

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 taps, strain and displacement sensors. The test program shall 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 towards 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, superconductors, nuclear fusion

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

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I. INTRODUCTION

THE development of superconducting coils has been a major item of the R&D activities of the experimental nuclear fusion reactor ITER for the past ten years. This development has gone through several steps. The first phase consisted of the qualification of full-size conductors and ITER-relevant coils in Nb₃Sn, 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

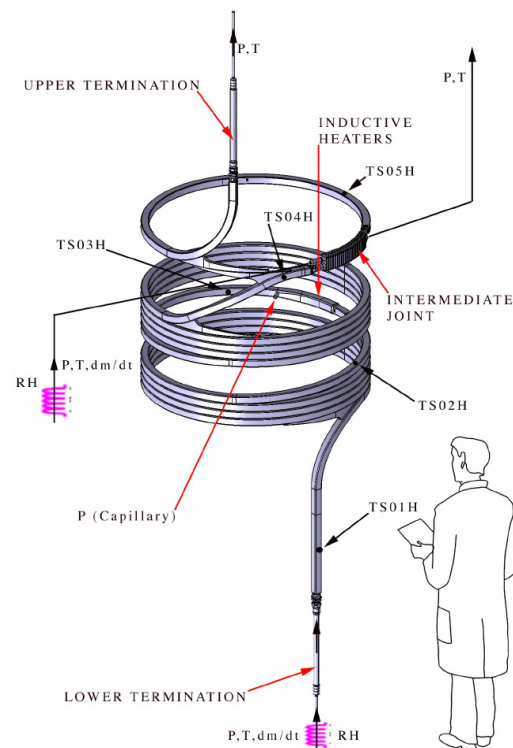


Fig. 1. Sketch of the ITER PFCI coil. Main winding (lower) and NbTi busbar (upper) are electrically connected by the intermediate joint and separately cooled by independent helium circuits. Thermal-hydraulic sensors and heaters are also shown. Courtesy of D. Duglue.

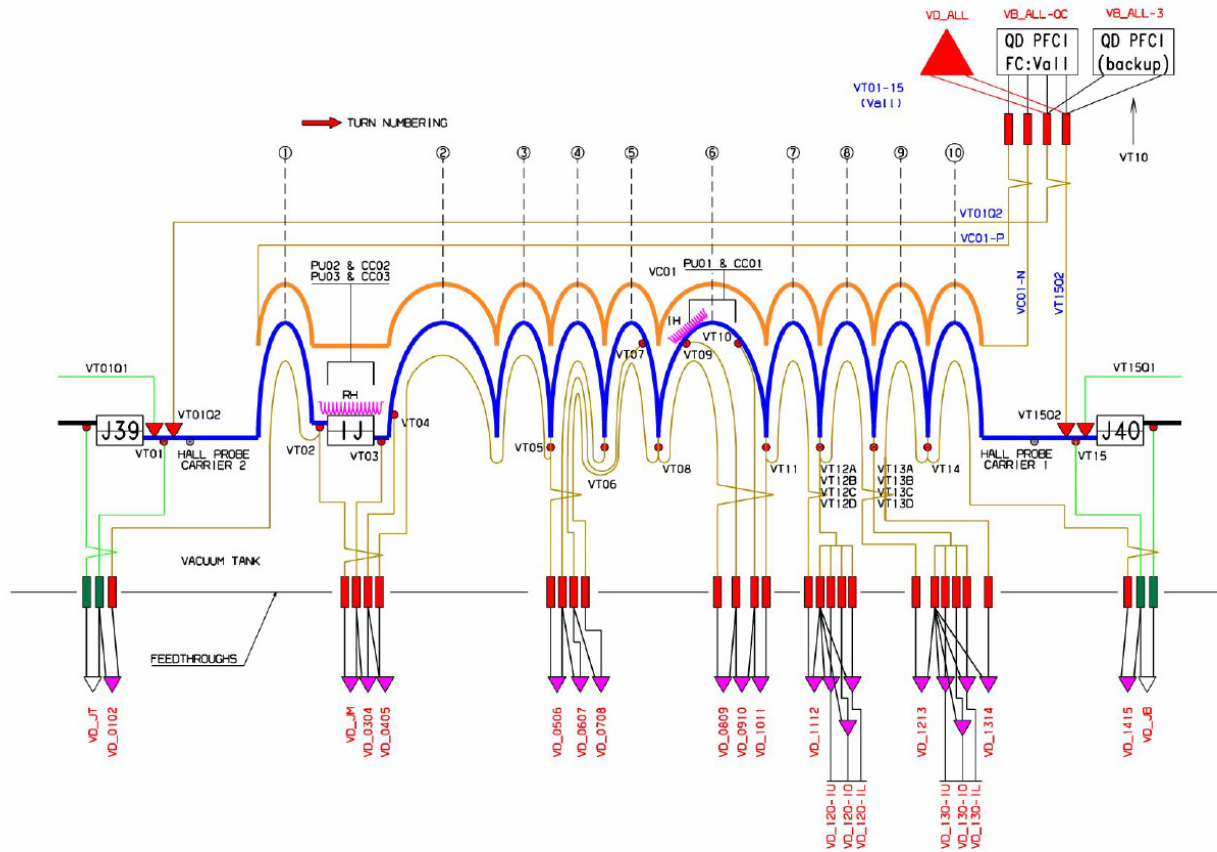


Fig. 2. Sketch of the ITER PFC electrical sensor location.

