R&D of the ITER Correction Coil magnet system in China

J. Wei 1), S.S.Du 1), A.Foussat 2), X.W.Yu 1), L.P.Liu 1), S.Q.Han 1),X.F.Liu 1), W.Y.Wu 1), N.Dolgetta 2), P.Libeyre 2)

1) Institute of Plasma Physics, CAS, P.R. China（ASIPP）
2) ITER Organization, CS 90 046, 13067 St Paul Lez Durance Cedex, France

E-mail contact of main author: jingw@ipp.ac.cn

Abstract. This paper is focusing on the analysis tasks and R&D of the ITER Correction Coils (CCs). Eighteen superconducting coils are used to compensate field errors arising from misalignment of the coils and winding deviations from the nominal shape as a result of fabrication tolerances, joints, leads, busbars and assembly tolerance. There are 6 top CCs (TCC), 6 bottom CCs (BCC), and 6 side CCs (SCC), arranged toroidally around the machine inside the PF coils and mounted on the TF coils.
The conductor used in the CCs is NbTi/Cu cable-in conduit (CIC) conductor and its operating current is 10KA. The primary FE analyses about the magnetic field, the structure and the thermal analysis for the CCs have been made and the design of the CCs has been optimized during the last two years. The R&D programs on the manufacturing of the CCs are in progress, which is focused on the pre-bending of the conductors, winding machine definition, short sample of Vacuum Pressure Impregnation (VPI), welding process of the coil case, and some other key technologies.

1. Introduction

The ITER magnet system is made up of four main sub-systems: the 18 Toroidal Field coils, referred to as TF coils; the Central Solenoid, referred to as CS; the 6 Poloidal Field coils, referred to as PF coils; and the 18 Error Field Correction Coils, referred to as CC. Pairs of diametrically opposite CCs are connected in anti series inside the cryostat. The top and bottom coil sets are essentially planar while the side coils assume a saddle shape developing on a cylindrical surface [1]. The Correction coils are wound with NbTi CICC conductor in square 316L stainless steel jacket and the winding consist in a total number of 32 turns in BCC and 20 turns in SCC embedded into Stainless steel case. The overall coils arrangement is shown in Fig.1. The main parameters (current, peak field and operating temperature) for the CCs are given in Table 1.

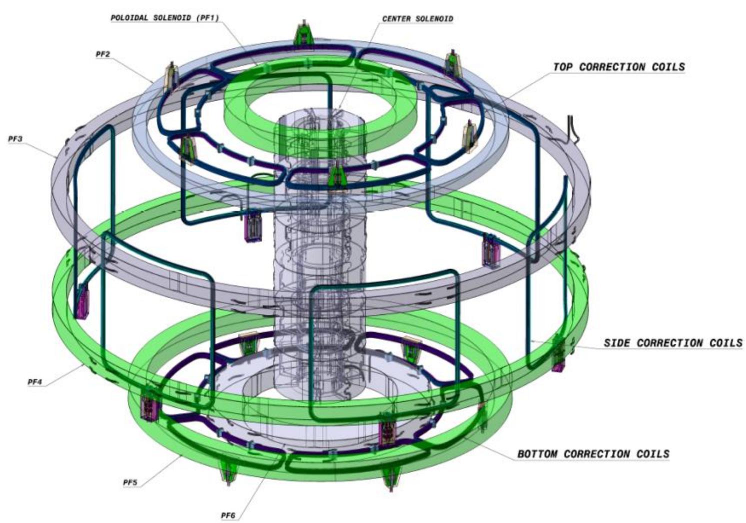


FIG.1. Layout of correction coils system

Table1. Main parameters of the CCs in normal operation

	BCC	SCC	TCC
Current per turn(KA)	10	10	10
Peak field(T)	4.06	2.45	2.26
Prescribed inlet temperature (K)	4.5(4.2K if subcooled PF He supercritical circuit)		

