Study of current distribution in ITER TFMC NbTi Busbar III

L. Zani, D. Ciazynski, R. Heller, F. Wüchner, H. Rajainmäki

***Abstract*— In the framework of the development of High Temperature Superconducting current leads (HTSCL), one demonstrator was tested at FZK in 2004 together with a conventional current lead, both were connected by a superconducting short circuit NbTi conductor, referred as busbar III (BBIII). Here the BBIII was used for current distribution measurements. In addition to a 64 Hall Probe (HP) system, two additional 4-HP heads from CEA were assembled at both ends of the BBIII. This system, already successfully used during the TFMC test phase II, was now adapted by FZK to the present BBIII set-up. Electrical tests were performed for conductor currents up to 80 kA without background magnetic field. In this paper, the analysis of the current distribution is presented using two methods:**

- First the current barycentre excursion was investigated in various runs. A comparative study is presented between resistive and inductive hypotheses where the current is supposed to be uniformly distributed. In particular, we show that the two hypotheses lead to different results.

- Second a global model of the current bundles distribution between four artificial subcables is investigated.

More quantitative results show current imbalances between subcables to be either significant or weak, depending on whether the resistive or the inductive hypothesis is considered. A discussion on why the second solution is thought to be more likely is presented. In addition, a global comparison with results previously obtained during the TFMC tests will be shown.

***Index Terms*—Superconductors, Fusion, NbTi, Conductor**

I. INTRODUCTION

In the framework of the International Thermonuclear Experimental Reactor (ITER) R&D on magnet systems, a specifically designed High Temperature Superconducting Current Leads (HTSCL) demonstrator was designed and tested in the TOSKA facility of the Forschungszentrum Karlsruhe (FZK) in 2004. In addition, a dedicated NbTi bus bar BBIII was used as short circuit for the HTSCL tests. This BBIII uses a Cable-In-Conduit Conductor (CICC) similar to that used for the TFMC Busbars [1] and relevant to the conductor designed for the ITER Poloidal Field (PF) Coils (Figure 1).

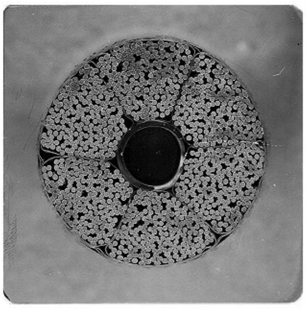

Figure1. Cross-section of the BBIII conductor

During the tests, the opportunity was taken to evaluate the current distribution inside this busbar similarly to what was performed previously for the TFMC busbars [2]. Contrarily to the tests performed with the TFMC, no coupling with a large inductive component occurred. Consequently fast ramp runs up to 1 kA/s were possible thus allowing the experiment running in conditions considered as purely inductive.

II. EXPERIMENTAL SET-UP

A. General Description

The 5 m long BBIII is connected in series at one end to the 70 kA HTSCL [3] and at the other hand to the Busbar II, which itself is connected to the conventional 80 kA CL (Fig. 2). Separated cooling circuits allow a decoupled control on quenches on each type of conductor and separated campaigns were performed between BBIII and HTSCL tests.

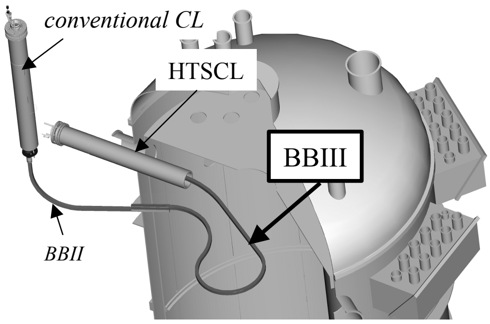

Figure 2. General view of the HTSCL-BBIII experimental set-up installed inside the vacuum vessel.

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B. Currents measurements set-up

The Hall Probes (HP) equipment used for this experiment is the same as that used for the TFMC tests [2]: two systems of 4 HP placed on a rigid support so as experienced to the self-field radially and relatively positioned in a quadrant (Fig. 3).

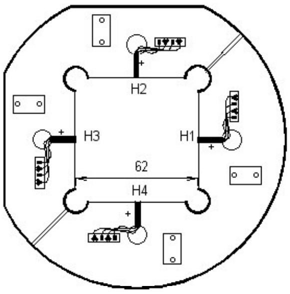

Figure 3. HP support scheme (Hx are HP labels)

Because the conductor diameter of the BBIII is different to that of the TFMC experiment, the HP framework assembly was adapted with the help of dedicated shims positioned so as to ensure the same distance between each HP and the conductor center. All HP's are indexed as shown in Figure 3 with an extra index related to the closest polarity where the framework has been placed (BB+ or BB-).

