Current Distribution Measurement on the ITER-Type NbTi Bus Bar III

R. Zanino, M. Bagnasco, F. Bellina, T. Bonicelli, A. della Corte, A. Di Zenobio, W. H. Fietz, A. Formisano, R. Heller, Yu Ilyin, V. Marchese, R. Martone, L. Muzzi, A. Nijhuis, M. Polak, P. L. Ribani, E. Salpietro, L. Savoldi Richard, S. Turtu', L. Verdini, and G. R. Zahn

***Abstract*—The Bus Bar III (BBIII), fabricated within the Toroidal Field Model Coil Task of the International Thermonuclear Experimental Reactor (ITER), was tested at the Forschungszentrum Karlsruhe, Germany, in the spring of 2004. The BBIII consists of an approximately 7 m long NbTi dual-channel conductor with a thick square stainless steel jacket, cooled by forced flow supercritical He. It was energized with currents up to 80 kA and operates in its self magnetic field (up to $\sim$0.8 T). The BBIII was instrumented with Hall-probe heads and arrays, voltage rings and longitudinal voltage taps for electro-magnetic measurements, in order to get experimental data to be used for the validation of a recently developed hybrid thermal-hydraulic electro-magnetic code (THELMA), as well as for the assessment of the possibility of performing a reliable reconstruction of the current distribution in the conductor cross section under controlled conditions. In the tests, current ramps at different rates were applied to characterize the conductor time constants, while two different resistive heaters (one upstream of the BBIII inlet, another one directly on the BBIII jacket) were separately operated in order to approach current sharing in the conductor and to observe the related current re-distribution. In this paper, a summary of the collected experimental results is presented, with particular emphasis on those aspects more relevant for the forthcoming THELMA analysis.**

***Index Terms*—Fusion reactors, ITER, NbTi, superconducting magnets.**

I. INTRODUCTION

THE ITER-type NbTi bus bar III (BBIII) consists of a curved cable-in-conduit conductor (CICC), about 7 m long, made of 1152 NbTi strands cabled with the sequence $3 \times 4 \times 4 \times 4 \times 6$ (wrapping around the last-but-one cabling stage). BBIII was tested in May–June 2004 during Phase II of the High-Temperature Superconducting Current Lead (HTS-CL) experimental campaign in the TOSKA facility at the Forschungszentrum Karlsruhe. In the testing configuration, BBIII is electrically in series with another NbTi bus bar (BBII) and the HTS-CL at + and − terminals, respectively [1]. The BBIII test program was specifically devoted to the current distribution measurement (CDM). Most of the tests were aimed at forcing a current re-distribution in different ways, e.g., approaching current sharing by means of resistive heaters or driving current ramps at different ramp rates dI/dt in the conductor, as listed in Table I. In this paper we present a summary of the measurements results, with emphasis on the aspects considered most interesting for the validation of the THELMA code [2].

TABLE I
OPERATION LOGBOOK FOR THE BBIII

Date	Operation	Comments
19/4 3/6 → 4/6	Hall probes calibration	Problems with current acquisition on 3/6
16/6 → 17/6	Heater tests	–
21/6	T_{CS} @ I = 10 kA	JH[a], no quench
	T_{CS} @ I = 30 kA	JH, quench
	T_{CS} @ I = 50 kA	JH, quench
22/6	T_{CS} @ I = 70 kA	JH, quench
	T_{CS} @ I = 10 kA	JH, quench at max heating power by increasing current
	Current scan test	dI/dt = 0.1 kA/s
23/6	T_{CS} @ I = 30 kA	HH[b], quench at max heating power by increasing current to 70 kA and reducing mass flow
	T_{CS} @ I = 10 kA	HH, quench
	T_{CS} @ I = 30 kA	HH, quench
	Current scan test	dI/dt = 0.1 kA/s
24/6	T_{CS} @ I = 50 kA	HH, quench
	T_{CS} @ I = 70 kA	HH, quench
	Current scan test	dI/dt = 10 kA/s
	T_{CS} @ I = 30 kA	HH, quench
25/6	Trapezoidal heating	JH, P_{max} = 350 W
	Trapezoidal heating	JH, P_{max} = 400 W
	Trapezoidal heating	JH, P_{max} = 450 W
	Trapezoidal heating	JH, P_{max} = 500 W
	T_{CS} @ I = 10 kA	HH, reduced dm/dt, quench

