IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
Plenary presentation 2PL_01 given at MT24; Seoul, Korea, October 18 to 23, 2015.

Progress on Conceptual Design of the K-DEMO Magnet System

October 20th, 2015

Keeman KIM

National Fusion Research Institute

미래창조과학부
Ministry of Science, ICT and Future Planning

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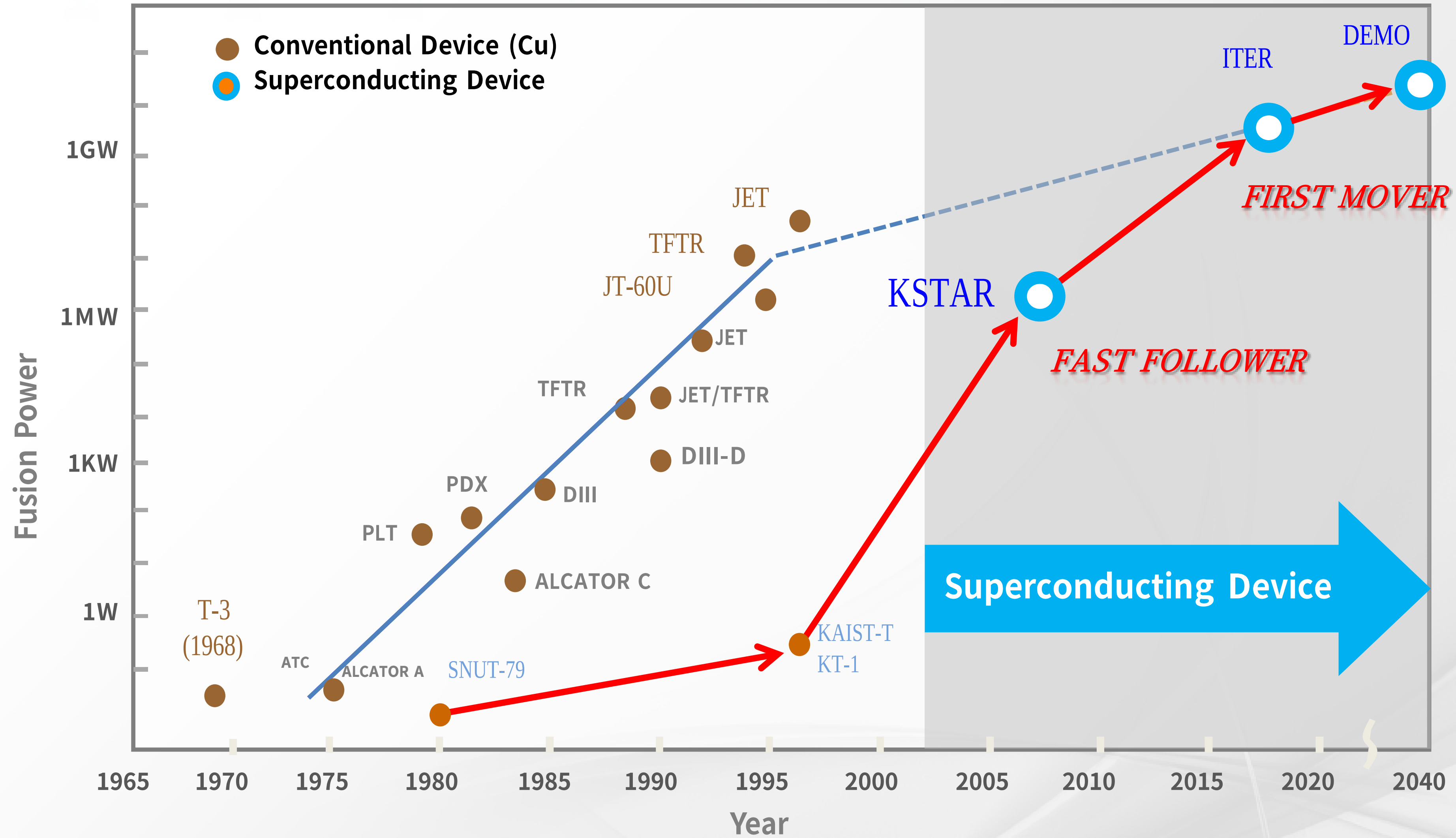
Mid-Entry Strategy : Korea, Year 1995



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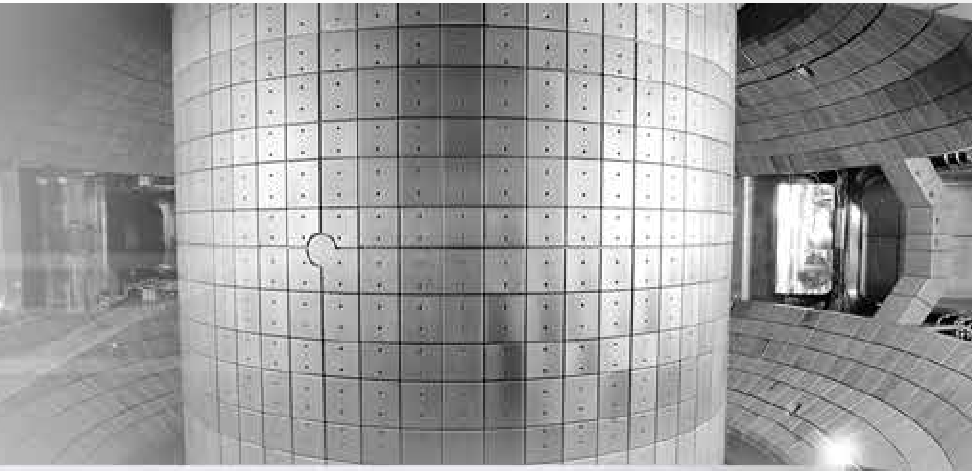
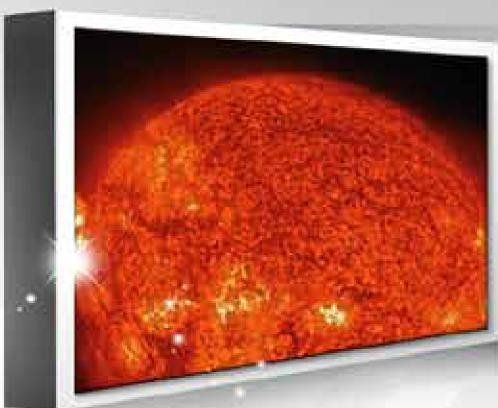


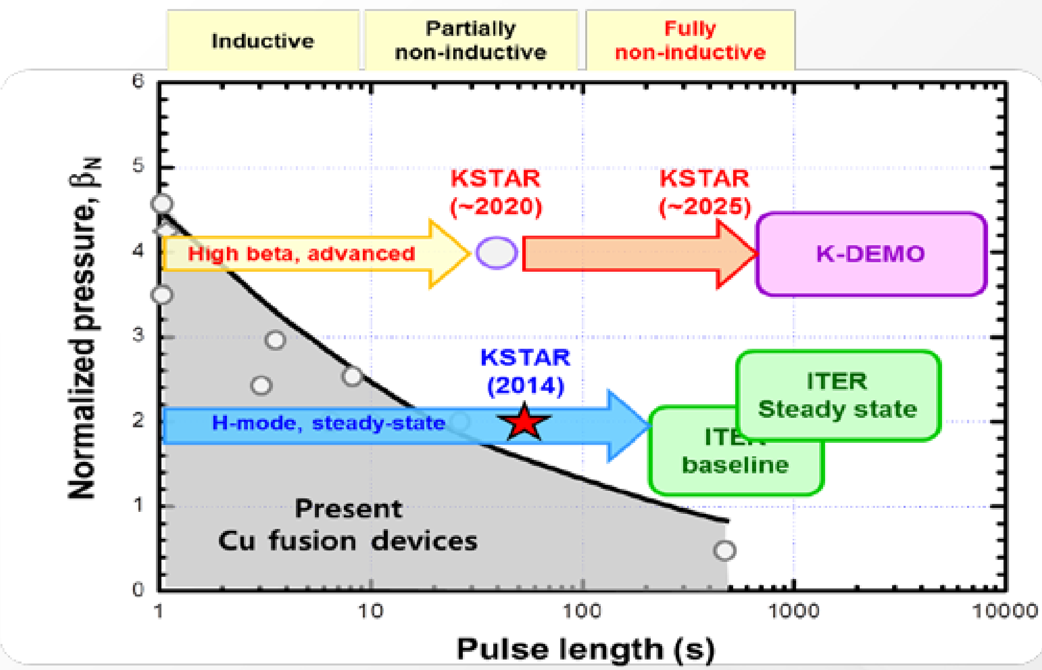


KSTAR and ITER Project

KSTAR Mission and Key Parameters

Ø 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



Ø Achieved key parameters

Parameters	Designed	Achieved (~2014)
Major radius, R_0	1.8 m	1.8 m
Minor radius, a	0.5 m	0.5 m
Elongation, k	2.0	1.8
Triangularity, d	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	45 s
b_N	5.0	4.0
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD	~ 28 MW	~ 7 MW
PFC	C, CFC, W	C

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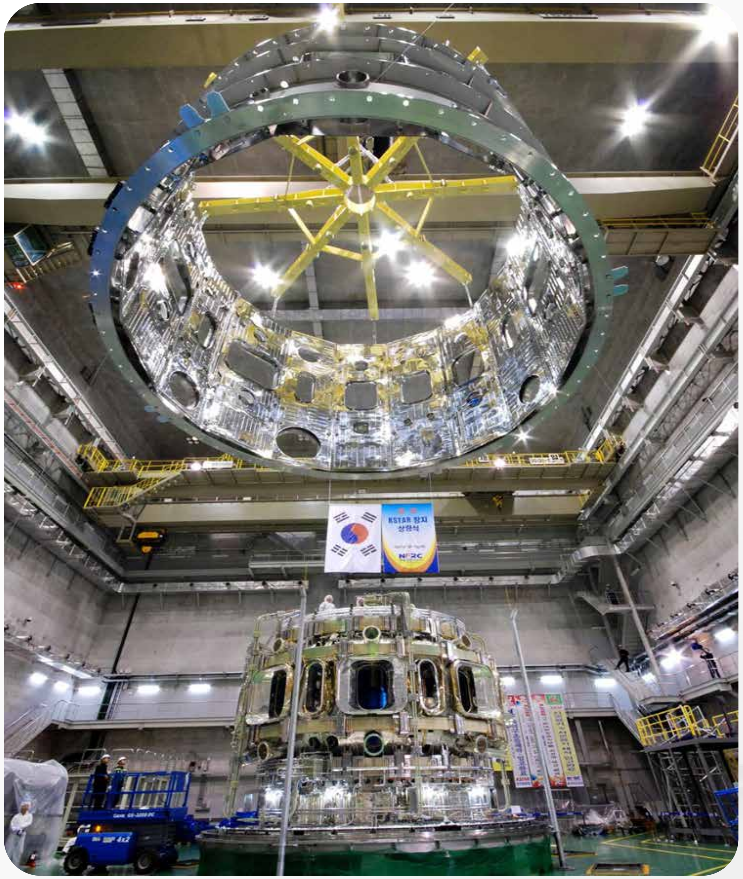
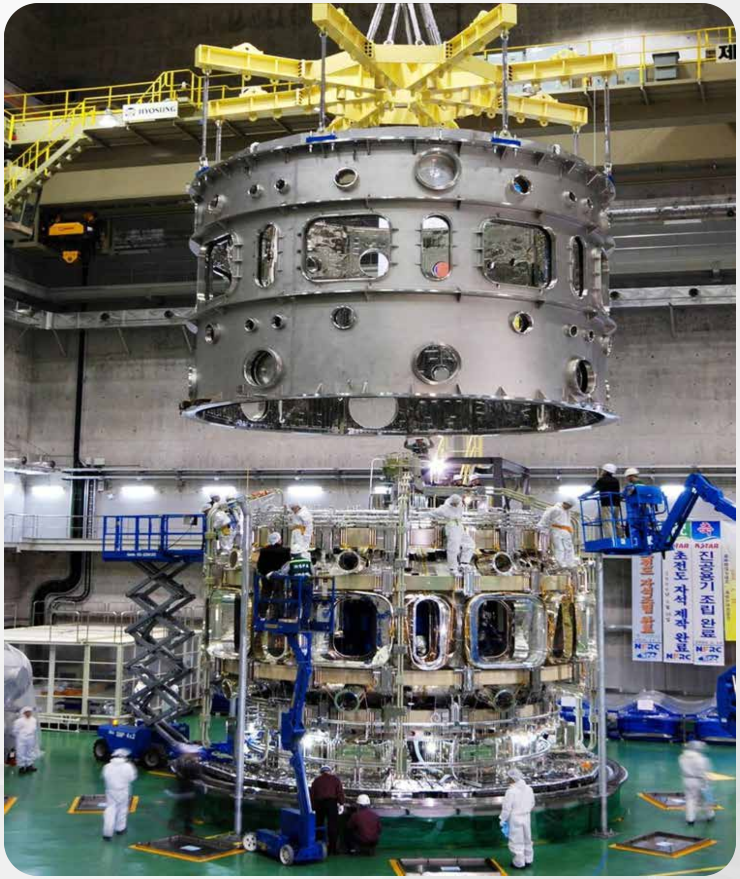
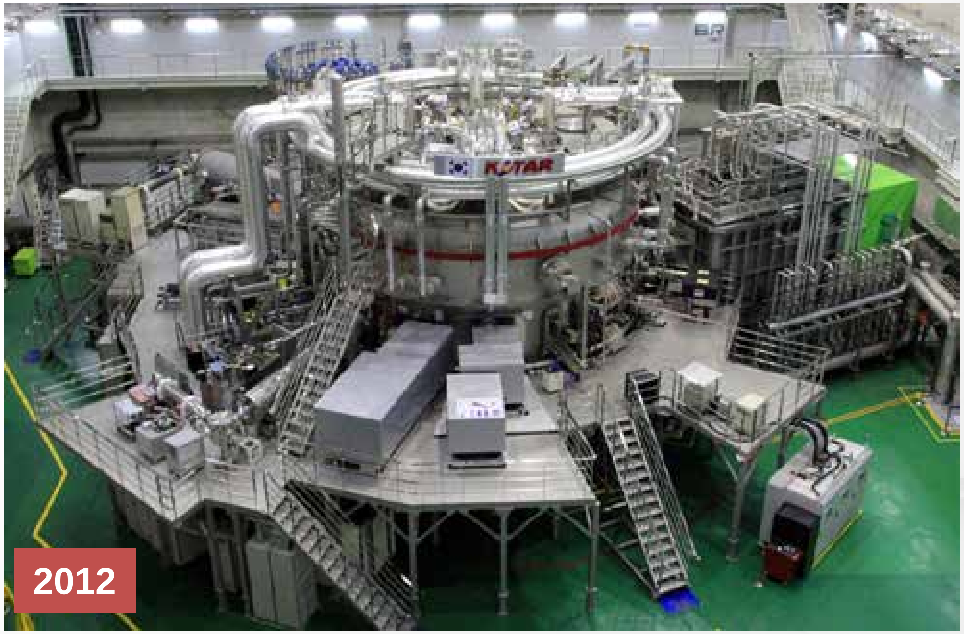
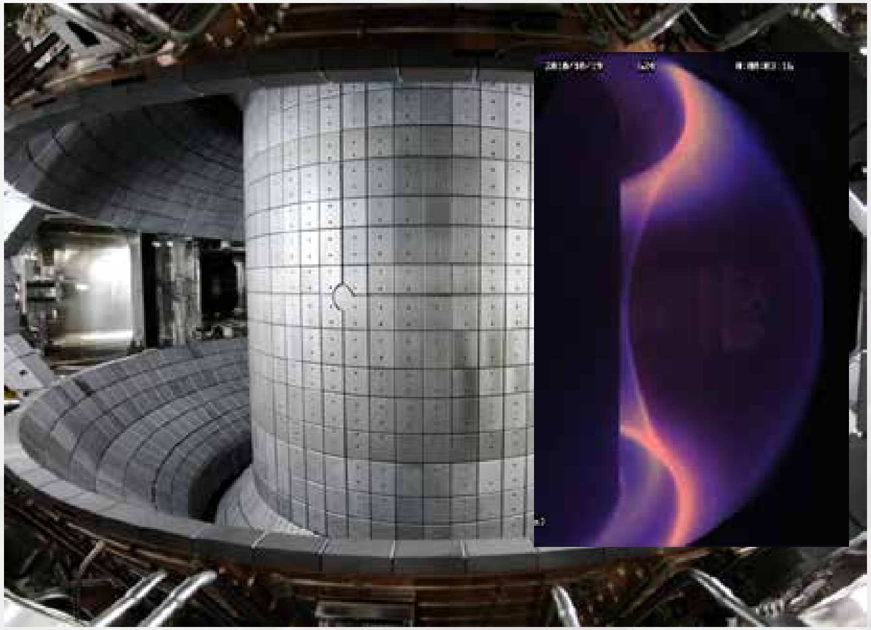
KSTAR Final Assembly (2007. 1)





