KSTAR CONSTRUCTION AND COMMISSIONING

Presented by ***Hyung-Lyeol Yang***

On behalf of the KSTAR team

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National Fusion Research Institute

NFRI 국가핵융합연구소 National Fusion Research Institute

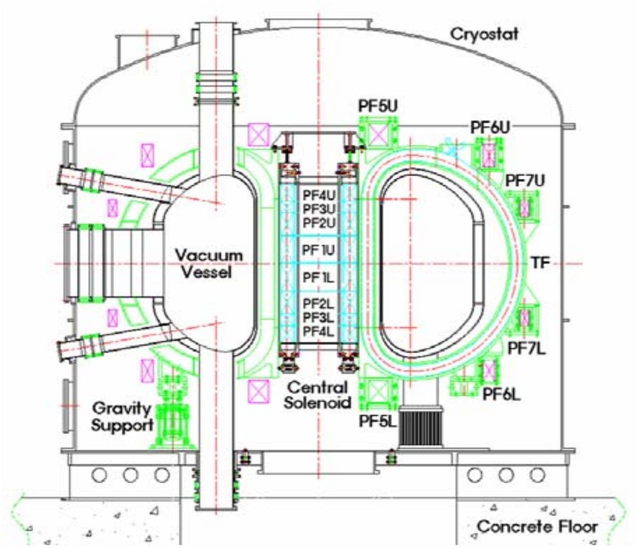
KSTAR

Contents

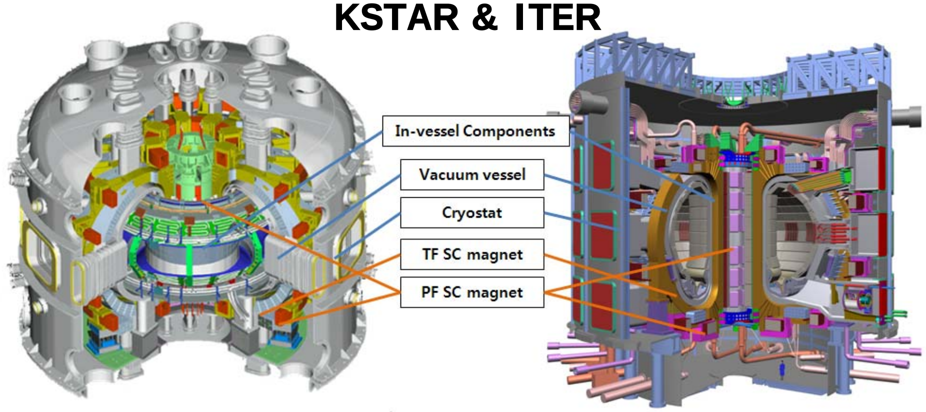
Introduction

- To develop a steady-state capable advanced superconducting tokamak
- To establish the scientific and technological base for an attractive fusion reactor

Elevation view of the KSTAR device



KSTAR & ITER

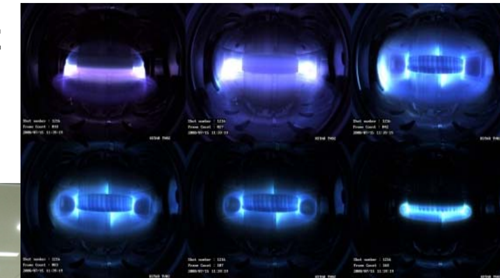


PARAMETERS	KSTAR	ITER
Major radius, R_0	1.8 m	6.2 m
Minor radius, *a*	0.5 m	2.0 m
Elongation, κ	2.0	1.7
Triangularity, δ	0.8	0.33
Plasma volume	17.8 m^3	830 m^3
Plasma surface area	56 m^2	680 m^2
Plasma cross section	1.6 m^2	22 m^2
Plasma shape	DN, SN	SN
Plasma current, I_P	2.0 MA	15 (17) MA
Toroidal field, B_0	3.5 T	5.3 T
Pulse length	300 s	400 s
β_N	5.0	1.8 (2.5)*
Plasma fuel	H, D-D	H, D-T
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Auxiliary heating /CD	~ 28 MW	73 (110) MW
Cryogenic	9 kW @4.5K	

* *M. Shimada, et al., Nuclear Fusion, vol. 47, pp. s1 (2007)*

Brief History

1st Plasma Achievement
(08. 6-7)

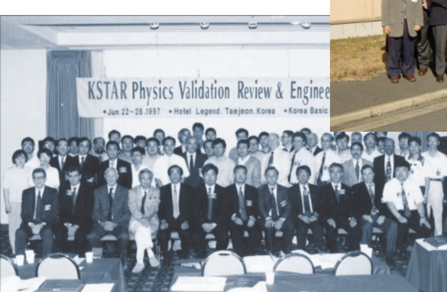


Integrated Machine Commissioning
(07. 9 – 08. 5)

Machine Construction & Assembly
(02. 6 - 07. 8)

KSTAR Building Construction
(98. 12 - 02. 9)

Engineering Design
(98. 9 - 02. 5)

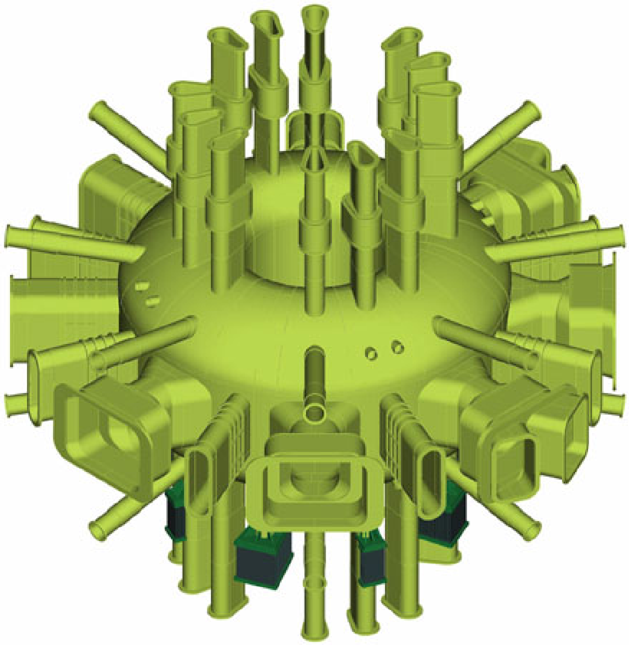


Basic R&D, Conceptual Design
(95.12 – 98. 8)

KSTAR

VV Fabrication (2002. 01 – 2004. 06)

- **Features**
  - **Double Wall Structures with Inner and Outer Shells**
  - Toroidal Ring and Poloidal Rib
  - Ports with Bellows
  - **Leaf Spring Style Support Structure**



- **Major parameter**
  - Volume : 100 m^3
  - Ultimate Vacuum Pressure : 1 x 10^{-8} Torr
  - **Material : 316LN, 12 t**
  - Body C.X. Width and Height : 1.88 m, 3.387 m
  - Torus Inner and Outer diameter : 2.22 m, 5.98

Fit-up of Sector 3

Site Welding of Sector 1,2

Pre-Assemble

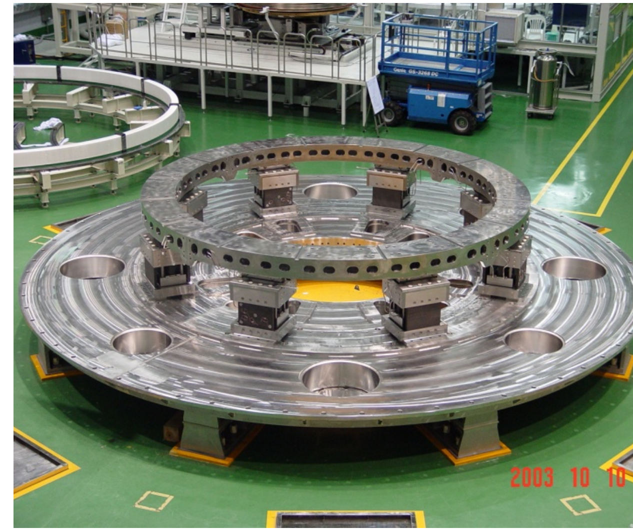
Welding of Sector 1

KSTAR

Cryostat Fabrication (2002. 01 – 2004. 06)

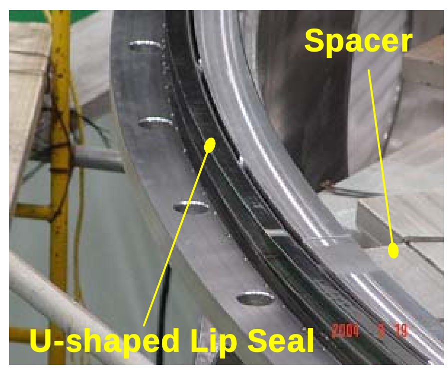
Diameter (Inside)	8.80 m
Height	8.56 m
Weight	
- Lid	35 ton
- Cylinder	57 ton
- Base	47 ton
Vacuum Volume	450 m^3
Number of Port	102
Thickness	Lid: 33mm
	Cylinder : 30 mm
	Base : 50 mm
Material	SA240 - 304L
Support	8 Beam

Cryostat Cylinder and Lid



Cryostat Base and Gravity Support

Lid & Cylinder Pre-Assemble

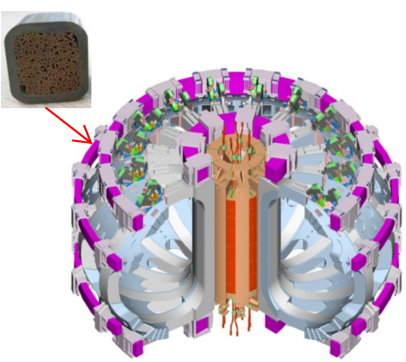
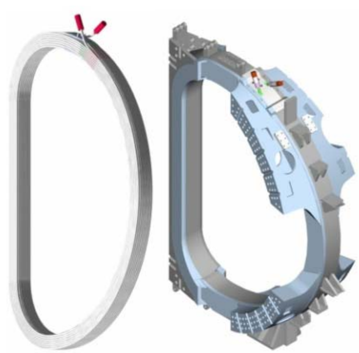


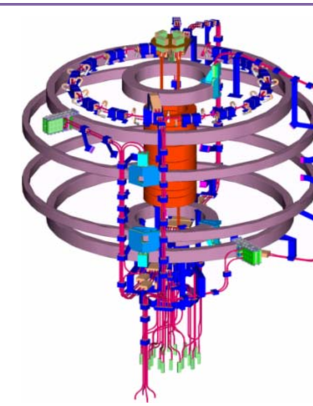
Vacuum Seal between Cylinder and Lid

Interface Check between Base and SC Bus-line Duct

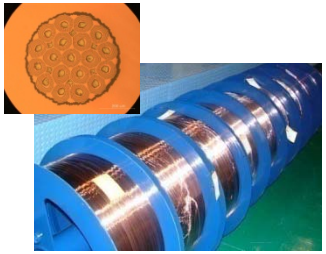
Key Parameters of KSTAR SC Magnets

	TF coil	CS coil	PF Coil
Conductor	Nb3Sn & Incoloy 908	Nb3Sn & Incoloy 908	Nb3Sn & Incoloy 908 (PF5) NbTi & 316 LN (PF6, 7)
No. of coil	16	4 pair	3 pair
Total length	10.2 km	3.8 km	11.2 km
Cooling channel of each coil	4	CS1 : 10, CS2 : 8 CS3 : 4, CS4 : 6	PF5 : 8 PF6 : 8, PF7 : 6
Length of each channel	160 m	67 m	PF5 : 176 m PF6 : 315 m, PF7 : 285 m
Cold mass	170 ton	60 ton	70 ton
Operating temperature	5 K	5 K	5 K
Coolant	4.5 K SHe P > 5.5 bar Mass flow rate > 300 g/s	4.5 K SHe P > 5.5 bar Mass flow rate ~150 g/s	4.5 K SHe P > 5.5 bar Mass flow rate ~ 150 g/s

TF Coil Manufacturing (2000. 09 – 2006. 01)