[a] Jacket heater (see text); [b] Helium heater (see text)

II. EXPERIMENTAL SETUP

The location of the main sensors of BBIII is sketched in Fig. 1 and reported in Table II. The instrumentation used for the CDM

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

R. Zanino, M. Bagnasco, and L. Savoldi Richard are with the Dipartimento di Energetica, Politecnico di Torino, I-10129 Torino, Italy (e-mail: roberto.zanino@polito.it).

F. Bellina is with the Dipartimento di Ingegneria Elettrica, Gestionale e Meccanica, Universita' di Udine, I-33100 Udine, Italy.

T. Bonicelli and E. Salpietro are with the EFDA-CSU, D-85748 Garching, Germany.

A. della Corte, A. Di Zenobio, L. Muzzi, S. Turtu', and L. Verdini are with the ENEA, I-00044 Frascati, Italy.

W. H. Fietz, R. Heller, V. Marchese, and G. R. Zahn are with the Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany.

A. Formisano and R. Martone are with the Dipartimento di Ingegneria dell'Informazione, Seconda Università di Napoli, I-81031 Aversa, Italy.

Y. Ilyin and A. Nijhuis are with the University of Twente, 7500 AE Enschede, The Netherlands.

M. Polak is with the IEE, Bratislava, Slovakia.

P. L. Ribani is with the Dipartimento di Ingegneria Elettrica, Universita' di Bologna, I-40136 Bologna, Italy.

Digital Object Identifier 10.1109/TASC.2005.849107

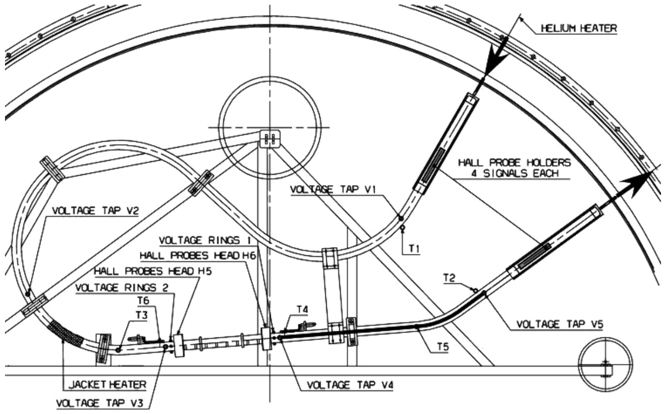

Fig. 1. Sketch of sensor and heater locations along the BBIII. Helium and current flow according to the arrow direction.

TABLE II
SENSOR LOCATION IN THE BBIII

Sensor type	Sensor name	Location from joint inlet (mm)
Hall probes	H5	4591.5
	H6	5014
	Linear array	4595-5010
Voltage tap	VT1	765.5
	VT2	3657
	VT3	4481.0
	VT4	5125.5
	VT5	6273.5
Voltage ring	VR2	4512.7
	VR1	5095.5
Temperature (He = helium, Jk = jacket)	TI770 [a] (He) TI770E (He)	~ – 2000
	TI774 [a] (He)	460
	JKT01 (Jk)	795
	JKT03 (Jk)	4257
	JKT06 (Jk)	4539.5
	JKT04 (Jk)	5154
	JKT05 (Jk)	5920.9
	JKT02 (Jk)	6243.5
	TI968 [a] (Jk)	6443.5
	TI771 [a] (He)	~ 8000
Pressure	PI770 [a]	~ – 2000
	PI771 [a]	~ 8000
Mass flow rate	MFI770 [a]	~ – 2000
	FI774	~ – 2000

[a] Signals acquired only by TOSKA DAS.

