

Korean Perspectives on Pathways and Technology Needs



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National Fusion Research Institute



Fusion Energy Development Roadmap in Korea

Alternative choice of clean energy for Korea

➤ Renewable energy in Korea ?

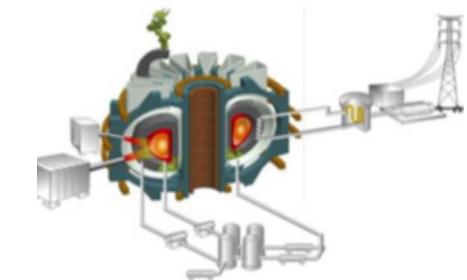
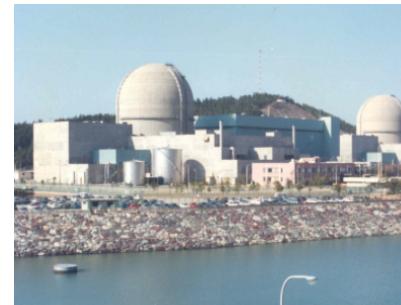
- Not enough space for solar panel and wind mill
- Not enough sunlight and wind

➤ Fission prospect ?

- Safety and efficiency has been improved
- Remained issues related with long term waste

➤ Fusion prospect ..

- Close to realize (ITER and DEMO)
- Need further research to be economic



Korea Fusion Energy Development Plan (revised in 2017)

Vision

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

Phase

Policy Goal

Basic Directions

Basic Promotion Plan

Phase 1 ('07~'11)

Establishment of a foundation for fusion energy development

- 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

Basic Promotion Plan 1 ('07~'11)

Phase 2 ('12~'26)

Development of Core Technology for DEMO

- 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

Basic promotion plan 2 ('12~'16)

Basic promotion plan 3 ('17~'21)

Basic promotion plan 4 ('22~'26)

Phase 3 ('27~'41)

Construction of DEMO by acquiring construction capability of fusion power plants

- 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 technol

Basic promotion plan 5 ('27~'31)

Basic promotion plan 6 ('32~'36)

Basic promotion plan 7 ('37~'41)

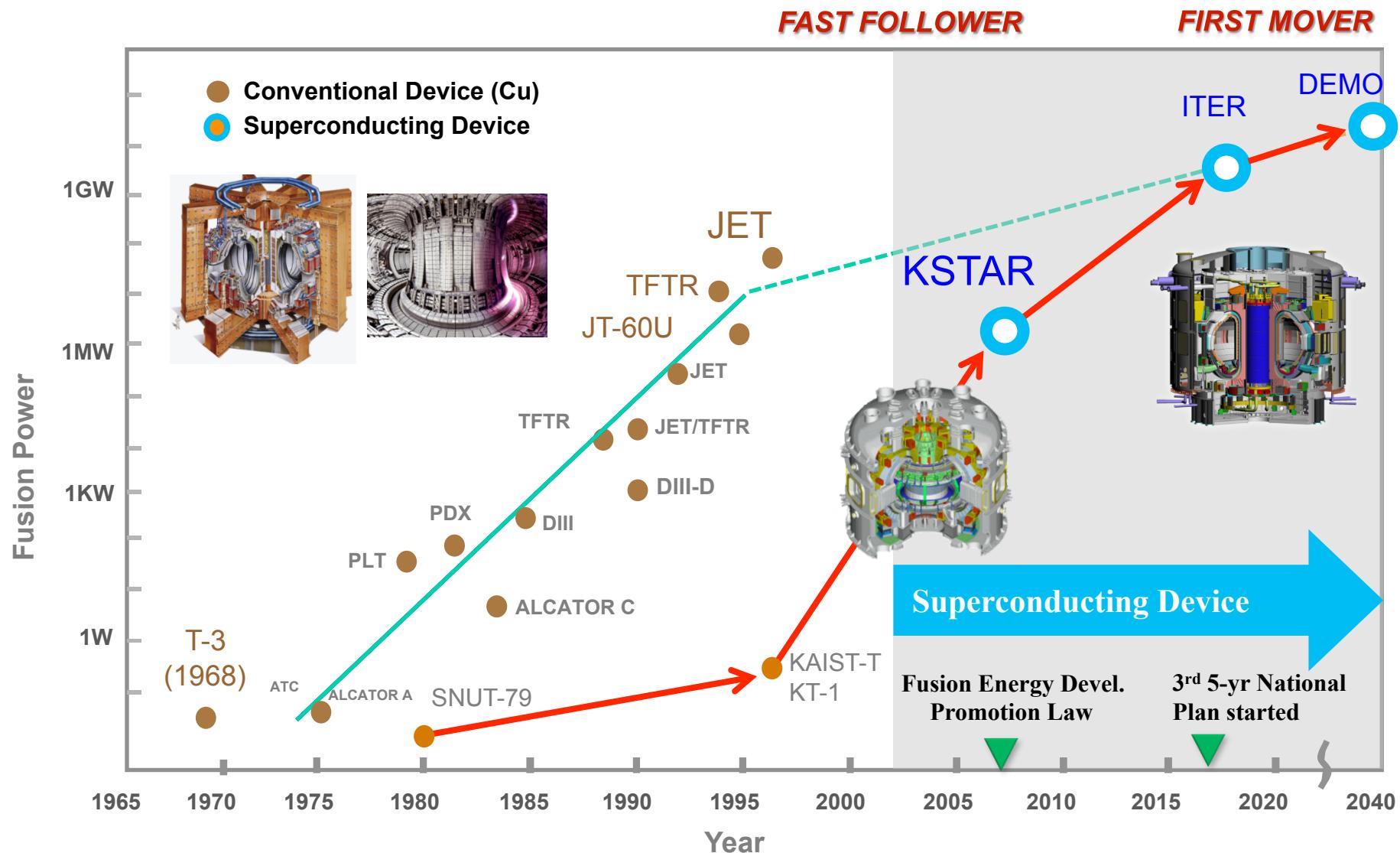
Policy Goal for Plan 3

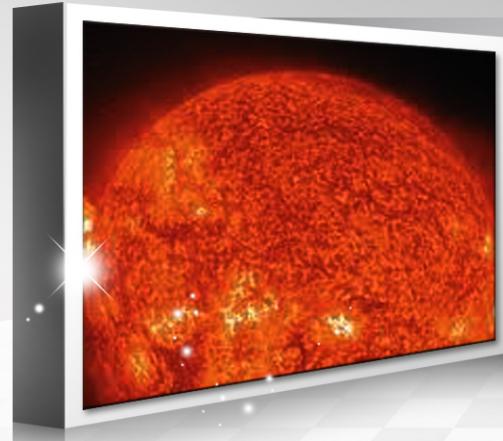
Establishment of foundation for fusion engineering technology development for demonstrating electricity production

Primary Strategy for Plan 3

- ❖ Acceleration for development of DEMO core technology
- ❖ Strengthening of basic research in fusion and manpower fostering system
- ❖ Broadening the base of support for fusion energy development

Strategy of the Korea fusion R&D programs : Paradigm shift from short pulse to steady-state operation

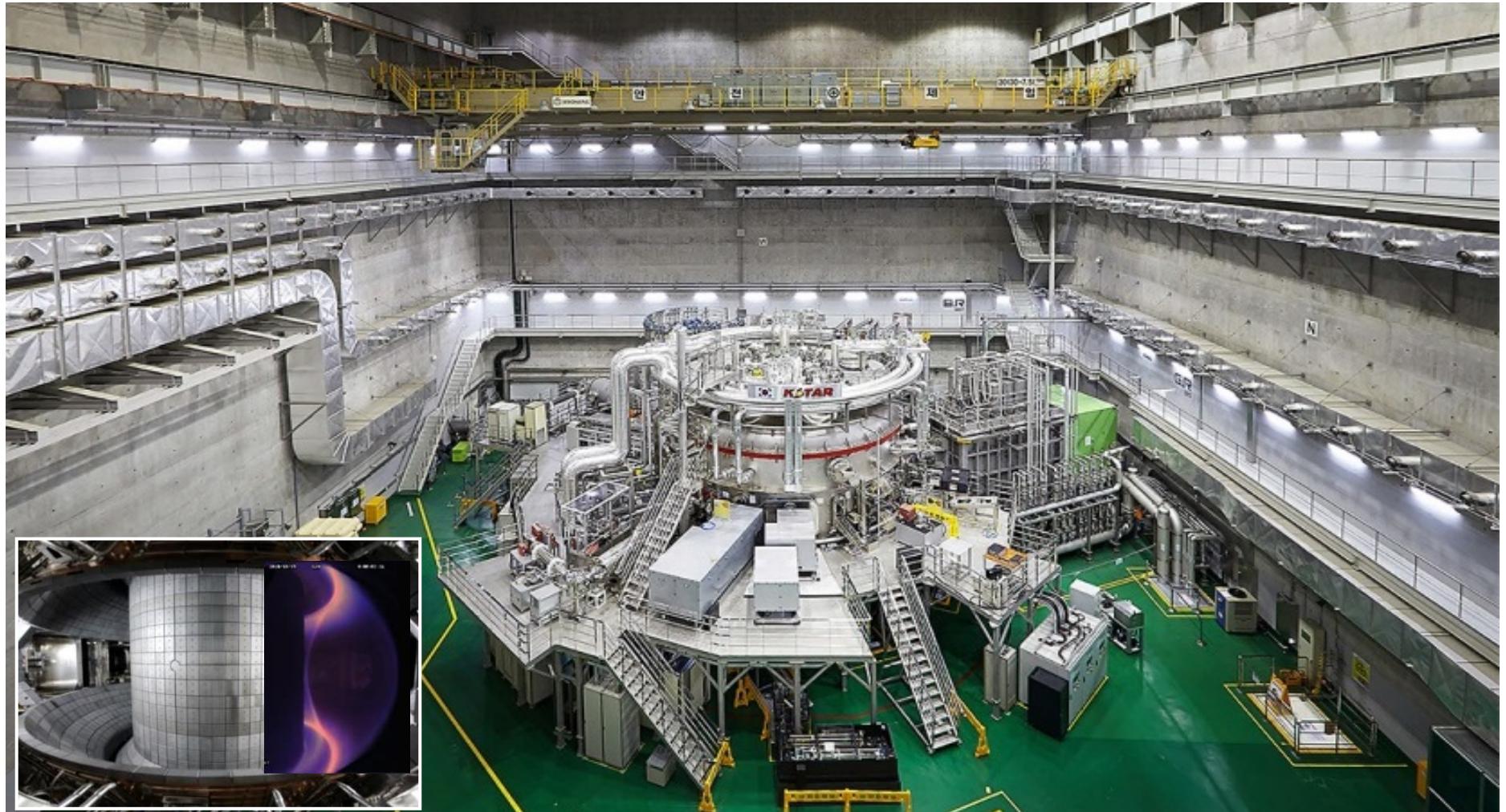




KSTAR :

Exploring steady-state high performance operation

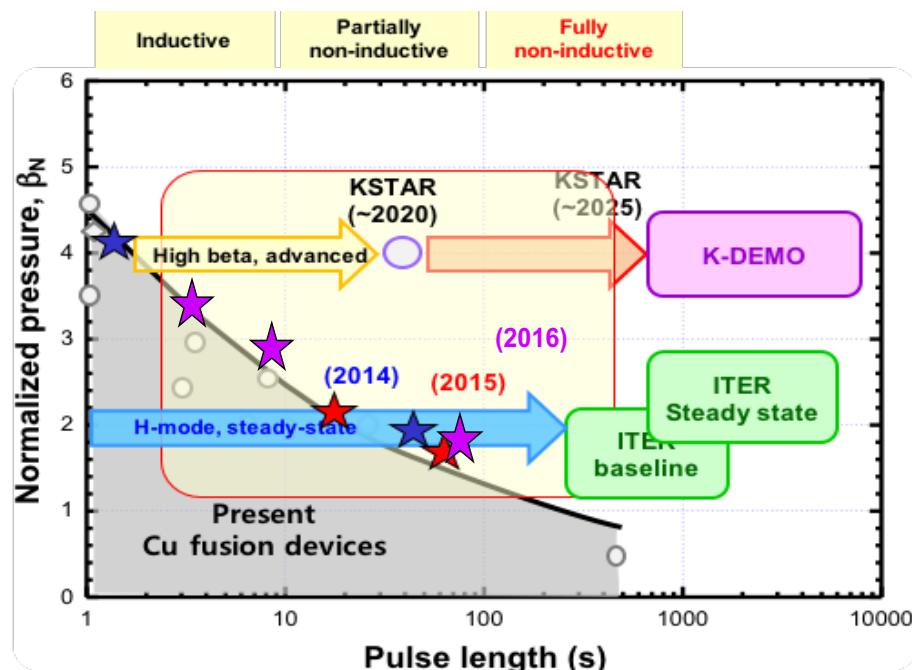
KSTAR program



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

Operation goal of KSTAR exploring steady-state and high performance plasma operation

