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Recent Fusion Activities of Korea toward DEMO

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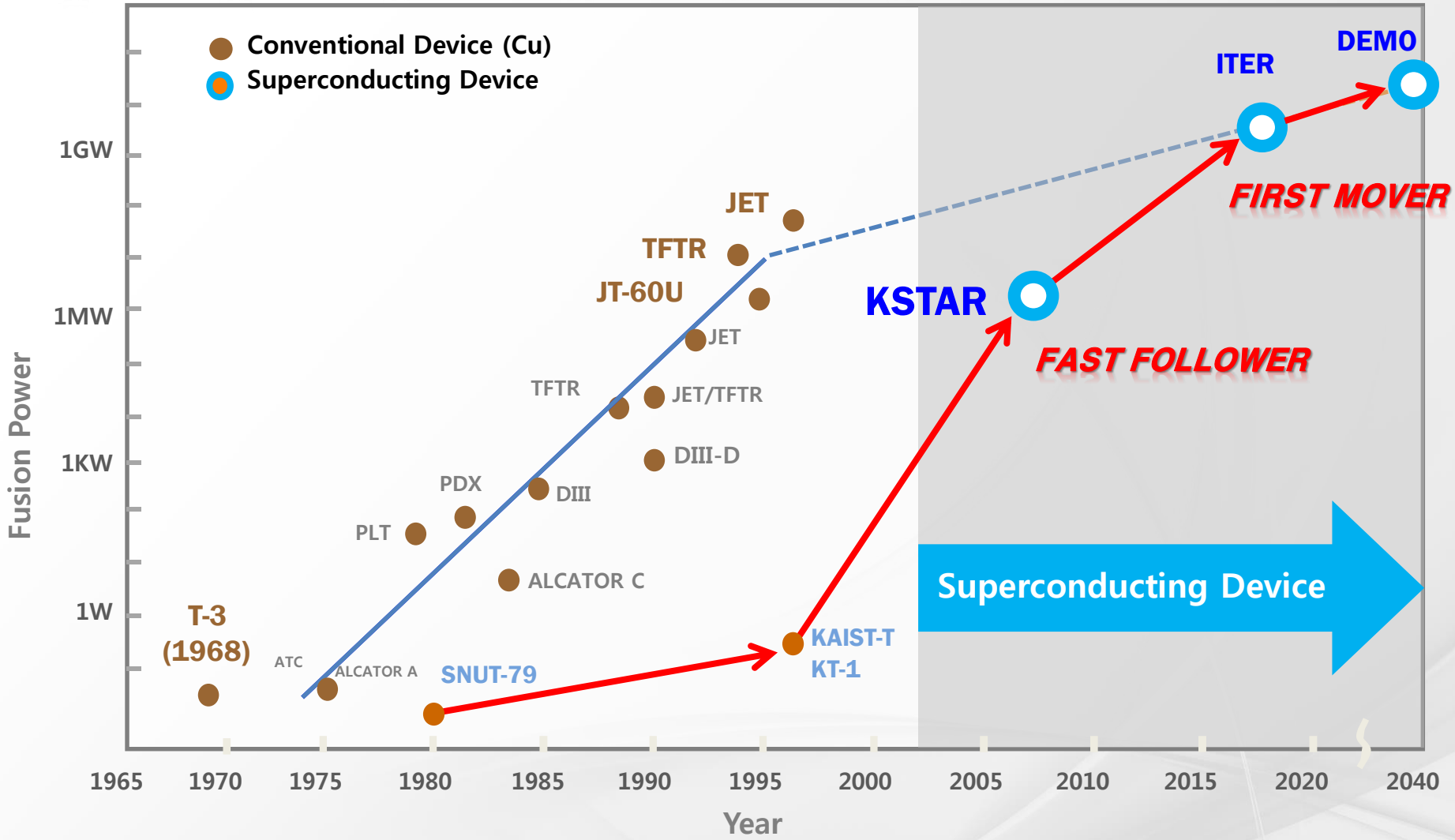
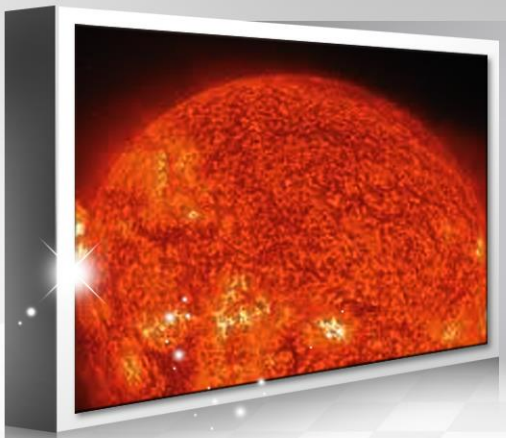
National Fusion Research Institute

국가핵융합연구소
National Fusion Research Institute

Mid-Entry Strategy : Korea, Year 1995

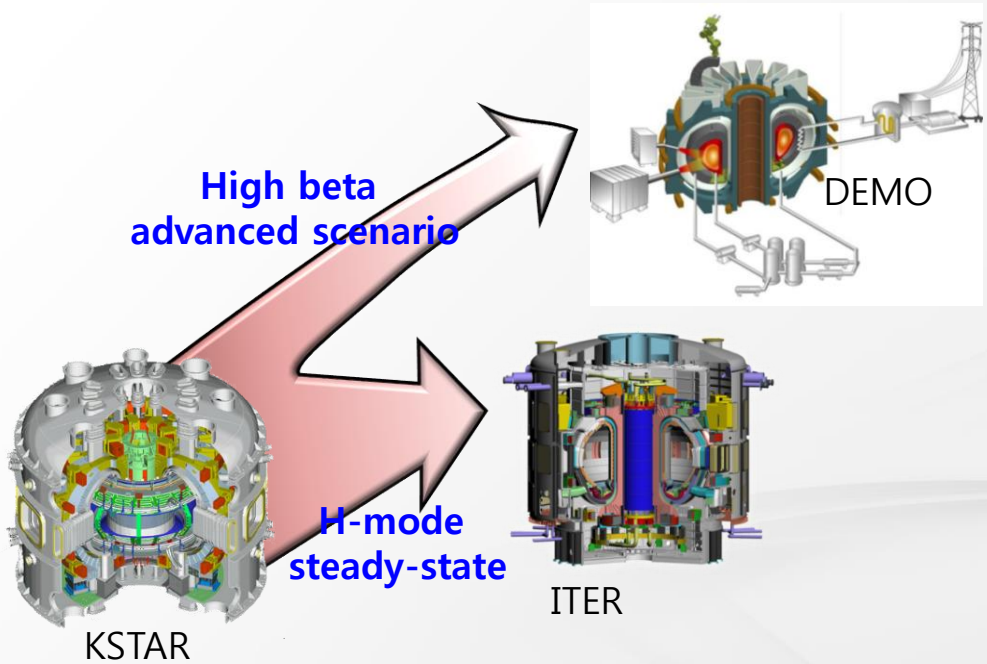




KSTAR and ITER Project

KSTAR Mission and Key Parameters

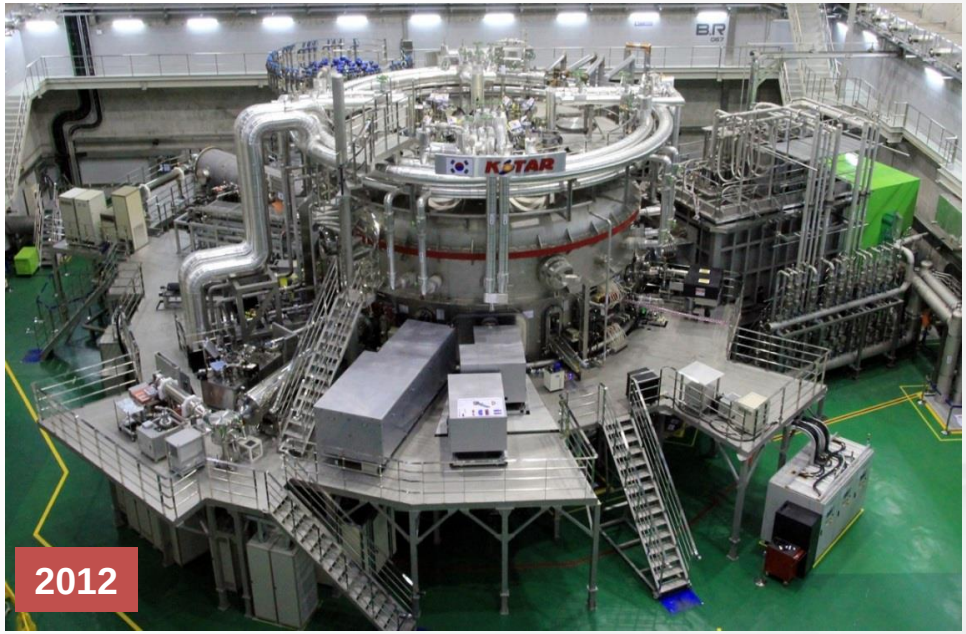
- **KSTAR missions**
  - To achieve the superconducting tokamak construction and operation experiences
  - To explore the physics and technologies of high performance steady-state operation that are essential for ITER and fusion reactor

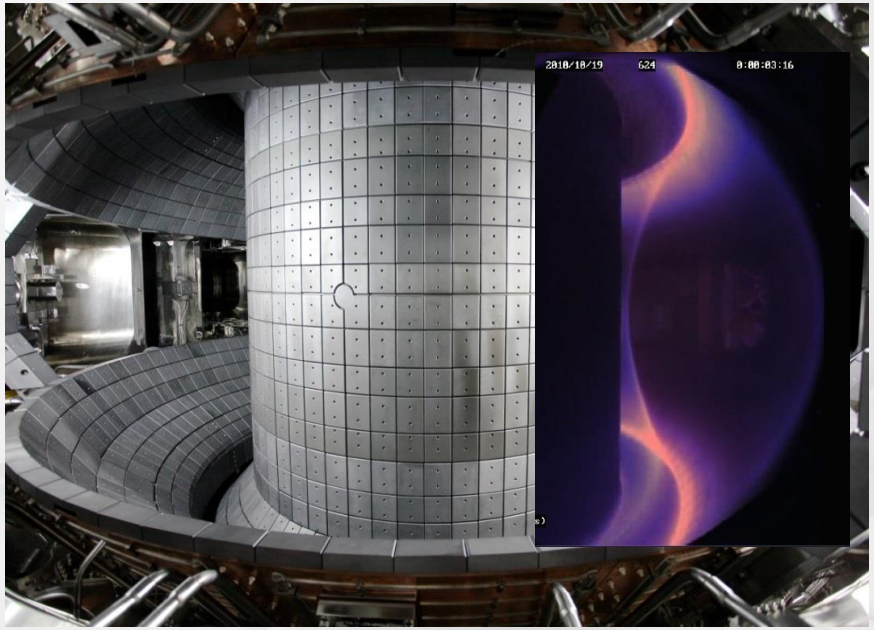


- **Achieved key parameters**

Parameters	Designed	Achieved (~2015)
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
H-mode duration	300 s	55 s
β_N	5.0	4.0
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD	~ 28 MW	~ 10 MW
PFC	C, CFC, W	C, (W)

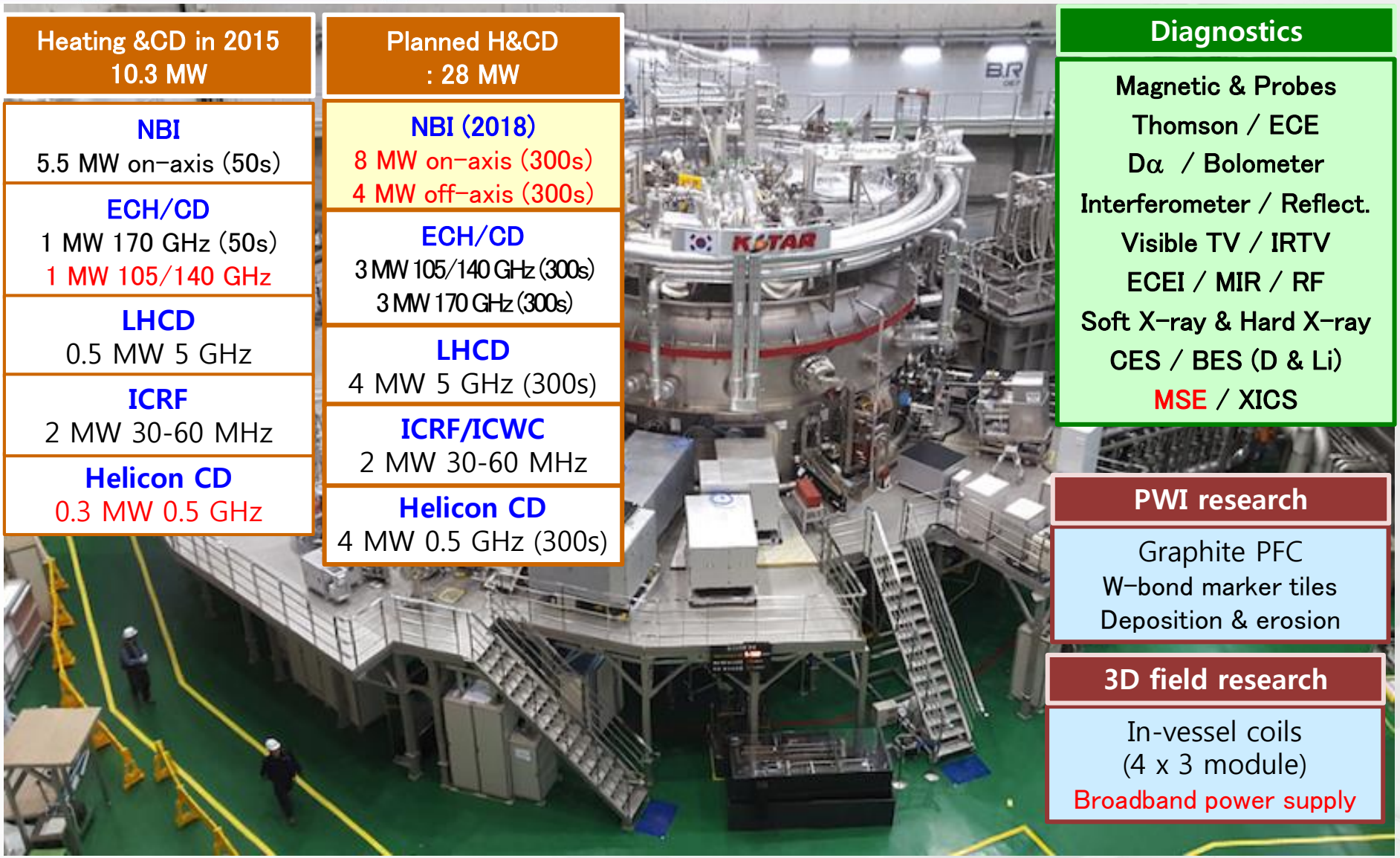
KSTAR Superconducting Tokamak





KSTAR Device and Key Components

Heating &CD in 2015 10.3 MW	Planned H&CD : 28 MW
NBI 5.5 MW on-axis (50s)	**NBI (2018)** 8 MW on-axis (300s) 4 MW off-axis (300s)
ECH/CD 1 MW 170 GHz (50s) 1 MW 105/140 GHz	**ECH/CD** 3 MW 105/140 GHz (300s) 3 MW 170 GHz (300s)
LHCD 0.5 MW 5 GHz	**LHCD** 4 MW 5 GHz (300s)
ICRF 2 MW 30-60 MHz	**ICRF/ICWC** 2 MW 30-60 MHz
Helicon CD 0.3 MW 0.5 GHz	**Helicon CD** 4 MW 0.5 GHz (300s)



Diagnostics

Magnetic & Probes
Thomson / ECE
Dα / Bolometer
Interferometer / Reflect.
Visible TV / IRTV
ECEI / MIR / RF
Soft X-ray & Hard X-ray
CES / BES (D & Li)
MSE / XICS

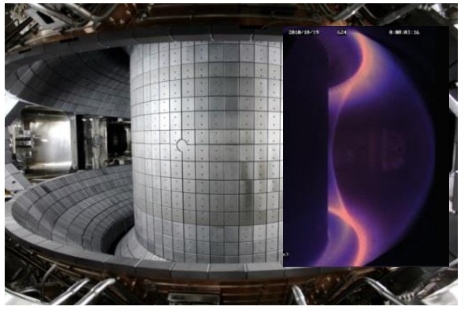
PWI research

Graphite PFC
W-bond marker tiles
Deposition & erosion

3D field research

In-vessel coils
(4 x 3 module)
Broadband power supply

Brief history of KSTAR operation



2015. **Longest H-mode** record(~ 55s at 0.6 MA)
Fully non-inductive SS operation (β_P ~3.5)
Stationary ELM-crash suppression (~10s)

2014. **Longest H-mode** record(~ 45s at 0.6 MA)
Large current H-mode (1 MA, 9s)
Low q95 operation (q95~2.0, Ohmic)
High normalized β operation (β_N ~4.0, transient)

