27th International Conference on Magnet Technology (MT27)
November 15th - 19th, 2021

WED-OR3-201-03

# Design study of superconducting TF coil concept with rectangular conductor layer winding with high manufacturability and insulation reliability for JA DEMO

Hiroyasu Utoh[1], Hideaki Miura[2], Hitoshi Arakawa[2], Daisuke Echizenya[2], Mitsuru Hasegawa[2], Kazuhiro Nomoto[2], Ryoji Hiwatari[1], Yoshiteru Sakamoto[1], Joint Special Design Team for Fusion Demo

[1]QST Rokkasho, [2]Mitsubishi Electric Corporation

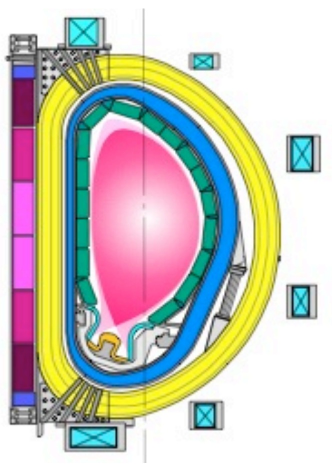
# Contents

- Introduction –Design issues of TF coil on JA DEMO-
- Design study of Rectangular conductors with double layer winding concept
  - ✓ Optimization of the conductor cross-sectional shape for reduction of the stress on the insulation
  - ✓ Conductor design study for cost reduction
- Summary

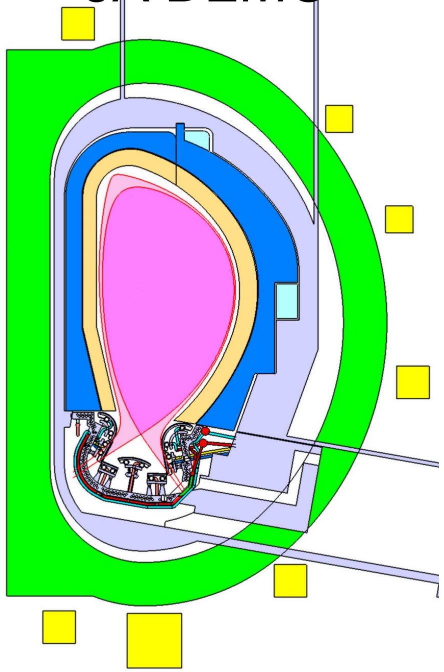
# Design issues of TF coil on JA DEMO

The design philosophy of Japan's DEMO (JA DEMO) is to be feasible on the premise of the success of ITER.
JA DEMO requires larger TF coils with higher B compared with ITER.

ITER



JA DEMO



| | ITER | JA DEMO |
|---|---|---|
| Major radius Rp | 6.2 m | 8.5 m |
| 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 |
| **Width / Height of TFC** | **8 / 12.6 m** | **12 / 19 m** |

**Main issue:** To reduce the difficulty of fabrication and the increase in fabrication cost due to the large size of TF coils.

The possibility of stress reduction of insulation and cost reduction was investigated for the RC w/ DL concept.