- Mission : To explore the physics and technologies of high performance and steady-state operation that are essential scientific and technological basis for ITER and fusion reactor



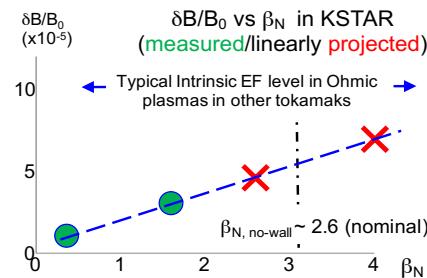
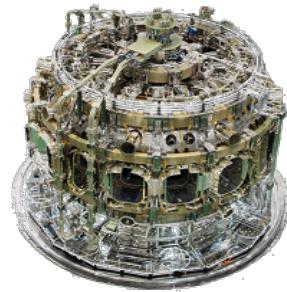
➤ Key parameters of KSTAR

Parameters	Designed	Achieved (~2017)
Major radius, R_0	1.8 m	1.8 m
Minor radius, a	0.5 m	0.5 m
Elongation, κ	2.0	2.15
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	73 s
β_N	5.0	4.3
Superconductor	$Nb_3Sn, NbTi$	$Nb_3Sn, NbTi$
Heating /CD	~ 28 MW	~ 10 MW
PFC	C, W	C, W

Unique features of KSTAR advancing the high performance operation R&D

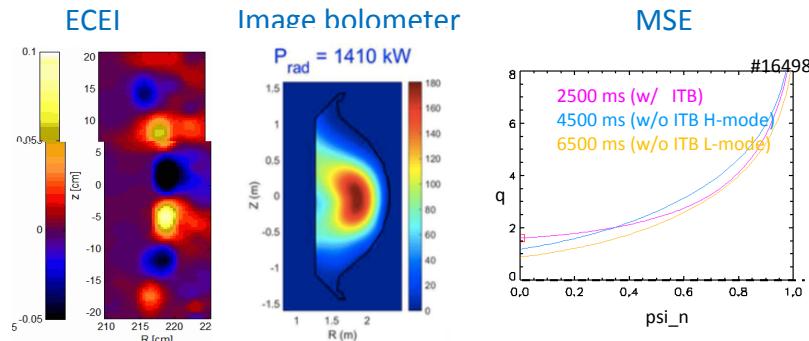
► Highly performance SC magnets

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



► Advanced diagnostic systems

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

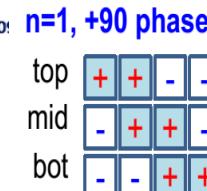
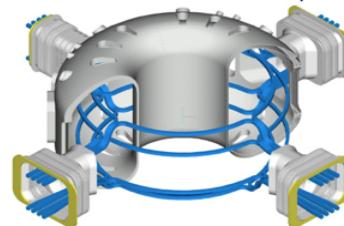


► ITER relevant In-vessel coils

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

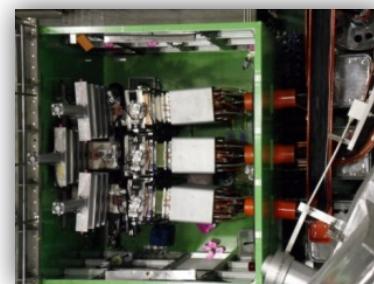
KSTAR In-vessel Control Coils
(IVCC): Top/Mid/Bottom

H.K. Kim et al, FED (2001)



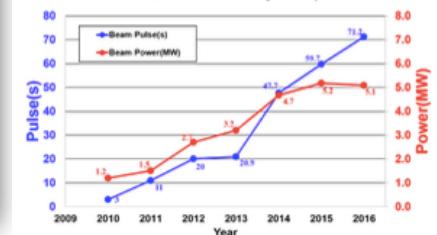
► Long-pulse heating & CD systems

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



Long pulse and high power of NBI-1

Enhancement of NBI injection power



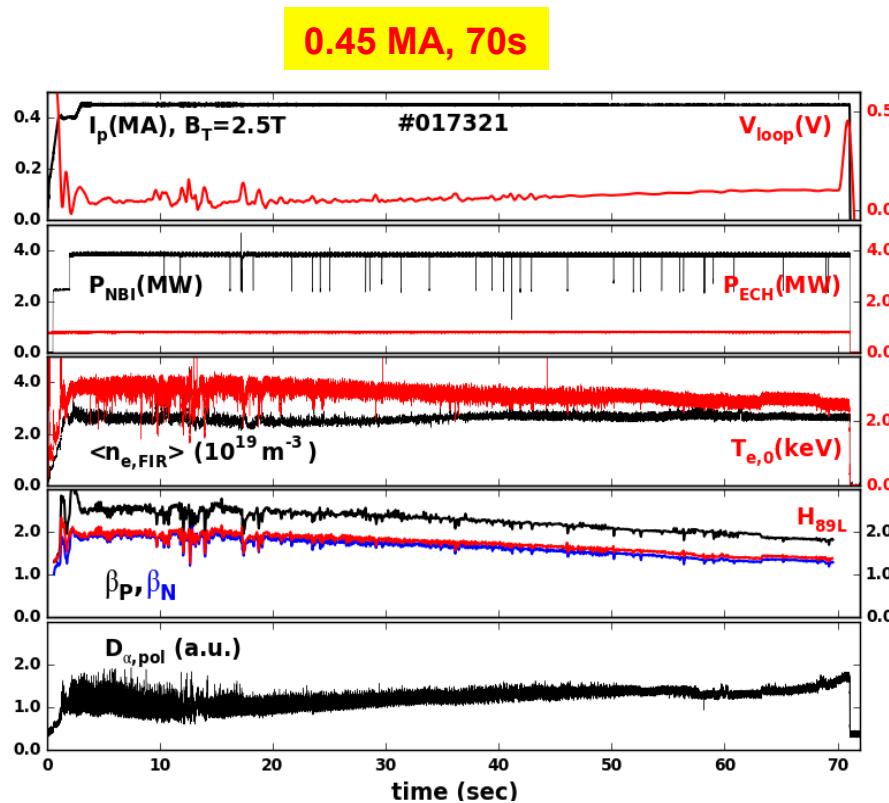
Research directions of KSTAR toward K-DEMO

- Explore the long pulse high beta operation with ELM-free H-mode
 - ELM-crash control with IVCC coils in case H-mode is the only choice
 - Establish physics based ELM-crash and routine recipe for suppression
- Explore new operating regime with less instabilities
 - Expand operation window to higher beta operation with intelligent control of MHDs (sawtooth, NTM, disruption, RWM)
 - Hybrid, ITB combined with low edge q, etc.
- Validation of MHD and turbulence models for predictive capabilities
- Test of innovative engineering and technologies
 - Innovative heat removal
 - Innovative current drive – explore new scheme with improved efficiency

Reproducible long pulse, NBI-heated H-mode operation (>70sec)

