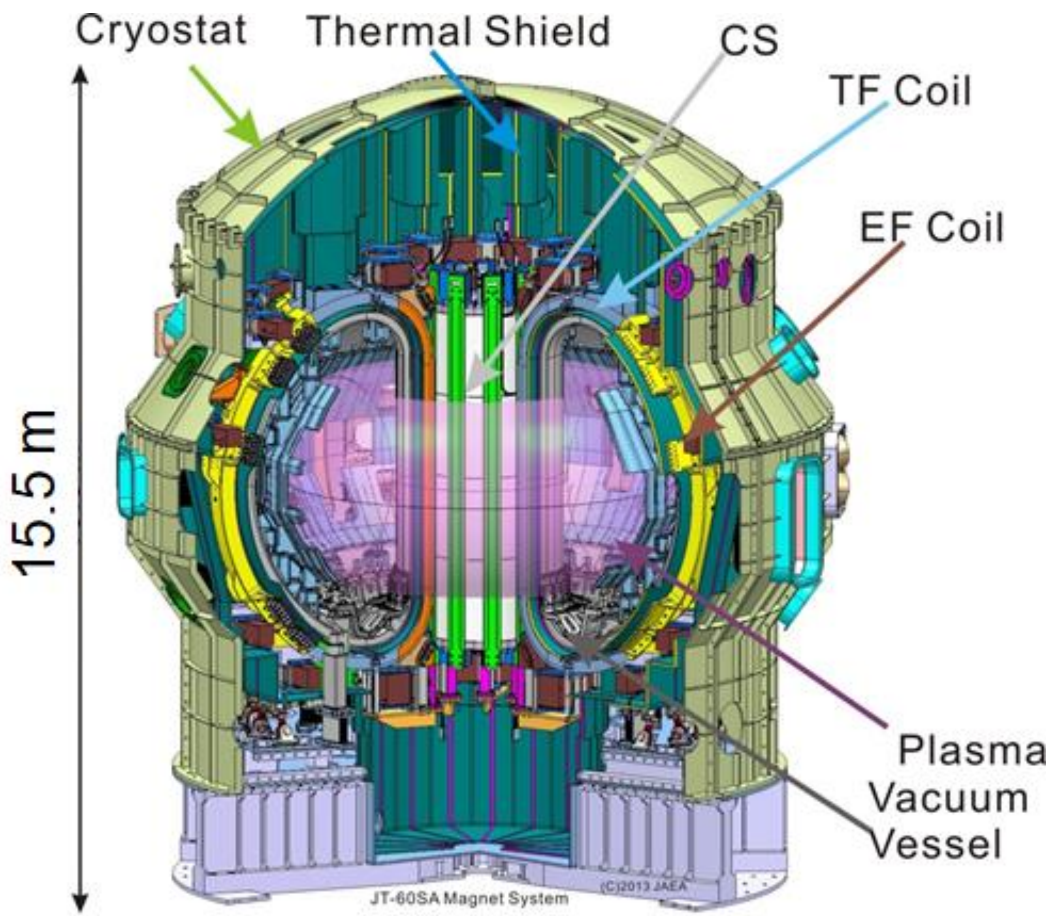
Overview of Construction and First Commissioning Results of JT-60SA Superconducting Magnets



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18 Nov 2021
27th International Conference on Magnet Technology

JT-60SA(JT-60 Super Advanced)

Mission: contribute to early realization of fusion energy by addressing key physics and engineering issues for ITER and DEMO

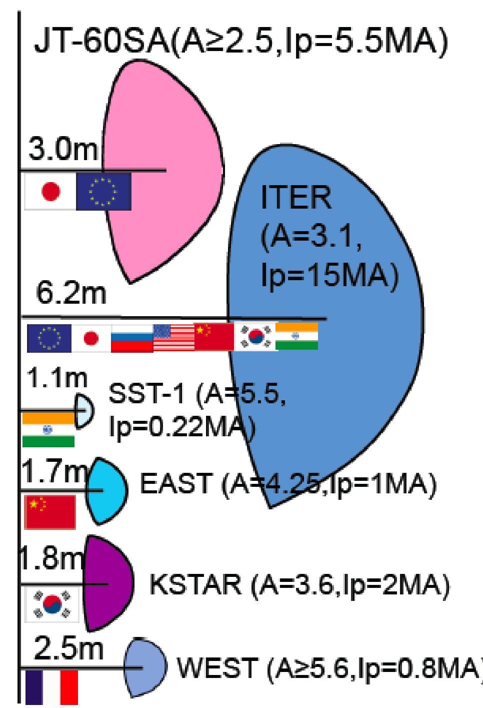
1. Support ITER
using break-even-equivalent class high temperature D-plasmas lasting for a duration (typically 100s)

Engineering contribution to ITER as the largest superconducting tokamak system. (size ~ 10 – 15m, weight ~2300 t)

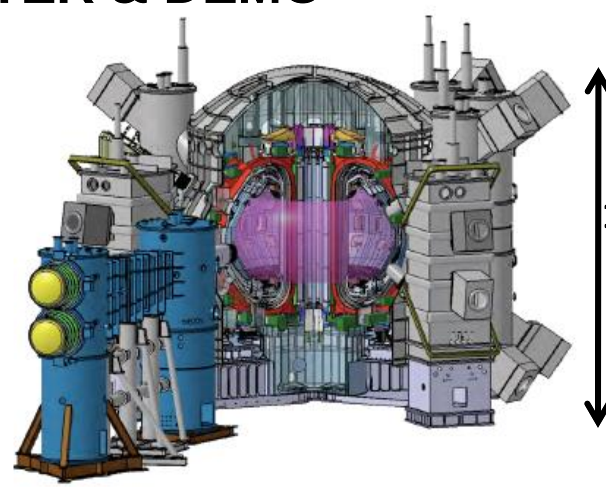
2. Supplement ITER toward DEMO
with long sustainment (~100s) of high pressure steady-state plasmas necessary in DEMO

3. Foster Next Generation
playing leading roles in ITER & DEMO

Superconducting tokamaks

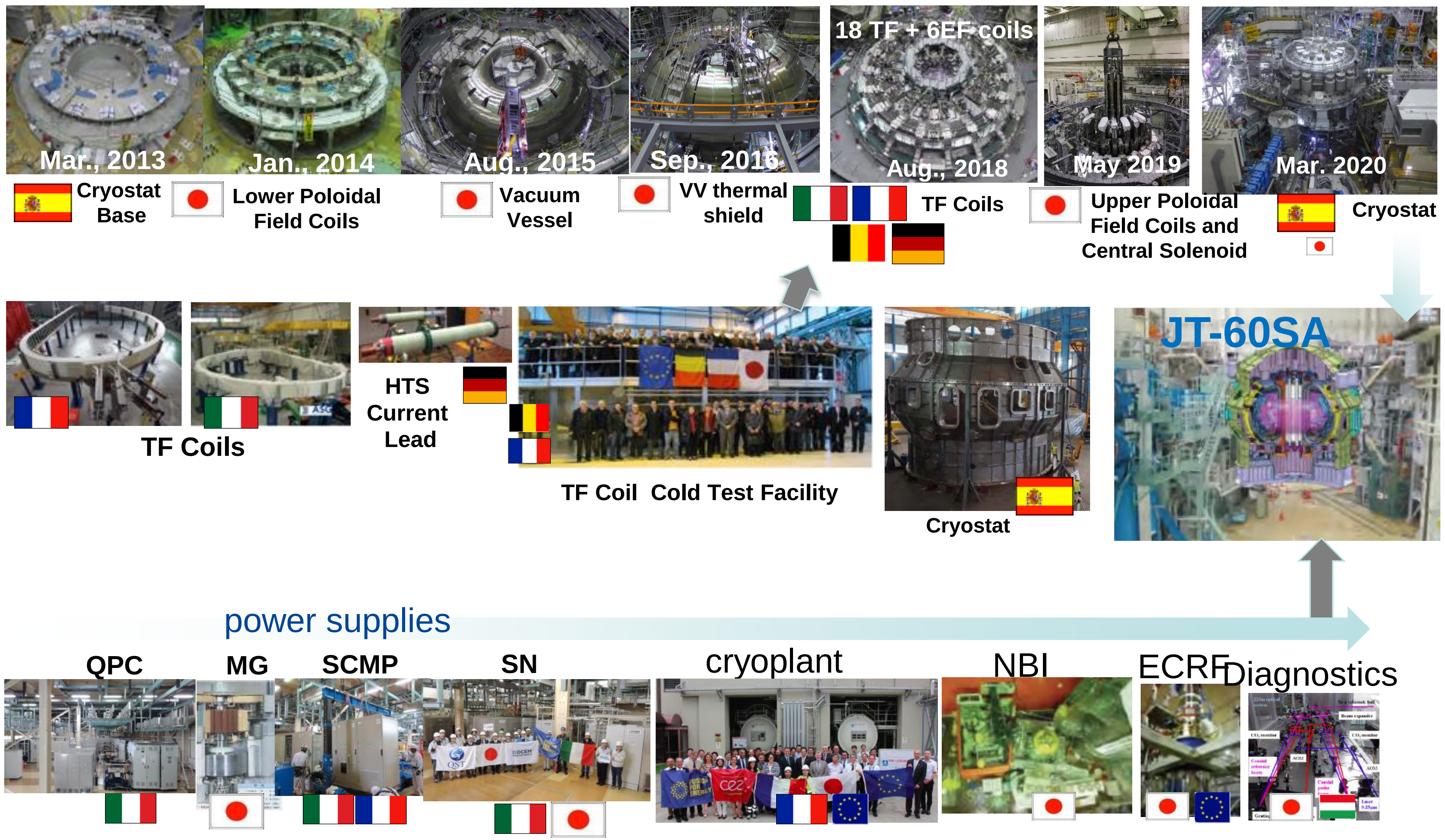


Plasma Current	5.5 MA
Toroidal Field	2.25 T
Major Radius	2.96 m
Minor Radius	1.18 m
Plasma Volume	131 m^3
Heating Power	41 MW
Normalized beta, β_N	3.1



JT-60SA
Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

JT-60SA Project: Started in 2007 between EU & Japan



JT-60SA superconducting magnet

Superconducting magnet system of JT-60SA

Superconducting magnets is used for JT-60SA because zero resistivity is required for long pulse (100 sec) of high-performance plasma.

18 Toroidal Field (TF) coils

- Generate magnetic field to confine charged particles in plasma

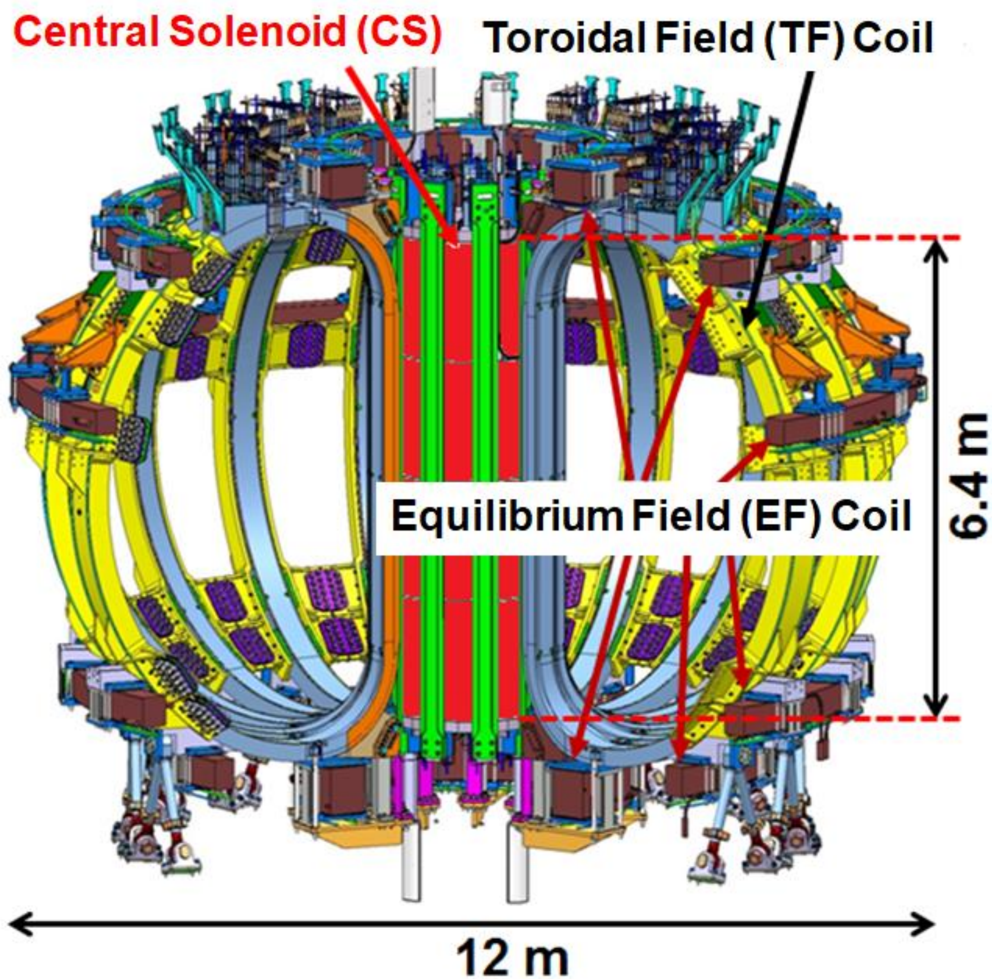
4 modules of Central Solenoid (CS)