Superconducting Strand

Chrome Plating

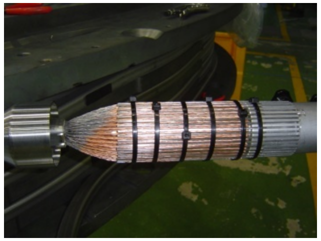
Cabling

CICC Jack Welding

CICC Spool

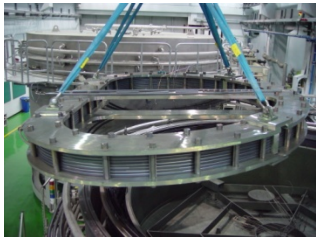
CICC Leak Test

Continuous Winding

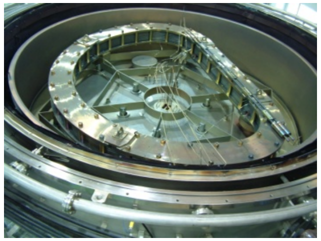


STS Joint Preparation

Leak Test



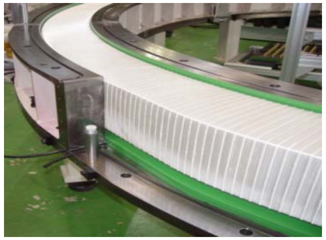
Heat Treatment Preparation



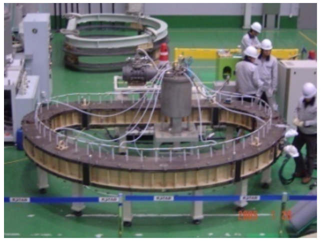
Heat Treatment

Turn Insulation Taping

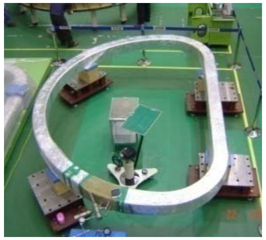
Ground Wrapping



VPI Die Assembly



VPI



Hi-pot Test

No. of Coil : 16
T_{OP} : 4.5 K
8 Pancakes × 7 Turns
$F_{centering}$: 15MN

KSTAR

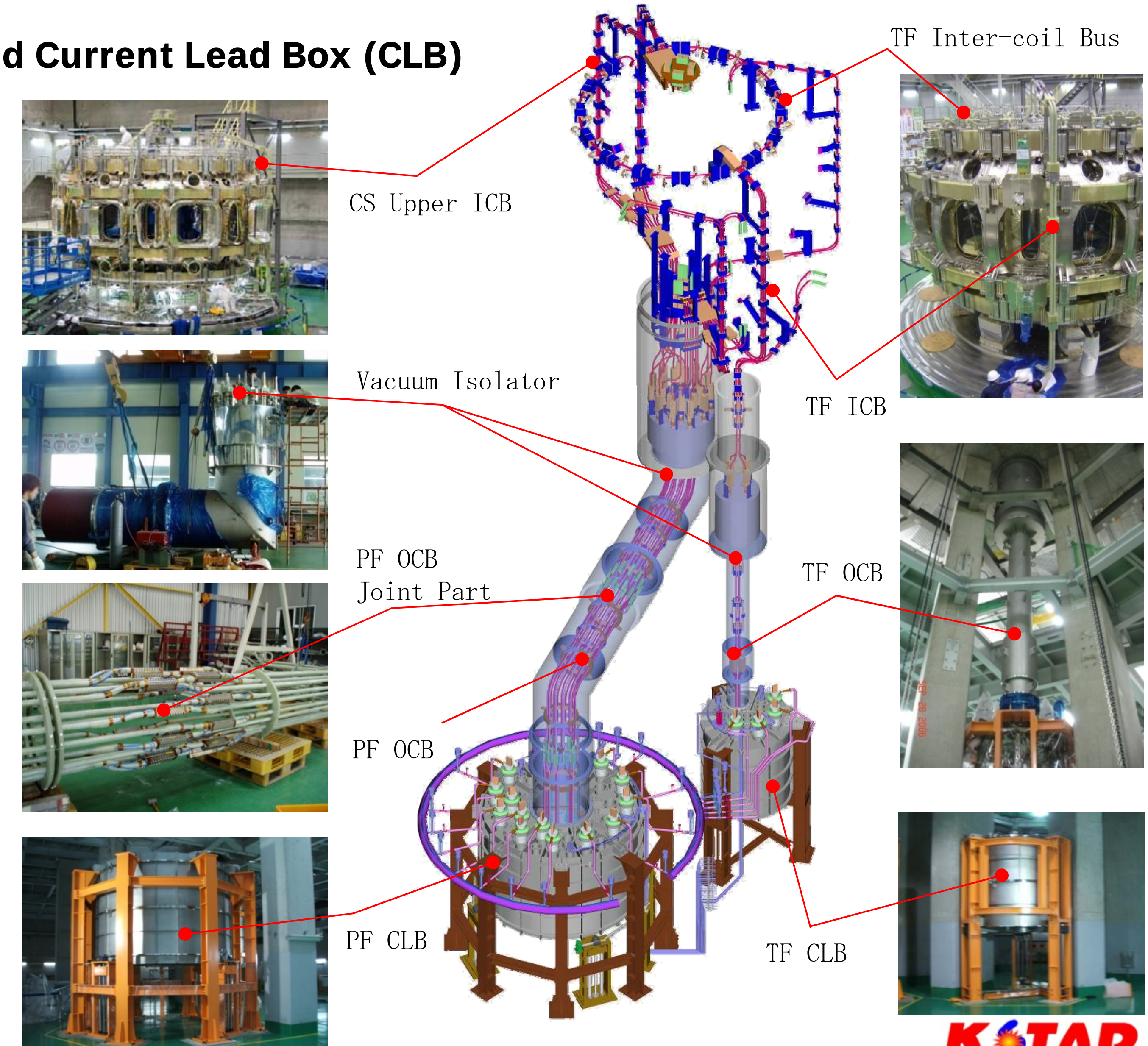
SC Current Feeder System

- **Buslines, Joints and Current Lead Box (CLB)**

Total Length of CICC : 821 m
# of Lap Joint : 136 ea
# of CICC
- 115 ea for bus-lines
- 15 ea for TF inter-coil bus

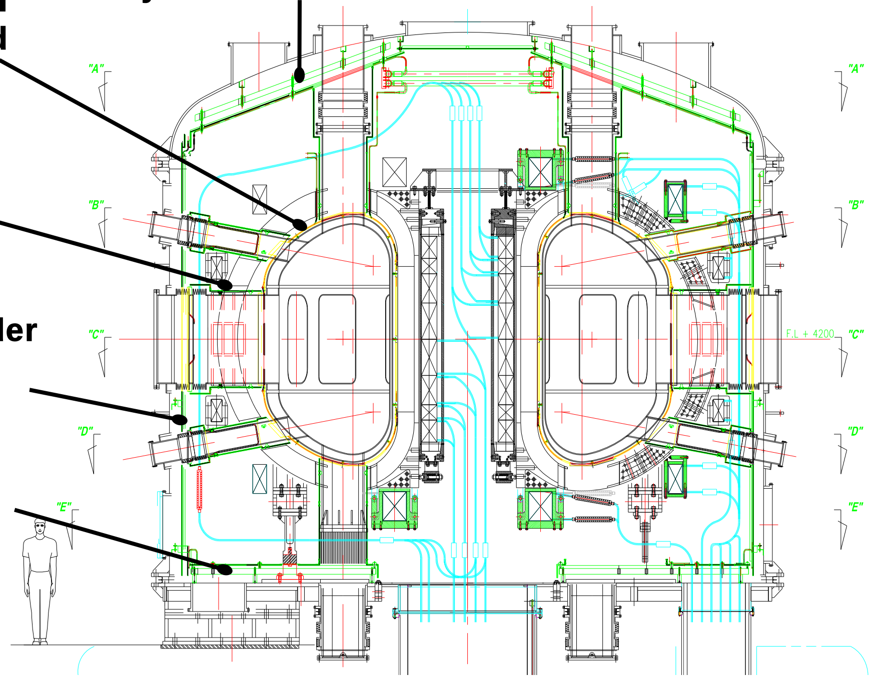
PF CFS
- **OCB Duct Length : 18.3 m**
- **OCB Duct O.D : 1420 mm**
- **OCB TS O.D : 1200 mm**
- **# of CL : 14 ea**

TF CFS
- **OCB Duct Length : 10.2 m**
- **OCB Duct O.D : 560 mm**
- **OCB TS O.D : 404 mm**
- **# of CL : 4**



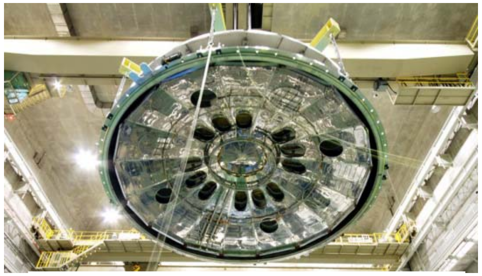
KSTAR

Thermal Shield (2004. 05 – 2007. 04)

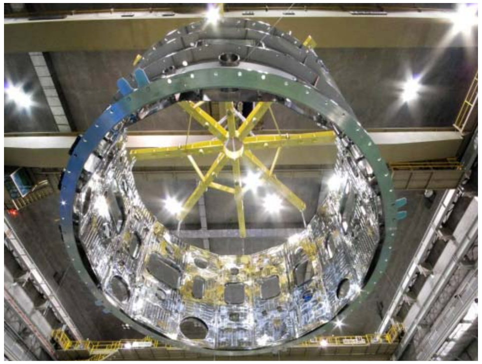


Material

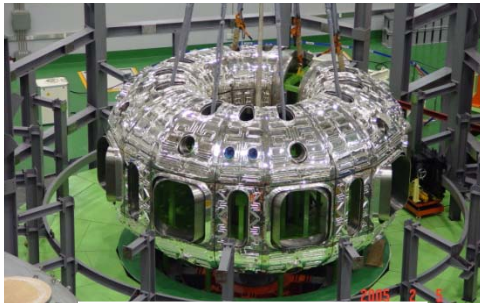
Panel	stainless steel 316L
VVTS support	G-11, 316L nut
CTS panel support	G-11, 316L bolt & nut
PTS panel support	G-11, 316L nut
Insulators	G-11
Silver coating	**VVTS, PTS : 10 μm thick**
MLI	**for CTS,** DAM with polyethilen spacer



Lid and Thermal Shield



Cylinder and Thermal Shield



VV Thermal Shield

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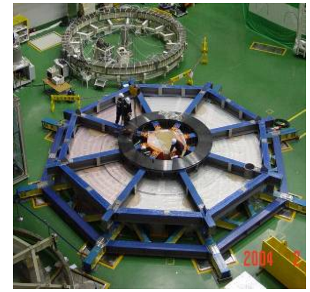
Site Assembly (04. 01 – 07. 05)

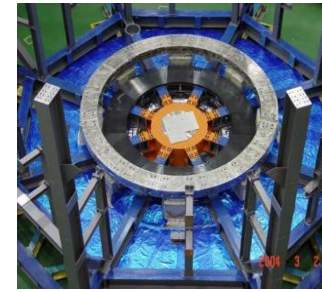
Cryostat Support Beam
(2002. 02)

Jig System: Base Frame
(2004. 01)

Cryostat Base
(2004. 02)



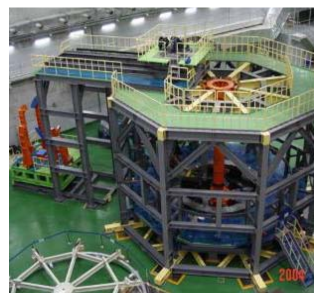
Jig System : Bottom Rail
(2004. 02)



Gravity Support
(2004. 03)

Jig System : Main Column

Main Jig : Top Frame
(2004. 03)



Completed Jig System

Assembly Test with TF00
(2004. 06)

Pre-install. of PF6L & PF7L
(2004. 07)

Install. of VV & VVTS Module
(2005. 02)

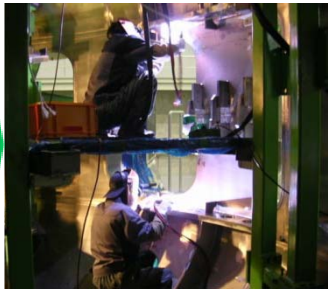
Re-construction of the Jig
(2005. 03)

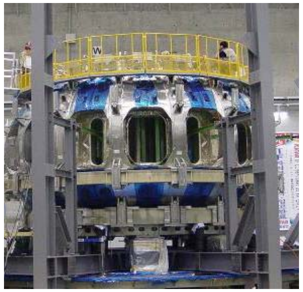
Start of TF Assembly
(2005. 04)

Completion of TF Assembly
(2006. 05)

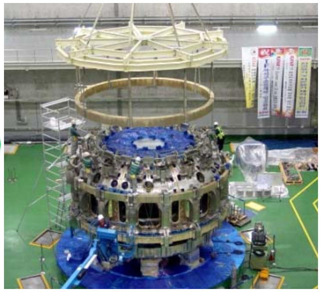
Install. of the VVTS Last Sector
(2006. 06)

