kA Parallel 5kA 1set



Newly installed motor generator for larger flux operation in PF magnets



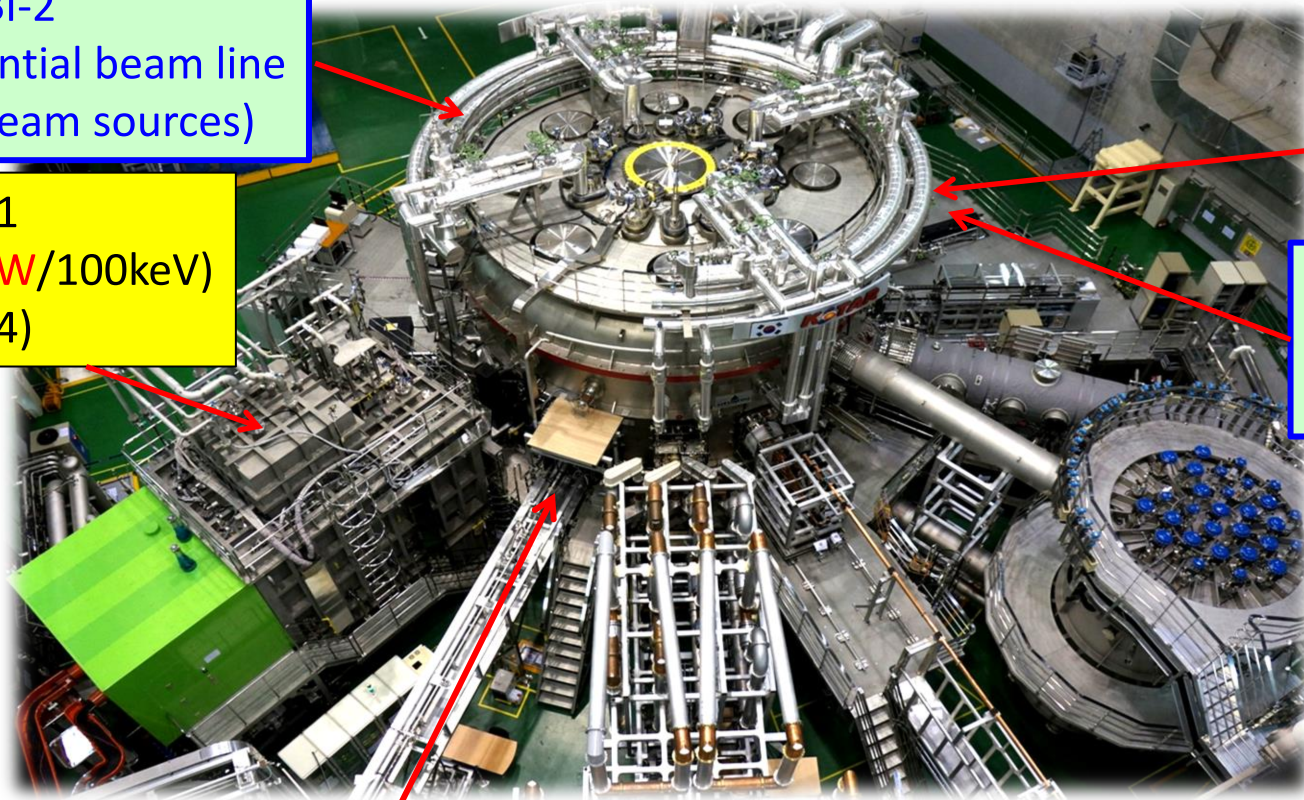
Upgrade in NBI heating & ECH systems

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

NBI-1
(3 beams, 6MW/100keV)
(2014)

170 GHz ECH
(1 MW/300 s)

105/140 GHz ECH
(2 MW/300 s)
(2016-2017)



105/140 GHz ECH
(1 MW/300 s)
(2015)

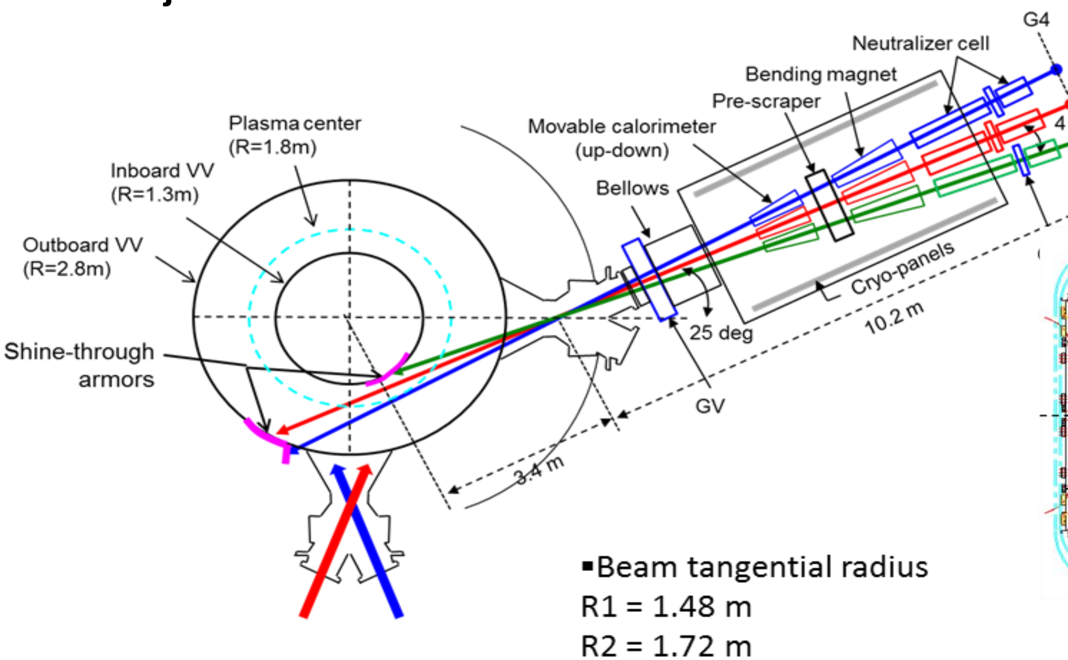
30 MHz ICRF
(2 MW/300 s)

