Manufacture and Acceptance Test of the Full Size ITER PF5 Conductor Sample

Long Feng, Wu Yu, Liu Fang, Liu Bo, Shi Yi, Lei Lei, Qin Jinggang, and P. Bruzzone

***Abstract*—In the R&D process of the International Thermonuclear Experimental Reactor (ITER) Poloidal Field (PF) coils, 16 m PF5 Cable-in-Conduit Conductor (CICC) was integrated at Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). The manufacture process of the qualification conductor was according to the ITER design. As required by the ITER Procurement Arrangement (PA), full size PF5 qualification conductor sample was manufactured and delivered to SULTAN facility (CRPP Villigen, Switzerland) for acceptance test. The PF5 conductor sample was made of two legs by one conductor bending, bottom hairpin box, upper terminations, support clamps, insulation, cryogenic piping and instrumentations. The concept of hairpin box and comb-type terminations configuration for ITER PF conductor sample which was co-contributed by ENEA and CEA was successfully verified by the first China PF2 conductor sample tested in SULTAN facility May 2010. The PF5 conductor sample test was initiated at the end of Feb. 2011. The test program included DC performance, cyclic loading, AC loss and MQE test. The conductor manufacture process, conductor sample assembly and test results were presented in this paper.**

***Index Terms*—Conductor sample, ITER, PF5.**

I. Introduction

THE ITER magnet system consists of 18 Toroidal Field (TF) coils, a Central Solenoid (CS), 6 Poloidal Field (PF) coils and 18 Correction Coils (CCs) [1]. The PF system consists of 6 coils which serve to shape and stabilize the position of the plasma in the tokamak [2]. All coils are built by stacking 6 to 9 double-pancake (DP) windings wound with two-in-hand NbTi superconducting CICCs (cable-in-conduit-conductors). The PF cable is enclosed and compacted in a 316 L circle-in-square jacket.

As one of the participants of ITER project, China Domestic Agency (CN DA) organized ASIPP as the supplier to contribute PF2/3/4 and PF5 conductors for PF magnet system. In the Process Qualification Phase, full-size conductor sample test was required according to the PA requirements. The first full-size PFCN1 conductor sample made by PF2 conductor was tested at SULTAN facility at May 2010 [3], [4].

The configuration and the geometry of the PF2 through PF5 conductor are the same except that the cable layout is different between the PF2/3/4 and PF5 conductor. The cable layout of PF2/3/4 is $((((2\ \mathrm{sc} + 1\ \mathrm{Cu\ strand}) \times 3 \times 4 + 1\ \mathrm{Cu\ core\ 1}) \times 5){+}1\ \mathrm{Cu\ core\ 2}) \times 6$ and which is $((3\ \mathrm{sc} \times 4 \times 4 \times 4) + 1\ \mathrm{Cu\ core\ 3}) \times 6$ for PF5 conductor [5]. After the successfully qualification test of PF2 conductor sample, one PF5 conductor was manufactured and the PFCN2 conductor sample was fabricated at ASIPP for qualification test.

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TABLE I
Parameters of the NbTi Strands

Parameter	Requirements	Measurements
Diameter	0.73 +/- 0.005 mm	0.73 mm
Twist pitch	15+/-2 mm	13.4 mm
Twist direction.	Right hand	Right hand
Ni plating	2.0+0, -1 μm	2 μm
Ic (5.0 T, 4.22 K) on ITER barrel	339 A	356 A (The Minimum)
Qh (+/- 1.5 T cycle, 4.22 K)	< 45 mJ/cc	40.5 mJ/cc
RRR	> 100	157
n value (5 T, 4.2 K)	> 20	34.9
Cu/non-Cu ratio	2.3 +/- 0.05	2.268

II. Manufacture of PF5 Conductor

Each process of the PF5 conductor manufacture was in compliance with the ITER PF PA requirements.

The NbTi superconducting strands were supplied by Western Super-conducting Technologies Company (WST). The parameters of the NbTi strands are listed in Table I. The Fig. 1 shows the cross-section of the NbTi strands.