- Magnetic flux supply for plasma initiation and plasma current

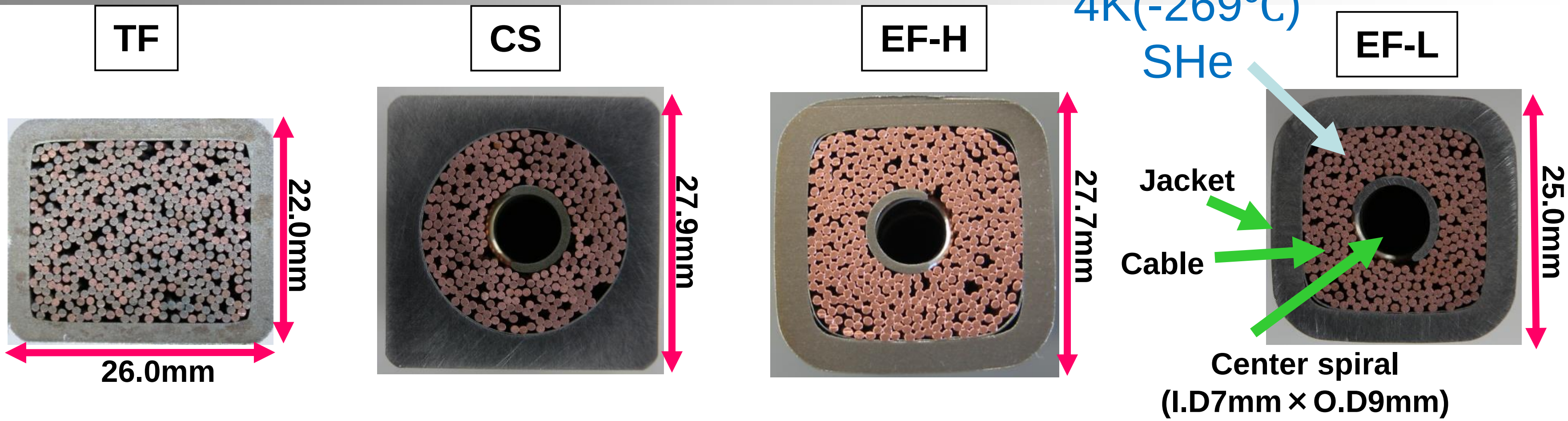
6 Equilibrium Field (EF) coils

- Plasma shape and position control

Magnet	Current	Magnetic Field	Weight
TF	25.7 kA	5.65 T	396 ton
CS	20 kA	8.9 T	114 ton
EF1	20 kA	4.8 T	Total 128 ton
EF2	20 kA	4.8 T	
EF3	20 kA	6.2 T	
EF4	20 kA	6.2 T	
EF5	20 kA	4.8 T	
EF6	20 kA	4.8 T	



Conductor for JT-60SA



	TF	CS	EF-H	EF-L
Maximum current(kA)	25.7	20	20	20
Magnetic field (T)	5.65	8.9	6.2	4.8
Operation pattern	Steady	Pulse	Pulse	Pulse
Jacket material	SS316L	SS316LN	SS316L	SS316L
Superconducting (SC) material	NbTi	Nb_3Sn	NbTi	NbTi
Number of SC strand	324	216	450	216
Number of Cu strand	162	108	0	108
Conductor length (km)	24.6	12.1	7.5	20.0
SC strand length (km)	8,000	2,610	3,380	4,320

Dimension Requirements for Superconducting Magnets

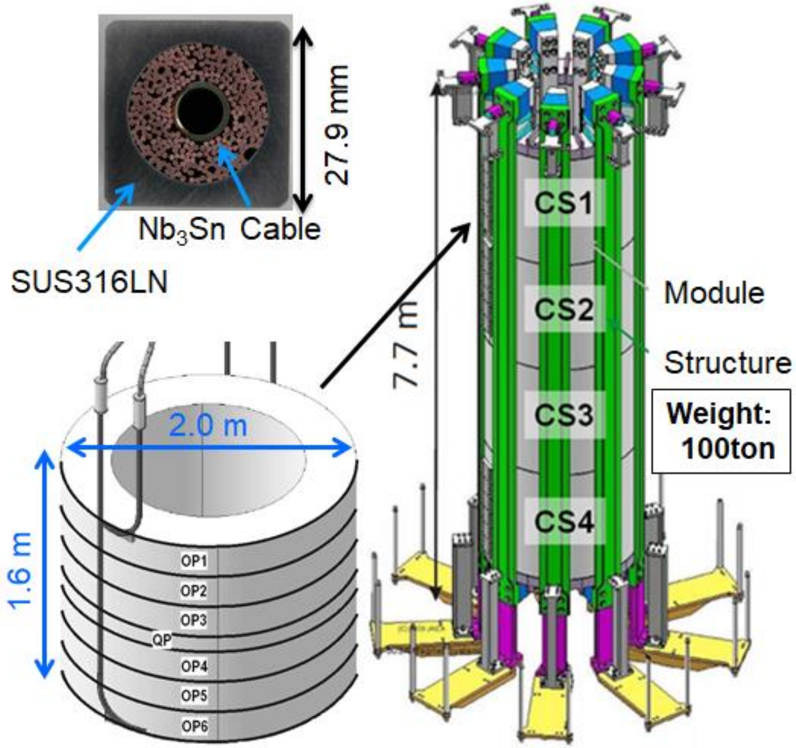
Requirements from plasma physics and engineering of JT-60SA system

- **Low error field (<10^{-4} B_{tor})**
- **Enough Gap between components including EMF, earthquake, thermal shrinkage.**

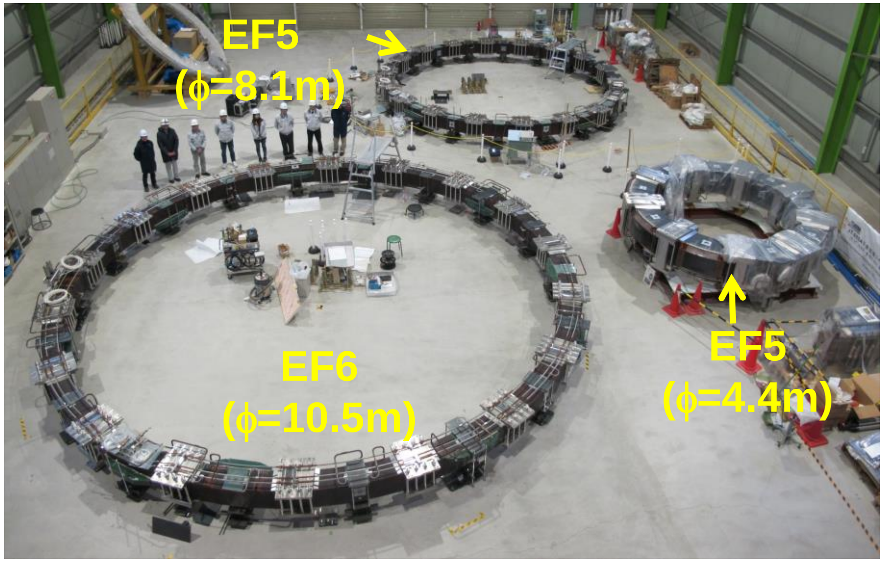
To satisfy these requirement…

→ High accuracy for manufacturing and assembly was needed though such a huge system. **Target accuracy: 0.01% = (few mm in 10 m)**

Magnet	Diameter	Circularity (Magnet)	Circularity (Assembly)
CS	2.0m	4.0mm	4.0 mm
EF1	12.0m	8.0mm	??? mm
EF2	9.6m	7.0mm	??? mm
EF3	4.4m	6.0mm	??? mm
EF4	4.4m	6.0mm	??? mm
EF5	8.1m	7.0mm	??? mm
EF6	10.5m	8.0mm	??? mm



Results of magnet manufacturing



First coil

Final coil

This is final value for EF coils

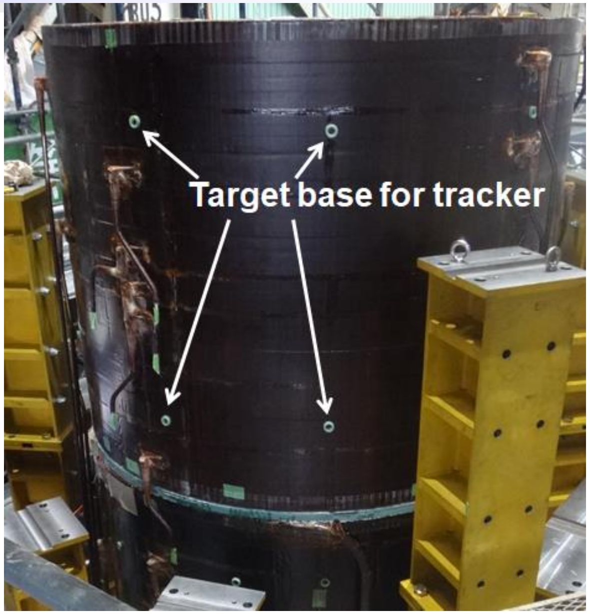
To be considered of stacking error for CS

Coil	Completion	Circularity	Requirement	O.D.
EF1	Aug 2016	0.3 mm	≤8 mm	12.0 m
EF2	Aug 2016	0.4 mm	≤7 mm	9.6 m
EF3	Aug 2016	0.2 mm	≤6 mm	4.4 m
EF4	Apr 2012	0.6 mm	≤6 mm	4.4 m
EF5	Jan 2014	0.6 mm	≤7 mm	8.1 m
EF6	Jan 2014	1.3 mm	≤8 mm	10.5 m
CS1	Sep 2016	0.3 mm	≤2 mm	2.0 m
CS2	Feb 2017	0.4 mm	≤2 mm	2.0 m
CS3	Feb 2017	0.4 mm	≤2 mm	2.0 m
CS4	Mar 2018	0.4 mm	≤2 mm	2.0 m

CS manufacturing in high accuracy

Stacking of CS modules

- Target bases for laser tracker were attached around CS module
- During stacking process, position of each module was measured and controlled
- After stacking process, position of each module was measured by laser tracker.



The center axis position of each module

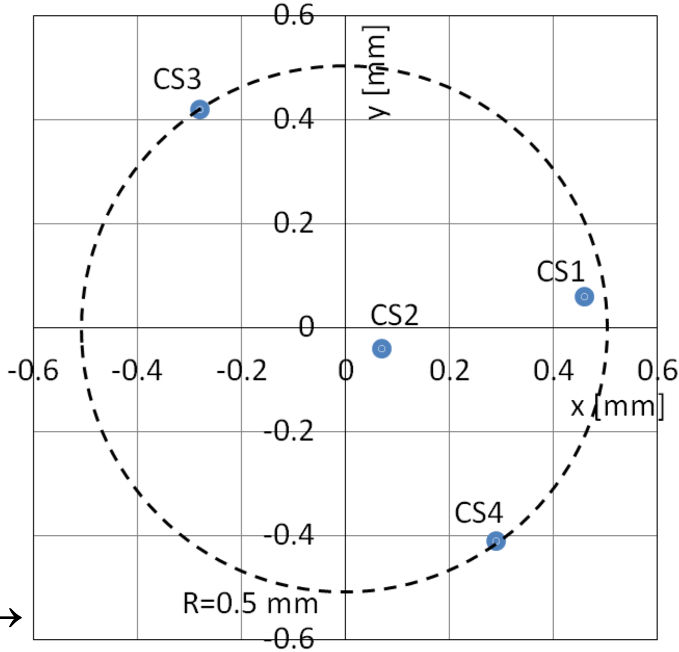
Maximum deviation of center axis is 0.5 mm.

→The impact on circularity is up to 1.0 mm

Total circularity of CS system is 1.4 mm (Module 0.4 mm + Stacking 1.0 mm), which meets the requirement of 4.0 mm.

