HIGH FIELD CABLE DEVELOPMENT FOR ITER

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Abstract
The milestones of over one decade conductor development for the high field magnets of ITER are reviewed, keeping an eye at the actual feed-back from the R&D results into the design. The review includes the fields of ac loss, stability, quench, n-index and joints. Finally, the issues of the transverse load degradation in Nb_3Sn CICC and the thermo-siphon effect in the dual channel CICC are discussed.

1. INTRODUCTION

In modern science, since Newton and Galileo, the idea (theory) always comes before the praxis (experiment). The progress is stimulated by models, hypothesis and abstractions. The experiments are not themselves the source of the progress, but the (mandatory) certification of an achieved advance. Atomic physics, relativity, quantum mechanics, standard model have been described decades before the related, crucial experiments.

In the field of technology, the roles are reversed. The practical achievements (inventions) are in use long before an organized understanding is established. Those who built (and partly still build) bicycles, medicines, generators and bombs are not necessarily aware of the "science" behind it. Our daily culture also privileges the practical know-how rather than the conscious understanding.

In the field of big science, it is not unusual to mix the traditional identity of science and technology, mostly due to the fact that the actors tend to be the same persons. It may happen to hear a young scientist claiming that the experiments are the source of the knowledge ("you must keep making experiments till you find something"). On the other hand, the progress in technology, outside the marketplace, is sometime slow down by dogmatic conservatism (fidelity to models) and reluctance to deviate from the beaten path.

Reading the following review of over one decade of R&D activity for the ITER conductor, the thought may arise that we are not dealing with fast developing, advanced technology items like cell phones, genetic engineering products, personal computers, power lasers, etc. The author actually shares such thought.

2. THE BASIC CONSTRAINTS FOR THE LAYOUT OF THE ITER CONDUCTOR

What makes different the superconducting magnets for "next step" fusion device in comparison to most superconducting coils is the large stored energy. Most constraints on the design choices for winding and conductor follow directly from the combination of large size and high field.

The electromagnetic loads for the ITER coils can be roughly represented by the product $B \cdot J \cdot R$, where B is magnetic field up to 12-13 T, J is the current density and R is the radius of the winding, up to 15 m. To withstand the huge loads, a large fraction of the winding cross section consists of structural material, typically austenitic stainless steel, resulting in smeared operating current density much lower compared, for example, to accelerator magnets. A bath-cooled option is forbidden for ITER magnets: the mechanical loads do not allow a helium transparent winding because of the poor smeared modulus and mechanical stability of such windings. The largest ever bath-cooled magnet is the large helical device (LHD), with 930 MJ stored energy [1]. The rigidity requirement for the big ITER coils, with stored energy in the range of 10 GJ, together with the need of removing the dissipated heat at high rate, imply monolithic, potted coils with direct cooling. The forced flow cooling option is mandatory.

The peak magnetic field for the toroidal field coils and central solenoid of ITER is in the range of 12-13 T. In principle, many superconducting materials can operate at the ITER field with adequate current density. However, considering that the need of superconducting, high field material is in the range of 500 t on a time scale of few years, the practical choice is restricted to Nb_3Sn because of the cost and the reliability of the industrial procurement. Alternative candidate materials, to be watched for the "over-next" step, could be Nb_3Al and doped MgB_2, providing that the market stimulates an adequate industrial development.

The size of the conductor, i.e. the range of operating current, is also indirectly dictated by the large stored energy. In case of quench, the stored energy is too large to be adsorbed in the winding without irreversible damage. An effective extraction of the energy requires a relatively short dump of the current (few seconds). To quickly dump the energy at reasonable voltage (≤ 14 kV), the self-inductance, i.e. number of turns must be small and the current must be large. All ITER conductors are at I_{op}> 45 kA.