Based on the measured critical current data by National Institute of Science and Technology (NIST), Parameterisation of Bottura scaling [6] for the NbTi strands of PFCN2 conductor sample was done by IO [7] and is listed in Table II.

The PF5 conductor cabling was done by Baiyin Non-ferrous Changtong Wire & Cable Co., Ltd. The parameters of the PF5 cable are shown in Table III.

The 316L circle-in-square stainless steel jackets were manufactured by Zhejiang Jiuli Special Material Technology Co., Ltd., using the raw materials from Fushun Special Steel Co., Ltd. Two pieces of stainless steel jackets were welded for the

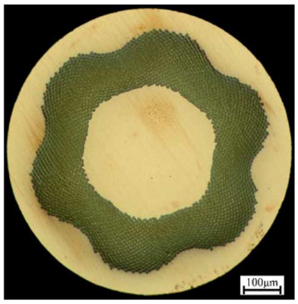

Fig. 1. Cross-section of the NbTi strands for PF5 conductor.

TABLE II
IO PARAMETERIZATION

Parameter	Value
T_{c0}	8.79
B_{c20}	13.72
C_0	113200
α	1.00
β	0.98
γ	1.96
n	1.7

TABLE III
PARAMETERS OF PF5 CABLE

Parameter	Requirements	Measurements
Twist direction	Right hand	Right hand
Twist pitch	450 ± 20 mm	440-450 mm
Wrapping direction	Left hand	Left hand
Wrap overlap	40 +0-10 %	34-36 %
Outer diameter of wrapped cable	35.6+0.2 -0.3	35.3-36.2 mm

PF5 conductor sample jacketing. The specification dimension of the stainless steel jacket is $54.2 \times 54.2 \times \Phi 38\ (\mathrm{mm})$.

After jacketing and compaction done by ASIPP, the elongation of the jacket and the cable were 5.84% and 0.199%, respectively.

III. FABRICATION OF PFCN2 CONDUCTOR SAMPLE

The PF5 conductor sample was made of two legs by one conductor bending, bottom hairpin box, upper terminations, support clamps, insulation, cryogenic piping and instrumentations.

The comb-configuration termination is a solution developed by CEA [8] to reduce the risk of unbalanced current distribution inside the cable.

The design of the hairpin box was based on the concept as successfully qualified for the JT-60SA project by ENEA [9]. The risk of unbalanced current was reduced by using the hairpin box instead of a resistive joint. Re-verified by PFCN1 conductor sample, hairpin box construction for ITER PF conductor sample was approbated by IO.

The conductor sample was cooled from the bottom to the top. The coolant flow entered through the hairpin box. One 80 W heater was used to heat the Helium during the tests for the two legs. To allow the proper diffusion of the helium into the cable annulus, one piece of stainless steel rod was inserted into the central spiral along the high field region of the conductor sample to force most of the flow through the over-compacted strand bundle.

The instrumentation comprised of voltage taps and temperature sensors at high field zone. The zero reference point was defined as the center of the magnet field of SULTAN facility. For the PFCN2 conductor sample this point is 2555 mm from the top of the terminations. Totally, there were 16 pairs of voltage taps and 17 temperature sensors were installed on the conductor sample. Two voltages, i.e. VL3 and VR4, were attached to the two legs of the conductor sample respectively for the resistance measurement of the two upper terminations by CRPP.

Final checks according to the SULTAN requirements [10] were performed after finishing the fabrication of the PF5 conductor sample. To limit the horizontal deviation from the surface to the end of the sample to less than 2 mm, straightening was done to reduce the deviation from 2–3 mm to about 1 mm. The insulation of the clamps to the jacket was checked by meg-ohmmeter under DC 500 V. The resistances were all larger than 1000 MΩ.

IV. TEST RESULTS

The PFCN2 conductor sample was tested in accordance to the agreement between IO, CRPP and ASIPP which lasted for three weeks. The sample was checked without background field first. After that, AC loss measurement, reference DC tests and MQE tests were performed before the cycling loading. Then 2000 cycling loading was performed at 7.5 T background with 30 kA sinusoidal current. Expanded AC, DC and MQE tests were performed after cycling [11].