2013. verify **Lowest Intrinsic Error field** *(~1 x 10^{-5})*

2011. **ELM-crash suppression** using *RMP*
(Unique in ELM-crash suppression using n=1 RMP)

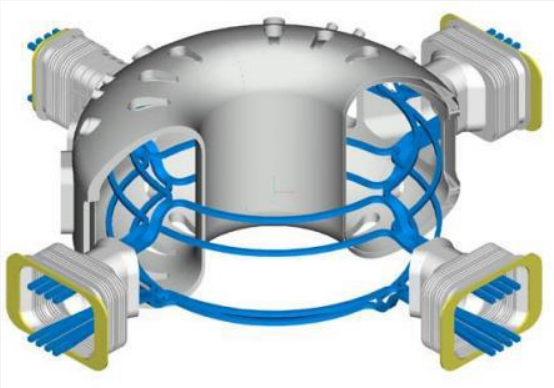
2010. **H-mode discharge** (*Ip ~0.6 MA, P_{NBI} ~1 MW)*
(First H-mode in superconducting tokamak)

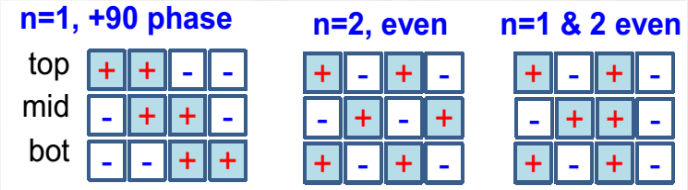
2008. **First plasma achievement** (*Ip >100 kA, B_T ~1.5 T)*
(Validation of ECH pre-ionization in 2nd harmonics)

ITER relevant Physics Program in KSTAR based on KSTAR Uniqueness

Uniqueness of KSTAR device

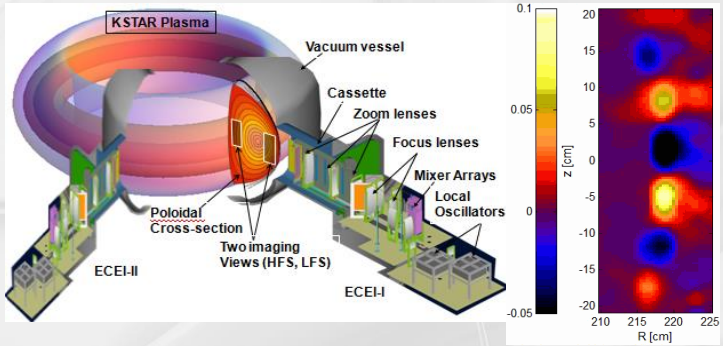
- Lowest error field and magnetic ripple
- ITER relevant IVCC (top, middle and bottom)
- The most advanced diagnostic systems
- High beta will be realized with 2nd NBI in 2018





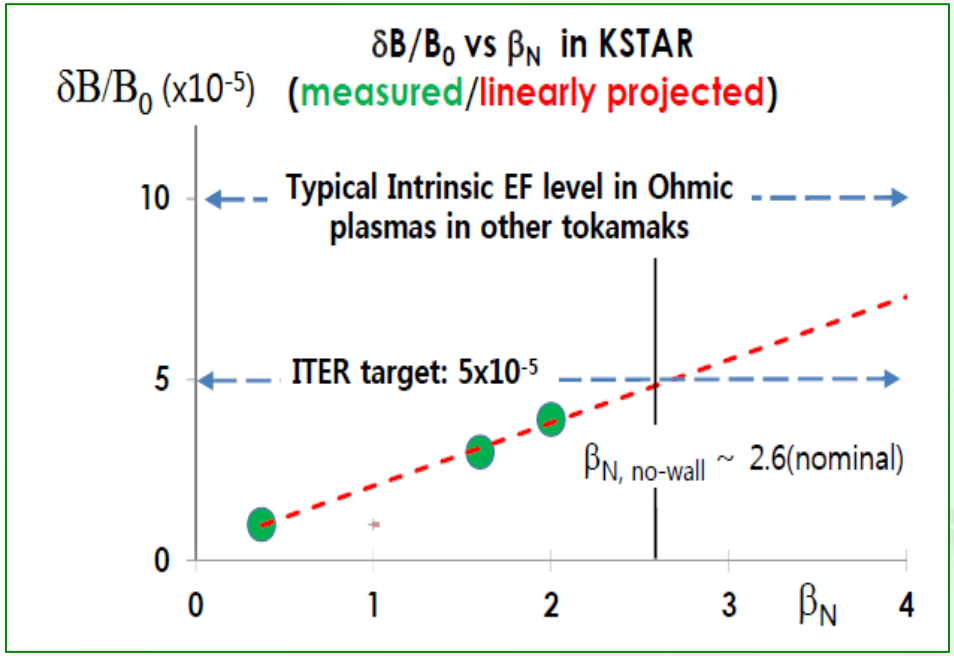
Current ITER relevant researches

- Long-pulse steady-state discharges : H-mode (> 55 s), high beta, hybrid ..
- ELM crash control with IVCC (full suppression for >10s)
- NTM control with ECH
- Disruption control

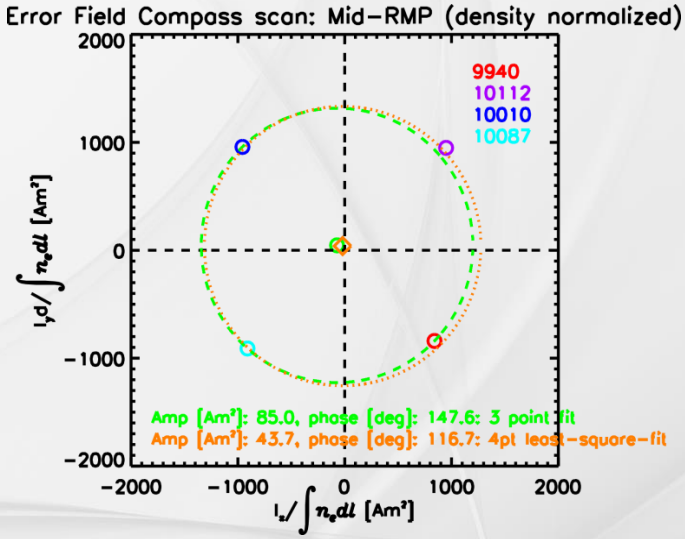


Excellent Testbed for Toroidal Symmetry of the Plasma in KSTAR

- **Lowest intrinsic error field ($dB/B_0 \sim 1x10^{-5}$) may allow higher stability limits**
- **Magnetic ripple is the lowest by design ($dB/B_0 \sim 5x10^{-4}$) : better trapped particle confinement and edge physics**



Measured intrinsic error field

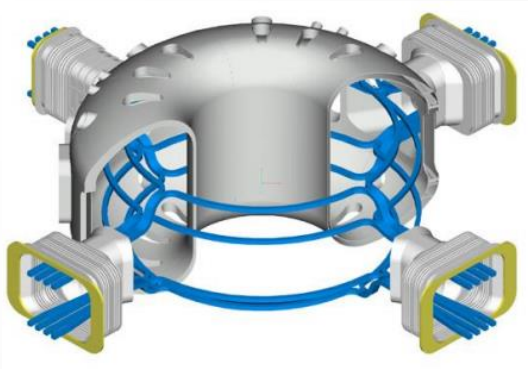


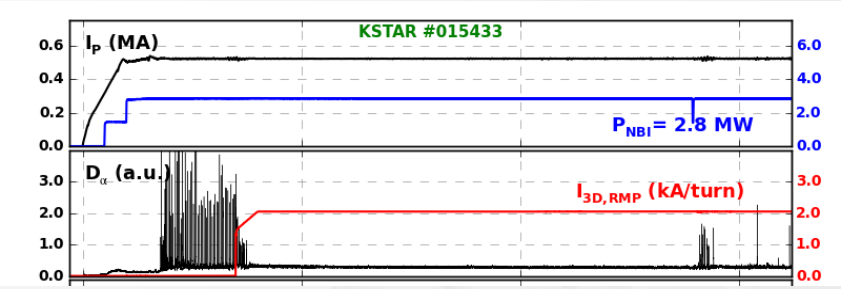
Standard compass scan of error field

(Y. In, NF, 2015)

Versatile Magnetic Perturbation Control System

- **Magnetic perturbation (n=1,2) with variety of phase and amplitude by IVCC**
- **In KSTAR, ELM-crash suppression has been demonstrated with MP induced by IVCC (n=1,2) with variety of phase and amplitude**
- **3D field research capability using in-vessel control coils & broadband power supplies**

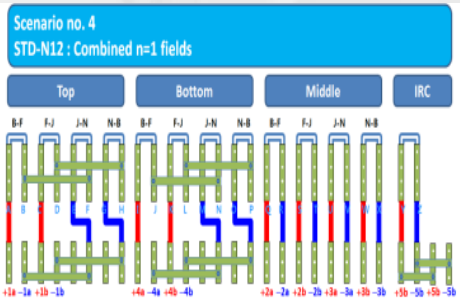




ELM-crash suppression using RMP

	n=1, +90 phase	n=2, even	n=1 & 2 even
top	+ + - -	+ - + -	+ - + -
mid	- + + -	- + - +	- + + -
bot	- - + +	+ - + -	+ - + -

Various mode and phase configuration

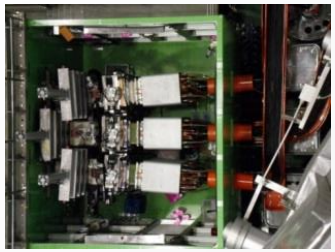


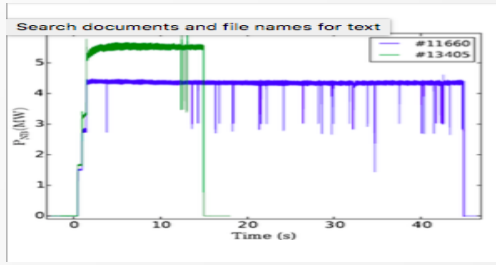
New broadband power supply and patch panel for In-vessel control coils

Long-pulse Reliable Operation of NBI System

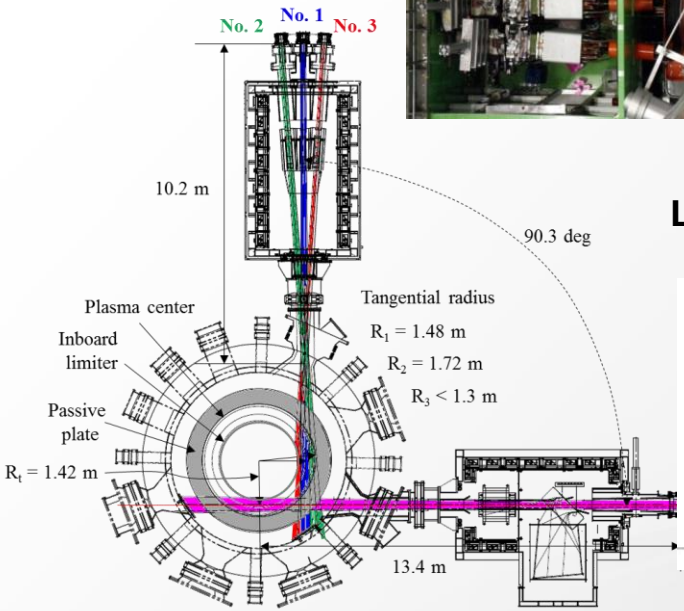
- **Reliable operation of the 1st NBI in long-pulse : 5.5 MW (12s), 4.2 MW (55s)**
- **Construction of the 2nd NBI for high beta (6 MW off-axis, 2 MW on-axis)**
- **Long-pulse operation of ECH/CD systems : 170 GHz, 1 MW (50s)**

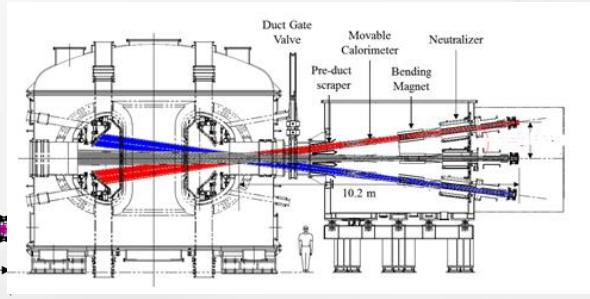
NBI-1





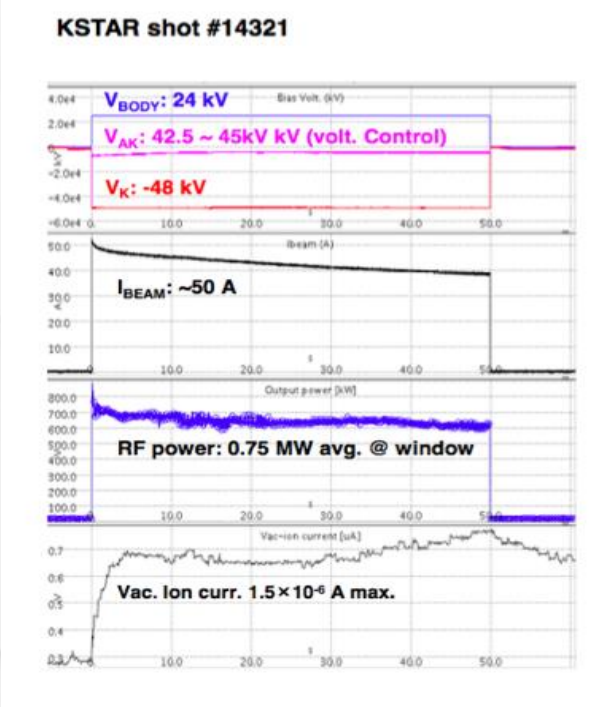
Long-pulse operation of NBI-1





NBI-2

Design of off-axis NBI-2

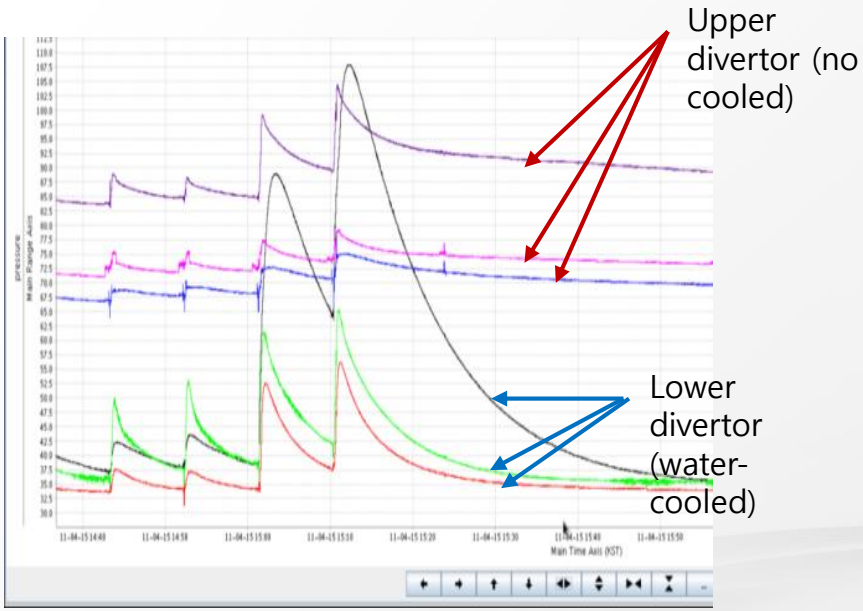


Long-pulse operation of 170 GHz ECCD

System upgrade for 2015 & 2016 campaigns

In-vessel Components

- **Demonstration of active water cooling for PFC & divertor ('15)**
- ***Preparing Pellet injection and In-vessel cryopump ('16)***