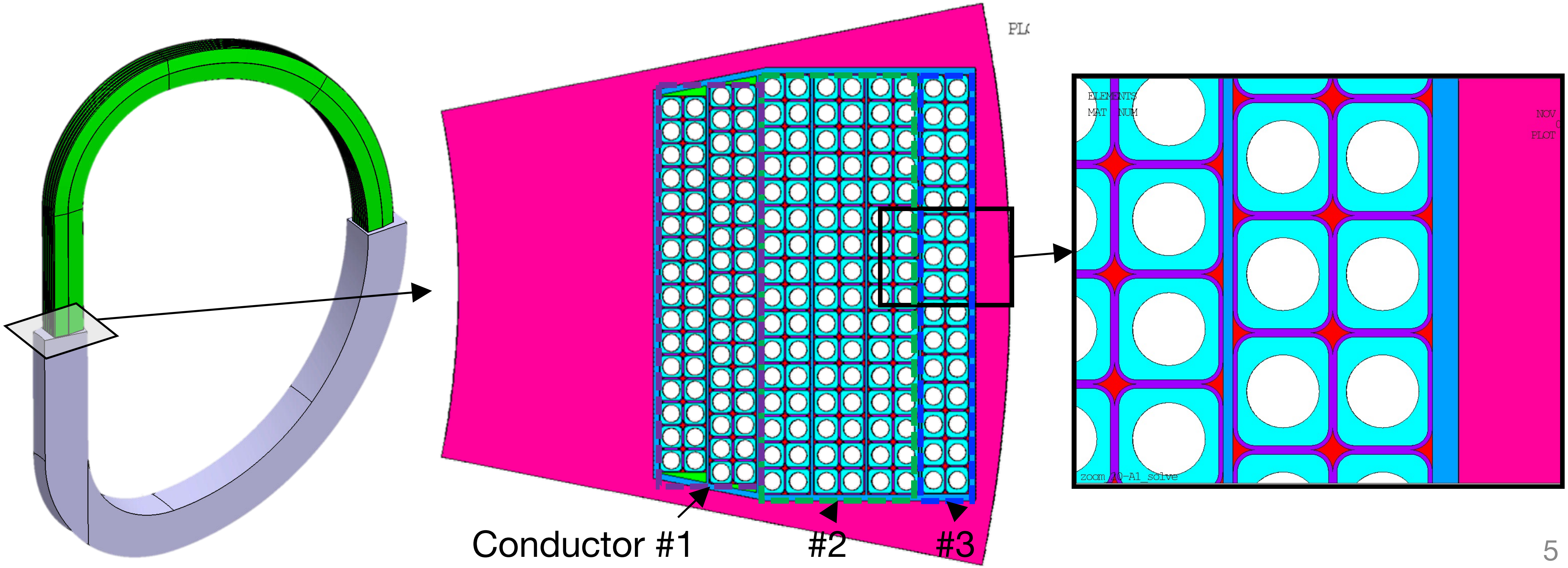
# Contents

- Introduction
- Basic concept of TF coil on JA DEMO
- Design study of Rectangular conductor with double layer winding concept
  - ✓ Optimization of the conductor cross-sectional shape for reduction of the stress on the insulation
  - ✓ Conductor design study for cost reduction
- Summary

# 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.

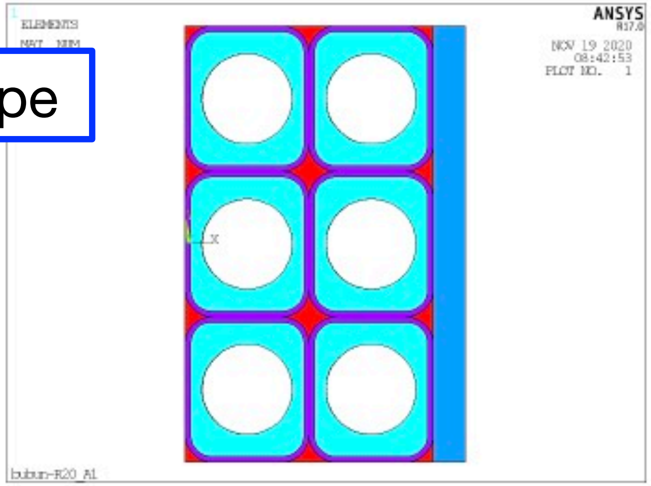
- Double layer (2 x 6 layer)     Total: 83 kA x 192 turn
  (Insulation layer is set between double layers)
- Conductor: Three types of conduit cross-sections are used
- Securing the case thickness on the center side



