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EXPERIMENT AND IEA LARGE TOKAMAK WORKSHOP
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Machine Design for JT-60SC

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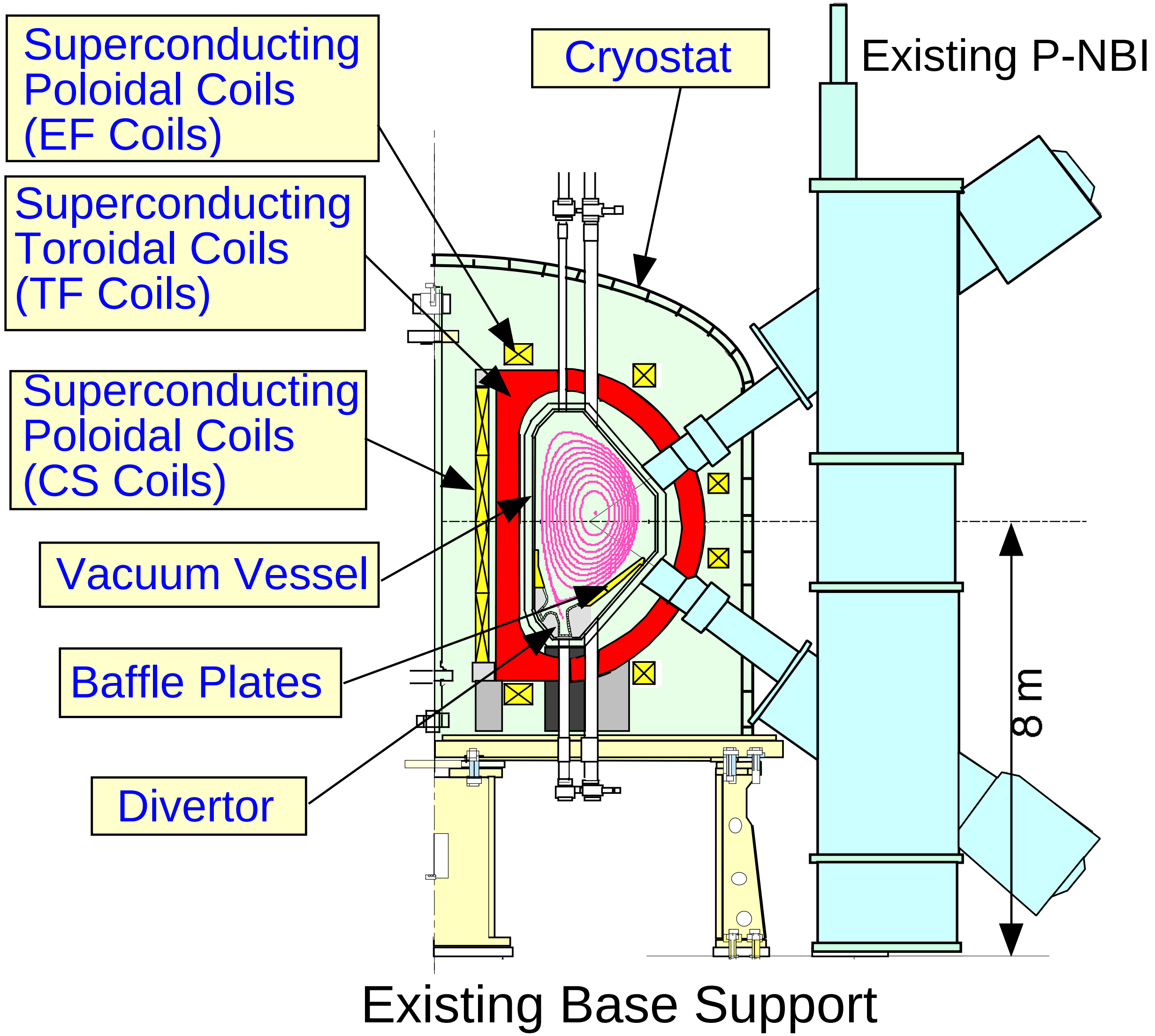
Contents

Feature of Engineering Design for JT-60SC

- Superconducting Coils
  - Full superconducting Tokamak device (ITER-FEAT, KSTAR, JT-60SC)
  - Nb_3Al wire rod for Toroidal Field Coils
- Stabilizing Baffle plates
  - Passive Stabilizer for VDE
  - Passive Stabilizer for RWM
- Plasma control
  - Vertical Position Control coils for VDE suppression
  - Sector coils for RWM stabilization
- Reduction of TF ripple
  - Ferritic Steel outside/inside Vacuum Vessel (1.2% ---> 0.4%)
- Forced cooling divertor
  - Water cooling divertor Unit for 10 MW/m^2

General View of JT-60SC


Superconducting Poloidal Coils (EF Coils)

Superconducting Toroidal Coils (TF Coils)

Superconducting Poloidal Coils (CS Coils)

Vacuum Vessel

Baffle Plates

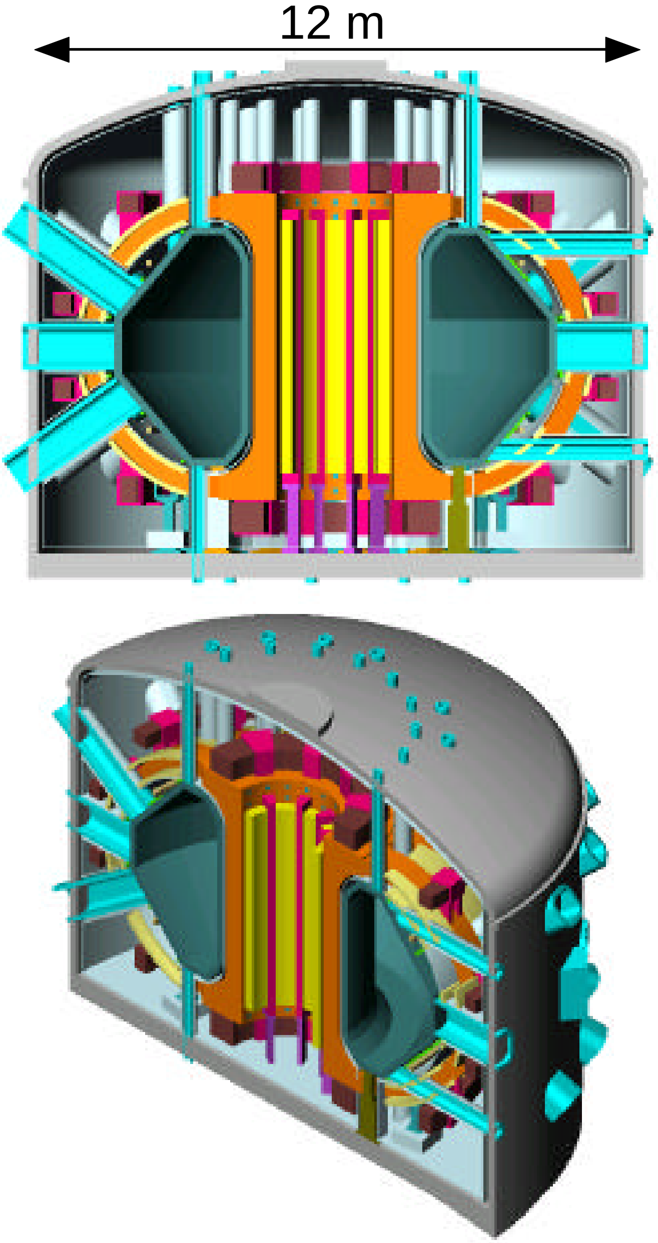
Divertor

Cryostat

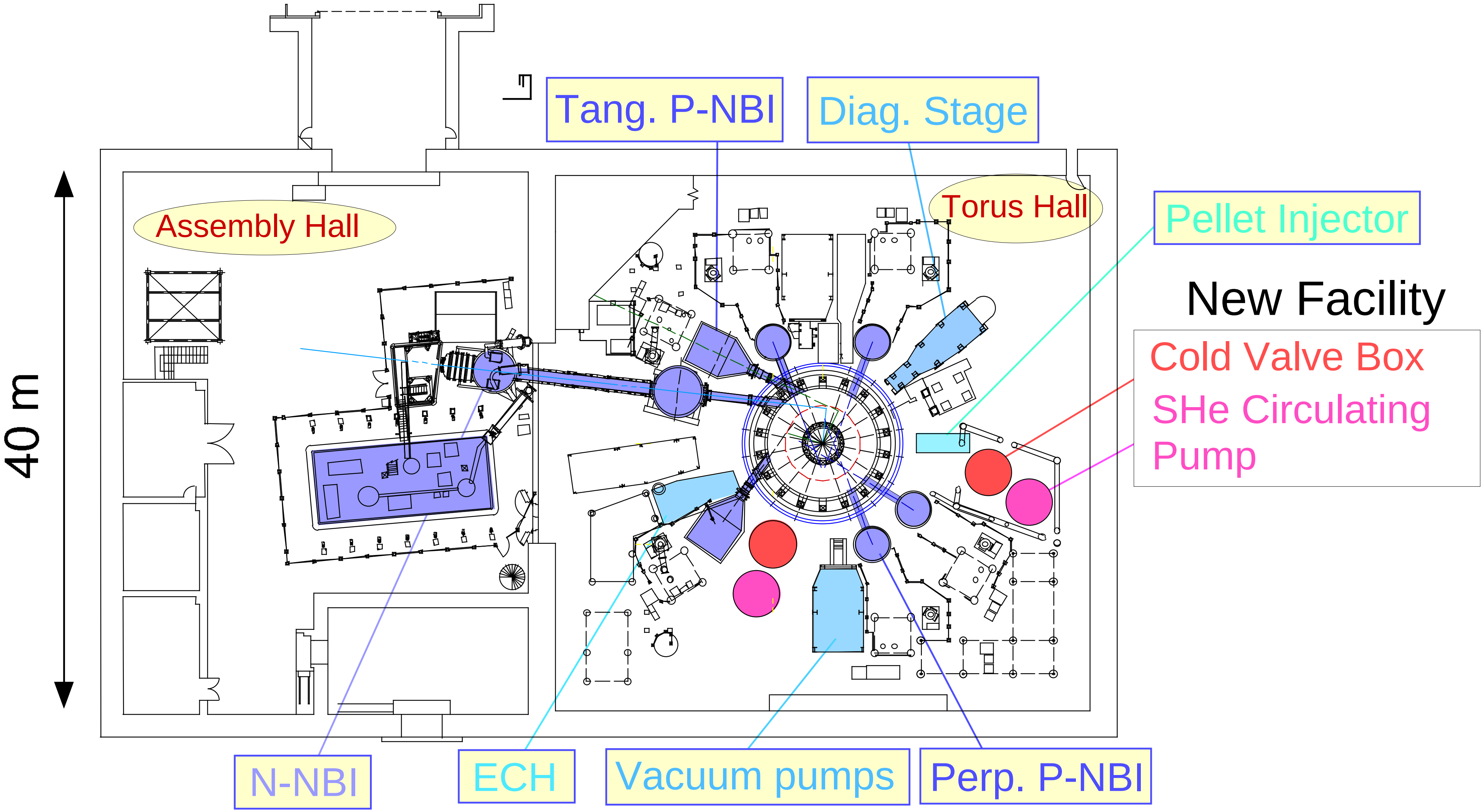
Existing P-NBI

8 m

Existing Base Support


12 m

Arrangements of Circumferential Systems in Torus Hall



Tang. P-NBI

Diag. Stage

Torus Hall

Assembly Hall

Pellet Injector

New Facility

Cold Valve Box

SHe Circulating Pump

40 m

N-NBI

ECH

Vacuum pumps

Perp. P-NBI

Design of Superconducting Conductors

TF Coils Nb_3Al strands (in comparison to Nb_3Sn):

- Degradation of J_c with thermal and bending strains is lower.
- Time of heat treatment is shorter. SUS316LN for conduits is utilized.
- Conductor with high voltage and forced cooling by SHe.
- Higher J_c with adoption of sc strand Cu : non-Cu = 4 is obtained (so far, ratio of 2 was established). ---> Cost reduction of sc cable and compact TFC

CS coils Nb_3Sn strands: AC losses are lower. SUS316LN for conduits is utilized.