Comparison of PFC temperature between no-cooled and water cooled divertors

Magnetics and electricity

- **Broadband IVCC Power Supplies**
- **Normal operation of Motor-generator**

Heating & CD

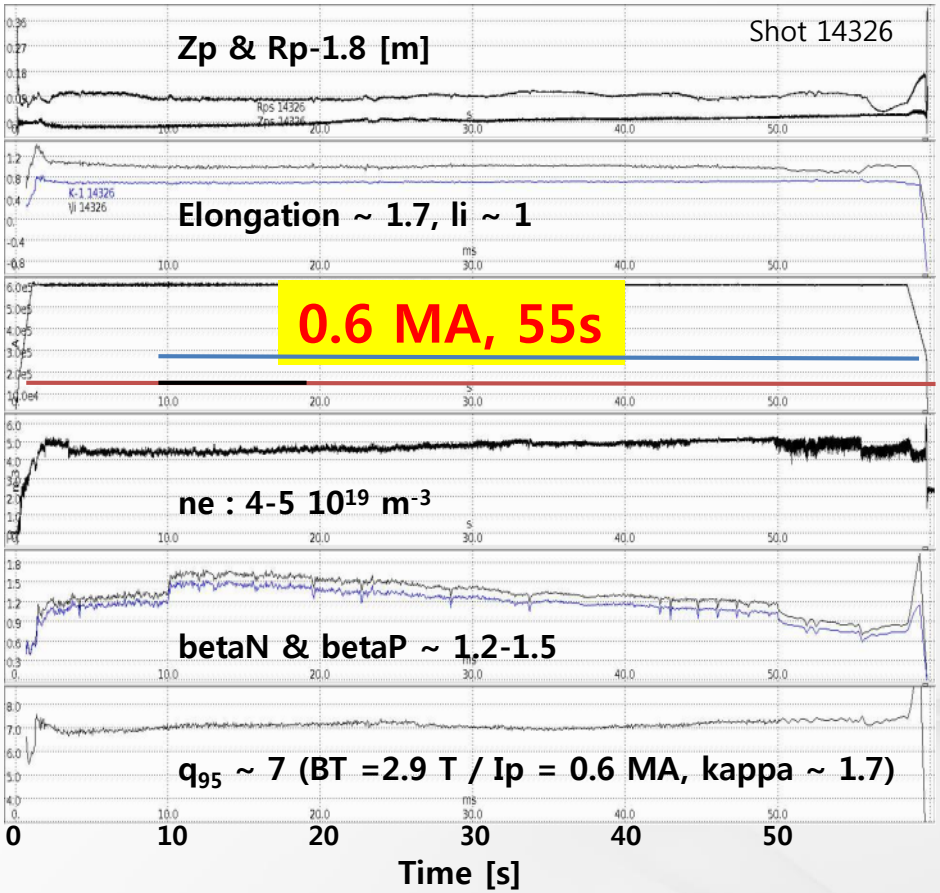
- **Prototype Helicon Current Drive system operation (0.5 GHz)**
- ***Installation 1 MW, 105/140 GHz ECH/CD system ('16)***
- ***Approval of NBI-2 (6 MW, on-and off-axis) construction ('18)***

Diagnostics

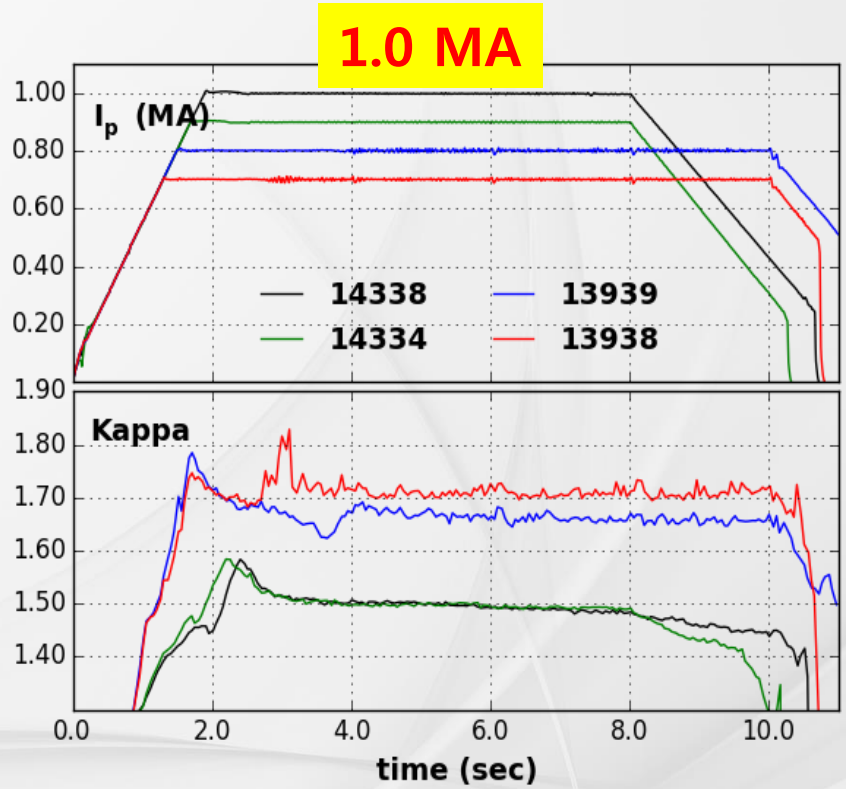
- **Laser Replacement of Thomson Scattering**
- **Commissioning of MSE diagnostics for current profile measurement**

Recent ITER relevant Research toward Long-pulse H-mode Discharges

- **Long-pulse H-mode discharge in 2015 up to 55s (0.6 MA), final goal : 300 s**
  - Ip = 0.6 MA, B_T=2.9T, t_{Hmode}~56s,
  - P_{NBI} ~ 3.0 MW, P_{ECH} ~ 0.6 MW,

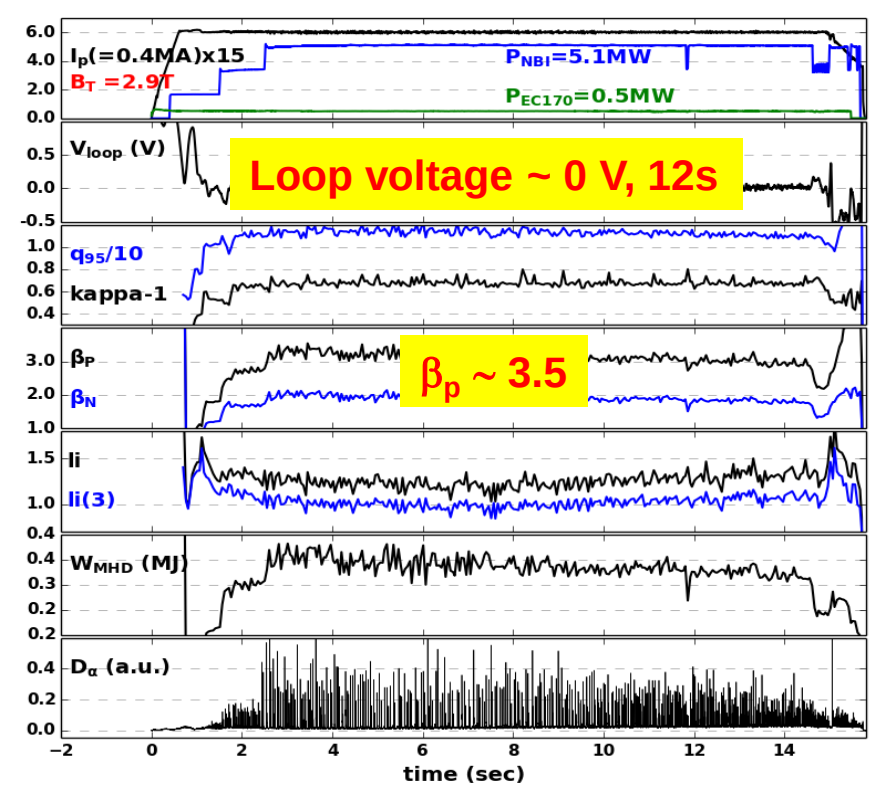


- **Large plasma current H-mode discharge in 2015 up to 1 MA, final goal : 2 MA**

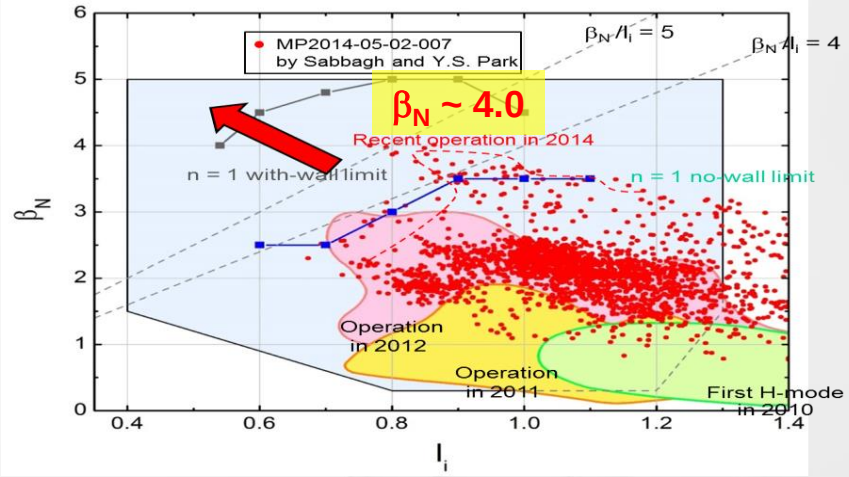


Exploring the advanced high performance scenarios development

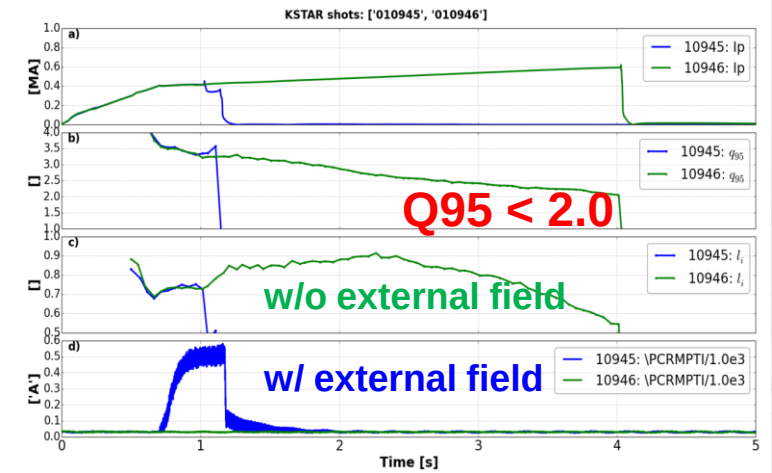
- **Fully non-inductive, steady-state H-mode discharge has been achieved up to 12s at 0.4 MA**
  - Ip = 0.4 MA, B_T=2.9T
  - P_{NBI} ~ 5.1 MW, P_{ECH} ~ 0.5 MW
  - β_p ~ 3.5 (β_N ~ 2.0), H89 ~ 2.2



- **High beta (β_N ~ 4.0) operation exceeding ideal n=1 no wall limit**



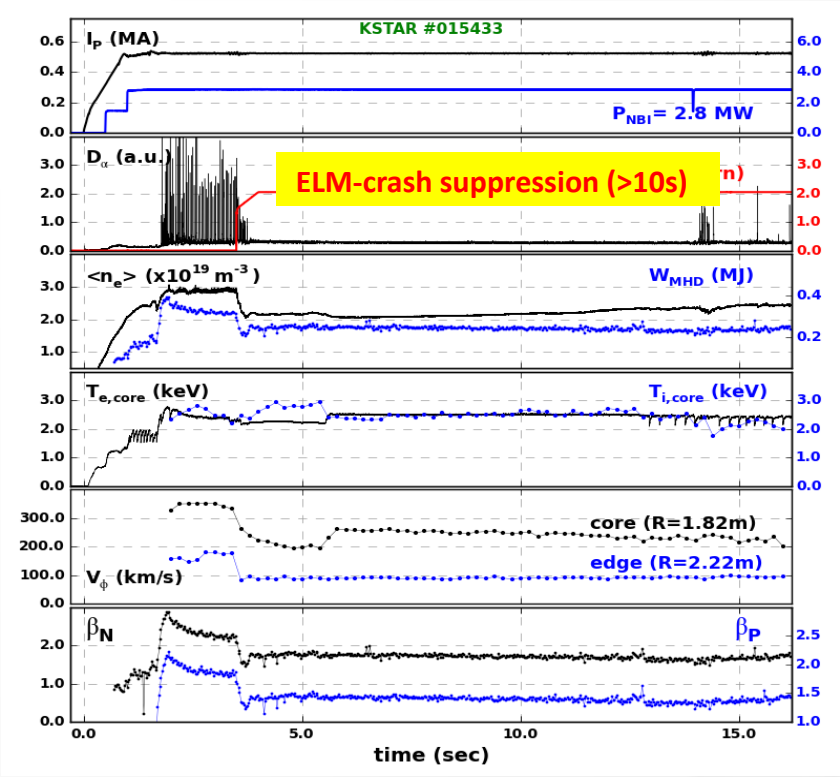
- **Extremely low q95 (q95 ~ 2.0) operation verifying extremely low error field**



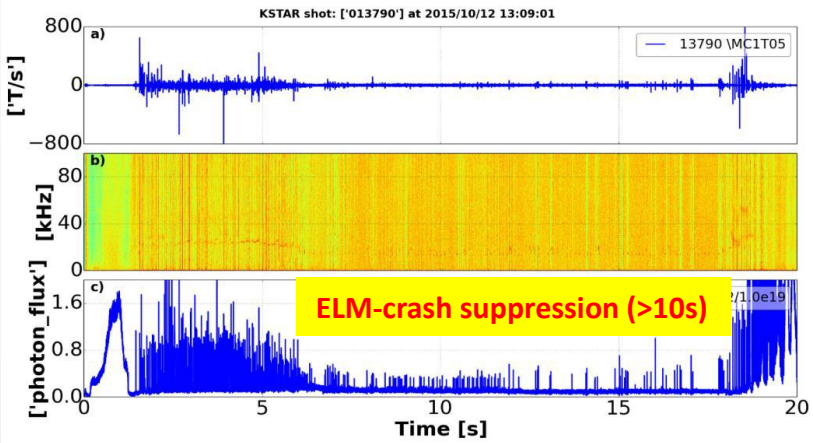
Edge Localized Mode (ELM) -crash suppression using low-n error field uniquely in KSTAR

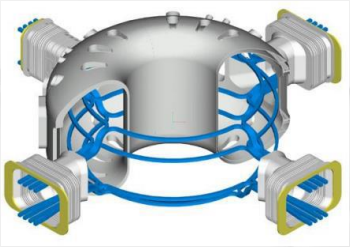
- **KSTAR is unique device showing the ELM-crash suppression at various combination of RMP fields at low n configuration (n=1 and n=2) .**
  - Successful ELM suppression at low n could be related to low error field.
  - Check the possibility of the ex-vessel control as for ELM control in ITER and DEMO

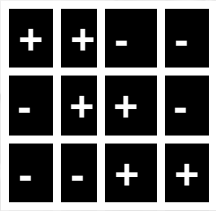
Stationary ELM-crash suppression at n=1 (> 10s)



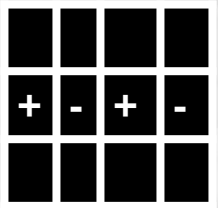
Marginal ELM-crash suppression at n=2 (> 10s) in 2015





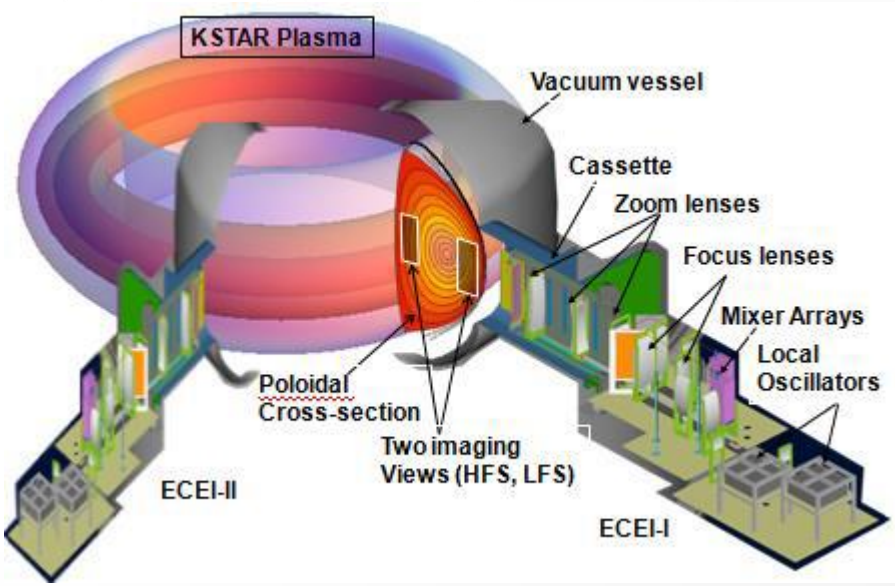


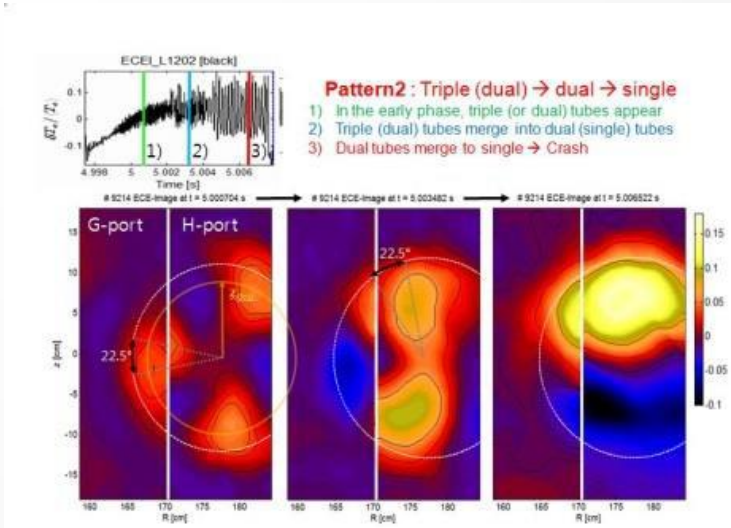
n=1 (+90 phasing)