The large size of the ITER conductors is actually the key issue for R&D investigations. In the past decades, large operating experience has been accumulated in the range of 10 – 20 kA conductors, but the engineering problems of very large conductors (up to 68 kA for the ITER toroidal field conductor) are still a virgin ground.

3. SELECTED OPTIONS FOR THE ITER CONDUCTOR

More practical constraints for the conductor design are given by the winding layout. The initial design of ITER coils was by layers, with substantial optimization of conductor size and cost by grading. Presently, all the ITER magnets are wound by double or multiple pancakes, which is a friendly approach for large magnet manufacture, but brings a penalty on the conductor cost (no grading). In other words, each coil is wound only from one conductor type [2].

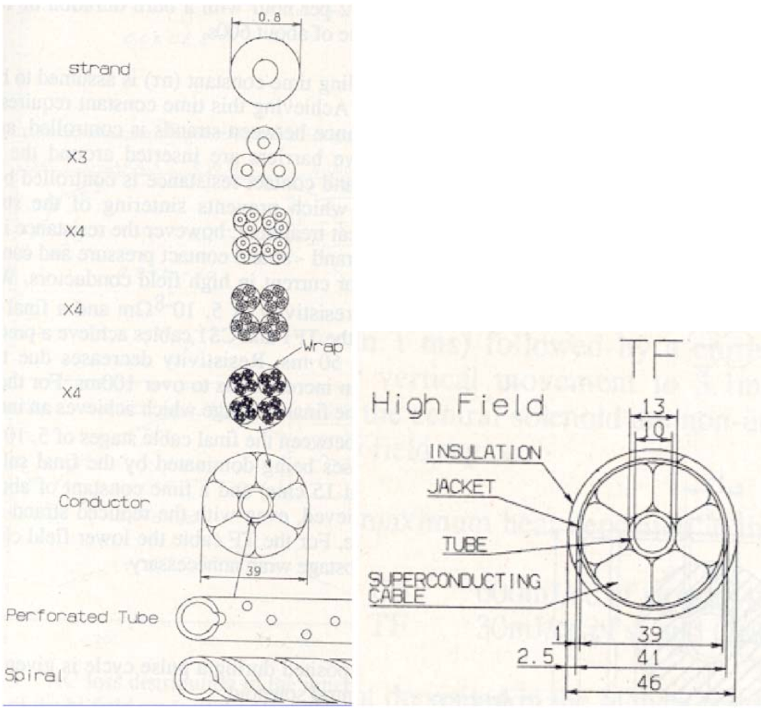

Fig. 1 ITER TF conductor layout according to 1993 design

Among the different design options for forced flow conductors, ITER adopted since the beginning the cable-in-conduit design for all the conductors, following an approach started in US over twenty five years ago [3] and also retained in the NET project [4]. A monolithic option design has been not considered in the ITER R&D. The current range for monolithic conductors is limited to about 20 kA [5]. At the size of ITER conductor, a traditional monolith would be very problematic because of the huge ac loss.

However, the large length of the conductor sections (over 500 m) and the heat removal requirement (high mass flow rate) do not allow a plain CICC design because of the large pressure drop. A parallel channel had to be added to decrease pressure drop, giving raise to the dual channel CICC, where the multistage cable is stranded around a helium transparent spiral, which defines the central channel.

4. DEVELOPMENT MILESTONES FOR THE ITER CONDUCTOR

The first sketches of the ITER conductor were drafted in 1992 and circulated at the MT-13 Conference in 1993, see Fig. 1. Comparing those early sketches with the latest conductor design [2], one could draw the conclusion that twelve years of intensive and expensive R&D activities have not substantially modified the conductor design. Indeed, the amount of feed-back has been intentionally very limited.