Site Assembly (04. 01 – 07. 05)

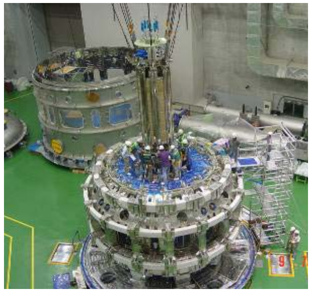

Install. of the VV Last Sector

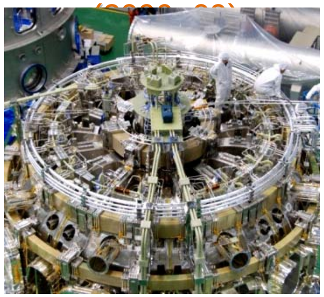

Install. of the PF6L & PF7L

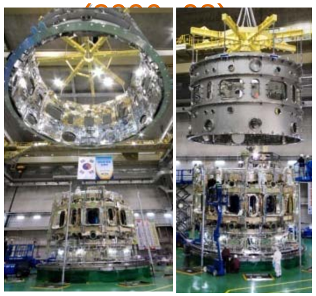

Assembly of VV Support

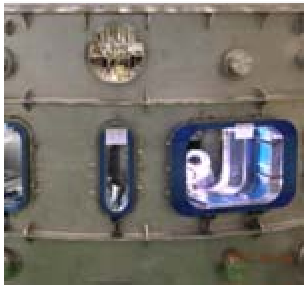

Install. of PF6U & PF7U

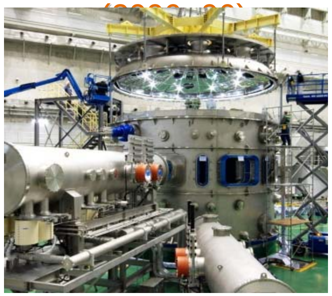

Install. Of PF5L
(2006. 09)


Install. of Central Solenoid
(2006. 10)


Final Inspection in Cryostat

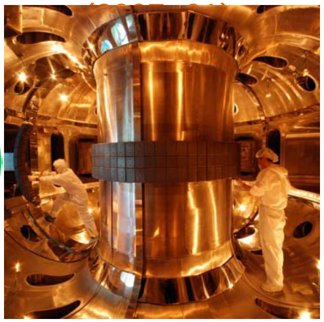

Assembly of Cryostat Cylinder

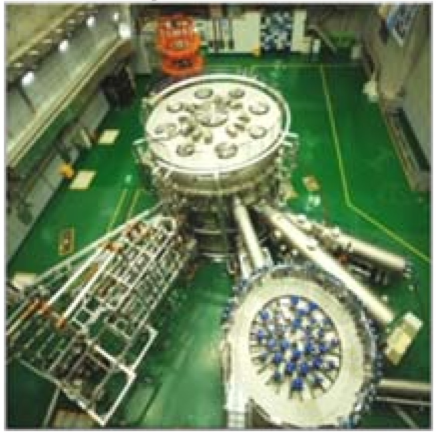

Assembly of VV Ports


Assembly of Cryostat Lid


Assembly of VV Vertical Ports
(2007. 05)


Finish of Tokamak Assembly
(2007. 05)


Install. In-vessel Component for 1st Plasma
(2007. 05)


Connection between Tokamak and HRS
(2008. 03)

KSTAR

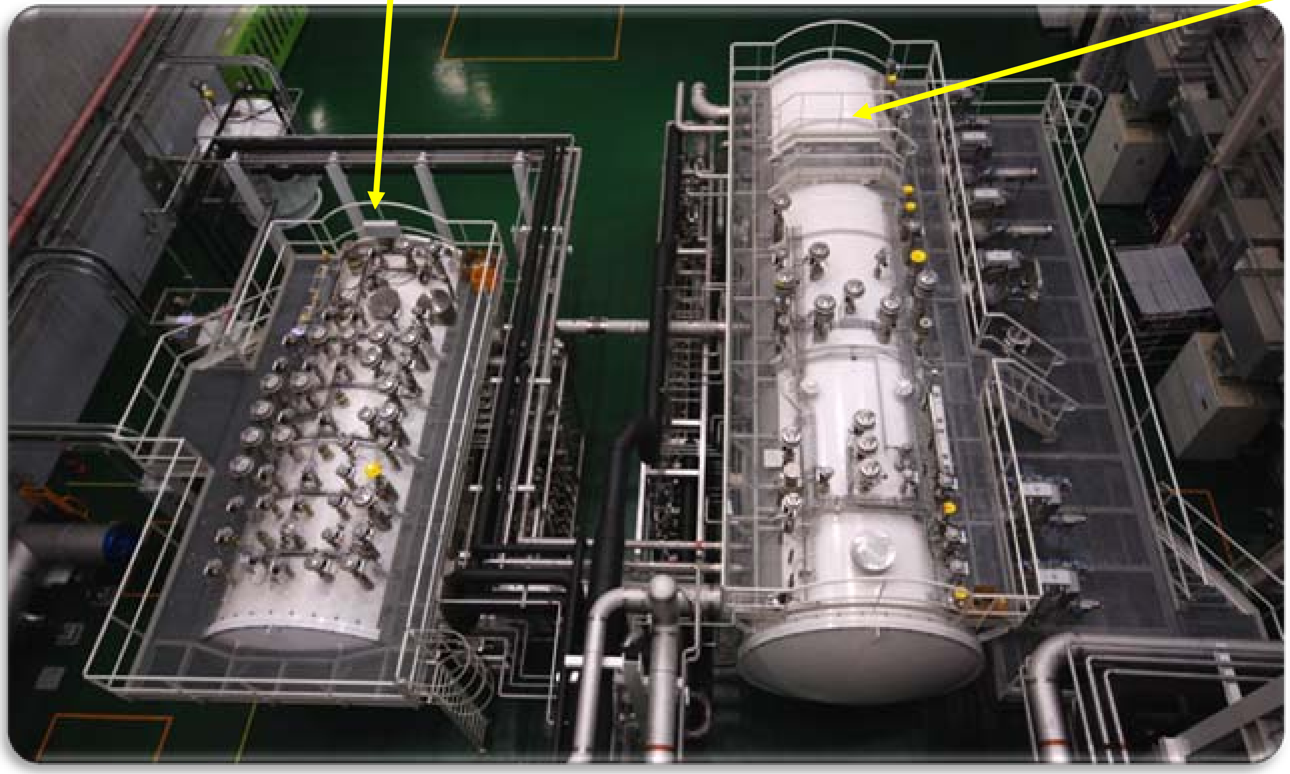
Helium Cryogenic Facility (03.12 ~ 08.03)

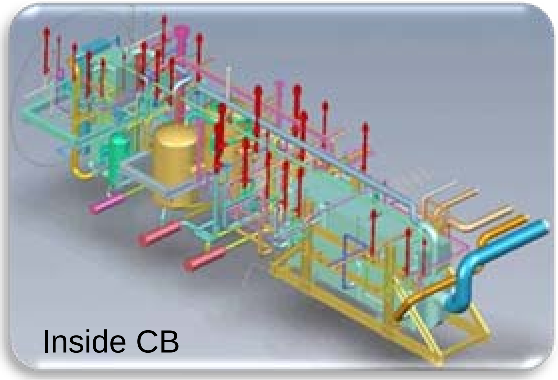
● Distribution Box (#1)

- Cryogenic valve : **49 ea** (Flowserve)
- SHe circulator : **2 EA, each 300 g/s** (Max. 420 g/s)
- Cold compressor : 310 g/s, 4.3 K GHe, ball bearing
- Heat exchanger : 7 aluminum plate-fin type
- Thermal damper : 6 m^3 filled with 4 m^3 LHe

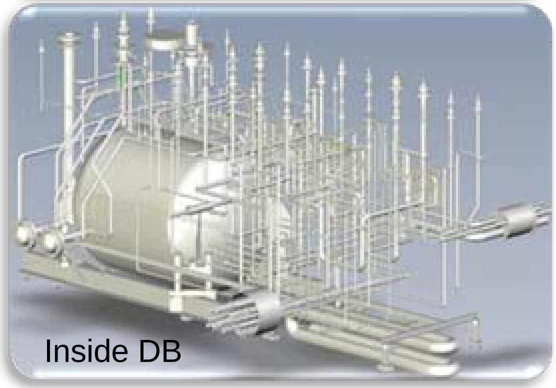
● Cold Box

- Cooling capacity : **9 kW@4.5 K equivalent**
- Turbine : **6 oil-free static gas bearing**
- Heat exchanger : 11 aluminum plate-fin type
- Adsorber : 80 K (Ar, O_2, N_2), 20 K (H_2, Ne)
- Cryogenic valve : **28 ea**