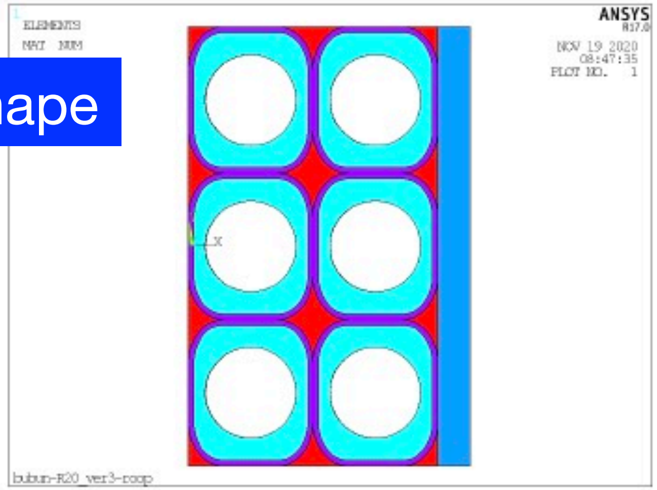
# “Hybrid R-shape” conductor

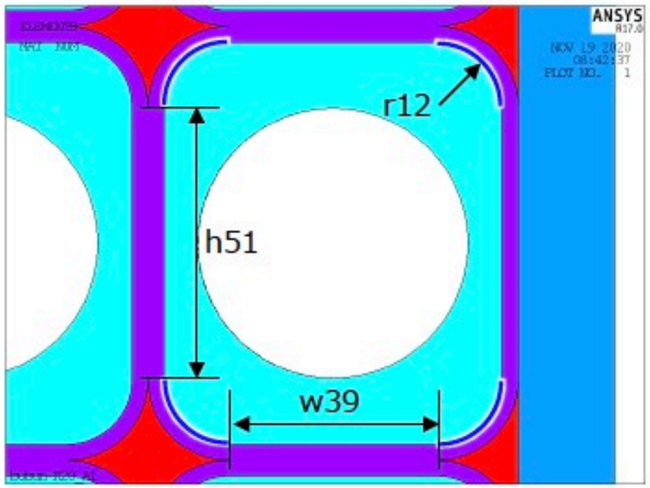
- Optimization of the conductor cross-sectional shape for reduction of the stress on the insulation
  Consider the shape of the conductor,
  especially on the plasma side where the stress in the insulation is higher.