KSTAR Superconducting Tokamak





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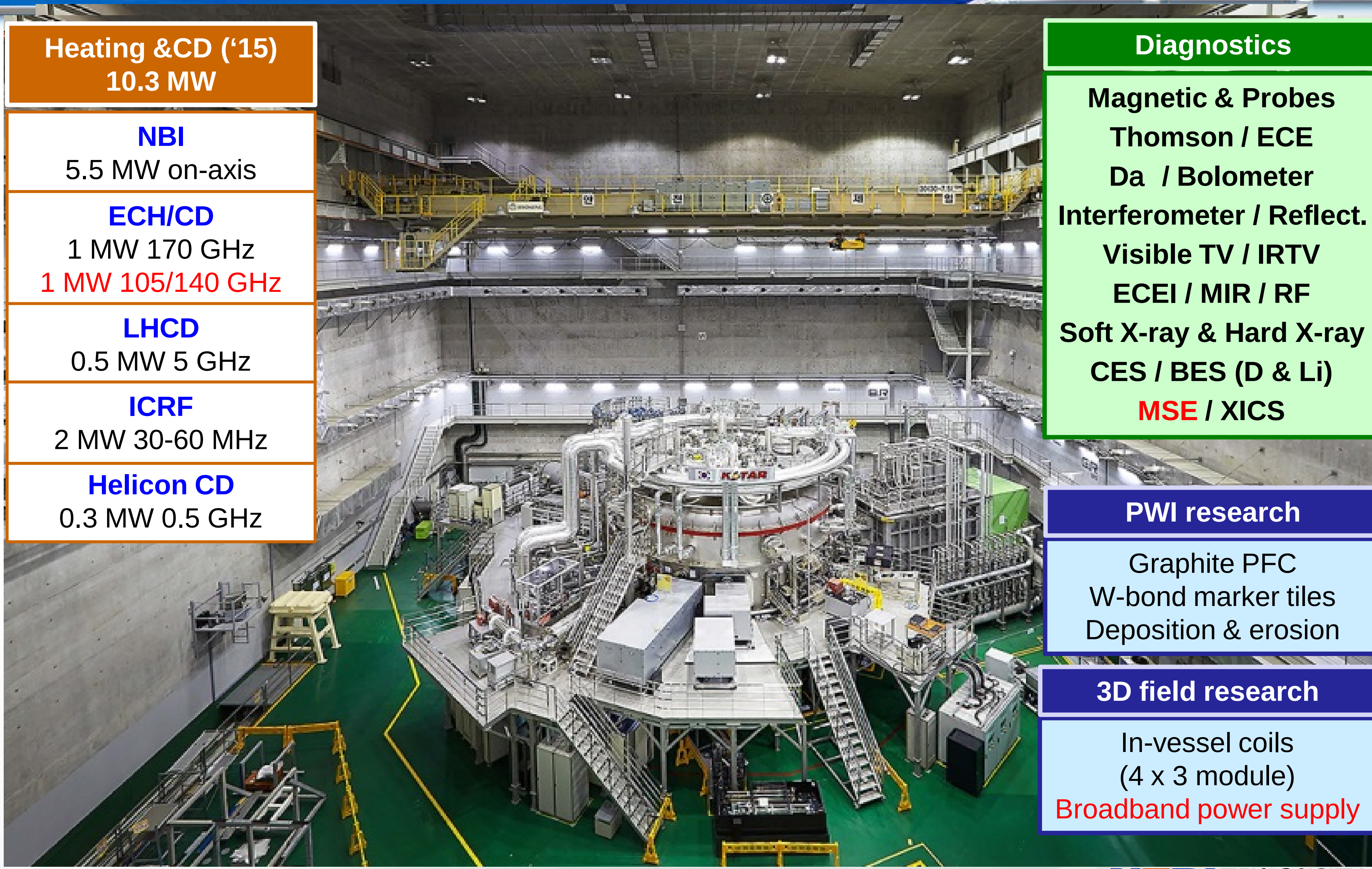
KSTAR Device and Key Components



Heading &CD ('15)
10.3 MW

NBI
5.5 MW on-axis

ECH/CD
1 MW 170 GHz
1 MW 105/140 GHz

LHCD
0.5 MW 5 GHz

ICRF
2 MW 30-60 MHz

Helicon CD
0.3 MW 0.5 GHz

Diagnostics

Magnetic & Probes
Thomson / ECE
Da / 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

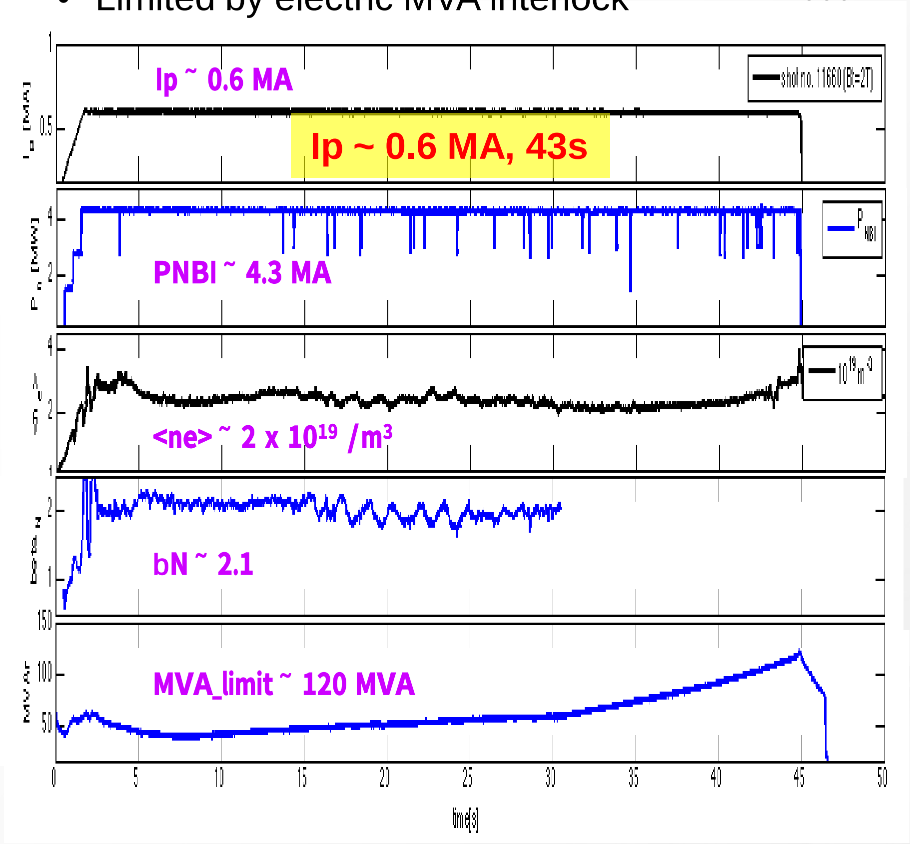
In-vessel coils
(4 x 3 module)
Broadband power supply

Recent operation results toward long-pulse large current H-mode discharge

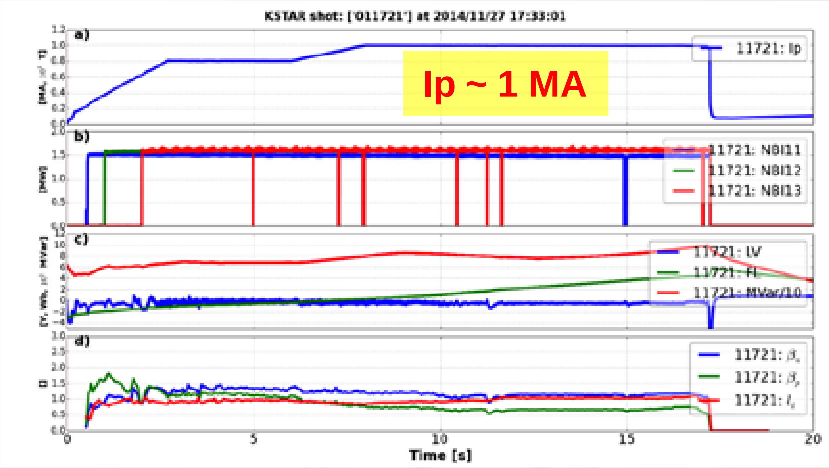
■ Long-pulse H-mode discharge : 48s (0.5 MA), 43s (0.6 MA),

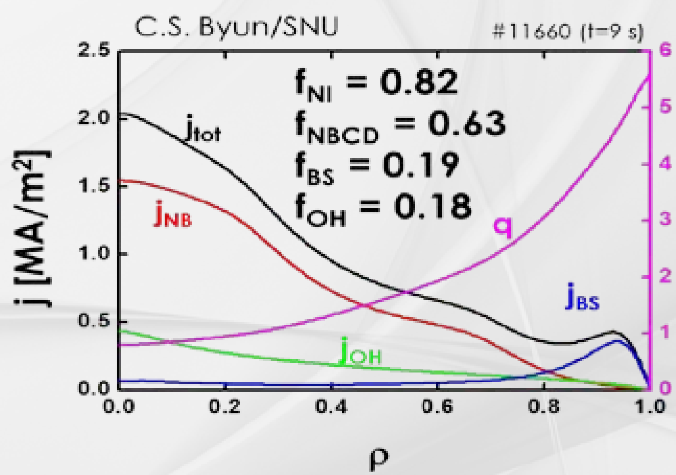
- Ip = 0.6 MA, t_{Hmode}~43s, B_T=2T, P_{NBI} ~ 4.3 MW,
- W_{dia} ~ 0.4MJ,<ne> ~ $2\times10^{19}/m^3$,
- b_N ~ 2.1, H_{89} ~ 1.7, f_{NI} ~ 0.8
- Limited by electric MVA interlock

#11660



■ Large plasma current H-mode discharge 1 MA (9s), goal : 2 MA (300s)





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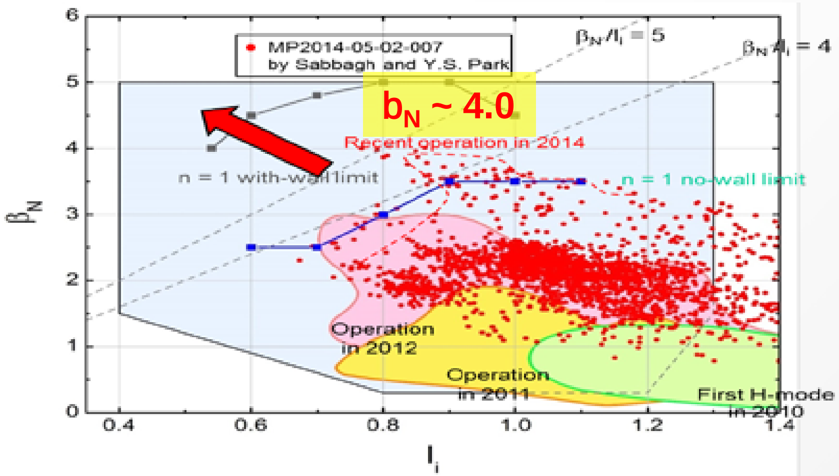
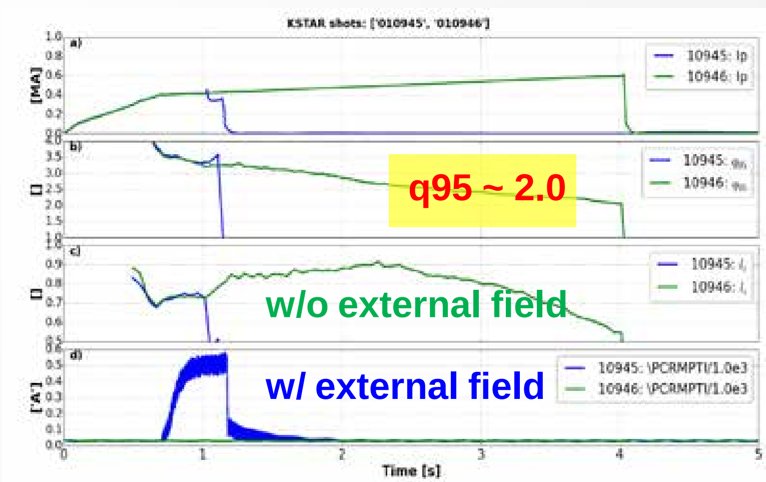
Exploring the advanced high performance scenarios development

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

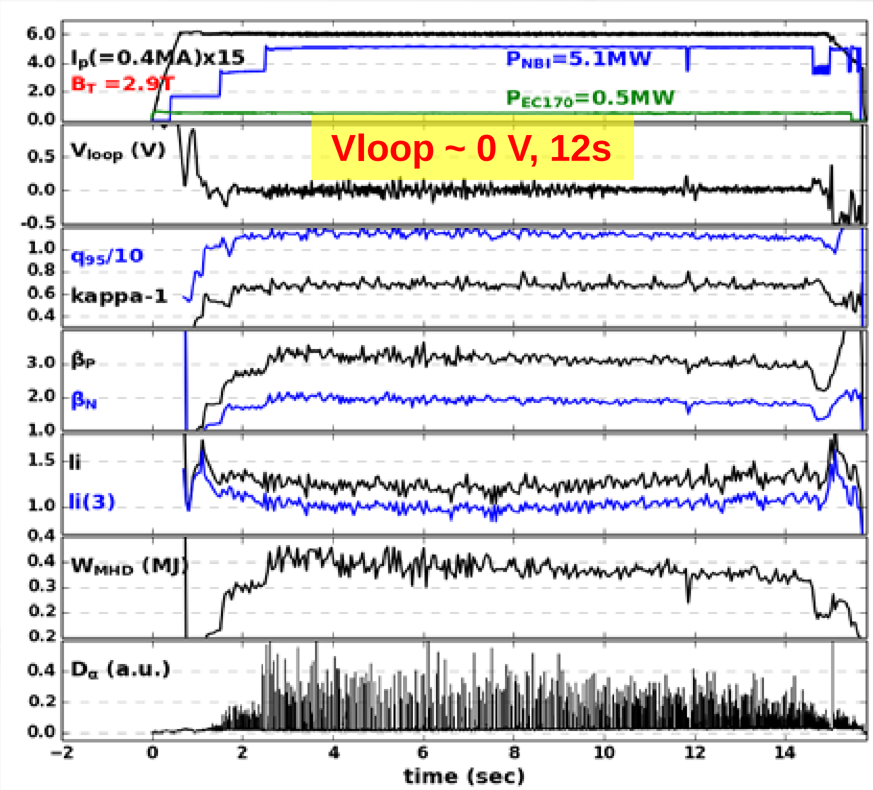


- **Extremely low q95 (q95 ~ 2.0) operation verifying extremely low error field**



- **Fully non-inductive H-mode discharge 12s (0.4 MA, fNI ~ 1.0)**
  - Ip = 0.4 MA, t_{Hmode}~14s, B_T=2.9T,
  - $P_{NBI+ECH}$ ~ 5.6 MW, W_{dia} ~ 0.4MJ,
  - b_N ~ 2.1, li ~ 1.3, f_{NI} ~1.0
  - Limited by limiter temperature interlock