III. MODELS

A. Current Barycenter model

The current distribution in the BBIII conductor is first addressed through the Current Barycenter (CB) model.

The CB is found by coordinates reconstruction through HP pairing depending on the coordinate to be calculated. An example is given in Figure 4 for the CB abscissa determination.

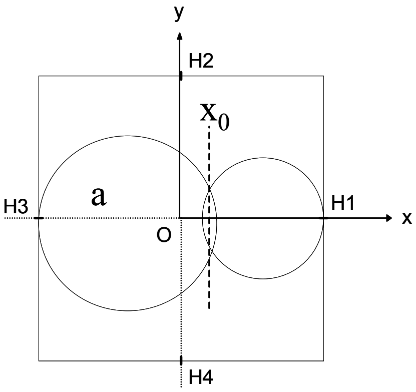

Figure 4. Example of CB abscissa x_0 calculation with help of {H1,H3} HP pair. Circles represent the possible CB location for given signal on HP.

The CB drift is relevant to the current distribution by mainly its amplitude. CB displacements between superconducting and normal state can be respectively compared to strand or bundles (i.e. petals) dimensions for slight or large current imbalance evaluation inside the conductor.

B. Bundle Current Distribution model

A more realistic so called bundle current distribution (BCD) reconstruction has been developed by considering four subcables whose shapes and locations are linked to the HP system geometry (Figure 4). Even if those artificial bundles are not directly related to the physical petal in the CICC, they represent a somehow average distribution between large zones of the conductor cross-section.

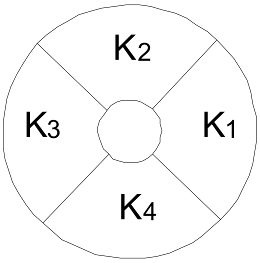

Figure 5. Schematic view of the chosen bundles. Index is related to the closest corresponding HP.

In this configuration, currents are reconstructed by considering perfectly balanced current inside the bundles and a signal derived from straight infinitely long current trajectories.

The typical parameter extracted from this configuration will be noted as $\delta I_n = I_n - I_{tot}/4$ where I_n is the reconstructed current inside the bundle n.

III ANALYSIS OF THE EXPERIMENTAL RESULTS

A) Experimental program

Typical BBIII runs consist of two-parts starting with an initial current ramping up with a controlled slope and a following temperature increase (either with external jacket heating or helium heating) by means of successive plateaus until conductor transition. The last temperature increase was around 0.05 K/min which is slow enough to ensure a minimum temperature gradient along the whole conductor length.

In order to obtain a reference configuration (homogeneous current), calibration runs were performed on one hand in conductor normal state at 1kA and on the other hand in inductive regime with fast current ramp rates (1000A/s).

B) CB location

First, the CB configuration is calculated using the resistive calibration run, the results are shown in Table I.

TABLE I
CB LOCATION IN NORMAL STATE (RUN#030504)

HP support location	X_0 (mm)	Y_0 (mm)
BB+	-4	0.27
BB-	2.8	0.56

A first comment can be drawn from these results: The CB horizontal position is found to be far from that expected from the resistive regime where the current homogeneity should have led to a nearly centered CB position ($X_0 \sim 0$). Because a badly conductor centering in its jacket is excluded by ultrasonic measurements of the jacket thickness, the hypothesis of a perturbation offset on the horizontal HP could be considered. The impact of a wrong position of the HP on the results should be then drastically larger for the CB hypothesis than with the BCD one. As a matter of fact in the

BCD case the sensitivity of all HP's to current flowing through every bundle tends to lower the impact of a perturbation signal experienced by one of the HP's.

Second, the same study was performed in the inductive regime. For that, a typical time is determined for which we can consider the inductive regime to be reached. This happens when the joint current loops are relaxed and the conductor current loops are still working. A rapid evaluation of the conductor loop time is given by a simple two-petal model with $\tau_{cond} = (L_1-L_2-2M)/(R_1+R_2)$ with L_i, M and R_i being inductances and resistances respectively of the petal i. Numerically, a value of 500 s was found. On the other hand the joint loop time τ_{joint} can be calculated from the formula from [4]:

$$n\tau_{int} = \frac{\mu_0 L}{12 R_j} \frac{d_c^2}{A_{STRAND}}$$

where L is the joint length, d_c the mean intercable distance, A_{STRAND} the strand cross section area in the cable and R_J is the joint resistance. In typical ITER-type joints this time constant has been evaluated to be around 50 s. This means that the typical time for inductive regime is around 200s (Figure 6). Therefore currents are supposed to be perfectly balanced 200 s after the plateau was started and stands as a reference configuration. The CB drift is then deduced after reaching steady-state conditions in the normal state.