Inside CB



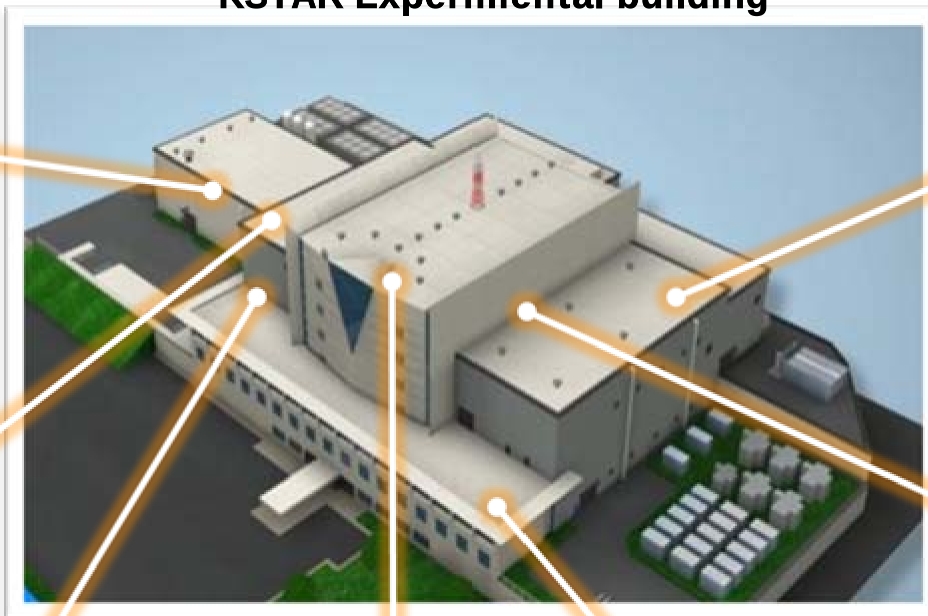
Inside DB

KSTAR

Other Ancillary Systems

Cooling water

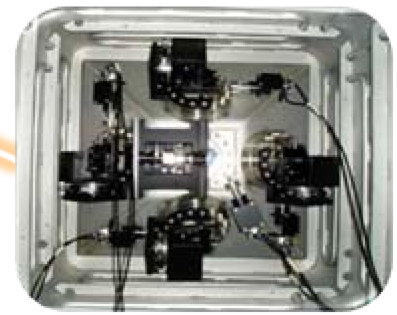
KSTAR Experimental building



Heating

Cryo-facility

Diagnostics



Magnet power supply

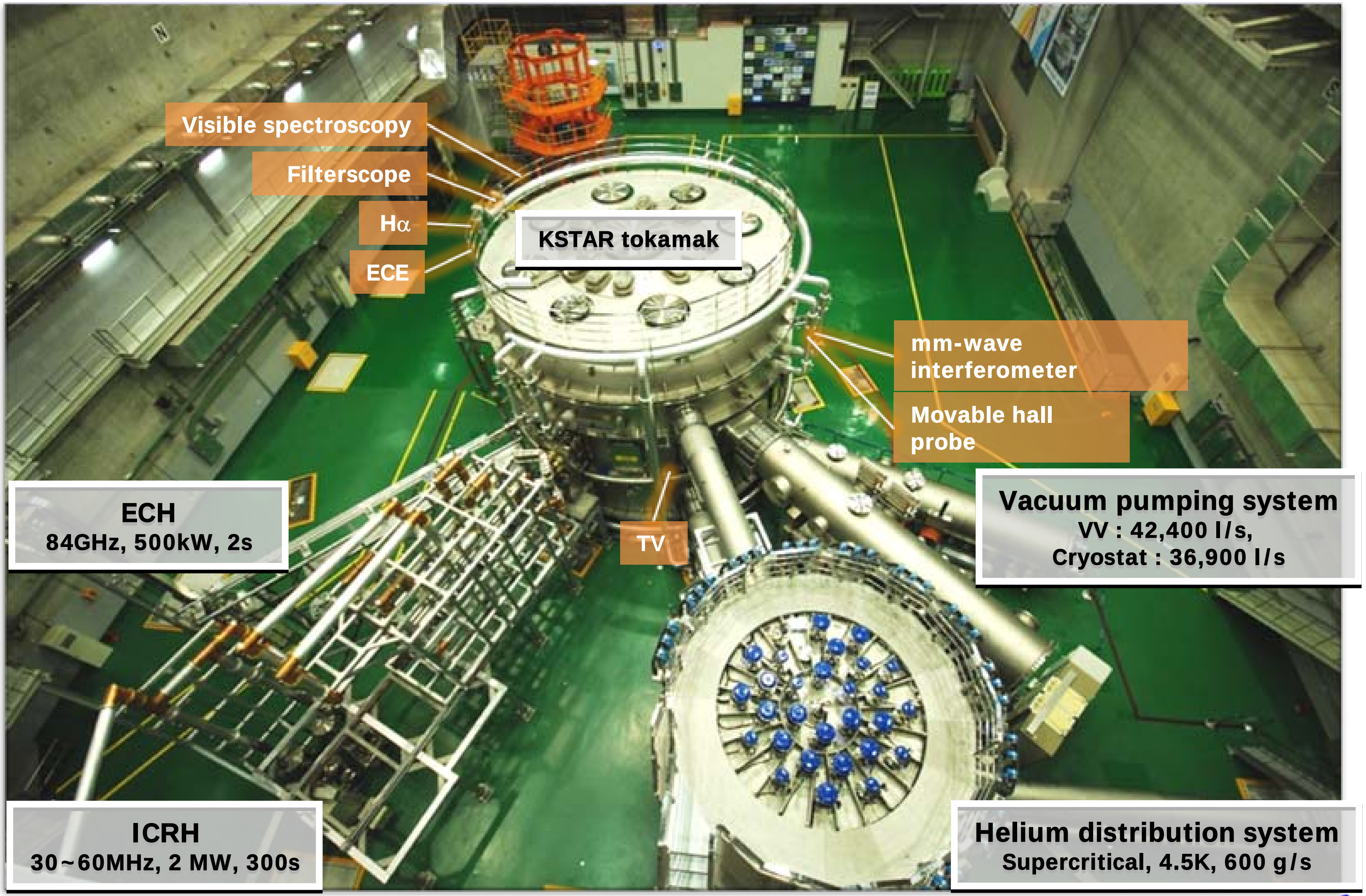
KSTAR

Main control

KSTAR

Ready for Commissioning

KSTAR device and initial ancillary systems was ready for the commissioning by February 2008!



KSTAR

Commissioning and First Plasma

●Objectives

- **To demonstrate that the system performances are in accordance with the design specification**
- **Target of first plasma over 100 kA, 100 ms**

Vacuum	Cool-down	SC magnet	Plasma
• VV base pressure < 5 x 10^{-7} mbar • Cryostat base pressure < 1 x 10^{-4} mbar	• Cool magnet system down to operating temp. • TF/PF coil temp. < 5 K • T. Shield temp. < 80 K	• Charge all SC magnet system without quench • Joint resistance < 5 nΩ • TF current : 15 kA • PF current : 4kA	• To make plasma discharge reliable • ECH pre-ionization • Ip > 100 kA • Pulse > 100 ms

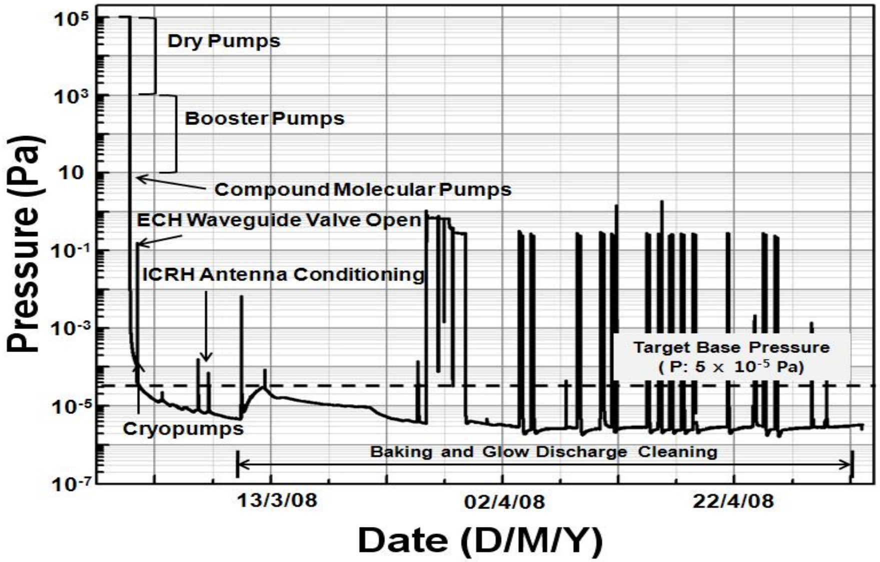
KEY DATES	COMMISSIONING PROGRESS
Sep. 14, 2007	Tokamak construction completed
Feb. 29, 2008	Vacuum pumping started after final inspection
Apr. 03, 2008	Magnet system cool-down started (9 kW refrigerator)
Apr. 23, 2008	SC phase transition detected (TF coil at 18 K)
Apr. 26, 2008	Cool-down completed (5 K, SHe 600 g/s)
May 05, 2008	Joint resistance & coil insulation measured
May 12, 2008	TF coil commissioning completed (15 kA, 8 hr)
May 27, 2008	PF coil commissioning completed (4 kA)
May 29, 2008	ECH pre-ionization test started (1.5 T, 84GHz)
Jun. 13, 2008	First plasma achieved (107 kA, ECH assisted)
Jul. 15, 2008	1st plasma campaign completed (pulse length over 800 ms)
Jul. 20, 2008	Warm up started

KSTAR

Vacuum Commissioning

Vacuum Vessel

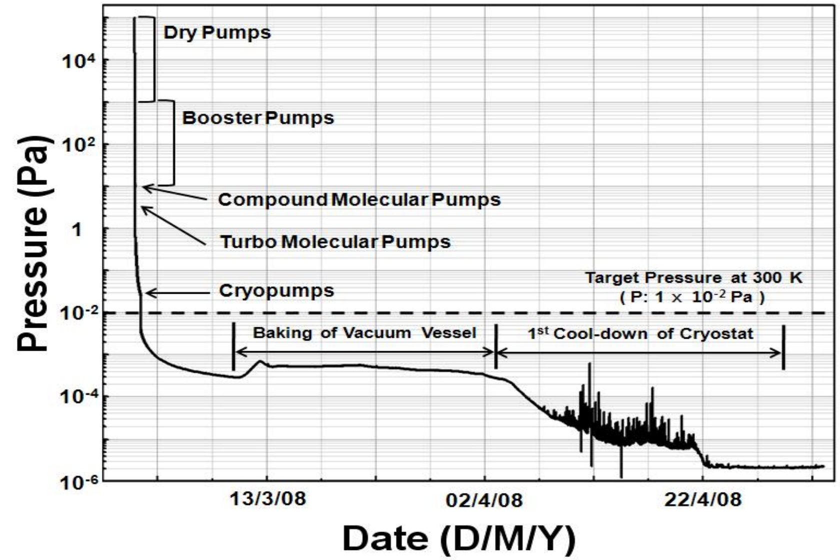
- Max pumping speed : 42,400 l/s
- Vacuum vessel volume : 110 m^3



- Target pressure < 5 x 10^{-7} mbar
- Achieved < 3 x 10^{-8} mbar
- Baking : ~ 100 °C
- Discharge Conditioning : GDC with H_2 & He (No boronization)

Cryostat

- Max pumping speed : 36,900 l/s
- Effective Cryostat volume : 240 m^3



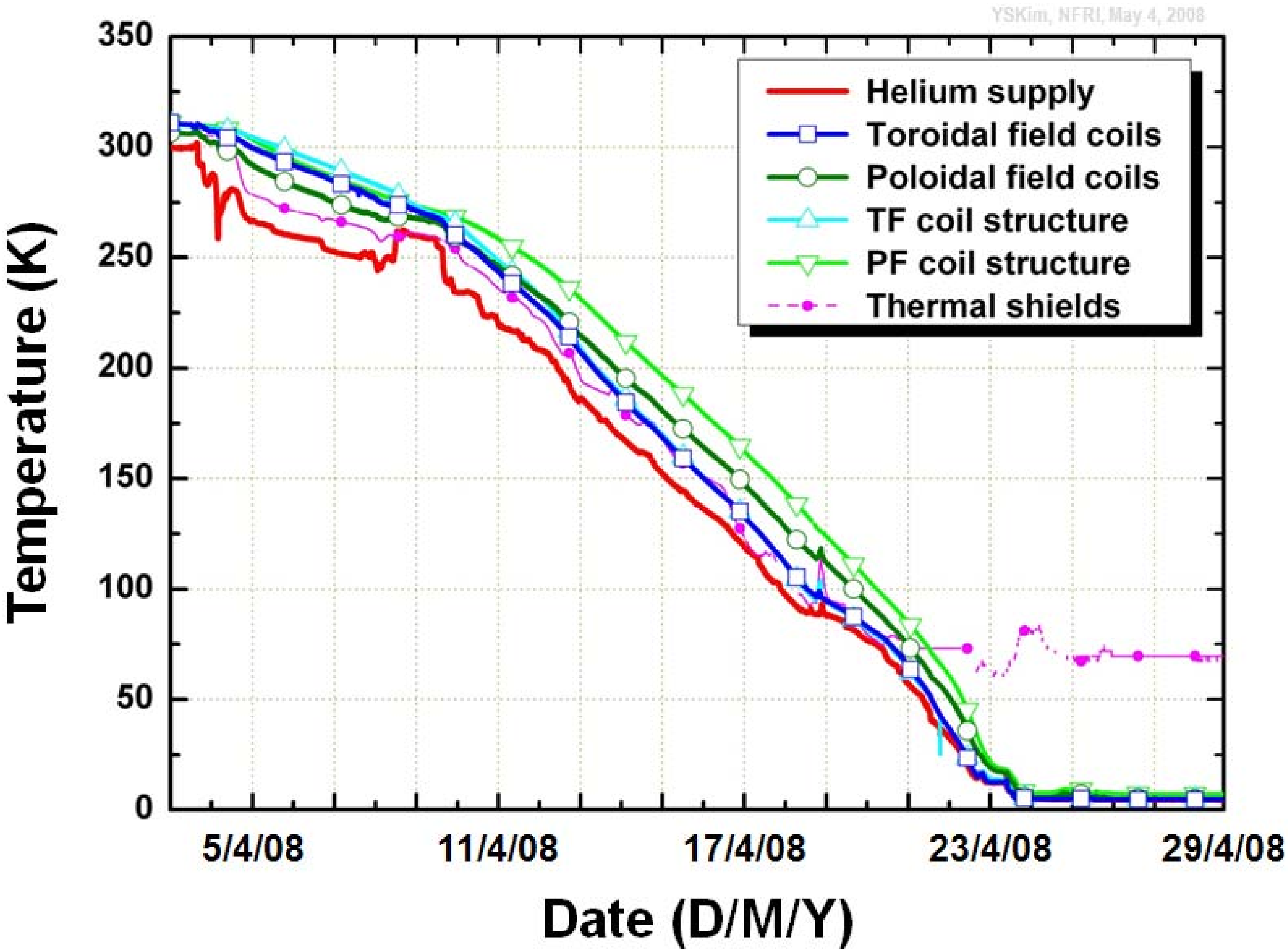
- Pressure :
  < 3 x 10^{-6} mbar (room temp.),
  < 3 x 10^{-8} mbar (after cool-down
- Total helium leak : < 9 x 10^{-8} mbar l/s
  (after cool-down)

KSTAR

Cryogenic Cool-down

● Cool-down History

In April 26, KSTAR superconducting coils were successfully cooled-down.