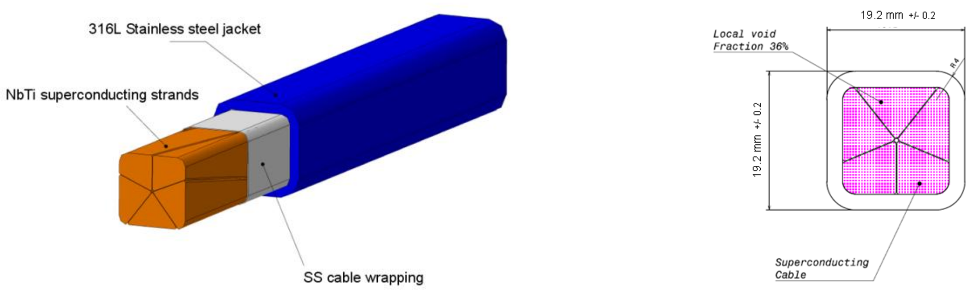


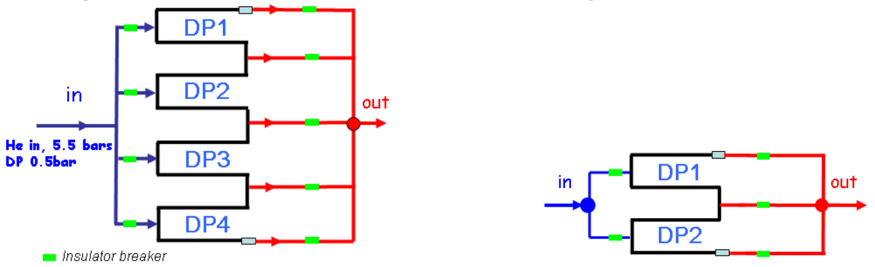
FIG.2. CC conductor configuration and dimensions

The conductor is a square cable-in-conduit (CICC) with a configuration as shown in Fig. 2. NbTi strands are cabled clock-wise as five petals with a cable strand pattern of 3x4x5x5 and are cooled by supercritical helium. Each winding pack (WP) is wound from a single one in hand length of NbTi-based CICC without internal joints. The conductor is insulated using interleaved fibre glass cloth with polyimide tape and the whole winding pack is wrapped with ground insulation. The main parameters of CC windings and insulation system are summarized in Table 2.

Table2. Major Parameters of the Correction Coils

	Top / Bottom coil	**Side coil**
Number of coils	6	6
Average turn length (m)	15.8	27.1
Turns per coil	32	20
Nr x Nz	4x8	5x4
Total conductor length per coil (m)	505	543
dR (winding section) (m)	0.089	0.108
dZ (winding section) (m)	0.173	0.089
Coil case thickness (mm)	20	20
dR (coil section) (m)	0.144	0.164
dZ (coil section) (m)	0.233	0.144
Total weight of each coil winding (kg)	1216	1312
Total weight of each coil (kg)	2880	3608
Number of in-cryostat feeder pairs	6	3
Number of terminal joints	12	12
Turn insulation (mm)	1.2	1.2
Pancake to pancake insulation (mm)	1	1
Ground insulation (mm)	4	4

The cooling channel length is optimised to the minimum pancake length in order to maximise the temperature margin on the SC conductor as shown in Fig.3.



Octo-pancake cooling scheme   Quadra - pancake cooling scheme

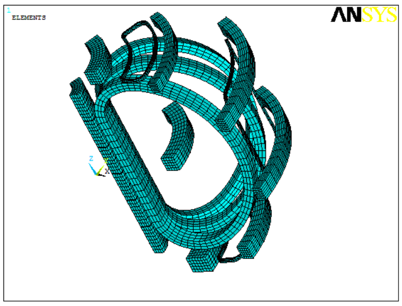
FIG.3. Hydraulic cooling circuit's layout on CC coils (B/TCC: Octo-pancakes, SCC: Quadra-pancake)

2. The FE analysis for the CCs

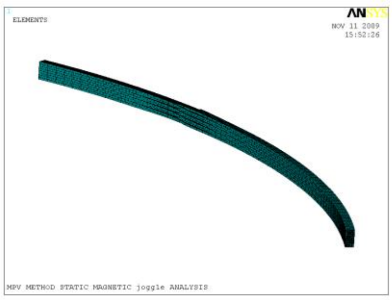
The electromagnetic loading distribution onto the CC coils for tokamak reference scenarios is determined by running the global magnet ANSYS FE-model. The maximum magnetic field of BCC is 4 T at EOB and SCC is 2.45 T at SOB. Electromagnetic resultant nodal force distributions on the CCs are then transferred to the CC coils stress analysis. The creation of a detailed local stress CC coil FE-model enables to determine the stress levels into the casing and insulation material system. All the results are provided for the BCC which include the electromagnetic analysis and structure analysis.

