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Current (re-)Distribution inside an ITER Full-Size Conductor: a Qualitative Analysis

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Abstract. The comprehension of the current re-distribution phenomenon inside multi-filamentary conductors is a crucial point for the design of ITER-relevant coils, as it is by now assessed that current non-uniformity among cable sub-stages may strongly deteriorate Cable-in-Conduit Conductors (CICC) performances.

The only feasible way to get information about the current flowing inside CICC sub-stages is an indirect evaluation by self-field measurements in regions very close to conductor surface. A 7m full-size NbTi conductor (Bus-Bar III) has been used as short-circuit during the test of an ITER Toroidal Field Coil HTS current lead at FzK. Its relatively simple shape and the absence of any other magnetic field source (background coils, etc.), made BBIII one of the most desirable candidate for a reliable measurement of the current distribution under controlled conditions. This is why it has been ad hoc instrumented with different arrangements of Hall-probes (rings and arrays), as well as with transverse and longitudinal voltage taps.

This paper gives a qualitative interpretation of the current (re-)distribution events inside the conductor as derived from the analysis of the Hall sensors and the voltage taps signals, during Tcs measurements and as a function of different dI/dt. It has been shown that Hall probes represent a very reliable tool to investigate this issue. In fact, re-distribution phenomena have been clearly observed during transition, and even far before reaching Tcs, when voltage transverse signals had not yet showed any appreciable onset.

1. Introduction

The BBIII, a 7m long NbTi full-size cable in conduit conductor (CICC), has been used as an electrical connection in series between a conventional NbTi current lead and a HTS lead, during the test campaign of the HTS lead in the TOSKA facility at Karlsruhe, from April to June 2004 [1], in the framework of ITER activities.

The BBIII is made up of 1152 NbTi strands arranged in a 3x4x4x4x6 structure, with wrapping around the last-but-one cabling stages (called “petals”). One of the main purposes of the experiment was the monitoring of the current distribution inside the 6 cable sub stages, for a general interest as well as for the validation of the THELMA code. In principle current cannot be homogeneously distributed inside the cable because of joint resistance non-uniformity and/or different inductances of the sub-cables, causing transverse voltages development just before or during transition. This phenomenon is usually considered as a possible cause of the observed critical current degradation of the cable, as compared to the strands characteristics. The distribution of current has been studied by means of Hall probes measuring cable self-field, and by voltage taps.

2. Instrumentation

Five different sets of Hall Probes have been mounted over the BBIII, four of these are rings and one is a longitudinal array. Two rings, mounted at a distance of about 1 twist-pitch, contain 12 probes each, measuring both radial and tangential components of the magnetic fields generated by the conductor transport current. In particular one of these two rings, called Head 5, held 4 radial and 8 tangential probes, while the other one, Head 6, contained 4 tangential and 8 radial ones. All the probes of the same type have the same distance from the centre of the cable. Between these two heads, 8 HPs are mounted forming a longitudinal array. The other two holders are mounted over the joints of the BBIII with the current leads and contain 4 HPs each. All the voltage taps are placed on the jacket. In particular, 5 voltage taps measure the longitudinal voltage over the whole conductor length, while the 2 voltage rings consist in 4 taps placed on each jacket side, at the same conductor cross-section, measuring the transverse voltages. In addition two resistive heaters are mounted, one on the jacket and one directly on the He pipe, upstream the inlet joint.

Temperature is monitored by means of 7 thermometers along the conductor, pressure data are collected at inlet at outlet, while mass flow is measured only at inlet [3].

ENEA has also been charged to develop and control the dedicated Data Acquisition System [4]: it has a nominal percentage error <0.2%, for V_i> 2.5 mV (which in the case of HPs signals corresponds to B >15 mT), and a sensitivity of 1.2 μV.

3. Data analysis

3.1. *Elaboration procedure.* During Tcs measurements, after the BBIII's transport current reaches the plateau, due to the low BBIII inductance it takes about ½ hour before the HPs signals relax to stationary values, corresponding to the current configuration due only to the joint not-uniform resistance distribution. For each run we subtract from the HPs signals these values, analysing the variations from such a current distribution before or during the transition.

3.2. *Current re-distribution just before transition* While approaching resistive transition, both via jacket heating or helium heating, a current transfer from one petal to the others is clearly detected. In fact, some seconds before the development of the longitudinal voltages, the HPs signals show a consistent variation (fig. 1), as well as during transition, when also the transverse voltage taps reveal a non zero signal due to current transfer. Such a behaviour is qualitatively repeatable in all different runs at same current.

