Preparation of the ITER Poloidal Field Conductor Insert (PFCI) Test

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***Abstract*—The Poloidal Field Conductor Insert (PFCI) of the International Thermonuclear Experimental Reactor (ITER) has been designed in the EU and is being manufactured at Tesla Engineering, UK, in the frame of a Task Agreement with the ITER International Team. Completion of the PFCI is expected at the beginning of 2005. Then, the coil shall be shipped to JAERI Naka, Japan, and inserted into the bore of the ITER Central Solenoid Model Coil, where it should be tested in 2005 to 2006. The PFCI consists of a NbTi dual-channel conductor, almost identical to the ITER PF1 and PF6 design, ~45 m long, with a 50 mm thick square stainless steel jacket, wound in a single-layer solenoid. It should carry up to 50 kA in a field of ~6 T, and it will be cooled by supercritical He at ~4.5 K and ~0.6 MPa. An intermediate joint, representative of the ITER PF joints and located at relatively high field, will be an important new item in the test configuration with respect to the previous ITER Insert Coils. The PFCI will be fully instrumented with inductive and resistive heaters, as well as with voltage taps, Hall probes, pick-up coils, temperature sensors, pressure gauges, strain and displacement sensors. The test program will be aimed at DC and pulsed performance assessment of conductor and intermediate joint, AC loss measurement, stability and quench propagation, thermal-hydraulic characterization. Here we give an overview of the preparatory work toward the test, including a review of the coil manufacturing and of the available instrumentation, a discussion of the most likely test program items, and a presentation of the supporting modeling and characterization work performed so far.**

***Index Terms*—ITER, NbTi, nuclear fusion, superconductors.**

Manuscript received October 5, 2004. This work was supported in part by the European Fusion Development Agreement (EFDA).

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Digital Object Identifier 10.1109/TASC.2005.849083

I. Introduction

The development of superconducting coils has been a major item of the R&D activities of the International Thermonuclear Experimental Reactor ITER for the past ten years. This development has gone through several steps. The first phase consisted of the qualification of full-size Nb_3Sn conductors and ITER-relevant coils, among which the Central Solenoid Model Coil (CSMC) [1], two (out of three) Insert Coils [2], [3], tested in the bore of the CSMC, and the Toroidal Field Model Coil [4].

The PFCI coil will be the first of the Insert Coils to be manufactured with NbTi. The main objective of this coil is the characterization of long lengths (several tens of meters) of full-size cable-in-conduit conductor (CICC) and joints under operational conditions (current & field) similar to those experienced by the ITER Poloidal Field coils [5].

At present, the knowledge of the behavior of ITER-type NbTi CICC is mainly based on the test of sub-size samples, and of short full-size samples and joints [6]–[8]. Among the interesting results of these tests (including some still open problems), we may quote the so-called sudden quench of the conductor at currents (and/or temperatures) lower than expected from the single strand performance [9]. The PFCI is the first long-length test of a full-scale, ITER-type NbTi CICC (same as the PF1&6 conductor but for a somewhat lower Cu/nonCu ratio—1.41 vs. 1.6), see Fig. 1. Also for the first time, an ITER-PF-type joint [10] will be tested in the PFCI in time-varying magnetic field acting both in axial direction, i.e., in the "plane" of the joint (as was already the case in [6]) and in radial direction, i.e., orthogonal to that "plane"—a completely new entry for this type of joint (although ITER-CS-type joints, US design, were tested in the past in both parallel and transverse pulsed fields, at the MIT Pulse Test Facility [11]).

II. Status of Coil Manufacturing

The PFCI coil is being manufactured by Tesla Engineering, Storrington (UK), under contract from EFDA. The superconducting and dummy (copper) cables for the coil and its Full Scale Joint Sample (PFCI-FSJS) [10] have been supplied to EFDA in 2002 by the Russian Federation under an ITER Task Agreement. The cables have been jacketed inside stainless steel square tubes by Ansaldo Superconduttori [5] and shipped to Tesla in mid-2003.