#13008



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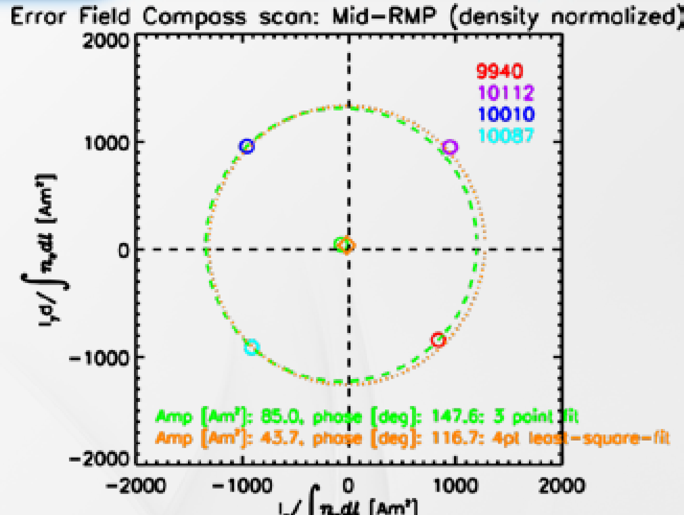
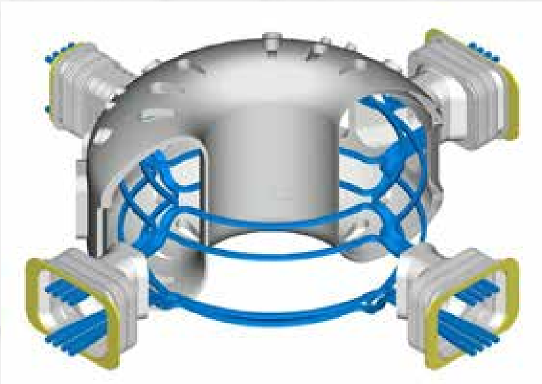
Validation of low intrinsic error field and potential of 3D field research

- **Lowest intrinsic error field (EF) and TF ripple compared to any other tokamaks**
  - Extremely low intrinsic error field measured by standard campus scan using IVCC
  - $\delta B_{2/1} / B_0 \sim 1 \times 10^{-5}$
  - TF ripple at edge ~ 5×10^{-4}
- **3D field research capability using in-vessel control coils & broadband power supplies**
  - Unique features of in-vessel coils with 3 poloidal rows
  - Magnetic perturbation at n=1, n=2, and mixed
  - Mixed mode error field perturbation study
  - Dynamic error field correction
  - NTV rotation control, RWM stabilization
- **Establish limits for confinement and stability of the tokamak plasmas**



Standard compass scan of error field



KSTAR in-vessel coils

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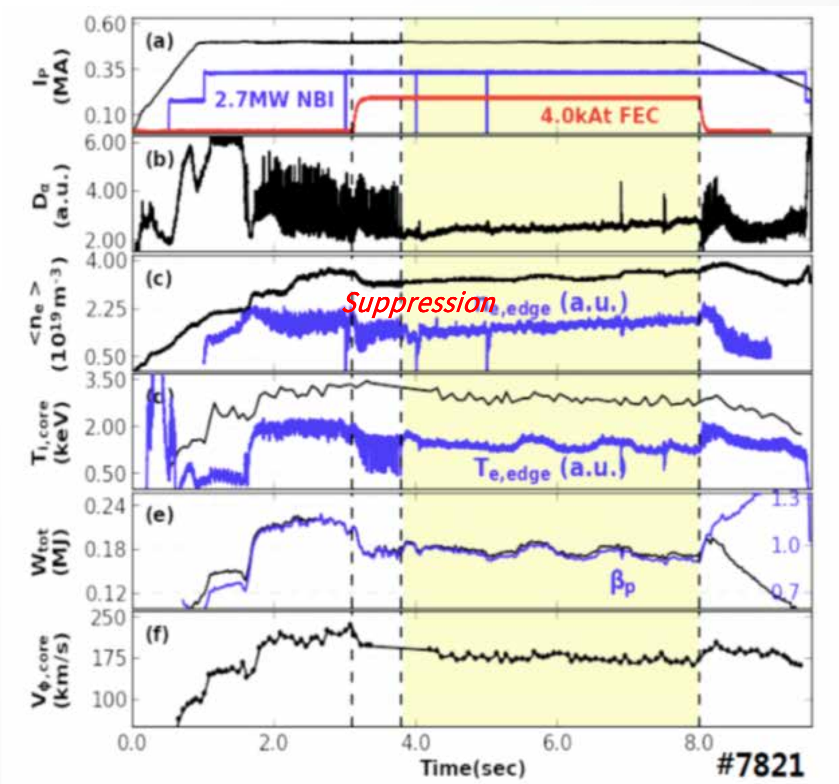
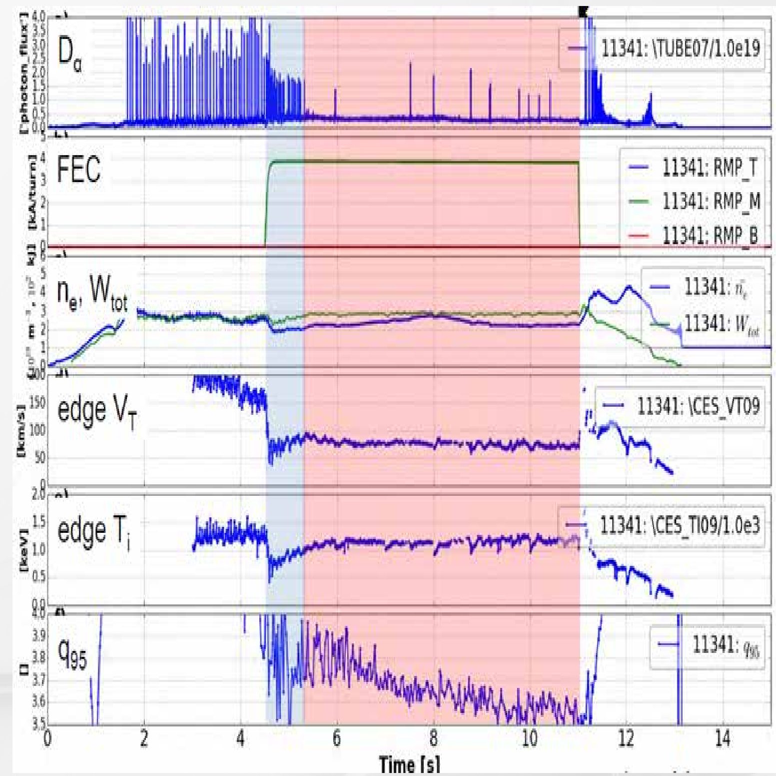
Edge Localized Mode (ELM) -crash suppression using low-n error field uniquely in KSTAR

- **KSTAR is unique device showing the ELM-crash suppression at n=1 (up to 4s) and n=2 middle coil operation (up to 5s) .**
  - 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



ELM-crash suppression at n=1 (4s)



ELM-crash suppression at n=2 (5s)

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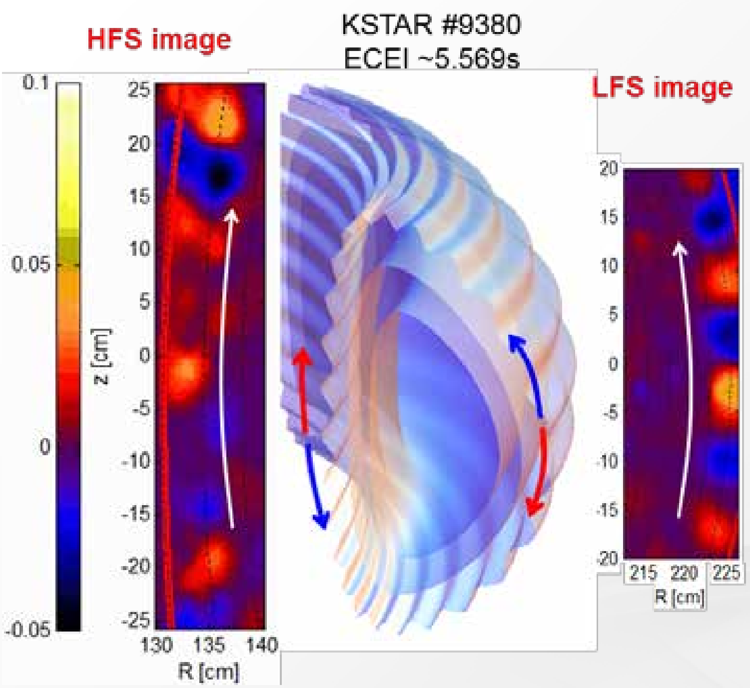
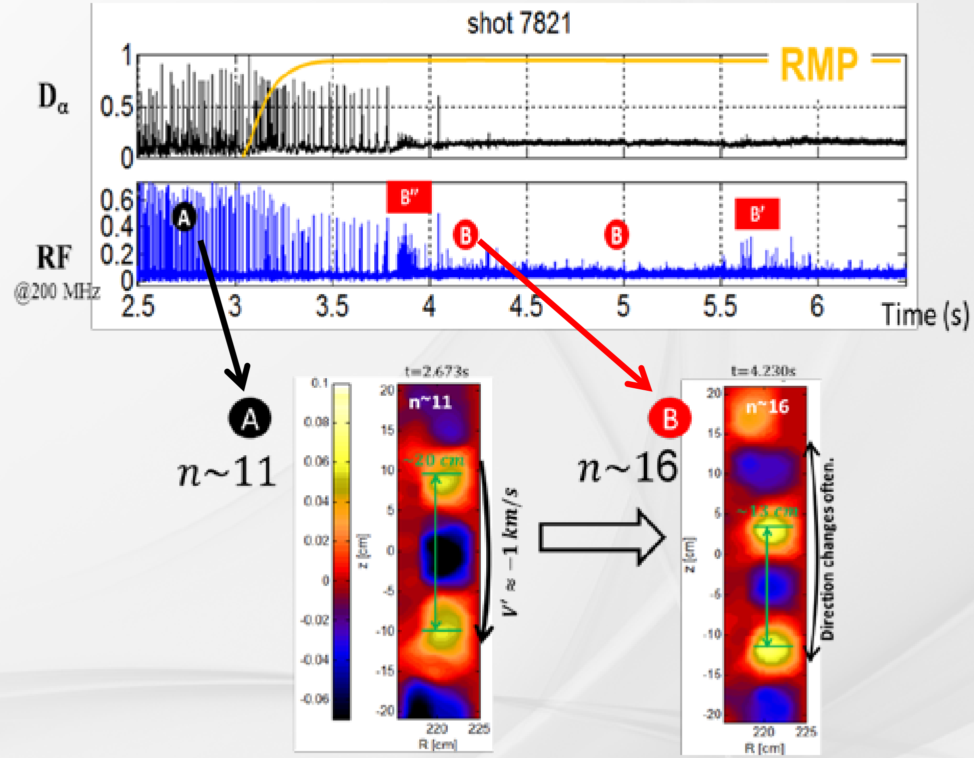
Re-assessment of ELM crash mechanism using advanced diagnostics (2D/3D ECEI, MIR, RF, etc)

- **2D/3D observation of the edge filamentary structure using ECEI advanced diagnostics gives a new assessment of the ELM crash and suppression mechanism**

- **Under ELM crash suppressed phase, conventional Da signal is suppressed.**
- **But Edge localized mode is remain (Higher-*n* coherent modes, marginally stable)**





Gunsu Yun, ITER ELM workshop (2015)

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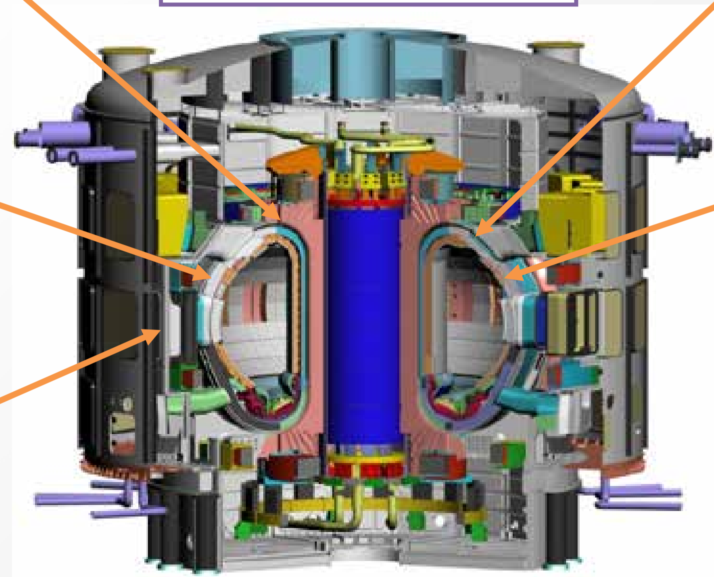
ITER Project : In-kind Contribution of Korea

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

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

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



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

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

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

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Procurement Schedule of the KODA

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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)

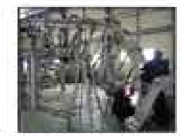
Shipping of Conductor to Japan

- **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

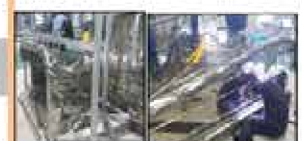
2D bending

3D forming



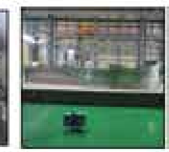
In-board welding

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.

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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:

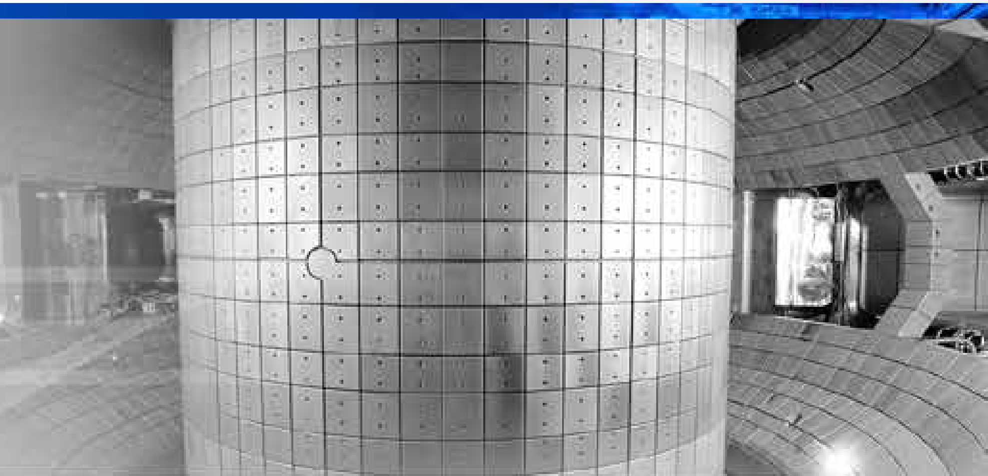
- Attainment of KSTAR high-performance plasma and development of DEMO basic technology
- Basic research in fusion and cultivation of man power
- International cooperation and improvement of status in ITER operations
- Commercialization of fusion/plasma technology and promotion of social acceptance

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.

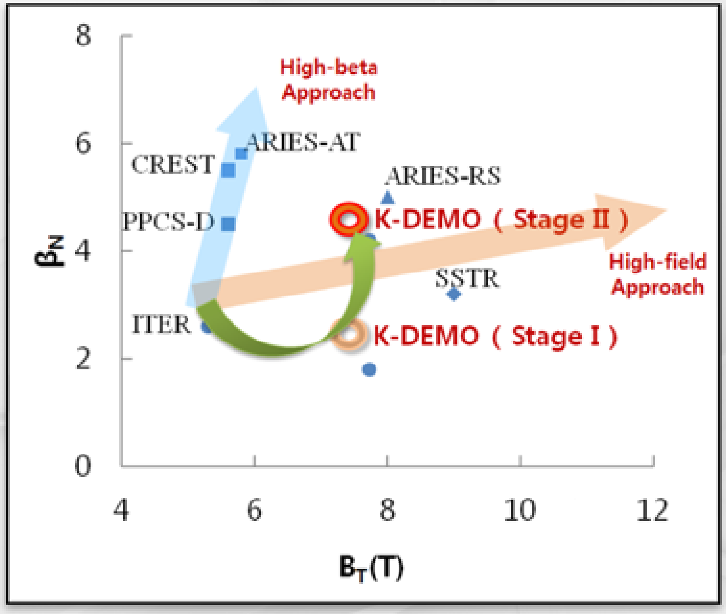
K-DEMO 3 Major Research Fields	K-DEMO 7 Core Technologies	Major Research Facilities
Design Basis Technology	Tokamak Core Plasma Technology	• Extreme Scale Simulation Center
	Reactor System Integration Technology	
	Safety and Licensing Technology	
Material Basis Technology	Fusion Materials Technology	• 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	



K-DEMO Magnet System

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.