EF coils NbTi strands: Low cost and easy fabrication for nominal peak field 5 T.

Items	TFC	CS/EF-4	EF-1, 2, 3, 5, 6
Structure of Conductor	cable-in-conduit	cable-in-conduit	cable-in-conduit
sc conductor	Nb_3Al	Nb_3Sn	NbTi
Operating Current (kA)	19.4	20	20
Nominal Peak Field (T)	7.4	7.4	5.0
sc strand Cu : non-Cu	4	2.3	7
sc strand diameter (mm)	0.74	0.78	0.74
Operating Temperature (K)	4.6	5.0	4.8
Temperature Margin (K)	2.4	2.5	1.5
Winding Arrangement	double pancakes	double pancakes	single/double pancakes
Helium Cooling Method	forced cooling (SHe)	forced cooling (SHe)	forced cooling (SHe)
Total Conductor length (km/coil)	2.2	2.5/6.0	4.3 - 5.4

TF Coil System Parameters

Coils :

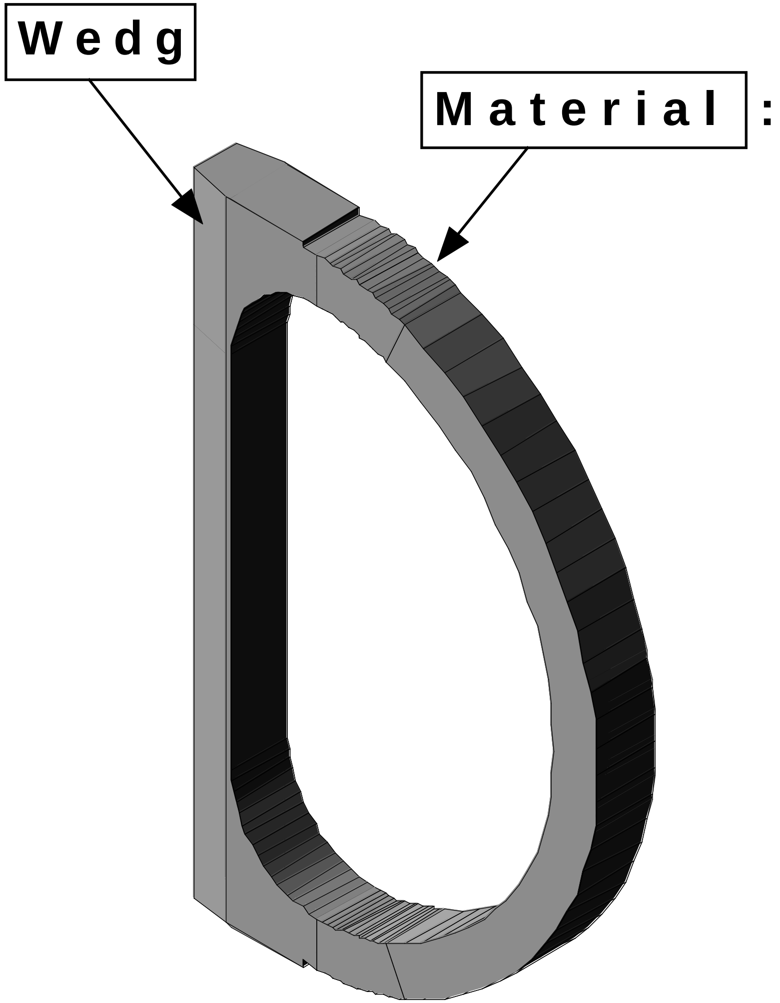
Coil shape	D shape
Numbers of TFC	18
Length round	14.4 m
Weight	23 ton/coil
Coil current	54 MAT
B_{tor}	3.8 T
Magnetic energy	1.6 GJ
Inductance	8.6 H
TF ripple	1.2%
	(0.4% by Ferritic Steel)

Conductor :

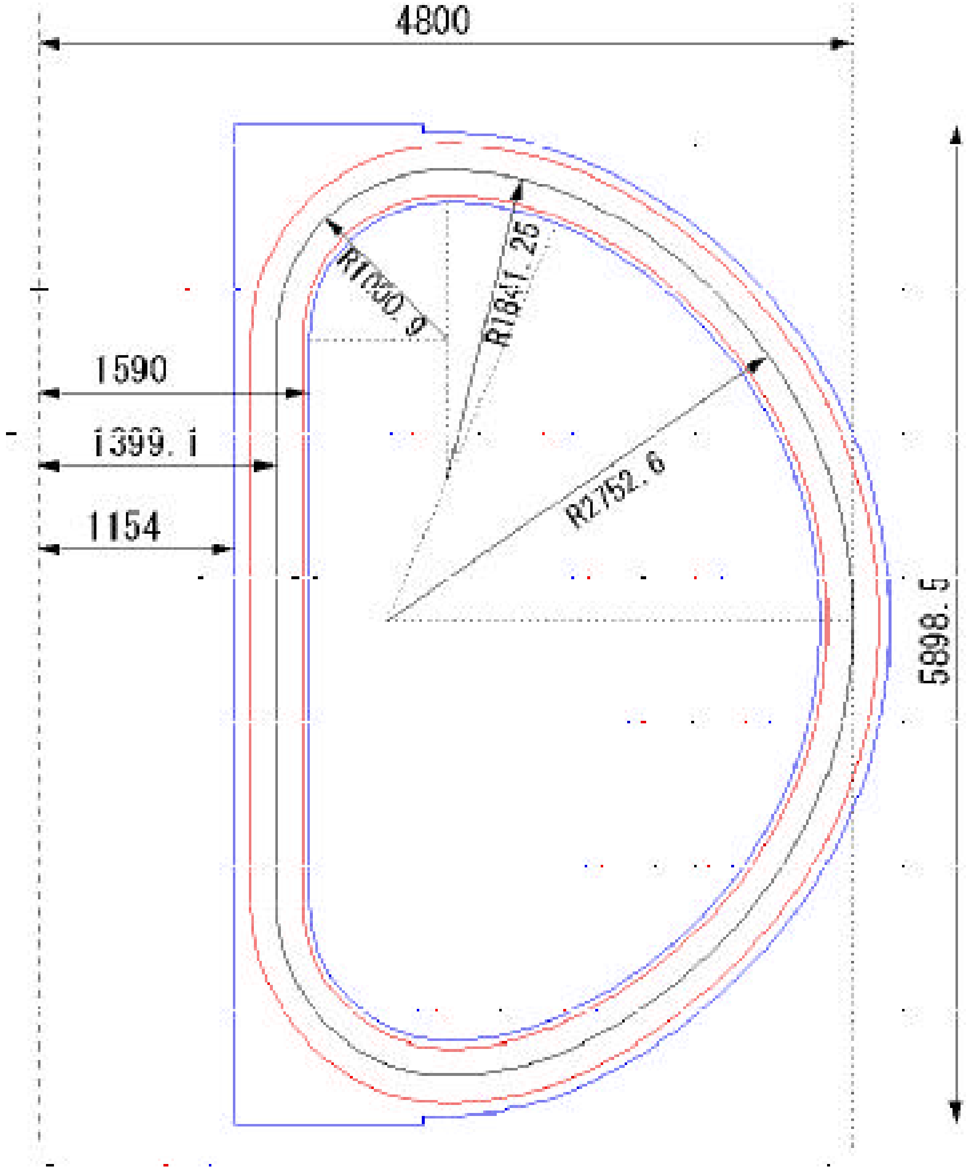
Number of Pancake	14
Total length	40 km

Cooling :

Method	forced cooling (SHe)
Number of path	14 paths/coil
Path length	159 m/path
Total liquefaction	302 g/s (SHe)