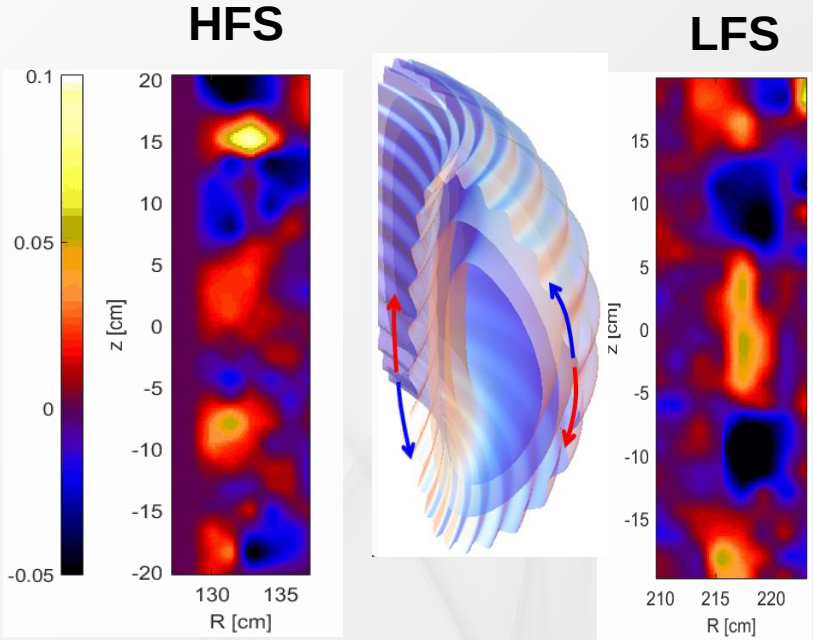
n=2 (mid-frame)

Advanced 2D/3D Imaging Diagnostics





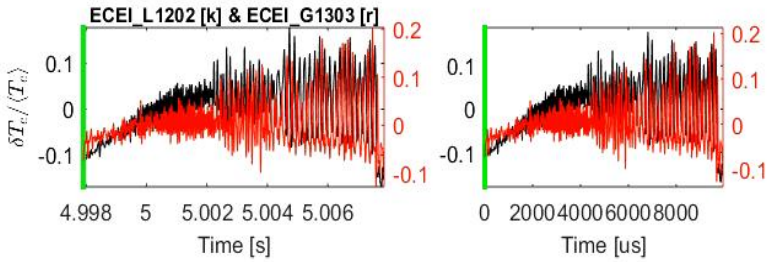
ELM-ing Phase

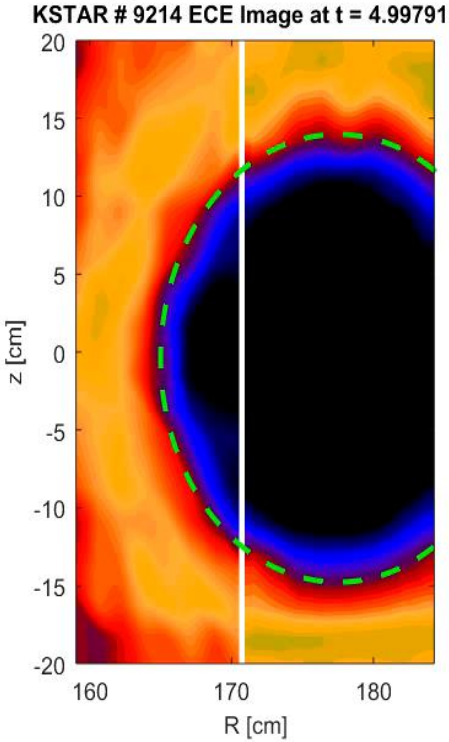


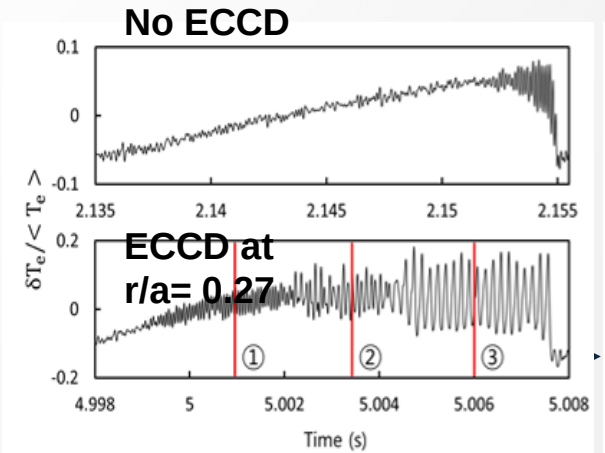
- **Most powerful tools to interpret the dynamics in fusion plasma**
- **ECEI, MIR, BES, MSE diagnostics are unique diagnostics in KSTAR**

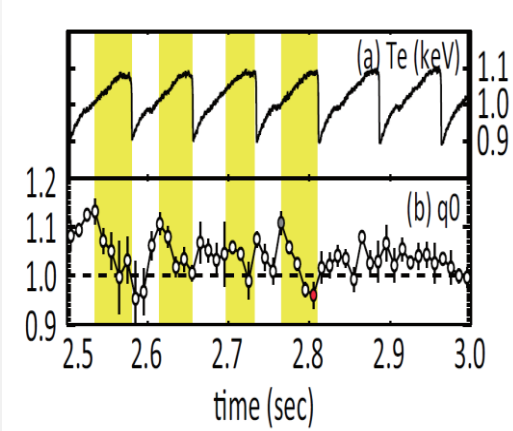
Validation q_0 in Sawtooth Instability

J. Ko (MSE, 2015)





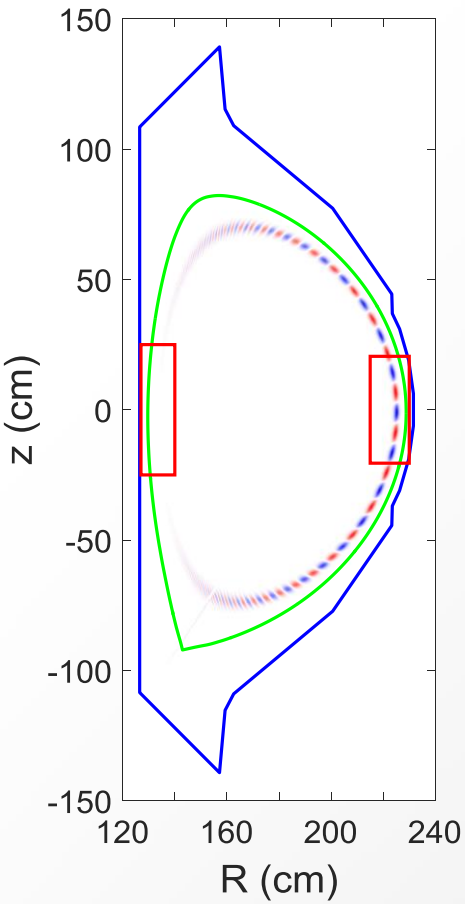




- Sawtooth with no current blip only has 1/1 mode just before the crash
- Initial excitation of the 3/3 mode with current blip at r/a=0.27 suggests q_0 >1.0 after the crash
- Transformation of the 3/3 mode into 2/2 mode suggests the current blip moves toward the center
- Transformation of the 2/2 mode into the 1/1 kink mode suggests q_0 drops below ~1.0 before the crash
- Results are consistent with those from the M3Dc1 code

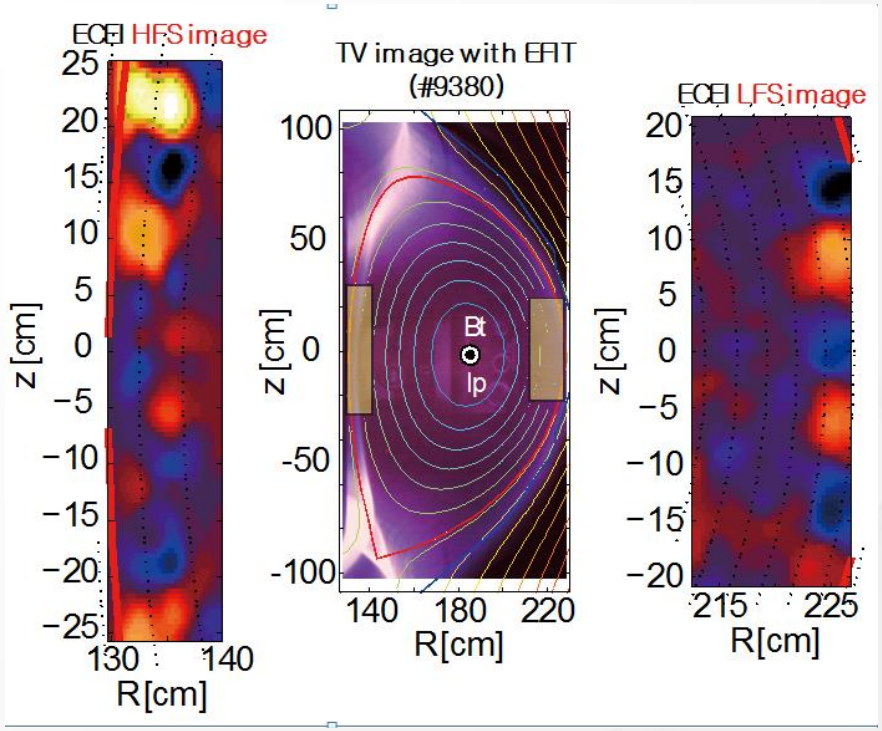
Global Simulation of the ELM (MHD vs. Kinetic)

n = 12 simulation (BOUT++) - MHD



M. Kim, and Xu

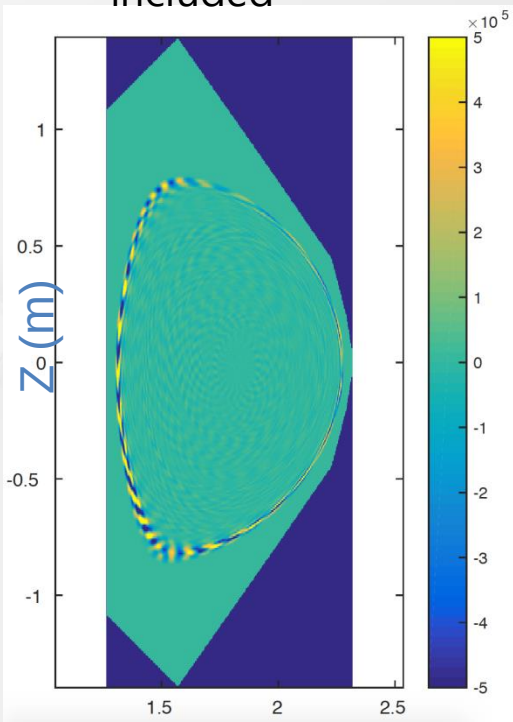
- KSTAR #9380



Controversies in 1) Mode intensity 2) Mode number 3) Rotation direction cast a doubt in PB modeling

Kinetic (XGC1) results are closer to the measurement

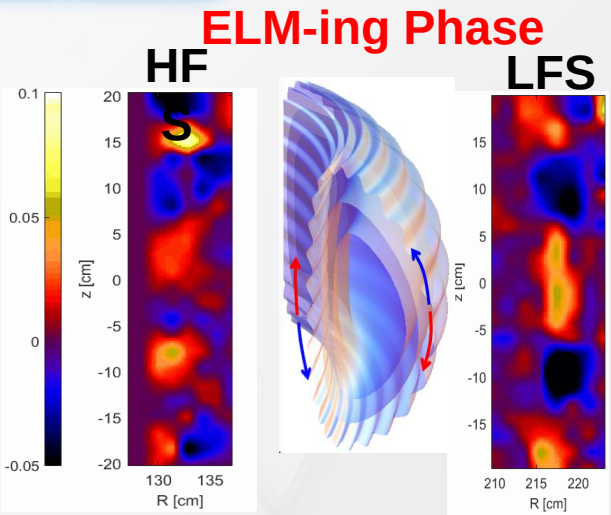
n = 12 simulation (XGC1)- kinetic Collision is not included

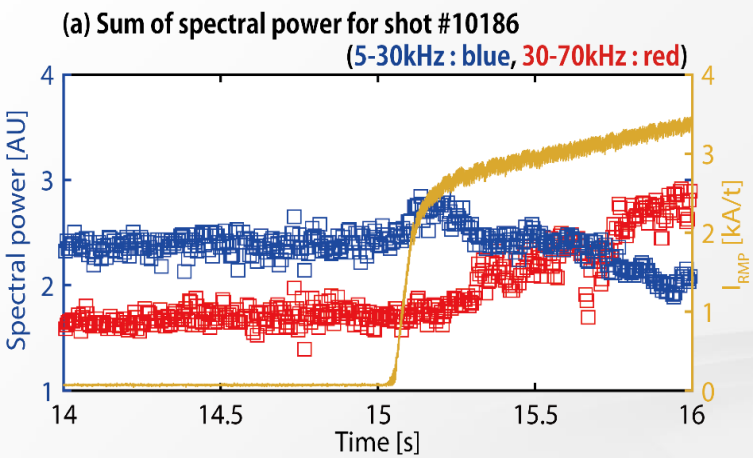


C.S. Chang, S. Ku, M. Kim

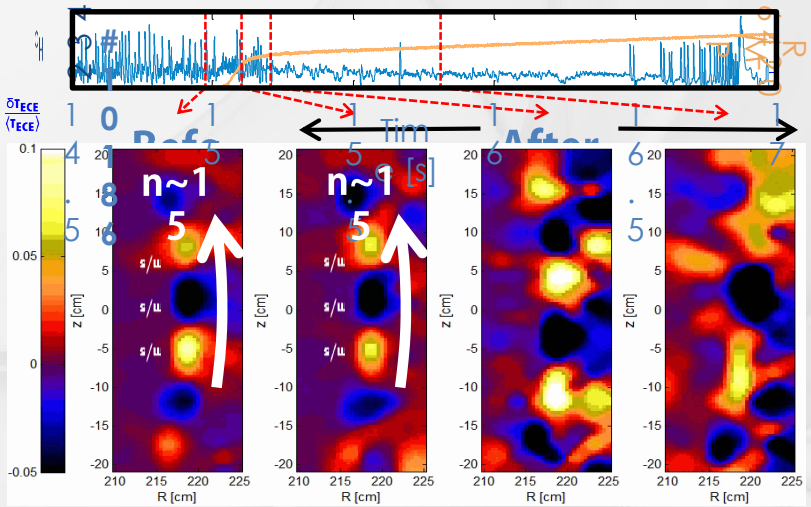
Challenge for Unresolved Physics Issues

- **Dynamics of ELMs and ELM crash suppression with RMP**
  - **Measurements are beyond H-alpha and magnetics**
  - **Interaction between turbulence induced by RMP and ELMs**
  - **Global ELM (HFS and LFS) points PB model is not sufficient**





PRL 2016 (J.H. Lee, UNIST)

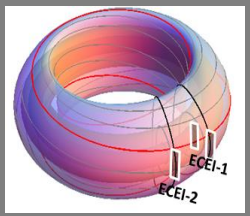


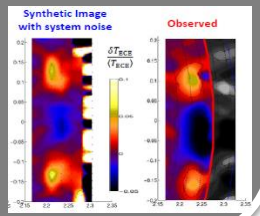
Fusion R&D collaboration network in Korea

Three core research centers and universities supporting the basic fusion research and HR development

Fusion Plasma Stability and confinement Research Center

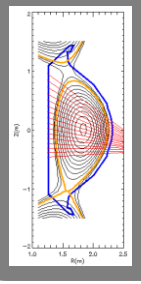
UNIST /POSTECH/ PU

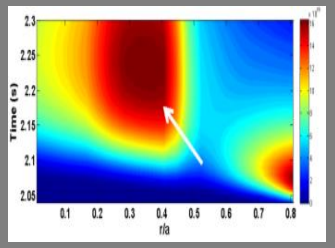




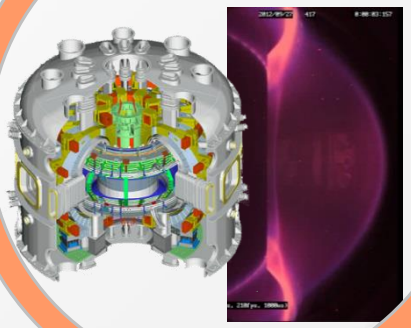
Impurity and Edge Research Center

KAIST /HYU/ SNU



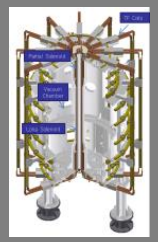


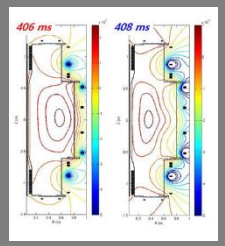
KSTAR



Center for Advanced Tokamak Study

SNU /KAERI





Universities & Research Institutes

Hanyang U.	Yonsei U.
Daegu U.	Dankook U.
Ajou U.	Chonbuk N.U.
Jeju N.U.	Kyungpook N.U.
KAERI	Chungnam N.U.
UST	

Worldwide collaborators in the KSTAR research and experiments

International Collaborators

- EUROfusion
- IPP
- CCFE
- CEA Cadarache
- ENEA
- Wigner
- TU/e
- York U
- Politechnico du Torino
- ITER

- Kurchatov Inst
- Gycom
- PELIN

KSTAR

- ASIPP
- SWIP
- HUST

- JAEA
- NIFS
- Nagoya U.
- Kyusu U.