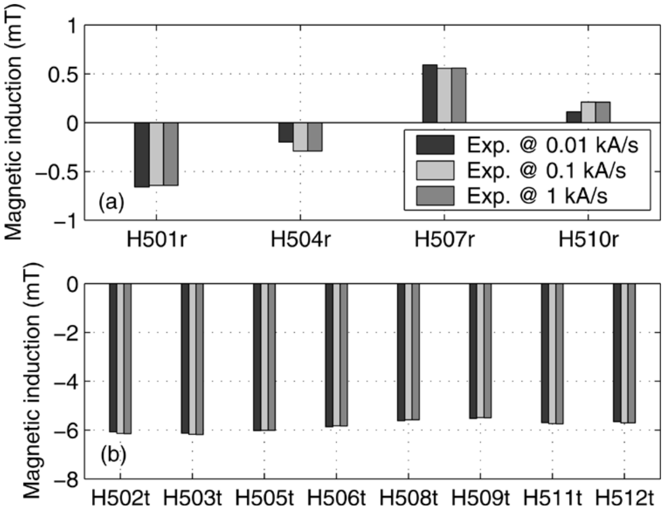

Fig. 2. Measured magnetic induction in the calibration shots @ 77 K (April 19): radial (a) and tangential (b) probe signals from H5, at different dI/dt, at the 1 kA (measured) current plateau.

consisted of five voltage taps (VT) along the conductor and the joints (located at the jacket outer surface), two voltage rings (VR), each consisting of four voltage taps located at a given cable longitudinal coordinate, two linear Hall probe (HP) arrays, and two HP annular arrays (called "heads", and referred to as H5 and H6 below). H5 and H6 were equipped with 4 radial and 8 tangential for H5, and the reverse for H6. In the presence of a strong transport current, radial field probes give signals much more sensitive to the current nonuniformity among the strands, while tangential probes are more sensitive to the cable transport current. The overall HP configuration leads to optimal robustness of the current identification process [3].

Seven temperature sensors (JKT01-06 plus TI968) were mounted on the conductor jacket, while one temperature sensor (TI774) was inserted into the inlet joint central channel. Inlet and outlet pressure and temperature were also measured together with the inlet mass flow rate. The measured data were collected and stored by a BBIII-specific data acquisition system (DAS) [4], and/or by the TOSKA DAS [1].

Two resistive heaters were also installed and could be operated independently. One of them (HJI710-He Heater, HH) was mounted upstream of the inlet joint directly on the He pipe, the other one (HJI774-Jacket Heater, JH) was glued in the middle of the BBIII, on the jacket.

All CDM tests were performed at the initial inlet temperature $T_{op} \sim 4.5$ K and inlet pressure $p_{op} \sim 5\ \mathrm{bar}$. In most tests, the initial mass flow rate $dm/dt \sim 15\ \mathrm{g/s}$.

A. Hall Probe Calibration

When the strands are fully resistive, the HP signals are assumed to refer to a uniform current distribution among the strands.

The calibration of the HP was done with a set of trapezoidal current pulses @ 77 K, during the cool-down of Phase I and II of the HTS-CL test campaign. For all calibration pulses, the transport current waveform consisted of a ramp-up, followed by a plateau at 1 kA—a plateau duration of ~60 s (April 19) and ~120 to 175 s (June 3)—and a ramp down. Different ramp rates dI/dt were applied: 0.01, 0.1 and 1 kA/s. Similar pulses were also performed @ 4.5 K (i.e., with strands in superconducting state).

The experimental results for the calibration of H5 are reported in Fig. 2, showing results independent of the ramp-rate within the measurement accuracy of $\sim\ \pm 0.05\ \mathrm{mT}$. The plateau radial field component (Fig. 2(a)) is about one order of magnitude smaller than the tangential one (Fig. 2(b)), and it is therefore much more sensitive to misalignments, or minor geometrical/manufacturing/positioning defects. The radial field probes H504r and H510r, located at the busbar equatorial plane, give nonzero signals, but the signal amplitude is comparable to the measurement sensitivity.

