

# Test Results of the ITER PF Inset Conductor short Sample in SULTAN

P. Bruzzone, M. Bagnasco, D. Bessette, D. Ciazynski, A. Formisano, P. Gislou, F. Hurd, Y. Ilyin, R. Martone, N. Martovetsky, L. Muzzi, A. Nijhuis, H. Rajainmäki, C. Sborchia, B. Stepanov, L. Verdini, R. Wesche, L. Zani, R. Zanino, E. Zapretulina,

**Abstract**—A short sample of the NbTi cable-in-conduit conductor (CICC) manufactured for the ITER PF inset coil has been tested in the SULTAN facility at CRPP. The short sample consists of two paired conductor sections, identical except for the sub-cable and outer wraps, which have been removed from one of the sections before jacketing. The test program for conductor and joint includes DC performance, cyclic load and AC loss, with a large number of voltage taps and Hall sensors for current distribution. At high operating current, the DC behavior is well below expectations, with temperature margin lower than specified in the ITER design criteria. The conductor without wraps has higher tolerance to current unbalance. The joint resistance is by far higher than targeted.

**Index Terms**—Cable-in-conduit conductor, self-field induced quench, joint resistance, ITER, niobium-titanium

## I. INTRODUCTION

THE Poloidal Field Conductor Inset (PFCI) is so far the only full size demonstration project for the NbTi conductors of the ITER magnets. Based on a cable prepared in Russia, the inset coil is being manufactured in Europe and will be tested in Japan [1]. Two short conductor sections have been assembled into a short sample [2] for the SULTAN test facility [3]. A testing group, including members of many European labs as well as ITER IT members, has been

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P. Bruzzone, B. Stepanov and R. Wesche are with EPFL-CRPP, Fusion Technology, 5232 Villigen PSI, Switzerland (phone: +41563104364 fax: +41563103729 e-mail: [bruzzone@psi.ch](mailto:bruzzone@psi.ch), [stepanov@psi.ch](mailto:stepanov@psi.ch), [wesche@psi.ch](mailto:wesche@psi.ch)).

D. Bessette is with ITER-CTA, 85748 Garching b. München, Germany (e-mail: [bessette@itereu.de](mailto:bessette@itereu.de)).

D. Ciazynski and L. Zani are with CEA Cadarache, 13108 St. Paul Lez Durance, France (e-mail [daniel.ciazynski@cea.fr](mailto:daniel.ciazynski@cea.fr), [louis.zani@cea.fr](mailto:louis.zani@cea.fr)).

A. Formisano and R. Martone are with Seconda Università di Napoli, 81031 Aversa, Italy (e-mail [A.Formisano@unina.it](mailto:A.Formisano@unina.it), [martone@unina.it](mailto:martone@unina.it)).

M. Bagnasco and R. Zanino are with Politecnico, 10129 Torino Italy (e-mail [roberto.zanino@polito.it](mailto:roberto.zanino@polito.it), [maurizio.bagnasco@polito.it](mailto:maurizio.bagnasco@polito.it)).

P. Gislou, L. Muzzi and L. Verdini are with ENEA, 00044 Frascati, Italy ([gislou@frascati.enea.it](mailto:gislou@frascati.enea.it), [muzzi@frascati.enea.it](mailto:muzzi@frascati.enea.it), [verdini@frascati.enea.it](mailto:verdini@frascati.enea.it)).

F. Hurd, H. Rajainmäki and C. Sborchia are with EFDA, 85748 Garching b. München, Germany (e-mail [hurdf@ipp.mpg.de](mailto:hurdf@ipp.mpg.de), [sborchc@ipp.mpg.de](mailto:sborchc@ipp.mpg.de), [hannu.rajainmaki@tech.efda.org](mailto:hannu.rajainmaki@tech.efda.org)).

Y. Ilyin and A. Nijhuis are with University of Twente, 7500 AE Enschede, The Netherland (email [Y.Ilyin@utwente.nl](mailto:Y.Ilyin@utwente.nl), [A.Nijhuis@utwente.nl](mailto:A.Nijhuis@utwente.nl)).