High accurate CS manufacturing has been achieved

(The origin indicates the machine center.)→



Assembly tool for high accuracy

- JT-60SA components have complicate 3-D shape.
- Requirement of accuracy for assembly : few mm (about 0.01%)

3-D CAD system

Ref

- Design of each components and assembly scenario
- Clearance estimation of both final position and during assembly

3-D measuring system

- Dimension check for manufactured components

- Position check for assembly

➢ About 100 reference points

→Laser tracker can define self

→0.5 mm measuring accuracy achieved by reference system

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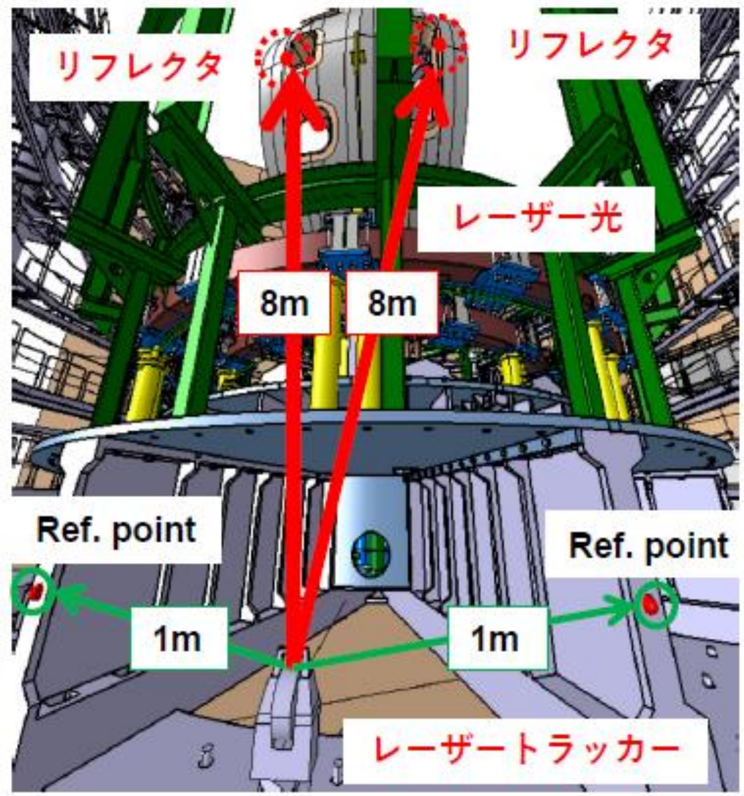
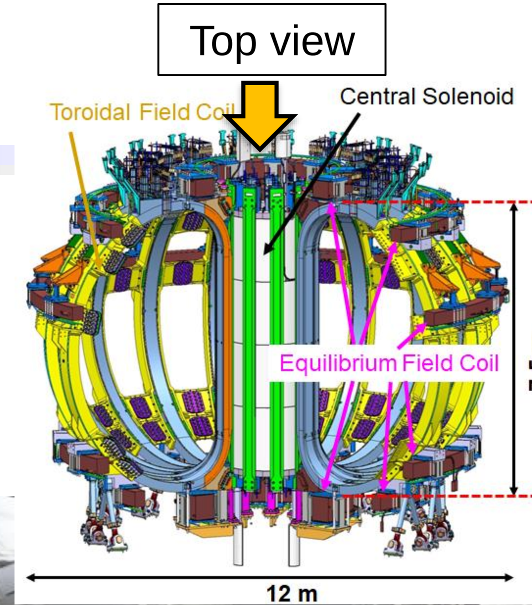


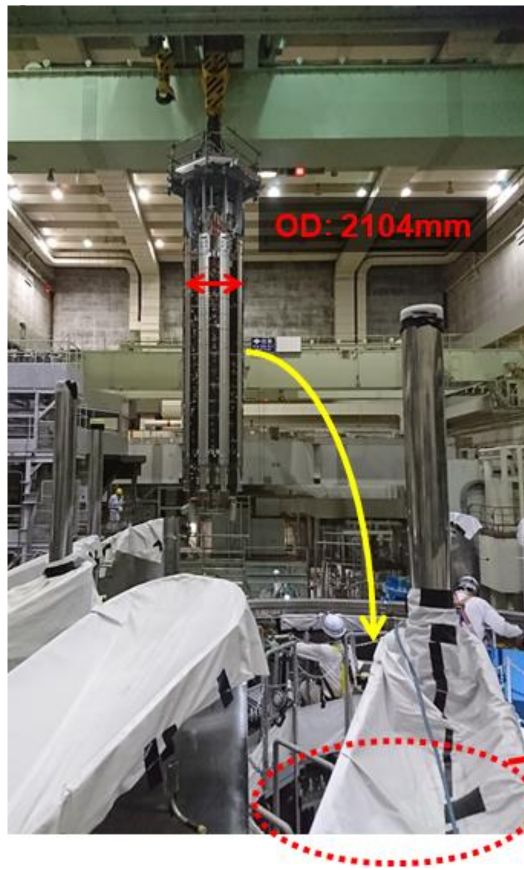
Insertion of CS



Clearance between CS and TF coil

CS is required to be able to pass through inside the assembled TF coils.

- TF coil inner diameter (ID) 2132 mm (design value)
- CS outer diameter (OD) : 2104 mm (design value)
- Gap between TF and CS: 14 mm (design value)



A surface measurement was performed before insertion.

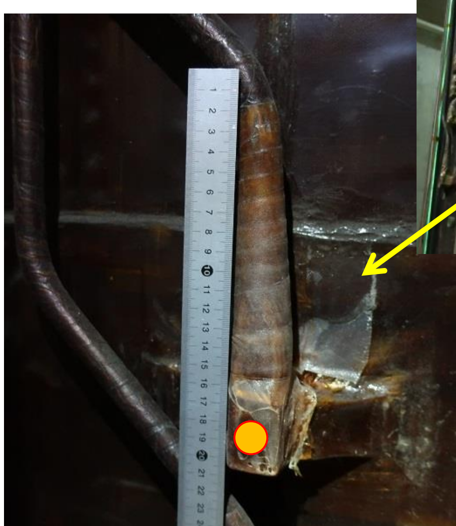
Measurement of TF coil inner surface and CS outer surface

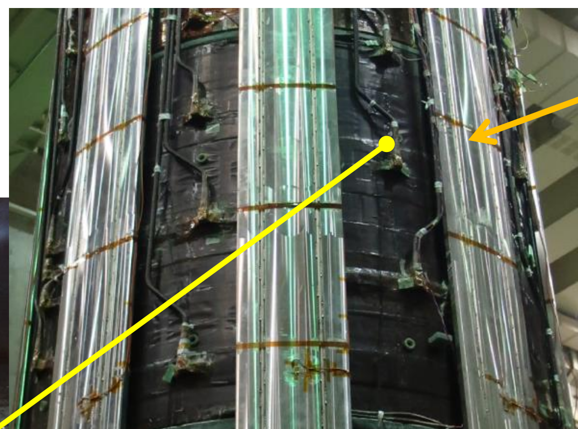
Surface measurement

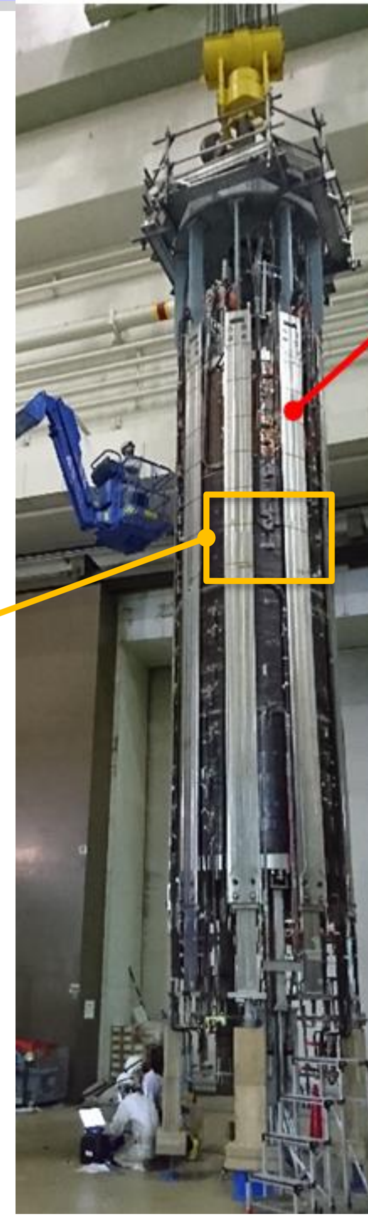
- TFC inner surface : a laser scanner.

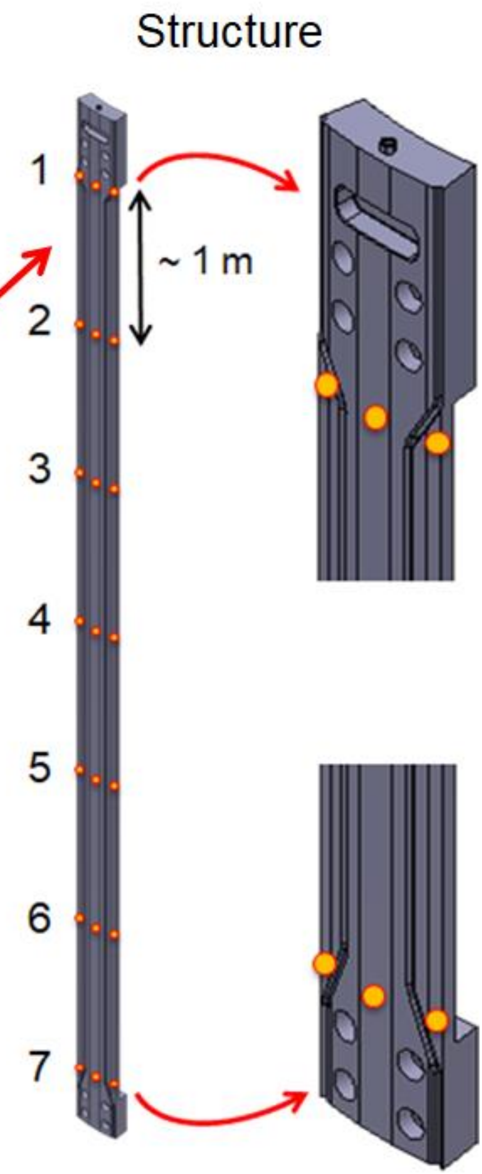
- CS outer surface : a laser tracker.
  →Total 189 points on structure
  (9 plates x 7 heights x 3 points)
  →104 points of SHe inlet

SHe inlet









Modification of CS/TF surface

Results of surface measurement

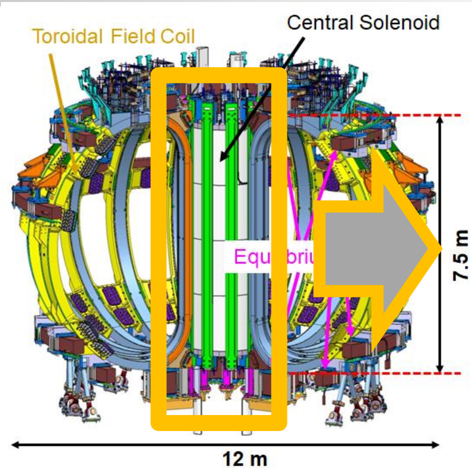
- Some part of TF coil case was manufactured thicker than design.
- TF inner diameter was up to XXmm smaller than it of design value.
- Position of CS structure and SHe inlet was shifted outward by up to XX mm from design position.

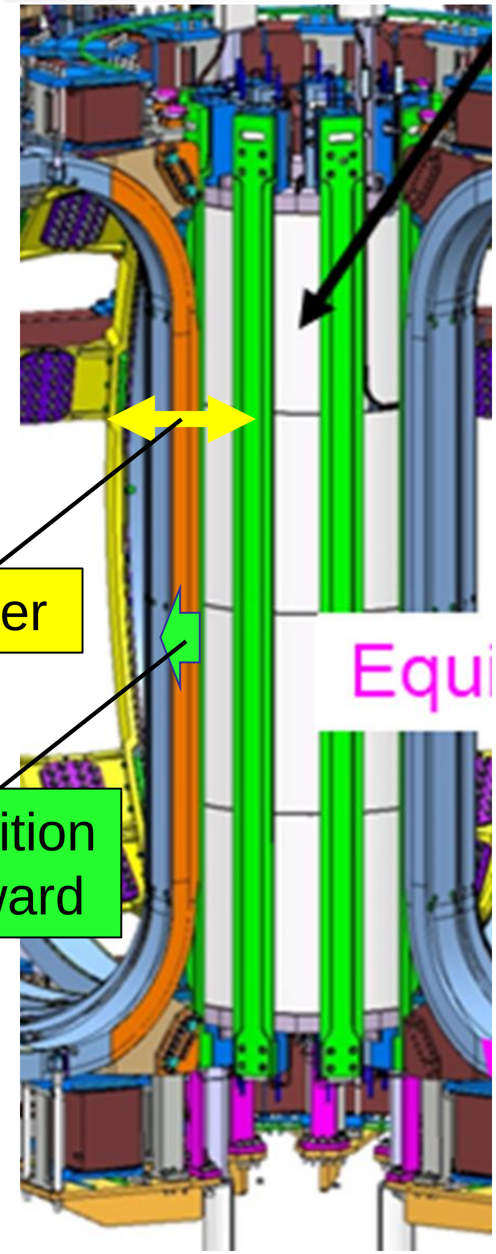
<u>Gap between CS and TF coil was almost zero</u>

Modification of CS/TF surface

- Additional machining was done for TF coil case on site.
- CS structure pushed to inward one by one to prevent sliding of module.