A. Self-Field Calculation of PFCN2 Conductor Sample

The self-field of the PFCN2 conductor sample was calculated by ANSYS software. The distance between the two legs axis is 60 mm. The current density was only loaded at the cable region by opposite direction and the magnetic flux parallel were applied at the outside air elements. The simulation results of the self-field distribution are shown in Fig. 2. The coefficient of self-field vs. current, i.e. $B_{self} = 0.016\ \mathrm{T/kA}$.

B. AC Loss Measurement

The AC loss measurement was performed before any electromagnetic loading and after a number of load cycles (2000 cycles) in order to define the impact of cyclic loads on the coupling currents constant of the cable. Before any electromagnetic loading, the AC loss measurement was performed at 2 T background field, ±0.2 T AC field, without transport current, at frequencies from 10 Hz down to 0.1 Hz adjusting the Helium mass

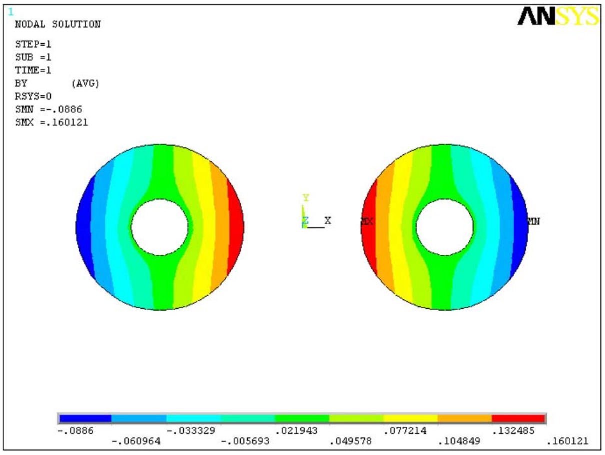

Fig. 2. Distribution of the self-field of the PFCN2 conductor sample.

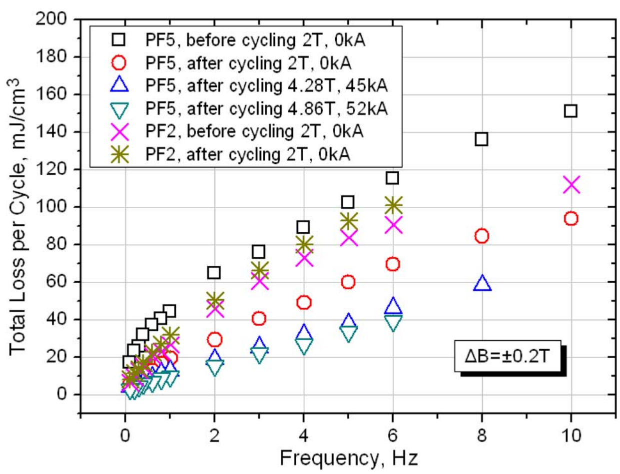

Fig. 3. AC loss of the right leg of the PFCN2 conductor sample at various field and current before and after cycling AC loss of the right leg of the PFCN1 conductor sample before and after cycling are also shown.

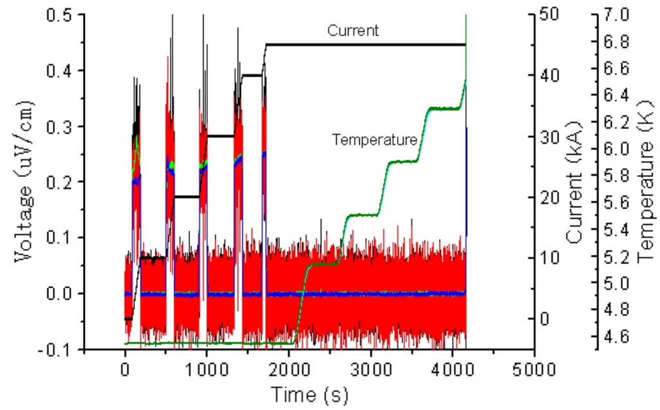

Fig. 4. The first reference Tcs measurement at 4.28 T, 45 kA.