N. Martovetsky is with LLNL, Livermore, CA 94550 (email [martovetsky1@llnl.gov](mailto:martovetsky1@llnl.gov)).

E. Zapretulina is with NIEFA, 196641 St. Petersburg, Russian Federation.

entrusted with the assessment of the test results. The main aim of the test, carried out in March-May 2004, is a wide characterization of the NbTi CICC and a qualification of the joint layout for the Inset Coil.

## II. CONDUCTOR AND SAMPLE LAYOUT

Although some parameters have been a priori dictated by the availability of material (e.g. Cu:non-Cu ratio and steel jacket size), the conductor layout of the PFCI reflects the design of the ITER PF1&6 conductors [4], see Table I.

A 74m long cable section has been manufactured at VNIIEP (Podolsk, Russia) [5], based on 130km of NbTi strand, 17 batches / 126 unit lengths, supplied by Bochvar RIIM (Moscow). Based on the results of all the  $I_c$  data sheets, the supplier proposed an interpolation formula for  $J_c$  in the strand [6], marginally corrected by the testing group:

$$J_c(B, T) = C_0 B_{c2}(T)^{m-p} B^{p-1} (1-b)^q$$

$$B_{c2}(T) = B_{c2}(0)(1-t^2)(1-c_1 t)$$

where

$$b = B/B_{c2}(T) \quad t = T/T_c$$

$B_{c2}(0)$	13.65
$T_c$	9.33
m	2.36
p	1.05
q	1.22
$C_0$	$2.89928 \cdot 10^8$
$c_1$	0.167

The above formula is retained in the predictive analyses [7]. Another fit, based on test results of a single strand over a broader range of temperature, is reported in [8].

The jacketing into circle-in-square stainless steel tubing was carried out at Ansaldo (Italy). A 59m long conductor section was supplied to Tesla (UK) to wind the Inset Coil. Three straight sections, each about 5m long, were also supplied. In one of the cable short section, the sub-cable and outer wraps have been removed and the jacket has been compacted to a slightly smaller size, see Table I.

The sample for SULTAN, named PFIS = Poloidal Field Inset(conductor) Sample, consists of one “regular” conductor section (PFIS<sub>w</sub>) and one “de-wrapped” section (PFIS<sub>nw</sub>), joined at one end by a hairpin joint, prepared by compacting the cable ends into CuCrZr sleeves and joining them by five copper saddles [2]. The Ni coating is removed from the strands in contact with the sleeve and replaced by Ag. The inner wall of the sleeve is tinned and the contact between sleeve and saddle is made by a number of indium wires,

TABLE I  
LAYOUT OF THE PFIS CONDUCTORS, COMPARED TO ITER PF1&6 DESIGN

	PFIS <sub>w</sub>	PFIS <sub>NW</sub>	ITER PF1&6
NbTi strand diameter (Ni coated), mm	0.73	0.73	0.73
Cu:non-Cu	1.41*	1.41*	1.6
Number of strands (3x4x4x5x6)	1440	1440	1440
Total Cu cross section, mm <sup>2</sup>	353	353	371
Total non-Cu cross section, mm <sup>2</sup>	250	250	232
Sub-cable wraps cross section, mm <sup>2</sup>	13.4	-	7.6
Outer wrap cross section, mm <sup>2</sup>	22.3	-	19.8
Cable space diameter, mm	37.53	36.89	38.2
Cable pitches, mm	42/86/ 122/158/	42/86/ 122/158/	45/85/ 125/165/
Estimated/retained cos $\theta$	0.96	0.96	0.95
Steel spiral for central channel, mm	10 x 12	10 x 12	10 x 12
Void fraction, %	33.5**	34.3**	34.5
Outer conductor size, mm	50.35 x 50.45	49.82 x 49.78	53.8x53.8

\* weighted average according to strand and cable QA sheets

\*\* calculated assuming zero elongation of the strands during compaction

pressed by the joint clamp to a 0.2mm thick layer.

