ID: 827 (TECH/P5-1)

Design study of large superconducting coil system for JA DEMO

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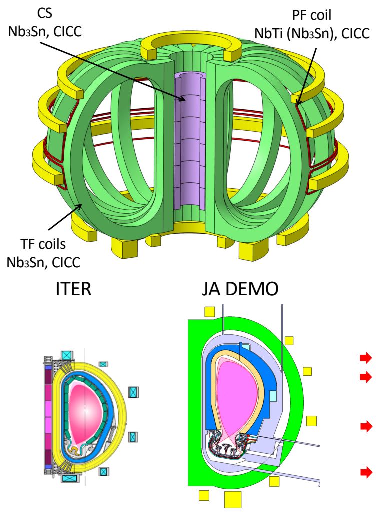
ABSTRACT

- Generally, DEMO requires larger toroidal field (TF) coils than ITER, resulting in some major difficulties, the tolerance in TF coil fabrication and installation, high strength cryogenic steel and the conductor on high electromagnetic force and high current.
- This paper presents the possible solutions these on the basis of the design study on Japan's DEMO (JA DEMO).

BACKGROUND / INTRODUCTION

- To demonstrate steady-state electric power generation in a power plant scale (JA DEMO) [1], a higher magnetic field strength and a 1.5 times larger TF coil bore than those in ITER are necessary [2].
- The adoption of such large TF coils results in the major difficulties,
  (1) large TF coil fabrication
  (2) development of high strength cryogenic steel
  (3) Conductor on high electromagnetic force and high current

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



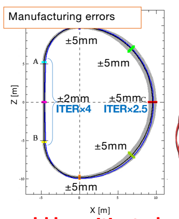
R_p / a_p	8.5 m / 2.4 m
Aspect ratio	3.5
Elongation	1.65
Fusion output	1.4 GW
Net electric power	~250 MW
Plasma current	12.3 MA
Toroidal field on axis	6.0 T
Max. toroidal field	~14 T

	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
Inductance per coil	0.98 H	2.77 H
➡ 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

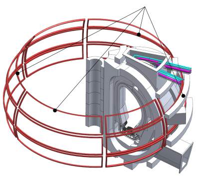
Simplification of TF coil fabrication

Mitigation of tolerance in TF coil fabrication and installation

- The manufacturing accuracy is directly linked to the processing accuracy of RP, and it is technically difficult to manufacture a larger coil with the same accuracy as ITER.
- Tolerances of ITER x (2.5~5) assumed.
- Evaluation of the effect of winding and assembly accuracy on the magnetic field.
- Designed an error field correction coil that matches the furnace structure



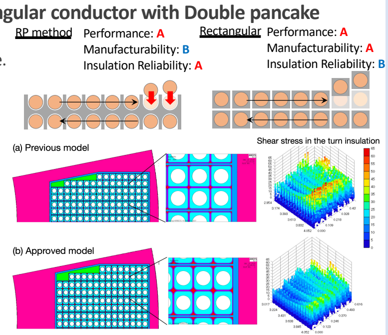
Error field correction coil
NbTi, CICC / 10kA



➡Tolerances of TF coil fabrication would be mitigated by adding Error field correction coils .

Alternative fabrication method: Rectangular conductor with Double pancake

- The RP method has many manufacturing processes such as welding of the cover plate.
- The conductor shape and configuration of the rectangular conductor method were examined by electromagnetic structure analysis focusing on the stress characteristics of the conductor insulating part, which can be a structural issue on the rectangular conductor method.
- By using a rectangular jacket extending in the toroidal direction, the maximum value of the shear stress in the turn insulation was reduced from 63.3 MPa to 47.2 MPa.



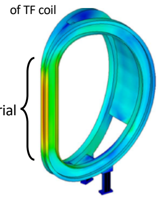
R&D of high strength cryogenic steel

- 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).