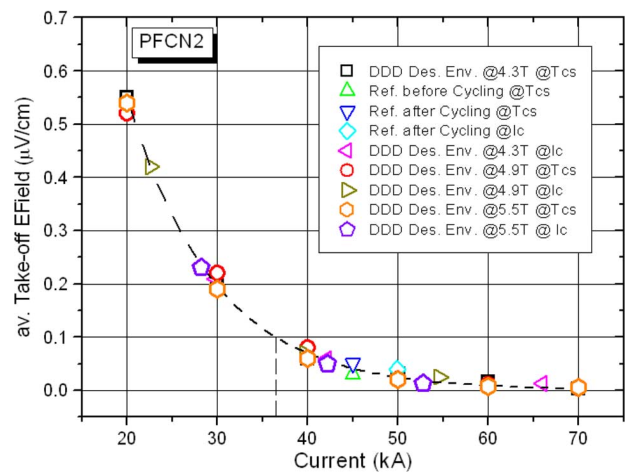

Fig. 5. Take-off voltage at various background fields and currents in Tcs and Ic runs.

flow rate in order to achieve a sound temperature increase. After 2000 cycles electromagnetic cycling, the AC loss measurements were performed at various background field and transport current combinations. Fig. 3 shows the AC loss before and after cycling of the right leg of the PFCN2 conductor sample at various field and current, the AC loss before and after cycling without transport current of the right leg of the PFCN1 conductor sample are also shown.

The AC loss curve of PF5 conductor changed after cycling and decreased as a function of the background field due to the copper magneto-resistance. Opposite to PF5 conductor sample, no AC loss decrease was observed after cycling of the PF2 conductor sample. This maybe caused by the different cable layout of the PF2 and PF5 conductor.

The AC loss of the PFCN1 and the PFCN2 conductor sample are normalized to the NbTi strands volume respectively. The coupling loss, Q_c, is obtained by subtracting the specified hysteresis loss from the measured total AC losses. The time constant $n\tau$ is defined as the quantity that reproduces the measured coupling loss at a certain frequency of the field sweep in the following equation [12].

$$\frac{\mu_0 Q_c}{\Delta B^2} = \frac{\pi^2 n\tau f}{2} \qquad (1)$$

where the ΔB is the peak-to-peak amplitude of the AC field. The $n\tau$ could be obtained from the fixed linear section of the loss curve. The $n\tau$ of PF5 conductor sample is 62.5 ms before cycling and 25.1 ms after cycling respectively. The $n\tau$ of PF2 conductor sample is 44.7 ms before cycling and 45.8 ms after cycling respectively.

C. DC Tests

The first reference T_{cs} measurement was done at 4.28 T background field with 45 kA current as showed in Fig. 4. When the temperature reached about 6.5 K, the conductor suddenly quenched. A set of T_{cs} assessments was performed before and after load cycles. Most of T_{cs} tests showed a sudden voltage take-off or fast voltage transition with take-off electric field below 10 $\mu\mathrm{V/m}$ threshold. The 10 $\mu\mathrm{V/m}$ criterion could be reached only at current ≤37 kA as showed in Fig. 5. The results of "T_{cs}" which did not reach the electric field criterion we call "T_q". As a result of the superposition of self-field and background field, the local electric field along a strand in the cable reached very high values at the peak magnetic field, driving a quench, although the average electric field, sensed by the voltage taps on the conductor jacket remained very low [13].

The electromagnetic cycling loading was performed at 7.5 T background field and 30 kA current without intermediate measurements. After 2000 load cycles were carried out, reference DC tests and tests of DDD design envelope were performed at various background field and conductor current combination