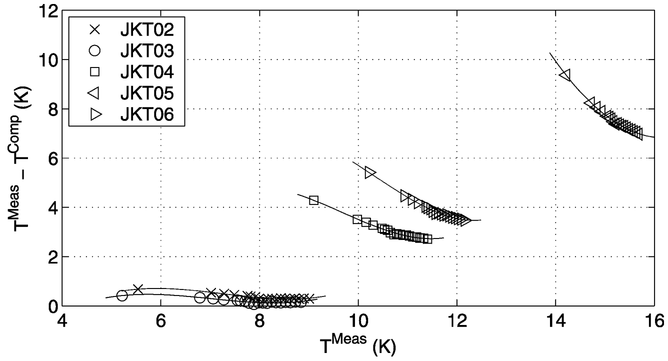

Fig. 3. In-situ recalibration of the temperature sensors along the jacket based on HH tests.

B. Discussion of the Temperature Measurements

During operation some doubts arose about the reliability of the temperature measurements. The status of this issue is briefly summarized in this section.

In steady-state operation, when the facility sensor TI770 at the CICC inlet (considered fully reliable) reads $T_{op} = 4.5$ K, the jacket thermometers gave temperatures much higher than the critical temperature (measured $T_C \sim 9.3 - 9.5$ K), which is very unlikely.

From the comparison with TI770, the TI774 signal is deduced to be reliable (at least in steady state), but it refers only to the He in the central channel (see Table II). Indeed, in the joint, the central channel is practically thermally decoupled from the annular region by a thick wall.

The steady state heat load balance on (BBIII)+(BBII)+(HTS-CL), (see also [1]), reveals the presence of a static (constant) heat load on the BBIII (∼14 W, independent of operating conditions), which can give a temperature increase of only up to ∼0.2 K. This is not sufficient to explain the measured (non monotonic) temperature profile as actually measured, meaning that the JKTxx need to be recalibrated.

Since different shots were performed with JH and HH @ $I = 0$ kA, the steady-state heating plateau can be used for the JKTxx recalibration assuming a uniform temperature on the conductor cross section and computing the corrected temperature from the following heat balance: (Input power) – (Heat transferred to BBII through the inlet joint) + (Static heat load) = enthaly flow below the sensor. The recalibration of the sensors (see Fig. 3) applies (both in steady state and transient) within a $\sim \pm 0.2$ K accuracy. However, it should be stressed that such recalibration is not feasible for the thermometers JKT01 in the case of HH tests (too close to the joint, to assume a uniform temperature on the cross section).

III. CURRENT-DRIVEN TRANSIENTS

Since at low T different dI/dt could, in principle, give different current distributions among the strands, a set of combinations of I and dI/dt was considered.

As an example, the time evolution of two HP signals (radial H602r and tangential H607t) during the $I = 70$ kA plateau reached by applying different ramp rates, is shown in Fig. 4. During the current plateau, Fig. 4, the nonuniform joint-strands electrical resistance drives the current distribution among the strands to a common value independent of the ramp-rate. Inductive effects lead to a long time constant, i.e. several hundred seconds (see Fig. 4), so that about 30 mins are needed for the signal stabilization. The signal values at the end of the plateau (t∼1800 s), when transient phenomena are relaxed and the current distribution is dominated by the joint-strands resistances, differ from those at 77 K, confirming some degree of current nonuniformity due to the joints. The evolution of the HP signals during the current ramp-up (not shown) is still obscure and requires more analysis/modeling for interpretation.