<u>Clearance check was performed again</u>





TF case was thicker

CS structure position was shifted outward

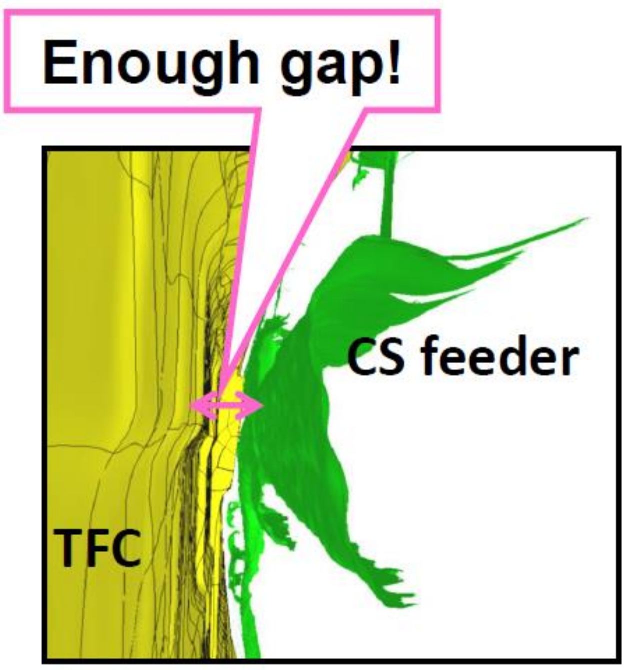
Clearance check between CS and TF coils

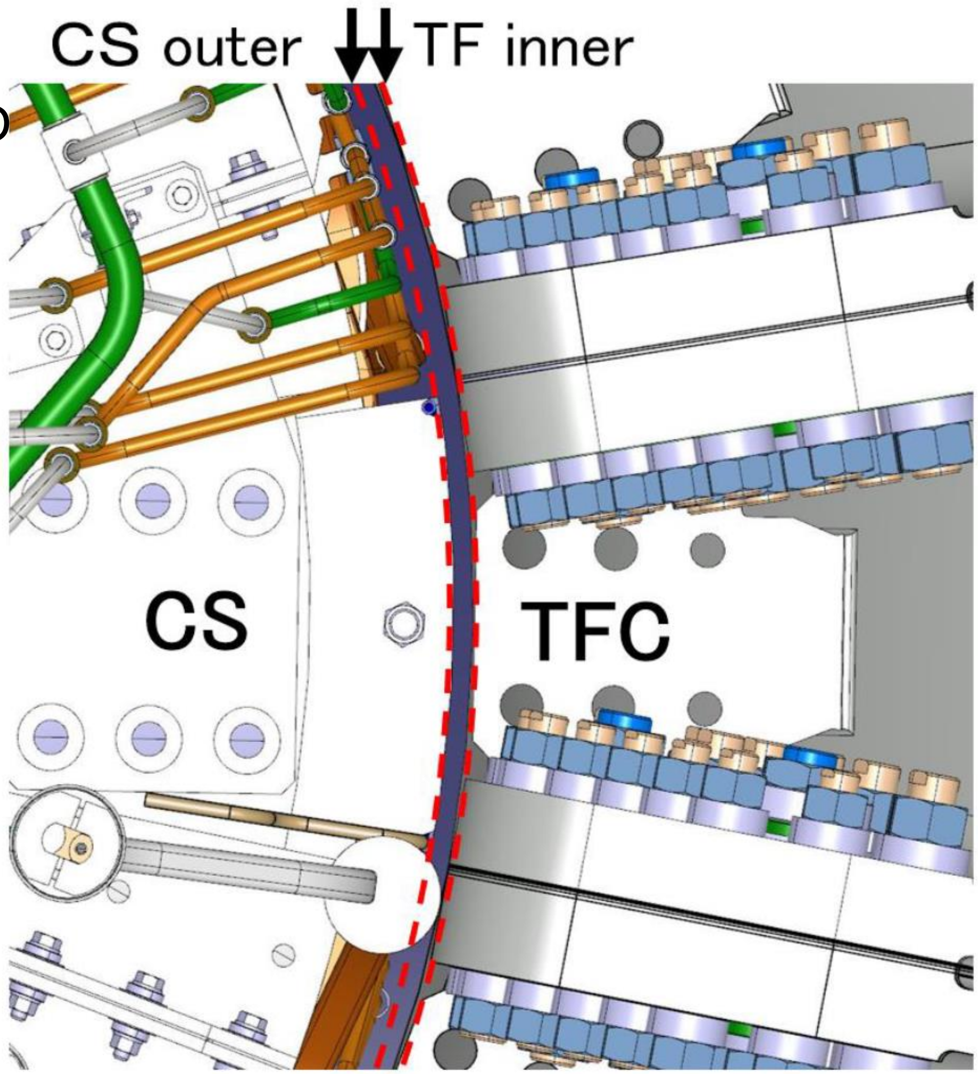
Clearance check

Actual gap was evaluated by 3-D CAD using surface measurement data.

Minimum clearance for CS insertion was 6.6 mm

It was less value than design value, but enough gap for insertion.



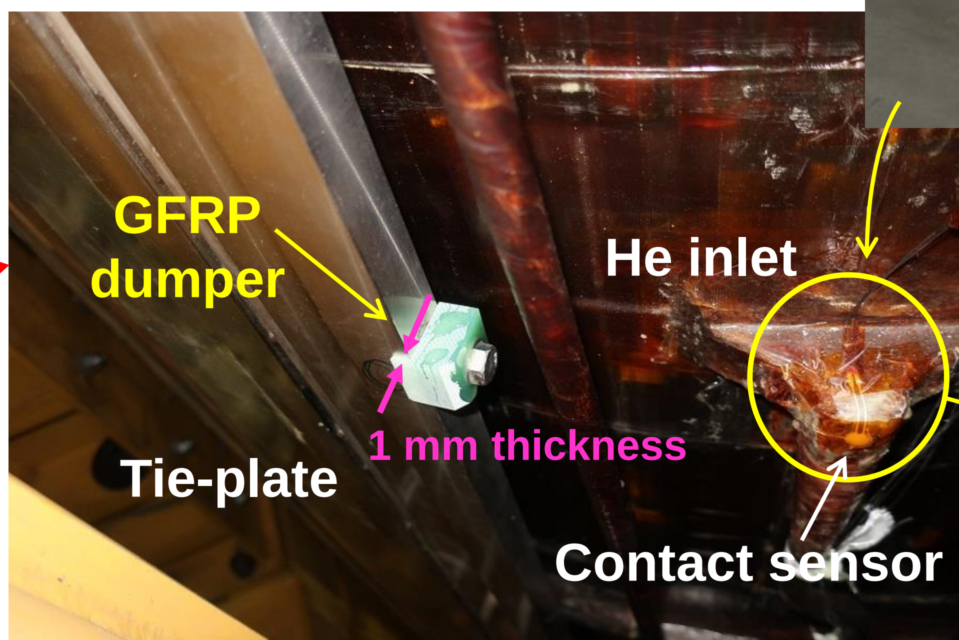


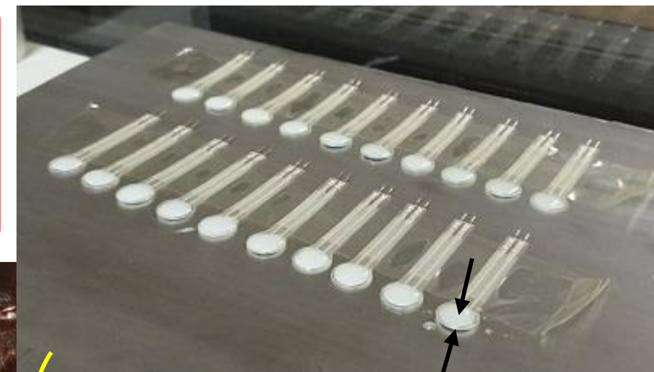
Protection tools for insertion

GFRP dumpers and contact sensors

- GFRP dumper had been attached on structures to avoid contact between CS structures and TFC inner surface.
- There were 80 contact sensors attached on the SHe inlets to detect the contact before crashing into TFC during insertion.

Real time position monitoring was conducted during insertion using laser tracker



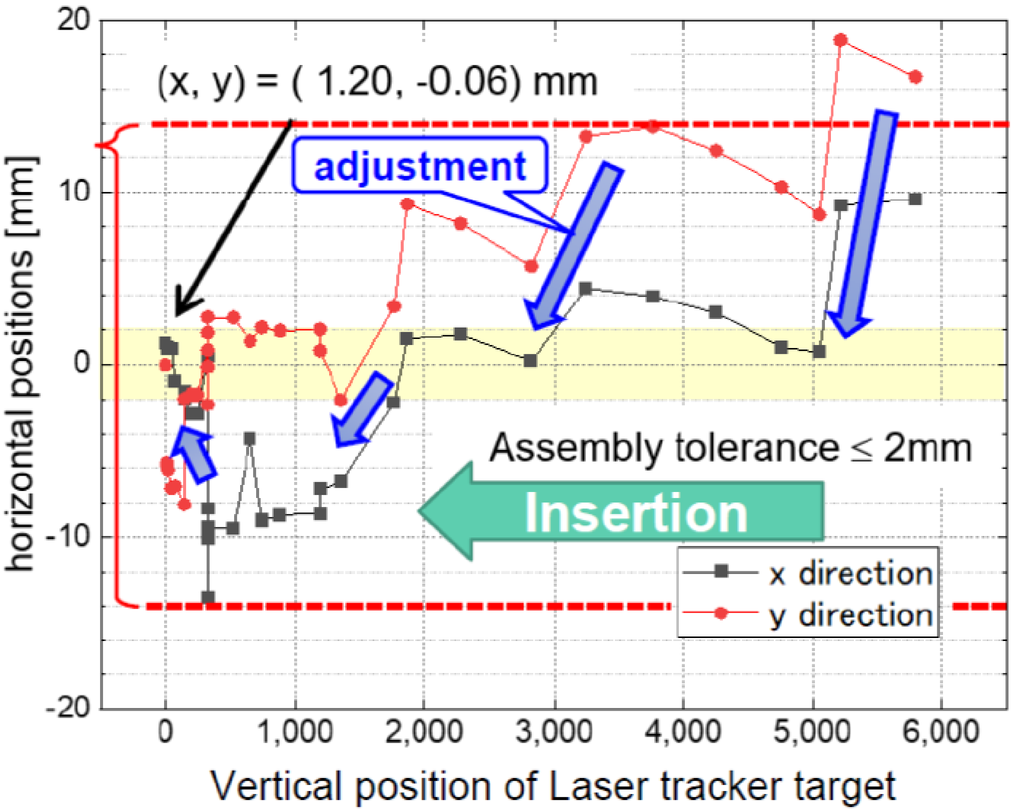


About 2 mm thickness

Real time position monitoring

The position of CS was monitored using target attached on the lower leg with laser tracker

- CS position was adjusted toward machine center using monitoring data.
- The target was 2mm if assembly tolerance