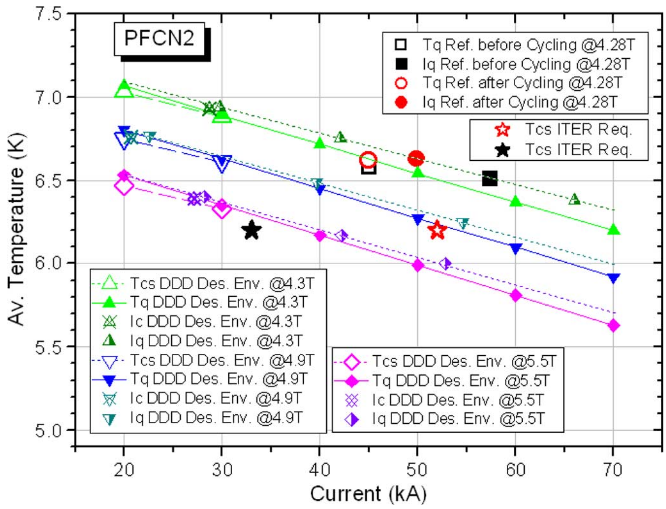

Fig. 6. Assessments of the Tcs and Ic runs before and after cycling for the reference DC tests and for DDD Design Envelope tests.

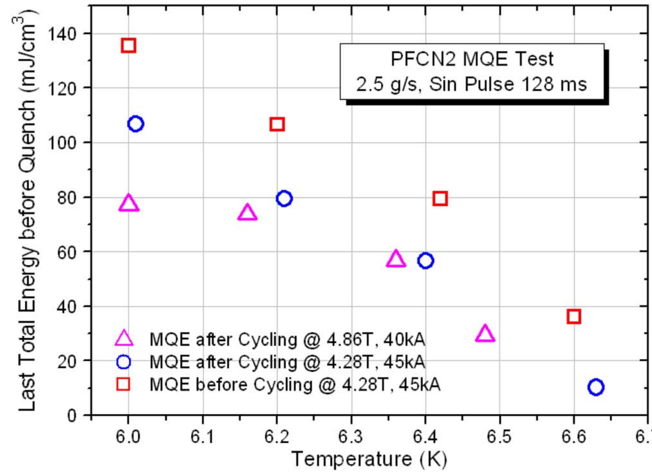

Fig. 7. Summary of the MQE tests before and after cycling.

after that. The minimum T_{cs} ITER requirement for the PF5 coils is 6.2 K both at 52 kA–5.7 T and 33 kA–6.0 T [2]. Considering the self-field of the conductor sample induced at 52 kA and 33 kA transport current, the background field of the SULTAN facility, i.e. B_{sultan} is 4.9 T and 5.5 T respectively. The T_{cs} measurements are the main goal of the sample test with a few I_c measurements. In general, the I_c runs showed a better performance compared to the T_{cs} runs. Fig. 6 shows the assessments of the T_{cs} and I_c runs before and after cycling for the reference DC tests and for DDD Design Envelope tests.

D. MQE Tests

The MQE (Minimum Quench Energy) test was performed after reference DC test before cyclic loading. The transient magnetic field was created by discharge of the capacitor battery (10 capacitors, 128 ms, full sinus) on pulse coil. The discharge voltage was increased in steps of 20 V till quench occurred. The tests were performed at various background fields, currents and temperature settings. The quench occurred when the energy deposited by AC loss caused the local coolant temperature to exceed the temperature margin. The better MQE performance after cyclic loading is consistent with the reduced AC loss. The summary of the MQE tests is shown in Fig. 7. All the MQE are normalized to the NbTi strands volume.

V. Conclusion

A 16 m long ITER PF5 NbTi superconducting conductor was integrated at ASIPP. The PFCN2 conductor sample was fabricated by ASIPP and tested in the SULTAN facility at CRPP from Feb. 28 to Mar. 17, 2011. AC loss measurements, DC performance and MQE tests were performed according to the ITER qualification test program.

The PFCN2 conductor sample meets the ITER PF5 coils T_{cs} requirements. The I_c runs showed a better performance compared to the T_{cs} runs. Most of T_{cs} tests showed a sudden voltage take-off or fast voltage transition with take-off electric field below 10 $\mu\mathrm{V/m}$ threshold. The "T_q" was used to assess the temperature margin when the current was large than 37 kA. The resistance of sample-to-transformer connection was 0.21 $\mathrm{n\Omega}$ for both connections at 45 kA current and $\mathrm{B} = 0$.

The AC loss of PF5 conductor sample was at low level and significantly decreased after the electromagnetic cycling which was different with the PFCN1 conductor sample.

Acknowledgment

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