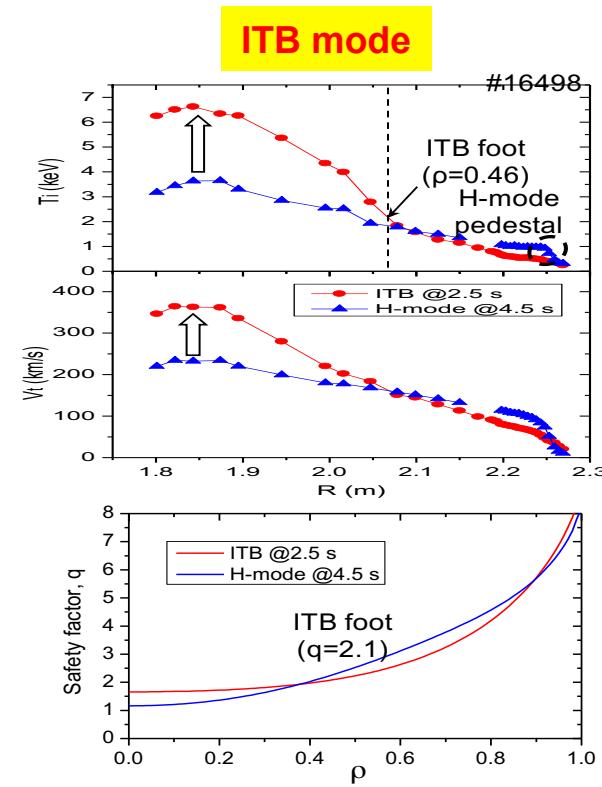
► long pulse H-mode discharge

- H-mode discharge : > **70 s** (0.45 MA)
- Nearly non-inductive discharge

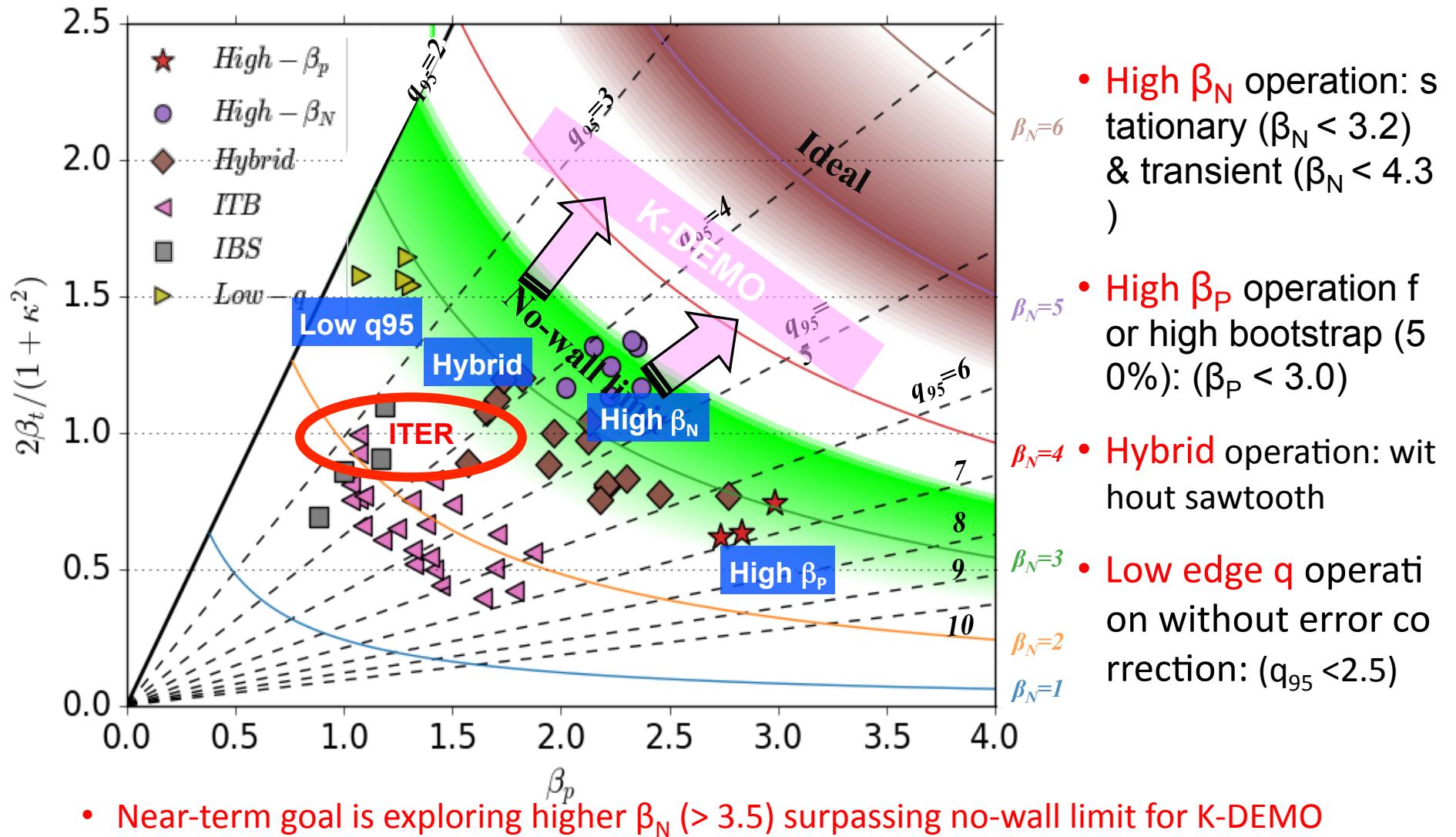


► Alternative operation mode development

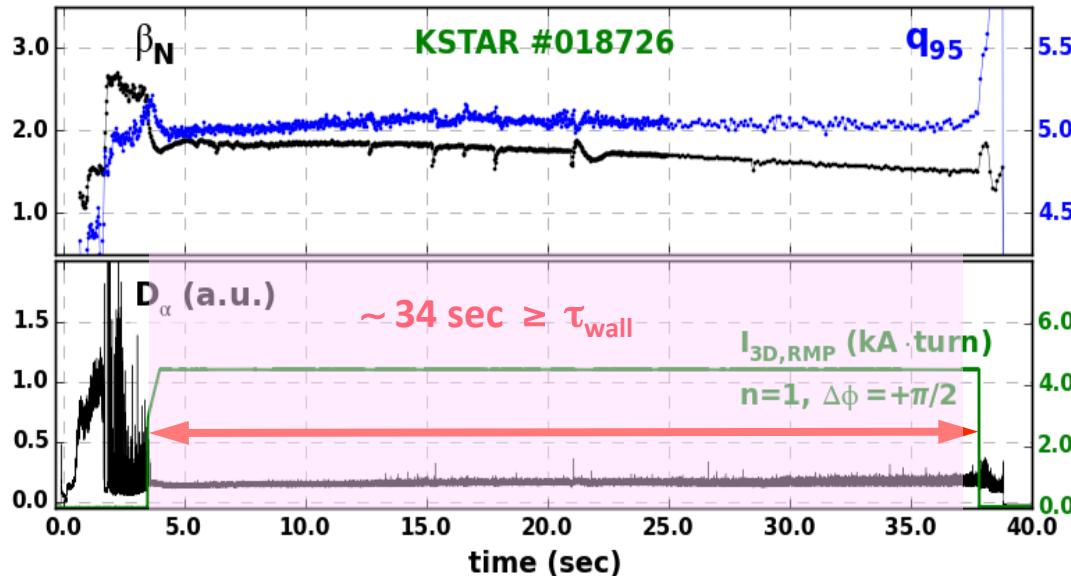
- Internal transport barrier (ITB) > 13s
- High beta operation ($\beta_N > 3.0, \beta_P > 3.0$) : > 3s



KSTAR has operation capability toward higher confinement beyond ITER baseline



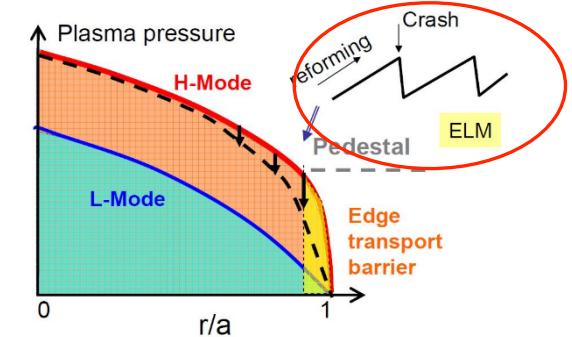
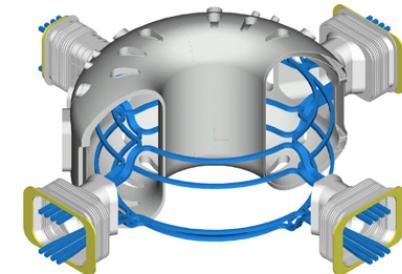
KSTAR could assess a very robust way for ELM-crash suppression (~ 34s) using IVCC



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

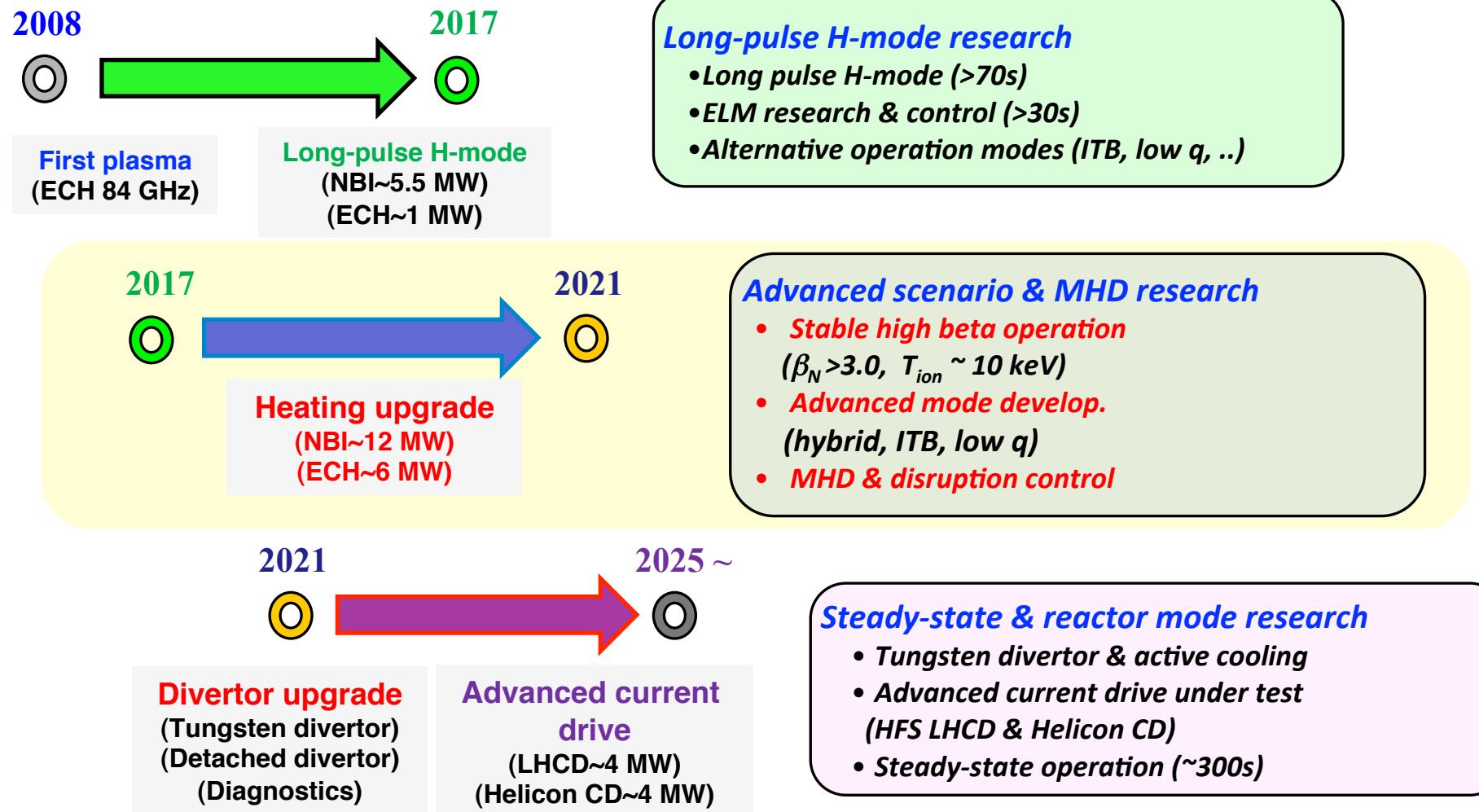
KSTAR In-vessel Control Coils
(IVCC): Top/Mid/Bottom

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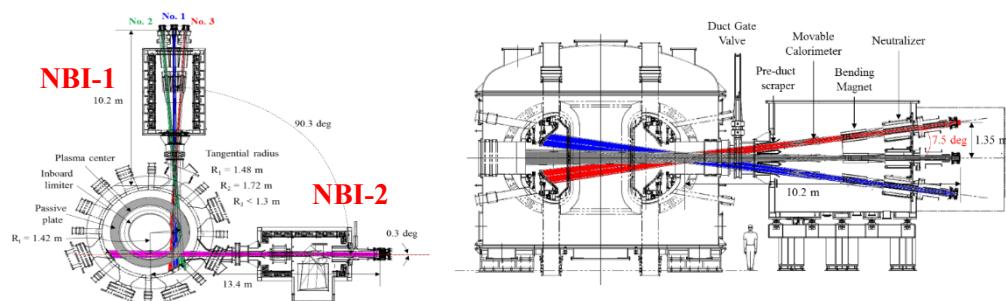
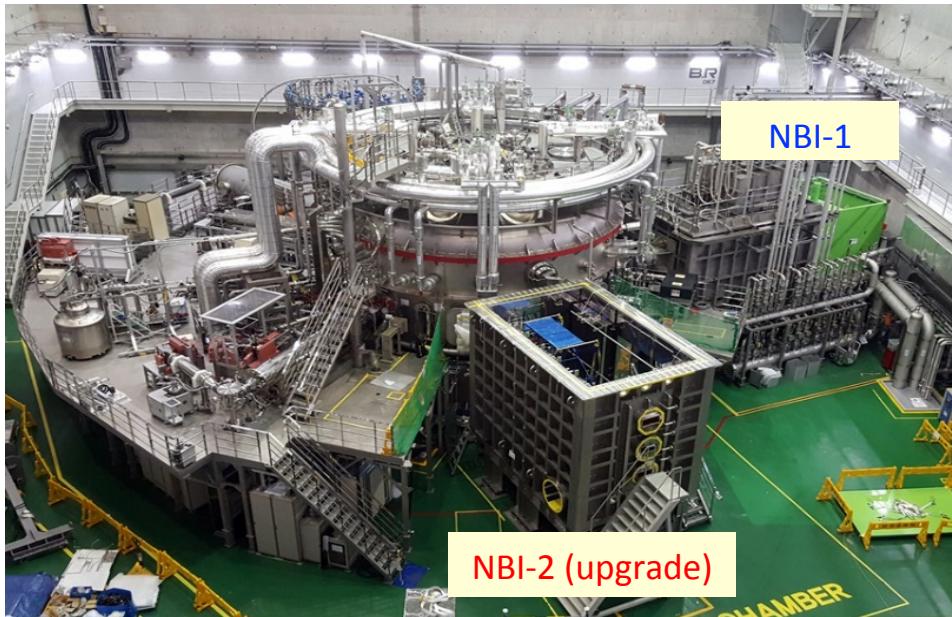
- KSTAR has unique 3 row RMP coils like as ITER (top/middle/bottom)
- Record long ELM-crash suppression (~34s) with $n=1$ RMP achieved in 2017
 - ITER comparable operation ($q_{95} \sim 3.4$, $\beta_N \sim 1.8$)
 - Validation of predictive model of ELM-suppression with experiments

Future research and upgrade plan for higher beta and steady-state operation toward K-DEMO

