1MOrC1-06

Evaluation of Inter-laminar Shear Strength of GFRP Composed of Bonded Glass/Polyimide Tapes and Cyanate-Ester/Epoxy Blended Resin for ITER TF Coils

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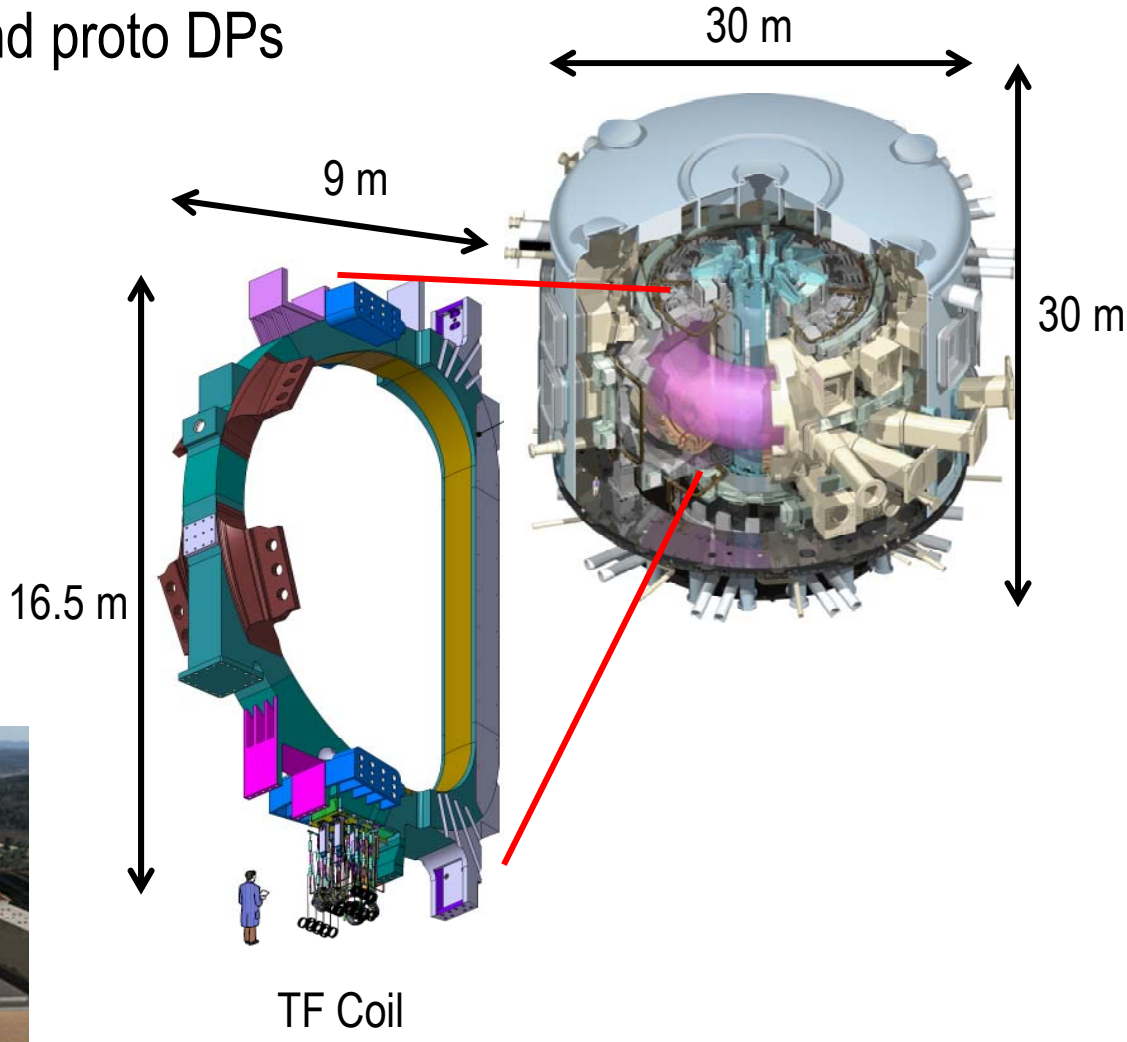
Outline

1) Background
2) Sample preparation and Test procedure
3) Test results after/before irradiation
4) 1/3-scale DP fabrication
5) Conclusion