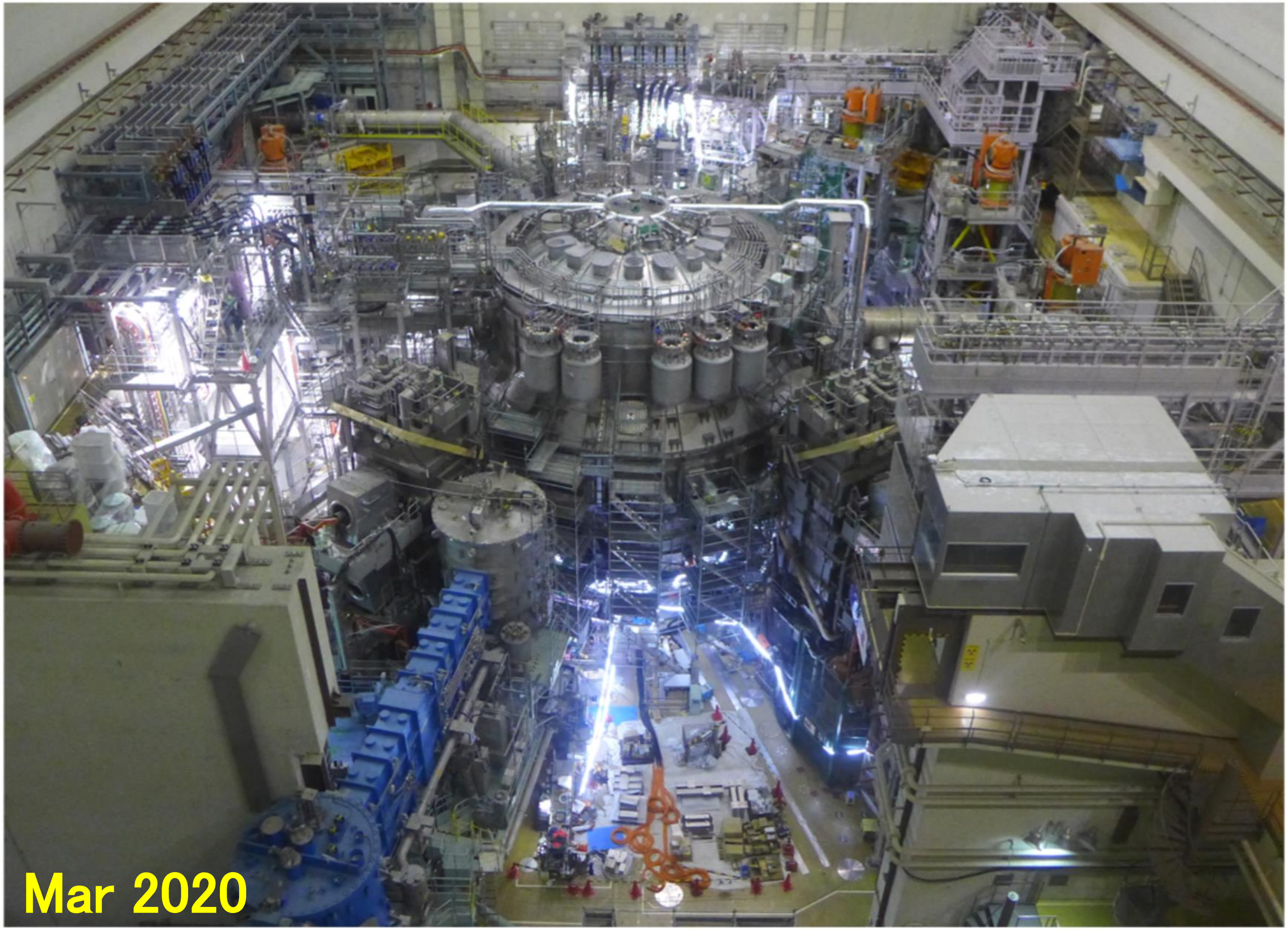


Insertion was successfully conducted

Results of assembly

Horizontal : 0.6 mm (<2 mm)
Verticality : 1.6 mm (<2 mm)
Height : 1.2 mm (<2 mm)
Toroidal : 1.0 mm (<2 mm)

Completion of JT-60SA



Completed on 31st March 2020 after 13 years' effort from 2007.

All members of the EU-JA JT-60SA Integrated Project Team share the same clear target (and problems..) of Construction

JT-60SA Advanced Superconducting Tokamak BA-Satellite Tokamak Program

Outline of integrated commissioning

- In Apr 2020, setup of measurement system and individual component tests (as for SC magnets, leak test and high voltage test) started.
- In Sep 2020, all individual component tests were finished.
  Then, vacuum pumping of vacuum vessel and cryostat started
- In Oct 2020, cool down of SC magnets started
- In Nov 2020, SC magnet reached 4K and SC transition was observed.
- In Dec 2020, baking of vacuum vessel in 200℃ was conducted
- In Jan 2021, energization test started.
- In March 2021 an incident stopped integrated commissioning

JT-60SA Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

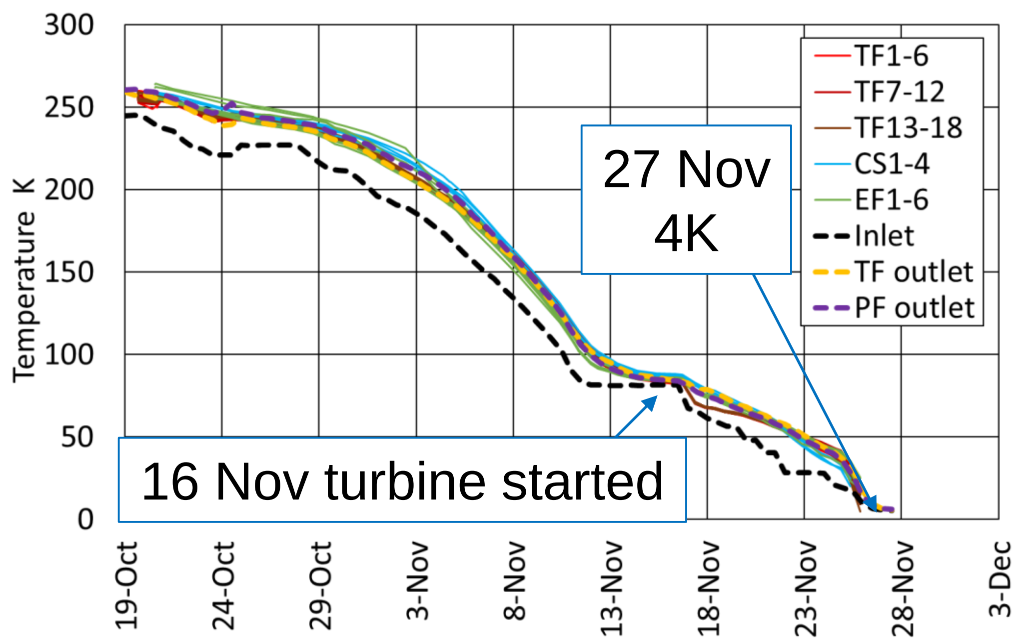
Cooldown of SC magnets

- 236 thermometer, 111 flow meter and XX valves were used for control.
    - To avoid the thermal damage, temperature control criteria were set.
    - Mass flow rates were determined by mass of each magnets
- Magnet temperature was estimated by resistance in 20A operation.

- Magnet temperature reached 4K in 47 days
- There was no cold leakage

Temperature control criteria

1. Supply SHe－Max. temp. < 50 K
2. Supply SHe－Return SHe < 35 K
3. Cooldown speed of magnet < 2 K/h
4. Temp. difference between TFCs <10 K
5. Temp. difference between winding and structure of TFC < 20 K
6. CS winding < CS structures

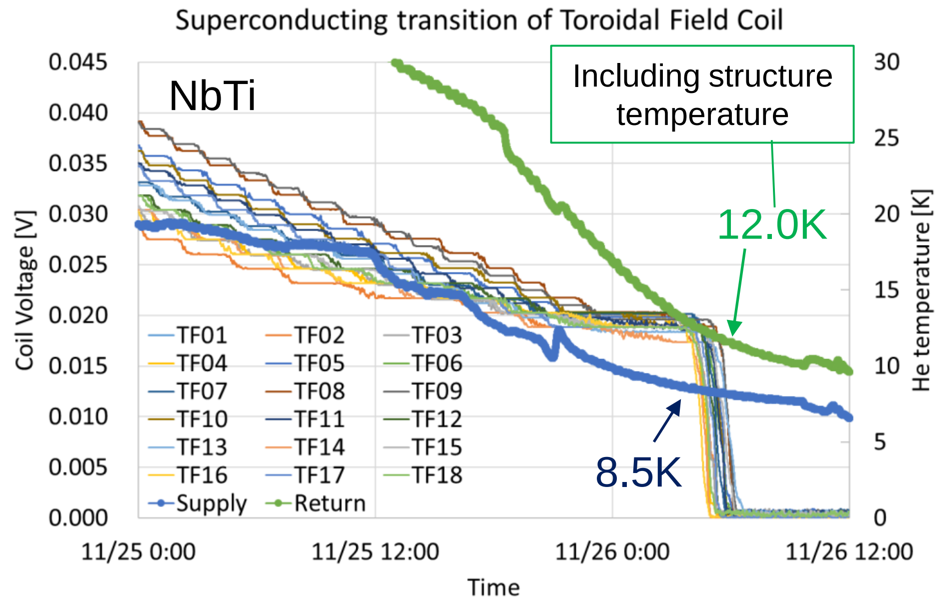


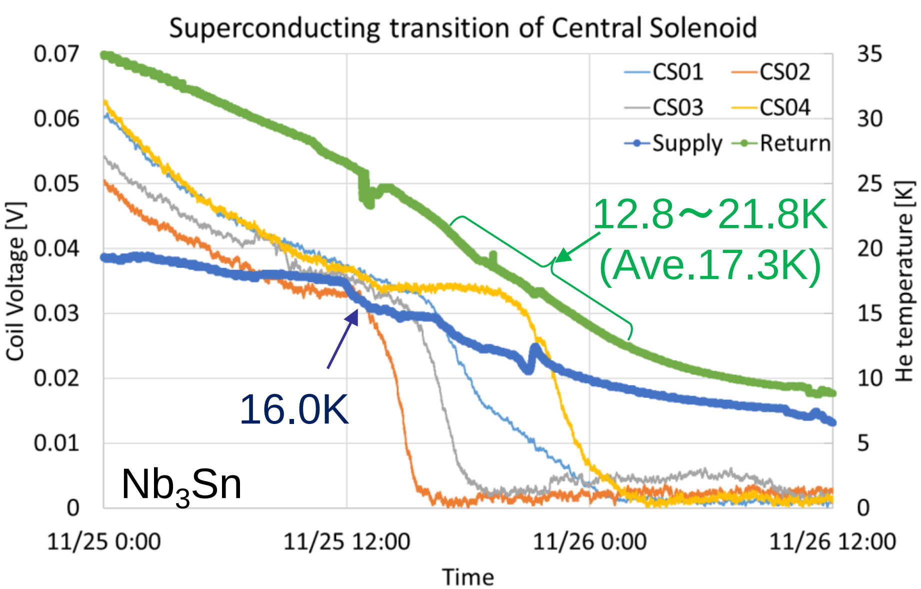
SC transition was confirmed

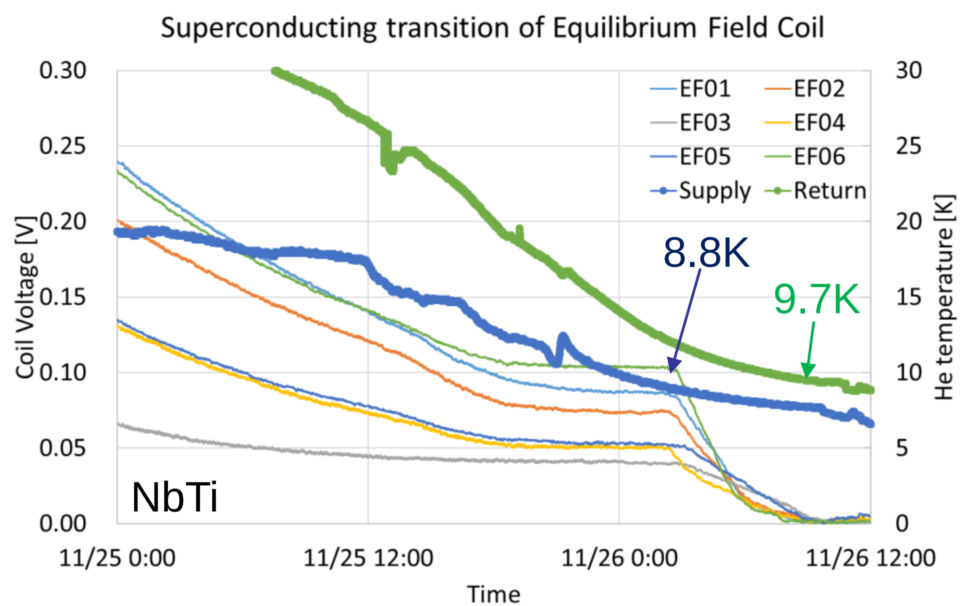
Voltage of 20A operation

- SC transition started at
  25Nov 14:00 for CS（Nb_3Sn）
  26Nov 3:00 for TF, EF (NbTi)
- SHe temperature was almost in good agreement with critical temperature
  (Nb_3Sn:18.3K、NbTi：9.5K)

All magnets changed to SC state







Energization test

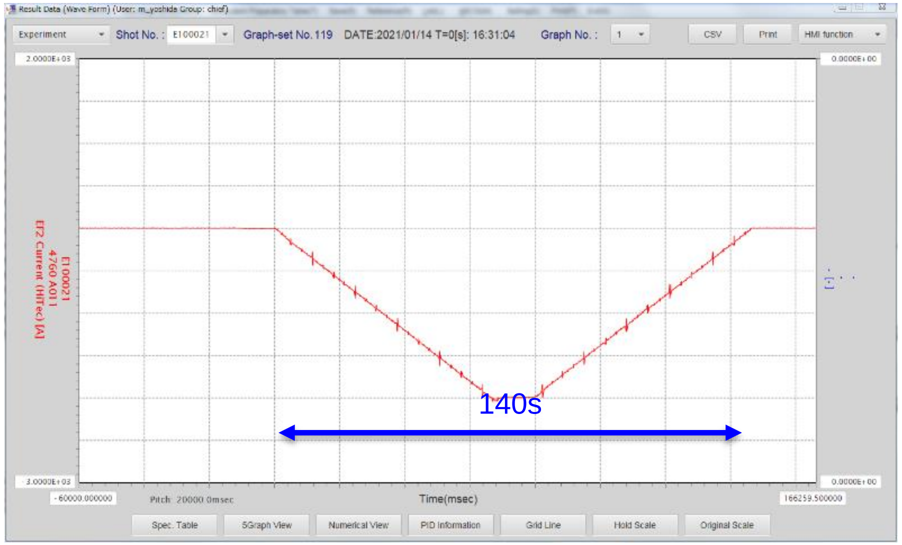
Plans for first plasma operation

1. 25.7kA (100% operation) for TF coils
2. ± 5kA (25% operation) for all CS and EF coils
3. Quench protection circuit test under 18kA for TFC, 5kA for CS, EFC.
4. High voltage operation (up to 5kV) for all CS and EF coils