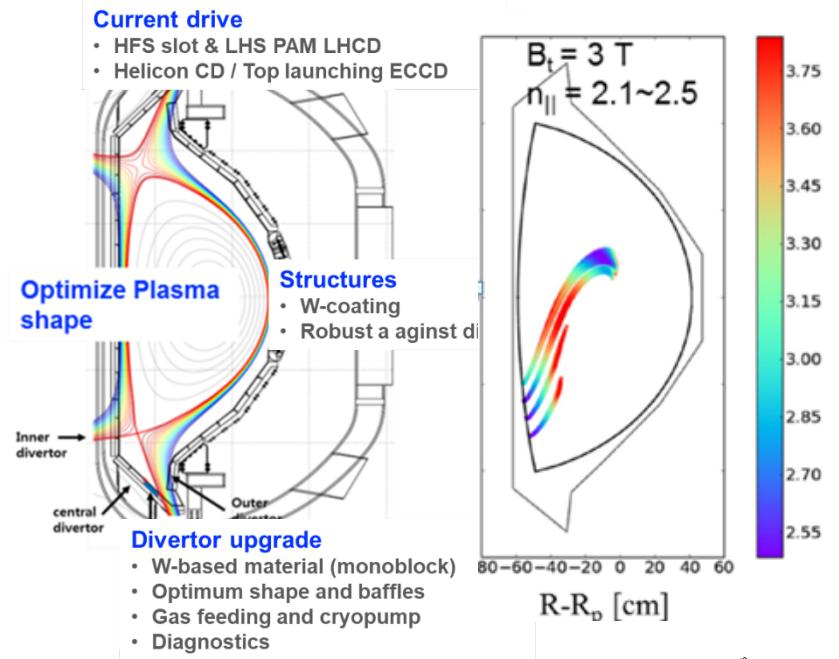


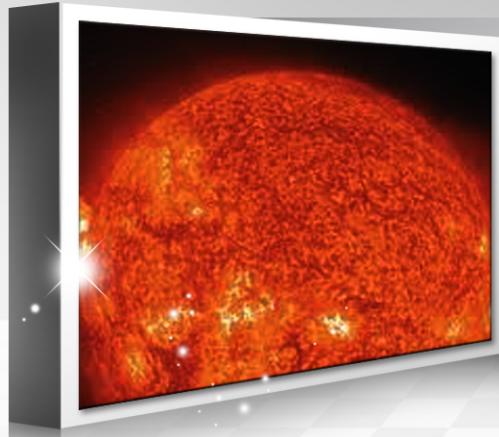
Heating & CD upgrade for higher beta and Divertor upgrade for steady-state operation

- Heating & CD upgrade (2018~)
 - 2nd NBI (6MW, off-axis) / ECCD (6 MW, total)
 - Innovative HFS LHCD, Helicon CD



- Divertor upgrade (2021~)
 - Tungsten-based metal
 - Fully active cooling
 - Diagnostics for Divertor physics

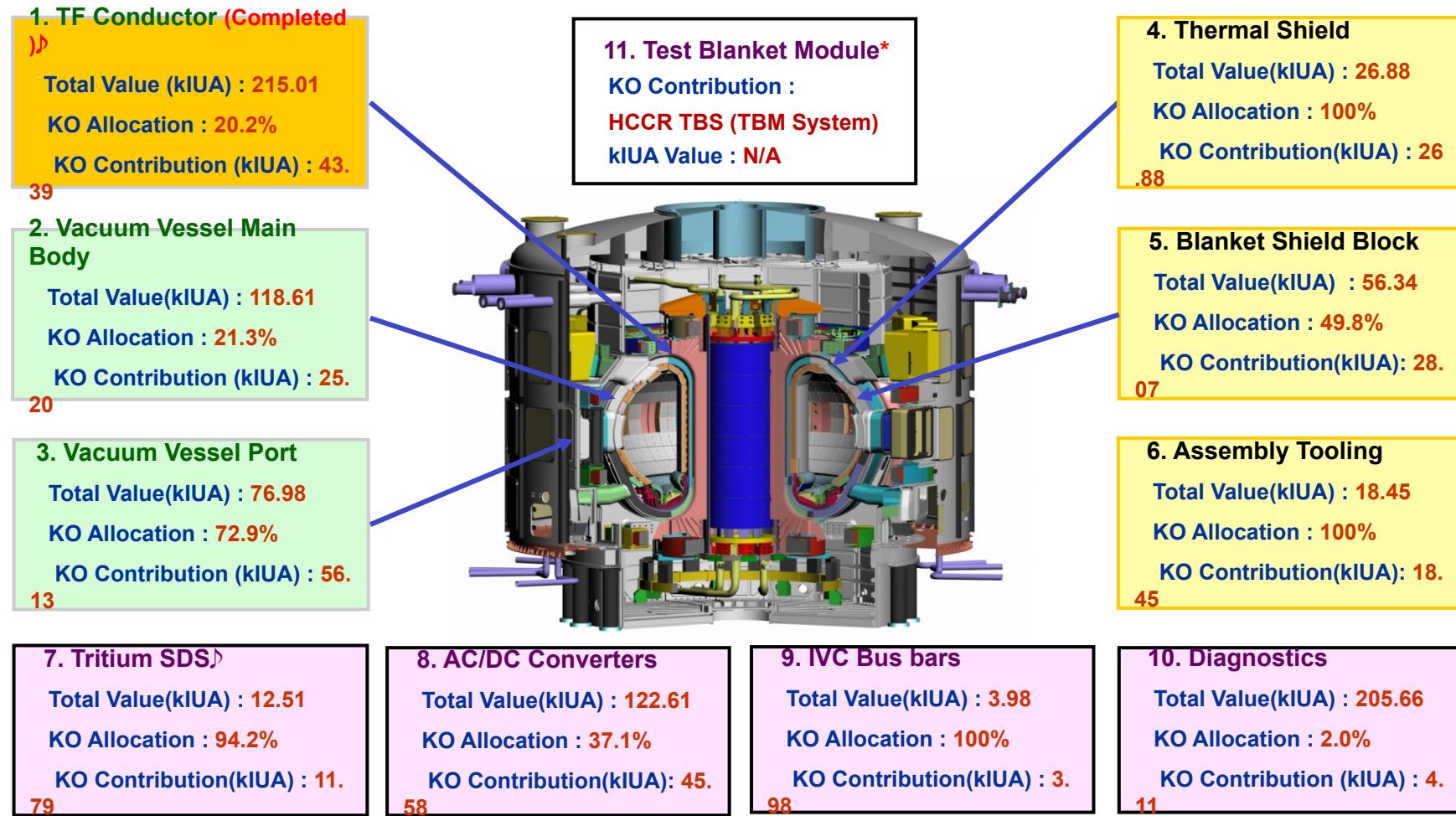




ITER :

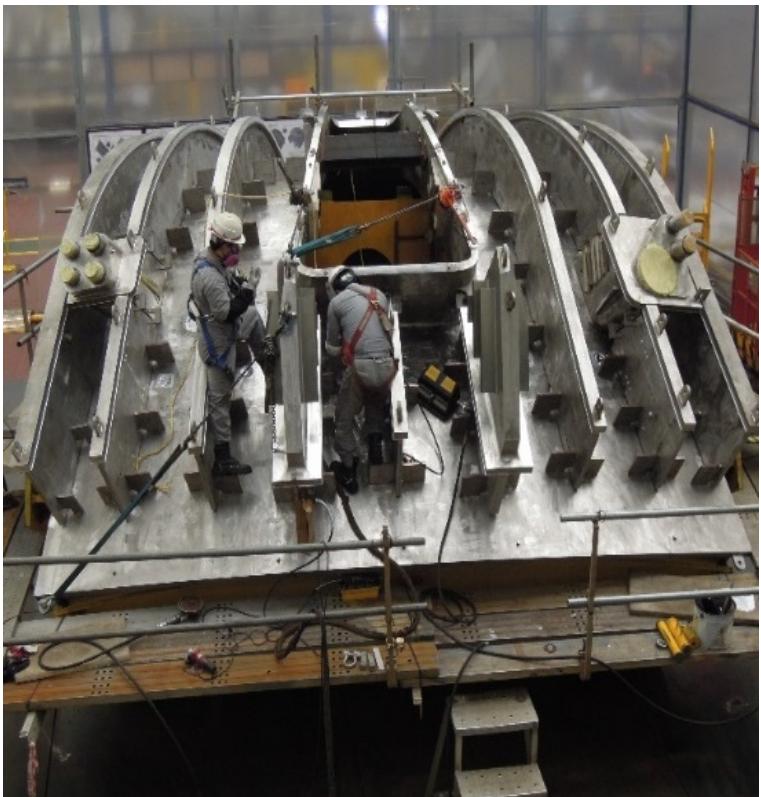
Construction and operation of reactor-scale tokamak

In-kind contribution of Korea



Fabrication of reactor-scale vacuum vessel and structures satisfying reactor-grade qualification

- Manufacture of Vacuum Vessel Sectors by KO Hyundai Heavy Industries Corporation is making good progress and will ensure to achieve the First Plasma in December 2025;



- Vacuum vessel : the first Sector 6 is about 76% (end of November).
- Assembly of inner shells for Lower Port Stub Extension (LPSE) has been completed
- Thermal Shield (VVTS) is about 55% as scheduled

Fabrication of vacuum vessel and port

Experience of accurate assembling of reactor-scale heavy structures

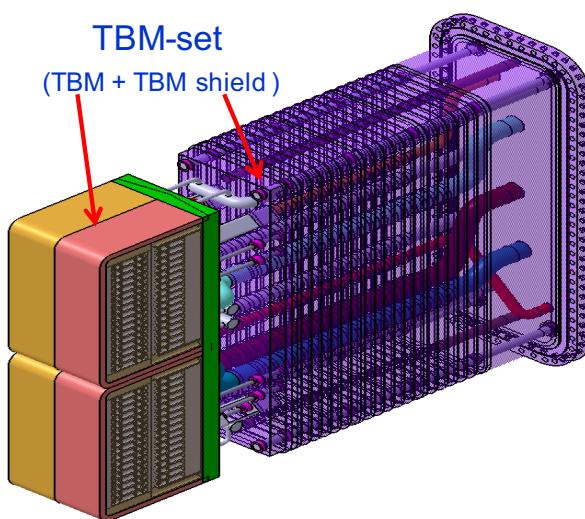
- ITER is challenging program requires high accuracy in assembly and alignment of massive structures



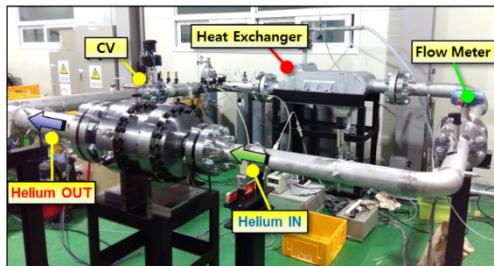
- Elements for the massive 800-ton Sector Sub-Assembly Tools are being delivered to ITER.
- Installation in ITER assembly hall is on-going

Test of blanket module (TBM) under neutron environment in ITER prior to K-DEMO

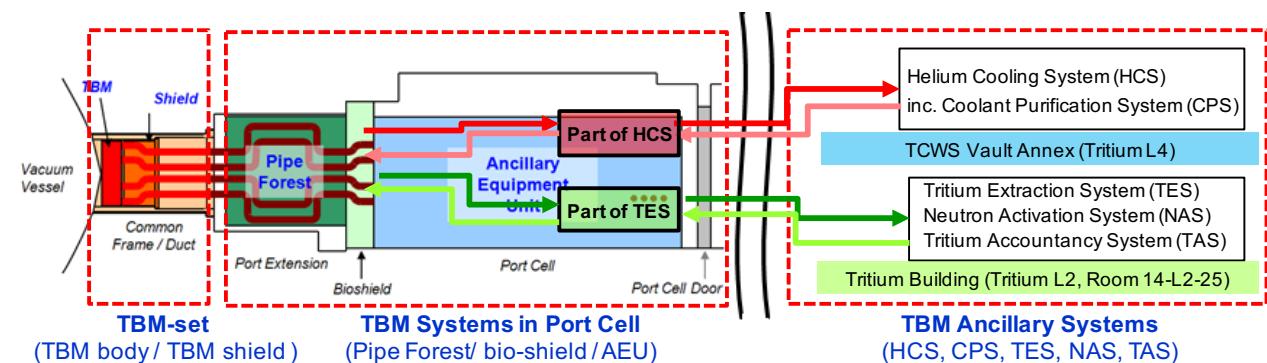
- KO Helium Cooled Ceramic Reflector (HCCR) TBM (DEMO-relevant breeding breeder concept)