During the EDA (Engineering Design Activity, 1992-2001), as well as CTA (Coordinated Technical Activity, 2001-2002) and ITA (ITER Transitional Activity, 2003 and following years), an International Team planned, coordinated and monitored the R&D tasks carried out at the National Teams in Europe, Japan, Russia and US. In the field of superconductivity, the major partners of the collaboration have been JAERI (Japan), MIT and LLNL (US), NIIEFA, VNIINM and VNIIKP (Russia), CEA, CRPP, ENEA, FzK, UT (Europe, under the management of EFDA-CSU, Garching).

Both laboratories and industries carried out development activities for ITER conductors. The performance of the Nb_3Sn strand has been in the focus of the industrial activity in the years between 92 and 97, i.e. the procurement time for the Model Coil conductors, see for example [6-7]. The improvement of the Nb_3Sn performance continued in the scope of the KSTAR conductor manufacture [8] and later. Strand coating involved several companies worldwide [9]. The cabling development was carried out at the manufacturers, i.e. Showa, New England Electric, EM-LMI and VNIIKP. The jacketing by pull-through method was carried out at three companies, Ansaldo, EM-LMI and VNIIKP [10].

4.1 Coupling currents loss

The interstrand coupling loss in large CICC's is an issue for fusion conductors. The available data base was not very solid fifteen years ago. It was generally accepted that the Cr plating on the strand surface cuts the interstrand current loops [11]. However, this statement went through plenty of corrections in the last decade.

Investigations on the role of the Cr plating were carried out with respect to the coating thickness and coating type. A surprising large variation of coupling loss was found comparing cable made by identical strands coated by different vendors [9], see Fig. 2.

Other parametric studies on ac loss in CICC of Nb_3Sn strands revealed a strong influence of the void fraction [12], the electromagnetic load [13], the bending load [14] and the number of load cycles [15]. In summary, the interstrand contact resistance is of frictional nature in CICC and it is found to evolve in time. The interstrand coupling loss is initially high and drops quickly, after few load cycles, to the level of the interfilament loss.

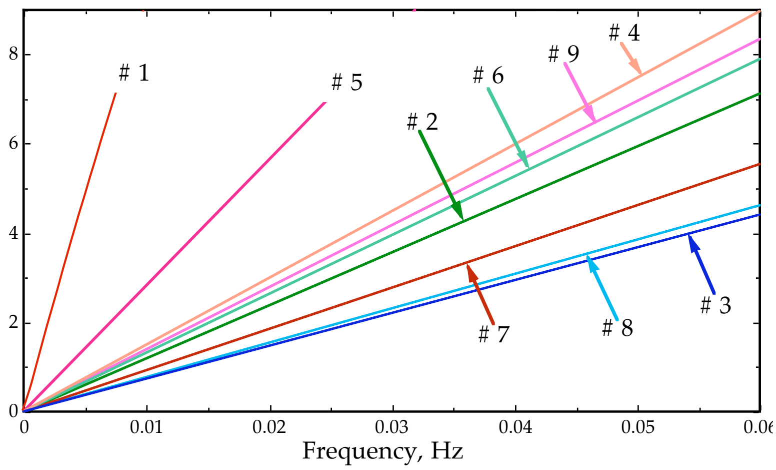

Fig.2 Coupling current loss vs. frequency of the ac field, normalized as mJ/cc of strand, for cables made from the same strand, but coated by nine different Cr vendors [9]. For comparison, #1 is made of non-coated strands. The lowest loss (#3) is about five time smaller than the largest loss (#5)

A number of large current loops with very long decay time constant seem to survive the cyclic load, see Fig. 3. The loss curve after cyclic load shows strong non-linearity at very low frequency, due to the overlapping effect of several loops with different time constant and affecting different volumes. The ac loss for fast field changes (t < 1 s) is negligibly low. For slow field changes (t > 100 s) the loss constant is larger, but the actual power loss is not an issue.

As the time constant is a function of the history and of the time scale of the field change, reliable ac loss calculations are not realistic. However, the largest incertitude in the loss estimate is in the less critical operation range (slow magnet charge). Generally, the ac loss is not seen as a major problem for Cr plated Nb_3Sn CICC. The criteria for ac loss presently retained in the ITER conductor design are conservative.