TF Coil Structure



Coil Case : JJ1

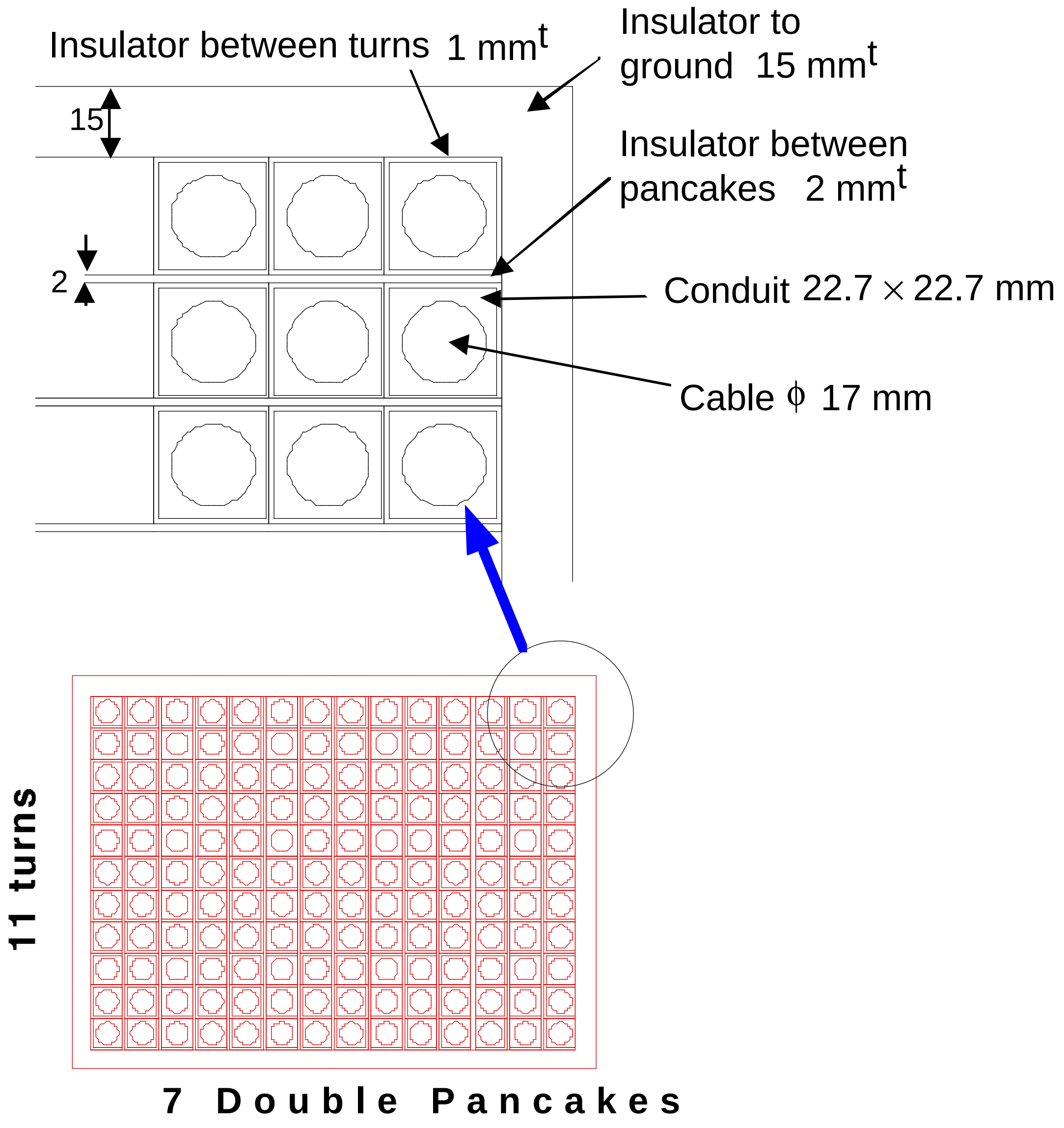
Conductor : Nb_3Al

Conduit : SUS316LN

Centering Force : Wedge Support

Toroidal Tension : Shear Panels

Structure of TFC Conductor



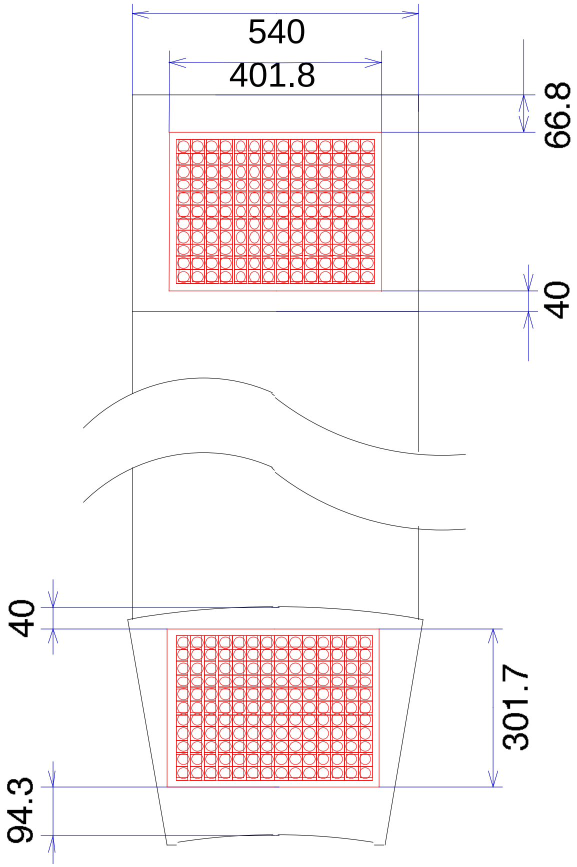
Insulator between turns 1 mm^t

Insulator to ground 15 mm^t

Insulator between pancakes 2 mm^t

Conduit 22.7 × 22.7 mm

Cable ϕ 17 mm



Structure of TFC Conductor

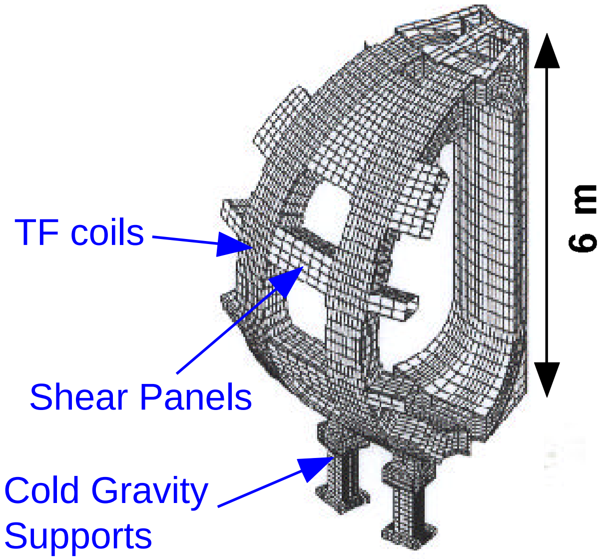
TFC Support Structure and Stress Analysis

TFC Support Structure :

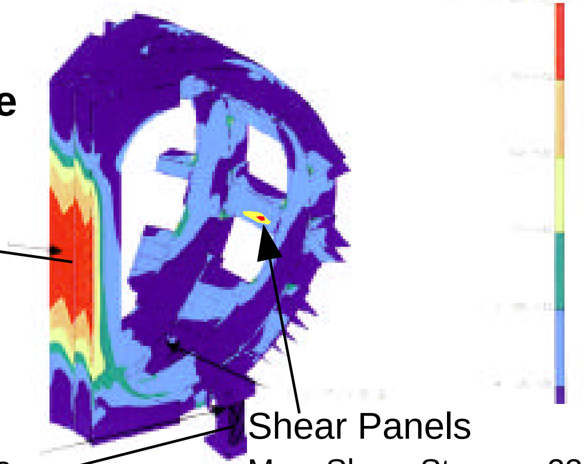
- Toroidal Tension
  1) Cold gravity support with plate springs
  2) Intercoil shear panels

  (Toroidal displacement : 5-10 mm)

- Centering Force
  Wedge support in inner structure



TFC Support Structure

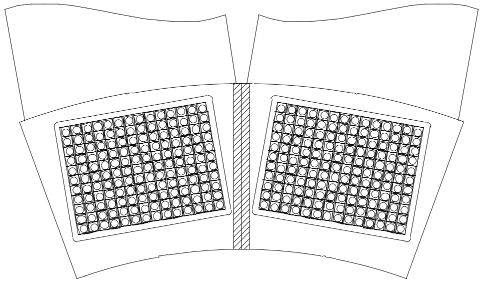


Coil Case
Max. Shear Stress = 206 MPa
Tresca Stress = 412 MPa

Gravity Supports
Max. Shear Stress = 39.5 MPa
Tresca Stress = 79.0 MPa

Shear Panels
Max. Shear Stress = 232 MPa
Tresca Stress = 464 MPa

Maximum Shear Stress at EOF (End of Flat-top)



Wedge Support Structure

Superconducting Conductor for TFC of JT-60SC

1) NbTi

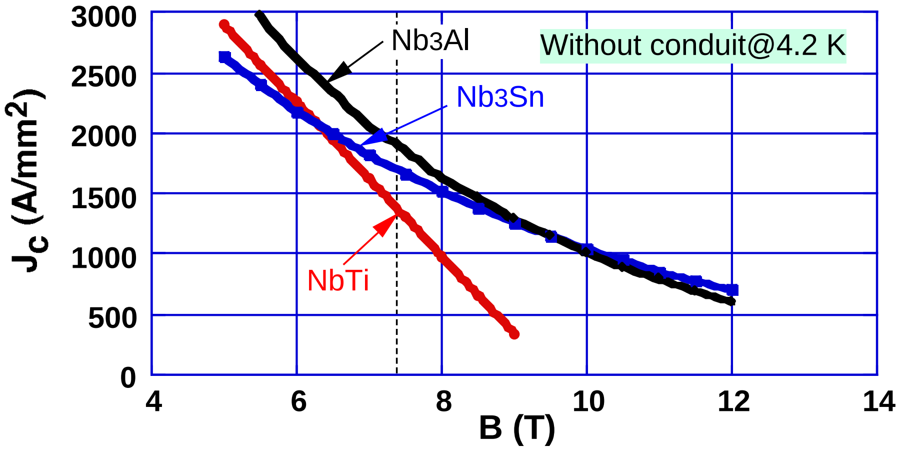
Strand J_c of NbTi conductor :

J_c = 1350 A/mm^2 (at 7.4 T) : without conduit at 4.2 K

J_c = 350 A/mm^2 (at 7.4 T): with SUS conduit at 5.6 K

Designed operating temperature : 5.6 K
(Inlet SHe temp. : 4.3 K, Nuclear heat load : +0.3 K,
Other heat loads: +1 K)

In the case of NbTi conductor, It is impossible to obtain the required I_{op} =19.4 kA (J_c=1100 A/mm^2).



Strand J_c without conduit at 4.2 K

If operating temp. is decreased to 4.4 K, I_{op} is obtained.