ITER Toroidal Field (TF) coil

- 2013-2014 Fabrication of tooling and proto DPs
- 2015 Delivery of first JA TF coil
- 2017 Completion of JA TF coils

Cadarache, France

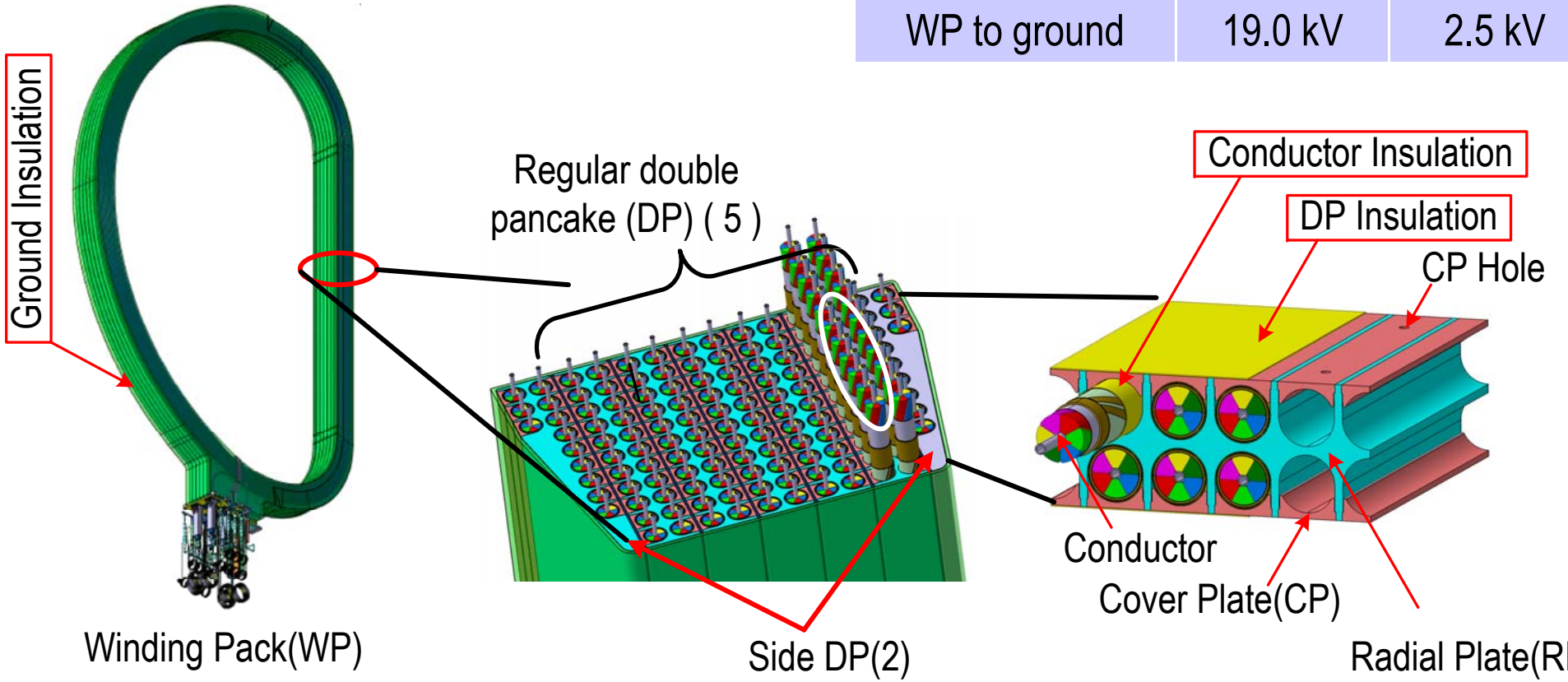


TF Coil

Insulation system of ITER TF coil

- Magnet materials required to withstand a total radiation dose of 10 MGy and a neutron flux of 10^{22} n/m^2.
- Required Inter-laminar shear strength (ILSS) is 65 MPa.