2.1. Electromagnetic analysis for BCC

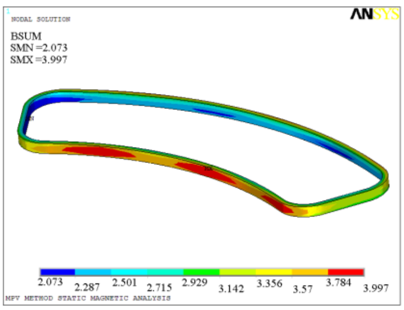
The electromagnetic analysis for the BCC has been carried out including the whole coil cross section model and the turn joggle region. The FE models and the result for electromagnetic analysis are shown in fig. 4. The maximum magnetic field of the BCC is 4 T and of the joggle region 3.8 T.



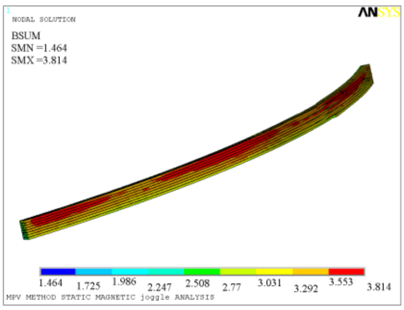
a) FE model for BCC



b) FE model for BCC joggle region



c) Magnetic field for BCC (T)

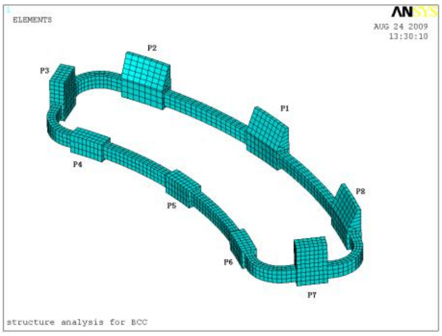


d) Magnetic field for the joggle region (T)

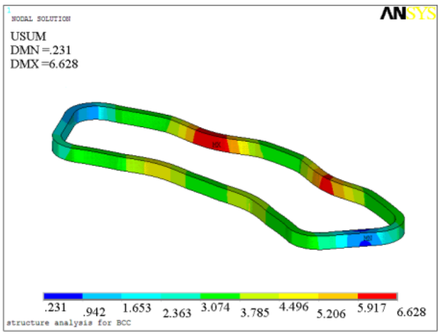
FIG.4. Magnetic analysis for BCC and the joggle region

2.2. Structure analysis for BCC

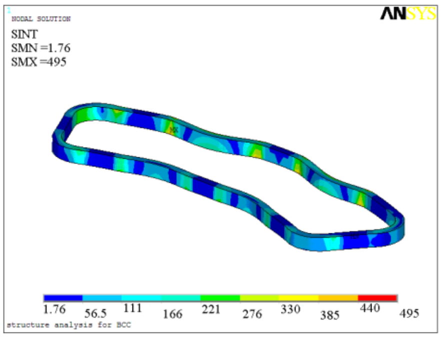
The BCC was selected to be analyzed in detail for the FE structural analysis as it is subject to the maximum magnetic load for the correction coils.



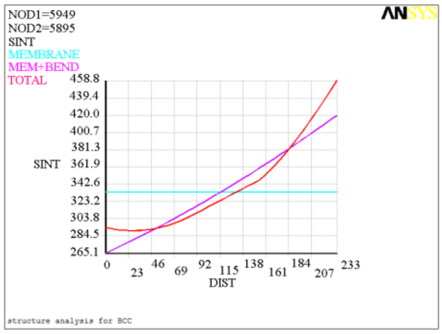
a) BCC model for structure analysis



b) Displacement of BCC (mm)



c) Intensity stress of BCC casing (Mpa)