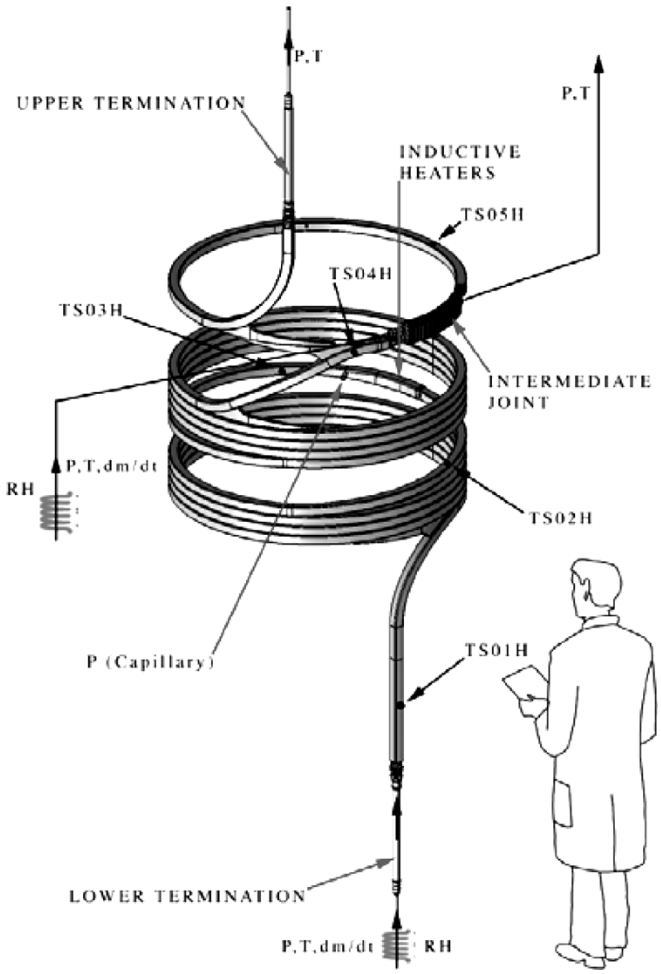

Fig. 1. Sketch of the ITER PFCI coil. Main winding (lower) and NbTi busbar (upper) are electrically connected by the intermediate joint and separately cooled by independent helium circuits. Thermal-hydraulic sensors and heaters are also shown. Courtesy of D. Duglue.

The PFCI-FSJS has been shipped to the Sultan facility in Villigen in February 2004 and tested in March-April 2004 [7]. The results of these tests have shown a high resistance of the joint (~ 10 nΩ) due to the low RRR of the Cu materials and the soldering procedure of the cable to the joint sleeve. Further R&D work has been now undertaken at Tesla to reduce the intermediate joint and lower termination resistance (the upper termination has already been manufactured according to the old design) [10].

A dummy winding consisting of a few turns is being completed to validate the manufacturing processes, in particular winding of the thick square conductor, application of the insulation and vacuum impregnation, and the inspection/testing procedures. The main winding of the PFCI has also been completed, as well as the upper busbar. It is expected that the impregnation of the coil will be completed by January 2005 and the assembly/shipment to the Naka facility should occur by March 2005.

III. Experimental Setup and Available Diagnostics

The PFCI will be installed for testing in the facility at JAERI Naka. Two DC power supplies (PS), 15 V, 50 kA and 12 V, 60 kA for the CSMC and the PFCI, respectively, will be available for DC operation. The inner and the outer module of the CSMC will be connected in series. Pulse mode operation will require the availability of the JT-60 PS.

TABLE I
PFCI Sensors

Sensor	Quantity [a]	Potential [b]
Voltage taps [c]	19 (M) + 2 (B)	H
Quench detection coil	1 pair (C)	H
Cernox temperature sensor	4 (M) + 1 (B)	H
Multiple Hall carriers	1 (M) + 1 (B)	H
Saddle-shape pick-up coils	3 (M)	L
Compensation coils	3 (M)	L
Cryogenic linear temperature sensor	1 (C) + 2 (S)	L
Strain rosettes (bi-directional)	5 (C)	L
Strain gauges (uni-directional)	3 (S)	L
Displacement Transducers	2 (S)	L

[a] M=main winding conductor, B=NbTi busbar, C=coil (after impregnation), S=structure
[b] H= high, L=low.
[c] Single taps, for standard diagnostics + 2 multiple taps (4 taps = "quadrupole" on a given conductor cross-section, one of which a common) for current distribution monitoring.