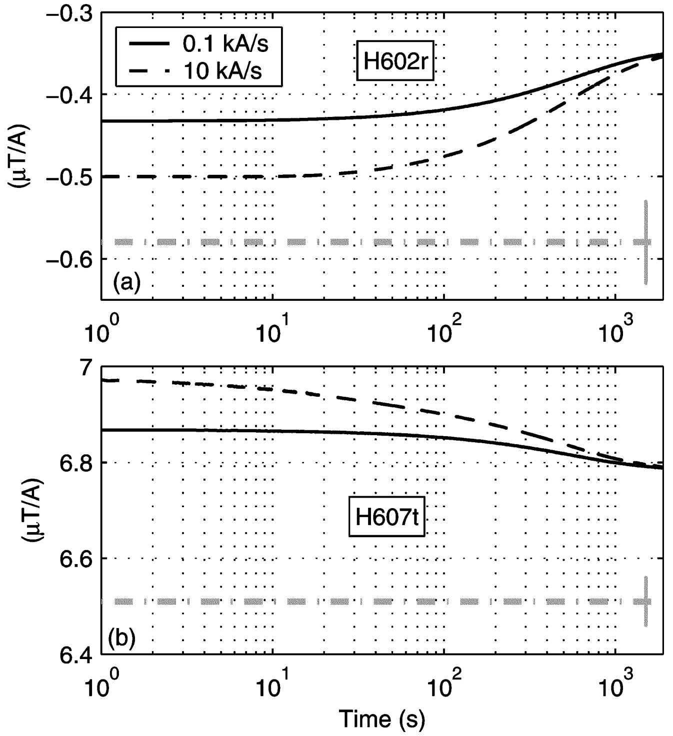

Fig. 4. Current scan tests @ 70 kA and $dI/dt = 0.1$ and 10 kA/s: radial (H602r) (a) and tangential (H607t) (b) HP signals normalized to the current value during the plateau ($\mathrm{time} = 0$ s at the end of the ramp). The 77 K plateau levels are also reported (dash-dotted line) with the respective error bars.

IV. HEATER-DRIVEN TRANSIENTS

A. JH-Driven T_{CS} Tests

The jacket heater was operated (after the decay to a resistive current distribution, see Fig. 4) with a multi-step strategy [5], see Fig. 5(a) to indirectly increase the strand temperature up to quench detection, when the current was dumped. The voltage take-off always occurred in the CICC region below the heater, as expected. The HP signals, see Fig. 5(b) for an example, show a variation long (=more than 0.5 K) before the take-off (although this is less marked at higher current, not shown), without any longitudinal voltage increase. This variation appears to be clearly correlated with the temperature variation, see Fig. 5(a), probably indicating early local current re-distribution processes within the cable cross section. Closer to take-off, step like variations of the measured field are recorded, which correlate well with spikes ($\propto dB/dt$) in the voltage ring signals, see Fig. 5(b).

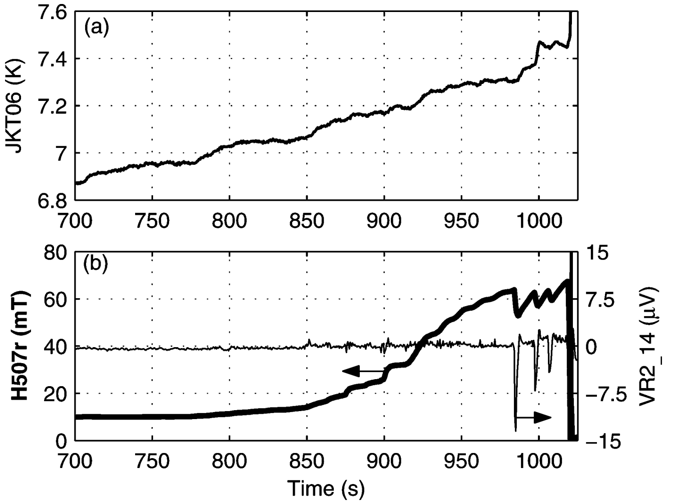

Fig. 5. JH T_{CS} measurement @ $I = 30$ kA: (a) measured (corrected) evolution of the JKT06 temperature; (b) H507r signal (left y axis) and voltage ring VR2_14 signal (right y axis). Time measured from start of heating.

