Magnet design for JA DEMO

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QST, Joint Special Design Team for Fusion Demo

Contents

- Introduction -Basic concept of JA DEMO-
- Superconducting magnets design for higher magnetic field and larger coil
  - ✓ R&D of high strength cryogenic steel
  - ✓ Simplification of TF coil fabrication:
    -Design study of Rectangular conductor with double layer winding concept
  - ✓ TF conductor design for JA DEMO
- Summary

Concept of JA DEMO

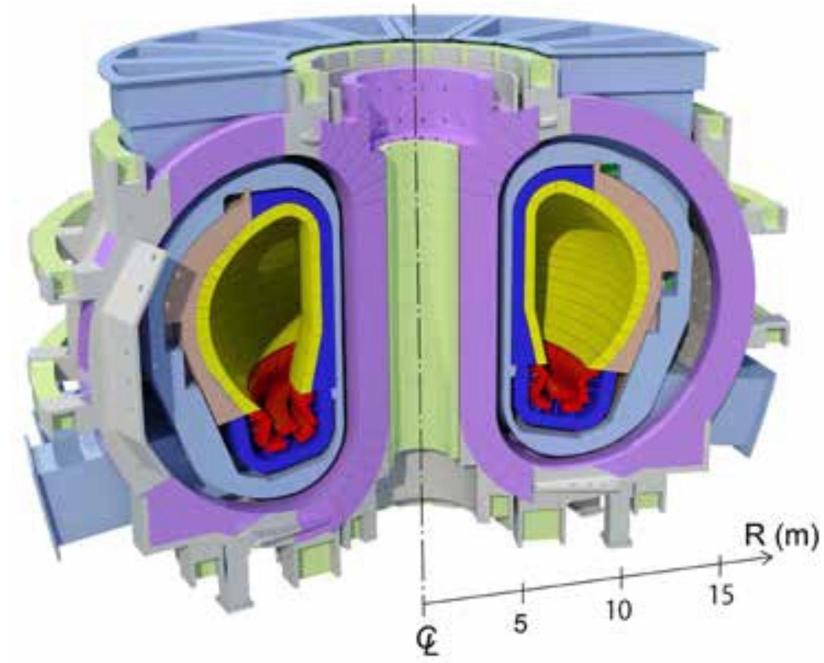
Since the original concept of the JA DEMO was defined in JA Model 2014 [1], the pre-conceptual design has been completed on the fusion DEMO reactor.

Operational flexibility

- JA DEMO was proposed in 2014 to provide operational flexibility from pulse to steady-state with R_p=8.5m for (plasma current lamp-up) large CS coil and P_{fus}~1.5GW for divertor heat load.
  ➡P_{fus}~1.5 GW for Steady state

Technological feasibility

- ITER technologies as much as possible
  - ✓ Blanket: ITER-TBM strategy in Japan
  - ✓ Divertor: Water cool. and W mono-block divertor
  - ✓ Magnet: Radial Plate, CICC etc.



R_p / a_p	8.5 m / 2.4 m
Aspect ratio	3.5
Elongation	1.65
Fusion output	1.4 GW
Net electric power	~250 MW
Plasma current	12.3 MA
Toroidal field on axis	6.0 T
Max. toroidal field	~14 T

[1] Y. Sakamoto et al., IAEA FEC 2014

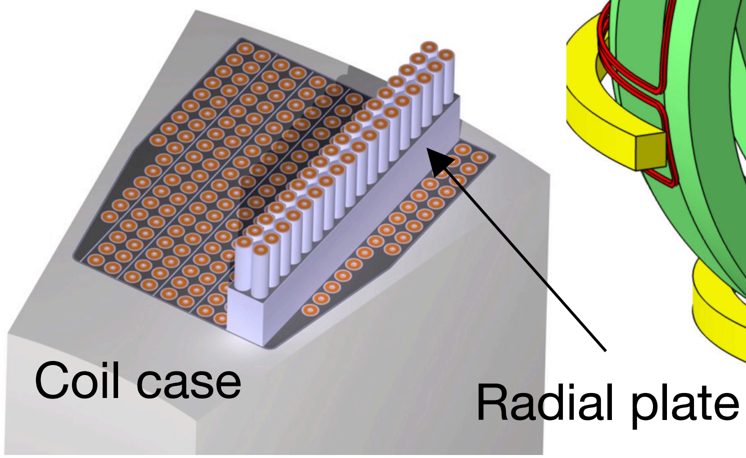
Superconducting Magnets

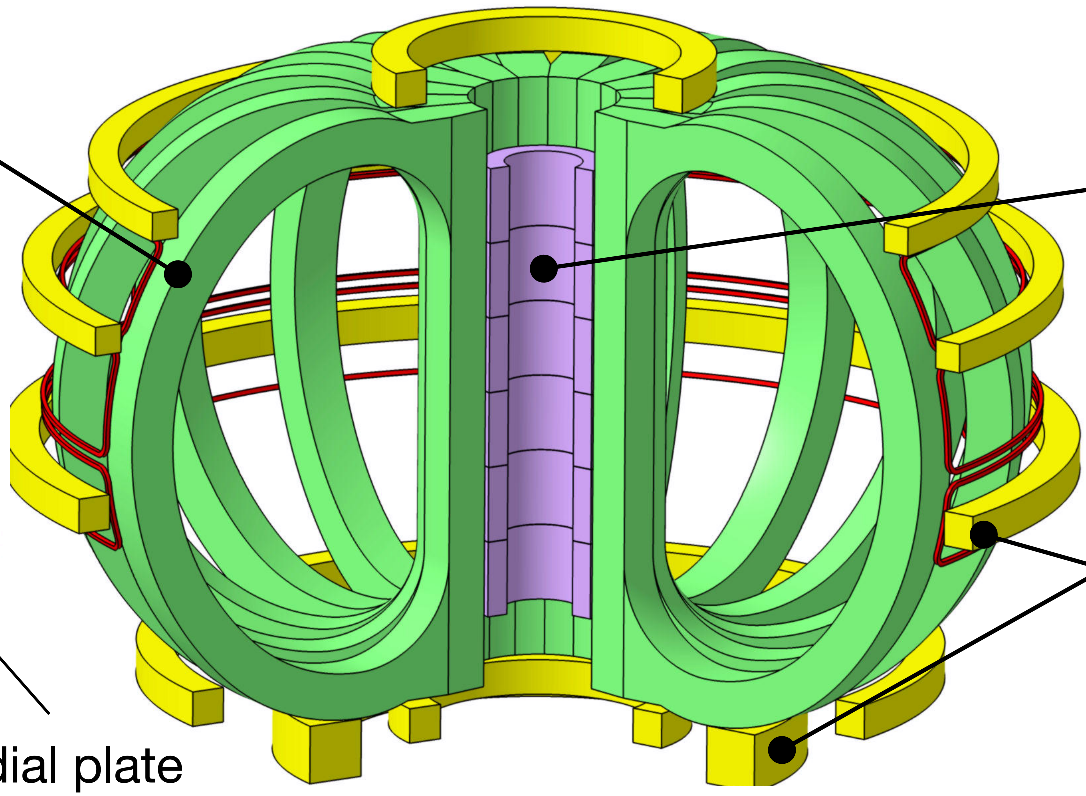
In order to minimize the technical jump-up from ITER,