Inductive (IH) and resistive (RH) heaters will drive several tests (see Fig. 1):

- One pair of IH will be co-wound on the full square conductor near the middle of the main winding.
- RHs from the JAERI facility will be available on the inlet piping of the PFCI main winding and upper busbar.
- Two additional RHs will be installed along the saddle pieces of the intermediate joint, on the inner and outer surfaces.

The available diagnostics for the monitoring of the coil conditions are summarized in Table I and the location of some of them is shown in Figs. 1, 2. The winding has been equipped with an adequate number of voltage taps along the coil for current sharing temperature (Tcs) and quench propagation measurements (Fig. 2). For current distribution measurements, multiple Hall probe (HP) carriers (see below) are used near the lower and upper terminations (Fig. 2), together with multiple voltage taps ("quadrupoles") around the cross section of the conductor at two axial locations (Fig. 2). The natural unbalance in the current distribution among the cable elements is known in short samples to affect the voltage-current transition of the conductor, and so the critical current (Ic) and Tcs measurements, and has been investigated using HPs [12] and transverse voltage measurements [13]. In the PFCI, the extent of current nonuniformity induced by the terminations in the different operating conditions will be assessed by the HP arrays, while the possible absence of a significant effect from current nonuniformity (transverse voltage) on the VI transition will be confirmed by the signals from the "quadrupole" voltage taps. Temperature sensors on the conductor jacket will be available for calorimetric measurements (Fig. 1) and saddle-shaped pick-up coils (in pairs with the respective compensation coil) for AC loss measurements (Fig. 2). Other thermometers and strain