Various runs have then been evaluated for CB calculations considering a wide range of current levels and the global study is summarized in Figure 6.

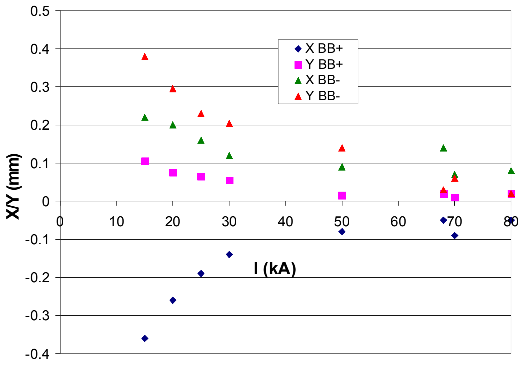

Figure 6. Illustration of the CB drift between the superconducting and the normal state vs. total current in BBIII. A time of 200s is considered for inductive state reaching.

Even if the variation of the CB motion with the total current is not clearly understood yet, we can obviously see that the drift amplitude does not exceed 0.5 mm which is more in agreement to that which was expected.

C) Bundles current

The current reconstruction has been performed with the previously mentioned hypotheses for the BCD model.

With the resistive regime as a reference, the current reconstruction show inconsistent results because one petals is supposed to carry a slightly negative current, which is unlikely in steady-state regime.

On the contrary, for the inductive regime hypothesis, a more realistic result is found with a less pronounced current imbalance. An illustration of the results is shown in Figure 7. We can clearly see that here the 4-bundles model results are in full agreement to what was previously found in the CB study. As a matter of fact, a current imbalance of less than 20% is found with the BCD hypothesis and a CB shift of smaller than the strand diameter of 0.81 mm (low current imbalance).

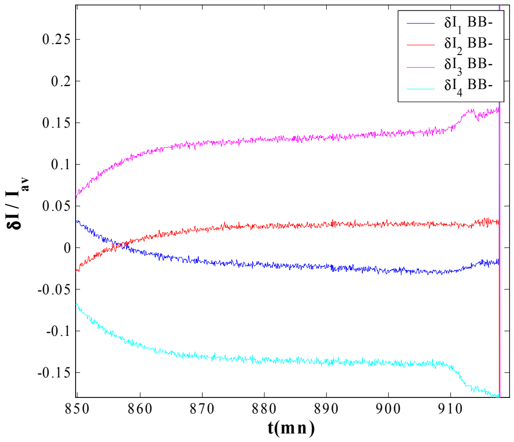

Figure 7. Bundles current in BBIII calculated from BB- HP support signal on the. Zero corresponds to the fully inductive regime.

On a comparative area, as BBIII and BBI joints were manufactured with the same conductor and are likely to have a similar joint geometrical configuration (i.e. similar manufacturing conditions), the results were expected to be much close. As a matter of fact our results, with a maximum of 20% current deviation from uniformity, are in full agreement with those found during the TFMC tests [2] where a 10% current deviation from uniformity was calculated. This very good quantitative consistency between results from two experiments operated in significantly different conditions can be also considered as a reliable assessment of the presented work.

On the other hand the poor consistency of the resistive regime results could derive from the very low HP signal level (current and so self-field one order of magnitude lower) where some planar (in-plane magnetic field component) effects could play a strong perturbating role.

Finally the results confirm also that this type of NbTi conductor (internal CuNi barrier) show reproducible and satisfactory performances when operating in ITER TF Coils-relevant conditions.

IV. CONCLUSIONS

We worked on the electromagnetic behaviour of the BBIII during the HTSCL experiment in order to evaluate the current distribution deviation from homogeneity inside the BBIII NbTi conductor. For that the same HP set-up as previously used in the TFMC tests was adapted to the BBIII system.

Two models were used for the reconstruction:

- one related to the CB motion in the cross-section, giving an average view of the current dynamics in the conductor

- one related to an artificial 4-bundles model, giving a view close to the one of the current dynamics between conductor petals.

Two reference configurations were also compared, one being the resistive regime and the other being the inductive regime. Depending on the reference chosen, the results showed contradicting results with high or low current imbalance for the resistive or the inductive reference regime, respectively.

The inductive regime was found to be more realistic because of its consistency between CB and BCD studies. The resistive regime deviation is thought to be due to a too weak HP signal.

Finally this view also claims for similarity with previously obtained results during the TFMC tests, where in both cases current deviations from the balanced configuration were not found to be larger than 20%.

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