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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**]

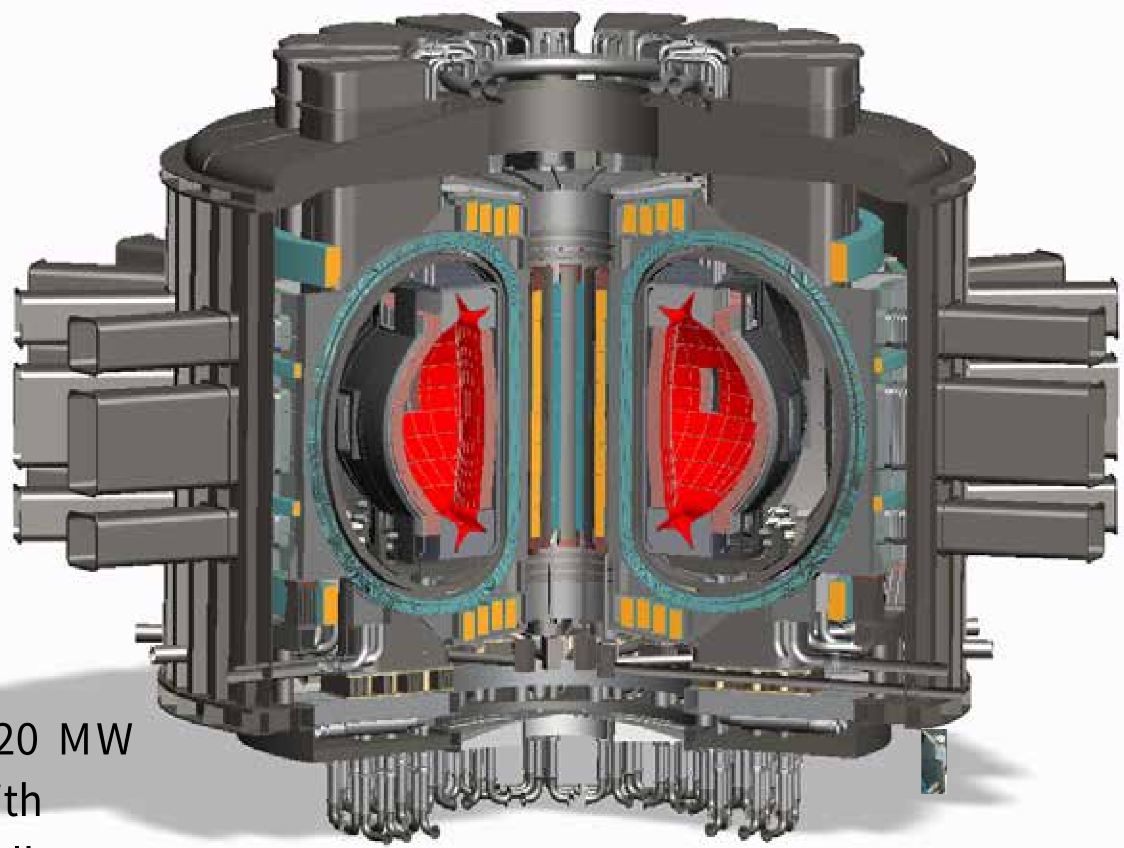
■ Choice of Coolant and Blanket System

- 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

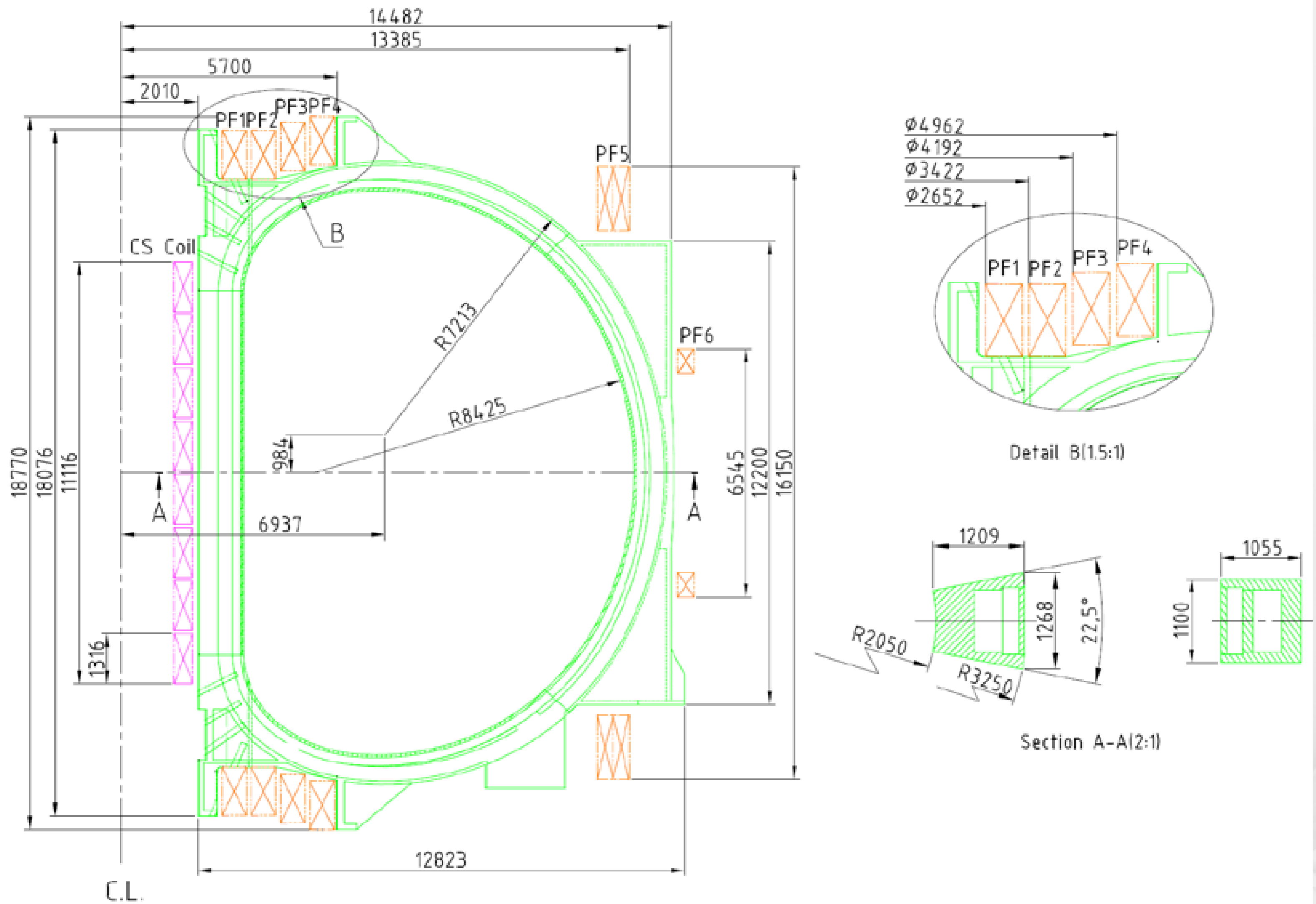
- R = 6.8 m
- a = 2.1 m
- B-center = 7.0~7.4 T
- B-peak = 16 T
- k_{95} = 1.8
- d = 0.625
- Plasma Current > 12 MA
- Te > 20 keV



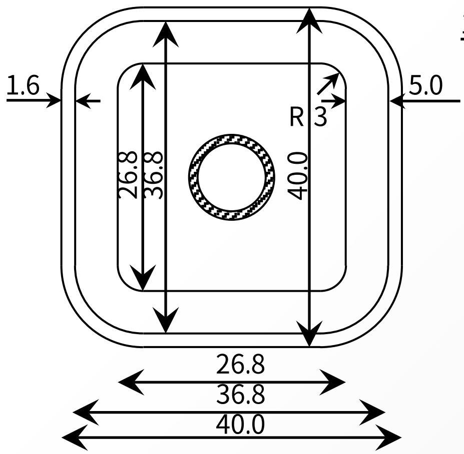
■ Other Feature

- 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

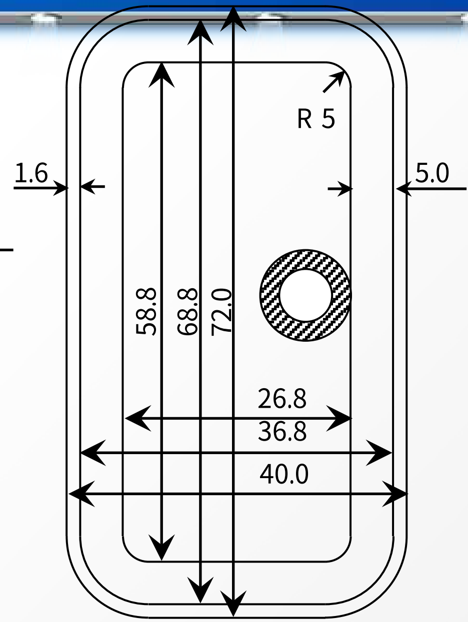
2D Drawing of Magnet System



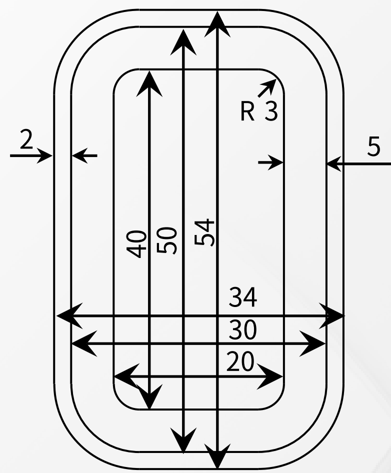
CICC Dimensions and Trial Fabrication



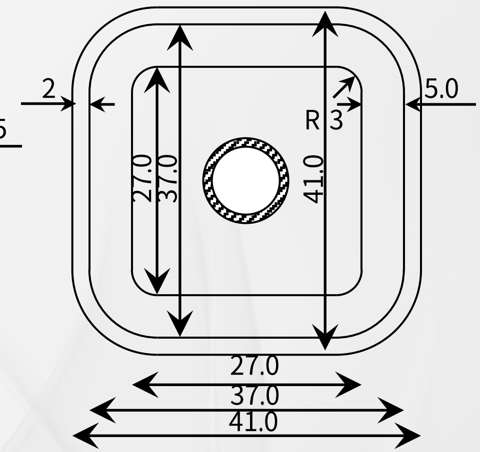
TF LF CICC



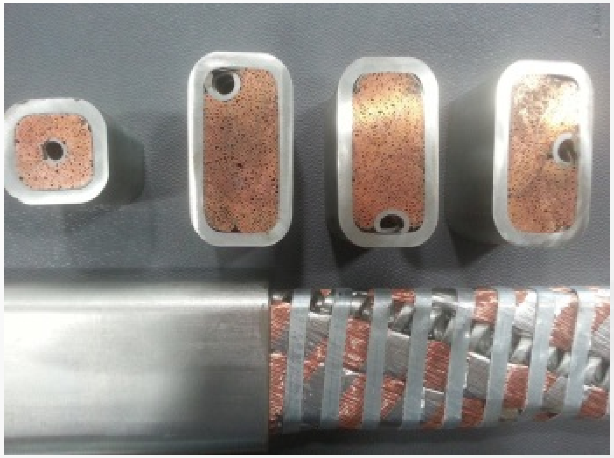
TF HF CICC

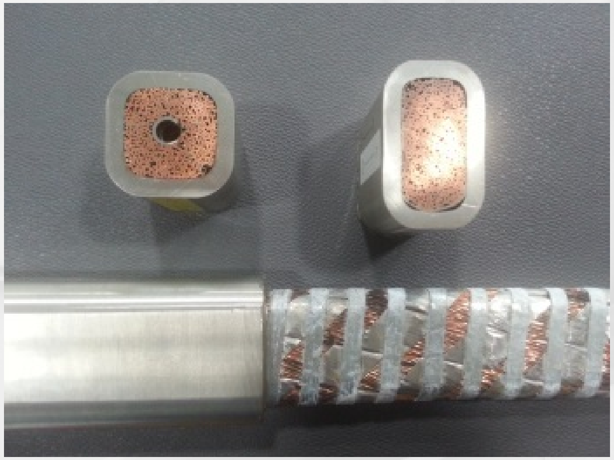


CS CICC



PF CICC





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 + Helical Spiral 1800 - ID 7 / OD 11	(((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 (%)	27.6	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				

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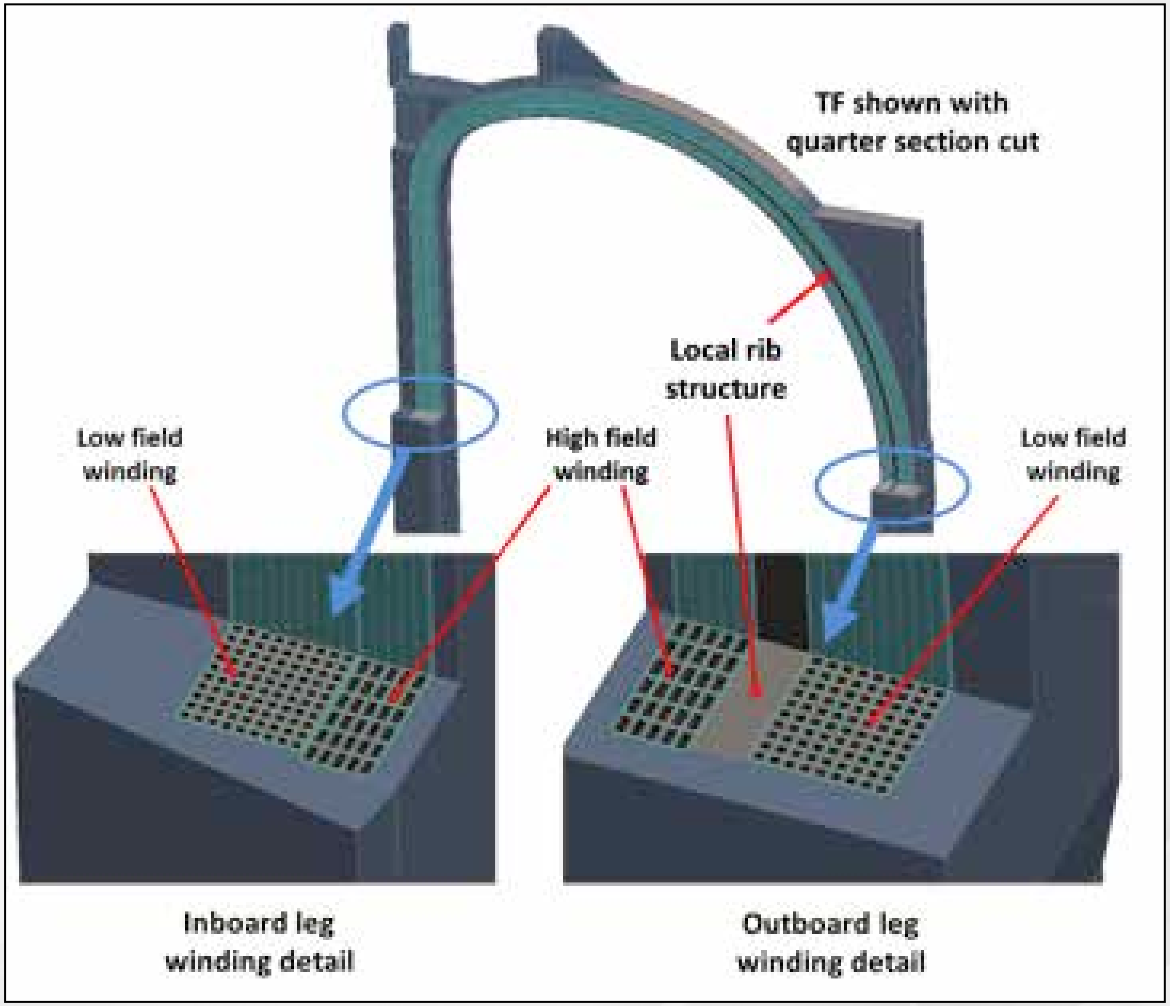
TF Winding and Structure