5 GHz LHCD
(1 MW/300 s)

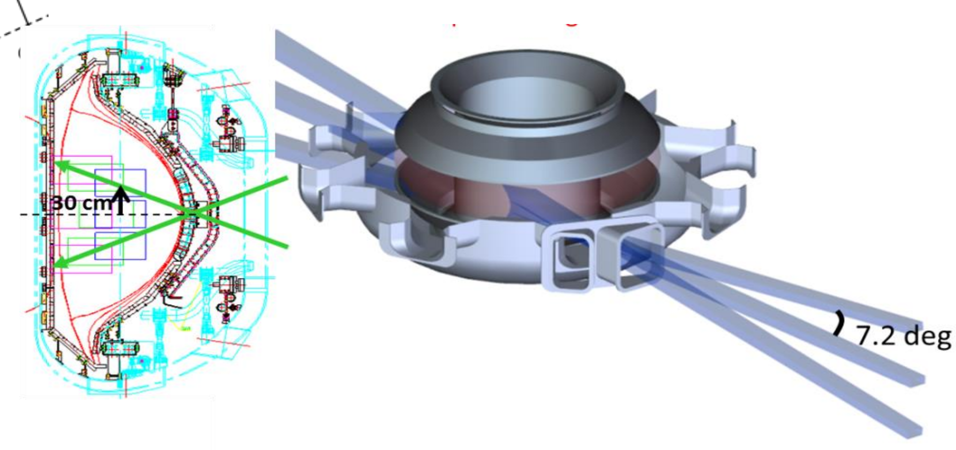
NBI-1 beam trajectory with 3 ion sources and pre-concept of NBI-2 system

- **Status and plan of NBI system**
  - So far, NBI-1 system with 2 ion sources operated reliably.
  - In 2014, NBI-1 system will be operated with 3 ion sources (~ 6 MW, 100 keV).
  - NBI-2 is under consideration with off-axis beam injection capability.
    with vertical offset of 30 ~ 40cm and considering co-and counter injection

Beam trajectories of NBI-1 with 3 ion sources



Pre-conceptual design of NBI-2 for the off-axis beam



Collaborative research activities

Domestic collaboration

- Operation scenario development (SNU)
- Impurity transport physics using tomography SXR and W-injection system (KAIST)
- Density fluctuation and temperature fluctuation using ECEI and MIR (POSTECH/UNIST/UCD)

International collaboration

- 110 GHz ECH for startup (GA)
- Steady state ECH launcher development (PPPL)
- ICRF heating and SS technology (PPPL)
- LHCD physics (CEA-IRFM & MIT)
- LH PAM launcher design and HXR camera (CEA-IRFM)
- 170GHz/1MW CW gyrotron & NBI steady state ion source development (JAEA)

- H-alpha Filter Scope (ORNL), ECEI & MIR (UCD)
- Thomson Scattering (JAEA & NIFS)
- ECE, p-CES, Bolometer (NIFS)
- Li-beam source and BES (Wigner RCP in Hungary)
- XICS (PPPL, ASIPP, HUST)
- Image MSE & CI (ANU)
- PCS (GA, PPPL)
- Others

Summary

- **KSTAR has been operated for 6 years since the first plasma in 2008.**
  - Reliable operation in H-mode enabled the ITER high priority research including ELM suppression in the range of 0.6 MA.
  - There are lots of contributions from domestic and international collaborators in design and developments of the key components and joint experiments.
- **KSTAR will be upgraded and operated to support the advanced research which are essential for ITER operation and DEMO design.**
  - Plasma operation in KSTAR will be extended longer pulse up to 50 s and higher current over 1 MA in Phase 2.
  - Some uniqueness in KSTAR could be a good potential in exploring new operation regime using low error field, low ripple, in-vessel control coils with 3 layer in poloidal, and advanced diagnostics.
  - Strengthened collaboration and contribution form the international partners are essential and will be appreciated for exploring the breakthrough for the next fusion reactors.

Thank you for your attention !