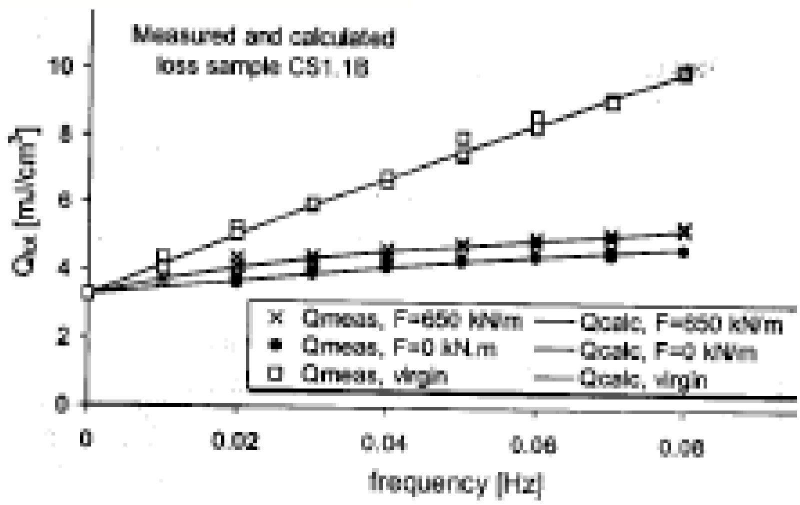

Fig.3 Coupling current loss vs. frequency of the ac field, for a full size Nb_3Sn CICC (Model Coil conductor) before any load (virgin), and after 38 load cycle (at 0 load and full load) [15]

4.2 Transient stability

The issue of transient stability has drawn lot of attention in the ITER conductor design, leading, in the initial phase, to a very conservative attitude, e.g. retaining a temperature margin of 2 K on top of the maximum predicted operating temperature, because of the unknown behaviour at plasma disruption and imposing a large copper fraction in the Nb_3Sn composite strand.

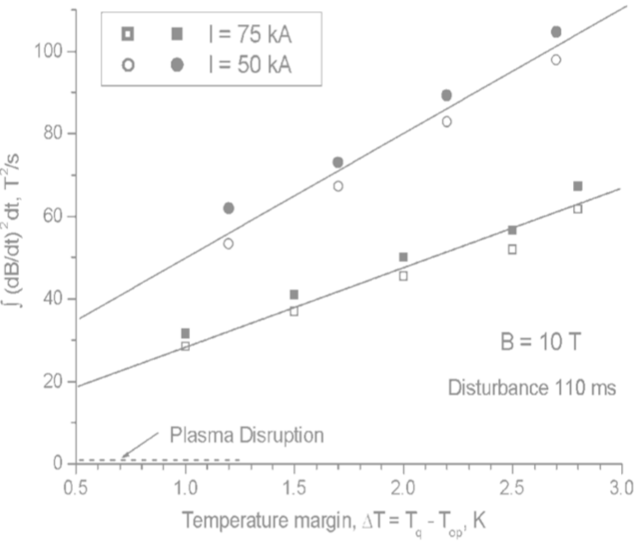

Fig.4 Transient field stability results on a Nb_3Sn CS model coil conductor at two levels of operating current. Open dots indicates recovery, full dots are for quench

During the test in SULTAN of a CS model coil conductor large field transients perpendicular to the conductor axis, well above the plasma disruption events, have been applied under relevant operating conditions. A convenient way to qualify a field transient of any shape is by the time integral of the square of the field change, $\int \dot{B}^2 \, dt$, in units of T^2/s. The field transient caused by a plasma disruption in ITER is smaller than 1 T^2/s at the high field section of the ITER coils. The test results on the Nb_3Sn full size conductor, see Fig 4 proved that a very marginal temperature margin is necessary to withstand a field transient like the plasma disruption [16].