- Dual winding packs with 2 types of CICC

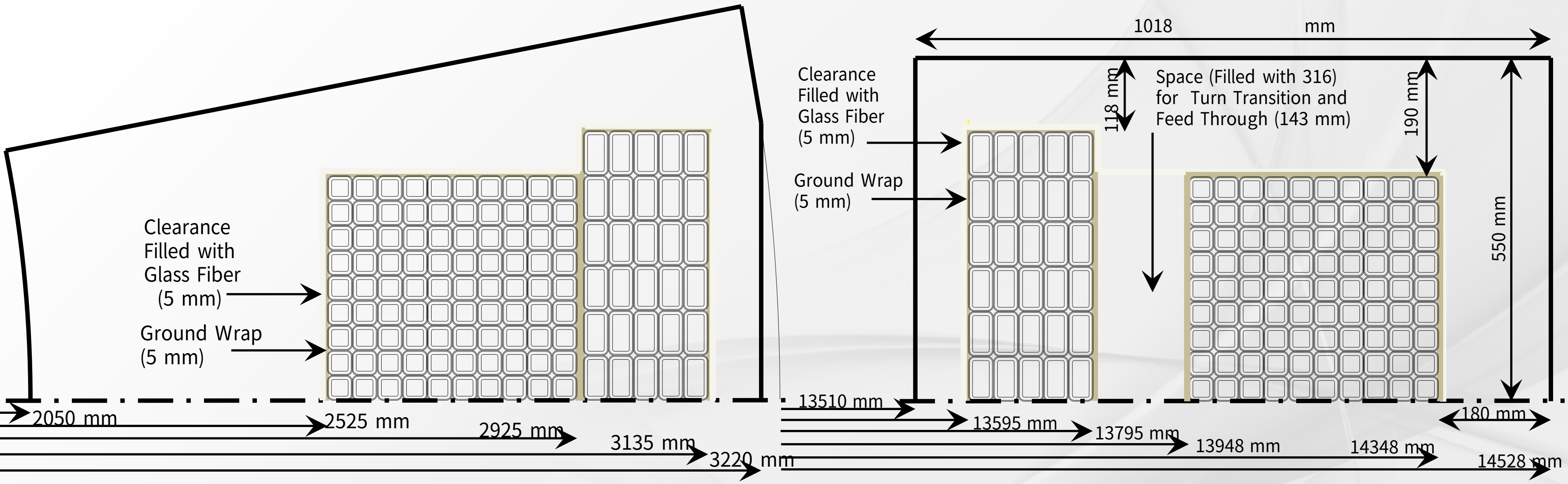
→ High magnetic field with huge Cost savings

- 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 m, a = 2.1 m
- Small CICC Coil : 18 x 10 turns Large CICC Coil : 12 x 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)



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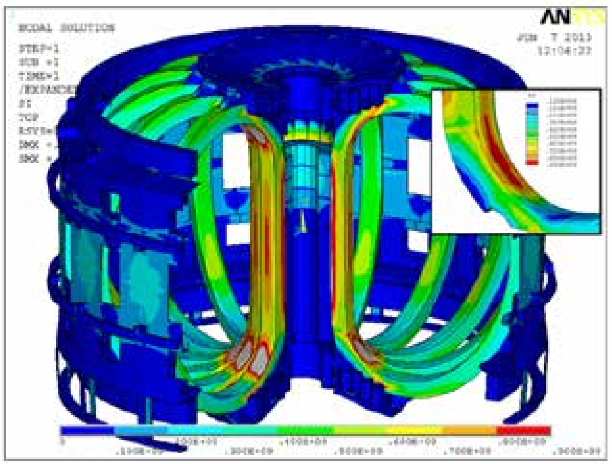
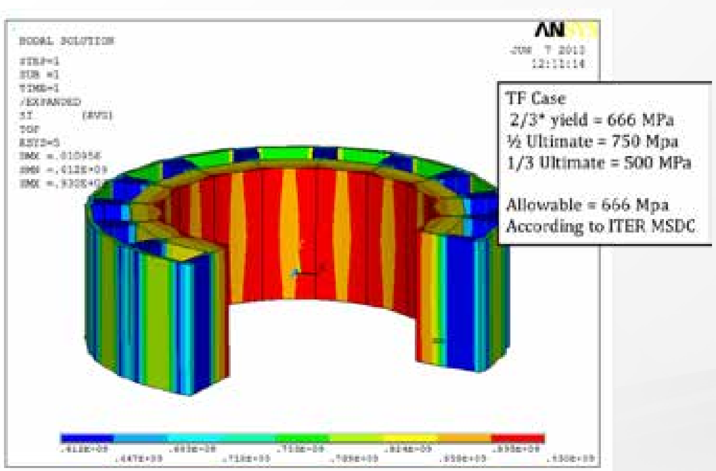
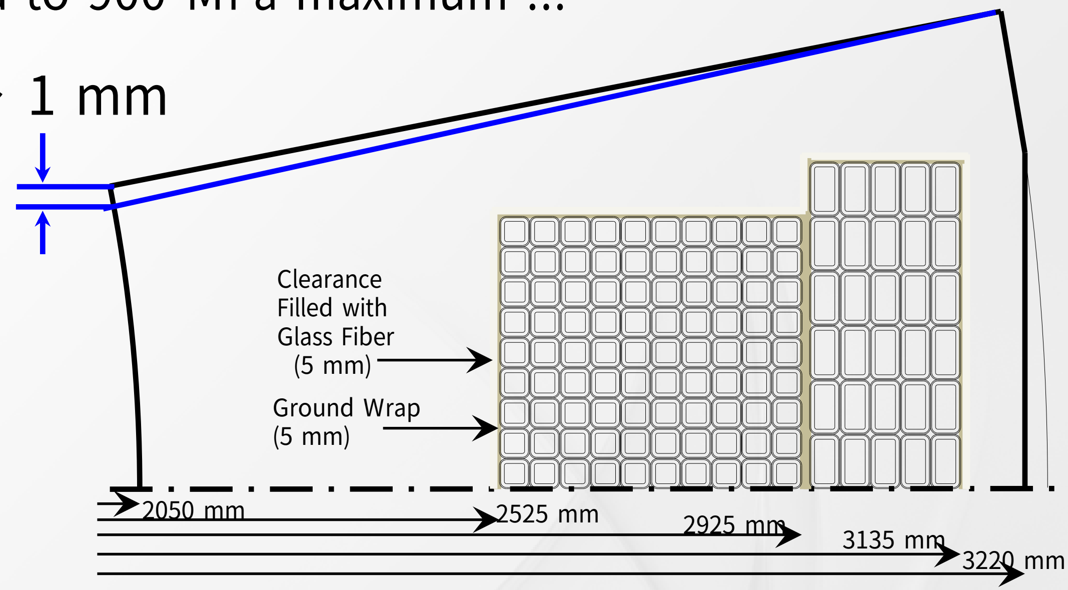
Structual Analysis of TF Case

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

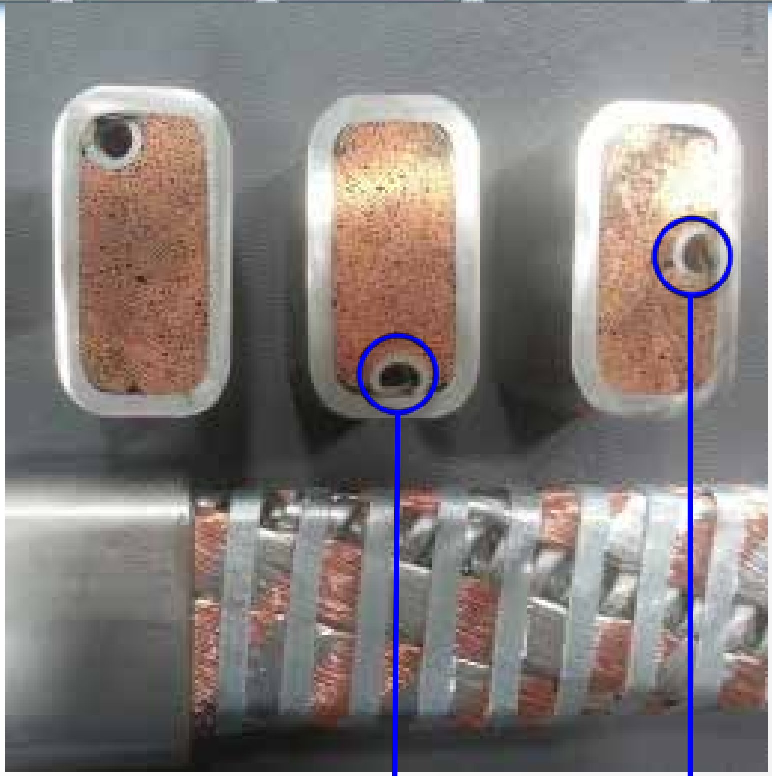




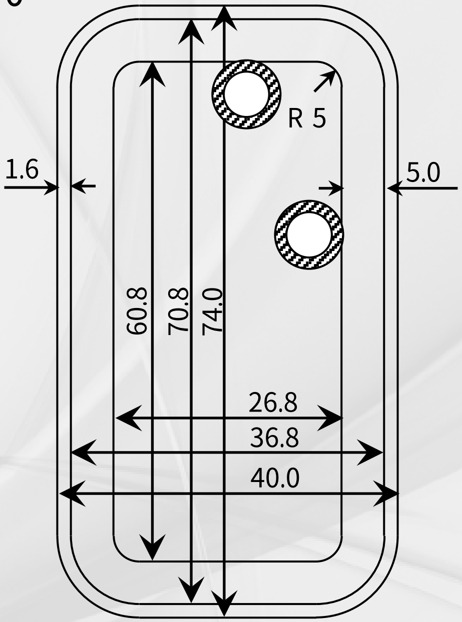


- Elastic deformation occurs from the top-right corner of TF inboard side and the maximum stress at the top-left corner can be reduced.
- A detail analysis required to make the stress almost uniform (à averaged stress)

Problem in the Helical Cooling Spiral Shape



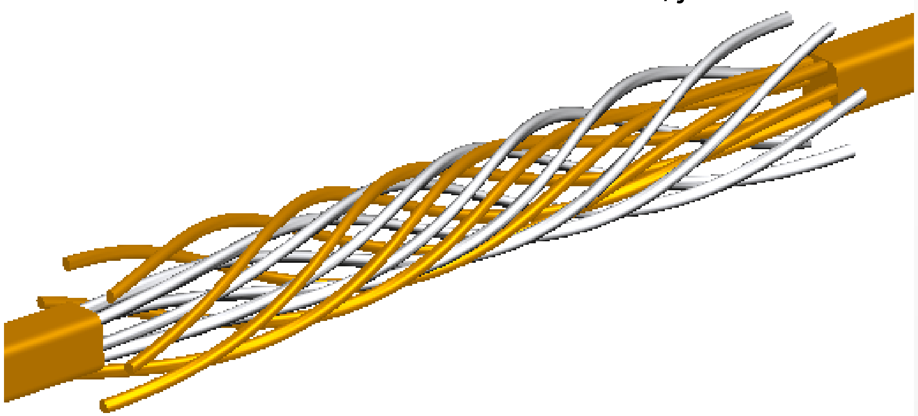
- One sub-cable between two smaller cooling spirals
- (3SC)x4x5x6x5 + 2 Helical spirals
- Spiral size : ID=6 mm, OD=9 mm
- CICC height increased to 74 mm (Reduction of peak field)
- Void Fraction = 28%