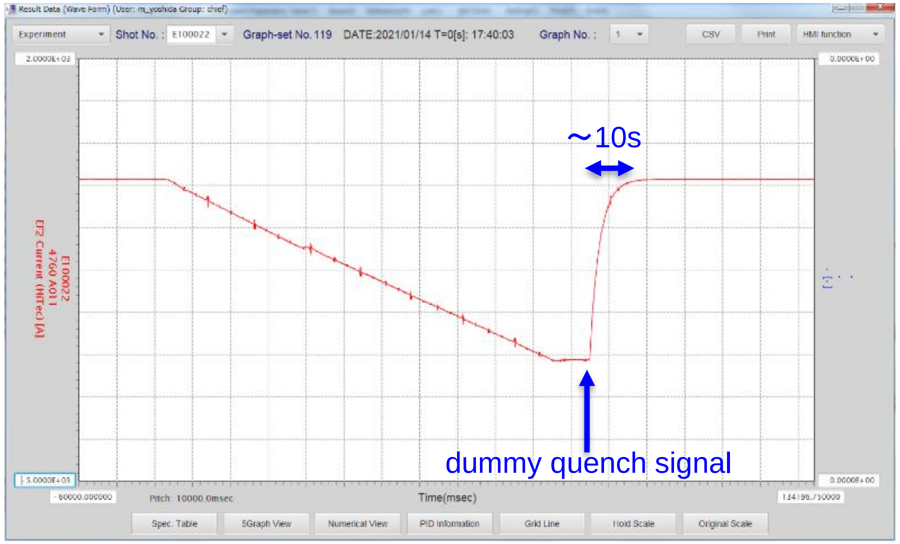
Results

・Plan 1, 2, 3 had been completed. Plan4 of 9/10 coils was finished.

preprogrammed current control test (2kA)



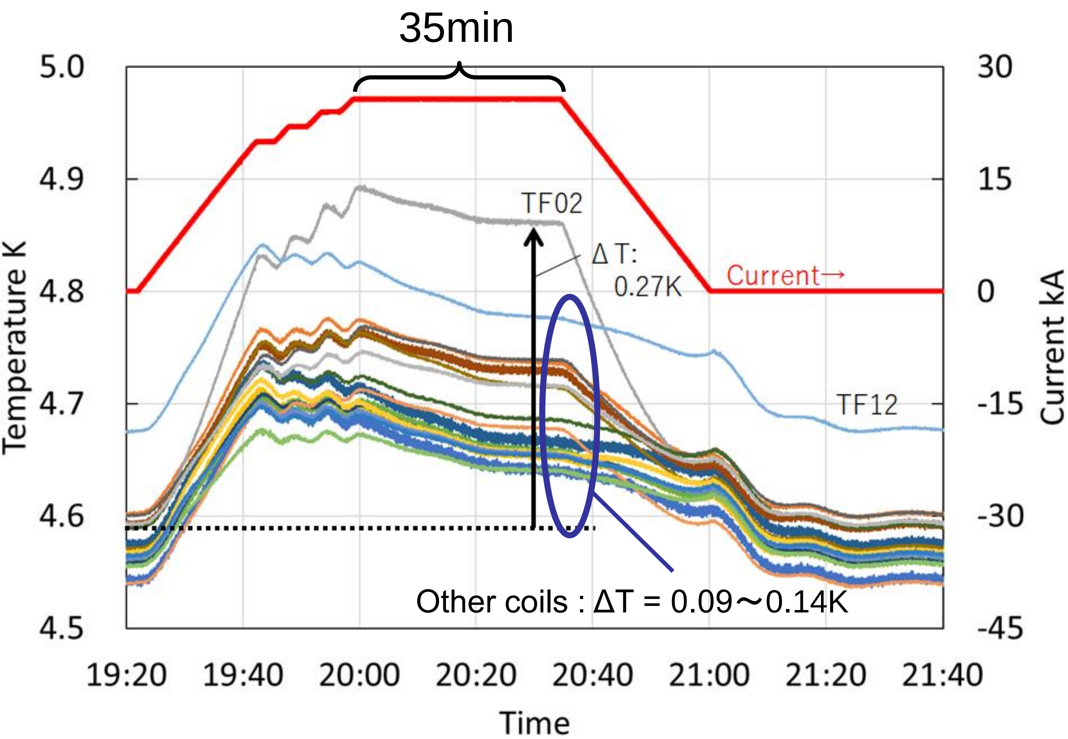
QPC test (2kA)

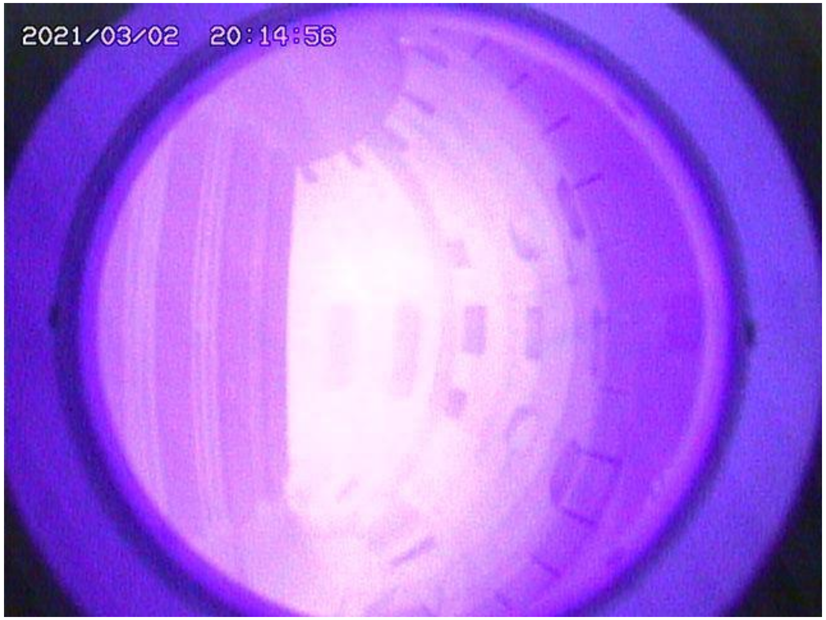


TF energization test and ECR plasma initiation

- TF coil current reached 25.7 kA with 1kA/min ramp up.
- For 35 min holding, no quench, steady temperature were observed.
- ➢ Main milestone of JT-60SA commissioning was achieved

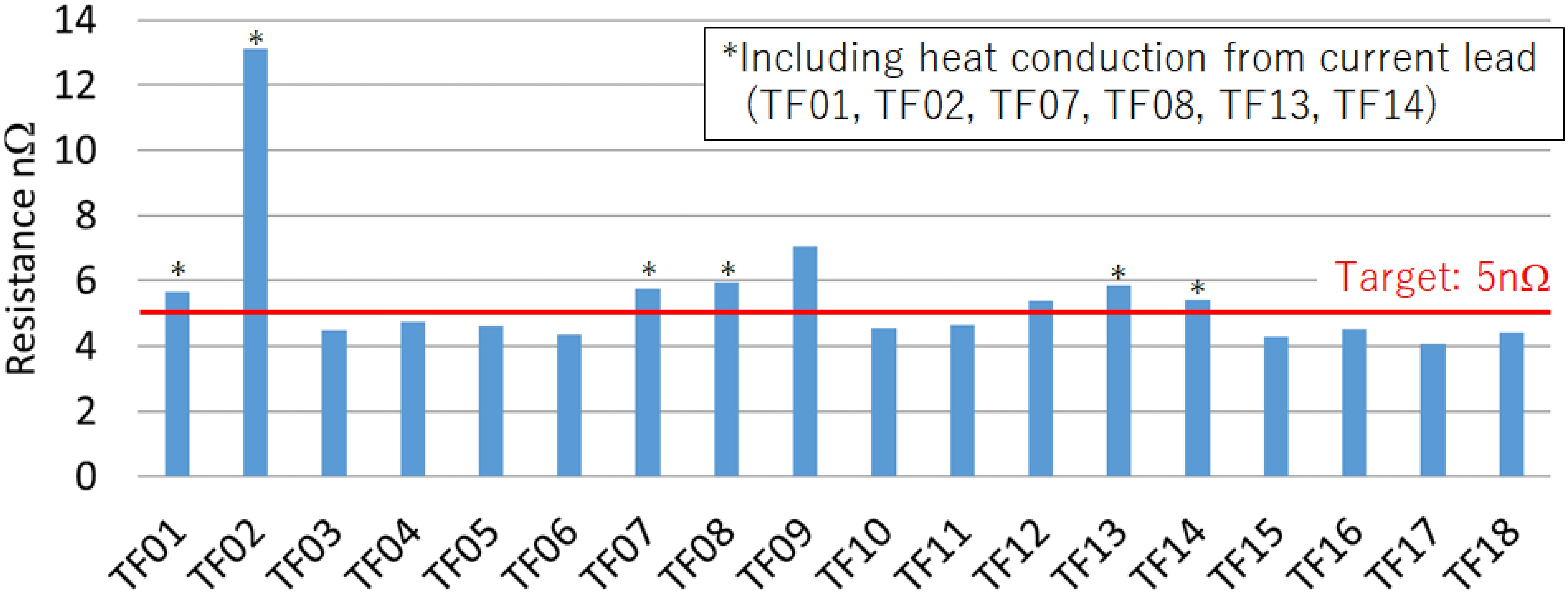
- During 25.7kA holding, 82GHz/760kW ECH (heating system) was operated.
- ➢ ECR plasma initiation was done in success





Joint resistance of TF coils

Average joint resistance of each TF coils (There are 7 or 9 joints per coil)