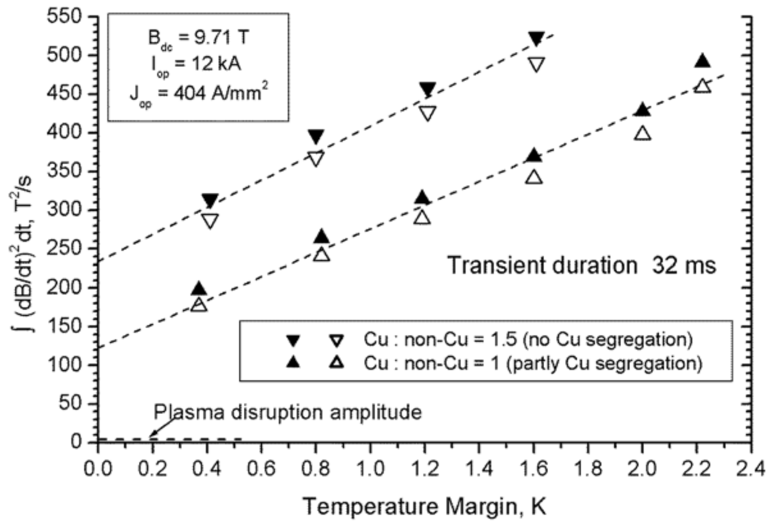

Fig. 5 Transient field stability results for two Nb_3Sn sub-size conductors identical except the location of the stabilizer, either fully included in the strand cross section or partly segregated

Encouraged by this result, another transient field experiment has been carried out, where two Cr plated Nb_3Sn cable-in-conduit conductors (CICC) are series connected and exposed to the same pulsed field. The only difference between the two sub-size CICCs is the location of the stabilizer, either homogeneously distributed in the composite with Cu:non-Cu = 1.5, or partly segregated , with

Cu:non-Cu = 1 in the composite and other Cu wires bundled in the cable. The transient field stability result, see Fig. 5, proved that, although the segregated copper marginally contributes to transient stability, the Cu:non-Cu = 1 is largely sufficient for the ITER stability requirement [17]. Other transient stability experiments, e.g. [18] on the effect of the void fraction, confirmed the very high stability of Nb_3Sn CICC.

The results on transient stability and copper segregation had a feed back on the conductor design: dropping the Cu:non-Cu ratio from 1.5 to 1 and giving up the large temperature margin, could have dramatically reduced the amount of strand to be procured. However, see section 5, the layout did not change substantially because the large engineering margin, originally retained for transient stability, was later re-allocated to balance the transverse load degradation.

4.3 Joint development

The joint development for ITER conductors was carried out independently, in parallel, by four participants of the project. The proposed joint layouts [19-20] are different in geometry (e.g. lap joint and butt joint) and use also different technologies (explosive bonding, vacuum brazing, soldering, etc.).

The test of the CS and TF model coils provided the opportunity to test a large number of joints, manufactured by the industry according to different layouts, under realistic operating conditions. The test results [21-22], showed that, whatever the joint design, the average resistance of over 50 joints falls into the same range, 1.2 – 2 nΩ, which is satisfactory for the ITER requirement.

As far as ac loss and resistance distribution, not all the joint perform in the same way. However, the importance of these issues for the ITER coils is not yet clarified.

4.4 Critical current vs. mechanical load

The test of Nb_3Sn strand under mechanical load has been a continuous activity for the ITER R&D. In the last two years, more effort has been done, mostly in Europe (Univ. of Twente and Univ. of Durham).