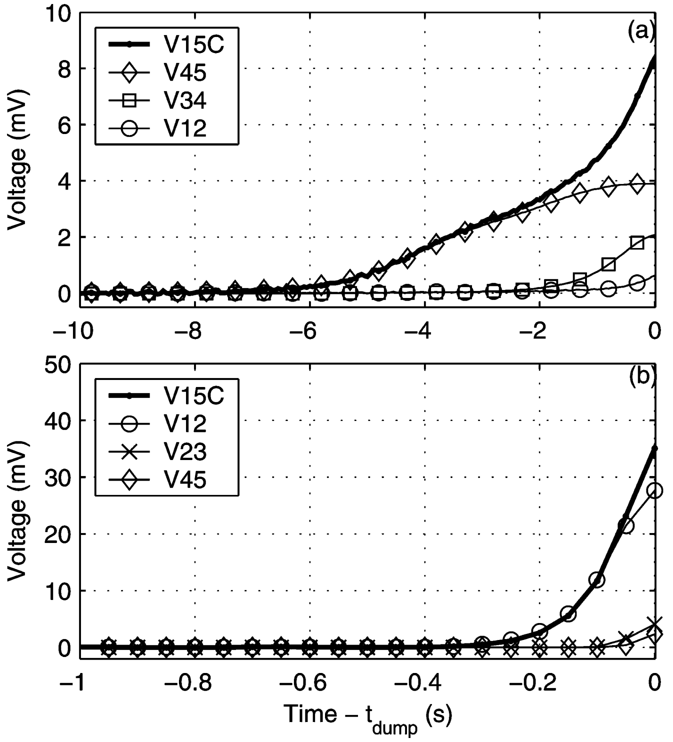

Fig. 6. HH T_{CS} measurement (20 Hz sampling rate). Measured voltage signals: (a) $I = 10$ kA, (b) $I = 50$ kA. Note the different scales on the x and y axes. V15C is the compensated voltage between VT1 and VT5.

B. HH-Driven T_{CS} Tests

The He heater was also operated (after the decay to a resistive current distribution, see Fig. 4) according to a multi-step heating strategy [5] albeit with obviously different plateau levels than the JH. Due to the high stability of the joint, already encountered during the T_{CS} tests of the Toroidal Field Model Coil [5], and to the good heat transfer in the joint region, a helium temperature T much higher than T_C could be reached at the joint inlet without originating any voltage across the joint. Both smooth transitions (at low current) and sharp ones (at high current) were observed, as shown in Fig. 6, which is typical of NbTi conductors, see, e.g., [6], and related to magnetic field variation on the cable cross section (~0.5 T in the case of BBIII @ 70 kA). The measured value of T_{CS} at 10 kA could be assessed as ~8.83 K (using V45 and the corrected JKT05). Being the magnetic field along the conductor is nearly uniform, it is not easy to predict a priori the location of the normal zone initiation. At $I = 10$ kA (see Fig. 6(a)), the normal zone does not arise close to the inlet joint, as it happens at larger I (see Fig. 6(b)), but further away along the conductor. This point needs further analysis.

Clear quench propagation (not shown here) could be observed only in the reduced dm/dt run (see Table I).

V. CONCLUSIONS AND PERSPECTIVE

The test of the superconducting ITER-type NbTi BBIII has provided useful field and voltage data on the current distribution in this type of conductor during current and/or temperature transients, thanks to accurate electromagnetic diagnostics. Based on the calibration of Hall probe signals at high temperature (above T_C), the current distribution at steady state is nonuniform. An early re-distribution of the current on the conductor cross section is observed approaching critical conditions. Problems in the temperature measurement can be partially overcome by in-situ recalibration.

The results of the tests will be analyzed in detail with the THELMA code as well as other tools for current reconstruction.

REFERENCES

[1] R. Heller *et al.*, "Test of the 70 kA HTS Current Lead in the TOSKA Facility—Results of Test Phases I and II," Forschungszentrum Karlsruhe Internal Report, FE.5130.0061.0012/A, 2004.

[2] F. Bellina *et al.*, "Superconductive cables current distribution analysis," *Fus. Eng. Des.*, vol. 66–68, pp. 1159–1163, 2003.

[3] P. Bruzzone, A. Formisano, and R. Martone, "Optimal magnetic probes location for current reconstruction in multistrands superconducting cables," *IEEE Trans. Magn.*, vol. 38, pp. 1057–1060, 2002.

[4] S. Turtù and L. Verdini, Data acquisition system for CDM on TFMC busbar, in EFDA Report Task TW1-TMC-CODES, Sub Task 1, January 2003.

[5] R. Zanino and L. Savoldi Richard, "Performance evaluation of the ITER toroidal field model coil phase I. Part 1: current sharing temperature measurement," *Cryogenics*, vol. 43, pp. 79–90, 2003.

[6] D. Ciazynski *et al.*, "Test results on the first 50 kA NbTi full size sample for the international thermotnuclear experimental reactor," *Supercond. Sci. Technol.*, vol. 17, pp. S155–S160, 2004.