	DC (5 min)	AC (1 min, 50 Hz)
Conductor to RP	2.2 kV	0.4 kV
DP to DP	3.4 kV	0.8 kV
WP to ground	19.0 kV	2.5 kV



Insulation process in the TF coil

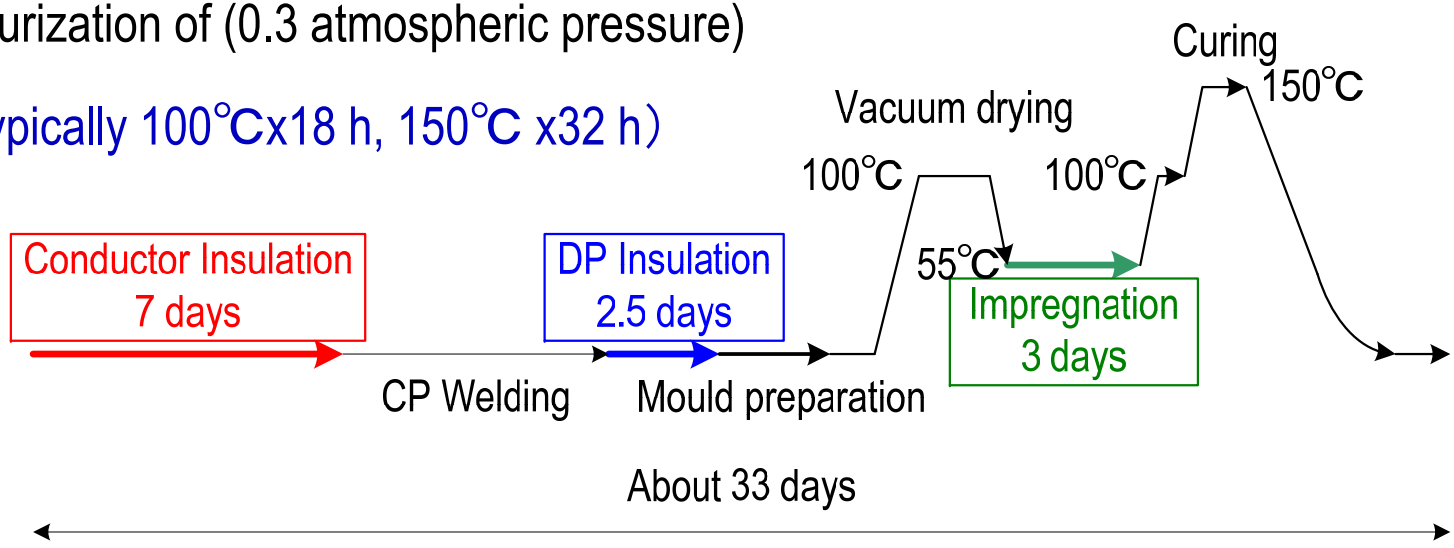
- Cyanate-ester (CE)/Epoxy (EP) blended resin（4:6）
- Multi-layer insulation composed of S-glass and polyimide

Parameters	Values
Impregnation temp.	< 60 ℃
Pot-life (viscosity < 100 mPas)	> 100 h at impreg. temp.
Initial viscosity	< 50 mPas
Max. temp. for curing	< 150 ℃

1) Insulating using S-glass and polyimide tape

2) Impregnation
   - Vacuum drying（100℃ × 24 h）
   - Input and penetration of the resin（60 h）
   - Pressurization of (0.3 atmospheric pressure)

3) Curing（typically 100℃x18 h, 150℃ x32 h）



Bonding agents for bonded glass/polyimide tape

- Several types of the bonding agent for bonded glass/polyimide tapes were fabricated for applying an insulation material of the ITER TF coils.
- Three types of the bonding agent were selected for the evaluation of the ILSS since the glass-transition temperature (Tg) measured by a differential scanning calorimeter (DSC) is more than 150 ℃ as one of important parameters considered for the radiation hardness.

Resin 1	Resin 2	Ratio
Cyanate-ester resin (CE)	Multi-functional epoxy resin (MF EP)	4 : 6
Cyanate-ester resin (CE)	Bisphenol A diglycidyl ether (DGEBA)	4 : 6
Bismaleimide-Triazine Resin (BT)	Multi-functional epoxy resin (MF EP)	4 : 6

Sample preparation

- A laminated sample was composed of 11 glass sheets and 10 polyimide sheets to fabricate a plate of L150 mm x W 100 mm x T 2.5 mm.
- The samples were impregnated by a cyanate-ester/epoxy blended resin at the temperature of 55 ℃ in a vacuum chamber with the pressure of around 100 Pa.
- After the impregnation, the samples were cured at 100 ℃ for 18 h and at 150 ℃ for 32 h in a thermostatic chamber. The rate of the temperature rise was 5 ℃ /h.
- The cured sample was cut into the test specimens of L15 mm x W10 mm.