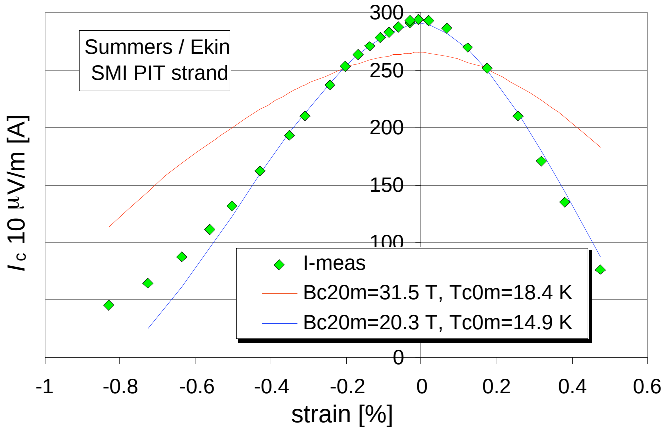

Fig. 6 The I_c vs. axial strain of Nb_3Sn strand is not properly fit by the Summers law [23]

The validity of the traditional scaling laws (Summers law) has been questioned by recent investigations in the range of high, axial compressive load. As an example, Fig. 6 [23] shows a curve of I_c versus axial strain. If the Summers law is applied using realistic, physical parameters for B_{c2} and T_c, red curve in Fig. 6, the fit is very poor. To improve the match, the critical parameters must be pushed into a non-realistic range. Yet, a satisfactory fit can be achieved only over a limited range of strain. Alternative scaling (deviatoric strain, interpolating fit) formulae are under discussion in the ITER community [23-24].

Other I_c experiments [25-26] focused on the sensitivity of Nb_3Sn strand to bending load, providing possibly a key to understand the transverse load degradation in CICC.

Plenty of I_c test vs. axial load have been carried out at the FBI facility at FzK on subsize CICC with different jacket material. Full size conductors are tested under electromagnetic transverse load in the SULTAN test facility.

The ITER conductor design criteria have been updated several times to update the improved strand performance as well as the degradation due to the transverse load. However, as the two effects somehow balance, no real feed back is observed on the conductor layout.

5. TWO OPEN ISSUES FOR DEVELOPMENT

5.1 Effect of transverse load on large Nb_3Sn CICC

Results obtained on ITER Model Coils and test conductors in SULTAN Test Facility revealed that Nb_3Sn strand properties are permanently reduced in the cable after operation. The results suggest that transverse loading during operation is causing a drop in J_c and *n*-value due to bending effects and/or enhanced local pressure at cable crossings [27]. A particular disturbing phenomenon is the a priori reduced index of resistive transition *n* of the cable compared to the value of the constituent strands.

A crucial experiment [28] has been set up to assess the actual amount of degradation which affects a Nb_3Sn CICC compared to a monolithic conductor where the strands are supported against local, enhanced transverse load. A section of a full size ITER CICC has been solder filled (except the central channel) after heat treatment.