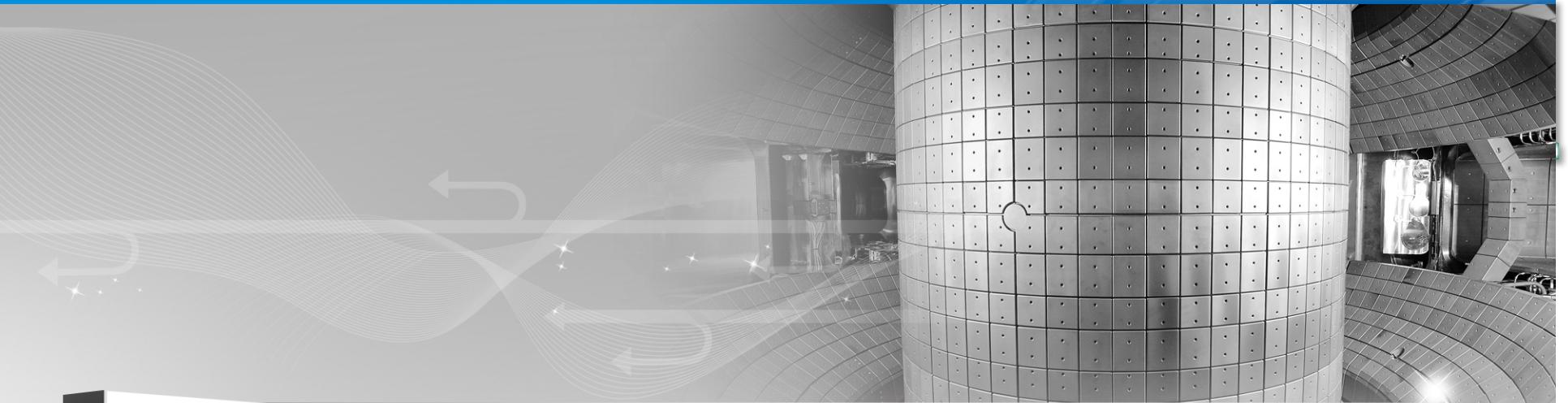


Ceramic pebble breeder



Performance test of He loop





K-DEMO Concept Study : *R&D for advanced fusion reactor*

Strategy for designing the K-DEMO

➤ Strategy for K-DEMO :

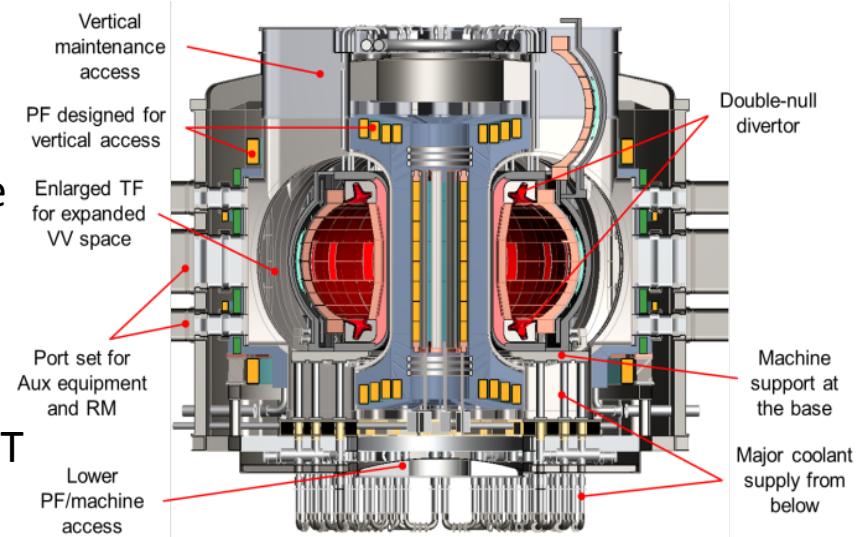
- Natural Path: KSTAR → ITER → DEMO
- Two phase operation to mitigate risks in the course of DEMO development

➤ The operation Stage I ($P_{\text{Fusion}} = 2,200 \text{ MW}$)

- At least one port will be designated for the CT F including blanket test facility.
- Demonstrate the self-sufficient Tritium cycle (TBR > 1.05)

➤ The operation Stage II ($P_{\text{Fusion}} = 3,000 \text{ MW}$)

- Major upgrade of In-Vessel-Components
- Demonstrate the net electricity generation (> 400 MWe)
- Demonstrate the competitiveness in COE.



■ Main Parameters

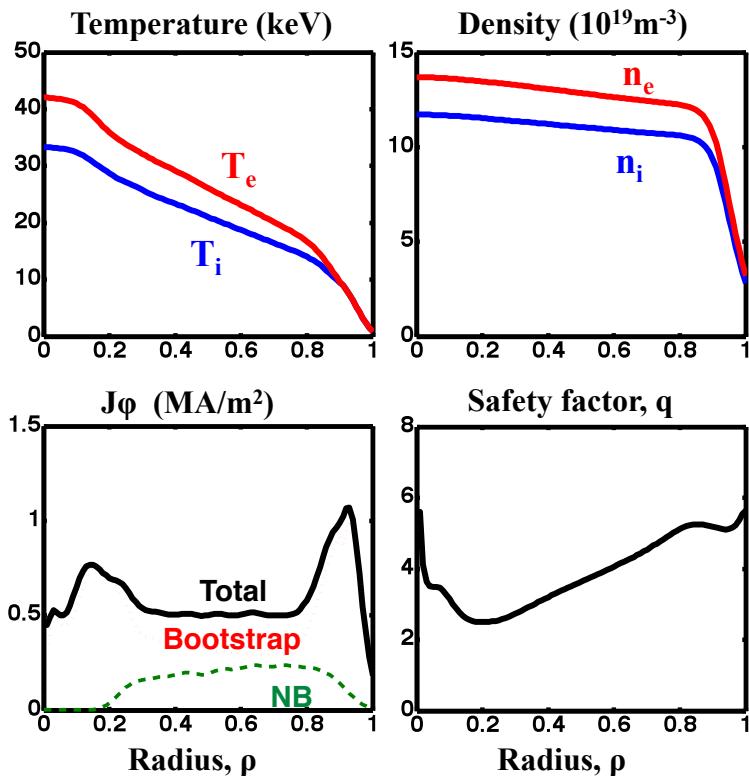
- $R = 6.8 \text{ m} / a = 2.1 \text{ m}$
- $B_0 = 7.0 \sim 7.4 \text{ T} / B\text{-peak} = 16 \text{ T}$
- elongation = 1.8
- triangularity = 0.625
- Plasma current > 12 MA
- $T_e > 20 \text{ keV}$

■ Other Feature

- Double-null & Single-null configuration
- Vertical Maintenance
- Total H&CD Power = 80~120 MW
- $P_{\text{fusion}} = 2200 \sim 3000 \text{ MW}$
- $P_{\text{net}} > 400 \text{ MWe}$ at Stage II
- Number of Coils : 16 TF, 8 CS, 12 PF

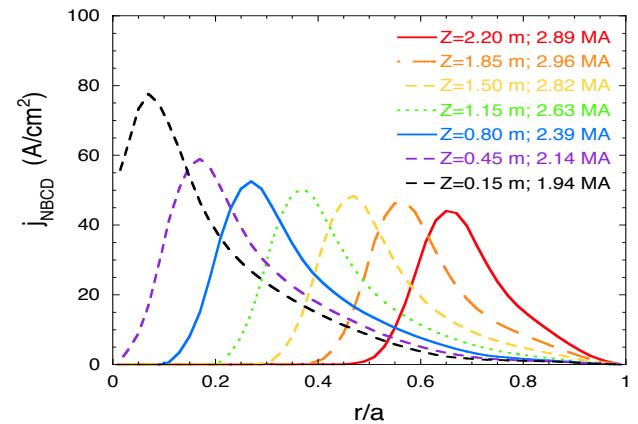
Simulation of K-DEMO operation Operation scenario and H&CD optimization

- Example of the developed steady profiles (
 $P_{\text{fusion}} \sim 2.1 \text{ GW}$ scenario)

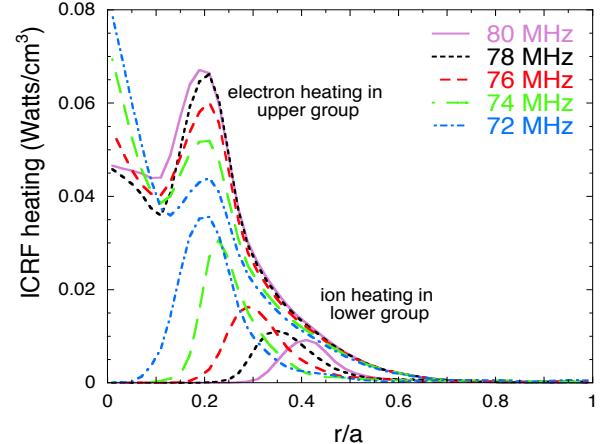


Parameters	Value
P_F (MW)	2080
Q (Fusion Gain)	18.8
P_{NB} (MW)	110 (500keV)
I_P (MA)	15.5
f_{BS}	77 %
β_N	2.8
H_{98y2}	1.2
T_{ped} (keV)	8.3
n_{ped} (/m ³)	9.9×10^{19}

- NBCD depending deposition (~1 MeV, NUBEAM code)



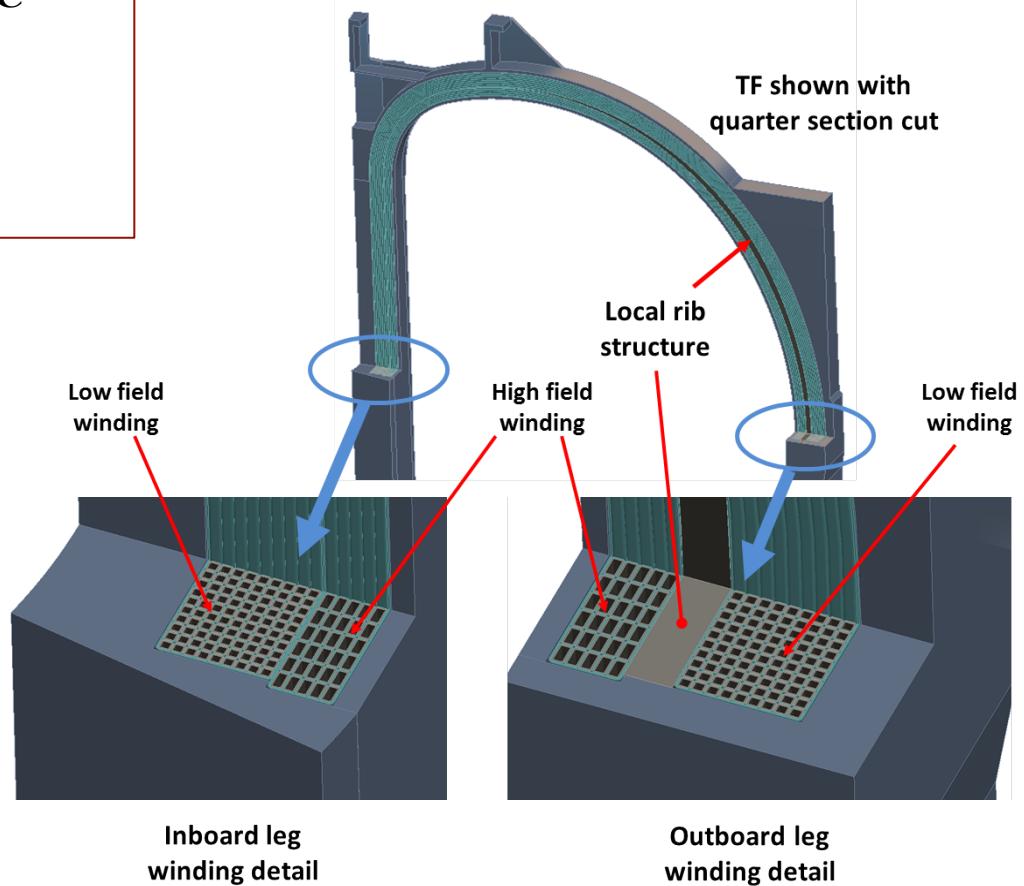
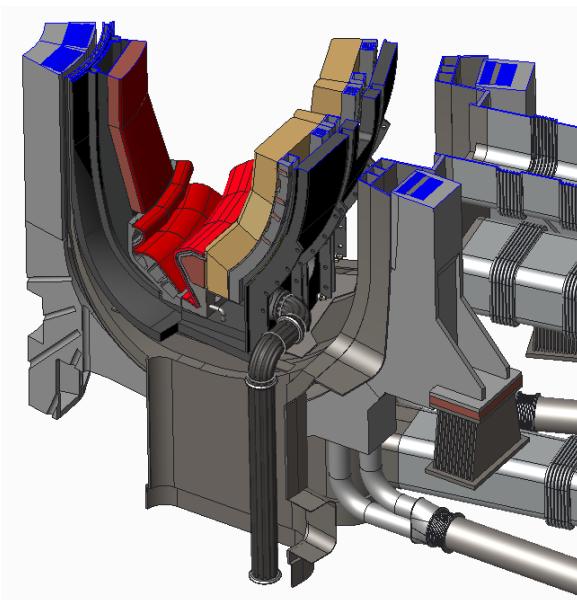
- FWCD (TORIC code)