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 lower currents and/or temperatures compared to what expected from the single strand performance [9]. The PFC1 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 PFC1 in time-varying magnetic field acting both in the axial direction, i.e., in the “plane” of the joint (as was already the case in [6]) and in the 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 PFC1 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 (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.

The PFC1-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 by 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 PFC1 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 PFC1 will be installed for testing in the facility at JAERI Naka. Two DC power supply (PS), 15 V, 50 kA and 12 V, 60 kA for the CSMC and the PFC1, 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.

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 non-uniformity (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 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
 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 hopefully 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 #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

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

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, 16], under different field/temperature conditions relevant for the test program.

Results are summarized in Fig.3 below, showing some scattering between the two labs results 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 [17] are $C_0 = 3.384 \times 10^{11}$ A T/m², $B_{C20} = 14.83$ T, $T_{C0} = 9.02$ 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 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 [18]. Inter-bundle contact resistances measured at these tests are required for analysis [19].

Hydraulic characterization (pressure drop measurement) of the annular (bundle) region of short PFCI conductor samples has been performed using pressurized water at room temperature [20]. 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 $\sim 95\%$ of its peak value after ~ 2 m from the lower termination inlet, then stays flat for most of the conductor. Note also the rather large field variation (~ 1 T in this case) on the conductor cross

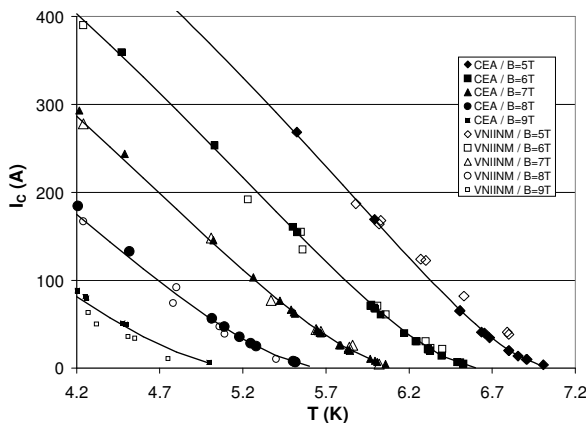


Fig. 3. Measured critical current (symbols) at different temperature and field for PFCI strands tested at different labs. The best fit of the whole data set (see text) at each field is also shown (solid lines).

section. Different models applied for this computation [21] agree within $\sim 1\%$.

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 feed-through 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.4b, 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 @ $I_{PFCI} = 45$ kA, $I_{CSMC} = 21$ 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 $\sim 5-6$ 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

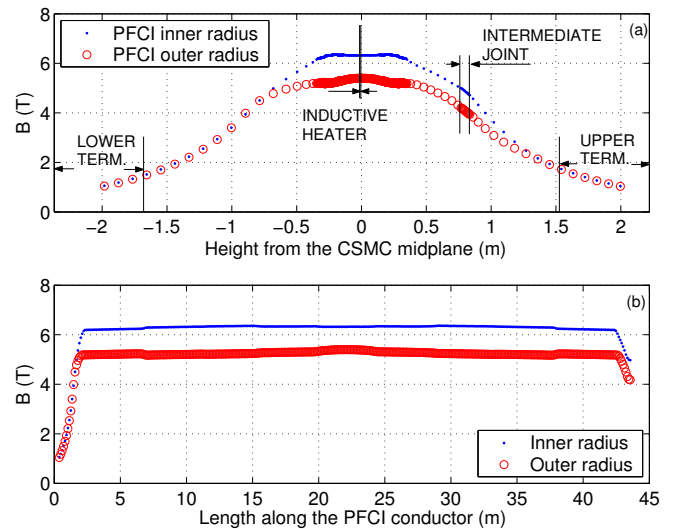


Fig. 4. Total magnetic field computed with 21 kA in the CSMC and 45 kA in the PFCI: (a) as a function of the height from the CSMC equatorial plane, (b) along the PFCI conductor main winding (curvilinear coordinate measured from lower termination He inlet). Two radial locations are considered on the cable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

IH. However, it should be pointed out that, although quench propagation analysis with the Mithrandir code was repeatedly validated in the past against Nb3Sn CICC data, see e.g. [28], 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) because 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.