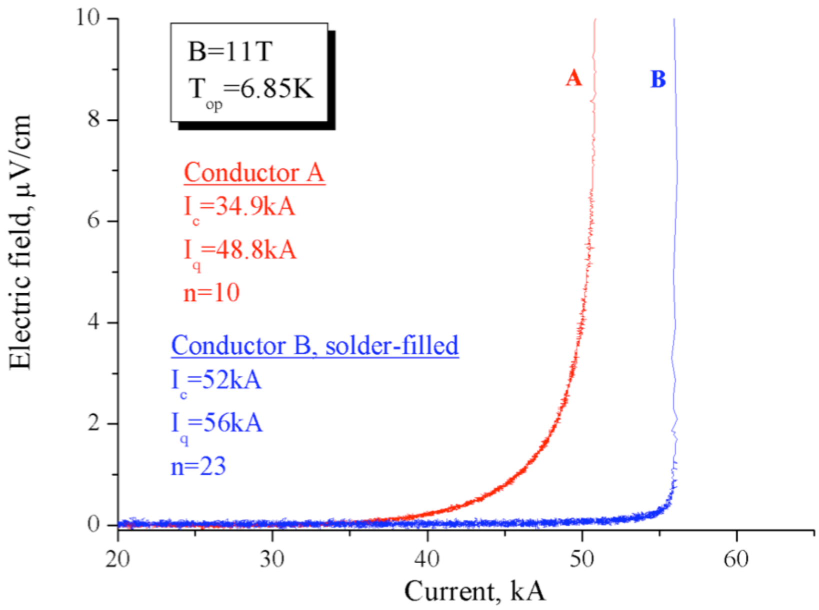

Fig. 7 Comparison of DC performance for a Nb_3Sn CICC and an equivalent monolith conductor [28]

The dc performance of the two conductors, identical except the solder filling, is shown in Fig. 7. Conductor A develops early voltage and a thermal runaway before any voltage can be observed on conductor B (the solder filled). A direct comparison between conductors A and B revealed a higher performance of conductor B in spite of a higher residual strain of the Nb_3Sn filaments in the solder-filled conductor B. The amount of degradation is of the order of 30-40% (although the background field was identical for the test in Fig. 7, conductor B has a higher peak field due to the higher current/self-field). The power-law index of conductor A drops from 15-20 for strands to n_A=10 in the cable, while in conductor B no such reduction of n is observed, n_B=23.

The sensitivity to mechanical loads, both axial compressive strain and transverse load, is the main open issue for Nb_3Sn CICC. In the medium-long term, the issue must be solved to exploit in full the potential of the newly developed Nb_3Sn strands. This may require a substantial design review and a deviation from the present CICC layout (not likely to happen within the ITER project)

5.2 Thermo-siphon effect on dual channel CICC

During an ac loss test in SULTAN of an ITER prototype conductor [29], it has been observed that the moderate heat generated by ac loss in the bundle region is poorly removed as the flow tends to stagnate in the bundle and the heat exchange with the helium flowing in the central channel is not effective. As a consequence the temperature slowly increases in the bundle, eating up the temperature margin of the conductor till, eventually, the conductor quenches.

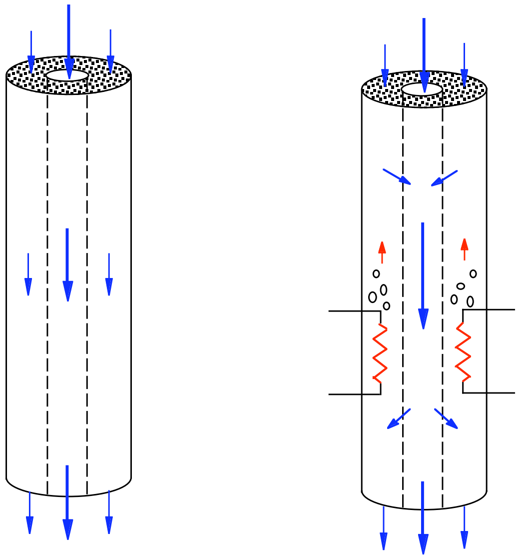

Fig. 8 Schematic view of a dual channel CICC vertically oriented, with flow from top to bottom