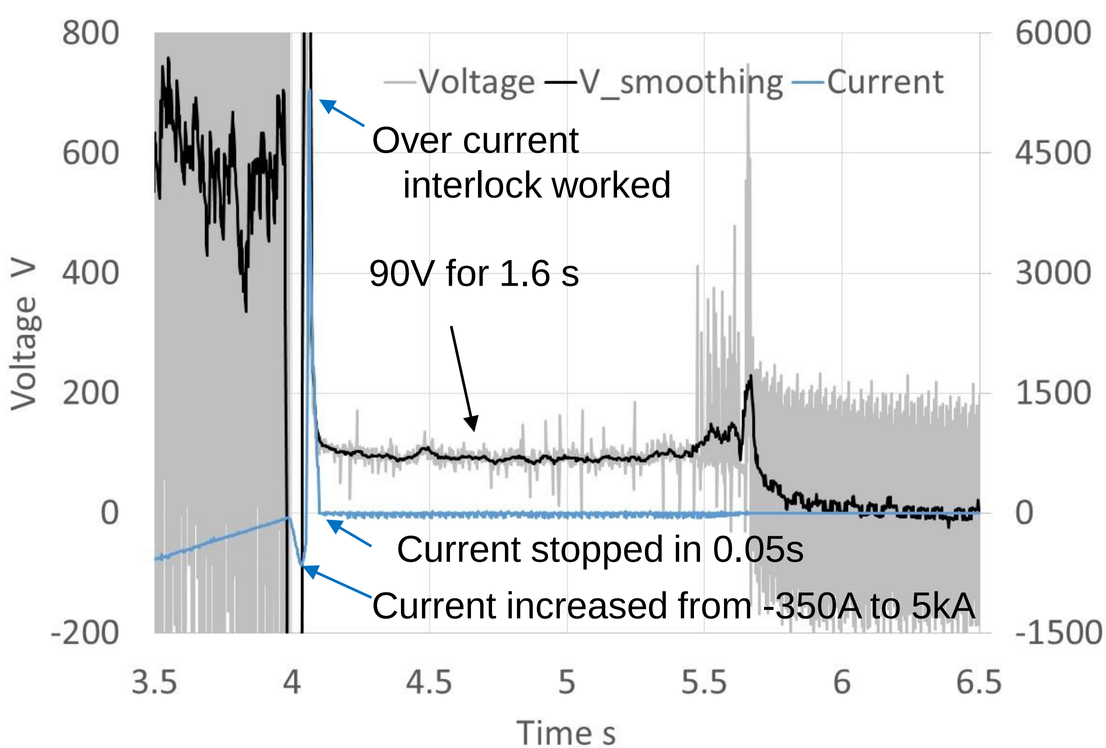


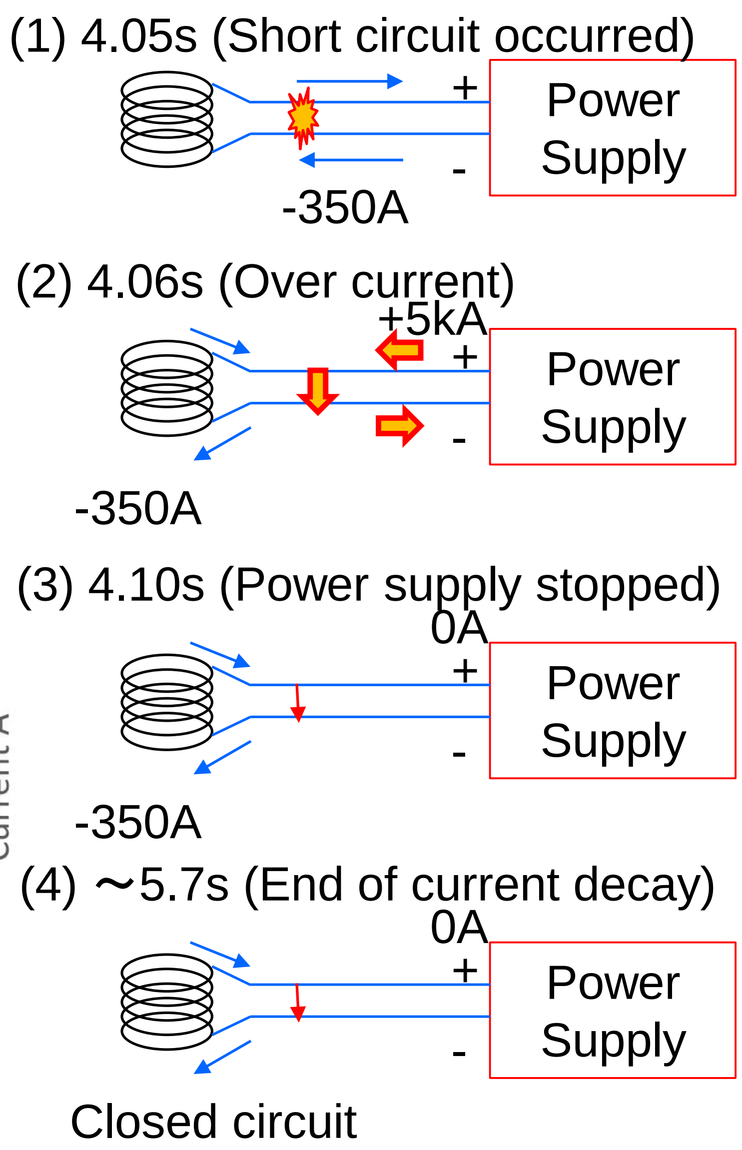
- Joint resistance was almost the same as target value of 5nΩ except TF02
  →It is acceptable for cryoplant regarding to the heat load
- TF inner joint showed lower resistance (1-2 nΩ) at individual cold test. Joint between magnet and feeders may have excessive high resistance.

We will monitor the TF temperature carefully in further operation

Incidence during test of EF1

- In Mar 2021, EF1 was operated in high voltage (5kV) test.
- Suddenly, operating current rapidly increased.
- Over current interlock system worked, and power supply current stopped in 0.05s.
- Voltage kept 90V for 1.6s.

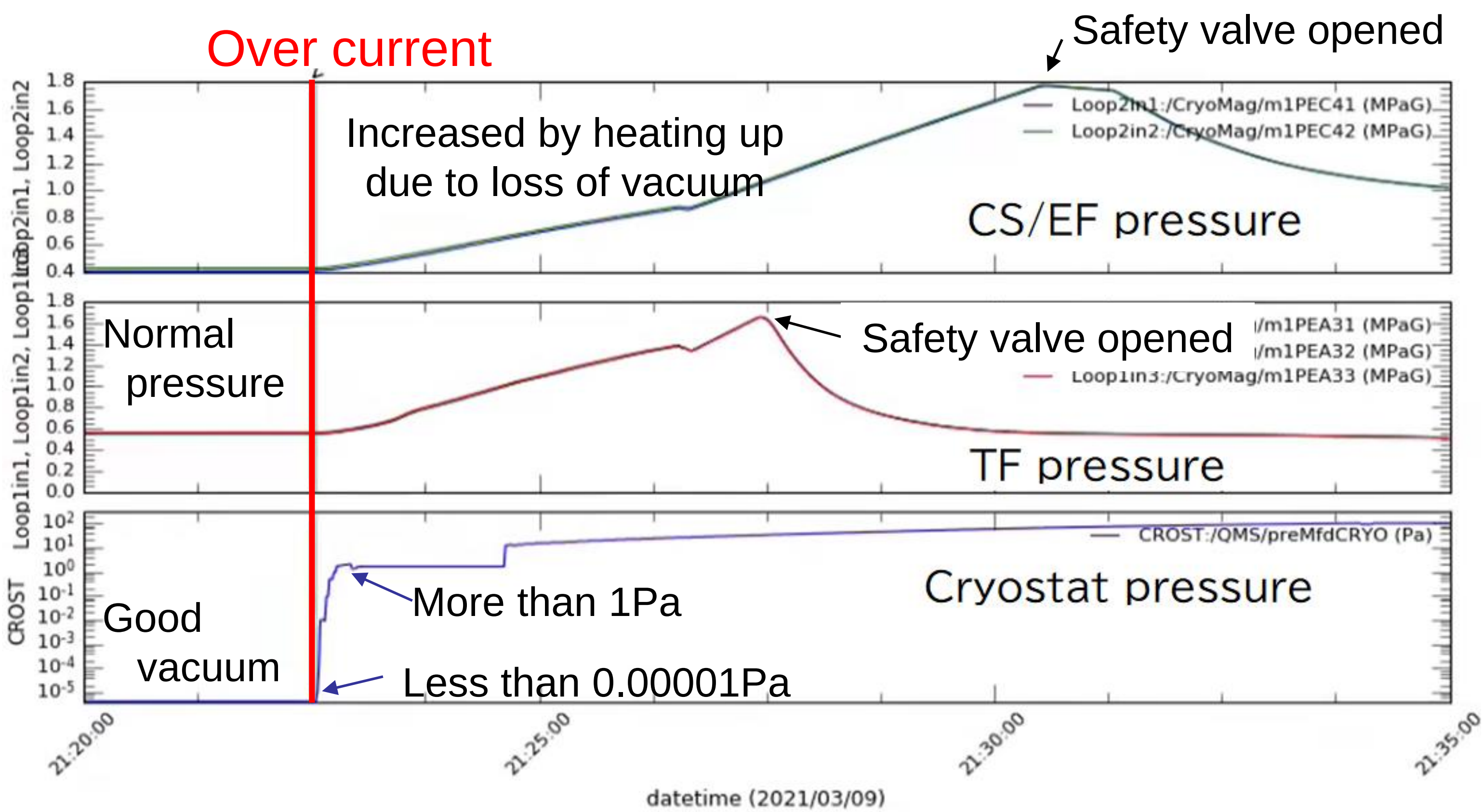




Incidence during test of EF1

- After over current, cryostat vacuum lost.
  - ➢ SHe leaked from coil to cryostat.
- Thermal insulation of cryostat lost, then coil pressure increased by heating up.
- Finally, safety valve opened, and helium was released to the air.

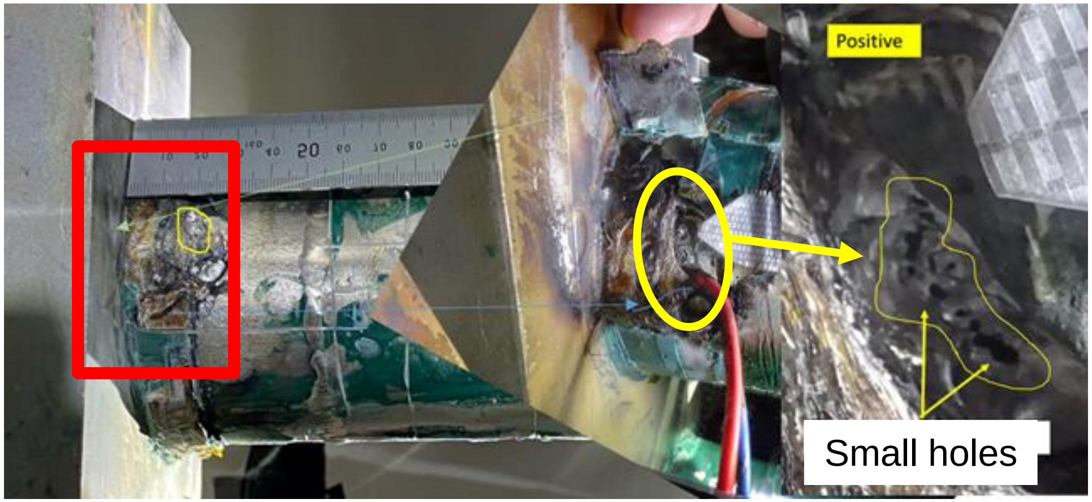
Warming up process started to investigate the magnet system.

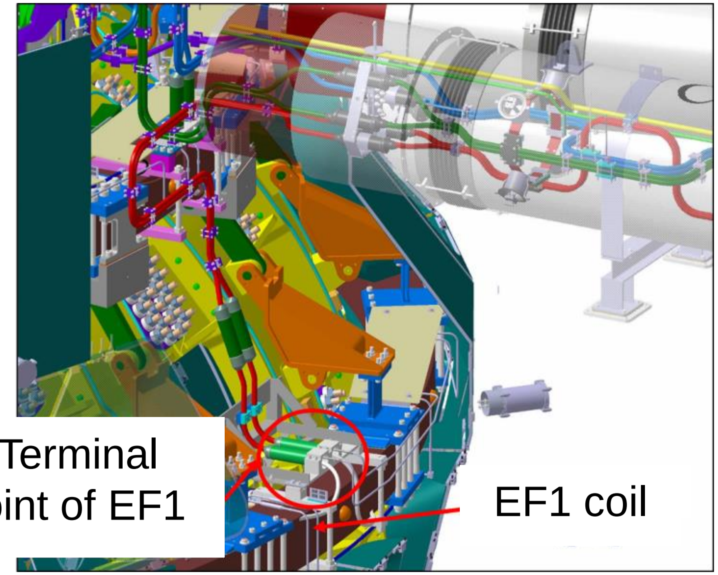


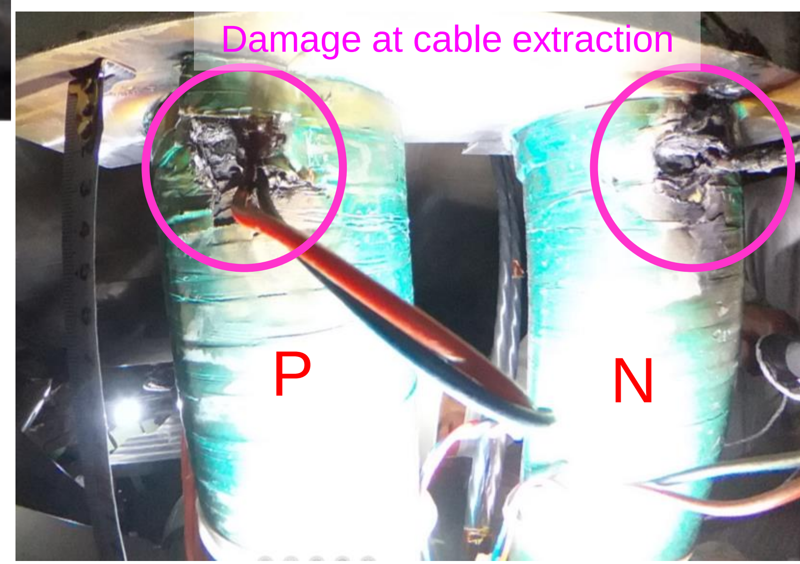
Trouble on current feeder

Summary of investigation

- Discharge occurred at terminal joint of EF1
- SHe boundary was melt, but no damage on SC.