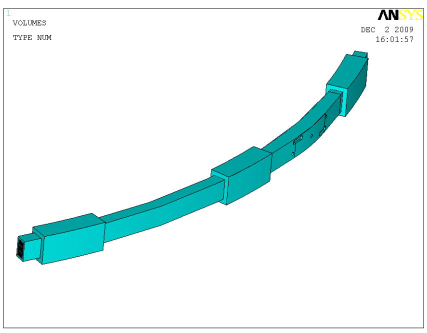


d) Membrane and membrane + bending stress of the BCC casing (Mpa/mm)

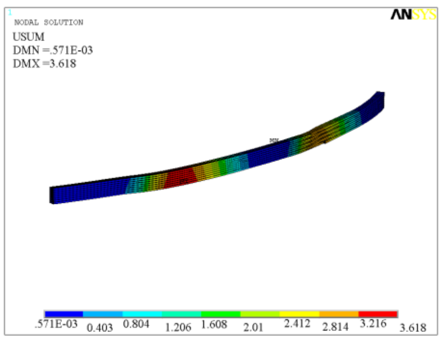
FIG.5. Structure analysis for BCC

The total intensity stress for casing material was linearized. The stress linearization on Maximum membrane stress path is within the admissible limit (265.1 MPa<Sm=466 MPa). Maximum membrane plus bending stresses is also within the limit (420 MPa< 1.5 Sm=700 MPa).

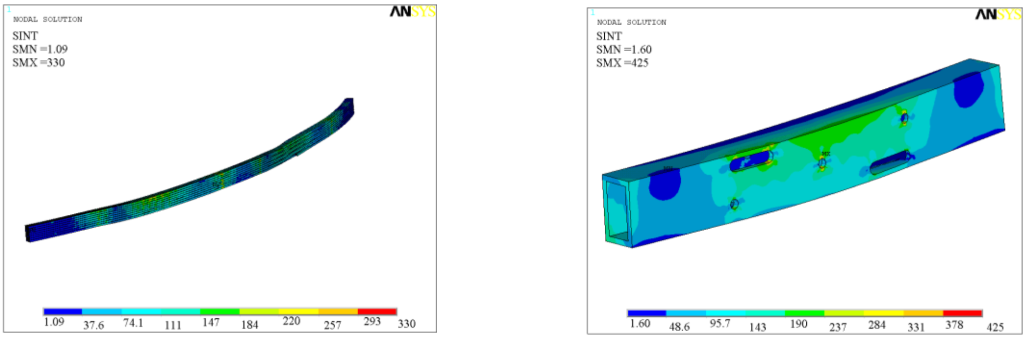
Based on the whole model of BCC, it can be found the concentration maximum stresses around the helium inlet and outlet also located at the joggle region. As the support system is in physical relationship with the TF coils, the joggle region has the same displacement which comes from the TF coils. And normally it is thought that both sides are free, so the displacement caused by the TF coils has been neglected. Fig.6 shows the intensity stress results of the BCC joggle region and Table 3 lists the Pm and Pm plus Pb result.



a) FE model for joggle region



b) Displacement of joggle region(mm)



c) Intensity stress of joggle region(Mpa) d) Intensity stress of casing for joggle egion(MPa)

FIG.6. Structure analysis for BCC joggle region

Table 3 Membrane and membrane + bending stress of BCC joggle region

Maximum stress in	Stress type	stress[MPa]	Allowable stress[MPa]
Path1 in BCC joggle region casing	Pm	362	466.7
	Pm+Pb	392	700
Path1 in BCC joggle region jacket	Pm	219	466.7
	Pm+Pb	248	700

3. R&D work for CCs

3.1. Winding tests

In order to characterise the CC winding pack manufacturability, several winding tests were performed to simulate the real winding procedure of the coil. For both B/TCC and SCC, two types of trials were carried out, single turn coil and 4 turns (2×2) coils using dummy conductor. Through these tests some key technologies like the corner and arc winding, the terminal area and the joggle region were simulated for establishing future winding procedure and parameters.

a) SCC single turn coil test b) BCC single turn coil test

FIG.7. Scaled single turn coil of BCC and SCC

The conductor used in these two winding tests was EAST conductor which was similar to the CC conductor in dimensions. The purpose was to define the primary equipment and process which will be used on the winding of the real coils. The dummy conductor of CC coil was used to do the winding test of 4 turns (2×2) coil. Up to now 4 turns coil of BCC has been completed and the winding test of SCC is in preparation. The experiment will allow a comprehensive inspection of the winding equipment and technology and will also be a preparation to the future coil production.