Main concept: similar to ITER technologies
- ✓ Superconductor strand: Nb_3Sn
- ✓ Radial plate, wedge support structure
- ✓ Cable-in-conduit conductor (CICC)

Toroidal field (TF) coil

~14T, CICC, >80kA Nb_3Sn





Center solenoid (CS)

~13T, CICC, >40kA Nb_3Sn

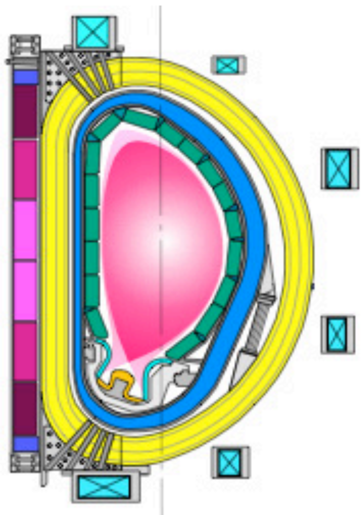
Poloidal field (PF) coil

~6T, CICC, >45kA NbTi

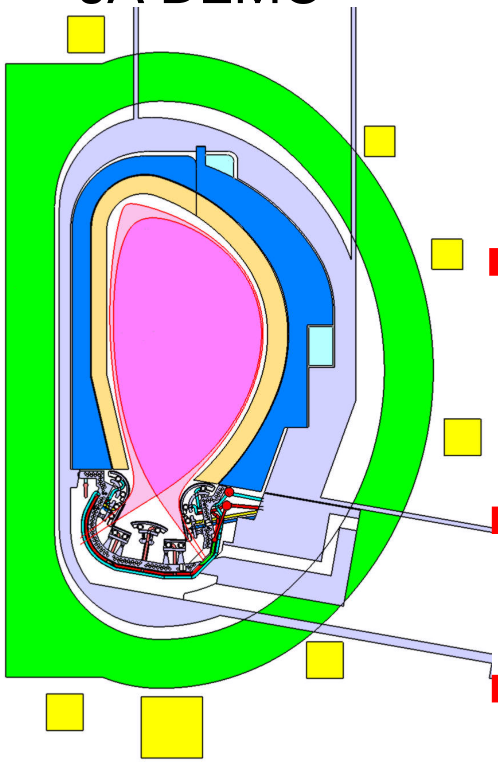
Design issues of Magnets

JA DEMO requires larger TF coils with higher B compared with ITER

ITER



JA DEMO



	ITER	JA DEMO
SC strand	Nb_3Sn	Nb_3Sn
Number of TFC	18	16
B_{tmax}	**11.8 T**	**13.9 T**
Conductor current	68 kA	83 kA
Number of turns per TFC	134	192
Design stress	**667 MPa**	**800 MPa**
Total magnetic energy	41 GJ	153 GJ
Width / Height of TFC	**8 / 12.6 m**	**12 / 19 m**

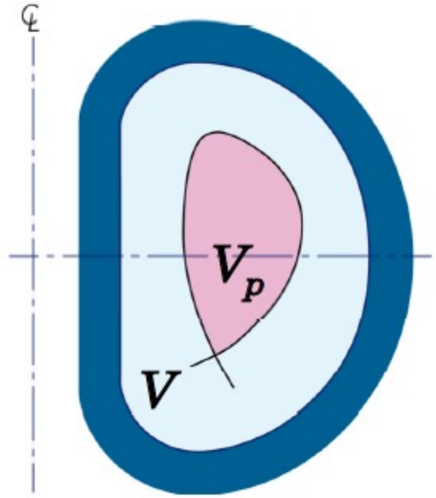
Important issues for improving feasibility are being considered.

High B, high W_{mag}, large TFC for DEMO

- For high fusion power (P_{fus})

$$P_{fus} \propto \beta_N {B_T}^2 V_p$$

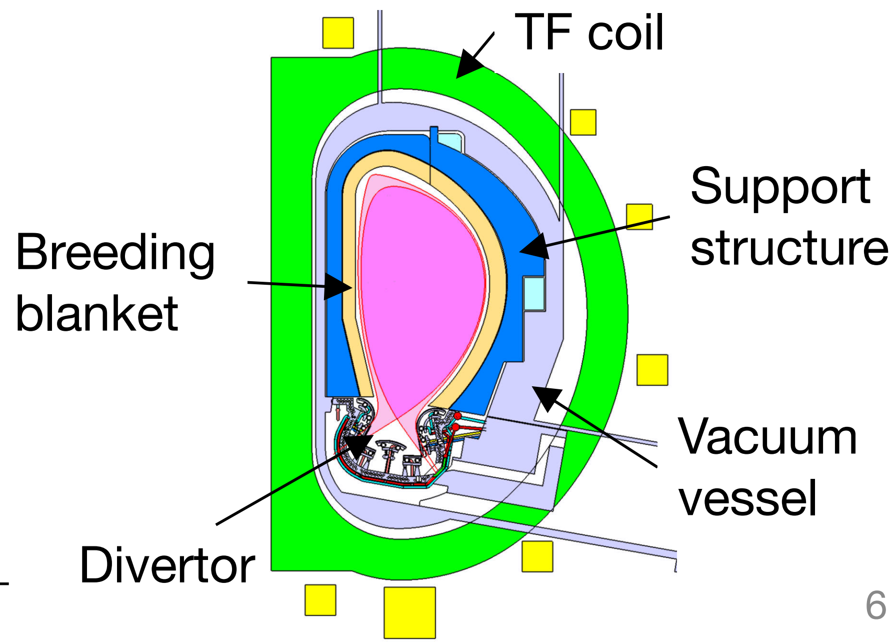
$$\int_V \frac{{B_T}^2}{2\mu_0} dV = W_{mag}$$



DEMO with a plant-level P_{fus}, requires a huge W_{mag}.