The PFIS dimension is the standard of the SULTAN samples [9], about 3.5m long including the hairpin joint and the upper connections. The two conductor lengths are cooled in parallel by independent circuits, with coolant flow from bottom to the top. To avoid temperature gradients over the conductor cross-section and improve the definition of the operating temperature, the central channel has been blocked in both conductor sections inserting a rubber pipe plugged at the outlet side. The central channel is free in the joint and in the termination.

The facility instrumentation, right end of Fig. 1, includes heaters, temperature and pressure sensors at inlets and mass flow meters cryogenic valves and temperature and pressure sensors at the outlets. Ten temperature sensors are attached to the PFIS (symbol "T" in Fig. 1), nested in holes drilled in the jacket. Two sensors are in the inlet pipes, next to the joint.

Two heaters are wrapped on the conductor jacket just downstream of the joint and two small heaters, 6mm x 20mm, are placed in the high field region for local energy deposition.

Six arrays of Hall sensors are attached to the conductors in high field, next to the joint and termination (symbol "H" in Fig. 1) to sense the self-field distribution. The conductor jacket is turned round to a constant wall thickness at the location of the arrays. Each array includes 10 sensors. Next to the upper termination, where the stray field from the facility is weak, the sensors are symmetrically distributed over the perimeter, at 10° from the radius. At the other four locations,

the 10 sensors are oriented parallel to the background field to improve the resolution of the self-field signal [10, 11]. The active spot of the sensor is placed at  $\varnothing = 49\text{mm}$ , i.e. about 6.5mm from the outer edge of the cable.

A saddle shaped pick-up coil is attached to each conductor in the high field/AC field region to detect the magnetization change, see Fig. 1. Compensation coils are placed outside the test well, next to the AC field coils.

A total of 37 voltage tap pairs are placed along and across the conductors and joint. Two synchronized data acquisition systems collect respectively 63 and 68 signal channels at 25Hz sampling rate (AC loss runs use a higher sampling rate). The ASCII files of the two systems are imported into a single spreadsheet. The unusual large number of channels leads to very bulky files, in the range of 20-70MB for each run.

### III. SUMMARY OF TEST RESULTS

The test campaign for PFIS lasted from mid March to the end of April 2004, with 50 critical current ( $I_c$ ) and 20 current sharing temperature ( $T_{cs}$ ) runs at various operating conditions and 100 bipolar load cycles ( $\pm 45\text{kA}$  @ 7T background field). Due to the high joint resistance, the  $I_c$  runs were not isothermal and the ramp rate was not constant. The AC test included loss curves vs. frequency by gas flow calorimetry and magnetization methods for both conductors in the background field of 2T, with AC field amplitude of  $\pm 0.2\text{T}$ , before and after cycling, at 4.5 K and above  $T_c$ . The current distribution, monitored by the Hall probes for all the runs, was investigated for different current ramp rate and long holding time.

#### A. DC Performance

The electric field at which the quench occurs,  $E_q$ , decreases at increasing current, as a result of the superposition of self-field and background field. The local electric field along a strand in the cable reaches 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 remains very low. Such self-field induced, sudden take-offs are typical of large size NbTi CICC [12, 13, 14].

The  $0.1\mu\text{V/cm}$  criterion for  $I_c$  and  $T_{cs}$  test could only be measured for current below 45kA (PFIS<sub>NW</sub>) and 38kA (PFIS<sub>w</sub>), see Fig. 2. The behavior vs. temperature is almost linear and the performance difference between the two conductors is within the error bar. The gap to the predicted performance, see [7] for discussion, is of the order of 0.1K.