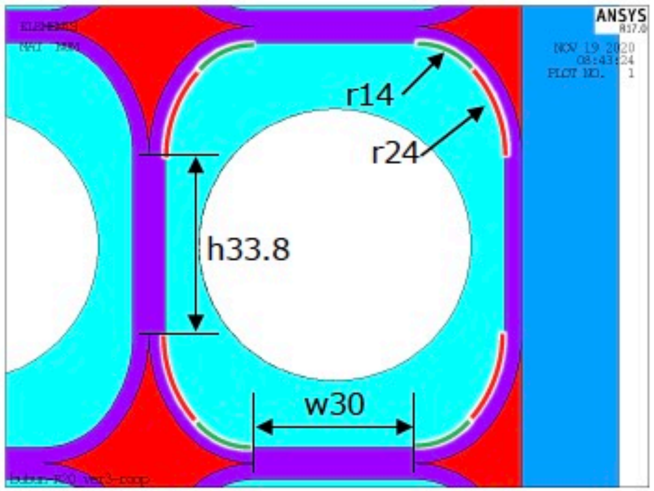
Single R-shape




Hybrid R-shape



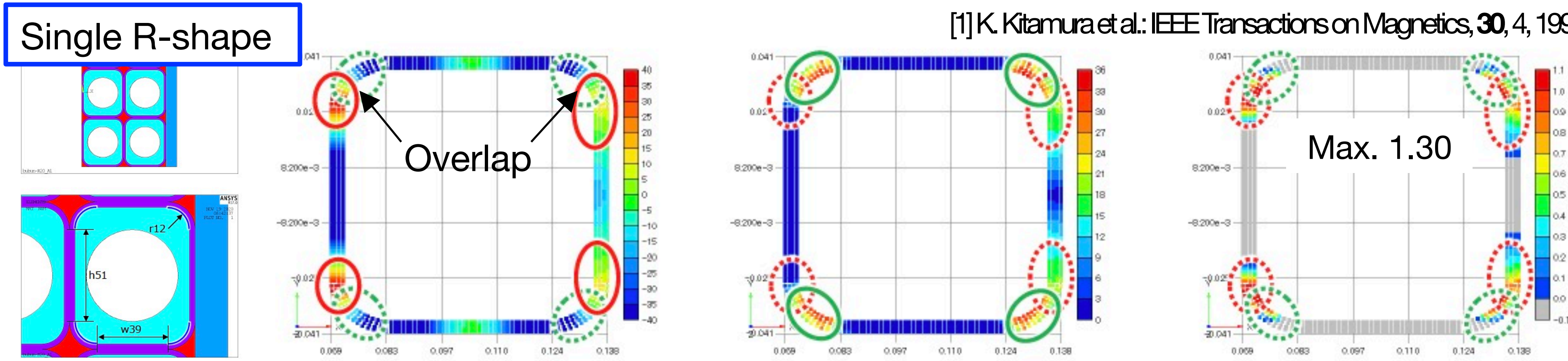



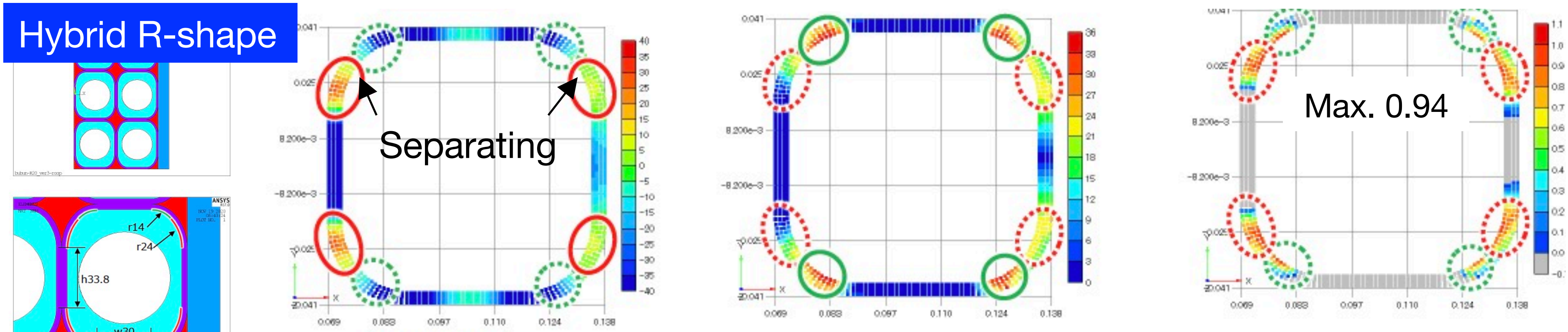
# "Hybrid R-shape" conductor

- 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)

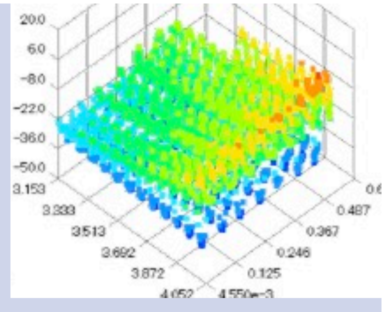
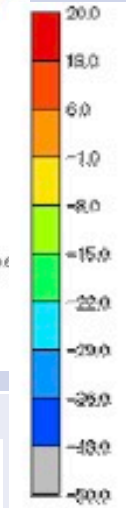
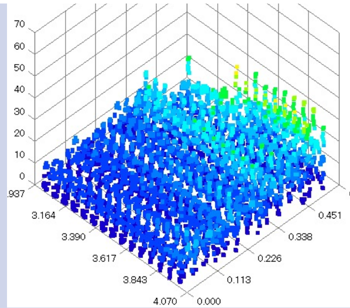
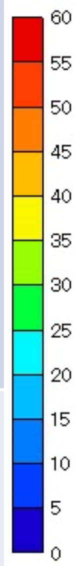
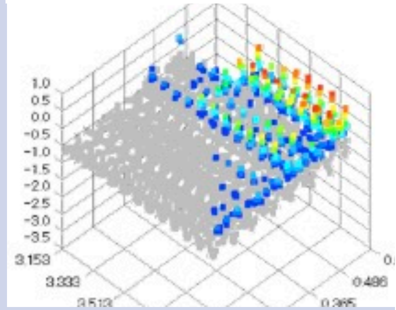
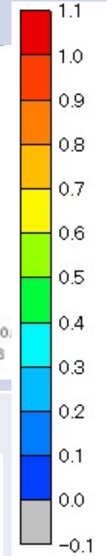
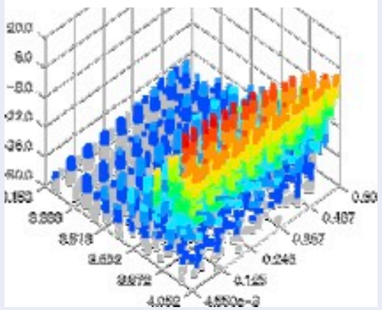
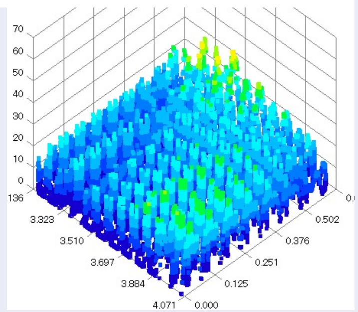
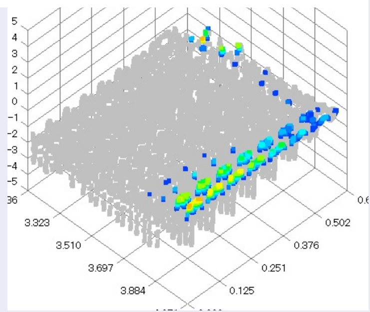
[1] K. Kitamura et al.: IEEE Transactions on Magnetics, **30**, 4, 1994