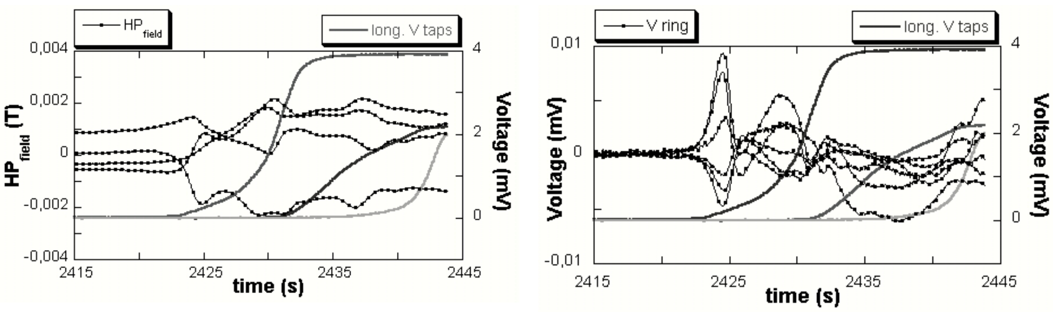

Fig. 1: The longitudinal voltages give evidence of a resistive transition; in the meanwhile all the HPs signals and transversal voltages vary, showing a redistribution of the currents among the 6 petals.

During Tcs tests at low current and with jacket heater, a peculiar behaviour of the longitudinal voltage taps appears, confirmed both by the Hall Probes readings and by the transverse voltage taps: a low frequency oscillation in the signals, interpreted as a partial transition/recovery of the BBIII (fig.2 left). The recovery is due, as far as we understand, to a small amount of current transferred inside the cable: when a strand bringing more current than the others, owing to the inhomogeneous joint resistance, reaches its Ic value at the actual temperature inside the cable, the exceeding current transfers to its neighbours that are still in the superconducting state. This causes the longitudinal voltages to rise and then to decrease. Such a phenomenon is observed also at higher BBIII current values (30 and 50 kA runs), even if it tends to diminish (fig. 2 right), while it vanishes at 70kA, where no voltage oscillation is observed, as sudden take-offs occur.

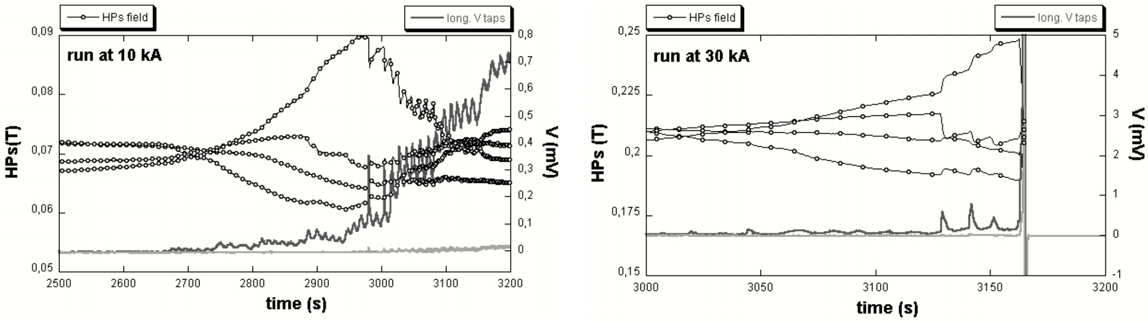

Fig. 2: at 10kA runs an oscillation in the longitudinal voltage taps when the transition begins is observed, clearly visible on some HPs (left); at 30kA only few spikes are observed (right).

3.3. *Premature current re-distribution*. Hundreds of seconds before the transition begins, i.e. at temperatures about 0.1-0.2 K smaller than Tcs, the Hall Probes show a significant variation in their signals (fig.3 left), indicating a redistribution of the petals currents that we call "*Premature Current Re-distribution*" (PCR). Such a re-distribution is not revealed by the transverse voltage taps nor by the longitudinal ones. The variation intensity scales with the nominal total current in BBIII (fig.3 right) and it is a repeatable phenomenon, if the thermo-hydraulic conditions are the same.