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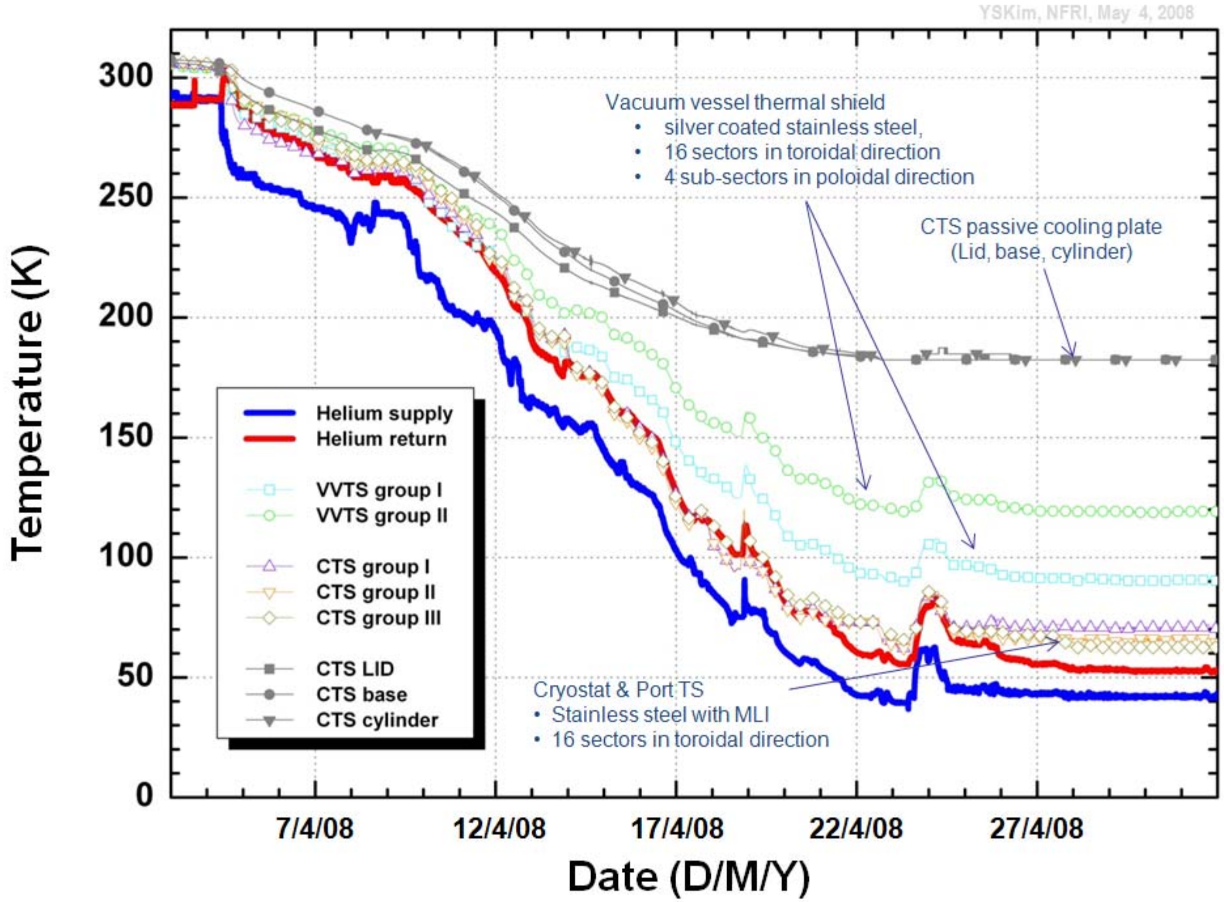
Cryogenic Cool-down

● Temperature Distribution in the Thermal Shields

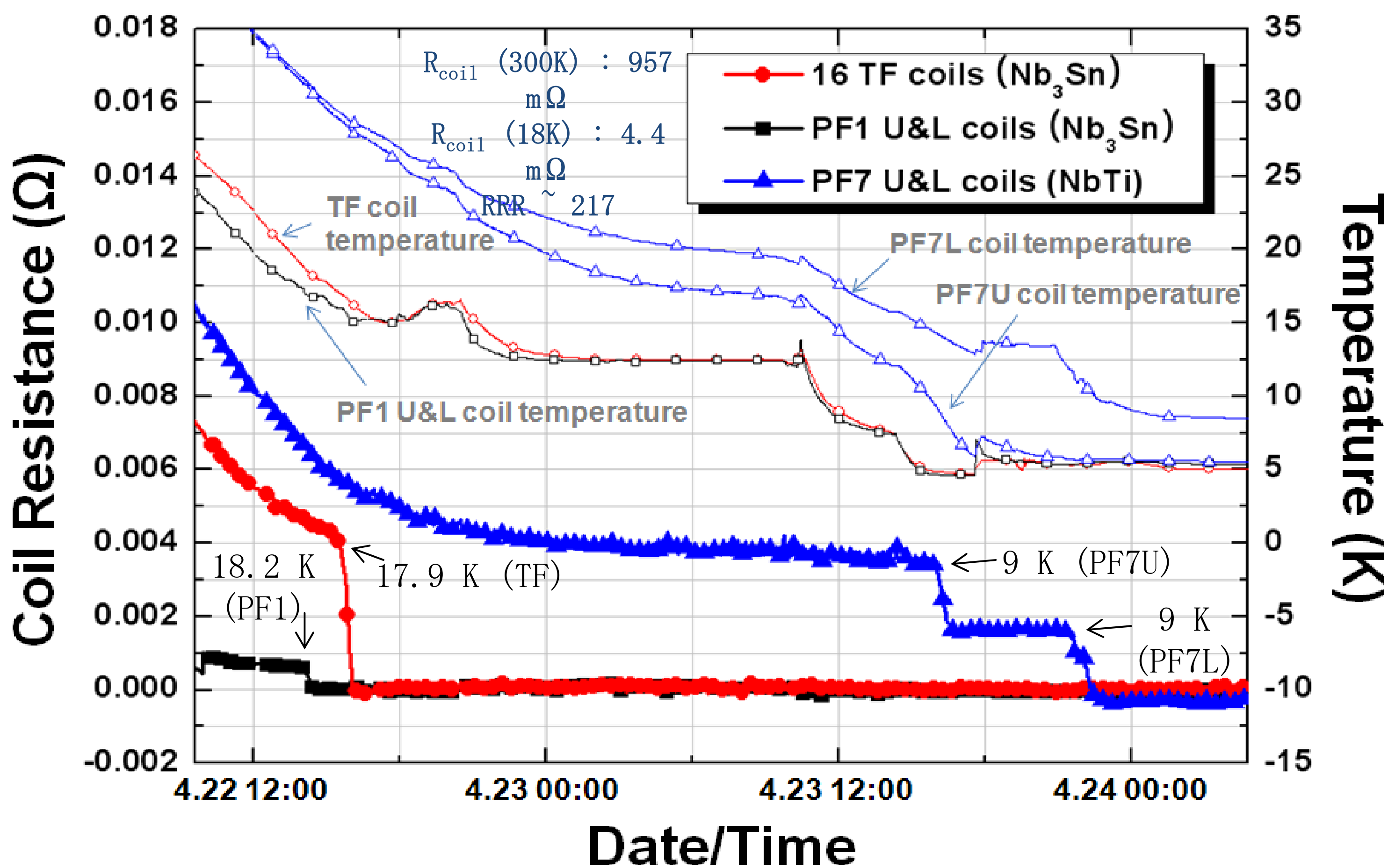
- **The cryostat thermal shields were well cooled below 70 K.**
- **The maximum temperature of the CTS measured in 180 K on the blank cover plate without cooling lines.**
- **The temperature of the vacuum vessel shield was distributed in 90 K ~ 120 K**



Cryogenic Cool-down

SC Transition

- The superconducting phase transition of the SC coils was clearly observed during the 1st cool-down.
- The SC transition of Nb3Sn and NbTi coils appeared at 18K and 9K, respectively.

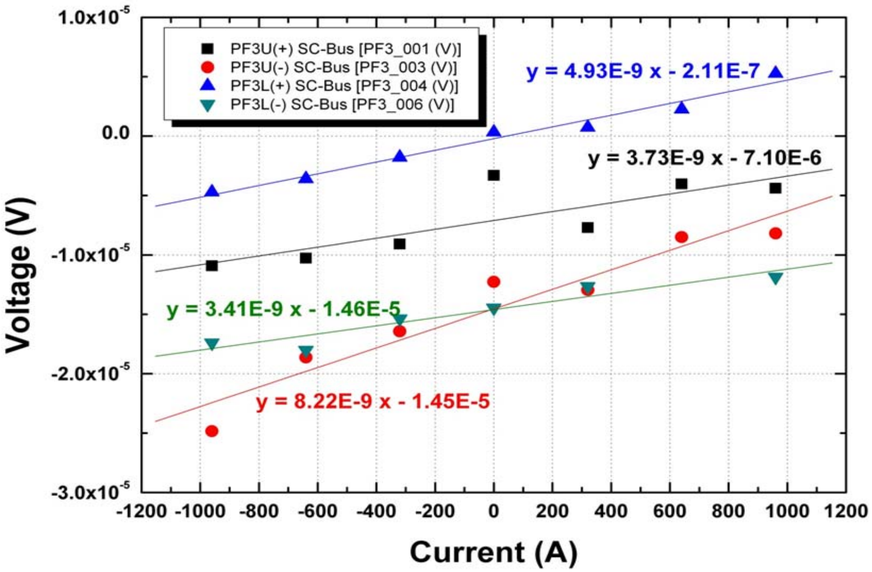


Cryogenic Cool-down

● Joint Resistance

- The voltage drops were measured at each SC bus-line, which consists of several numbers of electrical joints.
- The joint resistances were estimated by linear fitting to the measured V-I curves.
- All of the KSTAR lap joint resistances satisfied the design value of 5 nΩ.

[The KSTAR lap joint of the SC bus-line]



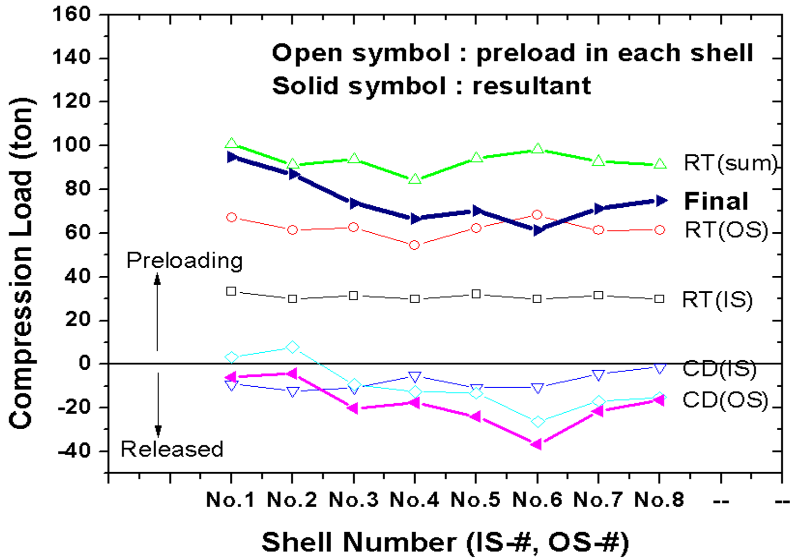
Coil	Lap Joints [EA]	Total R [nΩ]	Average [nΩ /joint]	Design Value
TF	6	11.1	1.85	< 5 nΩ
PF1	7	15.6	2.23	
PF2	7	11.1	1.59	
PF3	12	20.3	1.69	
PF4	12	17.4	1.45	
PF5	12	25.2	2.1	
PF6	14	11.2	0.80	
PF7	8	4.11	0.51	

KSTAR

Cryogenic Cool-down

● Pre-load Change of the CS Structure

- CS pre-load at room temp. was about **747** tons which is 58% of the required preload of **1300** tons
- However, there was additional pre-load release by **146** tons after cool-down
- It can be concluded that compression at coil interfaces can locally disappear due to cool-down.