Through-thickness tensile stress　　Shear stress　　LHD criteria

# 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.

# Contents

- Introduction
- Basic concept of TF coil on JA DEMO
- Design study of Rectangular conductor with double layer winding concept
  - ✓ Optimization of the conductor cross-sectional shape for reduction of the stress on the insulation
  - ✓ Conductor design study for cost reduction
- Summary

# Conductor design study for cost reduction

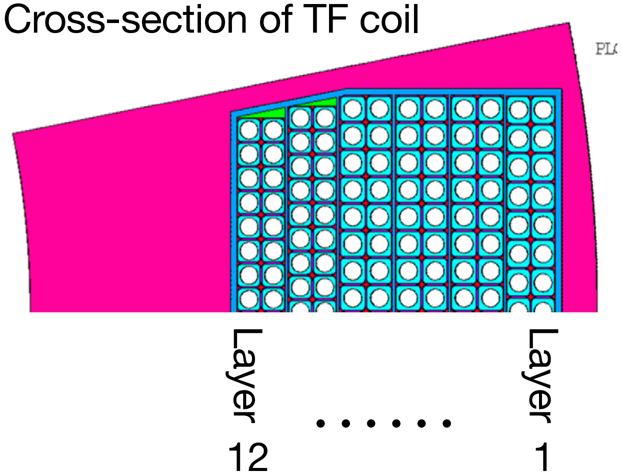
For conductor cost reduction, the temperature margin was calculated from the maximum magnetic field of each layer.

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

> 1.5 K

Depend on B, ε, J

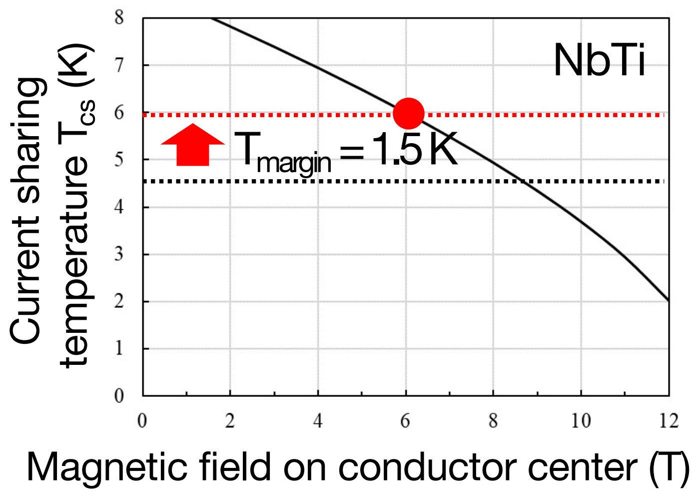
Depend on AC loss

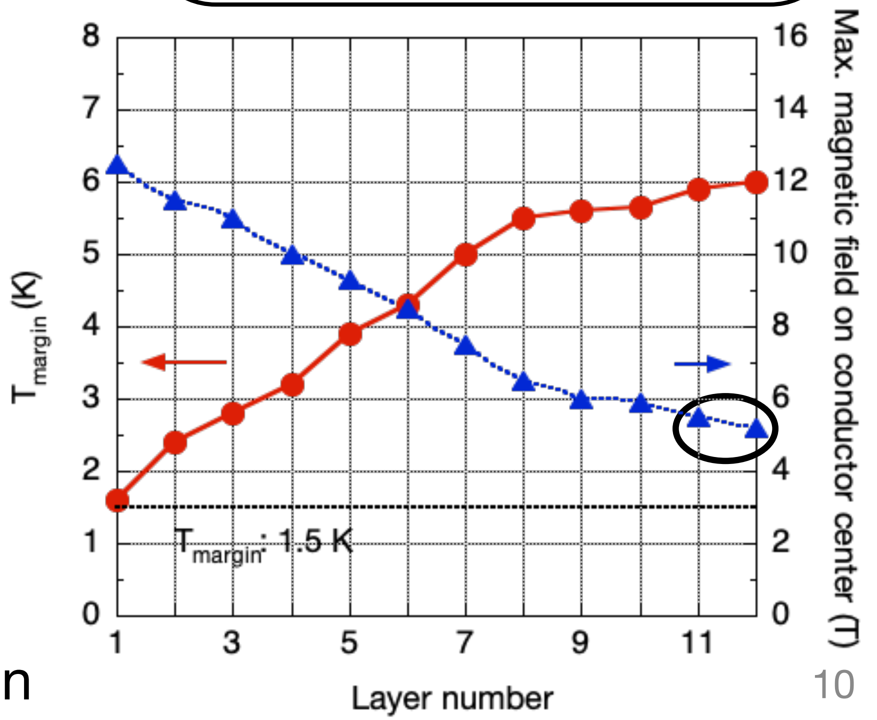



Option 1

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 11 and 12)