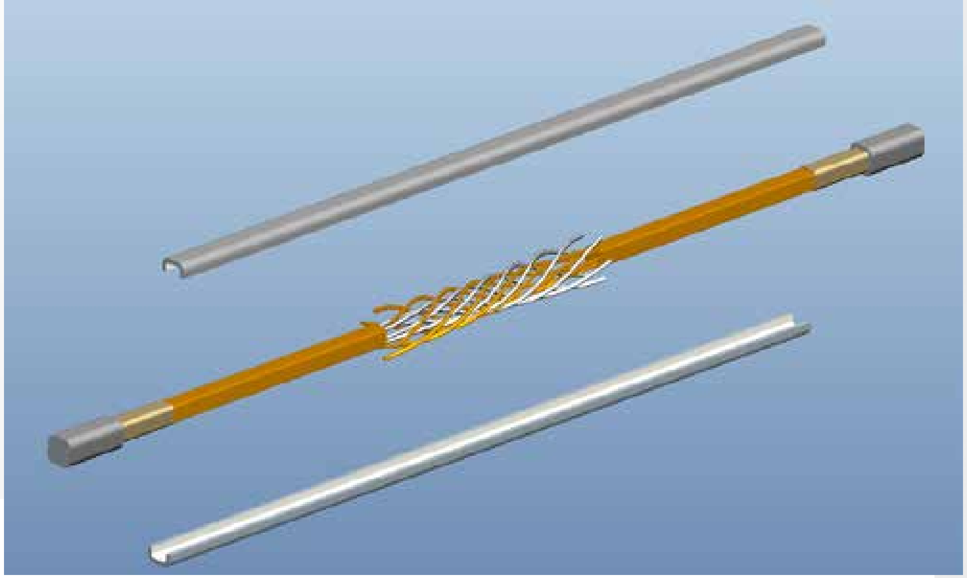


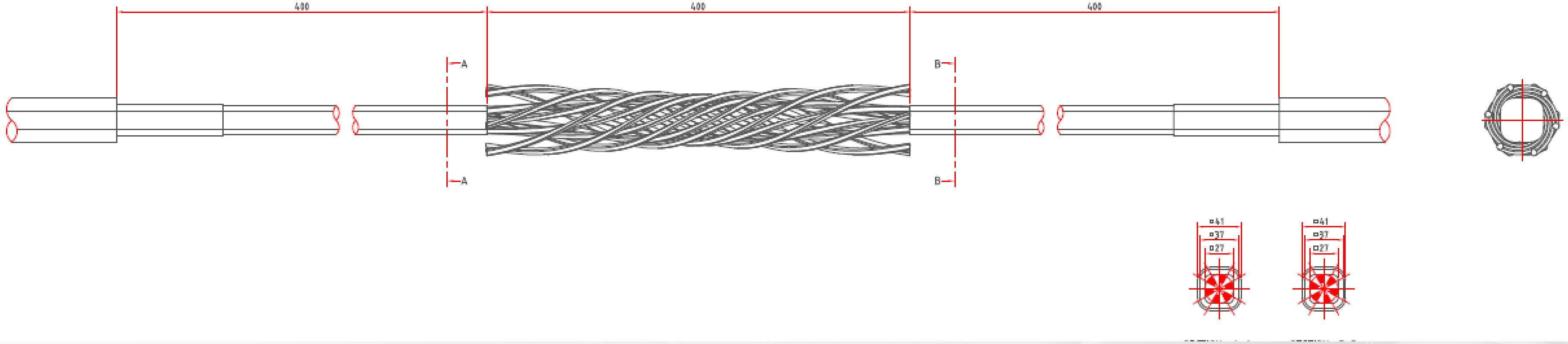
Elliptic !!!
Reduction of Void Fraction

Inter-coil Joint Scheme of Magnet

- ITER CS Inter-coil Joint Scheme used
  - Joint Resistance ~0.2 n-ohm/joint







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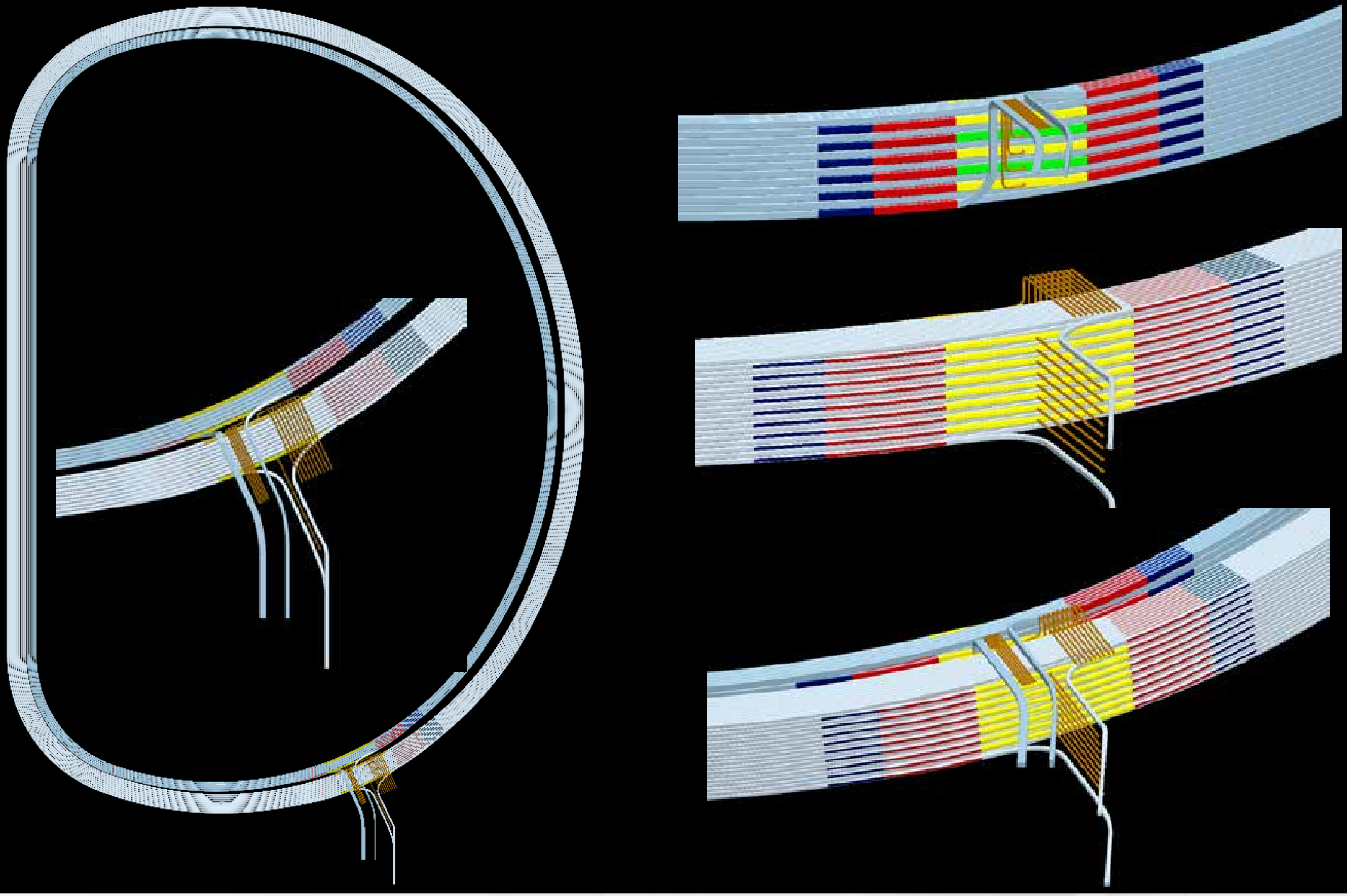
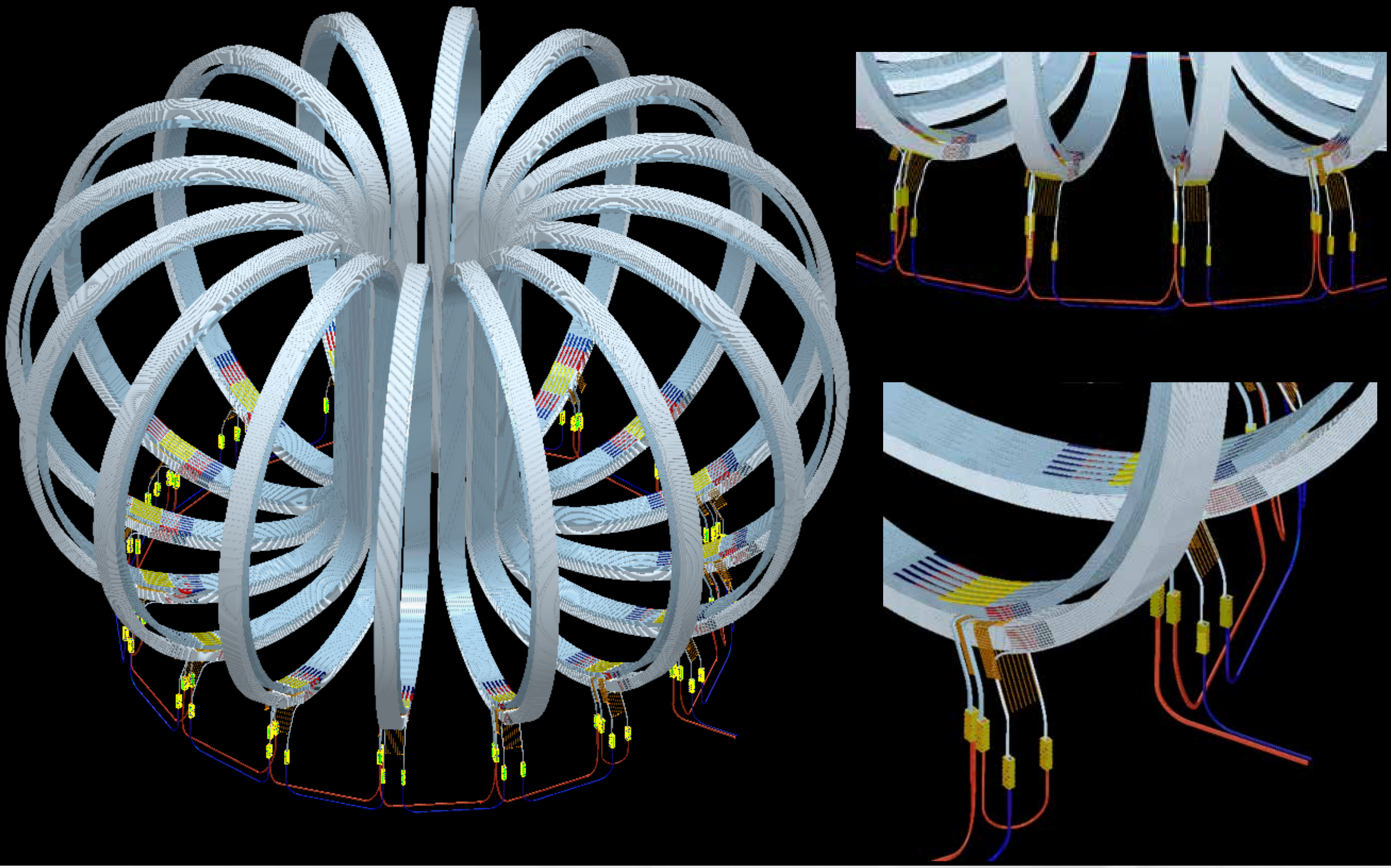
3D Modeling of TF Magnet



3D Modeling of TF Assembly



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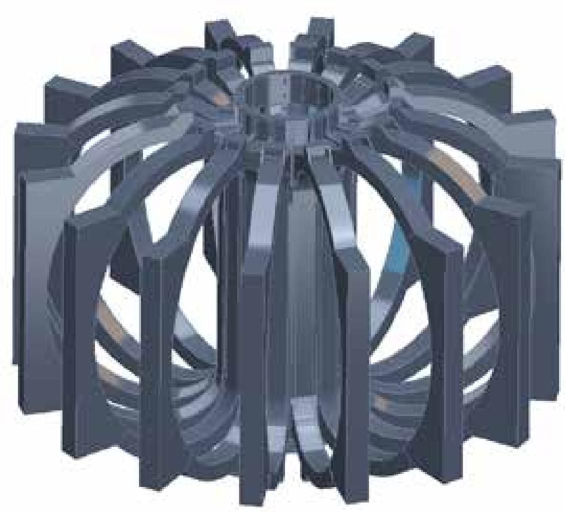
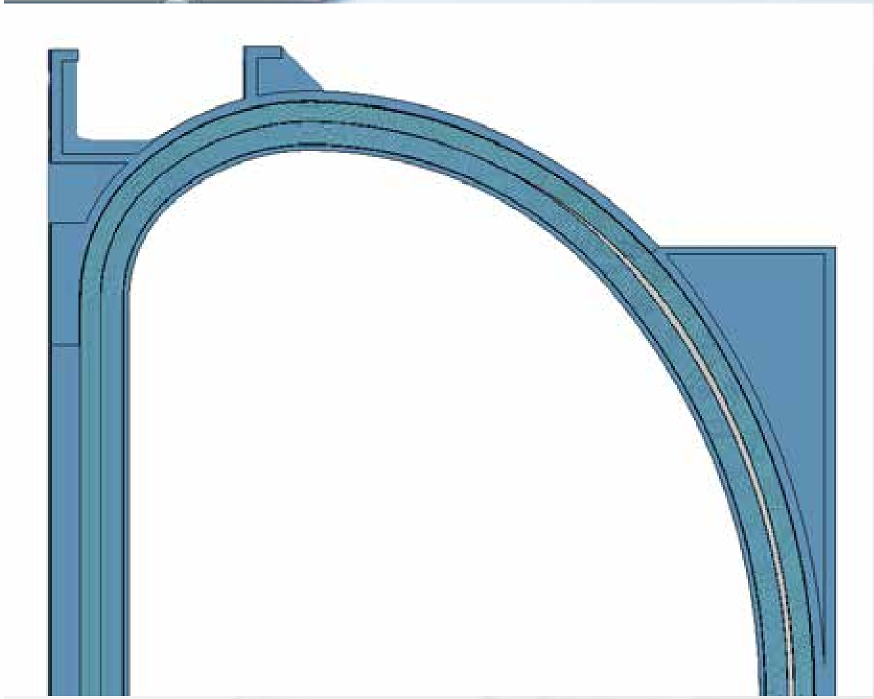
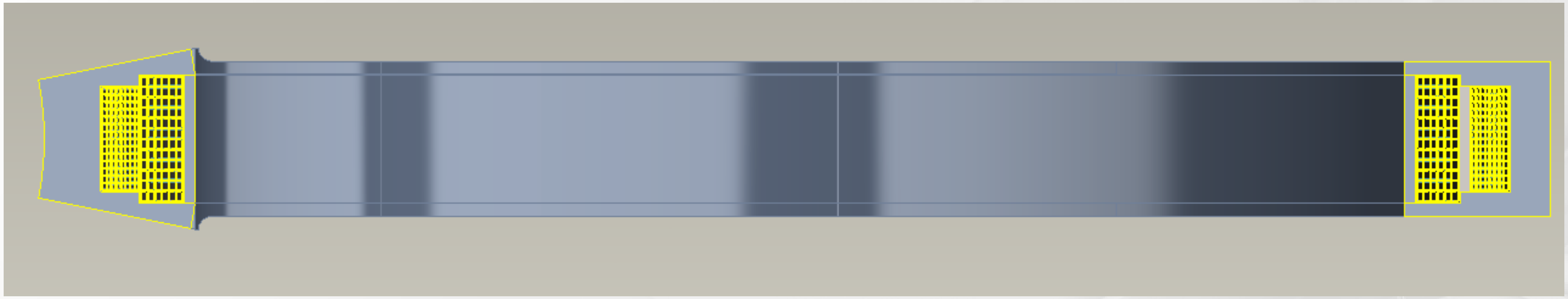
TF Coil Structure







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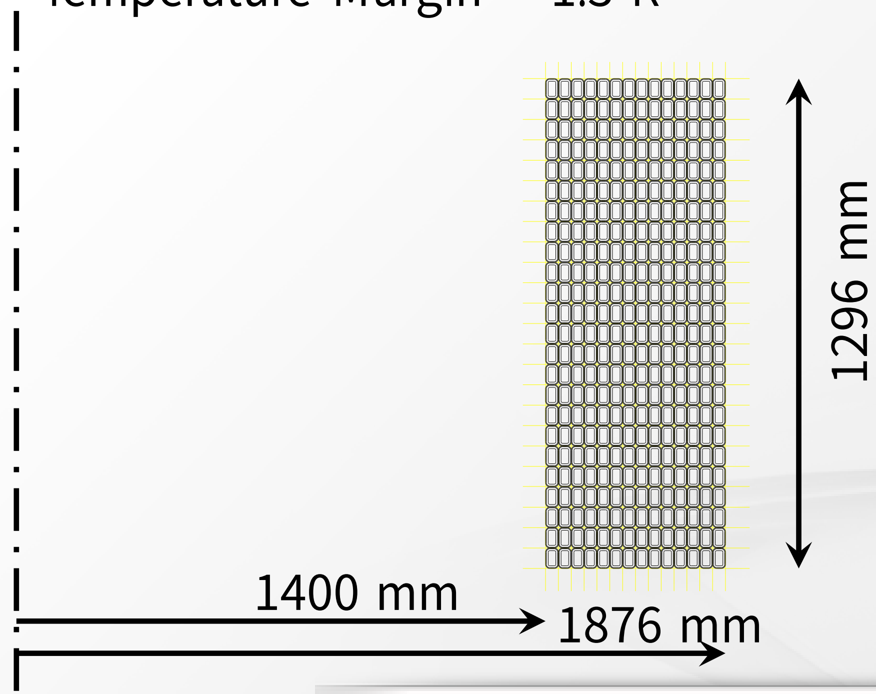
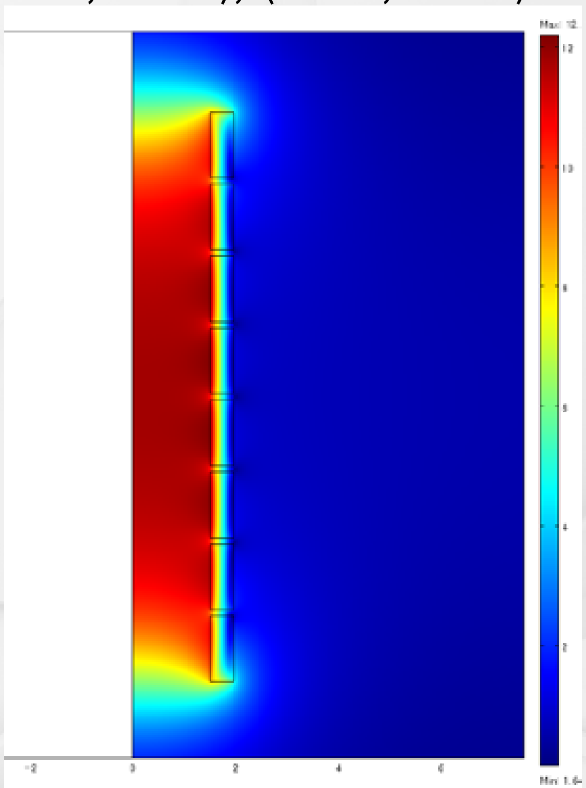
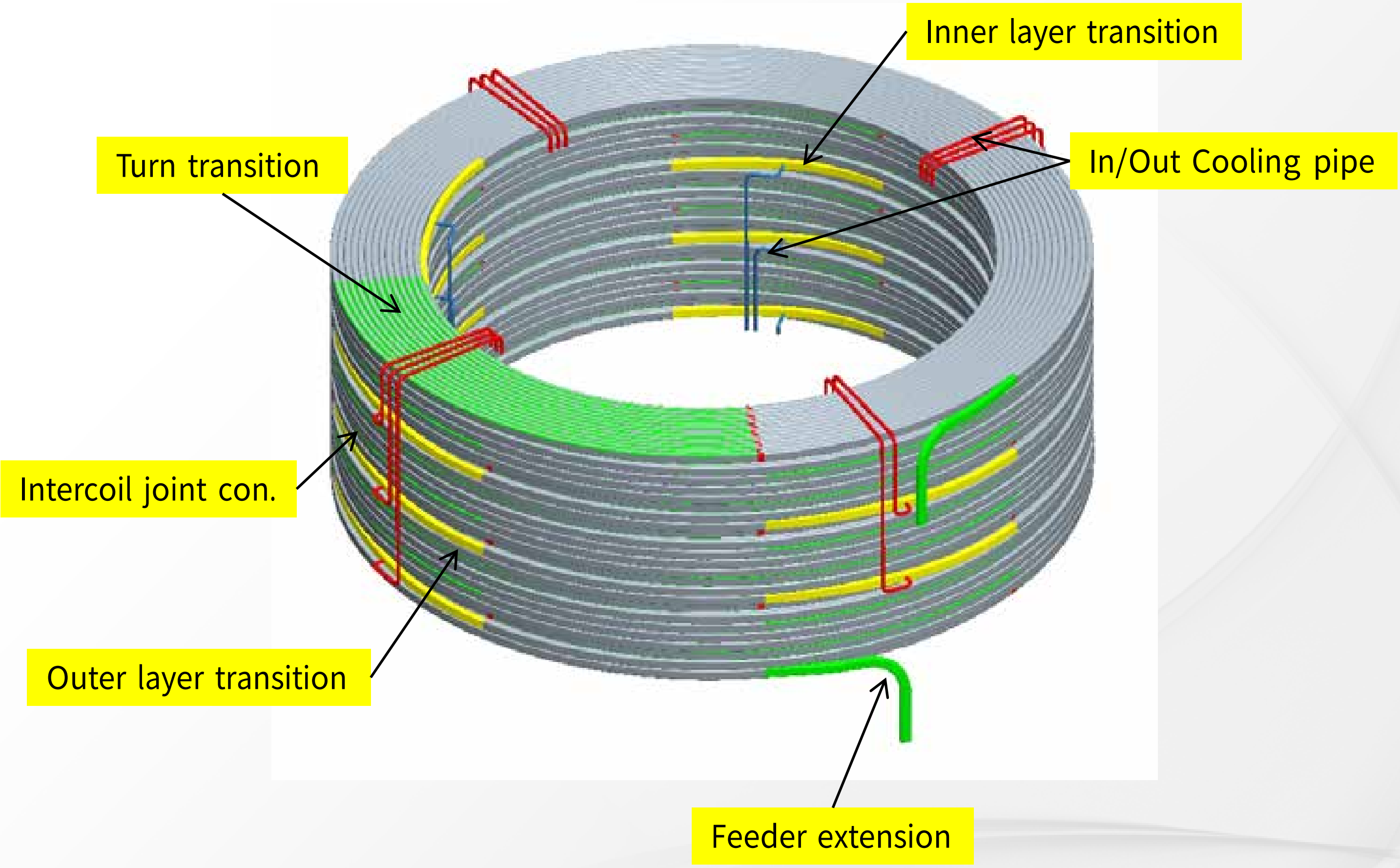
Cross-Section of CS Coils