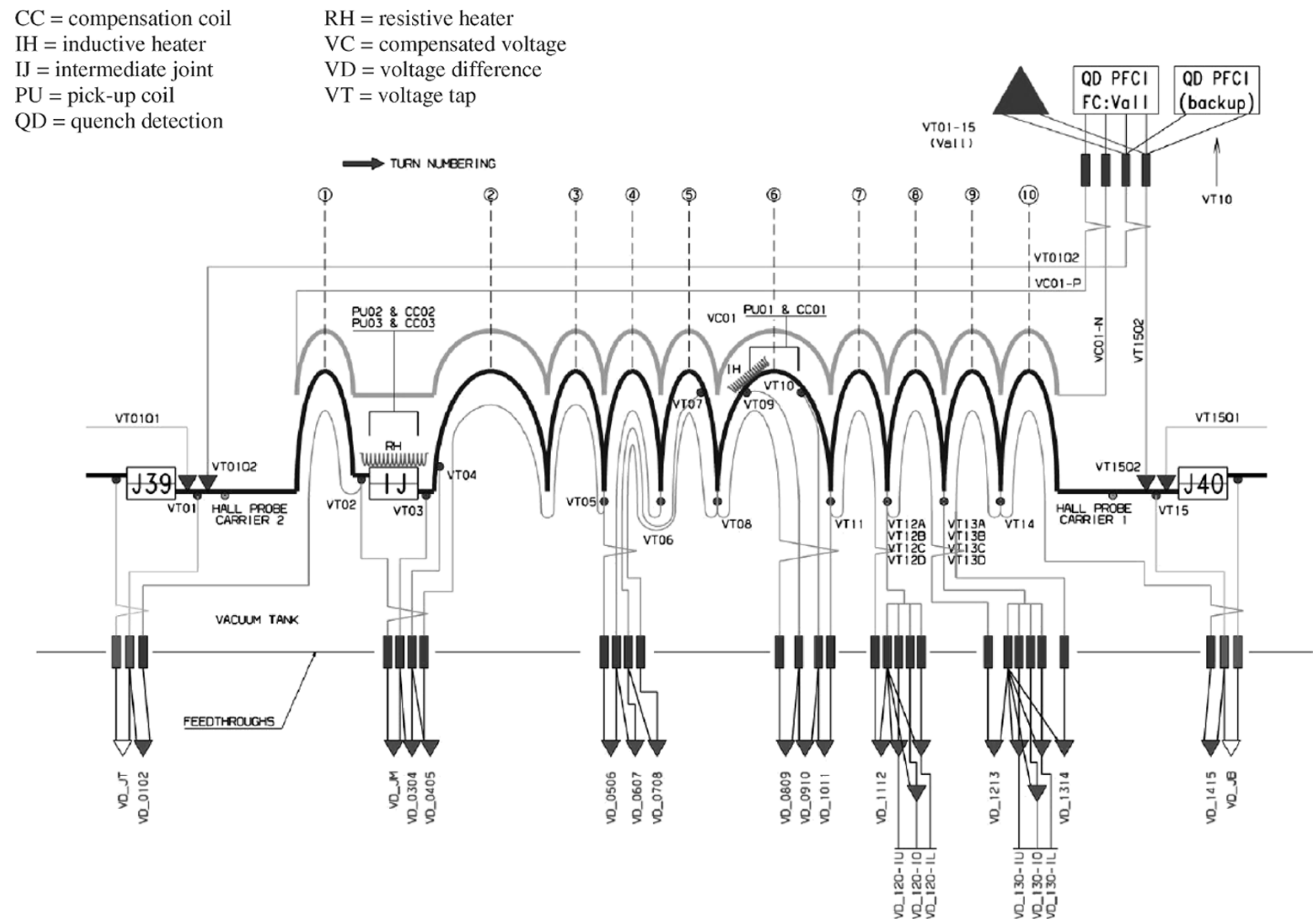

Fig. 2. Sketch of the ITER PFCI electrical sensor location.

gauges will monitor the temperature and deformation of the coil and structure during cooldown and operation.

The two measuring heads carrying HPs [14] will be fixed to circular machined sections of the PFCI conductor. Each circular head has 20 Hall probes distributed symmetrically around the cable (~24.3 millimeters from the conductor axis). To cancel, at least to a great part, the effect of the external (CSMC) field, the voltage difference between the Hall voltage of each HP and that of the probe located on the other side of the cable in the radial direction will be measured. While the Hall voltage due to the cable current has the same sign for both HPs, the voltages due to the external field have opposite signs and they cancel mutually. High linearity HPs with sensitivity of ~40–50 mV/T at control current of 100 mA will be used.

IV. Test Program

The test program for the PFCI relies heavily on the above-mentioned experience gained from the tests of the previous ITER Insert and Model Coils, as well as of the NbTi sub-size and/or short full-size samples. However, as the realistic schedule for testing appears at present to be around 2005 to 2006, the testing program is for the time being still in fieri. Also the restriction in the precise time available for testing will influence the final version.

The test program shall include at least a subset of the following items:

- Thermal-hydraulic tests
  1. Pressure drop measurements
  2. RH tests and calorimetry calibration
  3. IH tests
- DC mode
  4. Nominal DC charging
  5. Joint resistance measurement
  6. Tcs and Ic measurement (using RH)
  7. AC loss measurement in exponential discharge mode (conductor and joint)
  8. Stability and quench test (using IH)
  9. Cyclic test
- Pulse mode 42
  10. Nominal pulse operation
  11. AC loss measurement in pulse operating mode
  12. Ramp rate limitation test

A few comments/details on selected items of the test program follow. Item #5 should confirm the success of the joint re-qualification program [10], which started after the test of the PFCI-FSJS [7]. Item #6 should show if and how the different conductor length and magnetic field distribution (with respect to peak field and joint location) may affect the loss of performance of NbTi CICC observed at high currents in short samples. Items