Shell No.	Preload (ton), @ RT			Preload (ton), after cool-down			Remaining
	Inner	Outer	Sum	Inner	Outer	Sum	Total
No.1	33.4	67.2	100.6	-9.0	3.2	-5.8	94.9
No.2	29.8	61.5	91.3	-12.1	7.8	-4.3	87.0
No.3	31.3	62.7	93.9	-10.9	-9.3	-20.1	73.8
No.4	29.8	54.6	84.3	-5.3	-12.5	-17.7	66.6
No.5	32.0	62.3	94.3	-10.7	-13.2	-23.9	70.4
No.6	29.8	68.3	98.1	-10.3	-26.3	-36.6	61.5
No.7	31.5	61.2	92.7	-4.5	-16.9	-21.4	71.3
No.8	29.8	61.5	91.4	-1.3	-15.2	-16.4	74.9
Sum	**247.3**	**499.3**	**746.6**	**-63.9**	**-82.4**	**-146.3**	**600.3**

SC Magnet Commissioning

TF Magnet Commissioning

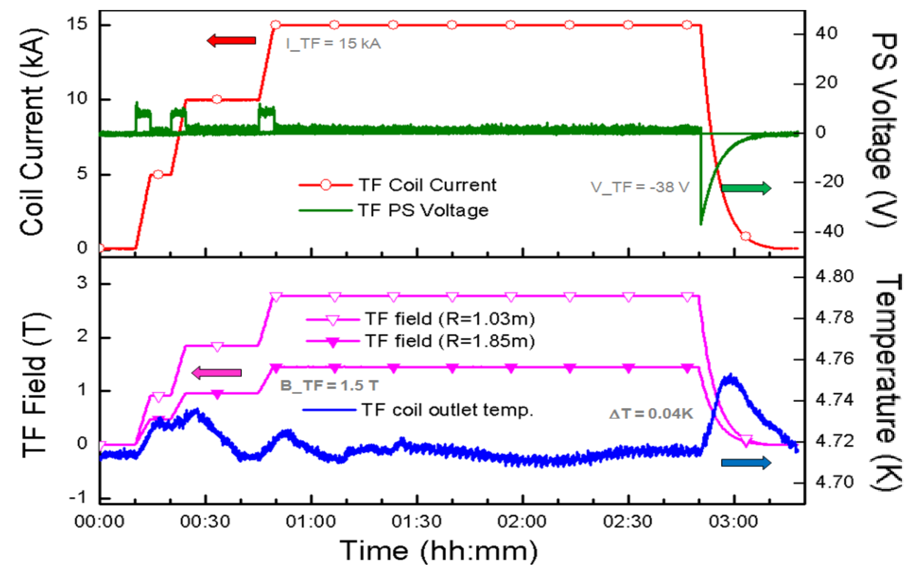
TF magnet & power supply test

- TF magnet system assembled assembly without individual cryogenic test
- Qualification test in each fabrication steps including strand Jc measurement after heat treatment

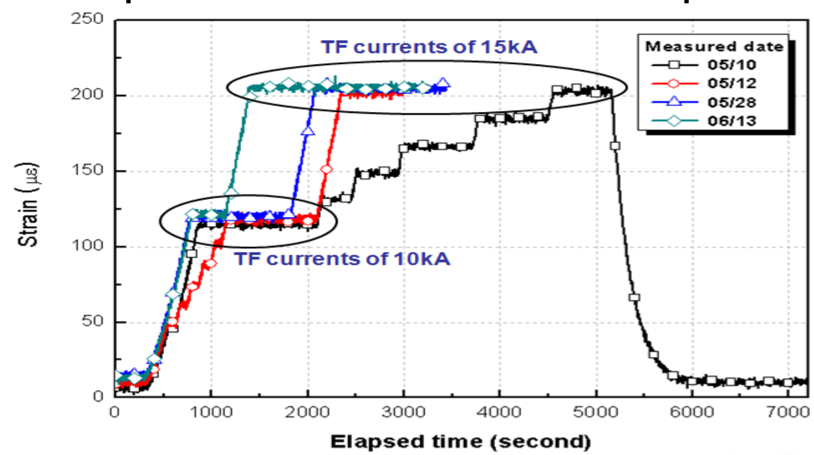
- Operation results:
- DC current operation :**15 kA, 8hr**
- B_{TF} : 1.5 T (R : 1.6 ~1.8 m) for ECH
- Slow & fast discharge
- Coil temperature rising **< 0.1 K**

- **All TF magnets operated stable in thermal and mechanical aspects up to 15 kA**
- **There was not any defects like quench during operation**

TF coil 15 kA operation and stability in coil temp.



Repeated strain values for various TF operations



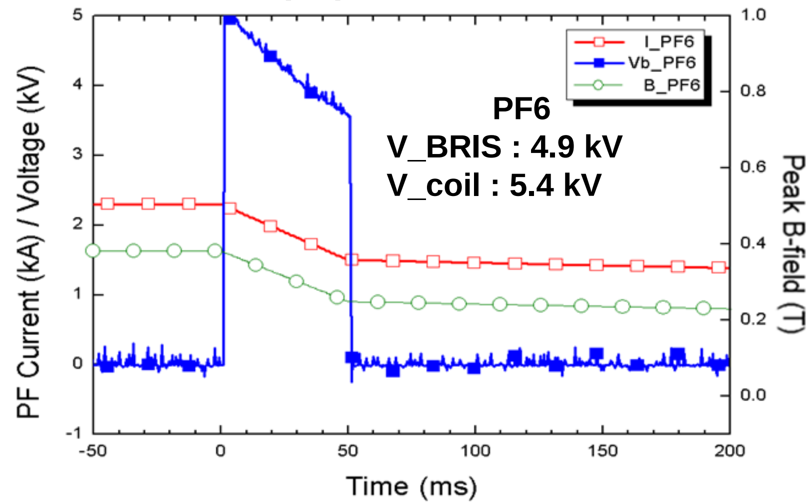
SC Magnet Commissioning

● PF Magnet Commissioning

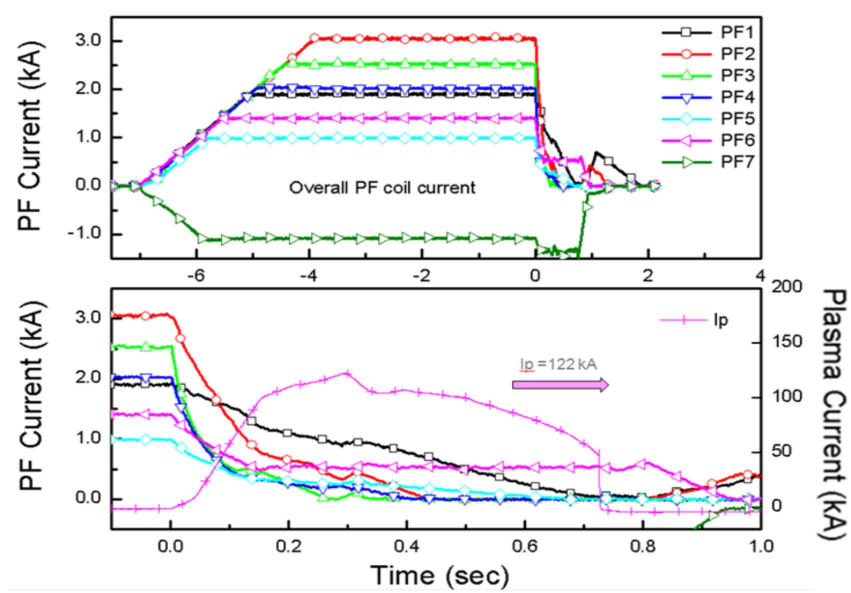
◆ Single PF coil test :
- Control gain tuning at 1 kA
- Current control using PCS (**within 4 kA**)
- Step response test
- Blip control test records
  - **dI/dt : -98.9 kA/s, dB/dt : -16 T/s**
  - **Peak voltage : 5.4 kV**
- Quench detection system tuning
- Safety interlock test

• Successful PF coil control and field null formation

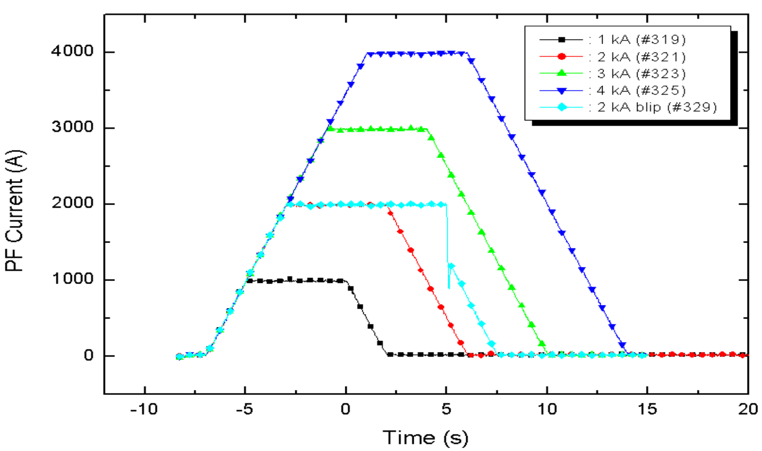
Blip operation test



Integrated PF coil operation



Current control for single PF coil



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First Plasma Discharge

● Field Null Formation

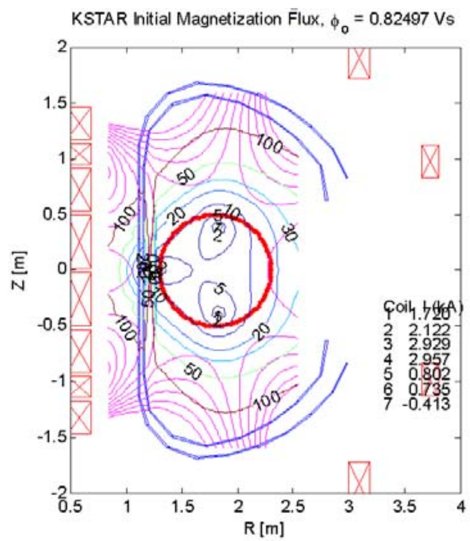
Conventional & dipole mode

- Conventional mode :
  - Large null-size but low loop voltage
  - R=1.8 m
  - Larger current in PF3 & 4 coils
  - Favorable for initial breakdown
  - used for first plasma

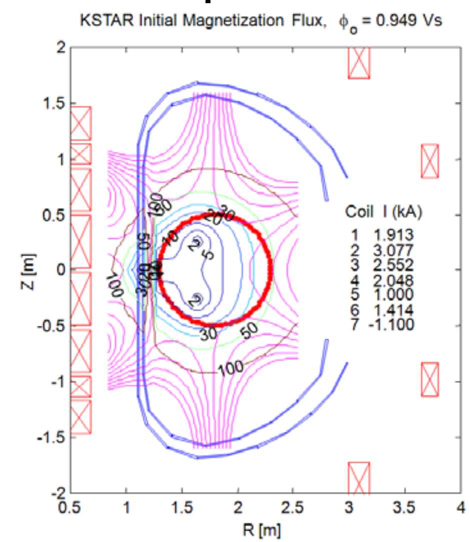
- Dipole-like mode :
- Small null-size, but higher loop voltage
- R=1.7 m
  - Larger current in PF6 & 7 coils
- Effective for current ramp-up & feedback control
- Used for feedback control

• In KSTAR, dipole-like mode was successfully developed.

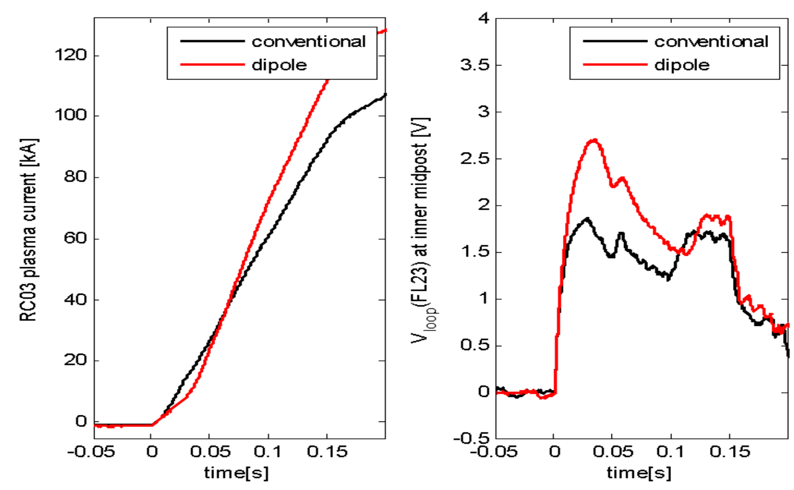
Conventional mode



Dipole-like mode



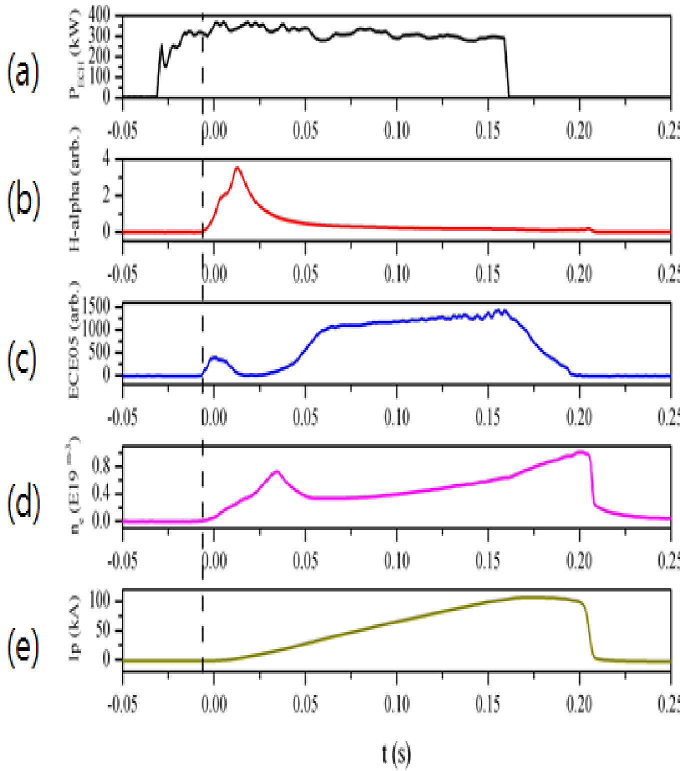
Conventional & dipole–like mode comparison