---> Inlet SHe temp. : 3.0 K, Running cost up

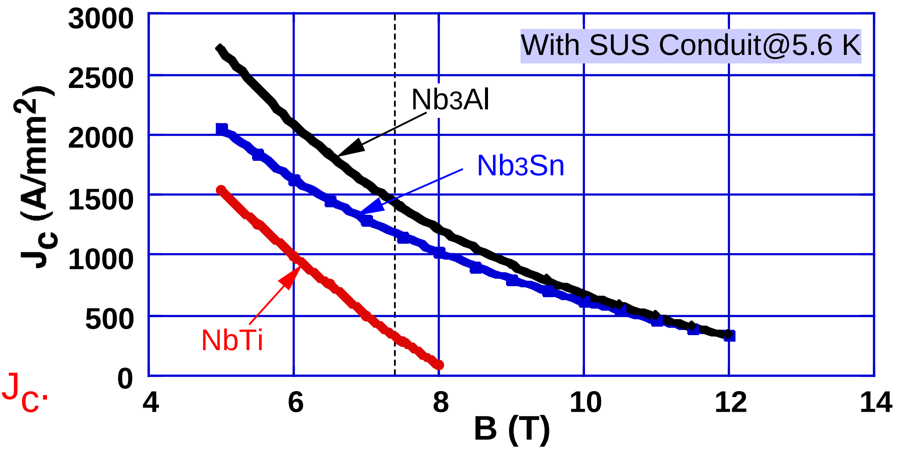
Insufficient temp. margin to T_{cs} = 4.5 K

2) Nb_3Sn and Nb_3Al

Strand J_c (with SUS conduit at 5.6K) :

Nb_3Sn : J_c = 1200 A/mm^2 (at 7.4 T)

Nb_3Al : J_c = 1450 A/mm^2 (at 7.4 T)



Strand J_c with SUS conduit at 5.6 K

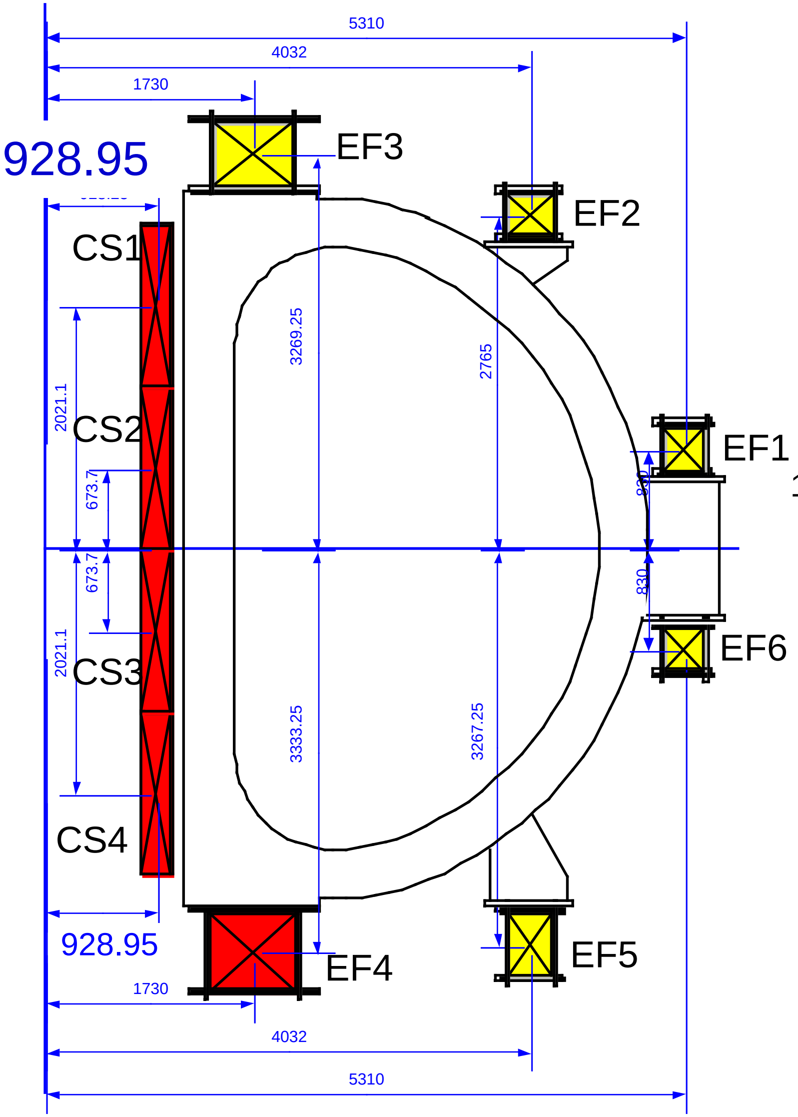
Nb_3Sn : Thermal strain sensitivity is higher, degradation of J_c.

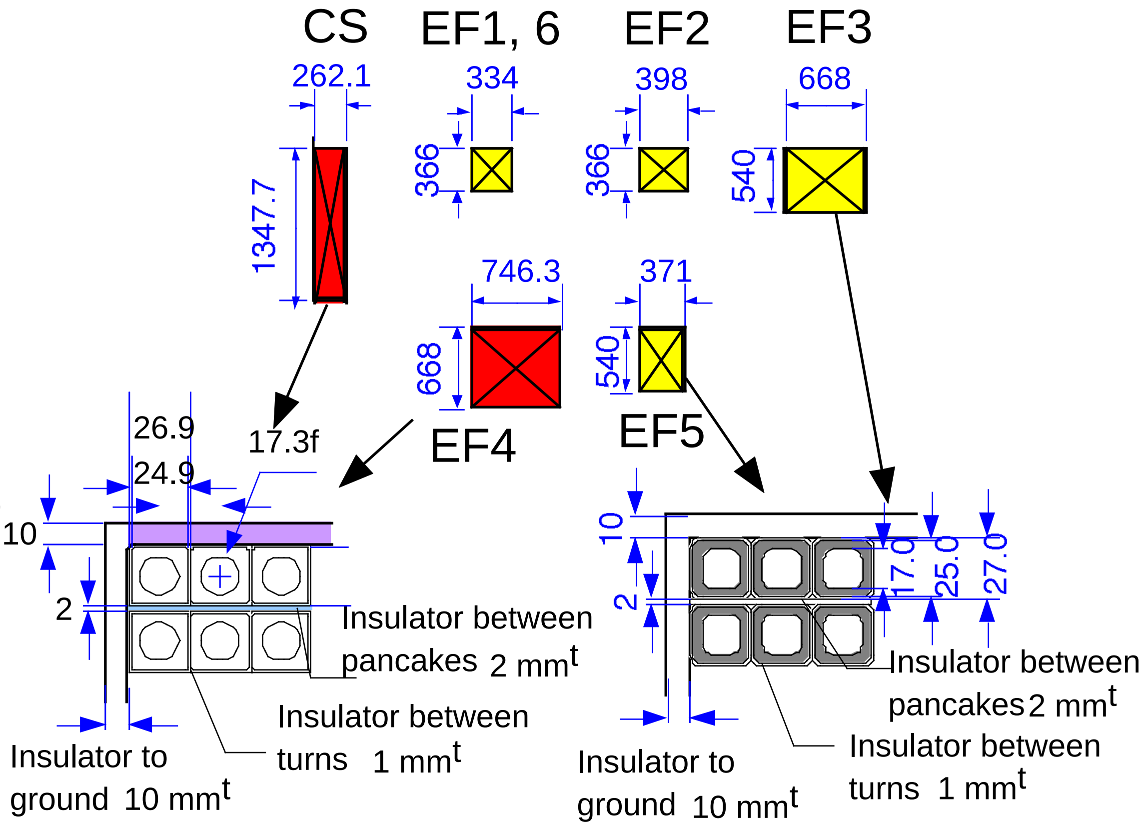
Nb_3Al : Ensure sc high performance above the required J_c.

PF coil System Parameters

Items	CS	EF1&6	EF2&5	EF3&4
Coils :				
Coil shape	Circular	Circular	Circular	Circular
Number of PFC	4	2	2	2
Averaged radius (m)	0.93	5.31	4.03	1.73
Weight (ton/coil)	12	22	20/27	21/30
Conductors :				
Coil current (MAT/coil)	8.3	2.9	3.4/4.2	8.6/10.8
Number of turn	9	12	14/13	24/27
Number of pancake	46	12	12/16	18/20
Magnetic energy (GJ/coil)	0.05	0.10	0.10/0.14	0.16/0.25
Inductance (H)	0.25	0.51	0.48/0.70	0.82/1.26
Cooling :				
Method	All forced cooling (SHe circulating)			
Number of path (paths/coil)	46	24	24/32	36/40
Path length (m/path)	53	200	177/165	130/147
Total liquefaction SHe (g/s)	202	48	43/51	54/56

PF Coil Structure





		I_{op}	B_{max}	T_{op}
CS, EF4	Nb_3Sn	20 kA	7.4 T	5.0 K
EF1,2,3,5,6	NbTi	20 kA	5.0 T	4.8 K

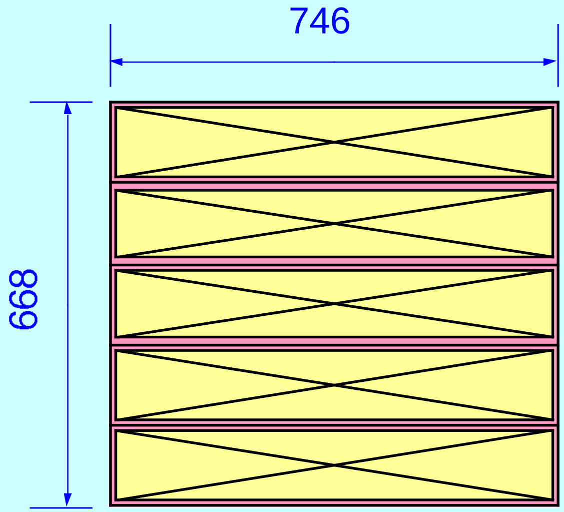
Block Structure of EF4 and EF5

- EF4 and EF5 are installed under TFC and VV.
  Adopt block structures for these EF coils.
  - Bad block is removed at troubles
    → Avoid repairs in large scale.
  - Usually, low coil current operation under the nominal I_{op}.
    → Reduce possibility of trouble.