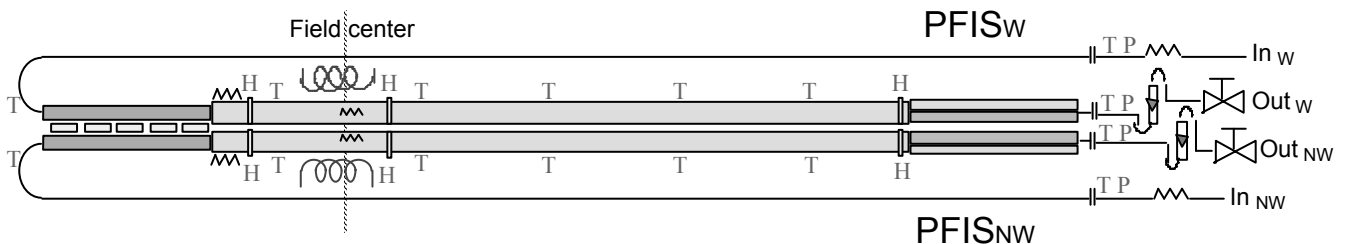


Fig. 1 Instrumentation sketch of PFIS: "H" is for the Hall sensor arrays, "T" and "P" for temperature and pressure sensors (voltage taps are not shown). The sample is positioned in vertical orientation with coolant flow from the bottom to the top

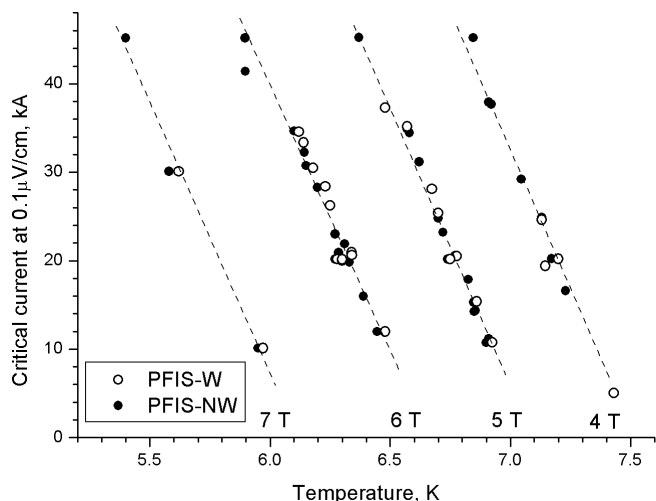


Fig. 2 Summary of critical current and current sharing temperature at the electrical field criterion  $0.1\mu\text{V}/\text{cm}$  at background field of 4, 5, 6 and 7 T. The dashed lines are linear interpolations.

The current at which the voltage take-off occurs, i.e. the quench current  $I_q$ , is shown in Fig. 3. Above 38 kA (PFIS<sub>W</sub>) and 45 kA (PFIS<sub>NW</sub>), i.e. when the take-off is observed at very low electric field level, the behavior of  $I_q$  vs.  $T$  strongly deviates from linearity and the performance is much poorer than expected from the strand. Despite some scattering observed in the high current  $I_q$  results, the performance of PFIS<sub>NW</sub> is better than PFIS<sub>W</sub>, i.e. the deviation from linearity is smaller and occurs at higher current.

The large deviation from the linear behavior is not an intrinsic feature of the self-field induced quenches. To understand the behavior in Fig. 3, we must postulate some current unbalance among the strands. When enough voltage builds up along the strands, see  $I_c$  results in Fig. 2, current redistribution from the overloaded strands is possible in both PFIS<sub>NW</sub> and PFIS<sub>W</sub>. In the condition of self-field induced quench, i.e. with high local electric field but very low average

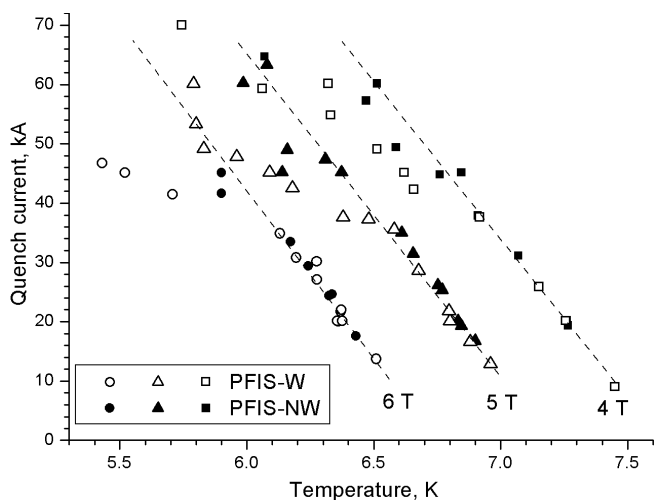


Fig. 3 Summary of quench current results from all the critical current and current sharing temperature runs at 4, 5 and 6 T. The dashed lines are linear interpolations for the low current range.