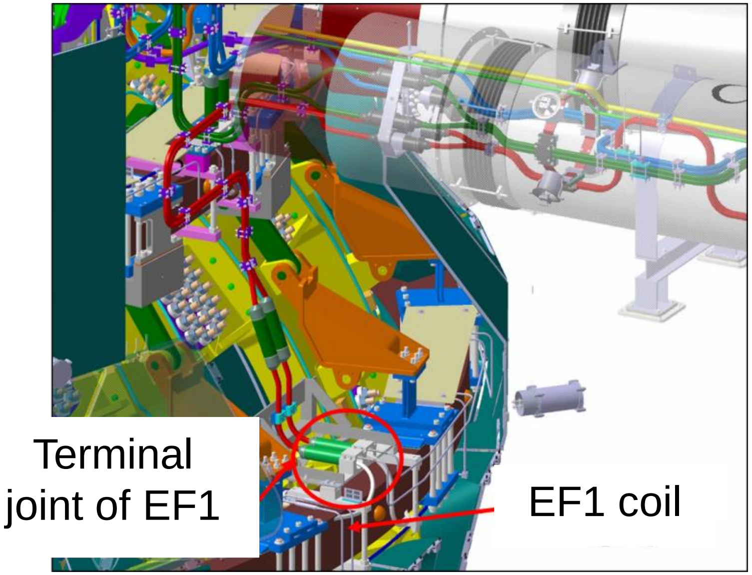


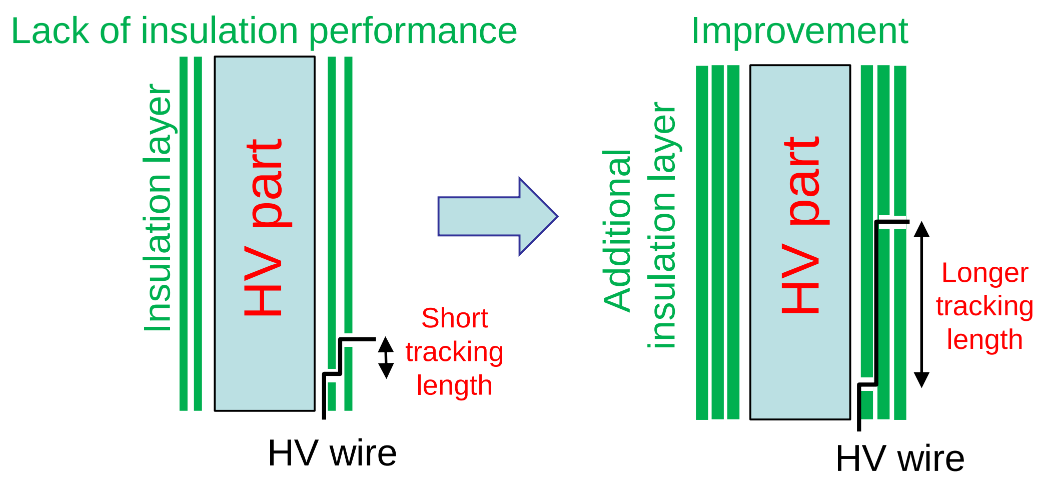


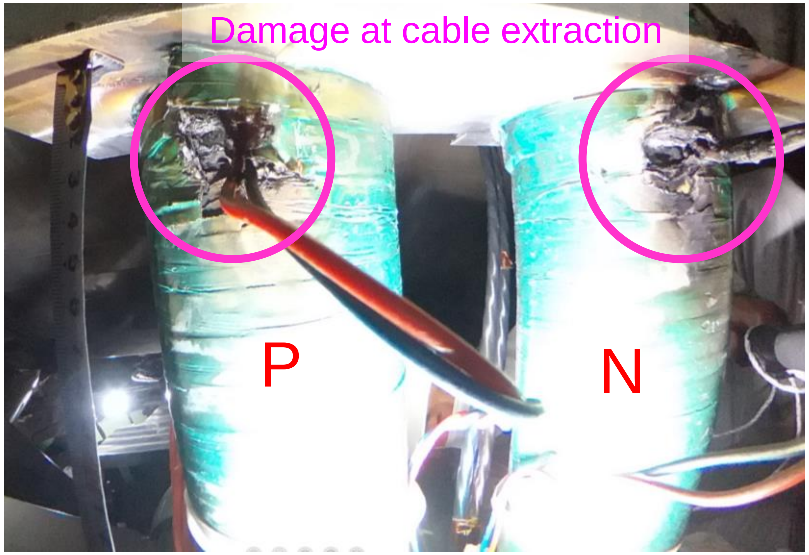
Trouble on current feeder

Summary of investigation

- Discharge occurred at terminal joint of EF1
- SHe boundary was melt, but no damage on SC.
- Main cause was insulation week point due to short tracking length (not paschen).
  - Good vacuum in cryostat before incident
  - Overlap length was less than 10 mm
  - Ground potential (joint support) located close to the cable extraction

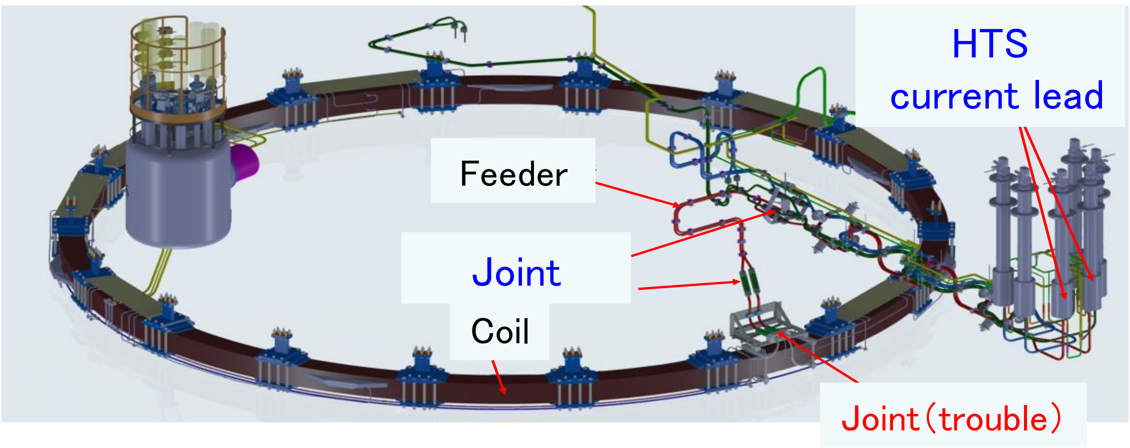




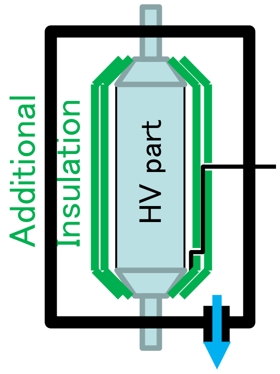


Repair plan and further schedule

- Repairing method has been established by making and testing mockup samples.
- Local paschen test (10kV at 10, 100, 1000 Pa) is planned after insulation improvement to confirm the cable extraction insulation quality.



Insulation mockups



- By the end of December, insulation of not only troubled joint but also similar joints and HTS current leads will be improved by the same repairing method.
- In January 2022, global paschen test will be performed using cryostat as vacuum chamber.

From February 2022, cooldown will restart

Summary

- Construction of JT-60SA was completed in March 2020.
  →High accuracy of components and assembly technique achieved.

- Integrated Commissioning started in April 2020
  - Vacuum pumping started in September.
  - Cooldown of superconducting magnets started in October.

  - Magnets reached 4K in 47days and SC transition was observed.

  - Energization test started in January 2021.
    - 25.7 kA (100% operation) of TF coils
    - 5 kA (25% operation) of CS and EF coils
    - Quench protection system operated well
    - ECR plasma initiation was achieved successful

  Basic performance of JT-60SA components has been confirmed.

  - Discharge incidence happened in March 2021 at 5kV operation.
  - Insulation improvement shall be finished by the end of Dec.
  - Commissioning expected to resume in Feb 2022

Thank you for listening

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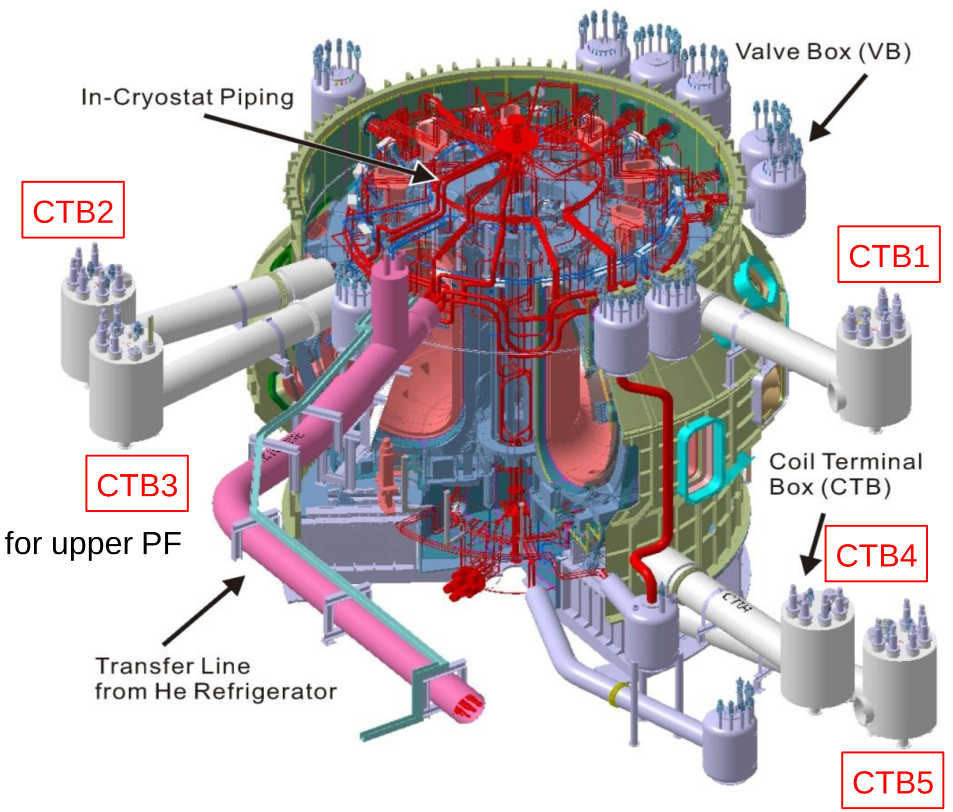
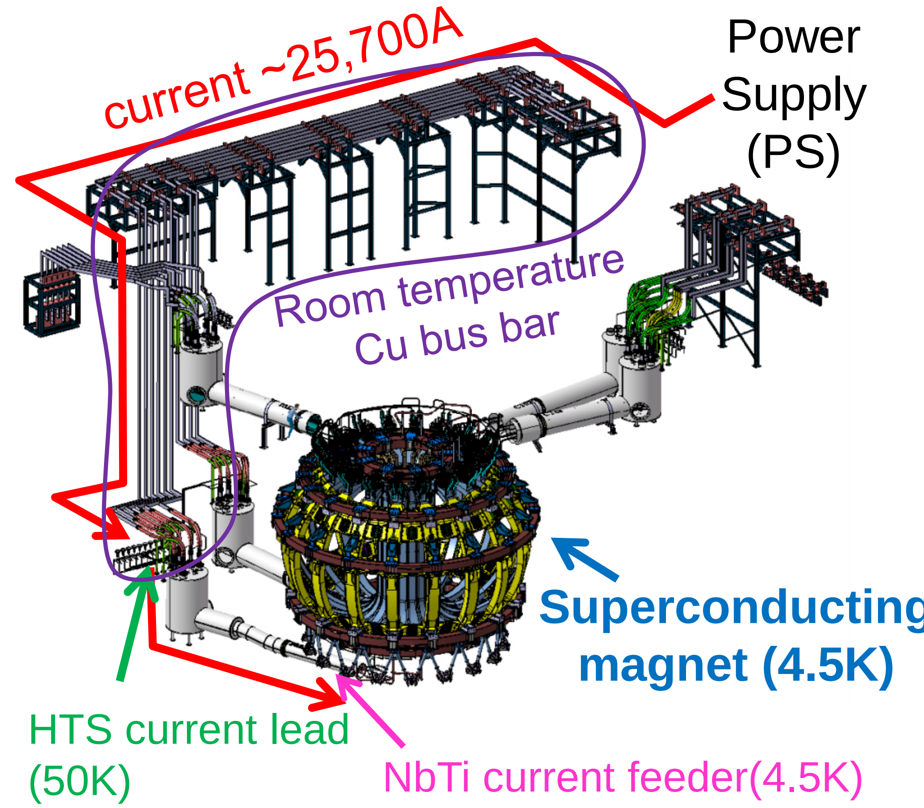
SHe and current supply system

- Coil Terminal Box (CTB) is connecting magnet and power supply.
- HTS current leads are used for the boundary of RT and 4K feeder.
- Valve Box (VB) is distributing SHe coolant for magnets.

→Because of the narrow available space in torus building, we use 5 CTBs and 11 VBs spread around the main cryostat.



Cryogenic system for JT-60SA



Current supply system for JT-60SA

Evaluation of circularity

Conductor position was measured by a laser tracker system.

- Current center was determined by the average of conductor position.
- Conductor position was measured every 40 degree for CS, every 20 degree for EF.
- Circularity was evaluated as the width between the maximum radius and the minimum radius.