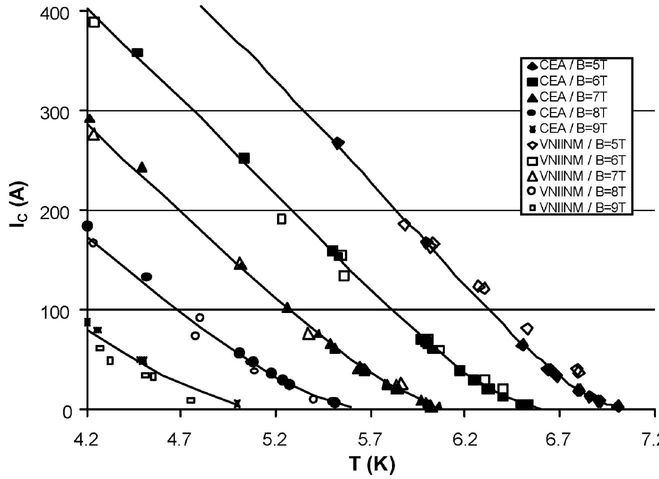

Fig. 3. Measured critical current (symbols) at different temperature and field for PFCI strands tested at different labs. The best fit of the whole data set (see text) at each field is also shown (solid lines).

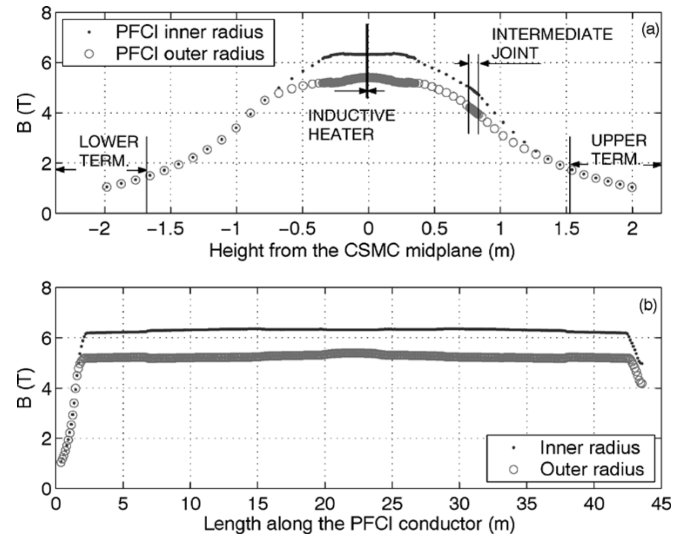

Fig. 4. Total magnetic field computed with 21 kA in the CSMC and 45 kA in the PFCI: (a) as a function of the height from the CSMC equatorial plane, (b) along the PFCI conductor main winding (curvilinear coordinate measured from lower termination He inlet). Two radial locations are considered on the cable cross section: the inner radius ($\mathrm{R} \sim 0.719$ m from the CSMC axis) and the outer radius ($\mathrm{R} \sim 0.757$ m).

#7 and #11 will rely on the separate calibration of the magnetization measurement in the JAERI dipole facility, as well as on the accuracy of calorimetry, which in the case of the joint may be complicated by heat exchange between conductor and neighboring structures. They will provide the first full dataset on joint AC losses for the PF coil. Item #8 will likely encounter similar limitations as in previous Insert Coil tests from the stability point of view (large fraction of the IH power going to the jacket instead of directly to the strands, to be confirmed by separate IH calibration tests in the JAERI dipole facility), but it will also provide the first quench propagation data for an ITER NbTi CICC.

V. Supporting Characterization and Modeling

A. Strand Characterization

The PFCI strand was characterized at different labs [15]–[17], in the range of magnetic field and temperature conditions relevant for the test program.

Results are summarized in Fig. 3 , showing some scattering between the results of the two labs, due to the probably different origin (billet) of the tested strands. Highest sensitivity appears in Tcs tests at low field (~0.2 K difference). The best-fit parameters of the critical current density temperature/field dependence according to the ITER design criteria [18] are $\mathrm{C_0} = 3.384 \times 10^{11}$ A T/m^2, $\mathrm{B_{C20}} = 14.83$ T, $\mathrm{T_{C0}} = 9.02$ K, $\alpha = 1.69$, $\beta = 1.91$, $\gamma = 2.13$.

B. Conductor Characterization

Short sample tests have shown that the AC loss, in terms of interstrand coupling loss, varies with the number of load cycles (= charges to some current I at some field B). From virgin state to roughly hundred cycles the coupling loss decreases while with a significantly higher number of cycles the coupling loss increases [19]. Inter-bundle contact resistances measured at these tests are required for analysis [20].