voltage, the overloaded strands are unable to transfer the excess current to the neighboring strands and quench.

The better behavior of PFIS<sub>NW</sub> suggests that the sub-cable wraps restrict the current re-distribution process. Indeed, for the same quench current, a higher  $E_q$  is observed at PFIS<sub>NW</sub> compared to PFIS<sub>W</sub> [13].

The ITER design values for  $T_{cs}$  of the PF1&6 conductor at 45 kA, 6 T peak field, is 6.5 K, i.e. 1.5 K above the operating temperature of 5 K. The test conditions of PFIS are not identical to ITER-PF: the self-field gradient is higher in PFIS and the joint is closer to the high field. The NbTi strand fulfills the ITER spec at 4.2 K, but the  $J_c$  interpolated at higher temperature is lower than retained in ITER. On the other hand, the non-Cu cross section of PFIS is 8% larger than in the ITER PF1&6 and the central channel is blocked.

Interpolating the experimental results, rescaled with the NbTi area with respect to the ITER coils, one gets a quench temperature of 5.80 K for PFIS<sub>W</sub> and 6.05 K for PFIS<sub>NW</sub> in the ITER PF1&6 coil normal operation, i.e. a temperature margin of only 0.80 K and 1.05 K for PFIS<sub>W</sub> and PFIS<sub>NW</sub>, respectively. These values are also lower than those obtained on a previous sample (PF-FSJS), i.e. 1.25 K and 1.40 K for the left and right legs, respectively [14]. Such a result can be explained both by a lower strand performance [8] and by highly uneven current distributions among strands [7].

Compared to the short sample test in SULTAN, the performance of the insert coil (PFCI) will benefit of a less steep self-field gradient, a longer distance between joint and high field, a longer section exposed to high field and (hopefully) a better balanced current distribution from the joint. On the other hand, the central channel will be open.

### B. Joint Resistance

The cable end for the upper termination of PFIS, connecting to the SULTAN transformer, is prepared like the joint, with the Cu saddle replaced by a flat Cu plate.

An unexpected high resistance was observed in the joint (about 10 nΩ) and in the termination (about 6 nΩ for PFIS<sub>NW</sub> and 18 nΩ for PFIS<sub>W</sub>).

The high resistivity of the CuCrZr sleeve,  $\rho = 9.5 \cdot 10^{-9} \Omega\text{m}$ , makes up to 4 nΩ of the joint resistance. The remainder is likely due to the cable-to-sleeve contact (Ag coated strands

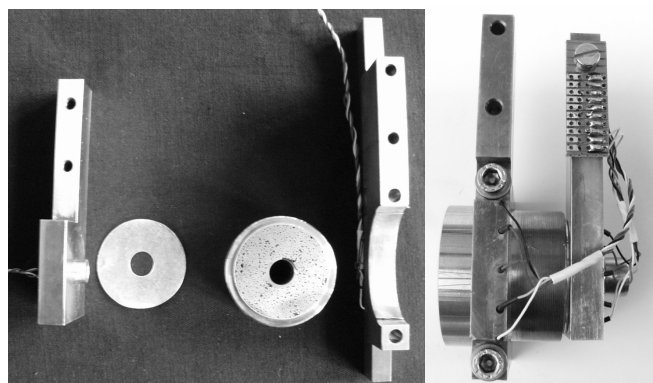


Fig. 4 The slice of conductor termination and its holder: exploded view (left) and assembled sample (right)

pressed/heated to the tinned inner wall of the sleeve).