EF4

Nb_3Sn

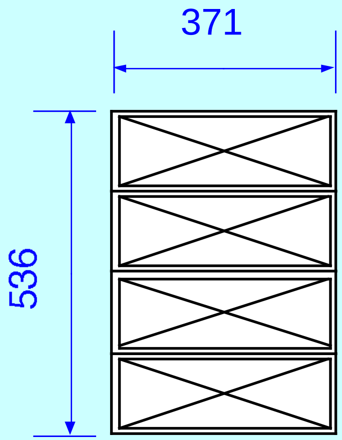
5 blocks



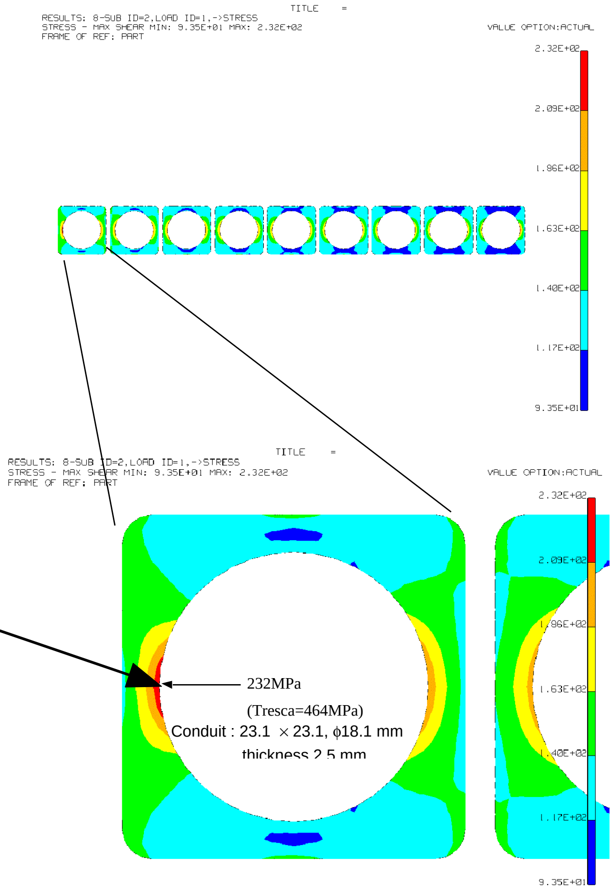
EF5

NbTi

4 blocks



Stress Analysis of CS coils



Inner Conductor of CS coils

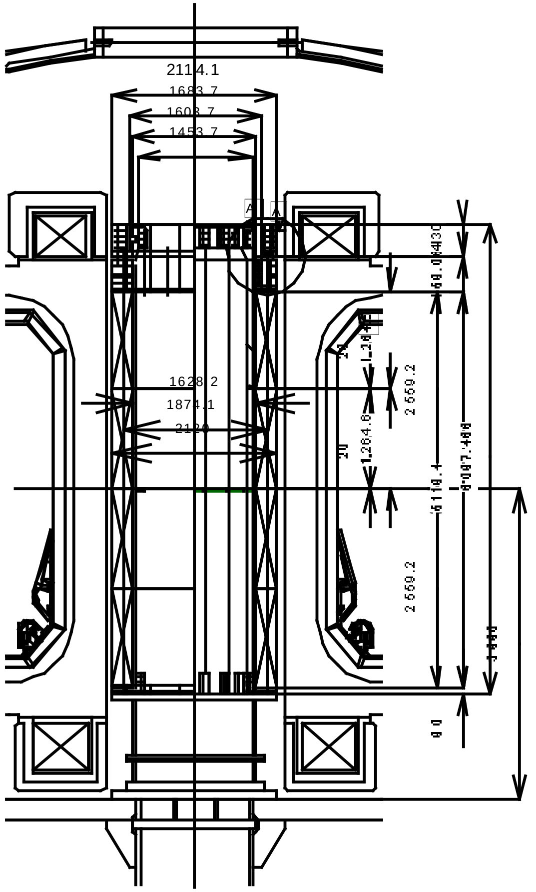
Max. Shear Stress = 174 MPa

Tresca Stress = 348 MPa

Conduit : 24.9 × 24.9, ϕ17.3 mm

thickness 3.5 mm

Maximum Shear Stress at EOF (End of Flat-top)



Cross Sectional View of CS Coils

- Evaluation of Fatigue Failure for CS coils

1) Discharge number of nominal operation (6000 shots)
2) Discharge number of 70% nominal operation
(12000 shots)

$$\rightarrow \frac{\text{(Number of applied stress)}}{\text{(Allowable failure life)}} \leqq 1$$

Superconducting Strand and Conductor R&D

Conductor R&D for TFC

- **Development of Nb_3Al strand and conductor (cable-in-conduit) with sc strand Cu : non-Cu = 4.**
- **Evaluation of sc performance**

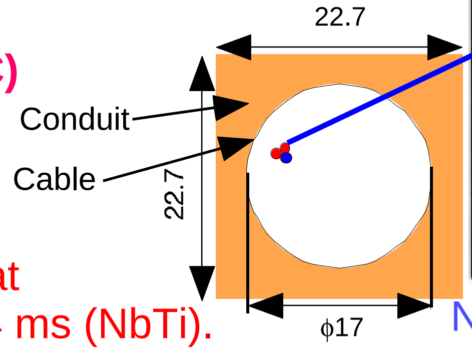
  Ic measurement

  (satisfy the sc specification for JT-60SC)

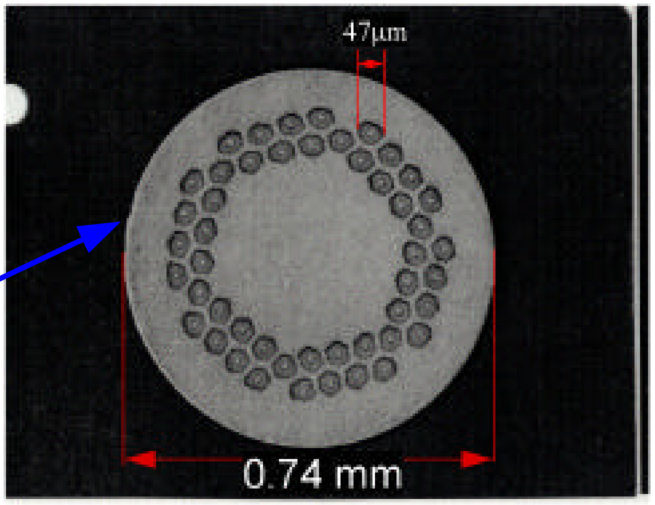
Strand R&D

- **Development of low AC loss strands**
- **Measurement of coupling losses**

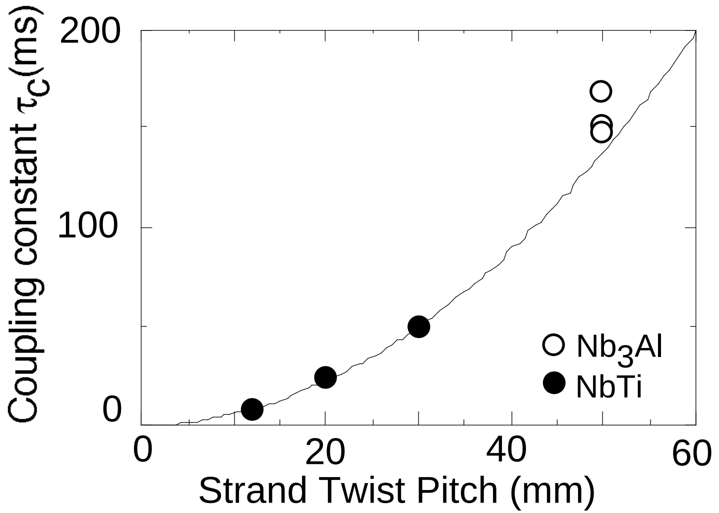
  No degradation with strand twist and heat treatment. Confirm 96 ms (Nb_3Al) and 4 ms (NbTi). Prospect 41 ms (Nb_3Al, twist pitch:40 mm) < 50 ms



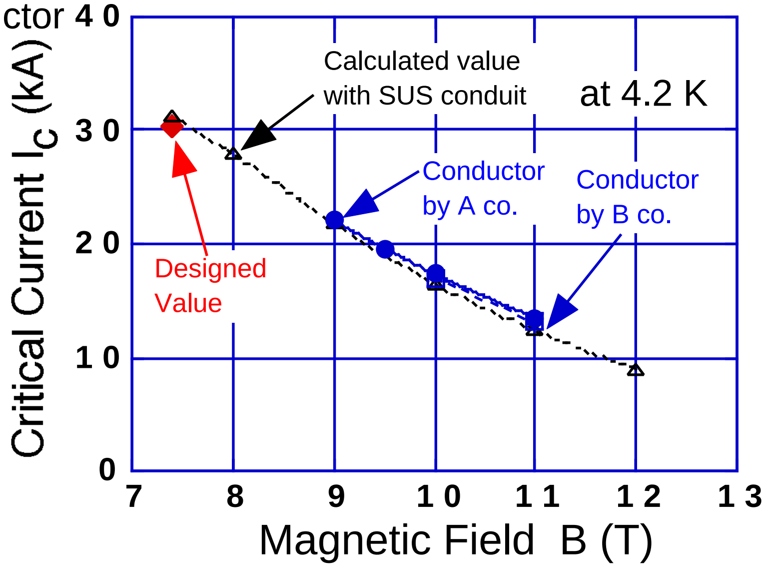
Conductor



Nb_3Al strand developed for JT-60SC



Coupling time constant (Nb_3Al and NbTi strands)



Critical Current I_c of Nb_3Al conductor

Neutron Shielding Efficiency of VV

- VV Structure No.1

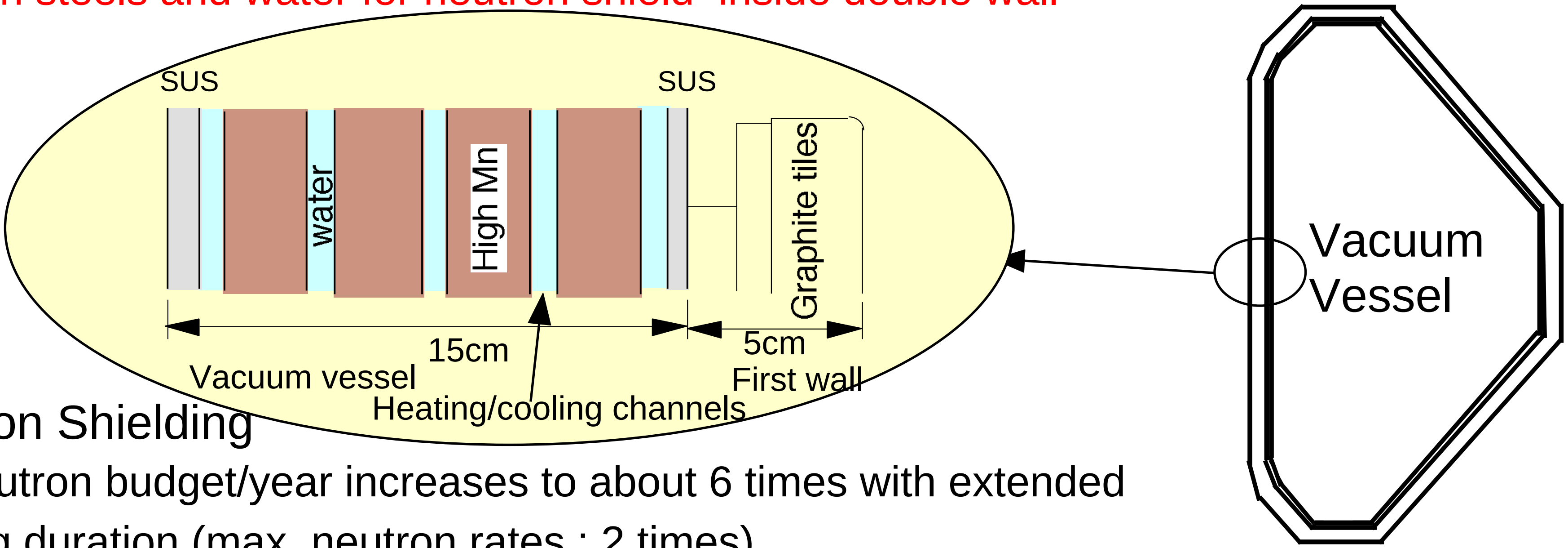
· Low Co contamination SUS with reduction of activation

· Elongated cross section (polygon poloidal cross section)

· Double wall structure with thin plates

· Heating/cooling channels inside double wall

· High Mn steels and water for neutron shield inside double wall



- Neutron Shielding

· DD neutron budget/year increases to about 6 times with extended heating duration (max. neutron rates : 2 times).