- Space for in-vessel components

larger plasma, breeding blanket, shielding, etc.
➡ large TF coil bore in DEMO



Need to simplification of large TF coil fabrication

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- Introduction -Basic concept of JA DEMO-
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  - ✓ R&D of high strength cryogenic steel
  - ✓ Simplification of TF coil fabrication:
    -Design study of Rectangular conductor with double layer winding concept
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R&D of high strength cryogenic steel

DEMO DESIGN
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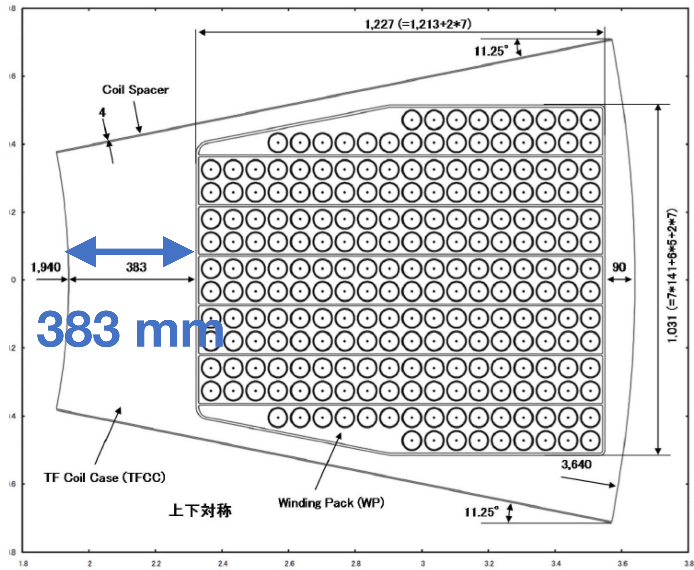
- The TF coil adopts the **0.2% yield stress of >1200 MPa**, which is larger than that of ITER TF coil material, JJ1 (0.2% yield stress of 1000 MPa).

$$S_m = \frac{2}{3} S_{Y0.2}$$

- The inner thickness of the TF coil of the current JA DEMO is 383 mm, and it is necessary to make it as thin as possible from the viewpoint of structure fabrication.

DEMO-TF



❖R&D target of high strength cryogenic steel

- ✓ **4K 0.2% yield stress (YS): 1,600 MPa**
- ✓ **4K fracture toughness (K_{IC}(J)): 120 MPa√m**

- To build a database in consideration of standardization **JSME**,
We decided to proceed with the development by two approaches:
  (1) Evaluation of existing steels that can be expected to have high strength
  (2) Trial production and evaluation of new materials with low C and high N small-scale melting (melting of about 50 kg).

Current status of Cryo. Steel R&D

- Evaluation of existing steels

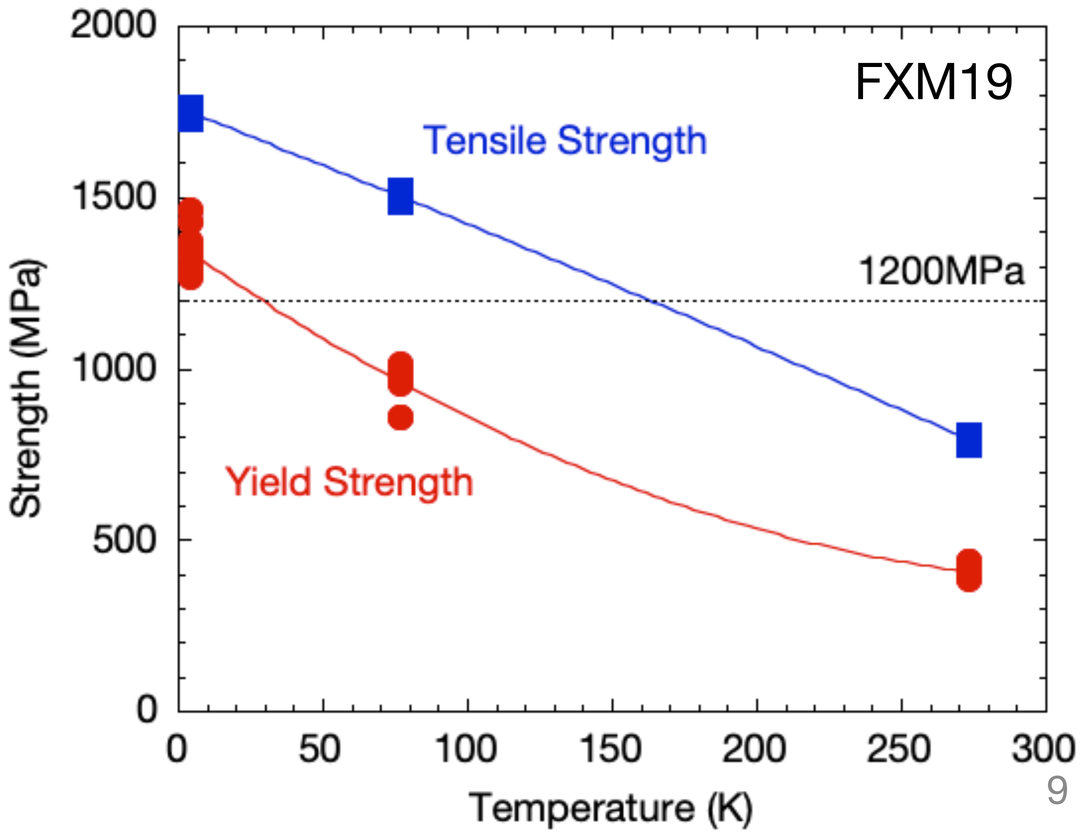
❖Material characterization of FXM19 (ASTM A965), forged steel

C	Si	Mn	P	S	Ni	Cr	Mo	N	Nb+Ta	V
0.06 Max.	0.75 Max.	4.0-6.0	0.040 Max.	0.030 Max.	11.5-13.5	20.5-23.5	1.50-3.00	0.20-0.40	0.10-0.3-	0.10-0.30

➢ Results:

The average value of 0.2% proof stress at 4K is 1,340 MPa (standard deviation 54 MPa).

➡0.2% proof stress of 1,200 MPa can be achieved with existing steel.



Current status of Cryo. Steel R&D

- Trial production and evaluation of new materials

Investigation of the Effect of Composition on Strength on the Basis of High Cr Austenitic Steel (XM19) (Prototype & Mechanical Property Tests)