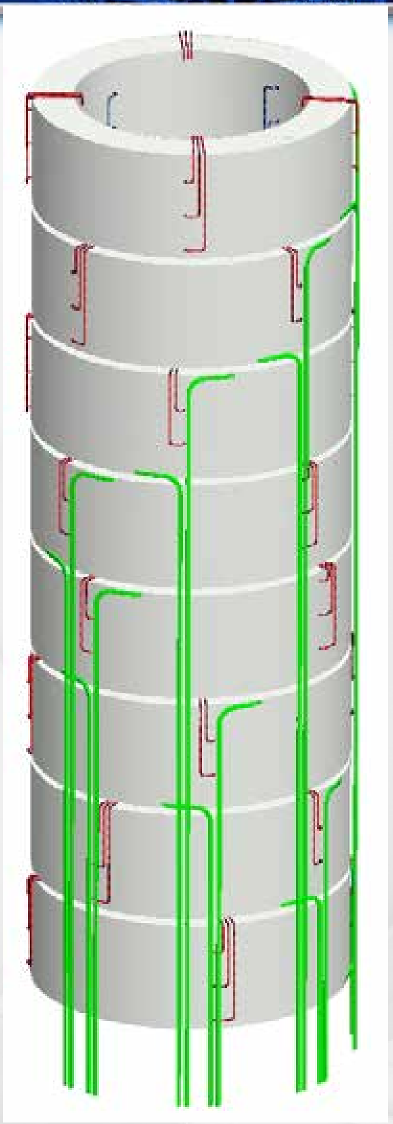
- Number of Turns : 14 (Total SC strand weight : ~102 tons)
- Number of Layers : CS1, CS2, CS3 & CS4 : 24 layers
- Magnetic Field at Center : ~11.8 Tesla (Bpeak < 12.194 Tesla, Half Flux Swing ~83 Wb)
- Conductor Unit Length : 885 m (CS1, CS2, CS3 & CS4 : UL x 4)
- Gap Between Coils : 104 mm
- Magnet Center Position : (1638, 700), (1638, 2100), (1638, 3500), (1638, 4900)
- Nominal Current : 42 kA (Current can be increased)
- Temperature Margin ~ 1.3 K





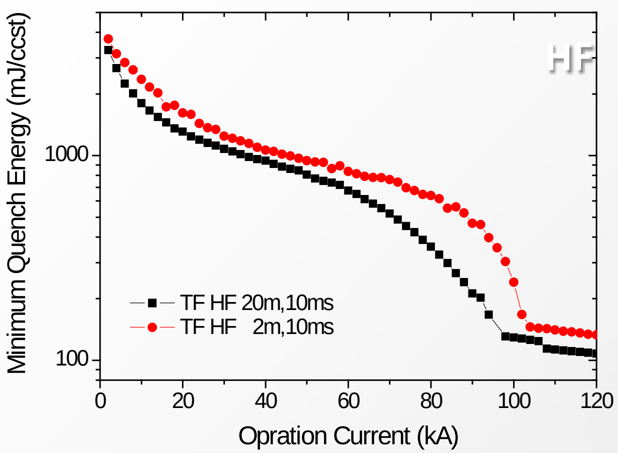
3D Modeling of CS Coils

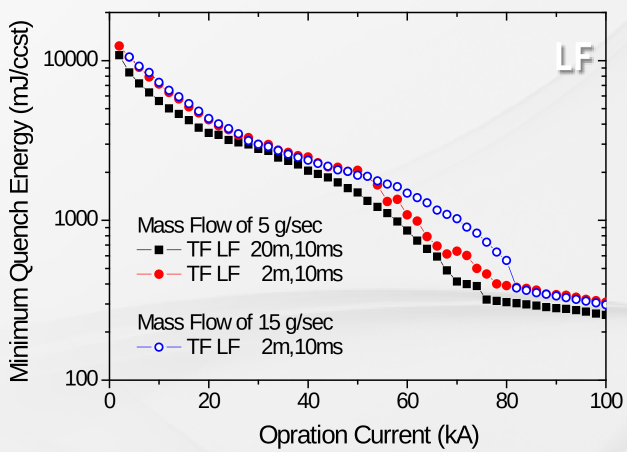


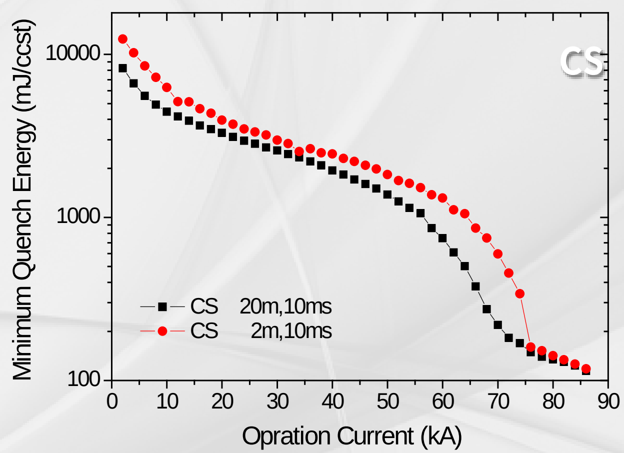


Stability Analysis of TF and CS CICC

- Gandalf Code has been used for the estimation.
- Assumption & Result
  - Gaussian shape DC heat pulse was applied for 10 ms at the center of the CICC's.
  - The nominal strain of -0.5% was assumed for the superconducting wires.
  - The field, temperature and strain dependence of the critical current density was estimated by the scaling law based on strong-coupling theory.
  - The percentage perforation of the separation perimeter between the bundle and hole He channels was set to 0.5 and the inlet pressure of 0.5 MPa case was studied.
  - For the HF CICC, the energy margin at an operation current of 65.52 kA is well above 500 mJ/ccst whether the heating zone is 2 or 20 m, even for the stagnant flow condition.
  - But for the LF conductor, the energy margin at the operation current is above 500 mJ/ccst, when there is a He mass flow of 5 g/sec at the flow path inlet. The energy margin was increased almost twice as the He mass flow increased to 15 g/sec,







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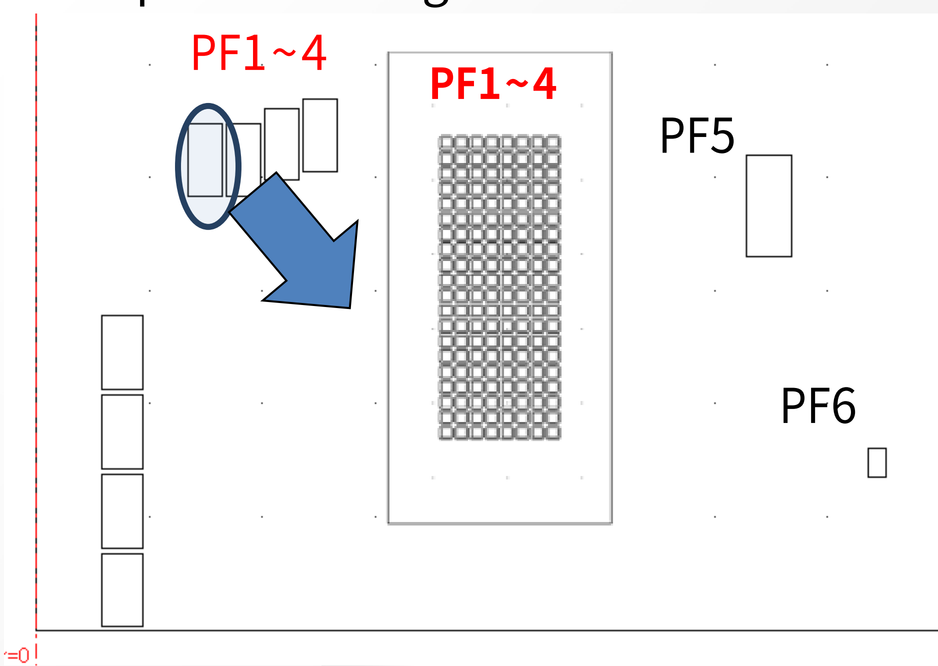
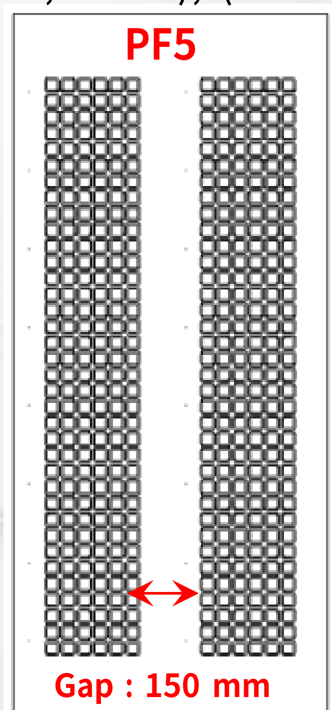
Cross-Section of PF Coils

- Number of Turns : 8 turns for PF1~4, 12 for PF5, and 2 for PF6
- Number of Layers : 20 layers for PF1~4, 36 for PF5 and 4 for PF6
- Nominal Current : 36, 50, 50, 44, 37, 28 kA for PF1 to 6, respectively.
- Conductor Unit Length : 620, 755, 890 and 1030 m for PF1~4
  980 & 1010 m for PF5 and 770 m for PF6
- Coil Center Position : (2980, 8310), (3660, 8310), (4340, 8590) - PF1~3
  (5020, 8750), (12762 & 13158, 7500), (14880, 2950) - PF4~6
- Temperature Margin > 1.5 K





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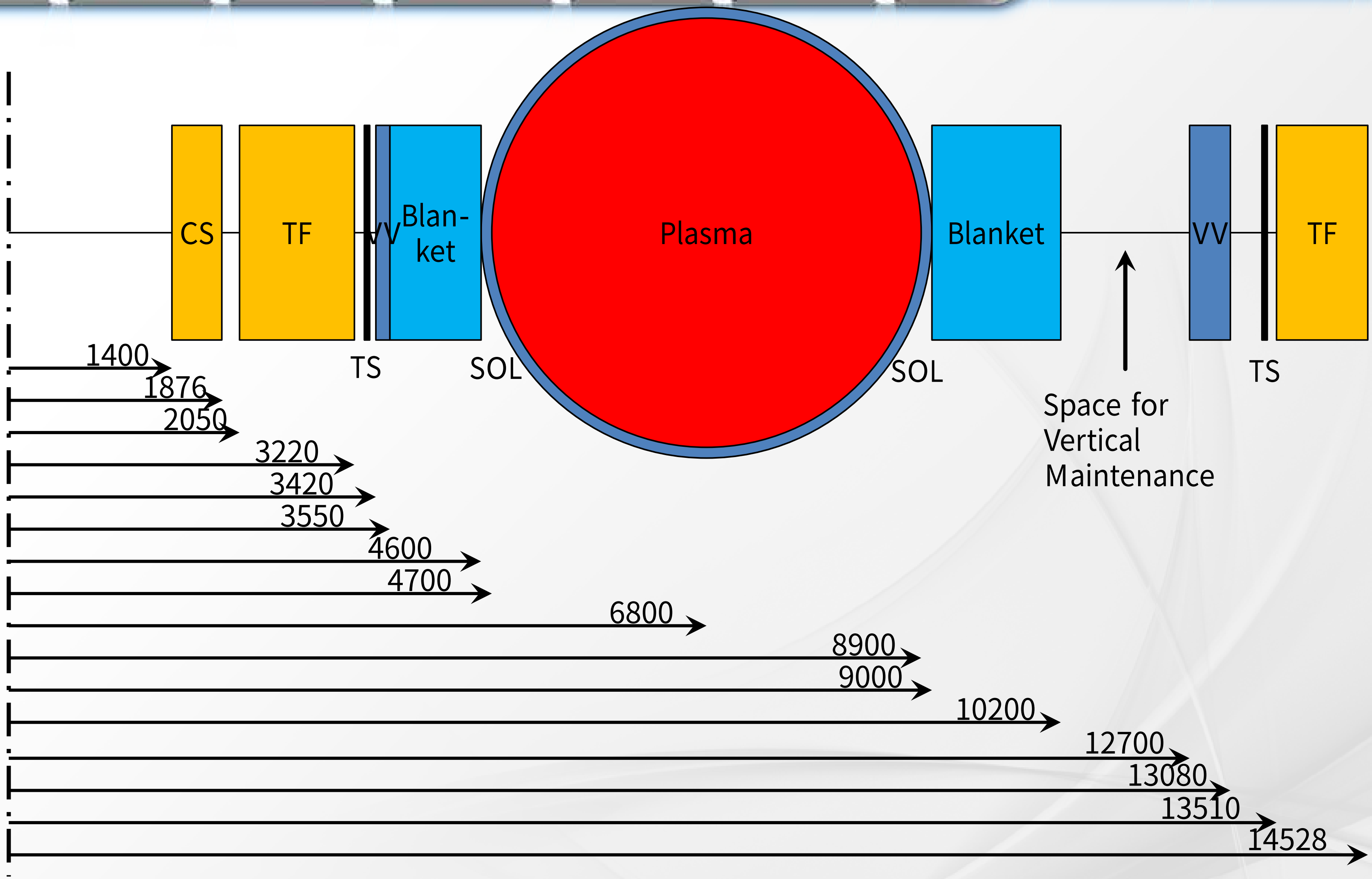
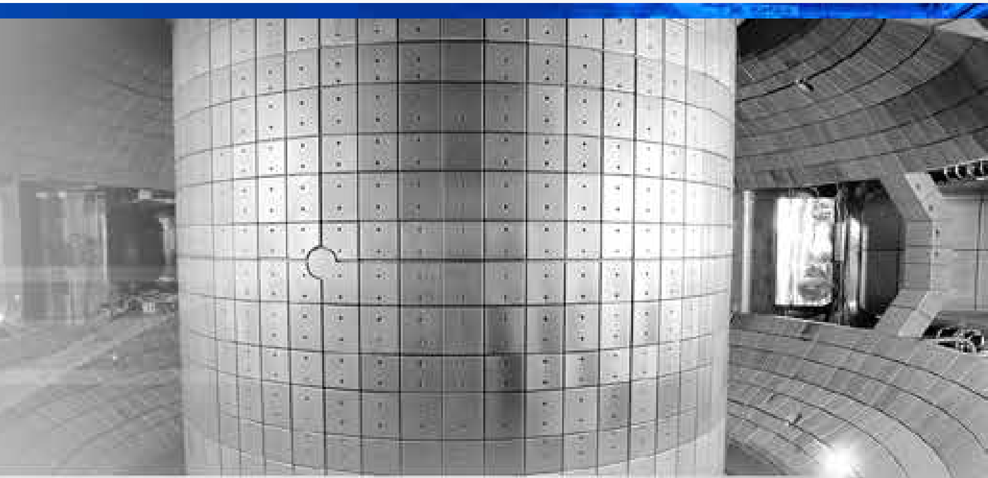
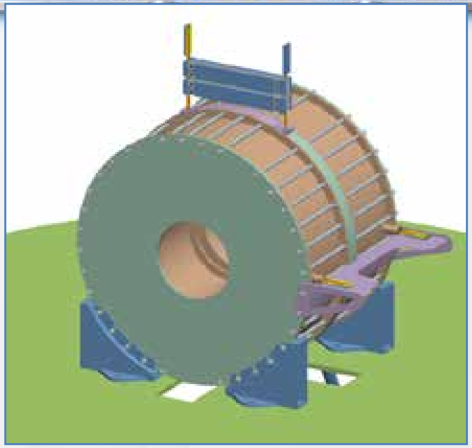
Radial Build of K-DEMO [unit : mm]