First Plasma Discharge

● ECH Pre-ionization

2nd harmonic ECH startup



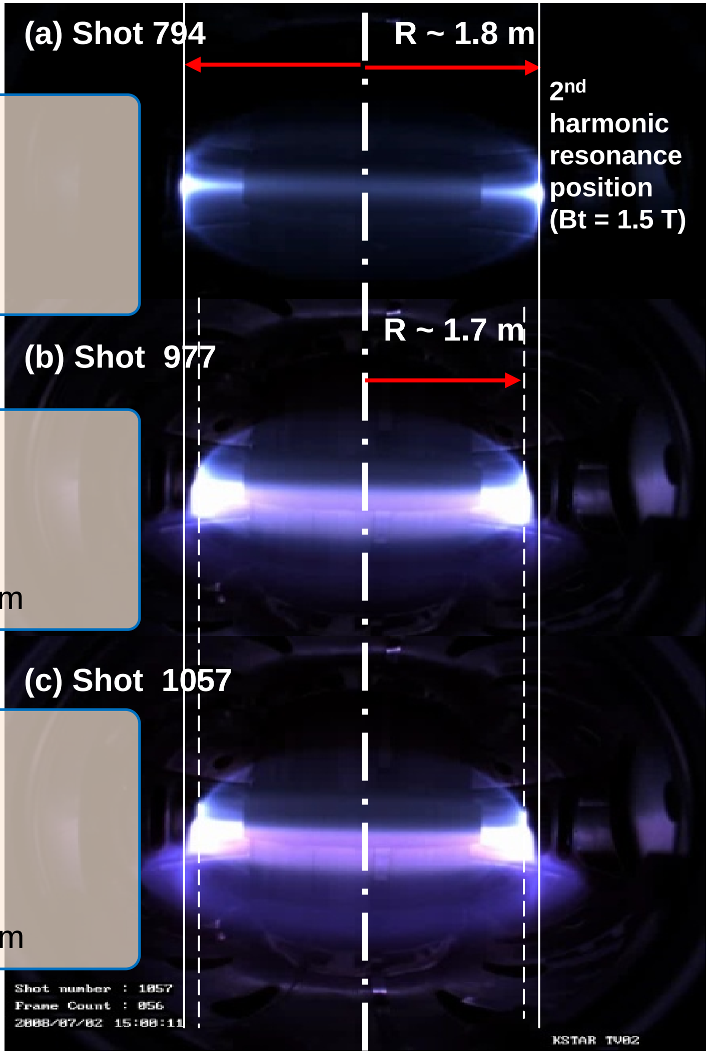
• Due to ECH, successful plasma discharge at low ohmic voltage

ECH pre-ionization

• Shot no. 794
Conventional mode
Perpendicular launch
EC beam target:
Z=0m, R=~1.8 m

• Shot no. 977
Dipole-like mode
Perpendicular launch
EC beam target:
Z=~ -0.1m, R=~1.7 m

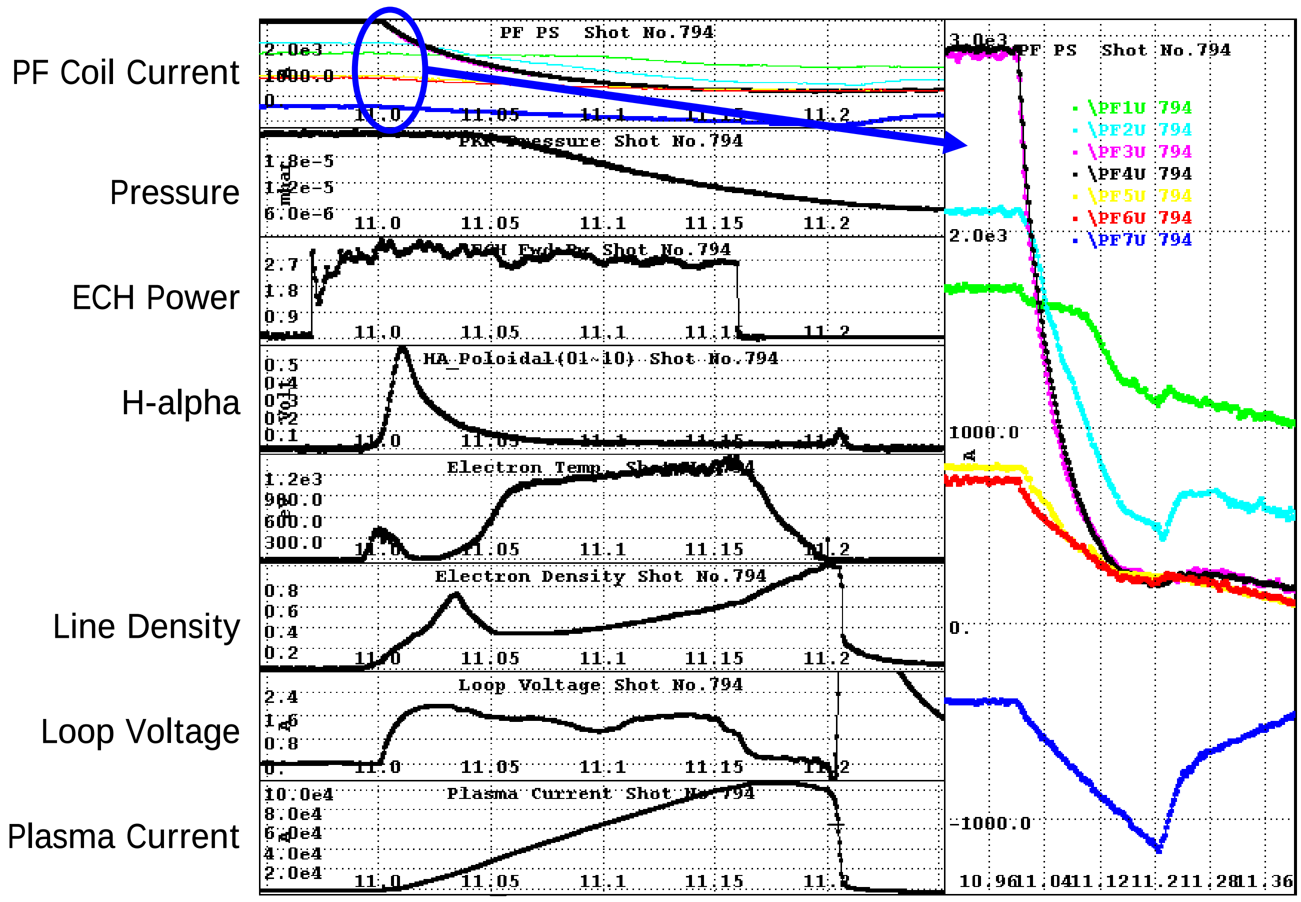
•Shot no. 1057
Dipole-like mode
Oblique launch
(tor. angle=-10°)
EC beam target:
Z=~ -0.1m, R=~1.7 m

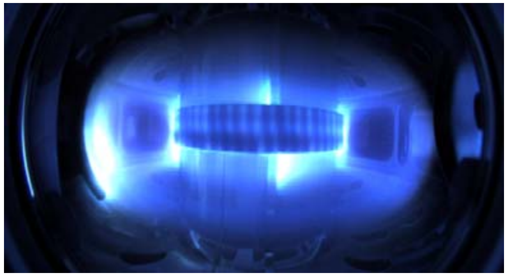


KSTAR

First Plasma Discharge

- **First Plasma (#794, '08. 6 .13)**





- B_{TF} : 1.5 Tesla
- R=1.8 m, a=0.3m
- P_{ECH} : 350 kW
- Line Density : 1x10 ^{19}/m^2(peak)
- **Peak loop voltage : 1.93 V**
  @ inboard mid-plane
- Plasma Current : **107 kA**

(peak)

- Pulse length : 210 ms

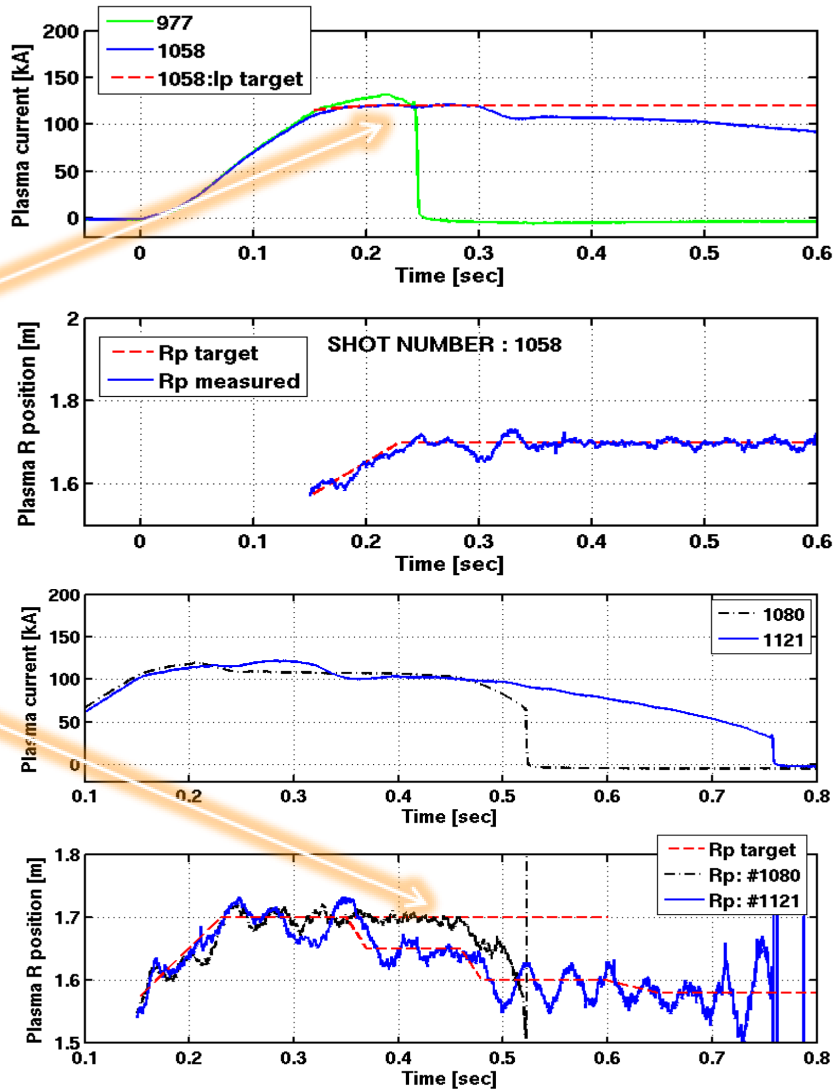
First Plasma Discharge

● Feedback Control for Longer Plasma

Ip, Rp, Ne feedback control

- Feedback on plasma geometry parameters (Ip, Rp) enabled stable ohmic plasmas after ECH turned off
  - •Plasma current (Ip) : by PF1~5
  - •Plasma radial position (Rp) : by PF6,7
- Vertical position control (Zp) was limited due to serial connection of PF up/down coil.
- By gradual decreasing of plasma radius (Rp) control, plasma pulse was extended due to reduction of volt-seconds consumption

- **Plasma could be sustained after ECH turn off**
- **Plasma pulse was up to 860 ms (under same volt seconds of 1.1 Wb)**