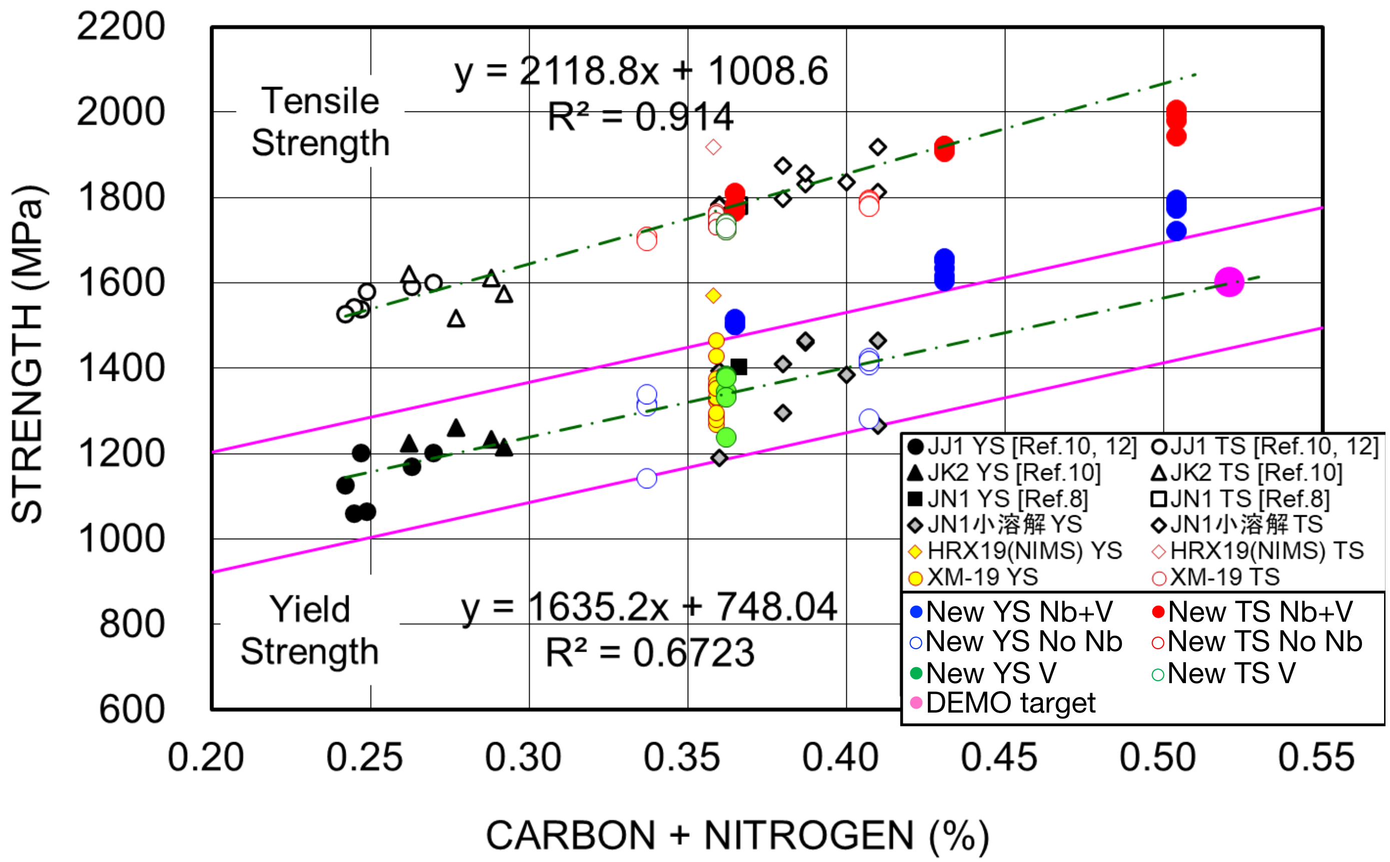
➢ Results:

YS increases with increasing N content

➡ Above the target of 1,600 MPa

YS is lower in the material without Nb because the effect of grain refinement by Nb disappears.

Little effect of V on YS increase

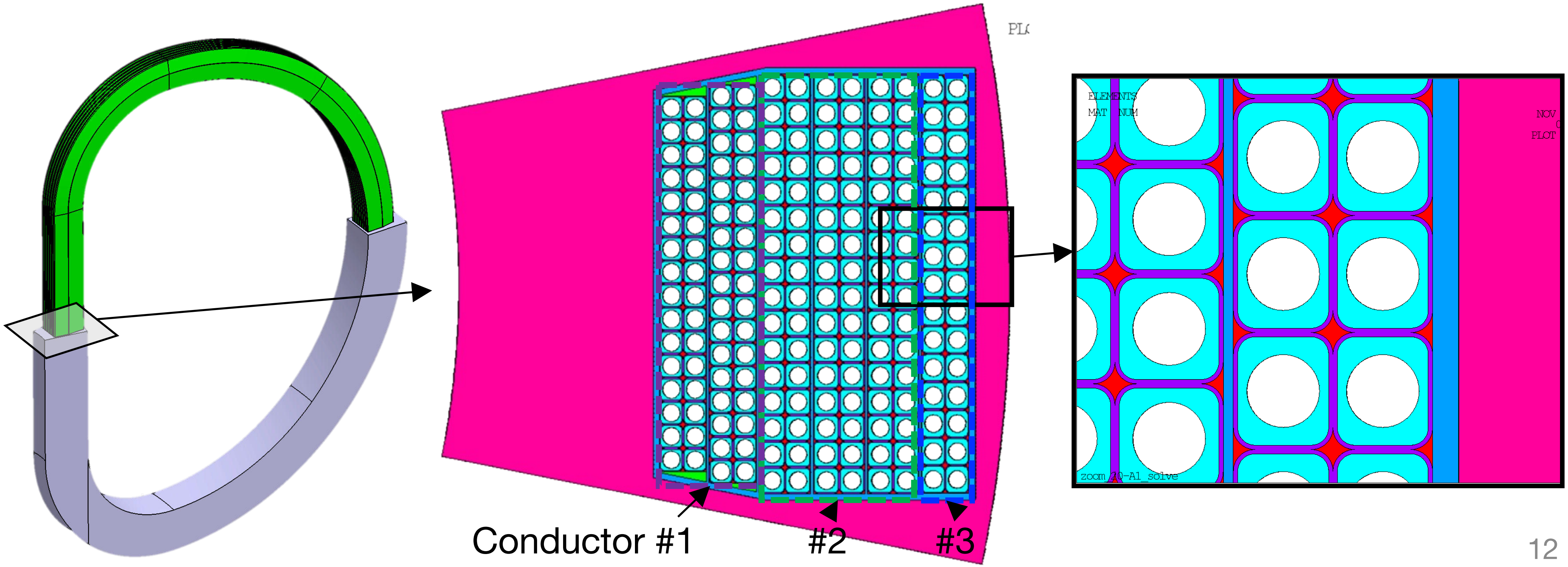


Contents

Rectangular conductor with double layer winding concept

Taking advantage of the grading in the layered winding concept, the conductor arrangement and the conductor cross-sectional shape for each layer were investigated and optimized to reduce the stress on the insulation.

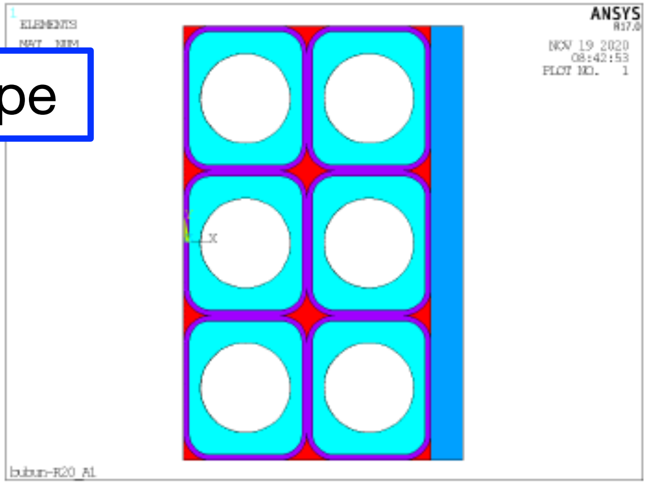
- Double layer (2 x 6 layer)   Total: 83 kA x 192 turn
  (Insulation layer is set between double layers)
- Conductor: Three types of conduit cross-sections are used
- Securing the case thickness on the center side