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%

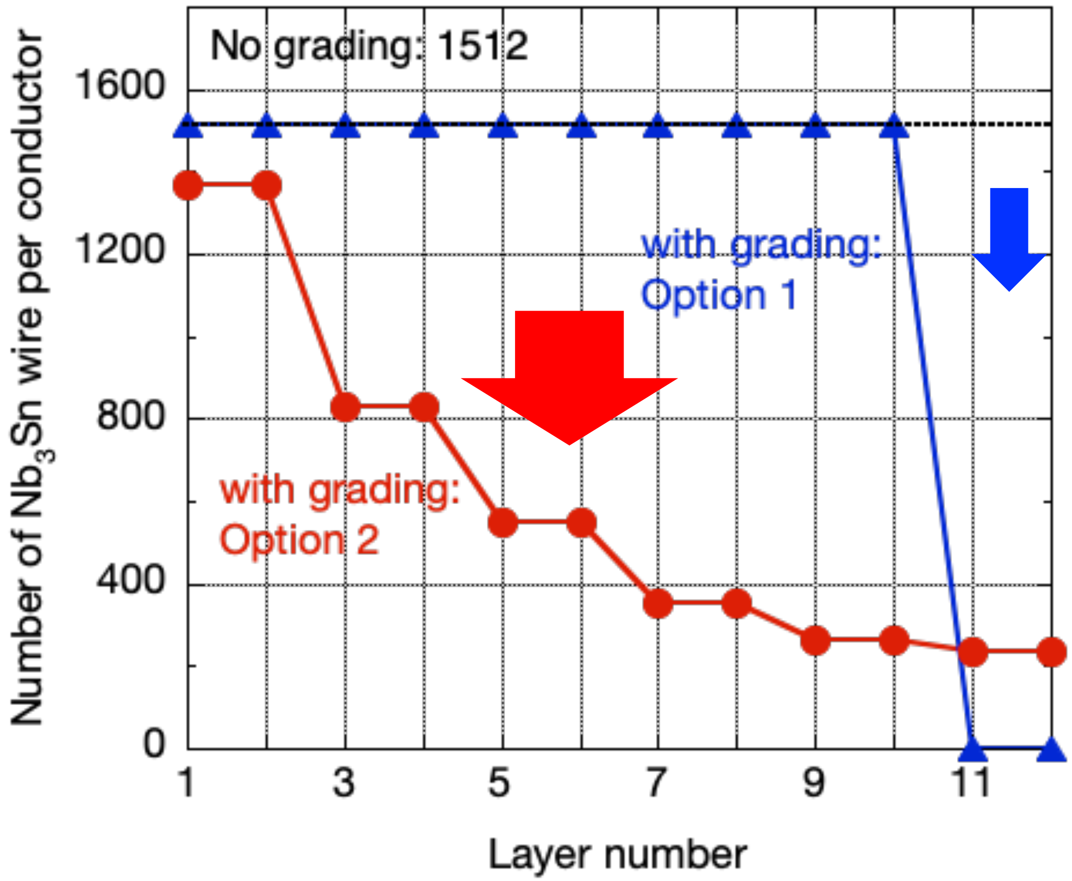
Option 2

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.

# Summary

- In this study, 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.
- 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.
  - ✓ By "Hybrid R-shape" conductor, lower shear stress on the insulation was achieved than the RP method.
  - ✓ The current sharing temperature $T_{cs}$ was calculated from the maximum magnetic field of each layer, and the amount of $Nb_3Sn$ strand was optimized to achieve a temperature margin of 1.5 K in each layer.
  - ✓ It was found that the double layer winding concept in which the amount of $Nb_3Sn$ wire can be reduced by up to 62% from the conventional RP method or the double pancake winding concept with rectangular conductors while maintaining the temperature margin by grading.