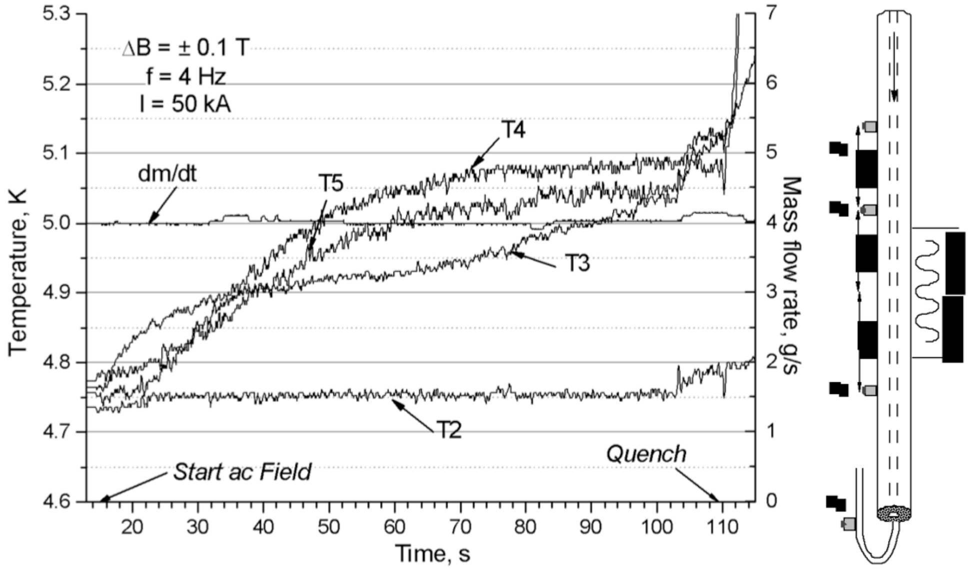

Fig. 9 Summary plot for the ac loss experiment showing how the thermo-siphon effect leads to a quench [29]

A schematic of the sample, vertically oriented with coolant flow from top to bottom, is shown in Figure 8. In the actual experiment, the “heater” is the ac loss generated in the strand bundle by ac field. The plot of the results in shown in Fig. 9. The ac loss power input, separately measured at another run, is in the range of 4 W, which, at an overall mass flow rate (bundle + central channel) of 4 g/s, corresponds to a temperature increase of ≈ 0.25 K (see also T5 behavior). During a run with long ac field sweep, it is observed that the overall mass flow rate is constant, but the temperature sensor T3, upstream of the ac field, increases, what brings evidence of flow stagnation/reversal in the bundle region. This effect, analytically investigated in [30], can be explained with the buoyancy of the lighter, heated helium in the bundle, which opposes the top-to-bottom flow. In the central channel the flow increases to maintain the overall flow constant. At the operating conditions in Figure 3 (6 T, 50 kA, 4.7 K), the temperature margin of the conductor is 1.2 K (separately measured) and no quench is expected for the moderate heat input of 4 W (+0.25 K). However, because of the poor heat removal due to the thermo-siphon effect, the actual local temperature keeps increasing (see T3 and T4 in the plot of Figure 9) till a quench occurs.

The above result is a serious warning for the straight leg of the toroidal field coils of ITER, where a similar situation (heat deposition in the strand bundle by nuclear radiation and ac loss) may lead to a dangerous reduction of the retained temperature margin in operation and eventually to a quench.

6. CONCLUSION

The R&D for high field ITER conductor, carried out in the last twelve years under an international collaboration, was intended rather as a validation than as an input for the design. Despite the efforts of the ITER team, the R&D activities suffered of lack of coordination, with un-necessary duplication and dispersion of resources.

The results of R&D experiments did not confirm in full the assumptions of the design criteria, which were in some area over-conservative (ac loss, stability) and in other area optimistic (mechanical load degradation). In technology area (e.g. joints and Nb_3Sn strand layout) where no detailed layout specification existed, it has been proved that several options lead to the same performance result.

The feed back of R&D in the design has been intentionally very limited. The initial, generous engineering margin has been largely (ab)used to balance the unexpected, negative results. For example, the extra margin resulting from unexpected high transient stability and from the strand performance, now largely exceeding the original specification, has been re-cycled to cope with the dramatic degradation due to transverse load (BxI) in the CICC.

The interest of the industry in the ITER conductor remains modest and insufficient to trigger internal activities in R&D and logistic (except Russia). The impressive progress in strand performance of the last three years has not been triggered by the ITER project.

There is good confidence that the ITER high field conductors will fulfill their duty. On the other end, the experience and the results accumulated in the last twelve years of R&D activity could allow a different design approach, should we start again from scratch in a new fusion project…

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