Hydraulic characterization (pressure drop measurement) of the annular (bundle) region of short PFCI conductor samples has been performed using pressurized water at room temperature [21]. These data could be used, in combination with the results of the test program item #1 above, to characterize the friction in the PFCI.

C. Magnetic Field Map

The magnetic field map in the conductor region was computed as shown in Fig. 4. The field reaches ~95% of its peak value after ~2 m from the lower termination inlet, then stays flat for most of the conductor length. Note also the rather large field variation (~1 T in this case) on the conductor cross section. Different models applied for this computation agree within ~1%.

D. Modeling

Different tools have been used in the past for ITER PF relevant simulations [22], [23], as well as for the analysis of NbTi short full-size samples [24], [25]. Indeed, it is expected that the PFCI test shall be an ideal test bed for the validation of tools aiming at the ITER PF simulation.

Simulations, specifically devoted to the PFCI, have been performed with the Mithrandir code [26] in order to assess the most suitable location of the voltage taps along the conductor, which are a critical item in view of the limited/fixed number of feedthrough available. Here we have at least two conflicting issues: the Tcs tests are driven by the RH at the conductor inlet, whereas the quench propagation tests are driven by the IH, which is located near the middle of the main winding.

In view of the relatively flat shape of the magnetic field, see Fig. 4(b), it is to be expected that during Tcs measurements, using a multi-step (staircase) heating strategy as for the previous ITER Insert and Model Coils [27], the normal zone will be initiated fairly close to the lower termination. Although the behavior of a NbTi conductor in this type of transients seems hard to predict with the present tools [25], preliminary simulations of a Tcs test @ $\mathrm{I_{PFCI}} = 45$ kA, $\mathrm{I_{CSMC}} = 21$ kA show that the normal zone should be initiated between ∼2 m and ∼4 m from the lower termination inlet, depending on the slope of the inlet temperature rise, so that VT14 will be located at ∼2 m from there and VT13 at ∼5–6 m.

Preliminary simulations of quench propagation @ $I_{PFCI} = 45\ kA$, $I_{CSMC} = 21\ kA$ and $T\ (t = 0) = 5\ K$, have shown that monitoring this propagation requires two voltage taps (VT10, 09) across the IH (virtual hot spot thermometers) and two additional voltage taps on each side, sufficiently close to the IH. However, it should be pointed out that, although quench propagation analysis with the Mithrandir code was repeatedly validated in the past against Nb_3Sn CICC data, see e.g. [28], [29] this is the first quench simulation of a NbTi CICC.

The JUST code [23] was applied to the analysis of AC losses in the PFCI intermediate joint. The reference scenario of an exponential discharge of the CSMC current from 21.2 kA with 20 s time constant ($I_{PFCI} = 0\ kA$) has been studied. The losses are split according to the two contributions from dB_R/dt and dB_Z/dt. The computed peak power is similar for both (∼15 W). Indeed a much longer time constant for the "radial" losses (due to large-area, low-resistance current loops flowing through a few petals of each connected conductor and crossing through the joint plane) partly compensates the fact that $dB_R/dB_Z = B_R/B_Z \sim 0.3$ at the joint location. (Note that the latter ratio is rather different from that, ∼1.3–1.7, expected for the ITER PF6 coil.) In the end, the computed energy loss due to the radial field is about 2/3 of the total.

VI. Conclusion and Perspectives

The manufacture of the PFCI is under way in the EU and the ITER parties are developing the test program collaboratively. The PFCI will be a significant item for the assessment of the NbTi conductor and joint design in the perspective of the ITER PF coils, with particular relevance for the verification of the present design criteria. Some experimental and first modeling results supporting the forthcoming test have been presented. Several items of the test program, e.g., the joint resistance and AC losses measurement, the quench propagation and, possibly, the DC characterization of the conductor, should provide new results useful in bridging the extrapolation gap between strand and coil performance. The database for the validation of modern ITER-relevant computational tools will also be significantly extended, with particular emphasis on coupled thermal-hydraulic electromagnetic transients.

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