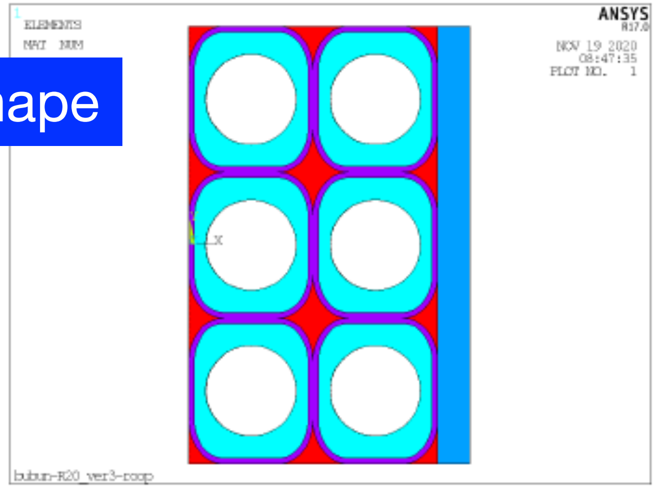
“Hybrid R-shape” conductor

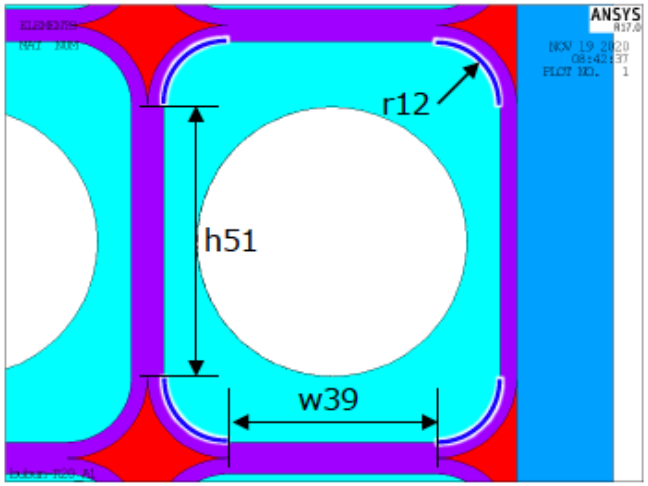
- Optimization of the conductor cross-sectional shape for reduction of the stress on the insulation
  Consider the shape of the conductor,
  especially on the plasma side where the stress in the insulation is higher.