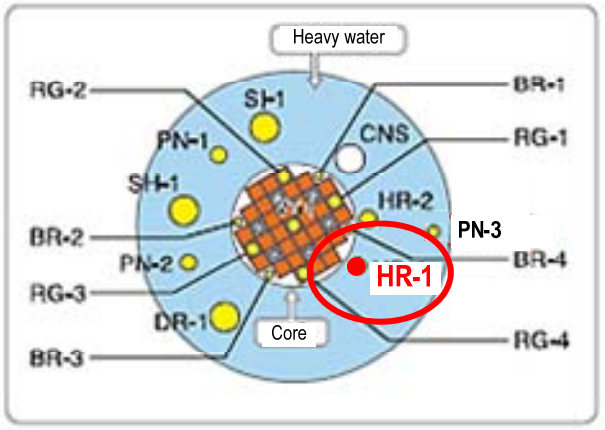
Glass sheet (Boron free S-glass)	
Thickness	0.13 mm
Plain weave	S-2 150 1/0 1Z = 2
No. of thread	31 p/ 30 mm (warp) 30 p/ 25 mm (fill)
Polyimide sheet	
Thickness	0.025 mm
Surface treatment	Corona surface treatment on both sides

Irradiation at HR-1 of JRR-3M

- Test specimens were irradiated during 16.4 h and 164 h in the hydraulic irradiation facility named HR-1 of JRR-3M to expose them by fast neutron fluencies (> 0.1 MeV) of 10^{21} n/m^2 and 10^{22} n/m^2, respectively.
- The irradiation temperature was approximately 373 K.

Irradiation	Value
Thermal neutron fluence (< 0.1 MeV)	9.6 x 10^{17} n/m^{2}s
Fast neutron fluence (> 0.1 MeV)	1.7 x 10^{16} n/m^{2}s
Gamma-ray dose rate	2.5 MGy/h* (16.4 h: 41 MGy, 164 h: 410 MGy)

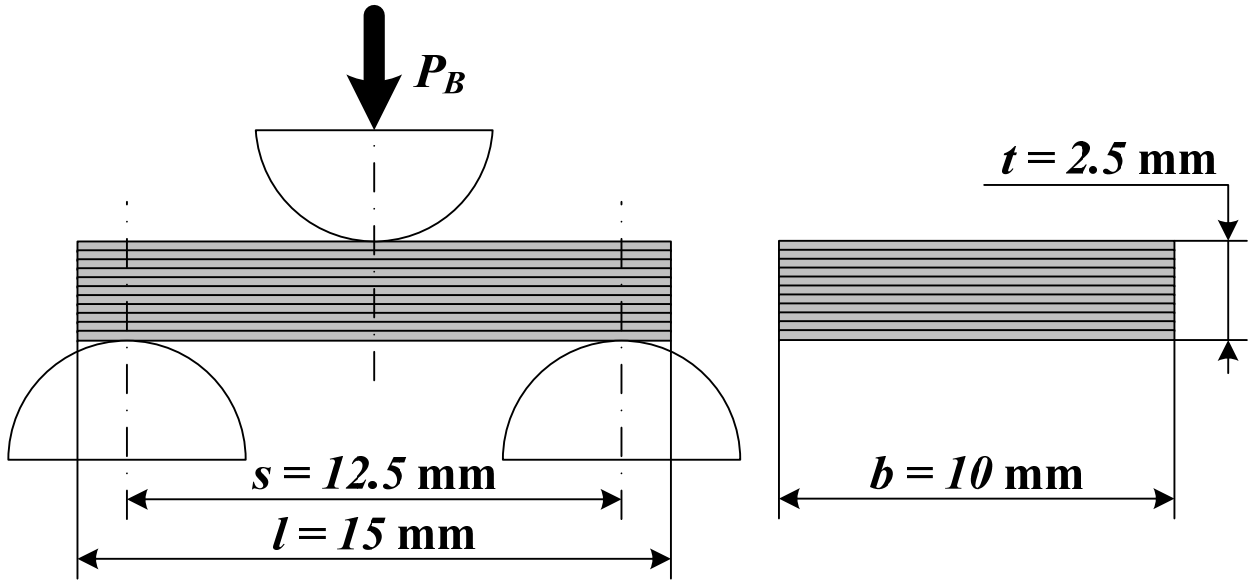
* This gamma-ray dose rate is a typical value. It is depended on the composition of the sample.