- IPR

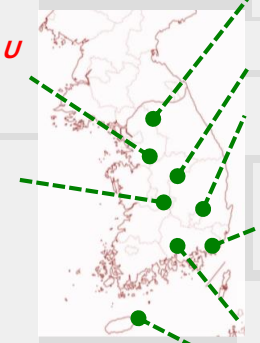
- ANU

- DOE
- PPPL
- Oak Ridge Nat'l Lab.
- General Atomics
- Columbia U.
- MIT
- UCSD
- UC Davis
- LBNL
- Princeton U.
- Wisconsin U
- D-TACQ

Korea Domestic Collaborators

MSIP
SNU
Hanyang U
Yonsei U
Ajou U

NST
NRF
NFRI
KODA
KAERI
KAIST
CNU
UST



KAPRA

Dankook U

KNU
Daegu U

POSTECH
UNIST
Pusan U

Chonbuk U
GIST

Jeju U

Current and Future KSTAR Research Plan

■ Main Research Program toward the high beta steady-state operation

- Establish the limits of the confinement and stability of tokamak plasmas through 3D field research (KSTAR uniqueness)
- Validation of MHD physics using 2D/3D imaging diagnostics to establish predictable capability of theoretical models (M3Dc1, BOUT++, JOREK, etc.)
- Validation of turbulence physics using 2D/3D imaging diagnostics to establish the hierarchy in transport physics using gyro-fluid & gyro-kinetic simulation
- **For advanced steady-state operation, upgrade of the heating & CD (off-axis NBI heating & ECH, LHCD, Helicon CD), diagnostics and control system, and density control (active cooling divertor, pellet, in-vessel cryopump)**

■ Special Research Program

- Tokamak simulator : based on validated simulation codes using KSTAR as testbed
- Divertor research program : advanced plasma image diagnostics for divertor physics
- Advanced current drive research program (high field side LH, Helicon, and others)

■ Easy Access of Experimental Data

- Direct access and faster network environment (Firewall Problem, Hadoop System)
- Standardization of experimental data (MDS+ → HDF5)

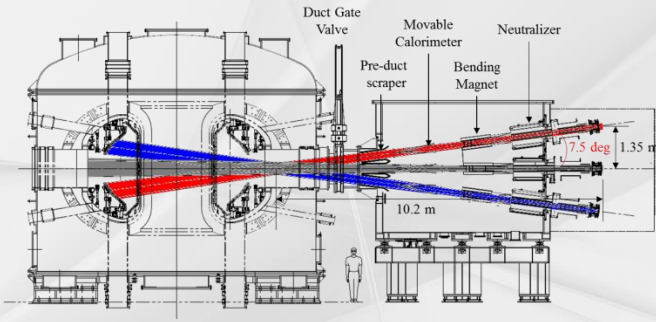
Long-term operation and upgrade plan of KSTAR

Phase I (FY08 ~ FY12)	Phase II (FY13 ~ FY17)	Phase III (FY18 ~ FY22)	Phase IV (FY23 ~)
Superconducting Tokamak operation	**Long-pulse H-mode and ITER pilot**	**Advanced scenario related to DEMO**	**Advanced Technology for K-DEMO**
• 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)	• Advanced operation scenario demonstrate • Integrated control of profile and stability • Research application to K-DEMO	• Stabilization and optimization of advanced scenario • Technologies at extreme environments

- **Targeted operation parameters**
  - I_p ~ 2 MA, $t_{H\text{-}mode}$ ~ 300 s, β_N : ~ 5, q95 : 2 ~ 6

- **System upgrade for advanced steady-state operation**
  - NBI ~ 12 MW (Co- : 8 MW, Counter- : 4 MW)
  - ECH/CD ~ 6 MW, LHCD ~ 4 MW, Helicon CD ~ 4 MW
  - Active cooling Divertor/PFC
  - Advanced divertor configuration and material R&D
  - Density control : pellet & cryopump
  - 3D field research using IVCC

Preliminary design of off-axis NBI



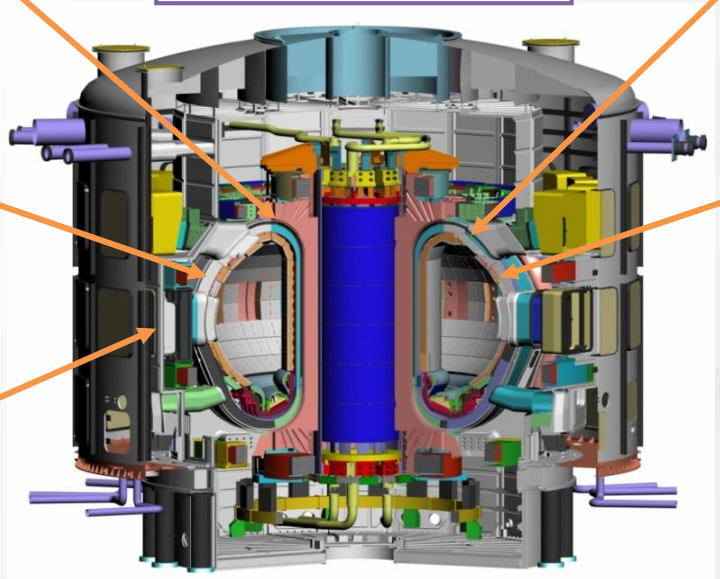
ITER Project : In-kind Contribution of Korea

1. TF Conductor (Completed)
- Total Value (kIUA) : 215.01
- KO Allocation : 20.2%
- KO Contribution (kIUA) : 43.39

2. Vacuum Vessel Main Body
- Total Value(kIUA) : 123.04
- KO Allocation : 21.3%
- KO Contribution (kIUA) : 26.20

3. Vacuum Vessel Port
- Total Value(kIUA) : 76.96
- KO Allocation : 72.7%
- KO Contribution (kIUA) : 55.98

11. Test Blanket Module*
- KO Contribution :
- HCCR TBS (TBM System)
- kIUA Value : N/A



4. Thermal Shield
- Total Value(kIUA) : 26.88
- KO Allocation : 100%
- KO Contribution(kIUA) : 26.88

5. Blanket Shield Block
- Total Value(kIUA) : 56.34
- KO Allocation : 49.8%
- KO Contribution(kIUA): 28.07

6. Assembly Tooling
- Total Value(kIUA) : 23.01
- KO Allocation : 100%
- KO Contribution(kIUA): 23.01

7. Tritium SDS
- Total Value(kIUA) : 15.21
- KO Allocation : 82.1%
- KO Contribution(kIUA) : 12.48

8. AC/DC Converters
- Total Value(kIUA) : 123.58
- KO Allocation : 37.3%
- KO Contribution(kIUA): 46.06

9. IVC Bus bars
- Total Value(kIUA) : 3.98
- KO Allocation : 100%
- KO Contribution(kIUA) : 3.98

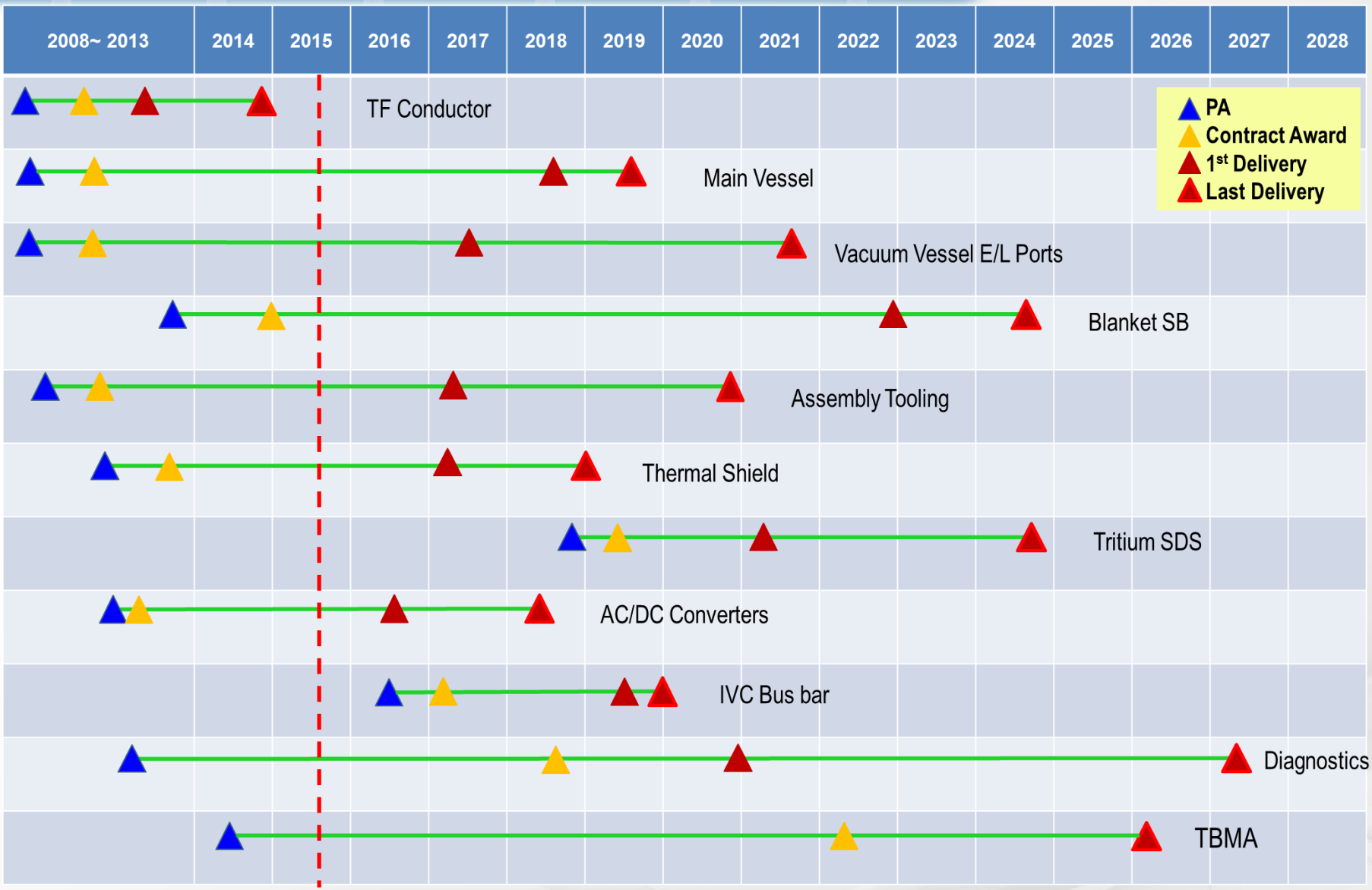
10. Diagnostics
- Total Value(kIUA) : 142.09
- KO Allocation : 3.2%
- KO Contribution (kIUA) : 4.49

* TBMA (TBM Agreement) was signed in 2014

Total Value : 270.54 kIUA

Leading Items | Tokamak Main | Ancillary

Procurement Schedule of the KODA

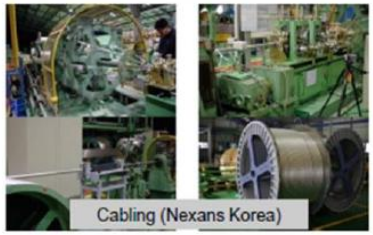


ITER Procurement Activities of Korea

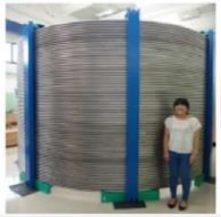
◆ **KO TF conductors (20.18 %) consist of 19 rDPs (760 m) and 8 sDPs (415 m).**

- Production of strands and cablings was completed in 2013 and in May 2014, respectively.
- All 27 TF conductors were delivered to JADA by the end of November 2014, on schedule.
  → This is the first successful procurement item from KO.

Nb_3Sn Strand (KAT)



Cabling (Nexans Korea)



Conductor (ICAS)

Shipping of Conductor to Japan

◆ **The thermal shields will be provided by Korea.**

- Preparation for fabrication of Vacuum Vessel Thermal Shield is on going;
  - Manufacturing drawing
  - Manufacturing procedure
- After manufacturing of VVTS 10-degree prototype.

Water-jet cutting

2D bending

3D forming

In-board welding

Out-board welding

Cooling tube fit-up and welding

Machining of in-board and out-board

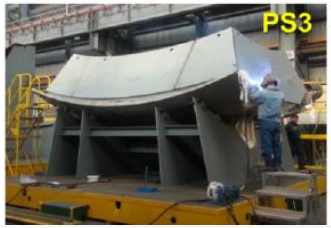
3D scanning

VVTS 10-degree prototype & its test

◆ **Manufacturing of vacuum vessel sector 6 is on-going at HHI of Korea.**

◄ Welding of inter-modular & centering keys of inner shell of upper segment (PS2)

◄ Forming of inner shell & machining of divertor rail, port stub corner, 4-pipe & penetration of lower segment (PS4)



◄ Start welding after inner and outer jigs for inner shell of equatorial segment (PS3)

◄ Inner and outer jigs for welding after forming of inner shell of inboard segment (PS1)

◆ **Manufacturing sequence of upper segment (PS2) of VV sector 6**

Fit-up for welding of 8 keys →

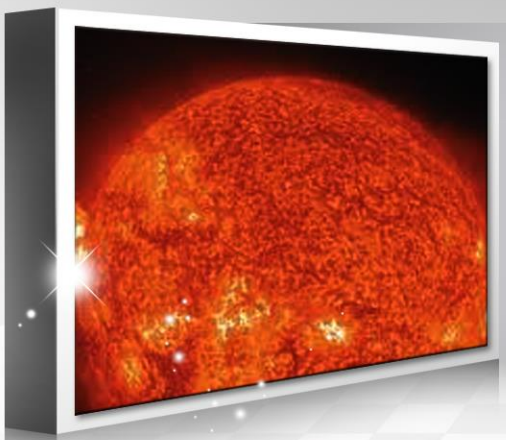
In & outside welding →

VT & PT →

→ RT →

Fit-up for welding of 6 keys →

Completion of inside welding



Fusion Energy Development Roadmap in Korea

Fusion Energy Development Promotion Law

- To establish **a long-term and sustainable legal** framework for fusion energy development phases.
- To **promote industries and institutes** participating fusion energy development by support and benefit.
- The **first country in the world** that prepared a legal foundation in fusion energy development.

History of the FEDPL

- 1995. 12 : National Fusion R&D Master Plan
- 2005. 12 : National Fusion Energy Development Plan

- 2007. 3 : **Fusion Energy Development Promotion Law**
- 2007. 4 : **Ratification of ITER Implementation Agreement**
- 2007. 8 : Framework Plan of Fusion Energy Development (First 5-Year National Plan)
- 2012. 1 : The **2nd 5-year National Plan has started.**

Vision and Goal of Fusion Energy Development Policy

Vision

Secure sustainable new energy source by technological development and the commercialization of fusion energy

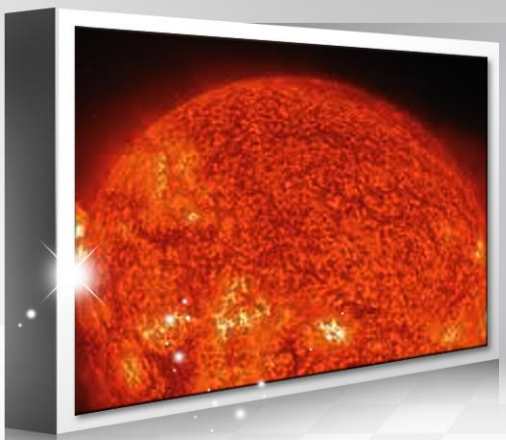
Phase	Phase 1 ('07~'11)	Phase 2 ('12~'21)	Phase 3 ('22~'36)
Policy Goal	Establishment of a foundation for fusion energy development	Development of Core Technology for DEMO	Construction of DEMO by acquiring construction capability of fusion power plants
Basic Directions	▪ Acquisition of operating technology for the KSTAR ▪ Participation in the international joint construction of ITER ▪ Establishment of a system for the development of fusion reactor engineering technology	▪ High-performance plasma operation in KSTAR for preparations for the ITER Operation ▪ Completion of ITER and acquisition of core technology ▪ Development of core technology for the design of DEMO	▪ DEMO design, construction, and demonstration of electricity production ▪ Undertaking of a key role in ITER operations ▪ Completion of reactor core and system design of the fusion power reactor ▪ Commercialization of fusion technology
Basic Promotion Plan	Basic Promotion Plan 1 ('07~'11)	Basic Promotion Plan 2 ('12~'16) Basic Promotion Plan 3 ('17~'21)	Basic promotion plan 4 ('22~'26) Basic promotion plan 5 ('27~'31) Basic promotion plan 6 ('32~'36)

Policy Goal for Plan-2

R&D for DEMO Technology based on KSTAR and ITER

Primary Strategy for Plan-2

- Attainment of KSTAR high-performance plasma and development of DEMO basic technology
- Basic research in fusion and cultivation of man power
- International cooperation and improvement of status in ITER operations
- Commercialization of fusion/plasma technology and promotion of social acceptance



DEMO Core Technology Development Plan

K-DEMO Core Technology Development Plan

Development of Core Technology

- 3 Major Research Fields, 7 Core Technologies, 18 Detail Technologies and 6 Major Research Facilities
- Through the complete technical planning process with the full participation of experts from all fields covering fusion, fission, physics, computing, mechanics, material, electrics, electronics, and so on.