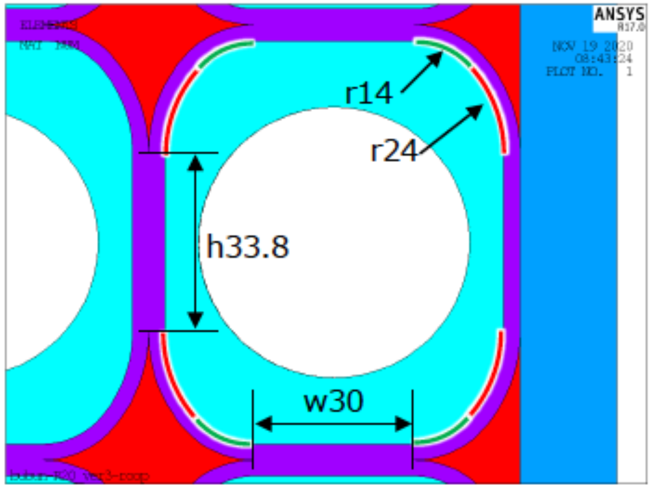
Single R-shape



Hybrid R-shape





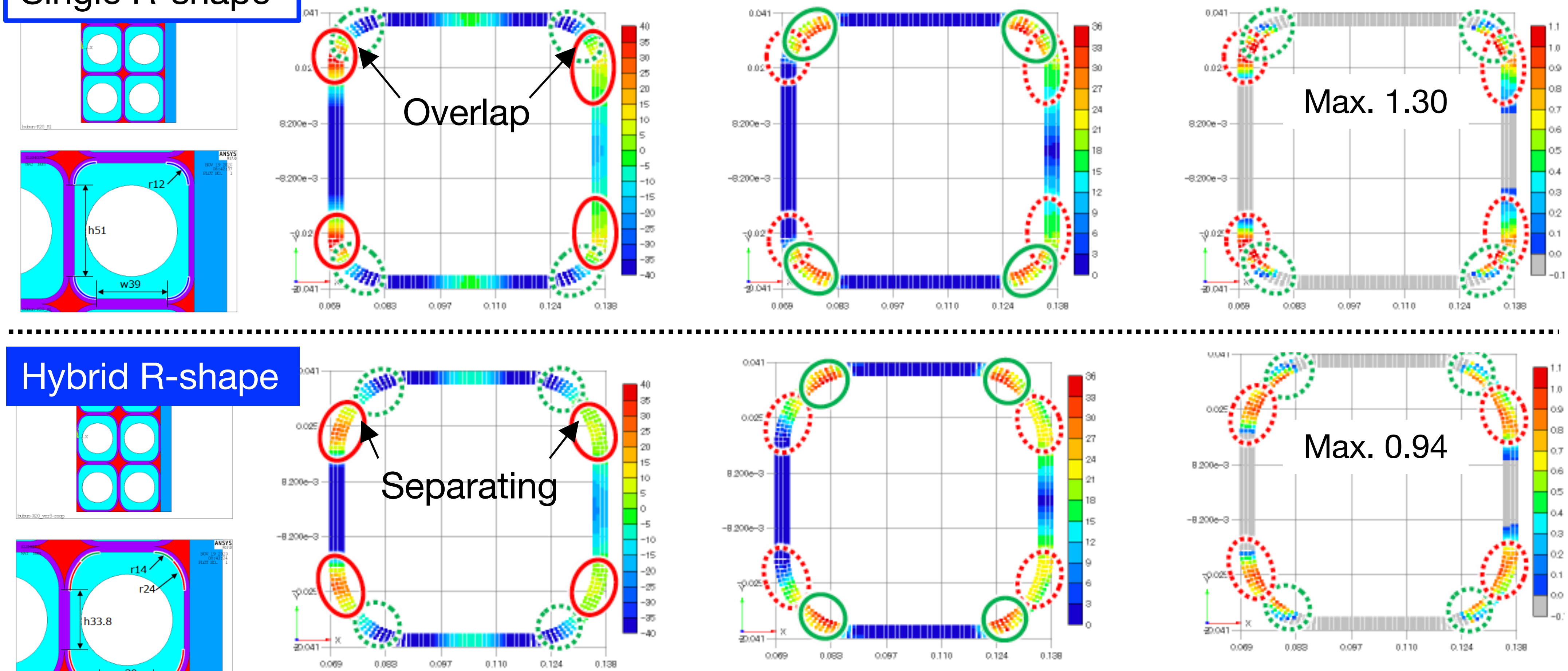


“Hybrid R-shape” conductor

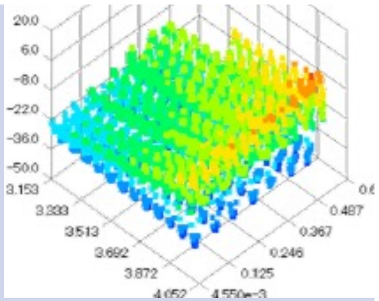
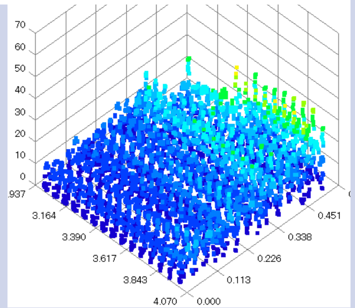
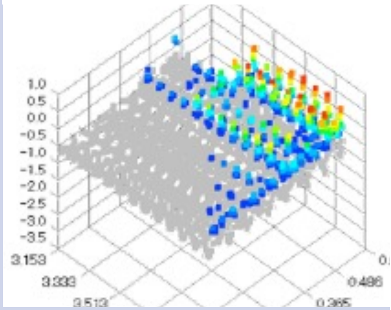
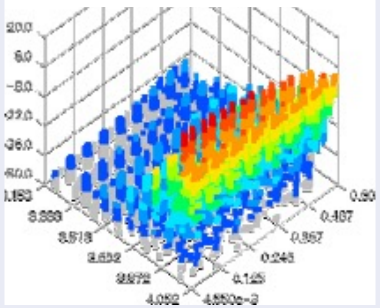
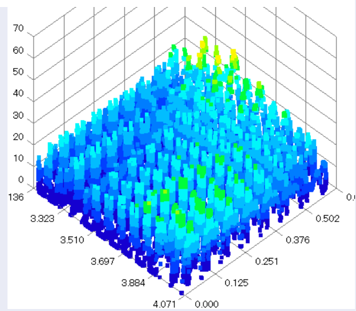
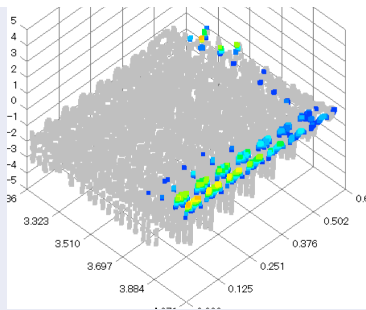
- Optimization of the conductor cross-sectional shape for reduction of the stress on the insulation

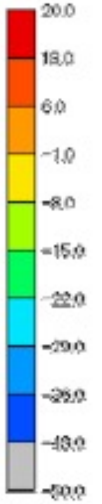
Hybrid R-shape achieves isolation for regions with high through-thickness tensile stress and high shear stress, respectively. ➡ Reduction of LHD criteria[1] (1.30 -> 0.94)

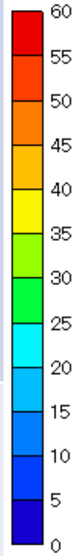
[1] K. Kitamura et al.: IEEE Transactions on Magnetics, **30**, 4, 1994

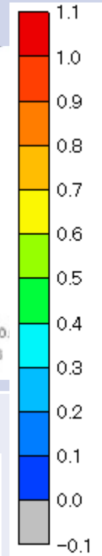


Comparison with RP method

	Through-thickness tensile stress	Shear stress	LHD criteria
RP w/ DP	Max. 7.6 MPa 	Max. 38 MPa 	Max. 1.65 
RC w/ DL	Max. 18.1 MPa 	Max. 39 MPa 	Max. 0.74 







RC w/ DL concept: Lower shear stress on the turn insulation was achieved than the RP method.

It is necessary to consider how to deal with localized through-thickness tensile stress.

Conductor design study for cost reduction

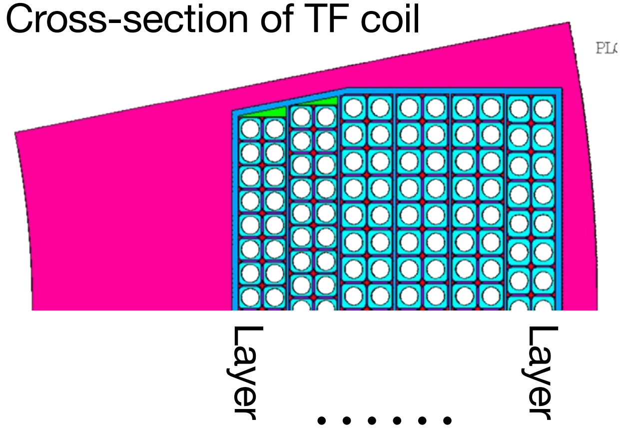
For conductor cost reduction, the temperature margin was calculated from the maximum magnetic field of each layer.