· Keep the same neutron flux level outside cryostat by shielding effects of VV and cryostat.

· Improve shielding efficiency by high Mn steel with Boron 1%w.

Test of Neutron Shielding Efficiency (R&D)

Neutron Irradiation Test of High Mn Steel with Boron

Development of high Mn steel (VC9) with natural boron

- Trial manufacture of high Mn steel with natural boron 1%w.
  (VC9 : high strength and low activation)
- High Mn steel with natural boron 2%w and 3%w were easily broken and the machining was difficult.

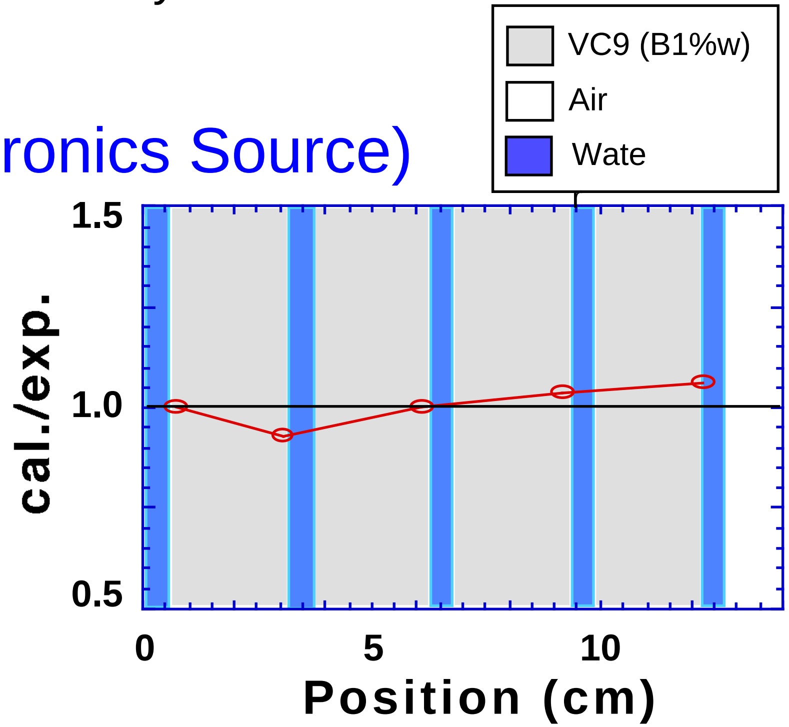
DD neutron irradiation test (Fusion Neutronics Source)

- Obtain shielding efficiency and activation.
- Comparison of experimental result with calculated result. ---> Bench mark

DD neutron (E_{DD} = 2.4 MeV)

Neutron irradiation : 10^9 n/sec × 7 hours

cal./exp. : 1.0 ± 0.1
Shielding efficiency of high Mn steel with boron agrees with calculated one.



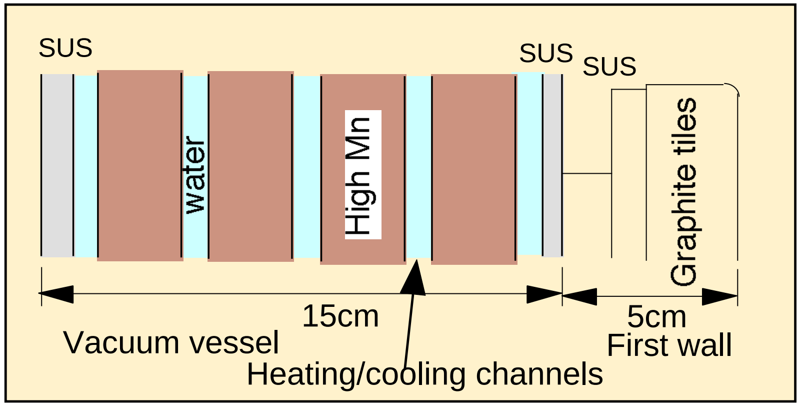
Sample for VV structure
(Multilayer structure)

Evaluation of VV Shielding Efficiency

● Nuclear Heat Load for DT exp.

At first, multilayer structure with high Mn steel and water was designed from the JT-60SU design (DT operation).

Nuclear heat load of TFC and radiation shield
---> high Mn steel : water = 7 : 3 is best for DT exp.



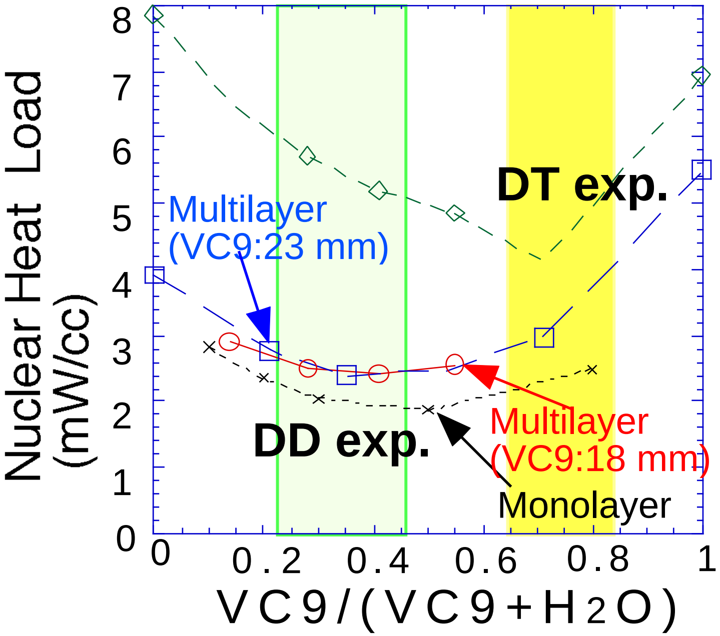
● Shielding efficiency for DD exp.

Multilayer structure : VC9 / (VC9+H_2O) = 0.2 - 0.4 for nuclear heat load

Monolayer structure is sufficient to nuclear heat load and radiation shield.

---> Reduction of shielding material amount and simple structure

	JT-60U		JT-60SC
Max. neutron rates	2 x 10^{17}	→	4 x 10^{17} (n/s)
neutrons/week	3.1 x 10^{18}	→	4 x 10^{19}
neutrons/3 months	2.1 x 10^{19}	→	1.5 x 10^{20}
neutronsn/year	3.1 x 10^{19}	→	2 x 10^{20}



Nuclear heat load of TFC v.s. Shielding structure

Vacuum Vessel Structure

● VV structure No.2

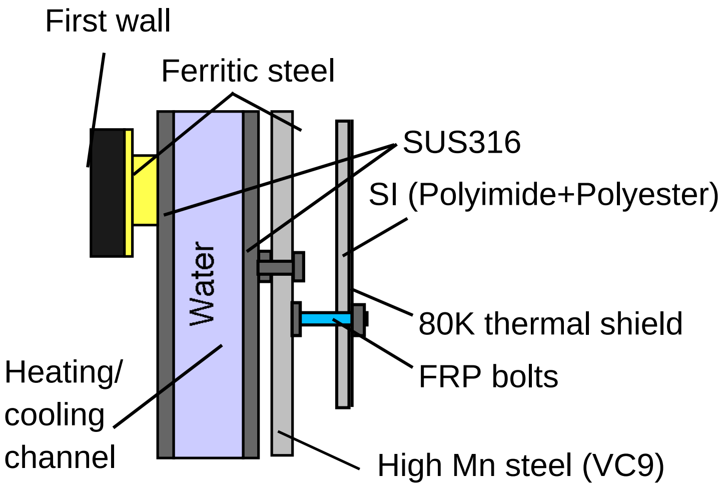
<Merit>

- **Heat removal from first wall by water is better.**
- **Baking temp. : 300°C after water removal**

<Demerit>

- **VV operation temp. : under 100°C**
  limited under 100°C because of using water inside double wall VV.
- **Development of super insulation (SI) with heat-resistance to 300°C for thermal shield.**

<VV Structure No. 2>



● VV Structure No.3

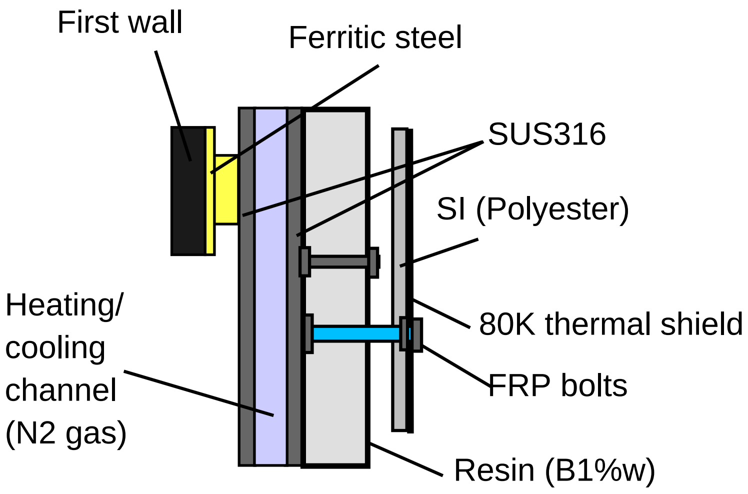
<Merit>

- **VV operation temp. : under 170°C**
  Heat removal from the wall by N2 gas is possible during shot interval.
- **Normal SI (polyester film) is utilized.**
  ---> Low cost thermal shield structure