K-DEMO 3 Major Research Fields	K-DEMO 7 Core Technologies	Major Research Facilities
Design Basis Technology	Tokamak Core Plasma Technology	• Extreme Scale Simulation Center
	Reactor System Integration Technology	
	Safety and Licensing Technology	
Material Basis Technology	Fusion Materials Technology	• Fusion Materials Development Center • Fusion Neutron Irradiation Test Facility • SC Conductor Test Facility
	SC Magnet Technology	
Machine and System Engineering Basis Technology	H&CD and Diagnostics Technology	• Blanket Test Facility • PMI Test Facility
	Heat Retrieval System Technology	

Major Facilities for DEMO R&D

High-field Superconducting Magnet Development Center

- SUCCEX (SUperConducting Conductor EXperiment) Facility
- High-temperature superconducting magnet development

Fusion Material R&D Center

- Fusion Material Test Facilities
- Blanket/FW/Divertor Material Development
- Neutron Irradiation Material Test Facility

Fusion System Engineering R&D Center

- Fusion Nuclear Test Facilities (Thermo-hydraulics, tritium, etc.)
- PMI Test Facility
- Tokamak Components Development (Heating and current drive, diagnostics, etc.)

Large-scale Simulation (Computational) Center

- System codes, Simulator
- Blanket design
- Power plant system design etc.

Nation-wide DEMO R&D Center Planning

Chonbuk Province

Daegu Province

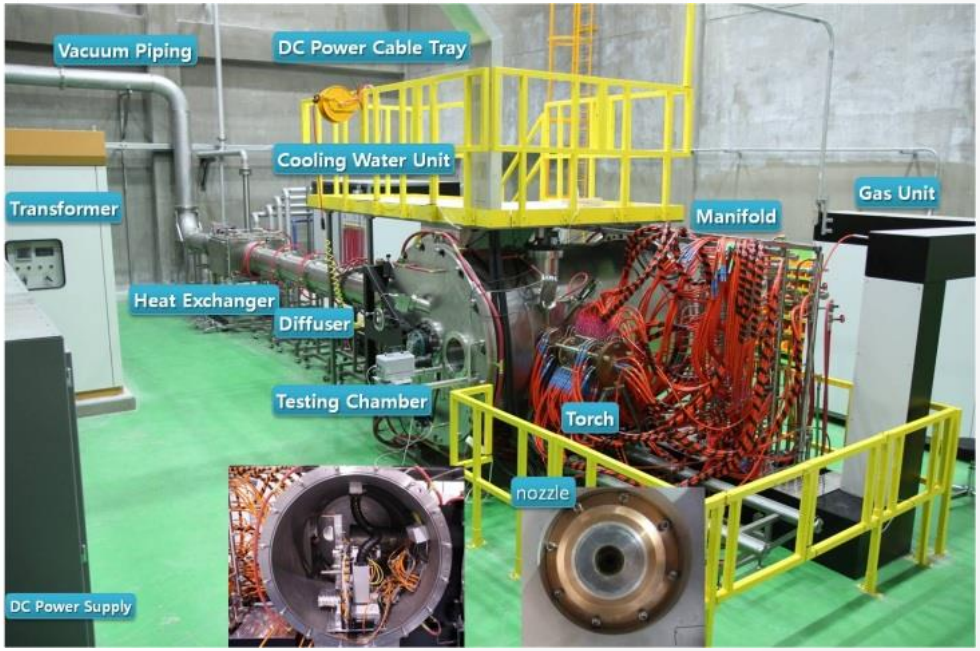
Busan Province

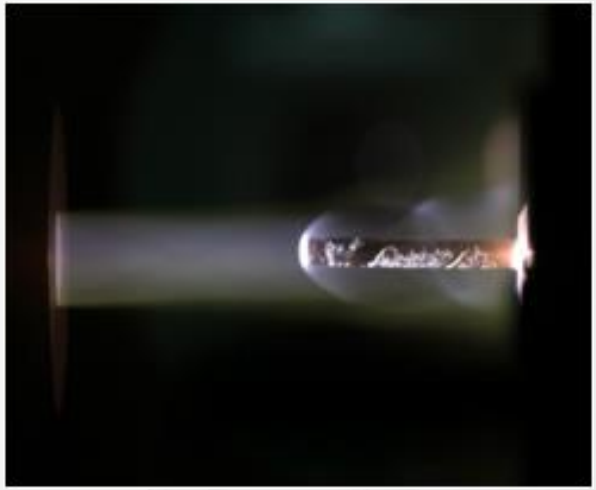
Extreme Environment Material R&D Hub
- Fusion Reactor Materials R&D

Advanced Magnetic Field Center
- Superconductor Test Facility (SUCCEX)

High Enthalpy Plasma Application R&D Center
- Plasma-Material Interaction Test Facility etc.

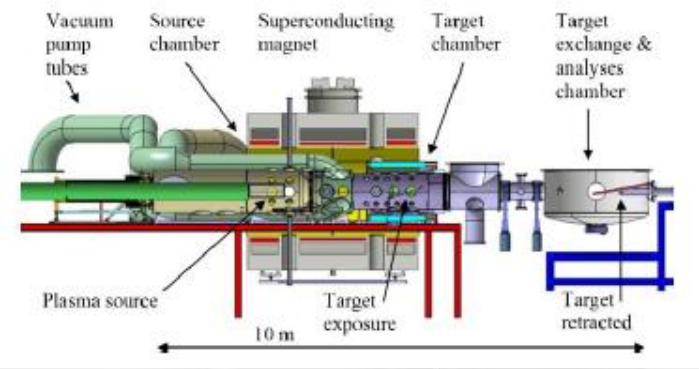
PMI Test Facility (Chonbuk Province)





- **2.4 MW High-Temperature Plasma Test Facility**

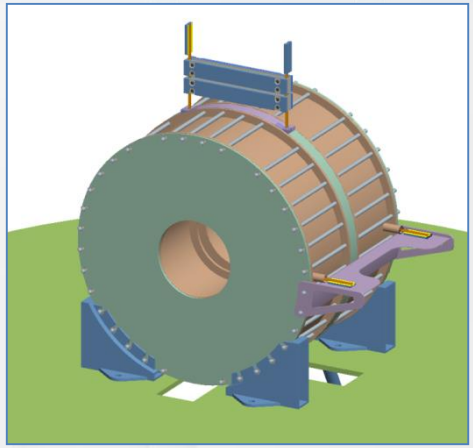
  - Upgrade Plasma Facility for PMI Test
  - Additional, Blanket Test Facility

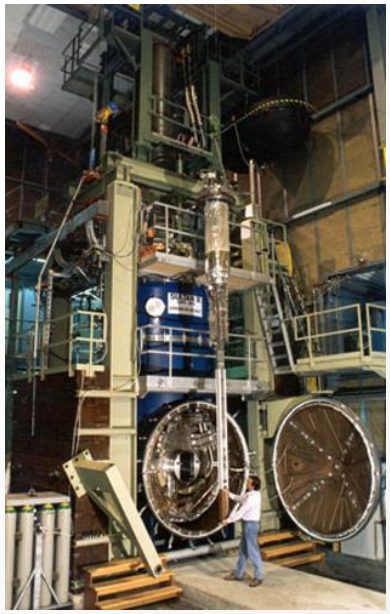


MAGNUM-PSI (Cf.)

Superconducting Conductor Test (SUCCEX) Facility

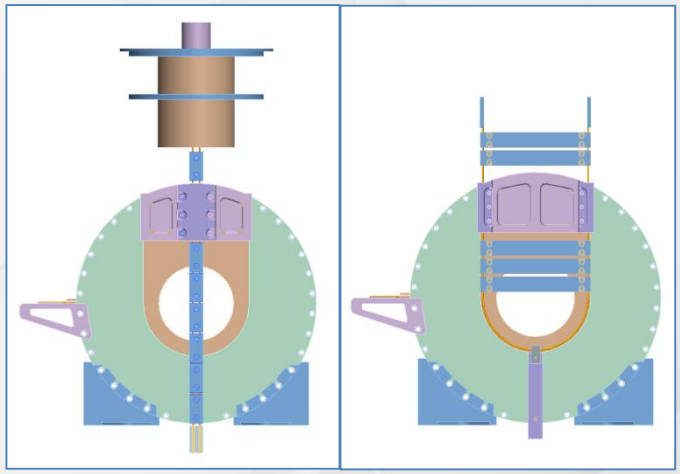
- **SUCCEX (SUperConducting Conductor EXperiment)**
  - **Background field : 16 Tesla**
  - **Split-pair Solenoid Magnet System**
  - **Inner-bore Size : ~ 1 m**
  - **Two Test Modes :**
    - ✓ **Sultan-like sample test mode**
    - ✓ **Semi-circle type conductor sample test mode**





(Cf.) SULTAN

- **Background field : 11 Tesla**
- **100 kA SC Transformer for the short sample test**



SULTAN-type **Semi-circle-type**

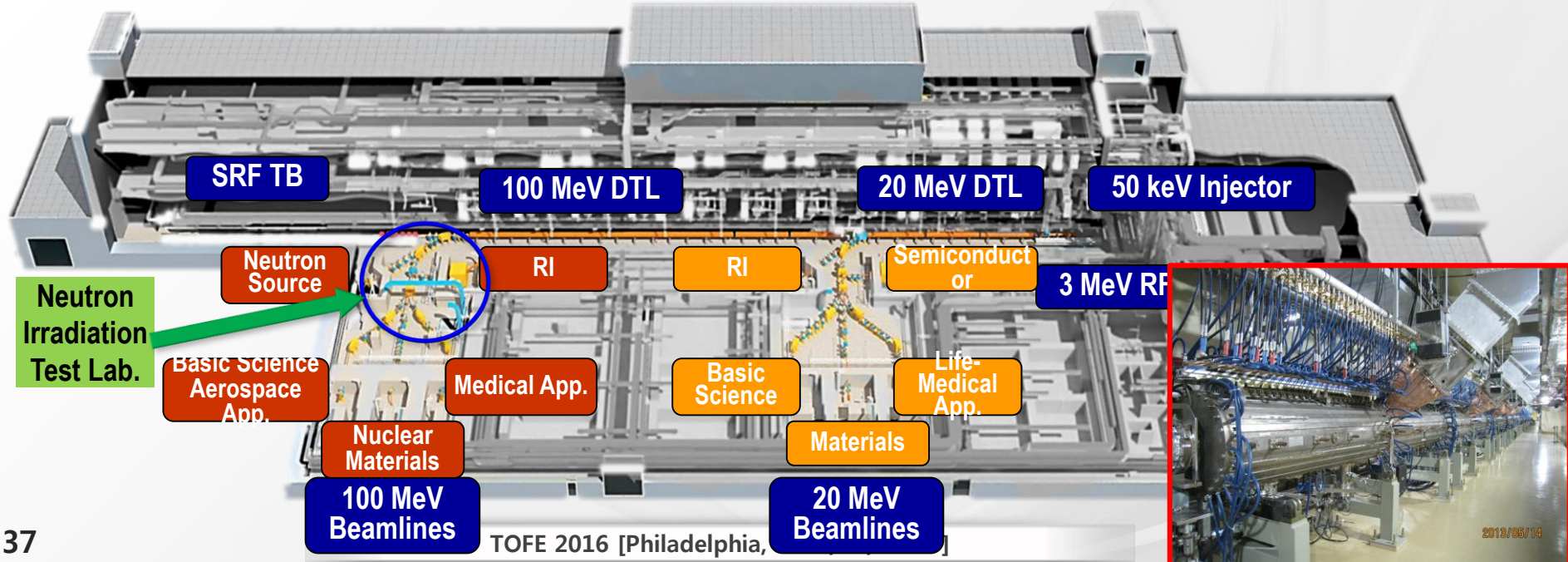
KOMAC Site (Gyeong-ju)

20 & 100 MeV KOMAC Proton Linac

Features of 100 MeV linac

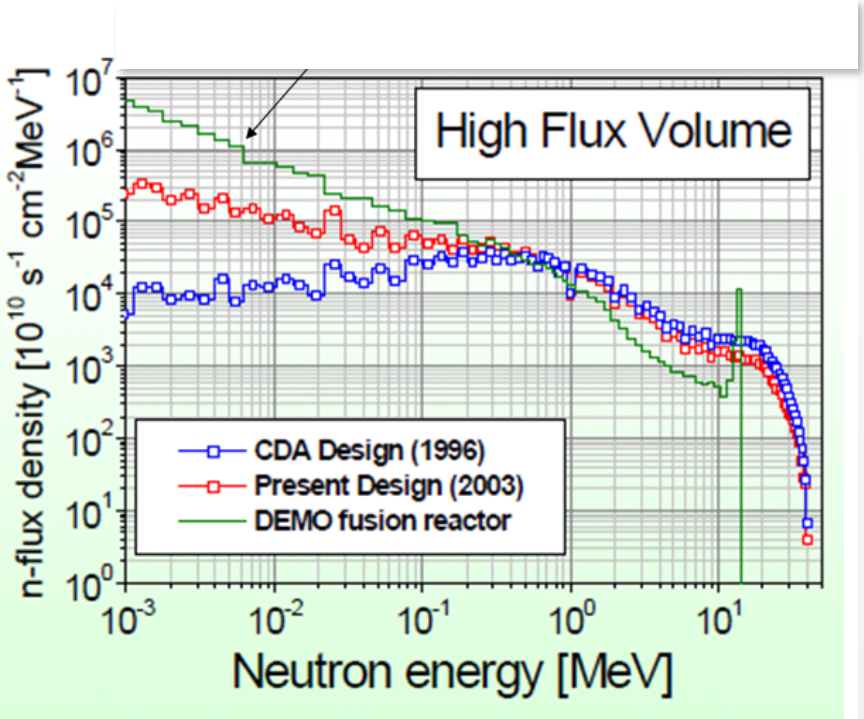
- 50 keV Injector (Ion source + LEBT)
- 3 MeV RFQ (4-vane type)
- 20 & 100 MeV DTL
- RF Frequency: 350 MHz
- Beam Extractions @ 20 or 100 MeV
- 5 Beamlines for 20 MeV & 100 MeV

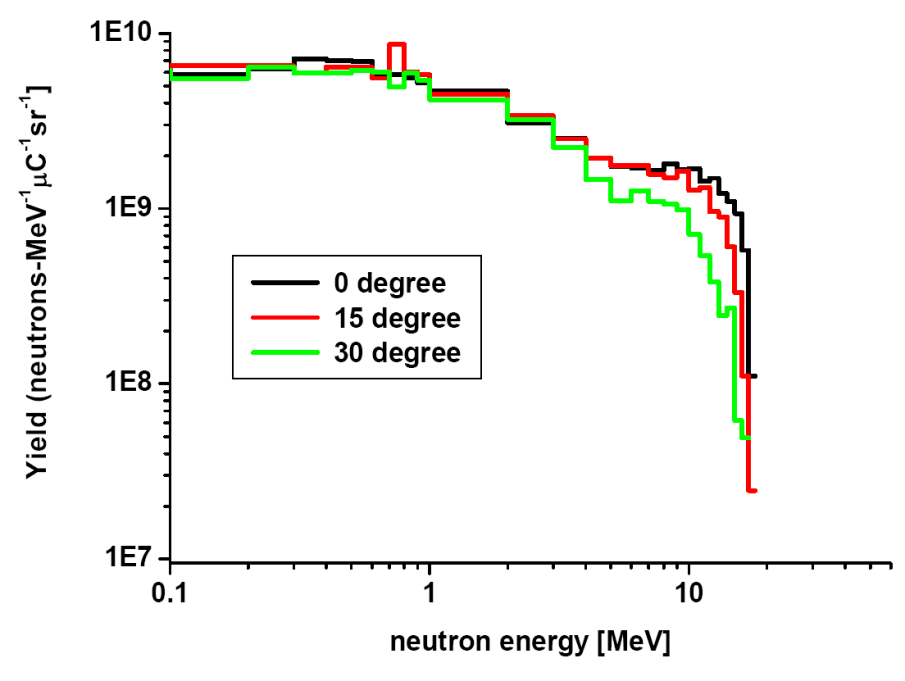
Energy (MeV)	20	100
Peak Current (mA)	0.1 ~ 20	0.1 ~ 20
Max. Duty (%)	24*	8
Max. Ave. Current (mA)	4.8	1.6
Pulse Width (ms)	0.05 ~ 2	0.05 ~ 1.33
Max. Repetition Rate (Hz)	120	60
Max. Beam Power (kW)	96	160
Emittance (mm-mrad)	0.22(x),0.25(y)	0.3 / 0.3