FIG.8. BCC 4 turns coil winding table layout

3.2. Short beam insulation tests

In order to ensure the structural safety of the CC coil, the winding pack wound with glass-polyimide composite insulation should be Vacuum Pressure impregnated (VPI) with epoxy resin. Based on the successful experience of insulation technology on EAST tokamak (CN), it was found that the bag mold VPI process could solve the issues related to mechanical machined molds, the need for control of uniform compression, mold fabrication tolerances and sealing. After some preliminary qualification of CC insulation system, two short winding pack beams representative of SCC coils were impregnated with epoxy by VPI method so as to qualify the insulation structure, the impregnation equipment and the associated process. Fig. 8 shows some cross sections samples of the two 1 m long beams.

a) The cross section of 1st sample

b) The cross section of 2nd sample

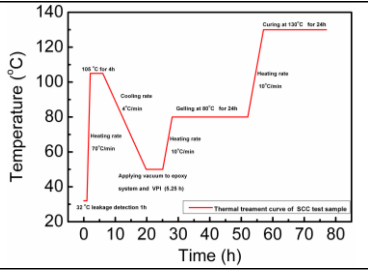
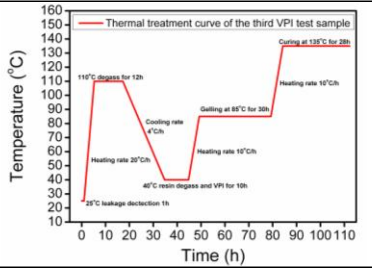
FIG.8. Picture of the two VPI samples cross sections

Tensile tests of the insulation system on the first test sample were performed (tensile tests at 77 K according to ASTM D3039) and the results showed that the insulation system satisfied IO requirements (see Table.4). Nevertheless there were still some non compliant features, such as a dimension deviation of the winding pack, some dry region in glass roving infill or the glass felt which did not satisfy the IO requirements. A second sample was impregnated with new features which showed some improvement with respect to the first one. Table 5 summarises the difference of insulation system between the two samples.

Table.4 The tensile tests of the insulation system at 77K

		1	**2**	**3**	**4**	**5**	**IO requirement**
Tensile strength (MPa)	warp specimens	395	425	385	420	380	⩾300
	woof specimens	390	365	390	405	380	⩾200
Young's modulus (MPa)	warp specimens	27.44	30.25	27.81	28.7	29.02	
	woof specimens	30.04	26.68	31.61	29.9	29.17	

Table.5 The difference between the two VPI short samples

		1st sample	2nd sample
Material of conductor		Aluminum bar	Dummy conductor
Insulation structure	Turn(mm)	1.2	0.92
	Pancake(mm)	0.6	1
	Ground(mm)	4 (not GKG)	4 (GKG)
Formula of insulation cement		DGEBF/DETD	DGEBF/DETD/PPGDGE
Thermal treatment process			
Dielectric strength	Turn insulation/ Duration (KV/Min)	14/1	5/5
	Ground insulation/ Duration (KV/Min)	50/1	20/5

3.3. CC case closure welding tests

The structural stainless steel 316LN CC coil case is a full welded structure. Due to the overall geometry features, the planar type B/TCC coil case will be formed by sub-assembly of U-shape and SCC by L-shape. Fig. 9 shows the cross section structure of CC case. Once the winding pack is inserted into the case, keeping an unfill gap to the side case walls, it will be welded along the perimeter length of the case. Considering the tolerances of fabrication of respectively +/- 2mm on BCC and +/- 4mm on SCC imposed over the radius central line of the casing along the 7 m branch, the welding process must be selected to match such level of deformation specification. In addition, it is important to choose a proper welding method, which will be compliant with tensile strength and fatigue structural criteria and will determine the quality of the whole CC coil assembly.