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

Tresca stress distribution of TF coil

New material



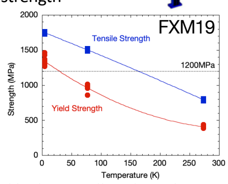
- We decided to proceed with the development by two approaches:
  (1) Evaluation of existing steels that can be expected to have high strength

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

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.



(2) Trial production and evaluation of new materials with low C and high N small-scale melting.

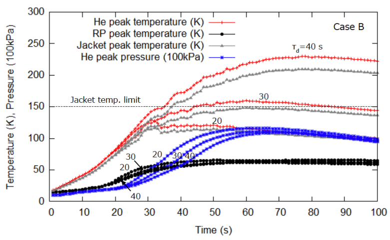
#	C	Si	Mn	P	S	Ni	Cr	Mo	N	Nb+Ta	V
1	0.02	0.50	6.00	0.02	0.002	13.00	23.50	2.50	0.35	0.20	0.20
2	0.02	0.50	6.00	0.02	0.002	13.00	23.50	2.50	0.40	0.20	0.20
3	0.02	0.50	7.00	0.02	0.002	13.00	25.00	2.50	0.45	0.20	0.20

Making high Cr (XM-19 base) and high Mn austenitic steels

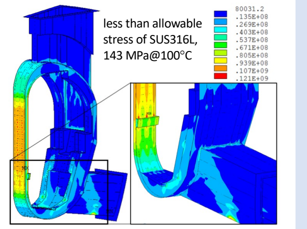
DEMO TF conductor design

Identification of discharge time constants

- The large TF coil size of the JA DEMO gives a 3 times greater self-inductance if the conductor current and the magnetic field strength are the same magnitudes as those of ITER and then generates a 3 times terminal voltage that is quite capable of losing reliability of TF coils.
- Focusing on issues related to increase in the coil self-inductance due to increase in the TF coil size, identification of discharge time constants that match other reactor systems were investigated.



Time evolution of peak temperature of helium coolant, radial plate and conductor jacket, and helium peak pressure on TF coil fast discharge event.



Tresca stress distribution of vacuum vessel on TF coil fast discharge event at discharge time constant of 30 seconds.

➡Identification of a reasonable TF coil discharge time constant consistent (30 second) with the design of the vacuum vessel.

Short twist pitch (STP) conductor design

- The EM force of the DEMO TF coil is quite higher than the ITER TF coil. (x 1.5)
- Investigation of the feasibility of STP conductor as a conductor structure to withstand the high EM force and high current (~80kA) requirements in DEMO reactors

			Original twist pitch	Short twist pitch
ε_{eff}		%	-0.87	-0.59
ITER-TF strand	J_{cn}	A/mm^2	2233	767
	J_{c_ave}	A/mm^2	854	854
	f	-	**2.61**	0.90

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%
f: ratio of J_{cn} and J_{c_ave}

➡Short twist pitch conductor can be used for DEMO conductor (83kA, ~14T) with current ITER strand (Nb_3Sn). ➡ **Verification by conductor trial (adoption of STP structure for 80kA class conductor) and test is essential.**

CONCLUSION

- In the case of adopting a mitigated tolerance by a factor of 2.5-5 compared with that of ITER, the resulting error field of TF coils is correctable to an acceptable level in terms of locked mode avoidance.
- It was expected that at least 0.2% yield stress of 1,200 MPa of strength could be achieved with the existing steel. Further development of high-strength materials will be promoted by trial manufacture based on these findings.
- Short twist pitch conductor can be used for DEMO conductor (83kA, ~14T) with current ITER strand (Nb_3Sn). The R&D regarding verification by conductor trial (adoption of STP structure for 80kA class conductor) and test (short conductor test and CS insert coil test) will be promoted.

REFERENCES

[1] Y. Sakamoto et al., 27th IAEA Int. Conf. on Fusion Energy (2018) FIP/3-2
[2] K. Tobita et al., 2019 Fusion Sci. Technol. 75 372-383