Neutron Energy Spectrum in KOMAC

Fusion Neutron similar Spectrum by Pulse-type Proton beam on Be-target (>1dpa/y)

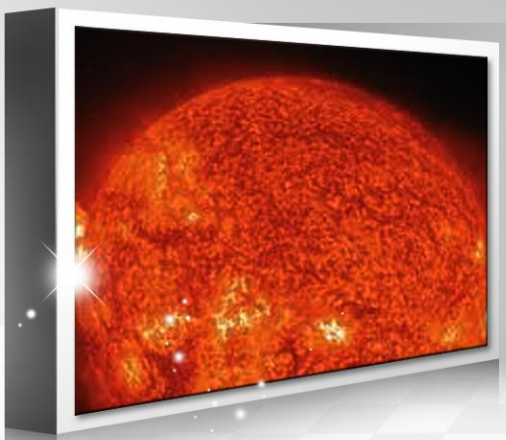




(Ref.) Institute for Materials Research, KIT
I A. Moslang

Neutron Energy Spectrum in KOMAC

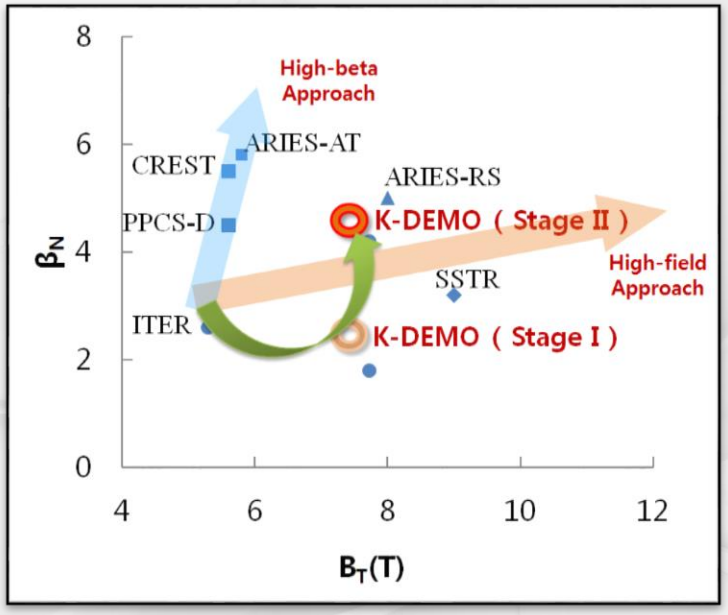
K-DEMO Plant Construction Model



K-DEMO Conceptual Design Activity

Mission & Strategy

- **Mission: To demonstrate the sustainable generation of electricity from fusion power**
- **Strategy:**
  - **Natural Path: KSTAR → ITER → DEMO (tokamak)**
  - **To mitigate risks in the course of DEMO development ➔ Two-Phased Operation strategy**
  - **The operation Stage I ➔ not considered as a final DEMO**
    - At least one port will be designated for the CTF including blanket test facility.
    - To demonstrate the net electricity generation (Q_{eng} > 1) and the self-sufficient Tritium cycle (TBR > 1.05).
  - **The operation Stage II**
    - Major upgrade of In-Vessel-Components
    - To demonstrate the net electricity generation > 400 Mwe.
    - To demonstrate the competitiveness in COE.



Key Idea of K-DEMO Design

Current Drive and Magnetic Field

- Considering the size, a steady state Tokamak is selected as a K-DEMO.
- Because of high neutron irradiation on ion sources, NBI is not practical for the main off-axis current drive of K-DEMO.
- Because of high density of K-DEMO plasma, high frequency ECCD systems (> 240 GHz) are required in order to minimize the deflection of wave.
- In order to match with the high frequency ECCD, a high toroidal magnetic field Tokamak is required and the magnetic field at plasma center requires > 6.5 T.
- Also, $I_{p,limit} \propto B$, $n_{e,\ limit} \propto B$, and **Power ∝ R^3B^4** [**Reactor Cost ∝ R^3B^2**]

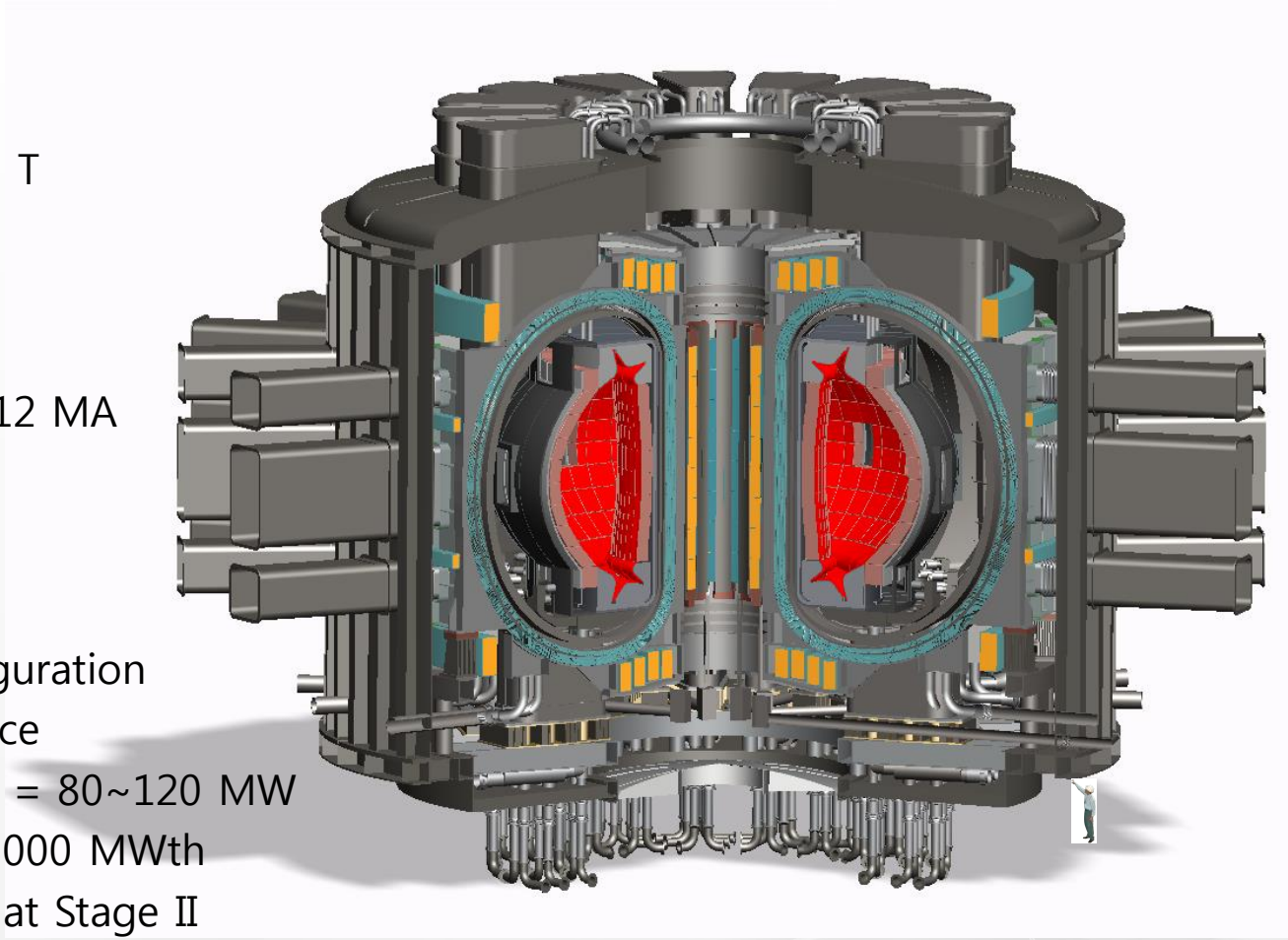
Choice of Coolant and Blanket System

- Pressurized water (superheated water) is considered as a main coolant of K-DEMO considering BOP(Balance of Plant).
- Supercritical CO_2 is also considered as a future coolant.
- Helium is also a candidate as a coolant of K-DEMO, but there are concerns about its low heat capacity, a required high pumping power and BOP.
- Both of ceramic and liquid metal blanket system is considered at this stage. But even in the liquid blanket system, the liquid metal will not be used as a main coolant and a water cooling system will be installed inside the liquid metal blanket.

K-DEMO Parameters

Main Parameters

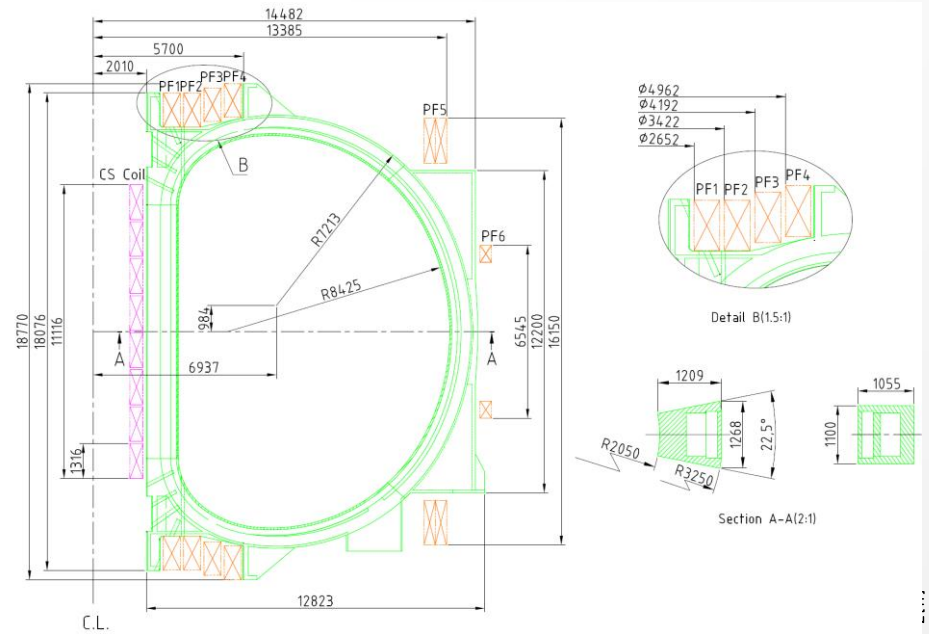
- R = 6.8 m
- a = 2.1 m
- B-center = 7.0~7.4 T
- B-peak = 16 T
- κ_{95} = 1.8
- δ = 0.625
- Plasma Current > 12 MA
- Te > 20 keV

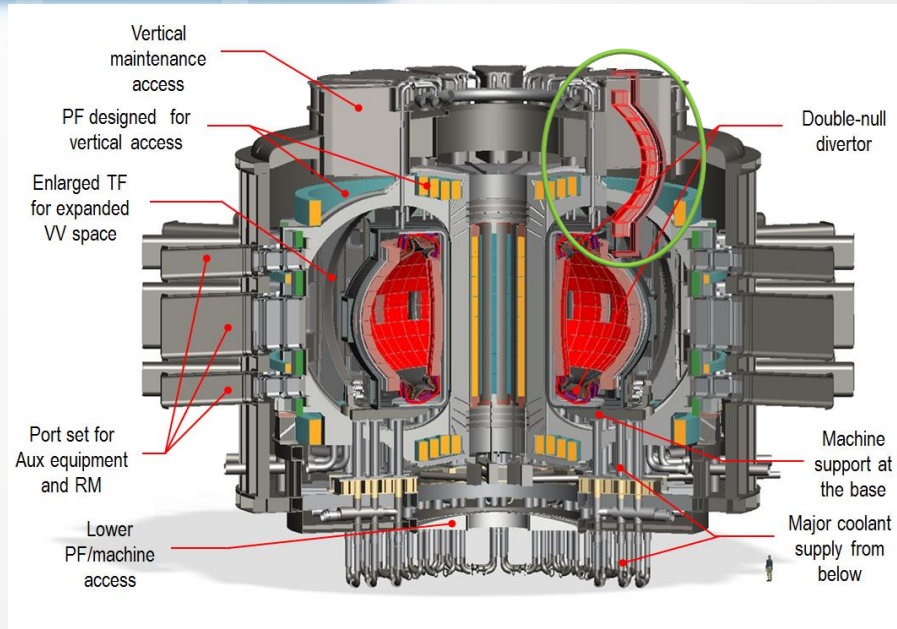


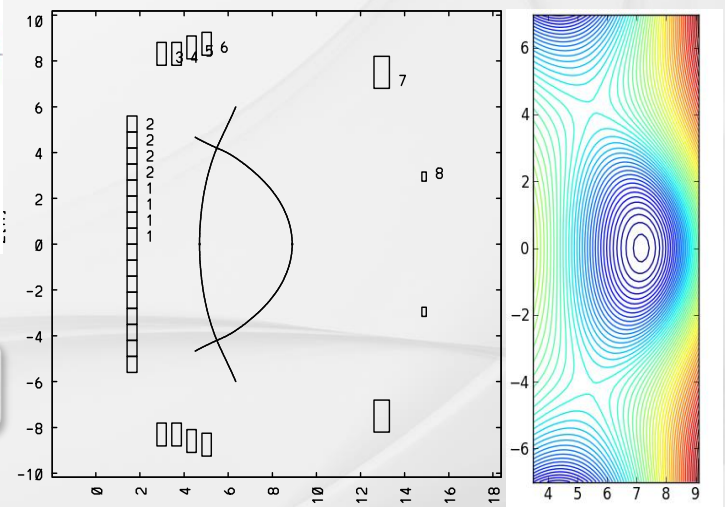
Other Feature

- Double Null Configuration
- Vertical Maintenance
- Total H&CD Power = 80~120 MW
- P-fusion = 2200~3000 MWth
- P-net > 400 MWe at Stage II
- Number of Coils : 16 TF, 8 CS, 12 PF

Magnet System (1/2)





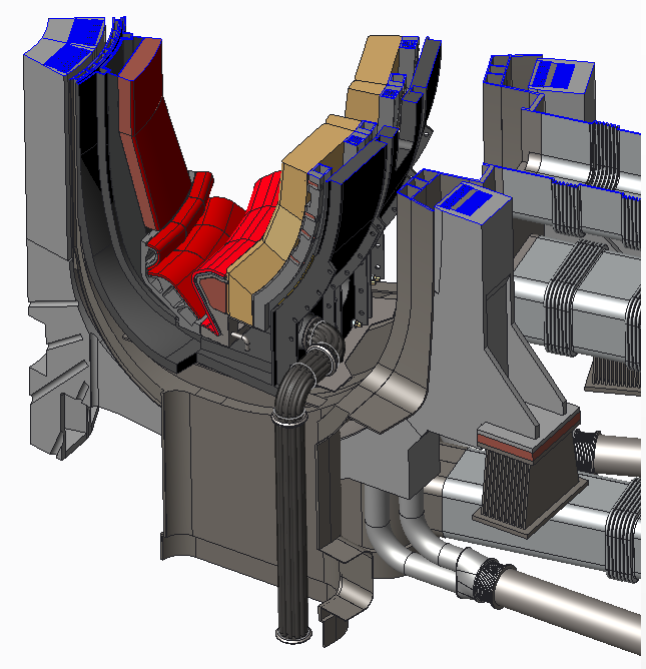


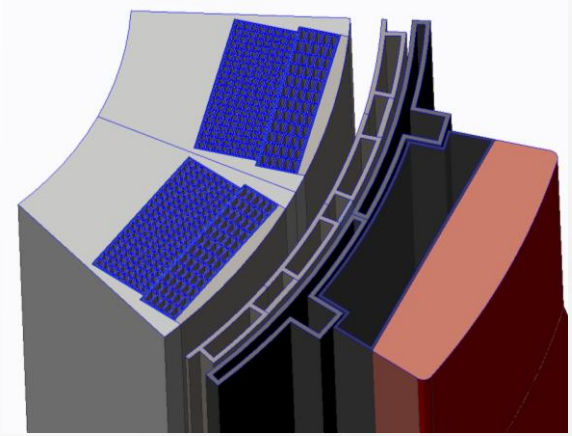
R = 6.8 m
a = 2.1 m
κ_x = 2.0
δ_x = 0.625
B_T = 7.4 T
I_p = 12 MA
$li(1)$ = 0.684
$li(3)$ = 0.52
R_X = 5.48
Z_X = 4.20