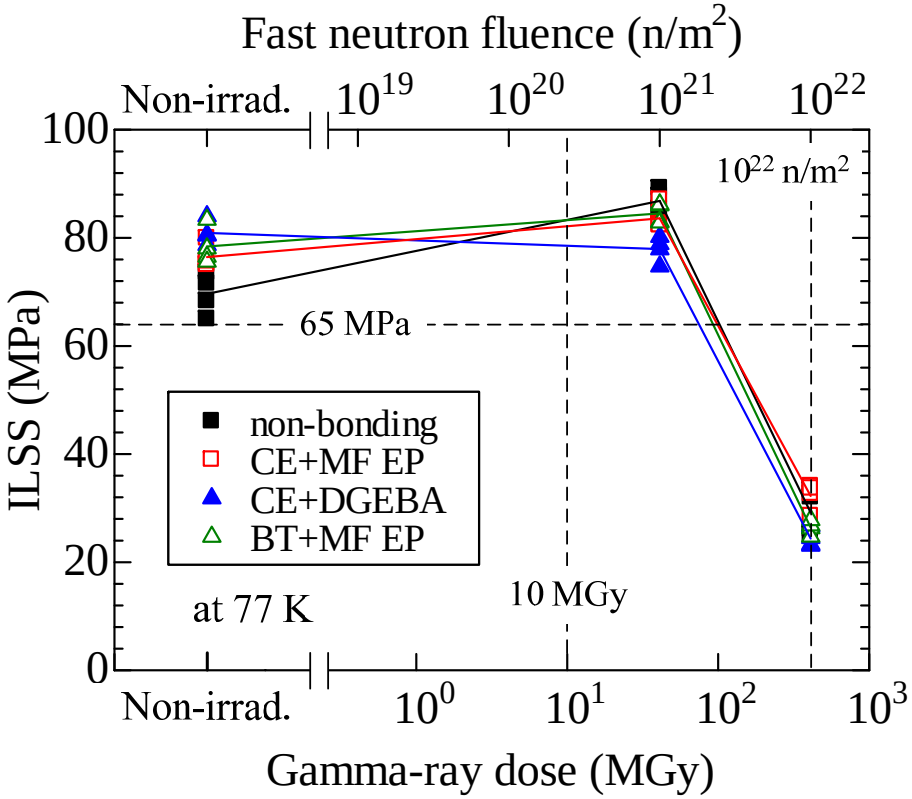
Test procedure of ILSS

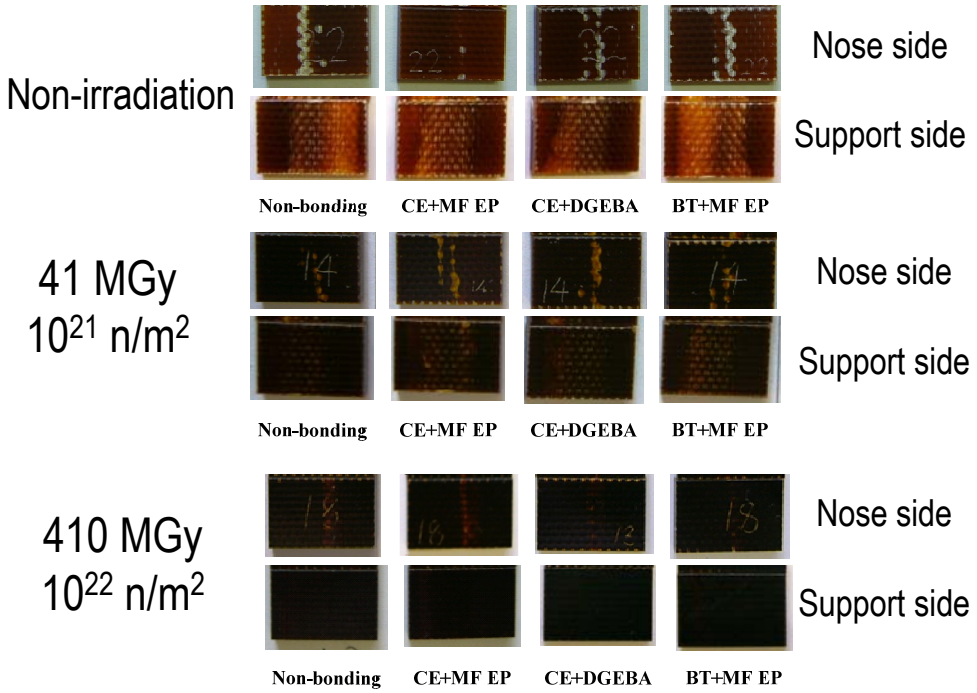
- Test specimens were tested under three-point bending in liquid nitrogen (77 K).
- Span-to-thickness ratio (s/t) is 5.0.
- Radius of a nose and two supports is 6.0 mm.
- Each specimen was placed on two supports and a load was applied with a loading rate of 0.75 mm/min through a nose at the center of the specimen.