REFERENCES

- [1] H. Tsuji, et al., “Progress of the ITER Central Solenoid Model Coil Program”, *Nucl. Fusion*, vol. 41, pp. 645-651, 2001.
- [2] N. Martovetsky, et al., “Test of the ITER Central Solenoid Model Coil and CS Insert”, *IEEE Trans. Appl. Supercond.*, vol. 12, pp. 600-605, 2002.
- [3] N. Martovetsky, et al., “Test of the ITER TF Insert and Central Solenoid Model Coil”, *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1441-1446, 2003.
- [4] A. Ulbricht, et al., “The ITER Toroidal Field Model Coil project”, submitted to *Fus. Eng. Des.*, 2004.
- [5] C. Sborchia, et al., “Design and Manufacture of the ITER Poloidal Field Conductor Insert Coil”, *Fus. Eng. Des.*, vol. 6668, pp. 1081-1086, 2003.
- [6] D. Ciazynski, et al., “Test result on the first 50 kA NbTi full size sample for ITER”, *Supercond. Sci. Technol.* vol. 17, pp. S155-S160, 2004..
- [7] P. Bruzzone, et al., “Test Results of the ITER PF Insert Conductor Short Sample in SULTAN”, presented at ASC04.
- [8] R. Zanino, et al., “Current Distribution Measurement on the ITER-type NbTi Bus Bar III”, presented at ASC04.
- [9] R. Wesche, et al., “Sudden take-off in large NbTi conductors: not a stability issue”, *Adv. Cryo. Eng.*, vol. 50 B, pp. 820-827, 2004.
- [10] F. Hurd, et al., “Design and Manufacture of a Full Size Joint Sample (FSJS) for the Qualification of the Poloidal Field (PF) Insert Coil”, presented at ASC04.
- [11] P. C. Michael, et al., “Qualification of Joints for the Inner Module of the ITER CS Model Coil”, *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 201-204, 1999.
- [12] A. Formisano, et al., “DC and transient current distribution analysis from self-field measurements on ITER PFIS conductor”, submitted to *Fus. Eng. Des.*, 2004.
- [13] Yu. Ilyin, et al., “Reconstruction of the current unbalance in full-size ITER NbTi CICC by self field measurements”, presented at ASC04.
- [14] J. Kvitkovic, et al., “Cryogenic microsize Hall sensors”, in *Proceedings of EUCAS 93*, Oberursel, 1993, p. 1629.
- [15] N. I. Kozlenkova, et al., “Study on $I_c(T, B)$ for the NbTi Strand Intended for ITER PF Insert Coil”, *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 1028-1030, 2004.
- [16] L. Zani, et al., “Task TW1-TMC/SCABLE: Final Report on Characterization of NbTi strands representative for the ITER PF Coils”, CEA Report AIM/NTT-2004.005, February 2004; L.Zani, et al., “ $J_c(B, T)$ characterization of NbTi strands used in the ITER Poloidal Field Coil-relevant Full Scale Joint Samples and Inserts”, presented at ASC04.
- [17] L. Bottura, “A Practical Fit for the Critical Surface of NbTi”, *IEEE Trans. Appl. Supercond.*, vol. 10, pp. 1054-1057, 2000.
- [18] A. Nijhuis, et al., “Change of Interstrand Contact Resistance and Coupling Loss in Various Prototype ITER NbTi Conductors with Transverse Loading in the Twente Cryogenic Cable Press up to 40,000 Cycles”, *Cryogenics*, vol. 44, pp. 319-339, 2004.
- [19] Yu. Ilyin, et al., “Effect of Cyclic Loading and Conductor Layout on Contact Resistance of Full-Size ITER PFCI Conductors”, presented at ASC04.
- [20] C. Marinucci, et al., “Pressure drop in the ITER PFI cable-in-conduit conductor”, presented at ASC04.
- [21] Y. Nunoya, private communication, 2004; E. Zapretilina, private communication, 2004.
- [22] S. Nicollet, et al., “Conductor Analysis of the ITER FEAT Poloidal Field Coil during a Plasma Scenario”, *Adv. Cryo. Eng.*, vol. 47A, pp. 431-438, 2002.
- [23] D. Ciazynski, et al., “Electrical and Thermal Designs and Analyses of Joints for the ITER PF Coils”, *IEEE Trans. Appl. Supercond.*, vol. 12, pp. 538-542, 2002.
- [24] R. Zanino, et al., “Modeling AC losses in the ITER NbTi Poloidal Field Full Size Joint Sample (PF-FSJS) using the THELMA code”, submitted to *Fus. Eng. Des.*, 2004.
- [25] D. Ciazynski, et al., “DC Performances of ITER NbTi Conductors: Models vs. Measurements”, presented at ASC04.
- [26] R. Zanino, et al., “A Two-Fluid Code for the Thermohydraulic Transient Analysis of CICC Superconducting Magnets”, *J. Fus. Energy*, vol. 14, pp. 25-40, 1995.
- [27] R. Zanino, et al., “Analysis and Interpretation of the Full Set (2000-2002) of Tes Tests in Conductor 1A of the ITER Central Solenoid Model Coil”, *Cryogenics*, vol. 43, pp. 179-197, 2003.
- [28] L. Savoldi, et al., “Inductively Driven Transients in the CS Insert Coil (II): Quench Tests and Analysis”, *Adv. Cryo. Eng.*, vol. 47, pp. 423-430, 2002; L. Savoldi Richard, et al., “Tests and Analysis of Quench Propagation in the ITER Toroidal Field Conductor Insert”, *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1412-1415, 2003.