- 16 TF coils, PF coils – 6 upper, 6 lower. 8 CS modules

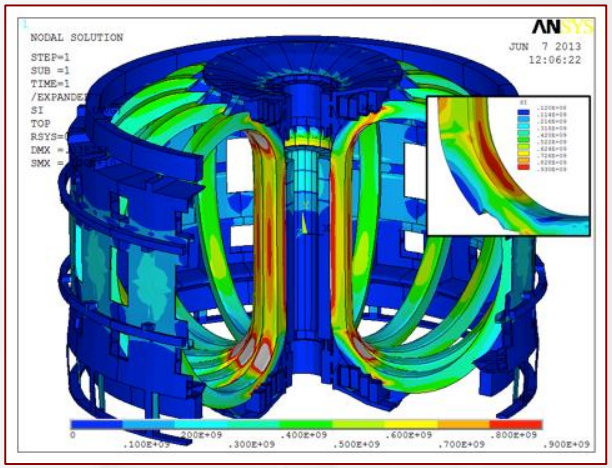
Magnet System (2/2)

■ TF Winding & Structure

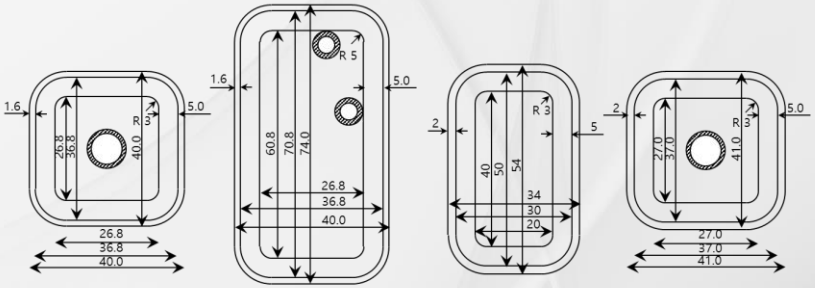


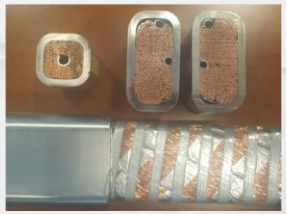


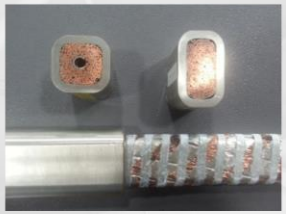
■ Electromagnetic Analyses



■ TF / PF / CS CICCs







Small & Large TF CICC (spiral) PF CICC CS CICC

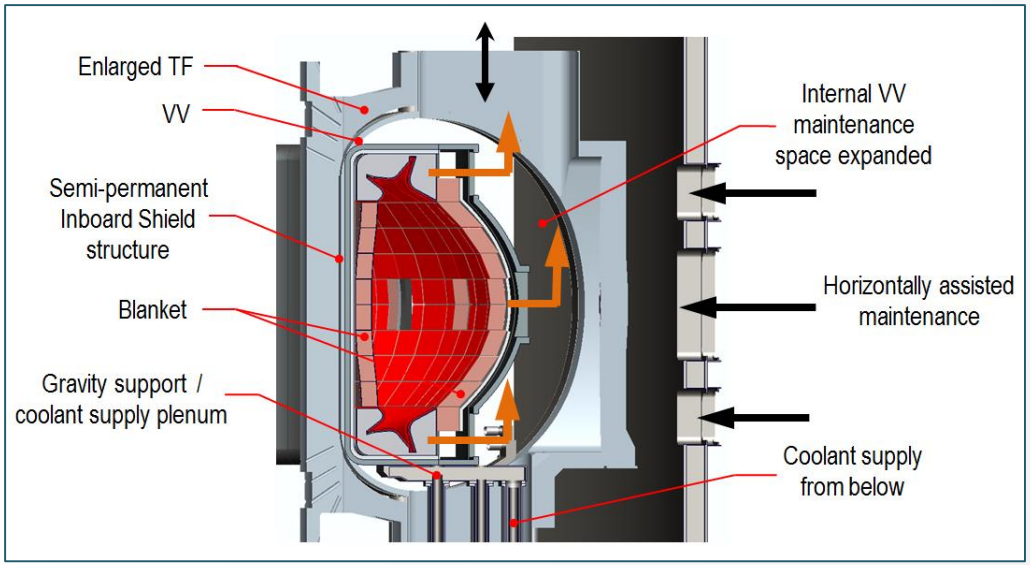
TF Coil :
Dual winding packs with 2 types of CICC
→ High magnetic field
with huge Cost savings
(Strands & No Radial Plate)

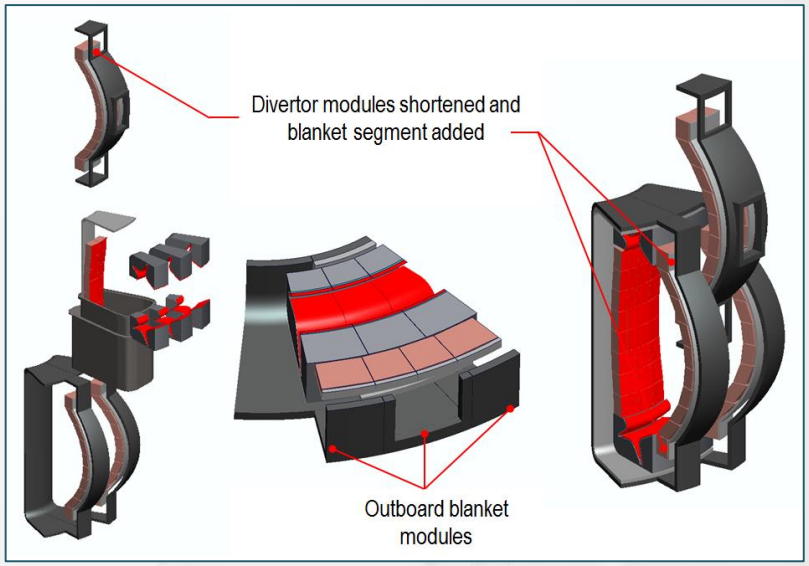
CICC Parameter

Parameter	TF HF	TF LF	CS	PF1-4	PF5-6
■ Cable pattern No. of SC strands No. of Copper strands Spiral Dimension (mm)	(3SC)x4x5x6x5 + 2 Helical Spirals 1800 - ID 5 / OD 8	(((2SC+2Cu)x5)x6+7 Cu)x6 + Central Spiral 360 432 ID 7 / OD 9	(2SC+1Cu) x3x4x4x6 No Cooling Spiral 576 288 -	(2SC+1Cu)x3x4x4x5+Central Spiral 480 240 ID 7 / OD 9	
■ Void Fraction (%)	29.8	26.0	36.6	32.5	
■ Strand Type	High Jc (> 2600 A/mm2) Nb3Sn Strand 0.82 mm diameter (~450 ton + ~280 ton)		ITER type (Jc ~ 1000 A/mm2) Nb3Sn Strand 0.82 mm diameter (~102 ton + ~90 ton)		NbTi Strand 0.82 mm diameter (~90 ton)
■ Cu/non-Cu of Strand	1.0				
■ Insulation	1.6 mm (including Voltage Tap) (0.1 mm Kapton 400% + 0.3 mm S glass 400%)		2.0 mm (including Voltage Tap) (0.1 mm Kapton 400% + 0.4 mm S glass 400%)		
■ Jacket Thickness	5.0 mm				
■ Twist Pitch (mm) 1st stage 2nd stage 3rd stage 4th stage 5th stage	 80 ± 5 140 ± 10 190 ± 10 245 ± 15 415 ± 20	 80 ± 5 140 ± 10 190 ± 10 300 ± 15 -	 27 ± 5 45 ± 10 85 ± 10 150 ± 15 385 ± 20	 35 ± 5 75 ± 10 135 ± 10 285 ± 15 410 ± 20	
■ Wrapping Tape Sub-cable wrap thickness Sub-cable wrap width Cable wrap thickness Final wrap width	0.08 mm, 40% coverage 15 mm 0.4 mm, 60% coverage 7 mm				

Vertical Maintenance Concept

■ Vertical maintenance scheme of in-vessel components



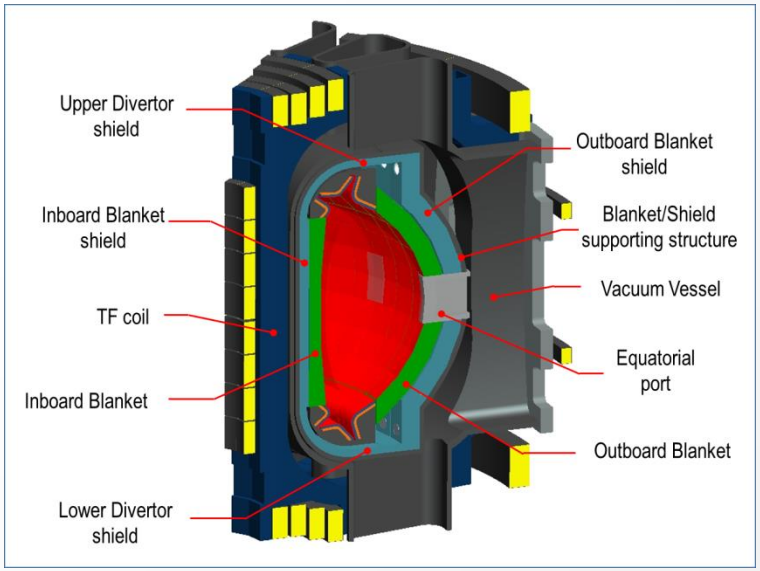


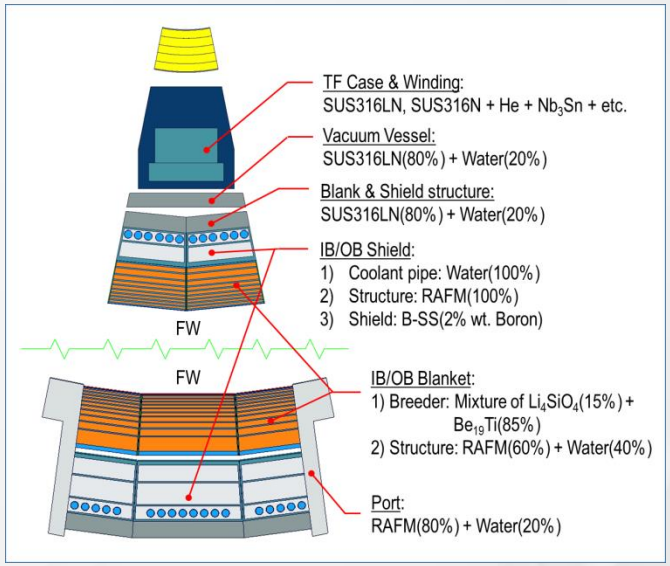
- For maintenance, in-vessel components are toroidally subdivided into:
  - Blanket: - 16 inboard sectors
    - 32 outboard sectors
  - Divertor: 32 modules (upper & lower each)
- Sectors / modules are removed through the enlarged top vertical ports of vacuum vessel.

Concept of Blanket

■ Layered Structure of Blanket & Shielding:

- ➢ Solid ceramic pebble type – breeders (Li_4SiO_4) and multipliers ($Be_{12}Ti$)
- ➢ Shielding: B_4C, Borated-SS, CW, ..
- ➢ Structural material: RAFM with water-cooling



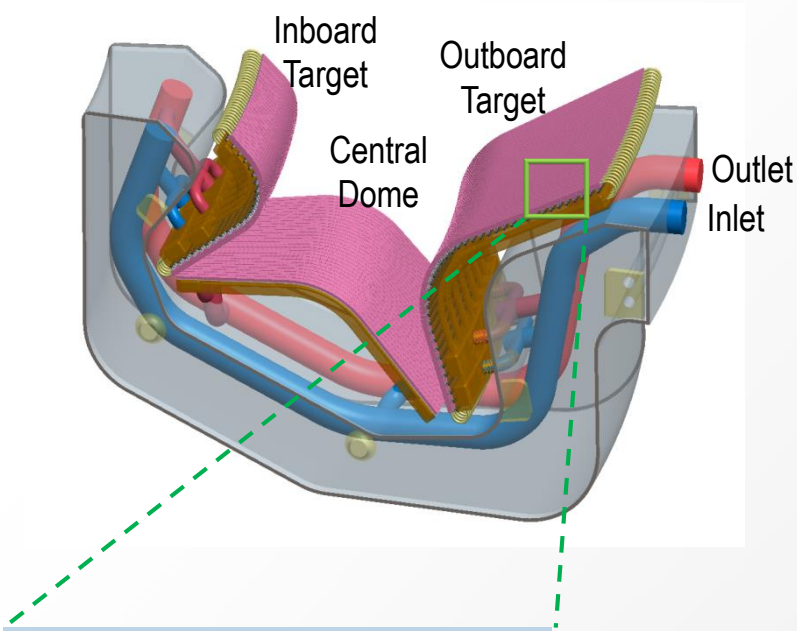


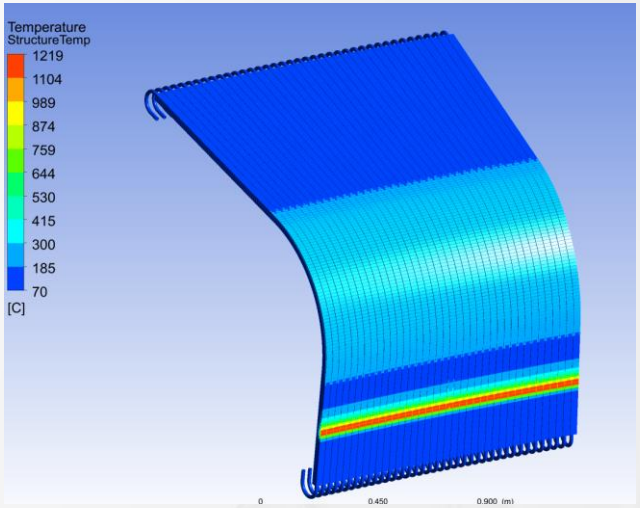
■ Neutronics Analyses

Breeder Pebble	Multiplier Pebble	Global TBR
Li_4SiO_4	**Be (*safety)**	**> 1.20**
Li_4SiO_4	**$Be_{12}Ti$**	**< 1.00 (so far)**
Li_4SiO_4 + $Be_{12}Ti$ (Mixed pebbles)		**~ 1.02 (so far)**

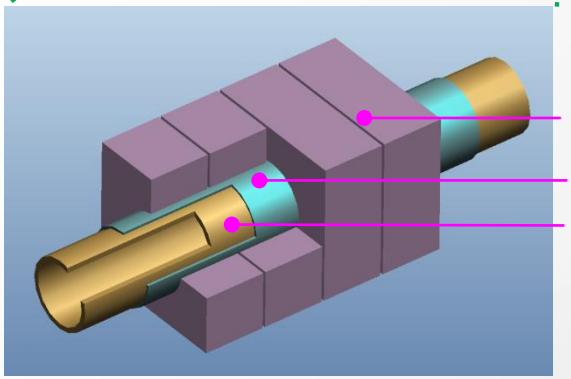
Concept of Divertor

■ Tungsten mono-block type target, with RAFM cooling tube, high pressure water-cooling





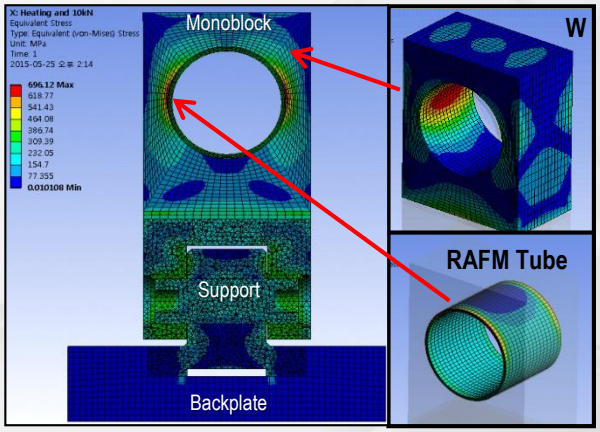
< Thermo-hydraulic Analysis for Outboard Divertor Target >



Tungsten mono-block
Vanadium interlayer
RAFM Cooling tube

- Coolant – PWR-like (inlet 290 °C, ΔT = ~ 40 °C)

Details of High Heat Flux Unit



- Thermal load
  - 10 MW/m^2
- Mechanical loads:
  - Water Pres. (15 MPa)
  - EM load (10 kN)

Material	Calculated [MPa]	$3S_m$ [MPa]
W	696	1800
RAFM	497	500

< Thermo-mechanical Analysis for a Monoblock w/ Support>

Conclusion

KSTAR : Physics Machine	ITER : Fusion Engineering
· High Performance (β_N > 4) Plasma Research for Fusion Power Plant · Fusion Physics Validation · Tokamak Simulator Development · Design Requirement for Fusion Plant	· Stable (β_N ~ 2) Burning Plasma & Fusion Nuclear Science Research (14 MeV Neutron Effect) · Confirmation of Engineering Feasibility for Fusion Power Plant

Construction & Operation of

Artificial SUN(=Fusion Power Plant)

[β_N > 4 required]