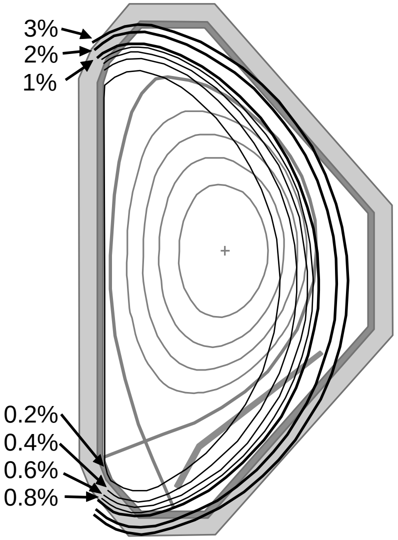
<Demerit>

- **Baking temp. is limited to 170°C from heat-resistance of resin.**

<VV Structure No. 3>

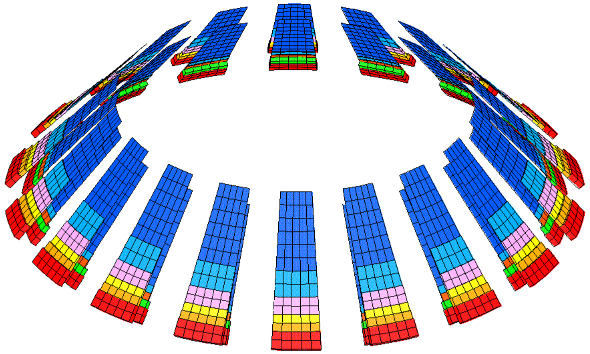


Reduction of TF Ripple by Ferritic Steel



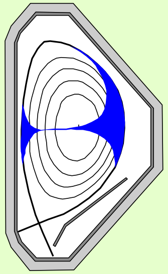
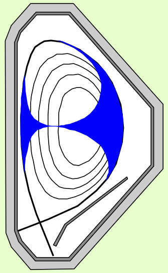
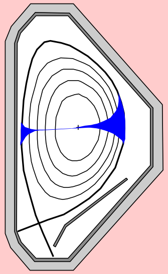
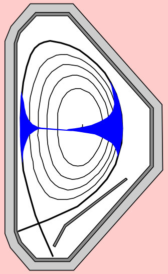
Max. TF ripple rate

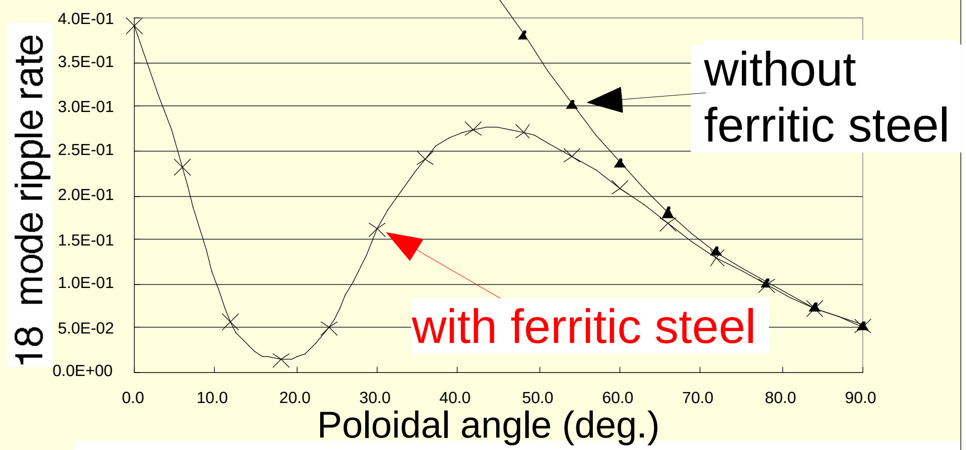
1.2% → **0.4%**



- Displacement of ferritic steel for TF ripple reduction

Ripple Well

	Positive shear (4MA)	Reversed shear (2.5MA)
1.2%		
0.4%		



18 mode TF ripple rate with ferritic steel

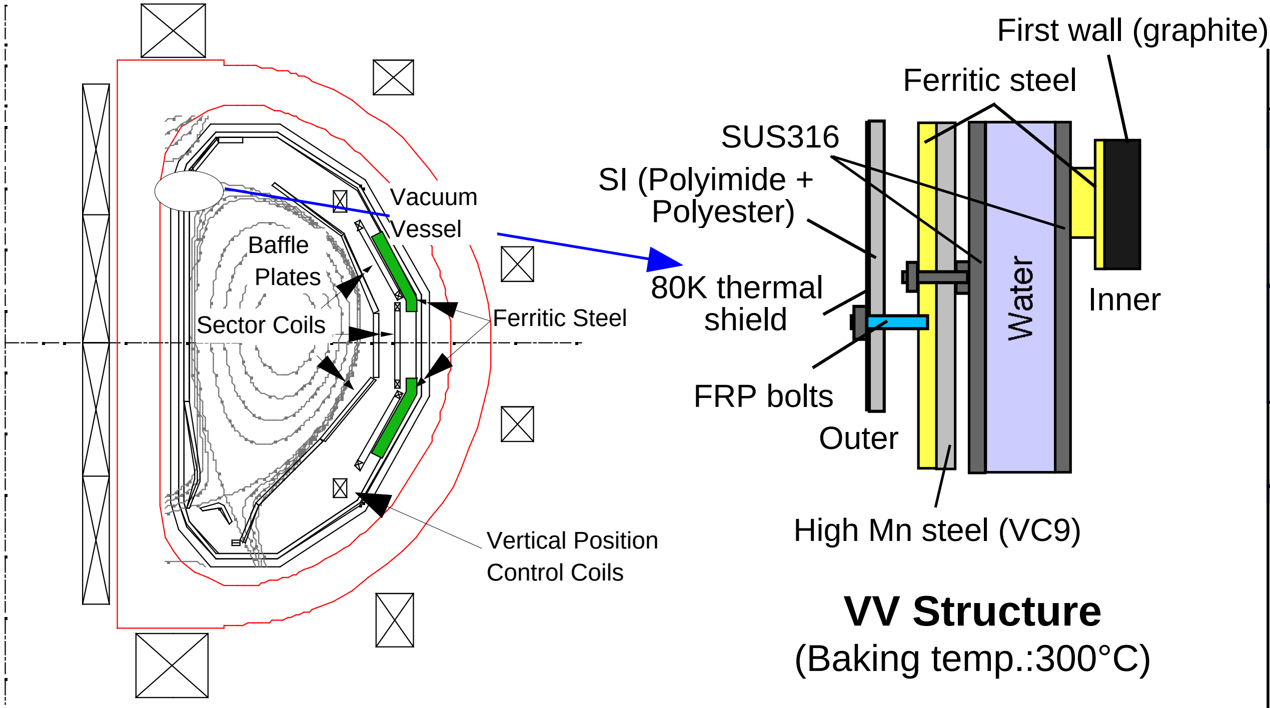
Structure of New Vacuum Vessel

Design of New Vacuum Vessel

1) Good controllability by In-vessel components are expected.
- Sector coils for high beta plasma sustainment (stabilized RWM)
- Vertical Position Control coils for VDE suppression
- Ferritic Steel for TF ripple reduction

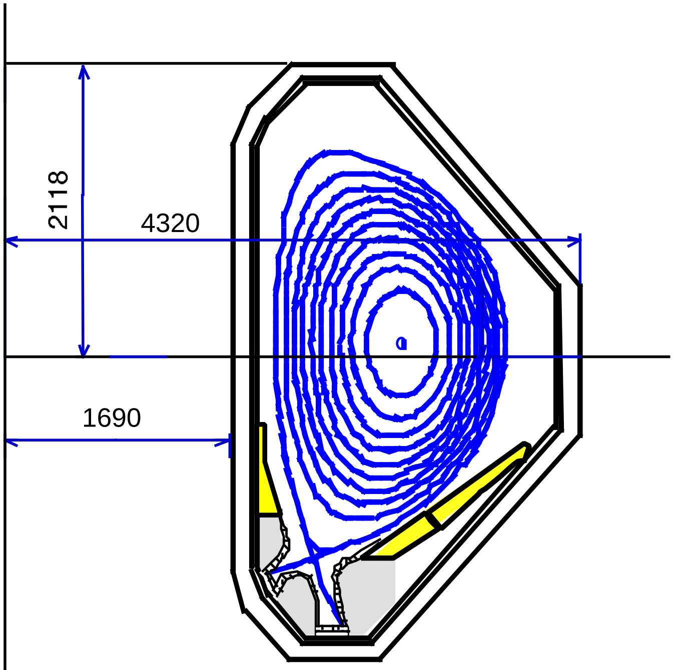
2) Upper Baffle plate is also installed for MHD stabilization

Large In-vessel volume → Full use of in-vessel



New Vacuum Vessel

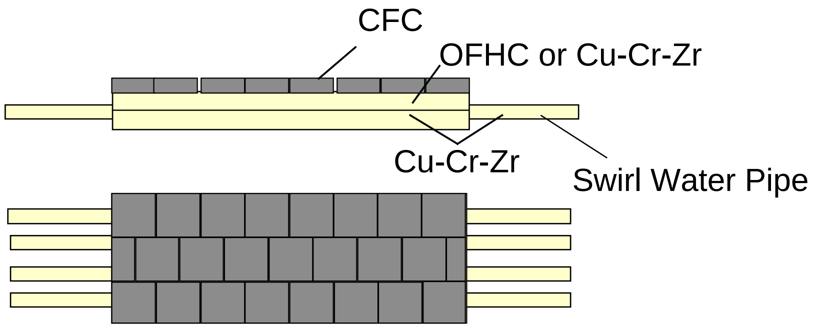
VV Structure
(Baking temp.:300°C)



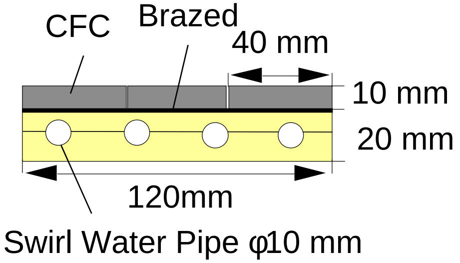
Former Vacuum Vessel

Divertor tiles : Forced Water Cooling (R&D)

<Heat Load Condition> Designed Heat load to Divertor ~ 10 MW/m^2 × 100 s



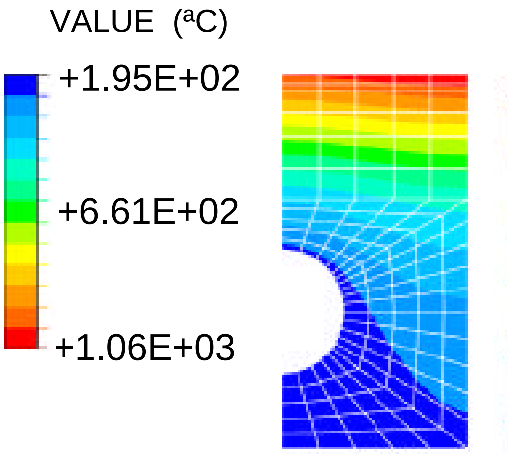
Structure of forced water cooling tiles



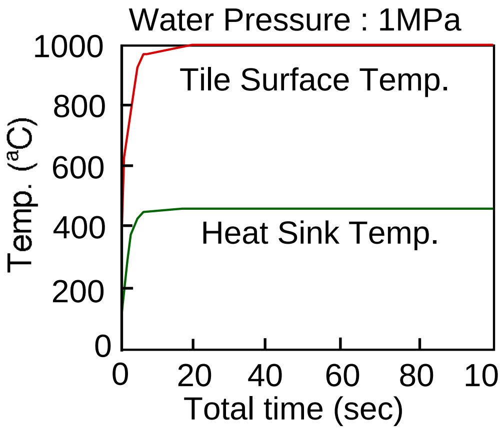
Cross Sectional View

<Heat Analysis>

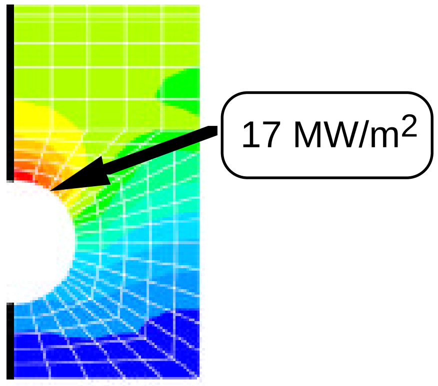
Inlet temp. : RT, Heat load condition : 10 MW/m^2 × 100 s, Water flow velocity : 5m/s