$$\underline{T_{margin}} = \underline{T_{cs}} - \underline{T_{op}}$$

> 1.5 K

Depend on B, ε, J

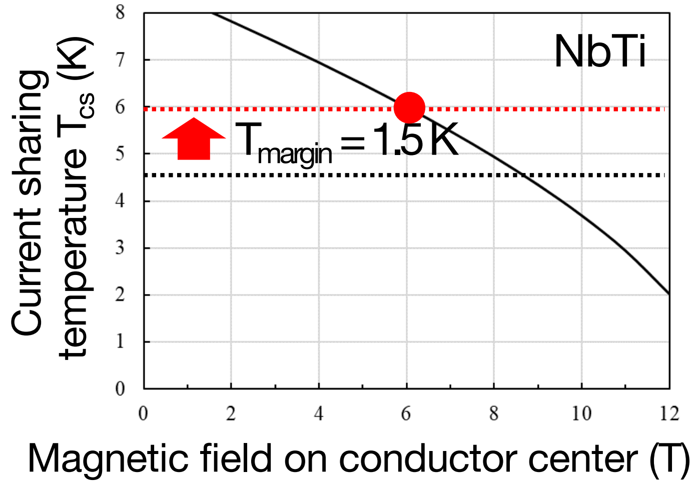
Depend on AC loss

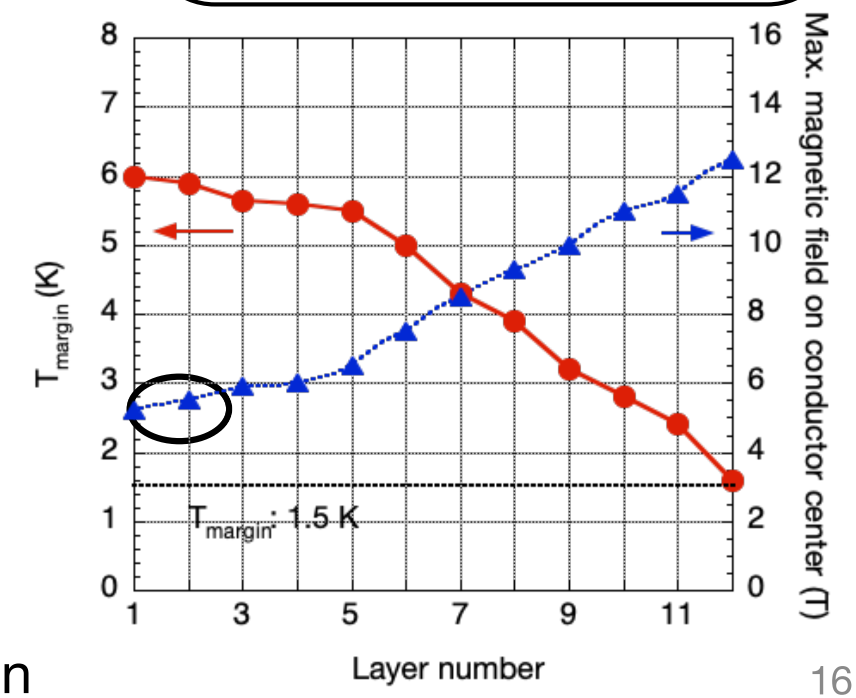


Option 1

Reducing the amount of Nb_3Sn by adopting NbTi in the low-field region

Possibility to adopt NbTi in the region of B < 6T (Layer 1 and 2)





Option 2

Reducing the amount of Nb_3Sn in the region with excessive temperature margin

Conductor design study for cost reduction

Option 1

Reducing the amount of Nb_3Sn by adopting NbTi in the low-field region

Total amount of Nb_3Sn:

127 m^3 -> 105 m^3

No grading case

-17%

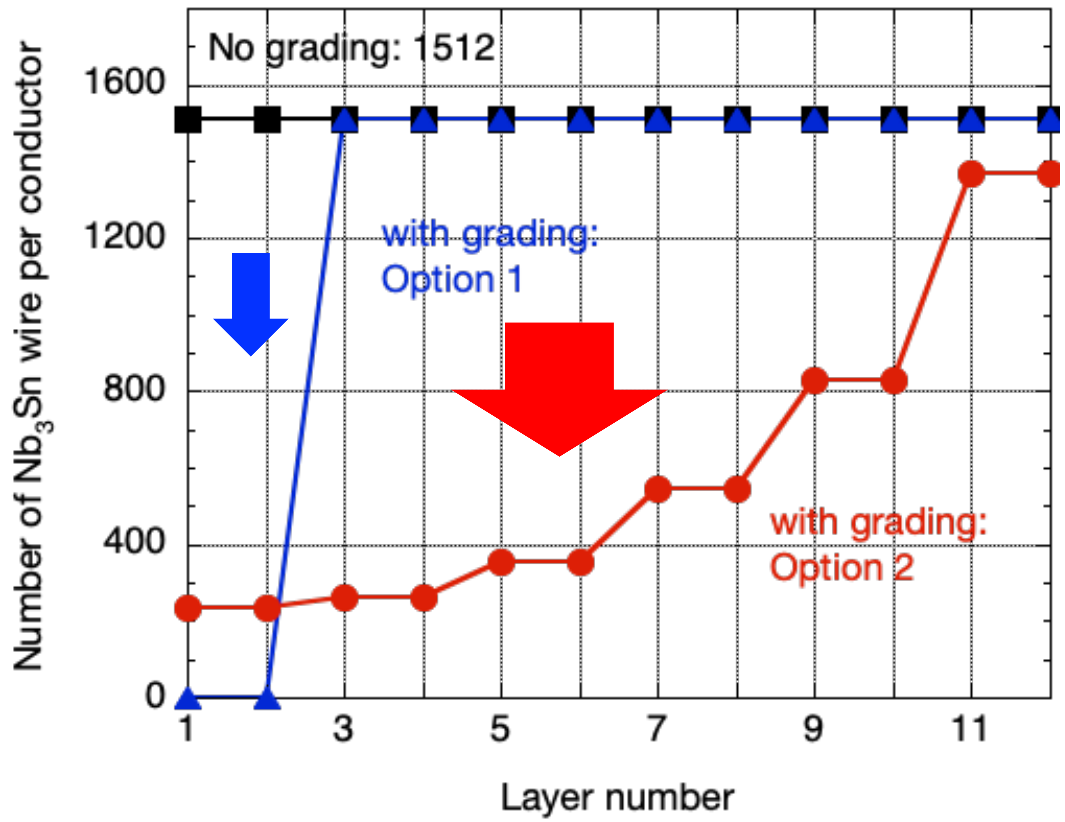
Option 2

Reducing the amount of Nb_3Sn in the region with excessive temperature margin

Total amount of Nb_3Sn:

127 m^3 -> **48 m^3**

-62%



The amount of Nb_3Sn wire can be reduced by up to 62% from the conventional RP method or the DP winding concept with rectangular conductors by grading.

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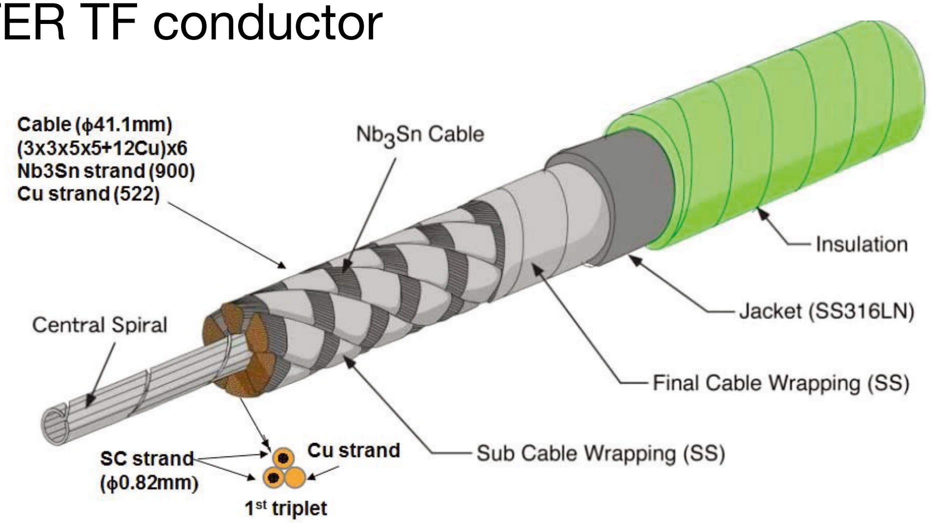
TF conductor design for JA DEMO

Design target:

✓Bt=6T at Rp=8.5m
(requirement from system design)
➡ 16MAT/coil
✓T_{cs} > 6 K (Temp. margin: 1.5 K)
✓Decay time: ~30 sec

ITER TF conductor



- Large TFC leads to increase coil inductance (long current decay time).
  ➔increase conductor current (83kA)