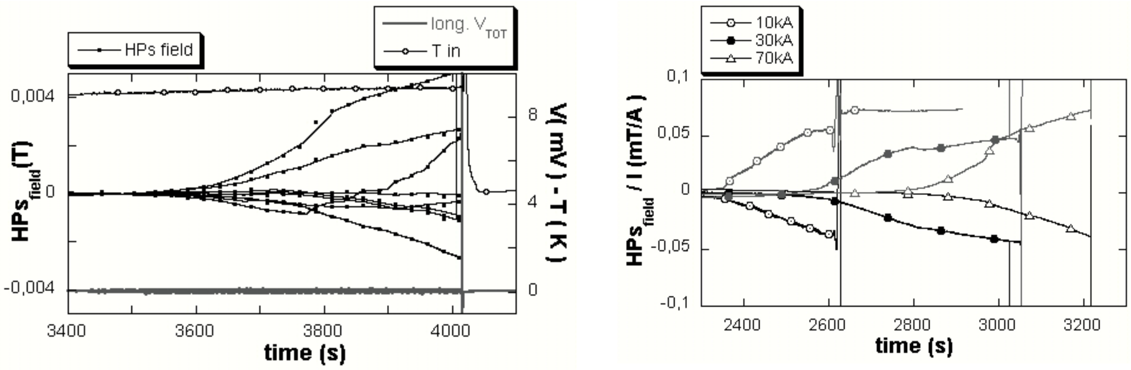

Fig. 3: HPs signals variation, evidencing a current redistribution phenomenon without any longitudinal voltage onset (left); HPs variations show quantitatively repeatable behaviour scaling with total transport current (two radial HPs are shown in 3 different runs) (right).

Such phenomenon has been previously observed also in the Poloidal Field Insert Sample, tested in the Sultan facility in 2004 [5], where considerable HP variations could be observed on both the wrapped leg side and, much more pronounced, on the un-wrapped leg side, where current re-distribution is more favoured. This further indicates that the observed signal variations are due to current transfer processes within the conductor cross-section.

In addition, the qualitative behaviour of the PCR does change (fig. 4) when heating via helium inlet pipe or via jacket; this is probably due to a different cable approach to Tcs when heating from the inner part or from the outer side, in addition to the fact that the cable cross-section experiences a magnetic field gradient.

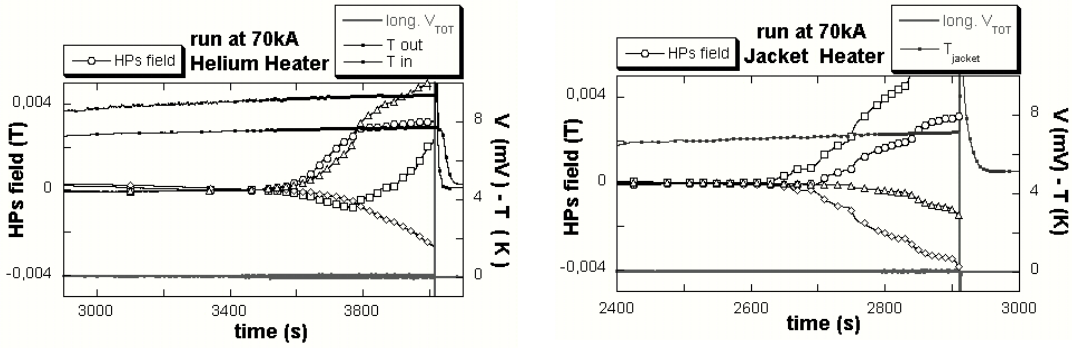

Fig. 4: When heating the BBIII by means of Helium inlet Heater (left) or by Jacket Heater (right) the qualitative response of the HPs well before approaching Tcs is different.

4. Conclusions

We studied the signals of Hall probes (HP) installed on the BBIII conductor, during Tcs measurement runs. From a qualitative data analysis, a premature current redistribution has been observed in all the runs (all BBIII current values, either with helium inlet heater and jacket heater) well before any voltage development. This phenomenon, clearly detected only by Hall Probes signals hundreds of seconds (i.e. some tenths of K) before the conductor transition, might be used as a powerful tool to predict a quench event, avoiding any joule heating of the conductor. Moreover, current transfer processes during transition can be qualitatively identified by HP and transverse voltage signals during longitudinal voltage development. In addition, current unbalance in stationary conditions has been quantified from HPs signals by inverse problem solution [6].

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