Magnet and Structure

■ TF Winding

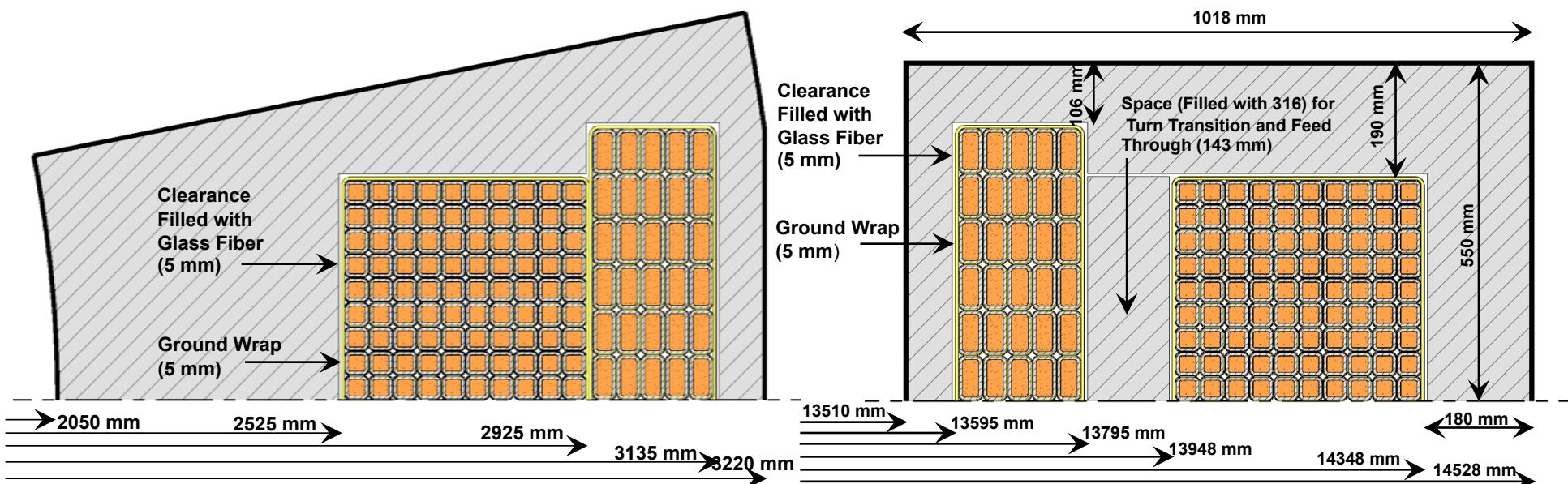
Dual winding packs with 2 types of CICC
→ High magnetic field
with huge Cost savings
(High Jc Strands & No Radial Plate)



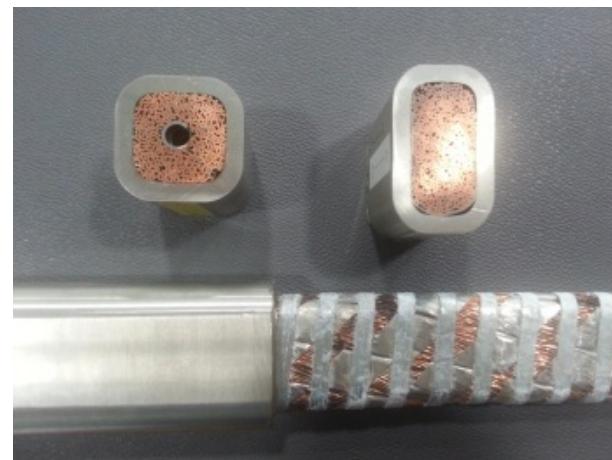
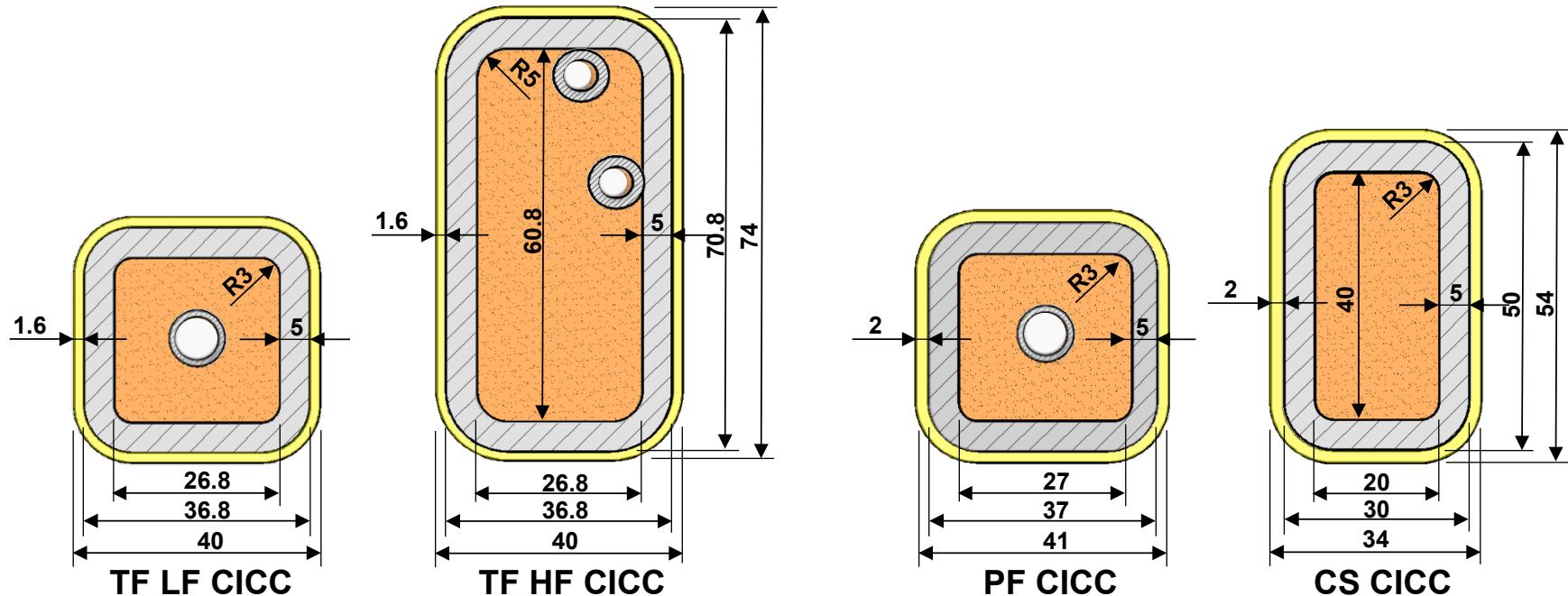
Cross-Section of TF Coil

■ Selected for Detailed Study (Maintenance Space = 2.5 m) Considering Vertical Maintenance Scheme

- $R = 6.8 \text{ m}$, $a = 2.1 \text{ m}$
- Small CICC Coil : 18×10 turns Large CICC Coil : 12×5 turns (Total : 240 turns)
- Magnetic Field at Plasma Center : ~ 7.4 Tesla (Bpeak ~ 16 Tesla, T-margin > 1 K)
- Nominal Current : 65.52 kA
- Conductor Length :
 - LQP = ~ 900 m (Quadruple Pancake) (Total : ~ 450 ton)
 - SDP = ~ 930 m (Double Pancake) (Total : ~ 280 ton)

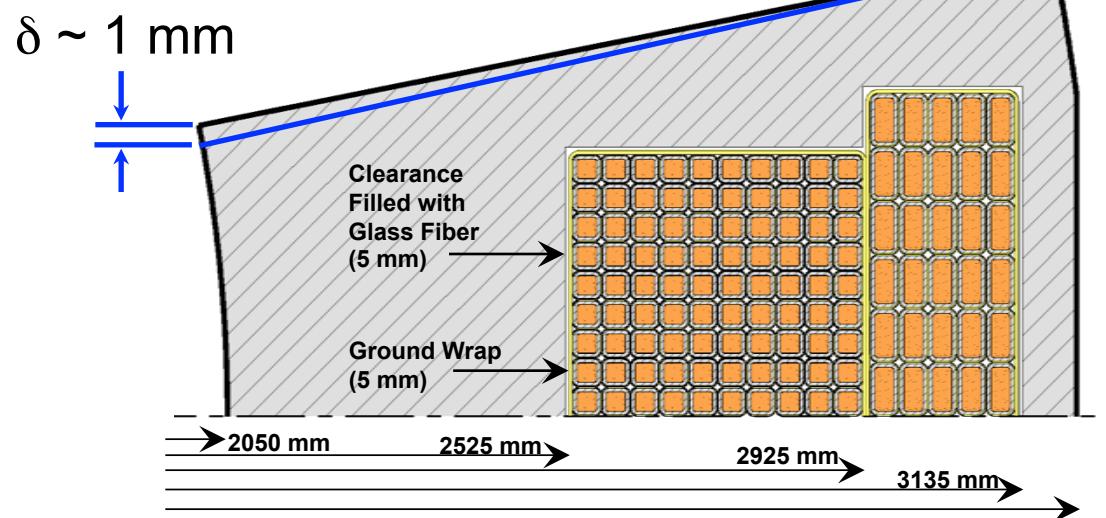
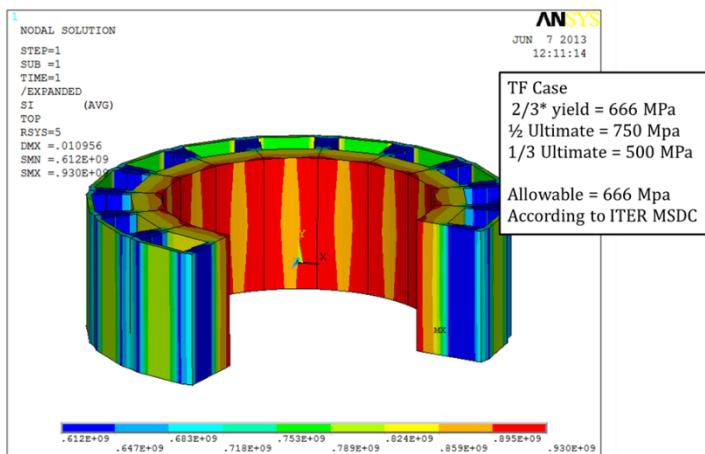
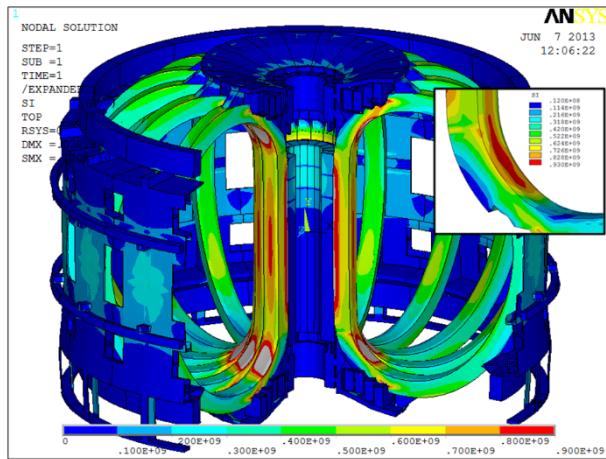