Temperature distribution (after 100 s)

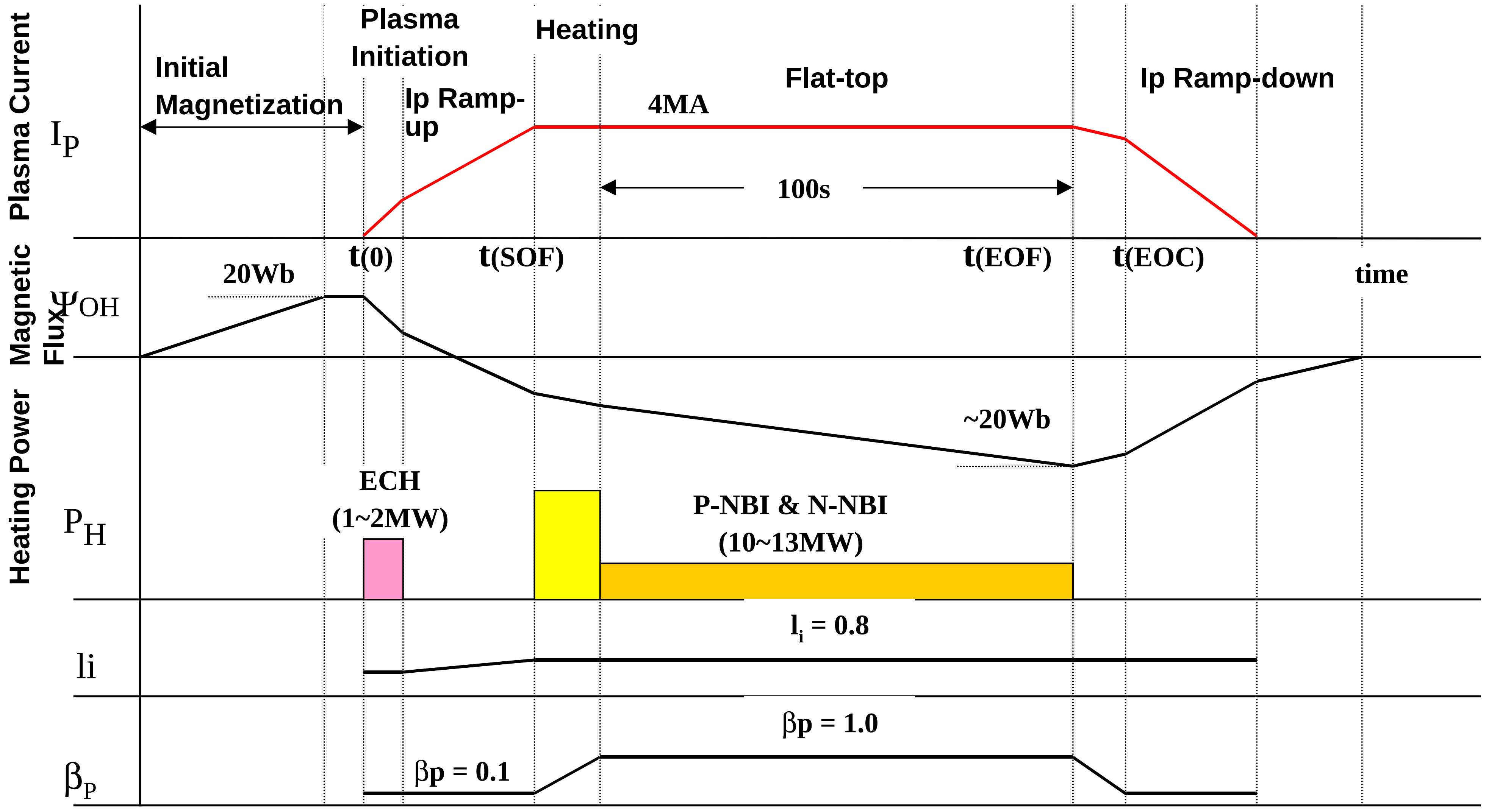


Temperature at tile surface and heat sink



Heat flux distribution (after 100 s)

Standard Operation Scenario



High power heating scenario : 40MW-10s

Plasma Current Ramp-up Scenario

0.1MA

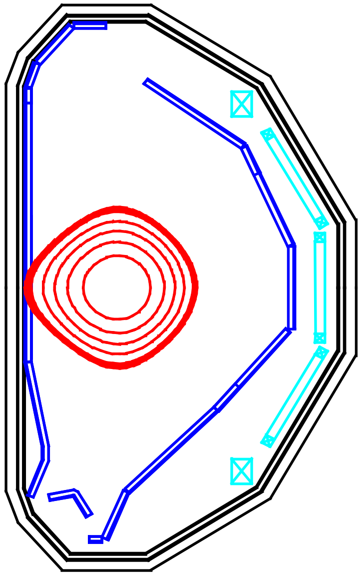
βp=0.1

li=0.5

κ=1.0

δ=-0.06

q95=49.1



0.5MA

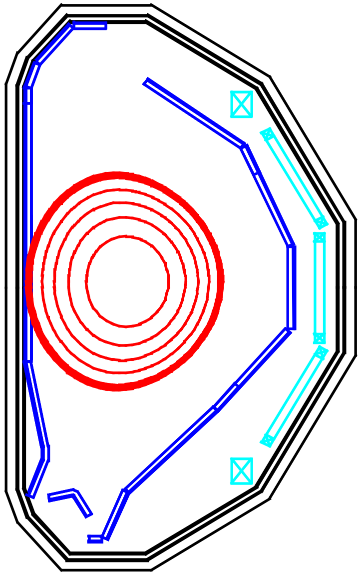
βp=0.1

li=0.53

κ=1.2

δ=0.07

q95=10.3



0.75MA

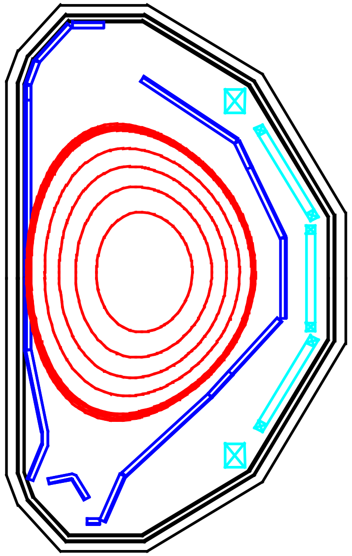
βp=0.1

li=0.56

κ=1.38

δ=0.18

q95=11.3



1.0MA

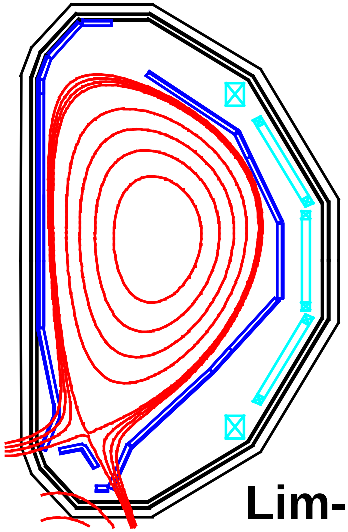
βp=0.1

li=0.62

κ=1.73

δ=0.44

q95=12.4



Lim-->Div

4MA (SOF)

βp=0.1

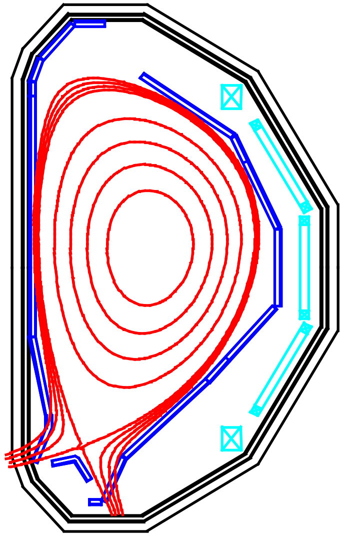
li=0.8

κ=1.66

δ=0.33

q95=3.0

(007a)



4MA (SOB)

βp=1.0

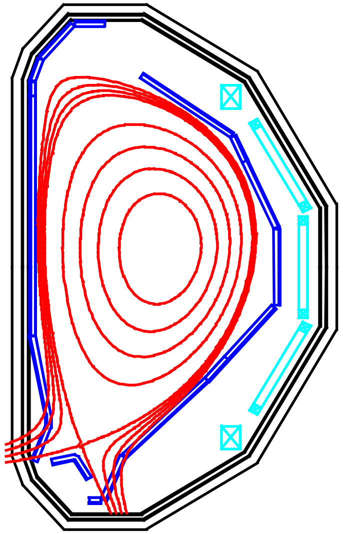
li=0.8

κ=1.61

δ=0.34

q95=3.0

(008c)



βp=0.1-->1.0

Summary

● Design of Superconducting

- Superconducting TF coils are designed with Nb_3Al conductors.
- Engineering prospect for TFC is established from Nb_3Al strand and conductor R&D (sc strand Cu : non-Cu = 4 and low AC losses).
- Designed D shaped TF coils satisfy allowable stress from the stress analysis of conductors and coil case.
- Superconducting PF coils are designed with Nb_3Sn and NbTi conductors.
- Nb_3Sn and NbTi for PFC are under strand and conductor R&D (sc strand Cu : non-Cu = 2.3 and low AC losses)

● Design of Vacuum

- Structure of vacuum vessel strongly depends on neutron shielding efficiency. The VV structure design is required the satisfaction of allowable nuclear heat load and radiation shielding, and installation of in-vessel components.
- Forced cooling divertor is designed for steady state research. Forced cooling divertor tiles with heat removal of 10 MW/m^2 in steady state.

Detailed design for main components will be done