$$S_H = \frac{3P_B}{4bt}$$



Test result of ILSS





- Relationships between the ILSS and the irradiation have the same tendency among four types of the sample.
- The ILSS of all test specimens evaluated before the irradiation satisfied the ILSS of 65 MPa.
- Although the ILSS was not changed by the irradiation of 10^{21} n/m^2, the ILSS was degraded to approximately 1/3 of the initial ILSS by the irradiation of 10^{22} n/m^2.
- The irradiation at HR-1 of JRR-3M is quite severe compared with the total irradiation dose of 10 MGy.
- It was considered that samples have sufficient radiation hardness on the requirement of the ITER TF coils.

Qualification perform by ATI at 77K

- For the qualification at ATI, the bonded glass/polyimide tape using CE + MF EP bonding agent was selected.
- In case of the irradiation at the TRIGA reactor, the samples is exposed the total absorbed dose of approximately 55 MGy by the fast neutron irradiation of 10^{22} n/m^2.
- The bonded glass/polyimide tape with CE + MF EP bonding agent satisfied the requirement of the ITER TF coil including tensile and fatigue properties.

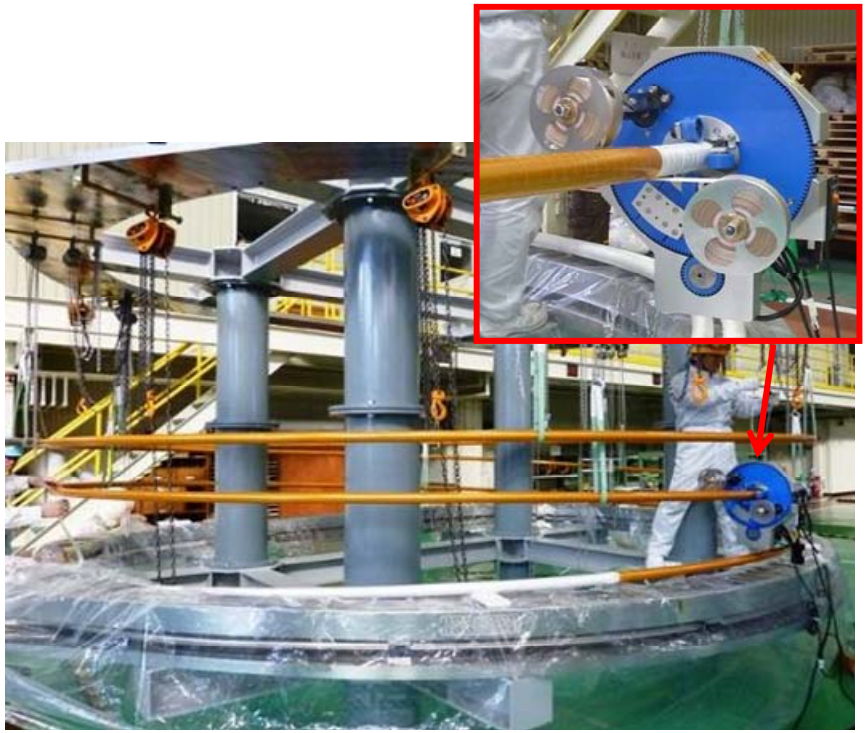
	Requirement	CE + MF EP	
		unirr.	2x10^{22} n/m^2
Young's modulus (77K)	16 GPa	22.1±2.8 GPa	
UTS 90°	280 MPa	445±13 MPa	407±15 MPa
UTS 90° after 30,000 cycles	125 MPa		170 MPa
ILSS 0°	65 MPa	89±4 MPa	89±8 MPa
ILSS 90° unirr.	65 MPa	84±8 MPa	75±6 MPa

Courtesy to R. Prokopec et al., FED

Insulation process of 1/3-scale DP

- To demonstrate insulation process, the conductor insulation and the DP insulation were performed.