CICC Dimensions and Trial Fabrication



Structural Analysis of TF Case

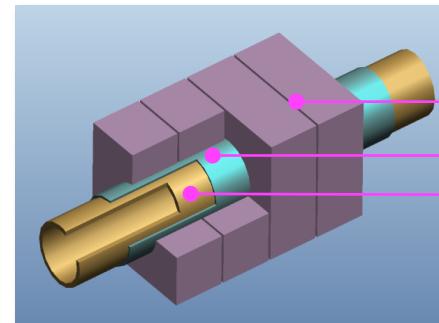
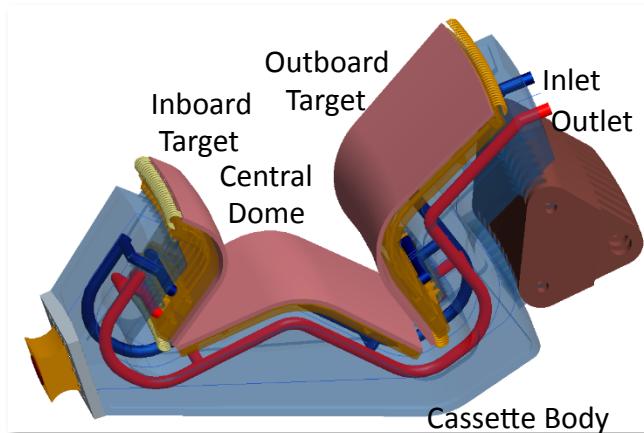
- TF coil case stresses contoured to 900 MPa maximum !!!



- Elastic deformation occurs from the top-right corner of TF inboard side and the maximum stress at the top-left corner can be reduced.
- A detail analysis required to make the stress almost uniform (\rightarrow averaged stress)

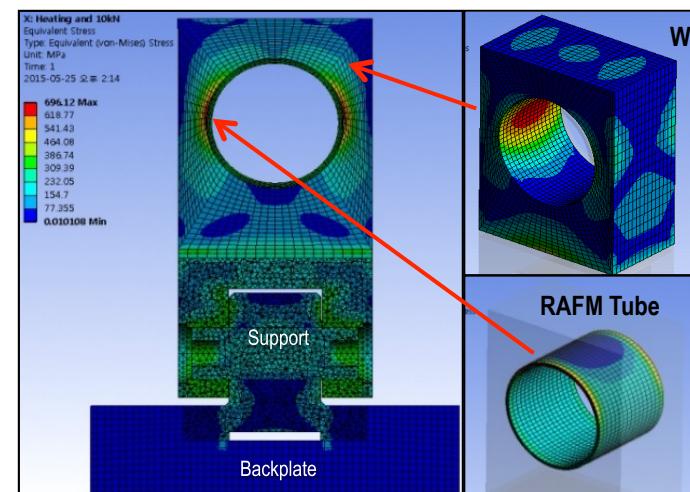
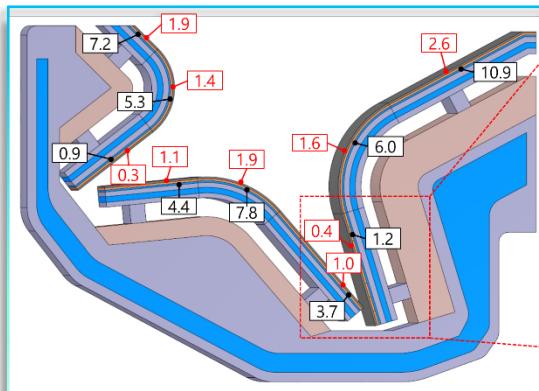
Concept design of Divertor for K-DEMO

- Divertor system with 32 toroidal modules actively cooled with high pressure water



Tungsten mono-block
Vanadium interlayer
RAFM cooling tube
• Coolant – PWR-like
(inlet 290 °C,
 $\Delta T = \sim 40$ °C)

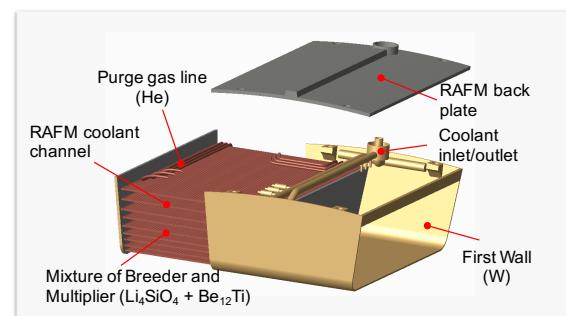
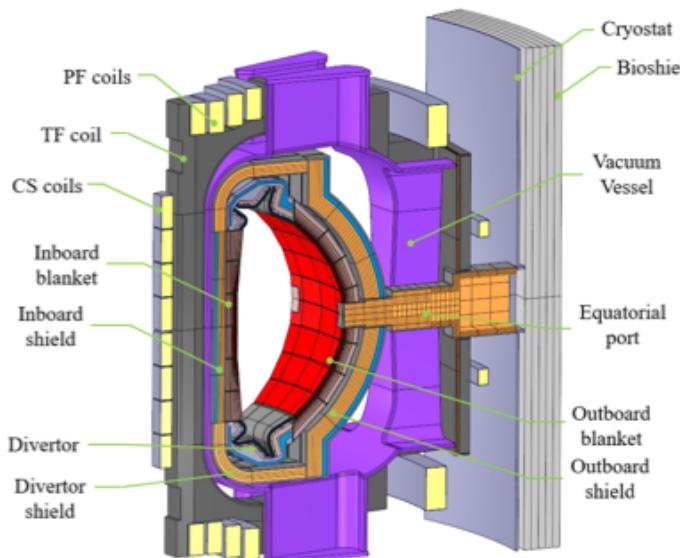
- Estimation of displacement damage on divertor target (peak ~ 2.6 dpa/fpy)



Design of blanket module and Neutronic analysis to achieve TBR > 1

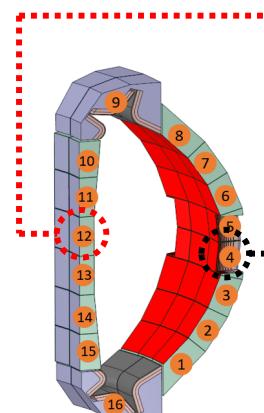
➤ Baseline blanket design with water-cooled solid breeder type

- Global TBR (Tritium Breeding Ratio) ~1.03 (with the double-null)

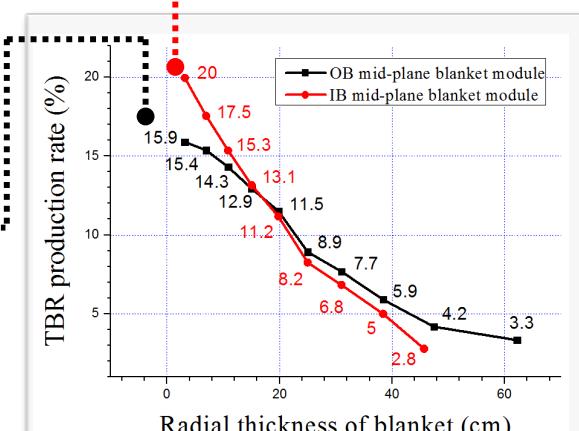


Concept of an indicative blanket module

- Breeder and multipliers: Mixture of Li_4SiO_4 and Be_{12}Ti ceramic pebbles
- Structural material: RAFM & Tungsten first wall
- Coolant: pressurized water (15 MPa, 290~330 °C)
- FW heat flux: 0.5 MW/m² (peak)
- Neutron wall load: ~2.5 MW/m² (avg.) / ~3.9 MW/m² (peak)



Breeding regions



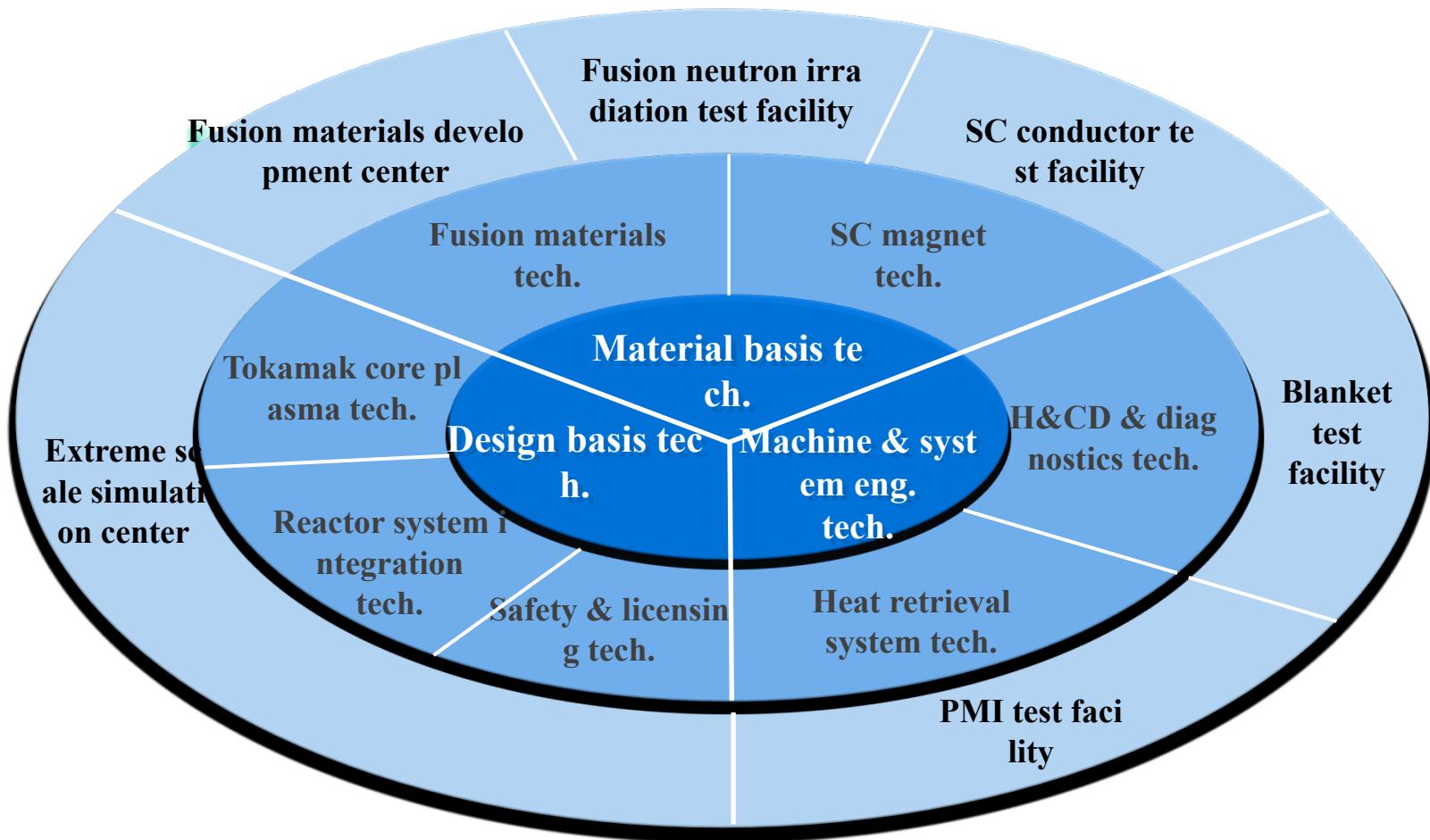
TBR production rate in IB/OB midplane blanket modules