A 28mm long slice was cut by electronic erosion from a conductor termination, prepared in the same way as for the PFIS joint. The resistance of the slice was measured at CRPP in liquid helium, with the holder shown in Fig. 4. The result,  $R_{\text{slice}} = 240\text{n}\Omega$  for a contact length of 10mm, scales satisfactorily to  $R_{\text{joint}} = 2 \cdot R_{\text{slice}}(10/450) = 10.6\text{n}\Omega$ , providing an easy method to quickly assess the improvements that are planned at Tesla for the PFIC conductor termination [1-2].

The maximum allowable resistance for the joints of the ITER PF coils is  $5\text{n}\Omega$  at 4T, 45kA [4]. Other full size NbTi joints for ITER have achieved resistance of  $\approx 1.5\text{n}\Omega$  (PF-FSJS [14]), and  $\approx 0.7\text{n}\Omega$  (CRPP low cost joint [15]).

### C. AC Loss

The AC loss results of PFIS are not fully satisfactory. The sensors for calorimetry were initially affected by the stray field. The magnetization signals could not be properly compensated due to inhomogeneous background field.

A test of AC loss and contact resistance on sections of PFIS<sub>NW</sub> and PFIS<sub>W</sub> has been carried out at the University of Twente [16]. The twist pitch of the PFIS<sub>NW</sub> section was  $\approx 670\text{mm}$  [17]. The loss is initially higher in PFIS<sub>NW</sub> and decreases in both conductors to about the level of strand loss ( $\tau \approx 10\text{ms}$ ) after the first load cycle. After 1000 load cycles, the loss increases. After 40000 cycles,  $\tau$  at zero/maximum load is 47/67ms (PFIS<sub>W</sub>) and 140/270ms (PFIS<sub>NW</sub>).

The resistance between adjacent strands is higher by over a factor of two in PFIS<sub>W</sub> compared to PFIS<sub>NW</sub> [16], suggesting that the paths to re-distribute the current are not "local" but extend outside the boundaries of the sub-cable.

### D. Current Distribution

Opposite to other SULTAN tests, in which sensors from other supplier were used [18], for the PFIS Hall sensors placed in high field and close to the joints, with large parallel field component, a strong non-linearity is observed for transverse field component [19]. Applying a superimposed AC and background field, the Hall coefficient was recalculated at the operating conditions.

The evolution of the Hall sensors signal during  $T_{\text{cs}}$  runs [13, 19] bring evidence of current re-distribution.

The algorithms for current profile reconstruction starting from the signal of the 10 Hall sensors [19, 11] must use models with a small number of current carrying elements, i.e. the current unbalance can be assessed only at the level of large sub-cables. The Hall sensors arrays are of little help to solve the (likely) case of large current unbalance between neighboring strands.

## IV. CONCLUSION

The conductor DC performances appear to be heavily influenced by a non-uniform current distribution: the PFIS<sub>NW</sub> shows a better behavior, probably due to its higher capacity to redistribute current. Nevertheless, the performance of both

legs is below ITER specifications.

Both conductors, as already observed in [14], suffers of self-field induced take-offs and have no measurable  $T_{\text{cs}}$  at high current. The removal of sub-cable wraps helps to increase the threshold for instability.

The quench temperature,  $T_{\text{q}}$ , of the self-field induced take-offs is very sensitive to current unbalance and cannot be predicted based only on strand properties and cable geometry.

The high joint resistance,  $\approx 10\text{n}\Omega$ , is not acceptable for ITER coils and appears as a sign of fabrication problems. The high resistance is likely responsible for the high imbalance of current distribution. Improvements of joint layout are on going at Tesla for the PF Coil Insert.

In the SULTAN test, the AC loss is in the range of the strand loss, for both conductors, with and without wraps.

From the Hall sensors, the current unbalance is slightly larger in the conductor without wraps, but the extent of current re-distribution is also larger and the electric field before take-off,  $E_{\text{q}}$ , is therefore larger in PFIS<sub>NW</sub>.

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