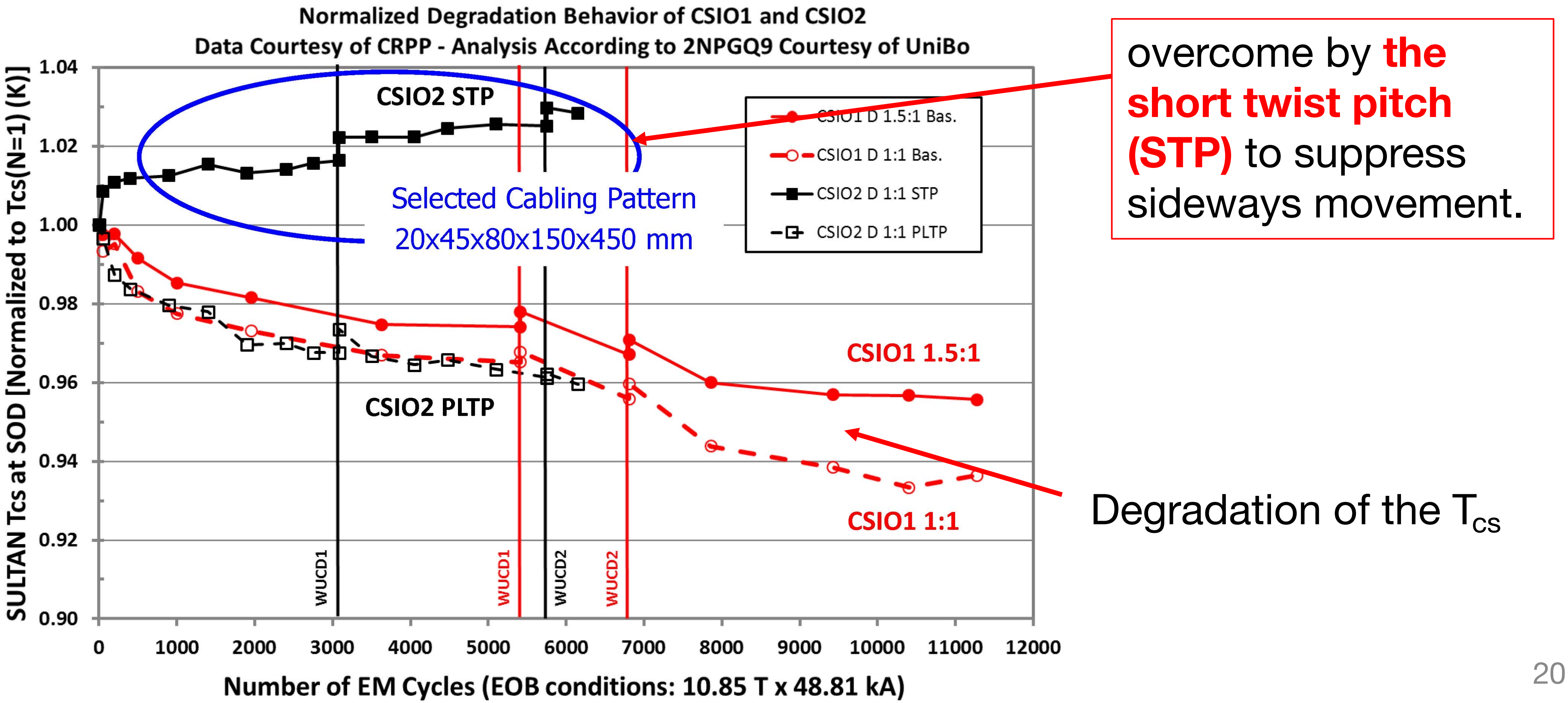
- The EM force of the DEMO magnets is quite higher than the ITER magnets. (**x 1.5**)

	ITER	JA DEMO
SC strand	Nb_3Sn	Nb_3Sn
Number of TFC	18	16
B_{tmax}	11.8 T	13.9 T
Conductor current	68 kA	83 kA
EM force (B x I)	802 kN/m	1154 kN/m
N. SC strand	900	1512
N. Cu strand	522	906
Cable diameter	39.7	50.4

x 1.5

Degradation of T_{cs} of ITER CICC

- Degradation of the current sharing temperature T_{cs} occurred in heat cycle and cyclic loading of ITER TF conductors.
- This degradation was caused by the crack should be induced by **excess strain due to EM force** and thermal strain.



TF conductor design for JA DEMO

- From the CS insert coil test (13 T, 40 kA) results of the ITER conductor, the effective strain under the DEMO reactor conditions is extrapolated, and the requirements for the DEMO reactor strands were evaluated.
- Extrapolating from the ITER-CS insert coil test (13 T, 40 kA), if a **short twist pitch conductor** equivalent to the ITER-CS conductor can be adopted in the 80kA class, it is expected that the current ITER SC strand (Nb_3Sn) can be used.

			Original twist pitch	Short twist pitch
ε_{eff}		%	-0.87	-0.59
TF strand	J_{cn}	A/mm²	2233	767
	J_{c_ave}	A/mm²	854	854
	$J_{c\_2\sigma}$	A/mm²	827	827
	f	**-**	**2.70**	**0.93**
CS strand	J_{cn}	A/mm²	3628	828
	J_{c_ave}	A/mm²	1107	1107
	$J_{c\_2\sigma}$	A/mm²	992	992
	f	**-**	**3.66**	**0.83**

Verification by conductor trial (adoption of STP structure for 80kA class conductor) and test (short conductor test and CS insert coil test) is essential from 2021, conceptual design phase.

J_{cn}: the required performance of the JA DEMO @12T, 4.2K, -0.25%

J_{c_ave}: Average Jc of mass-produced wire (ITER Nb_3Sn) @12T, 4.2K, -0.25%

$J_{c\_2\sigma}$: Ability value of mass production wire (J_c-2σ)

f: ratio of J_{cn} and $J_{c\_2\sigma}$

Summary

- The Japan pre-conceptual DEMO design was investigated by the Joint Special Design Team for fusion DEMO to establish the Japan's DEMO concept, named "JA DEMO".
- Under the design basic concept to minimize the technical jump-up from ITER, the basic specifications of the superconducting coil have been established.
- Important issues for improving feasibility are being considered.
  - ✓ To produce higher magnetic field, the development of improved cryogenic steel has been started in the JA DEMO design activities.
  - ✓ For simplification of large TF coil fabrication, we focused on the layered winding concept, in which the conductor can be optimized for each layer by grading, and succeeded in the significant improvement of the conventional rectangular conductor winding concept.
  - ✓ Extrapolating from the ITER-CS insert coil test, if a short twist pitch conductor equivalent to the ITER-CS conductor can be adopted in the 80kA class, it is expected that the current ITER SC strand can be used.

Collaboration with Institutes, Universities, Industries

QST	NIFS	NIMS	
U Fukui	Fukui U Tech.	NIT, Gifu College	The graduate school for the Creation of New Photonics Industries
U Hyogo	Ibaraki U	Keio U	KINDAI UNIVERSITY
Kyoto U	Kyushu U	Nagoya U	Osaka U
Shinshu U	Shizuoka U	Tohoku U	U Tokyo
Tokyo Inst. Tech.	U Toyama	U Tsukuba	Sophia U

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