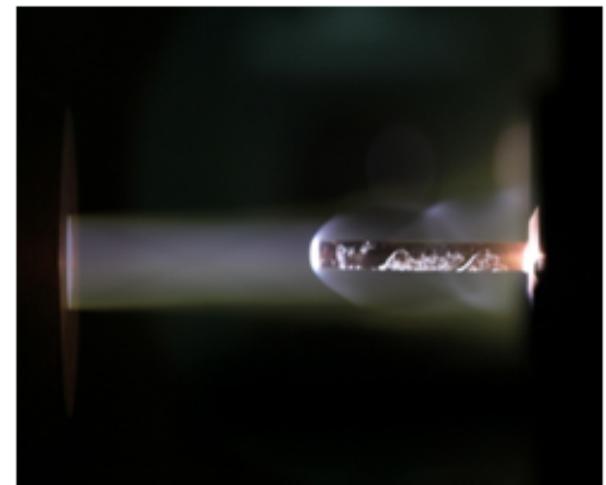
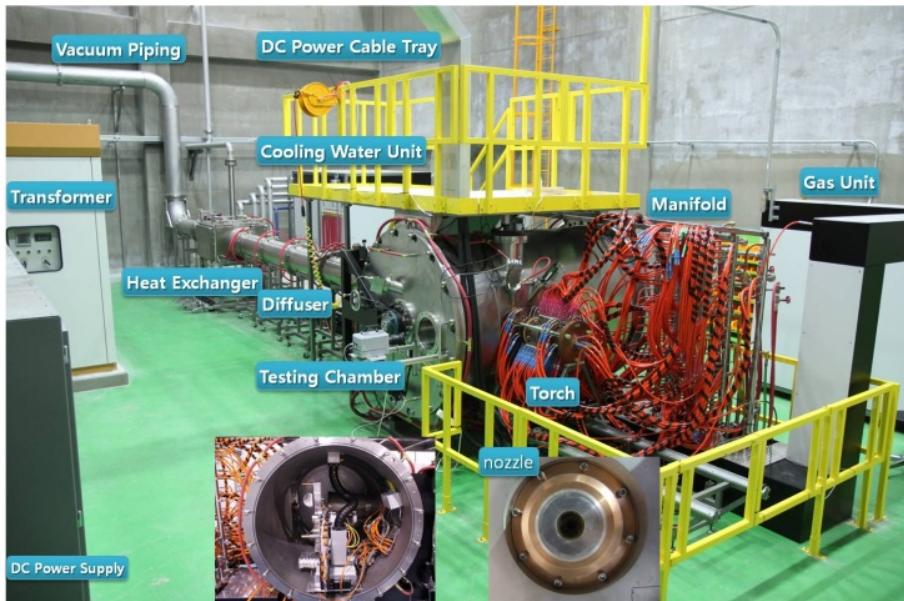
DEMO Core Technology Development Plan

K-DEMO Core Technology Development ♪

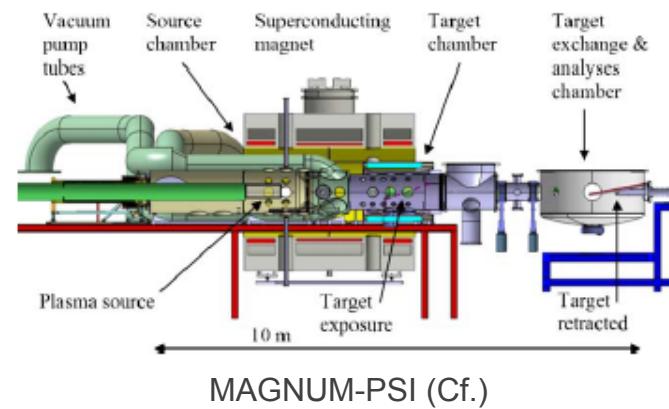
- **3 Major Research Fields, 7 Core Technologies, 18 Detail Technologies and 6 Major Research Facilities** were identified to develop K-DEMO.



PMI Test Facility (Chonbuk Province)



- **2.4 MW High-Temperature Plasma Test Facility**
 - Plasma-Material Interaction(PMI) Test facility
 - Upgrade Plasma Facility for PMI Test
 - Additional, Blanket Test Facility

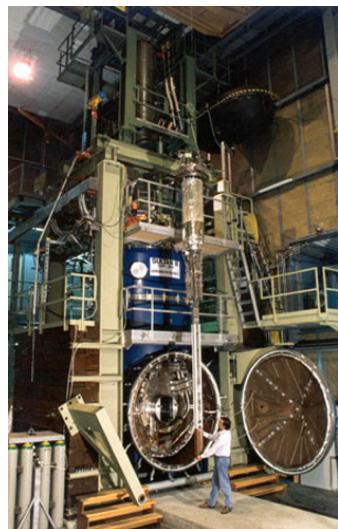
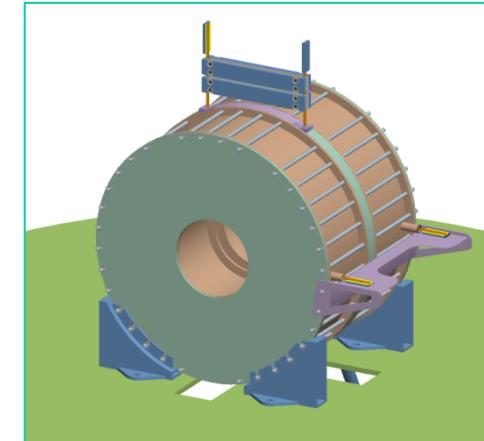


Superconducting Conductor Test (SUCCEX) Facility



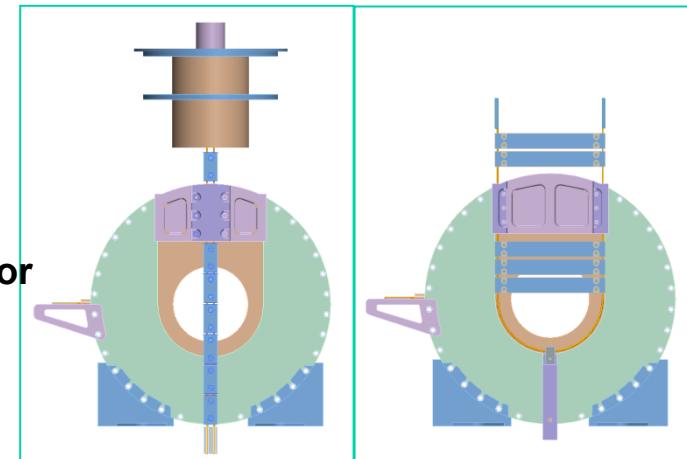
■ SUCCEX (SUperConducting Conductor EXperiment)

- 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

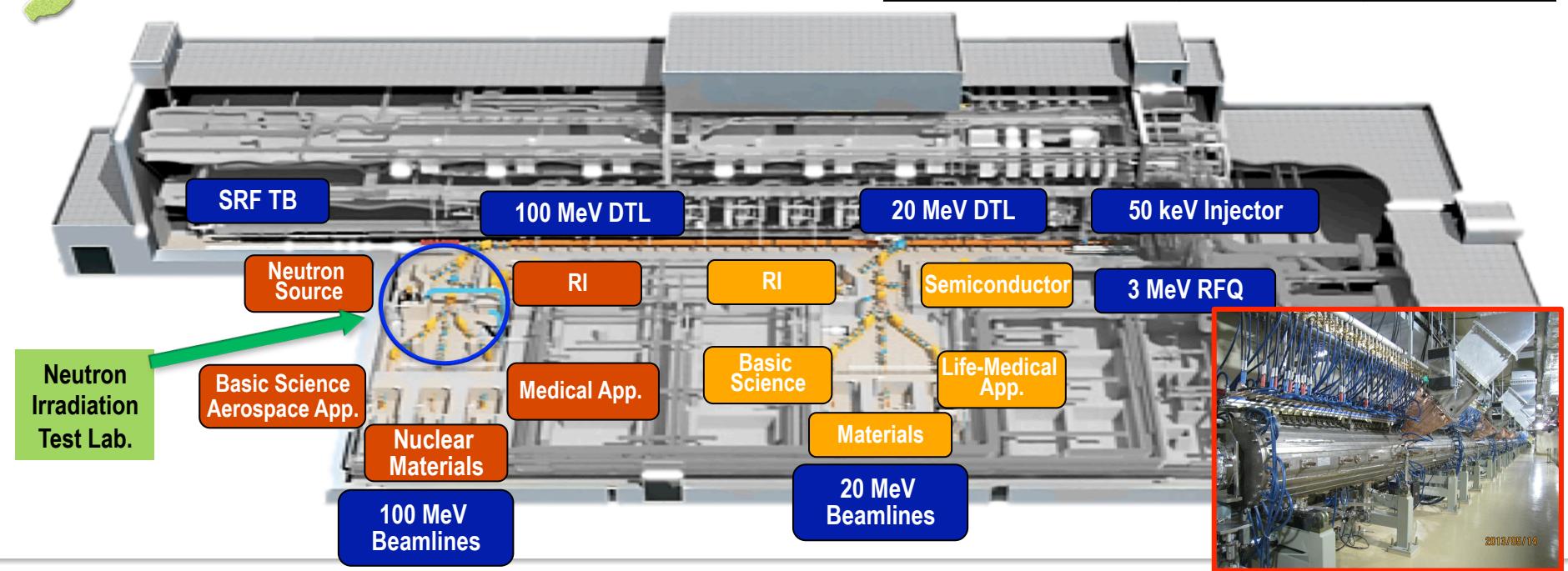
20 & 100 MeV KOMAC Proton Linac



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



Fusion Reactor Materials R&D



Advanced research reactor



Radioisotope fusion research institute



Dongnam institute of radiological & medical sciences

Extreme Environment Material R&D Hub



Electric power semiconductor research



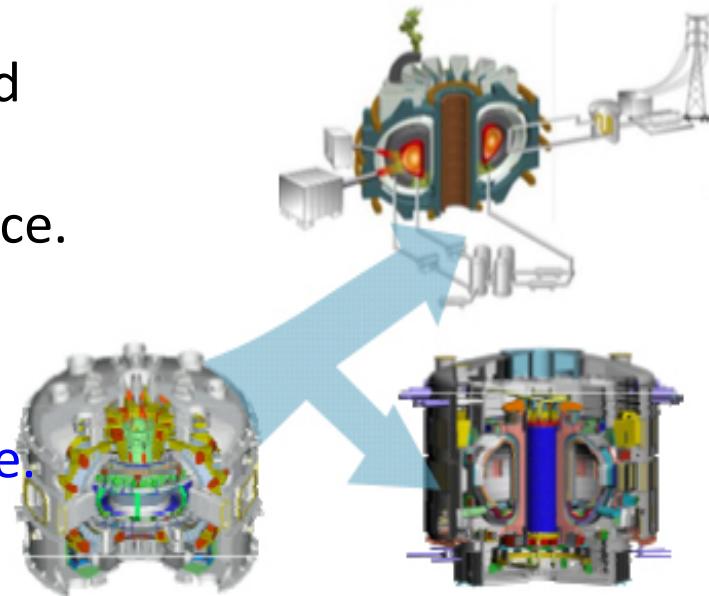
Korea heavy ion medical accelerator center



Korea institute of radiological science and tech.

Summary

- Korea fusion R&D programs are supported under “Korea Fusion Energy Promotion Law”.
- KSTAR made outstanding progress in achieving steady-state high performance plasma and achieving ELM-free H-mode
- KSTAR will explore advanced higher performance operation to contribute K-DEMO by heating & CD
- The contribution to ITER construction and operation could convince the burning plasma operation with reactor-scale device.
- Design of K-DEMO accompanied by simulation is on-going to get reasonable values of TBR, heat flux, and performance.
- Separate R&D program for K-DEMO technology development is TBD.



Thank you for your attention !



Stronger efforts are necessary to ensure the fusion energy for the next generation..