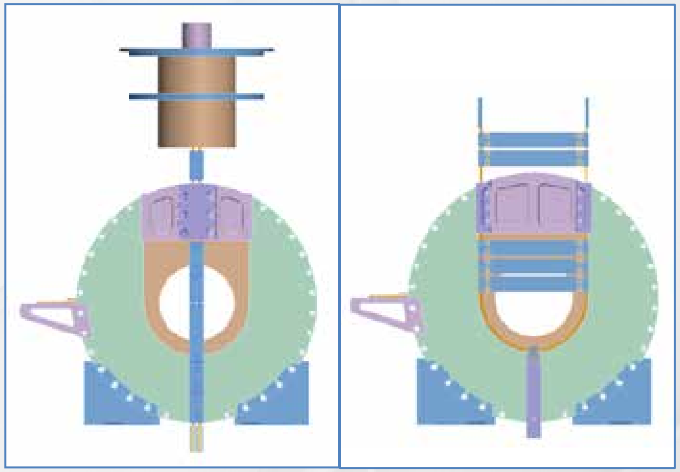
Superconducting Conductor Experiment Facility [SUCCEX]

SUCCEX Facility



SUCCEX (SUperConducting Conductor EXperiment)

- Background field : 16 Tesla
- Split-pair Solenoid Magnet System
- Inner-bore Size : ~ 1 m
- Two Test Modes :
  - ü Sultan-like sample test mode
  - ü Semi-circle type conductor sample test mode



SULTAN-type Semi-circle-type

(Cf.) SULTAN

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

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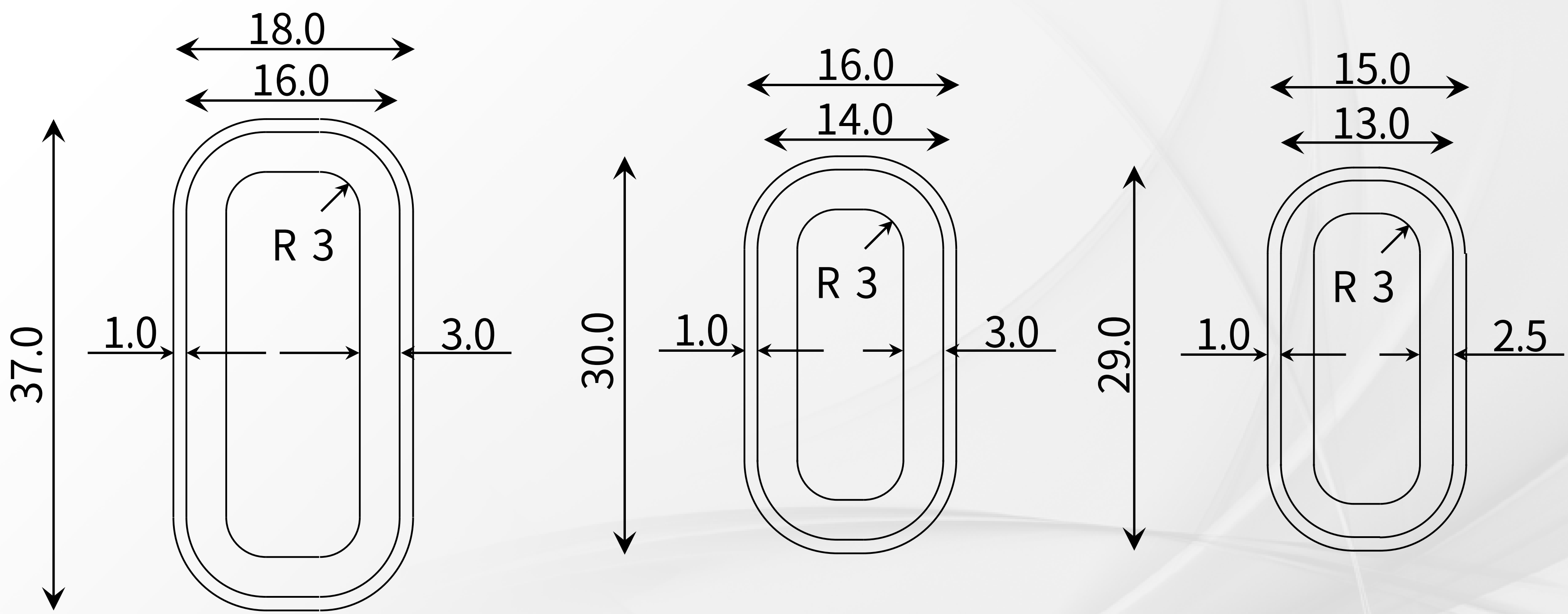
Conductor Parameter of SUCCEX Magnets

- IC (Inner Coil) CICC : (3SC)x4x5x6[360 SC strand], VF = 27.62%
- MC (Middle Coil) CICC : (2SC+1Cu)x3x4x6[144 SC strand], VF = 26.96%
- OC (Outer Coil) CICC : (1SC+2Cu)x3x4x6[72 SC strand], VF = 26.96%
- Strand : High Jc (> 2600A/mm2) Nb3Sn (total ~ 6.8 ton)
- Twist Pitch : 50 mm - 110 mm - 170 mm - 290 mm
- No Sub-Cable Wrapping

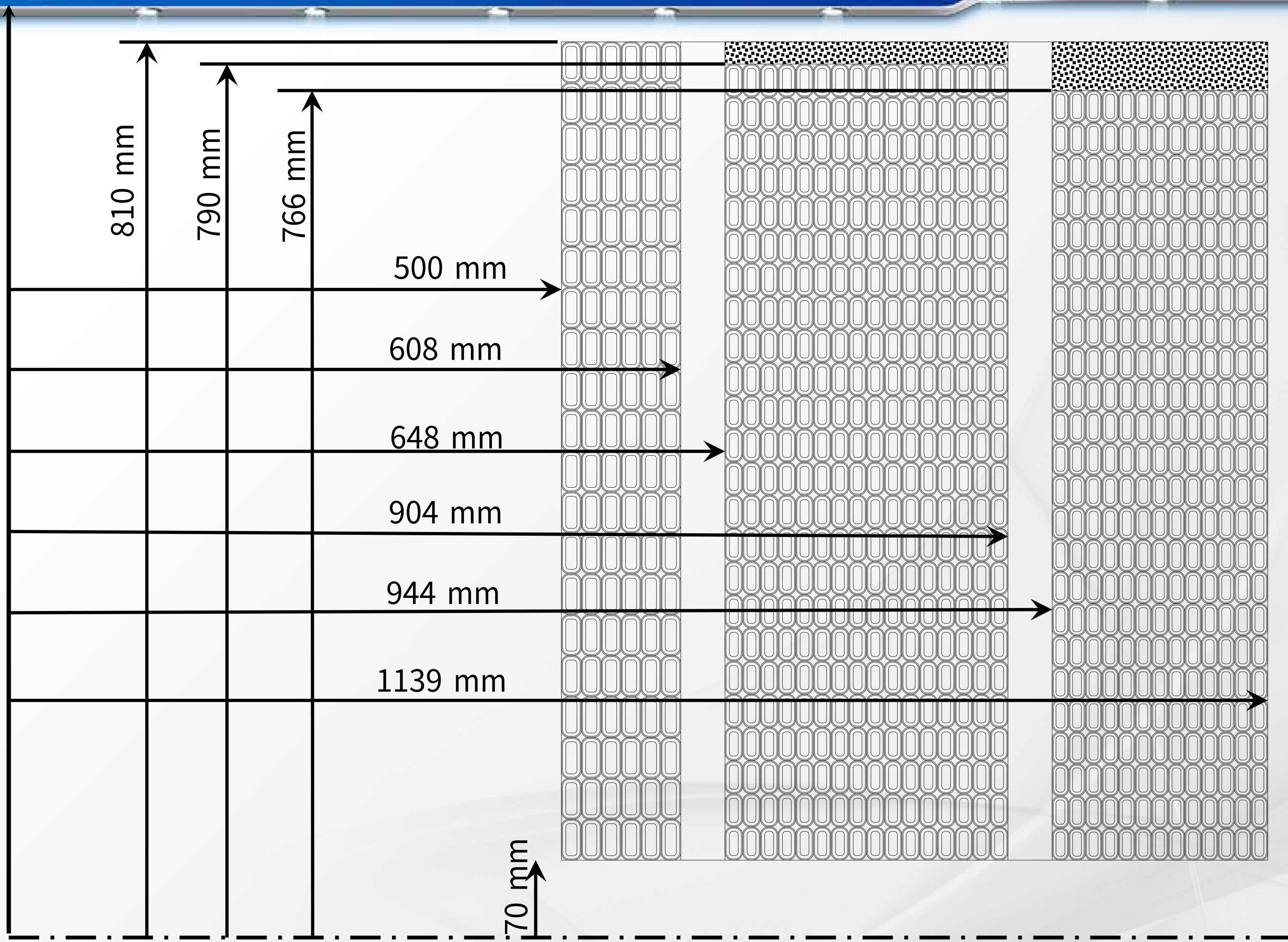


IC CICC Cross-section

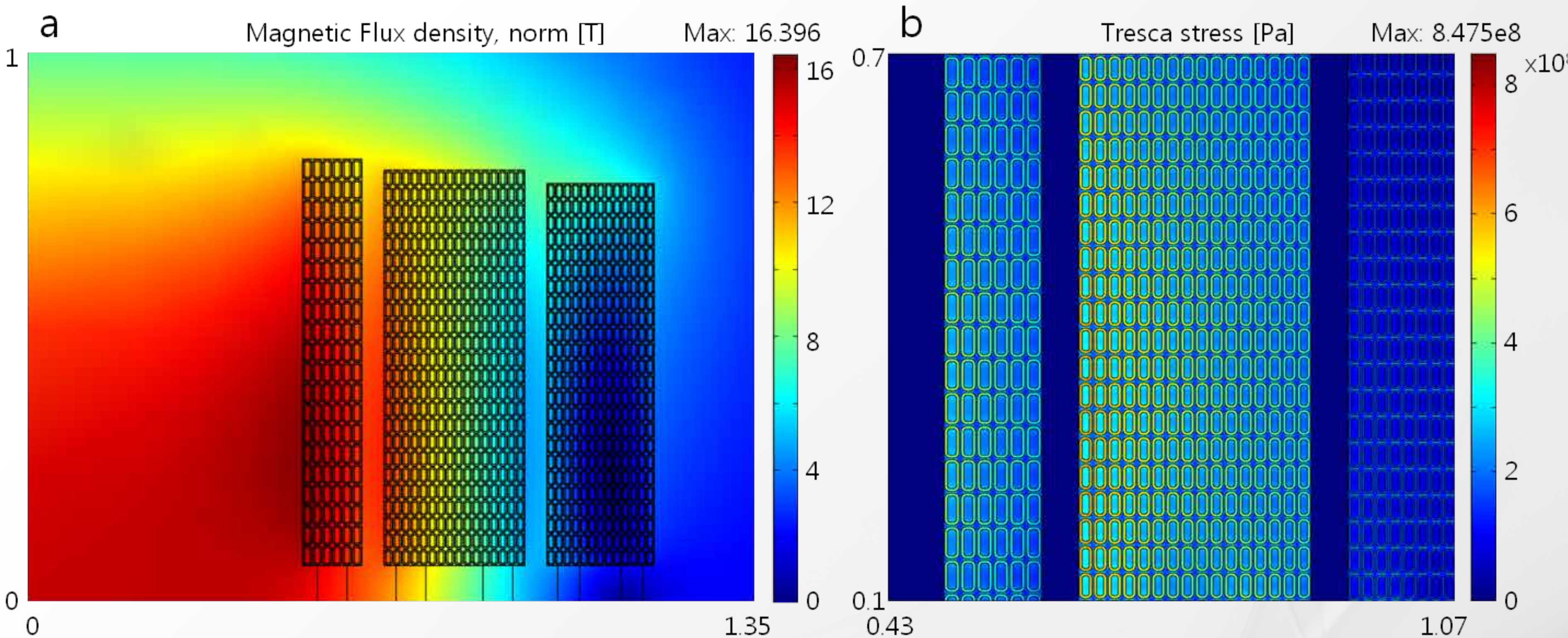
MC CICC Cross-section

OC CICC Cross-section

SUCCEX Magnet Cross-Section (Upper Coil)



Magnetic Field & Stress of SUCCEX Magnets



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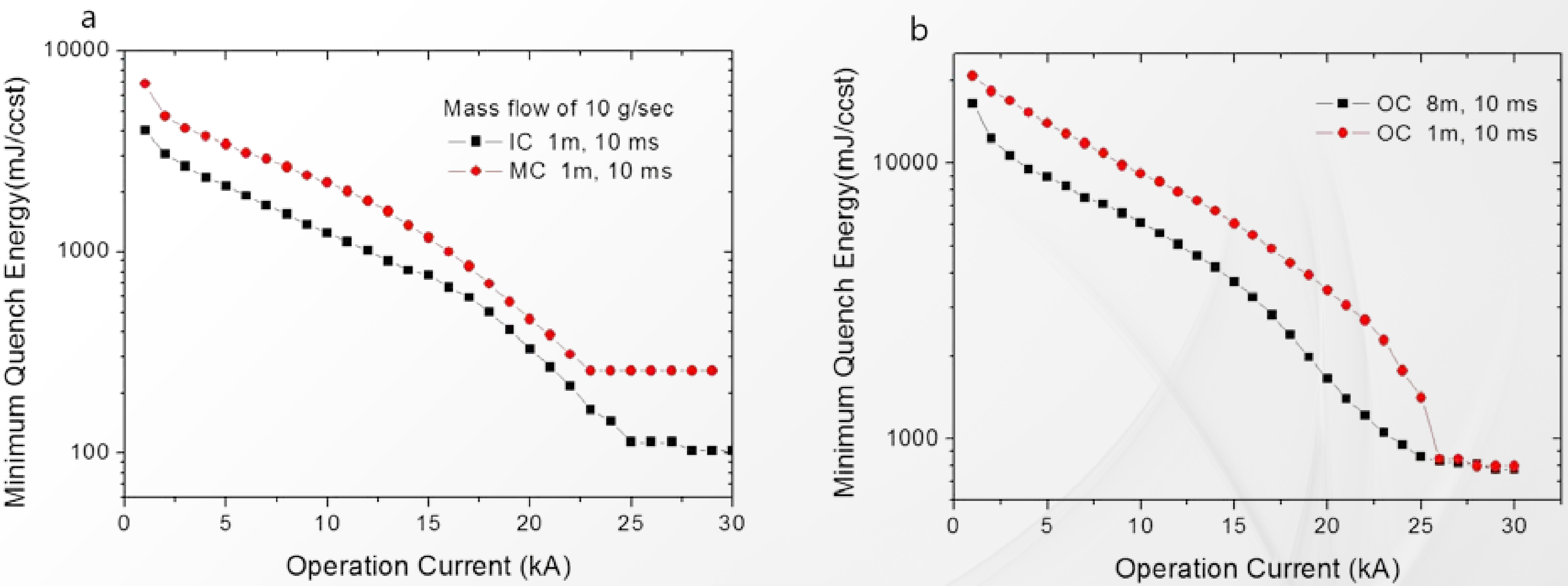
Stability Analysis of SUCCEX Magnets



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Conclusion

KSTAR : Physics Machine

- High Performance (β_N > 4) Plasma Research for Fusion Power Plant
- Fusion Physics Validation
- Tokamak Simulator Development
- Design Requirement for Fusion Plant

ITER : Fusion Engineering

- 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]