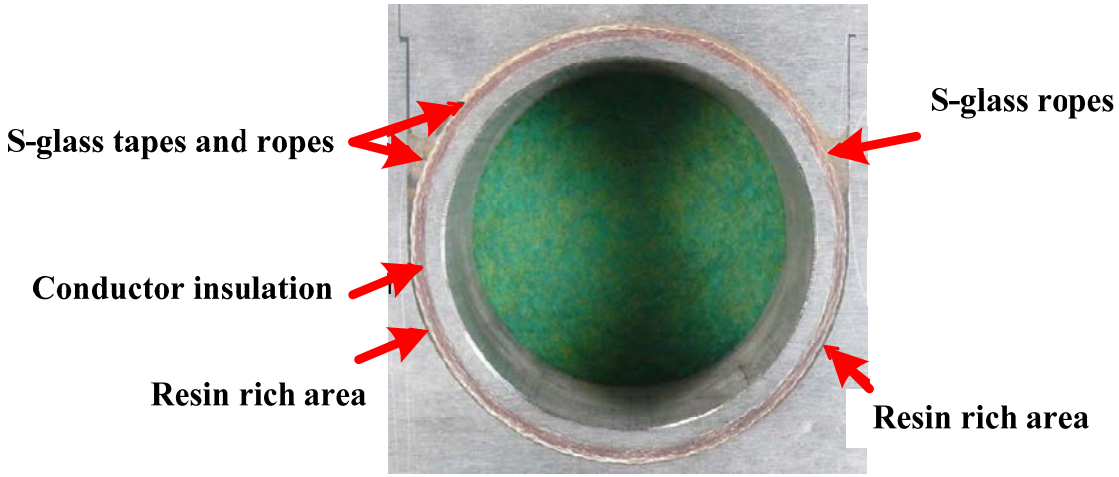
Taping tool

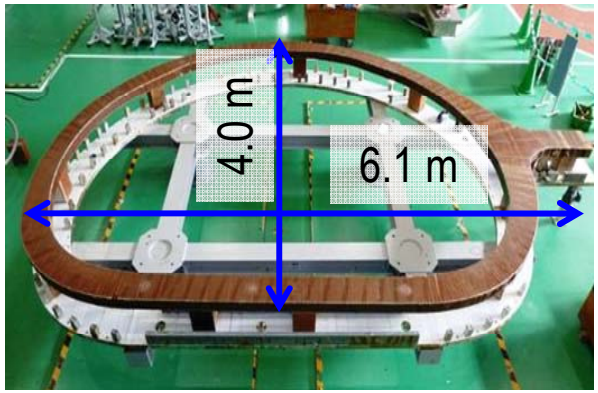


Conductor insulation

DP insulation

Results of 1/3-scale DP fabrication





Conductor-RP	RP-Ground
DC 2.2kV 5 min → OK	DC 3.4 kV 5 min → OK
AC 0.4 kV (50Hz) → 21 mA, 161 nF	AC 0.8 kV (50 Hz) → 38 mA, 143 nF

- No breakdown occurred in high voltage test, it was confirmed that the insulation of 1/3-scale DP satisfied the withstanding performance of the TF coil.
- No voids were observed in the insulations layer with glass/polyimide tapes.

Conclusion

- The evaluation of the ILSS of the GFRP composed of four types of the glass/polyimide tapes and a cyanate-ester/epoxy blended resin for ITER TF coils were performed before/after the irradiation at HR-1 of the JRR-3M.
- The ILSS property of the GFRPs using different bonding agents has a similar behavior on the irradiation and excellent radiation hardness.
- A bonded glass/polyimide tape using the CE + MF EP bonding agent was selected for the qualification test. From the qualification result at ATI, it was confirmed that the selected bonded glass/polyimide tape satisfied the radiation hardness on the requirement of the ITER TF coils.
- In addition, the manufacturability of insulation technique using the bonded glass/polyimide tape and the cyanate-ester/epoxy blended resin has been confirmed in the 1/3-scale DP fabrication.

⇩

➢ From these results, the insulation and impregnation techniques using the bonded glass/polyimide tape and the cyanate-ester/epoxy blended resin was established.