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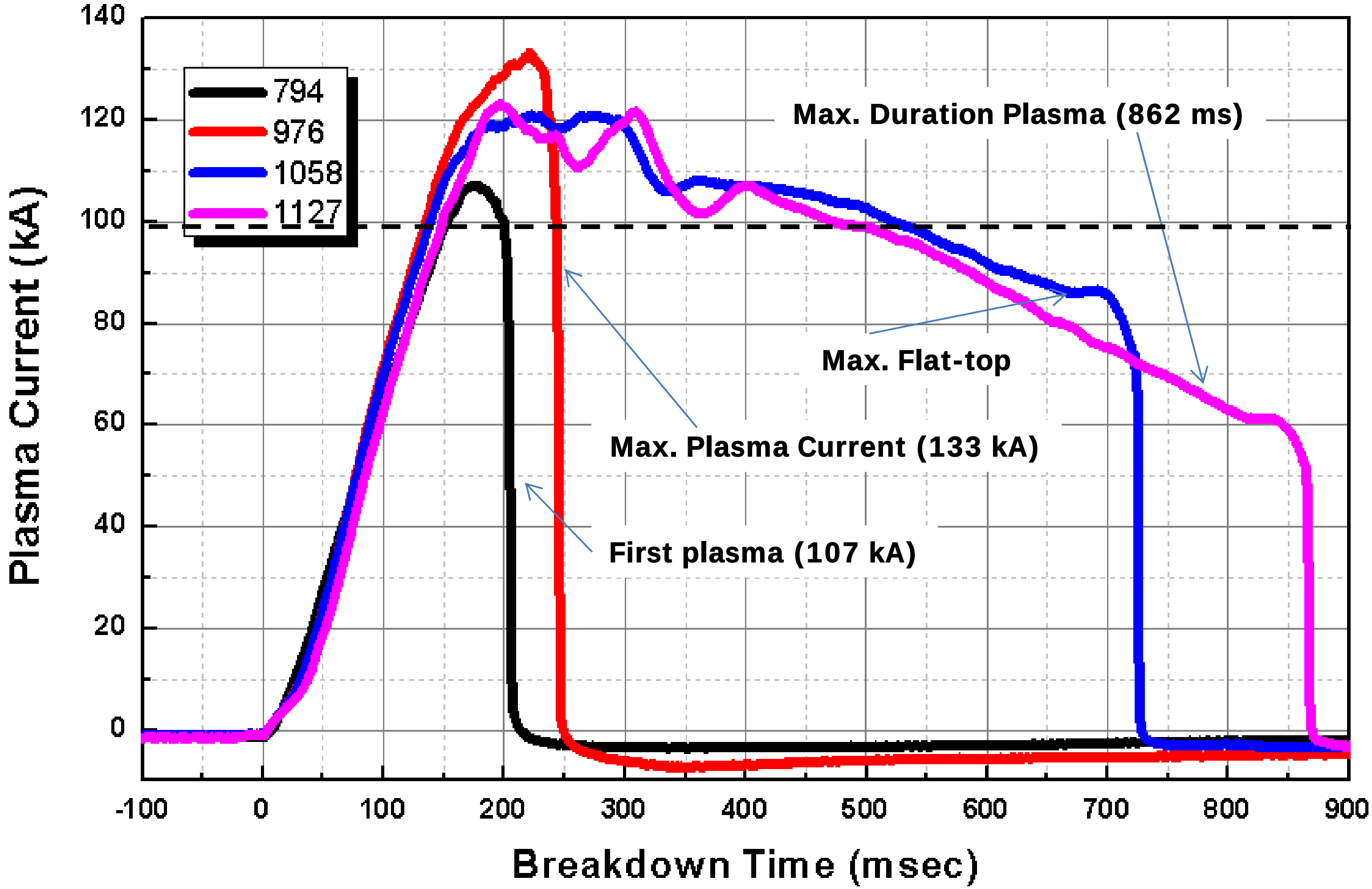
First Plasma Discharge

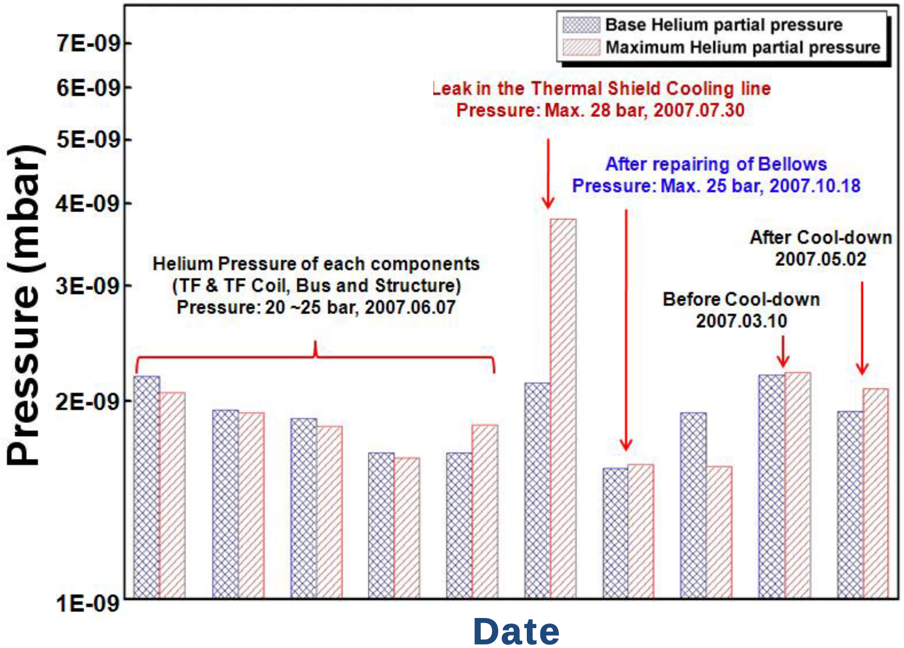
- **Representative Shots**



Troubleshoots

● **Helium Leak in the Cryostat Thermal Shield @ Room Temp.**

Small He leak was found in the cryostat thermal shield (CTS) during final inspection!



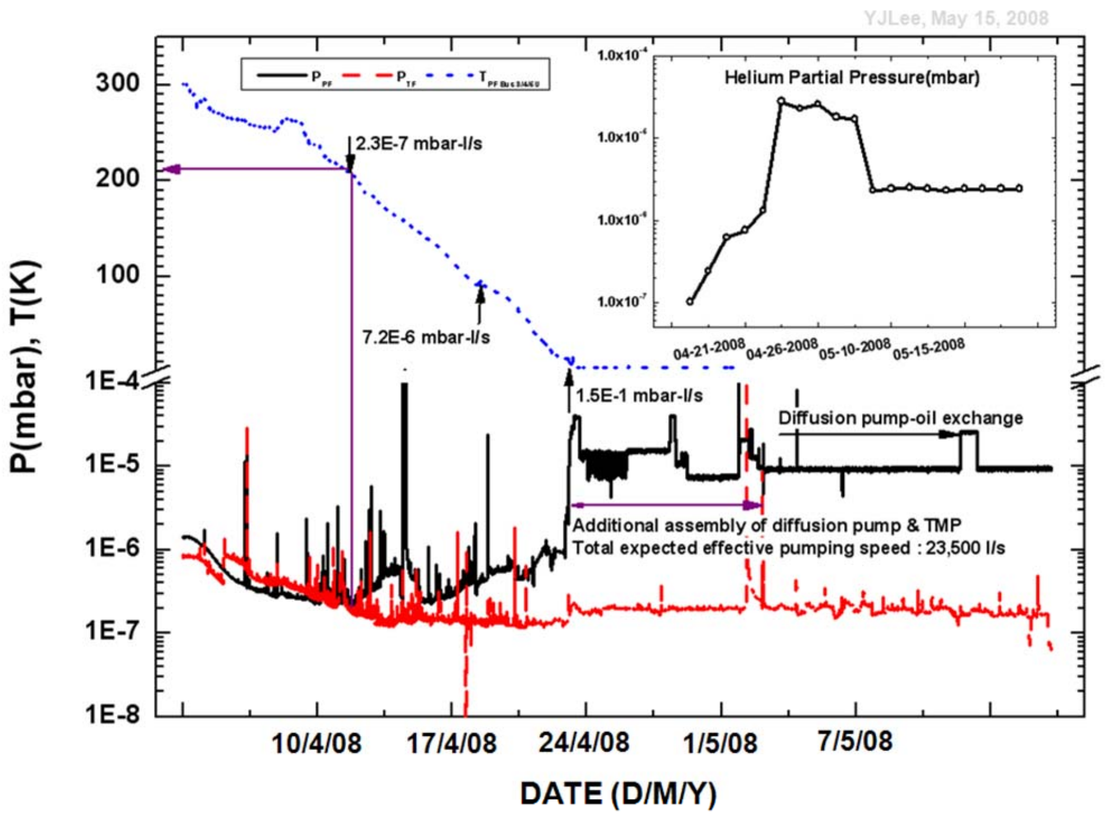
Leak detected
(2007. 07. 30)

Leak Point : bellows in the CTS
(repaired on 2007. 10. 18)

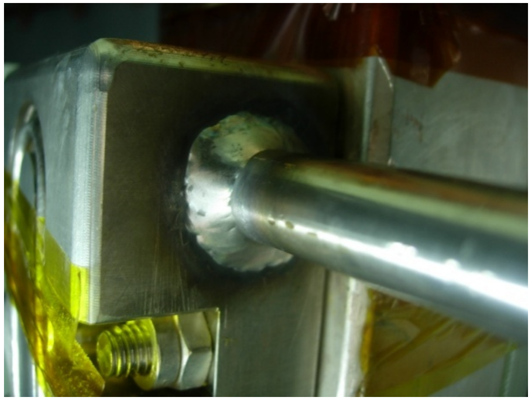
Troubleshoots

● Cold Leak in PF Current Lead System during Cool-down

- The TF CLB maintained bellow 2.0E-7 mbar after cool-down, but the PF CLB pressure started to increase at 210 K due to a cold leak.
- The additional high vacuum pumps to pump-out helium was mounted in PF CLB.
- The final pressure was maintained bellow 1E-5 mbar and passed the high electrical potential break-down test (up to 6 kV).



PF3,4,5U Lap joint case remove



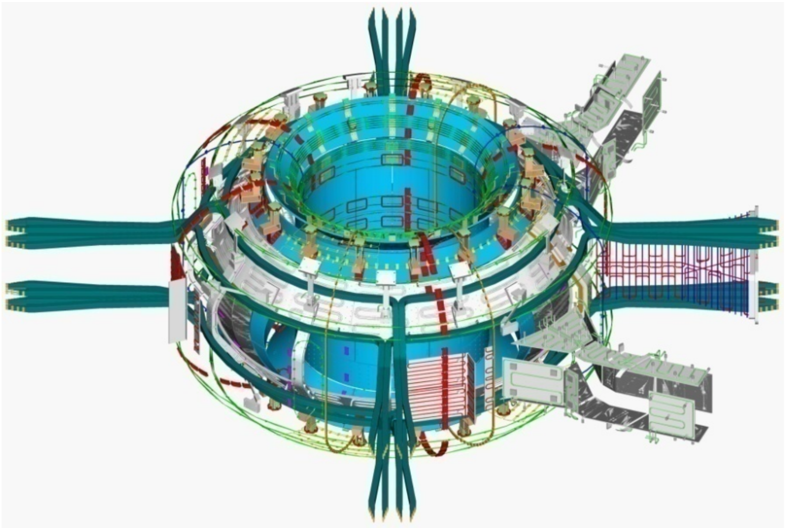
After repair

KSTAR

Near Term Plans

- After the first plasma achievement, the KSTAR device is under the maintenance period for the device inspection and for the system upgrades.
  - **Investigation of Nb_3Sn superconductor under the severe dc and ac operation condition (2009)**
  - **Preparation for D-shape H-mode operation (2010)**
  - Control and stabilization of high temperature plasma for steady-state operation especially using **in-vessel control coils** and ECCD.
  - Characterization of heating and current drive system in steady-state operation with relevant to ITER (5 GHz LHCD, NBI, etc)
  - **Diagnostic system upgrade for the steady-state physics under the international collaboration ; Thomson scattering, Bolometers, ECE, XCS, etc.**

In-Vessel Components (PFC & IVCC)



Neutral beam injection system development

Summary

- **The successful commissioning and the first plasma achievement in KSTAR validates the design, engineering and construction aspects of the first major Nb_3Sn superconducting tokamak.**
- **KSTAR has achieved the first plasma on June 13 (Fri). Plasma current was ramped up to 133kA with rate of 0.8 MA/s, and well-controlled with duration up to 862 ms.**
- **It is remarkable that all the commissioning were achieved without any serious problems in the first attempt.**
- **By adopting the 2^{nd} harmonic ECH pre-ionization, plasma start-up was possible under the loop voltage less than 3 V (R=1.68 m).**
- **KSTAR will be operated as an international collaboration device to contribute the science and technology for the future fusion reactor development including ITER**

The speaker would like to thank all the KSTAR participants from Korea domestic and international collaboration partners who gave efforts to make successful construction and commissioning !

Thank you for attention !