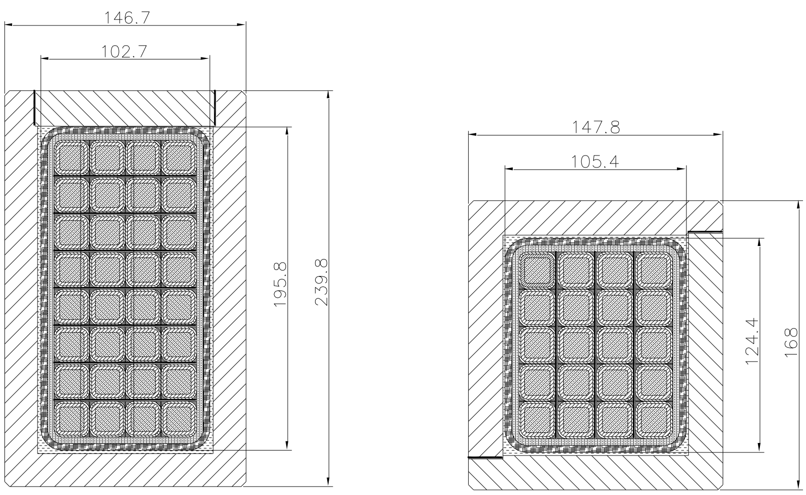
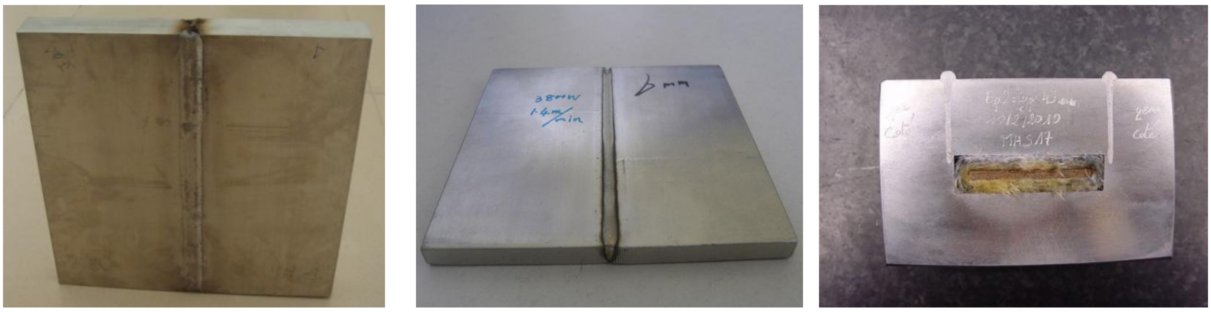


Fig.9 The cross section structure of CC case

The three methods of narrow TIG welding, laser welding and EB welding are suitable candidate to the closure welding of the CC case. As a traditional welding method the narrow TIG butt welding will be used on the connection of sub-cases parts in combination with some post machining. Considering the requirements on deformation level and mechanical properties of the weld, the EBW method was selected as a baseline closure welding method for further qualification test. Some laser welding trial which do not need a vacuum chamber unlike EBW, have been implemented but this technology requires an hybrid combination with TIG welding as the full penetration by power laser (YAG or CO_2) is not easily achievable with current state of the art. So some samples of these three kinds of methods are made to test the welding deformation and process (see fig.10).



a)TIG welding test sample b) Laser welding test sample c) EB welding test sample

Fig. 10 Test samples for TIG, laser and Electron Beam welding

3.4. The next engineering work plan for CC R&D includes the following items:

- To research and develop the equipment for the winding line
- To perform impregnation trials to establish the basic suitability of the chosen insulation system for the industrial process
- To perform welding trials to demonstrate that the surface temperature of the winding pack remains less than 200 °C under all possible contact conditions for 2 min (gap or close contact with the case)

4. Conclusion

Some preliminary R&D activities have been performed to qualify the winding procedure, the vacuum pressure impregnation equipment, the case closure welding process involved in the fabrication of coils during the last two years at ASIPP. Some key experimental trials are currently carried out on the definition of real scale production line. The results of these tests and trials will be used to define the manufacturing processes of the ITER Correction coils.

References:

[1] A. Foussat, P. Libeyre, N. Mitchell, Y. Gribov, C.Jong, D. Bessette, R. Gallix, P. Bauer, A. Sahu, Overview of the ITER Correction Coils Design, IEEE Trans. Appl. Supercond. 20 (3) (2010), pp 402-406.