Recent Results from R&D on Superconductors at CRPP

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Abstract. Prototype conductors for the ITER magnets have been tested extensively in the SULTAN facility at CRPP in the last decade. The in depth characterization of the high current carrying conductors provided a valuable feedback in the design, with performance optimization and cost reduction. From the transient stability results, the temperature margin required to withstand the plasma disruption has been found to be much smaller than originally assumed. A comparison between two specially designed conductors showed that the copper fraction in the superconducting Nb_3Sn composite can be reduced without affecting the stability, leading to a substantial reduction of the overall amount of superconducting composite to be procured for the ITER magnets. AC loss measurements carried out over a broad range of frequency, brought evidence of two regimes of losses, complementing the test results of the ITER model coils and indicating that the correct eddy currents loss to be retained in the design for plasma disruption and initiation is much smaller than the value extrapolated from the slow charge of the model coils. Other results on current distribution, cyclic load and joint performance are briefly reported.

1. Introduction

In the early eighties, the construction of a high field test facility started in Villigen (North-West Switzerland) as a joint effort of a Swiss, Italian and Dutch Team, under the sponsorship of EURATOM. The nickname SULTAN was given as an acronym of the German SUpraLeiter TestANlage. The facility evolved into a split coil of three pairs of graded, NbTi and Nb_3Sn coils with high field access for straight conductor samples, powered by a 100 kA superconducting transformer. The superimposed, pulsed field capability was also added. SULTAN is now the world wide reference test facility for large, force flow superconductors, with dc field up to 11 T, superimposed, quasi steady state, ac field up to ± 0.5 T, superimposed transient field up to 4 T, 140 ms and a broad range of operating temperature and mass flow rate [1].

During the ITER EDA and CTA, a dozen of full size conductors and joints (prototypes of model coils, inserts and busbar conductors, made of Nb_3Sn, Nb_3Al and NbTi) have been tested as a short, straight samples. Seven subsize cable-in-conduit conductor samples of NbTi and Nb_3Sn have been prepared at CRPP and tested in the frame of parametric studies. Two experiments with coiled conductor samples have been also carried out in the 600 mm bore of the SULTAN magnets, the QUELL (QUench Experiment on Long Length) [2] and the SeCRETS (Segregated Copper Ratio Experiment on Transient Stability) [3]. About half of the samples are prepared outside of CRPP by international teams from EU, JA , US and RF, who participate to the test activity in SULTAN. The sections below summarize the design relevant results from selected tests carried out recently in SULTAN.

2. Transient Field Stability and Segregation of Stabilizer

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 because of the unknown behavior at plasma disruption and imposing a large copper fraction in the Nb_3Sn composite strand.

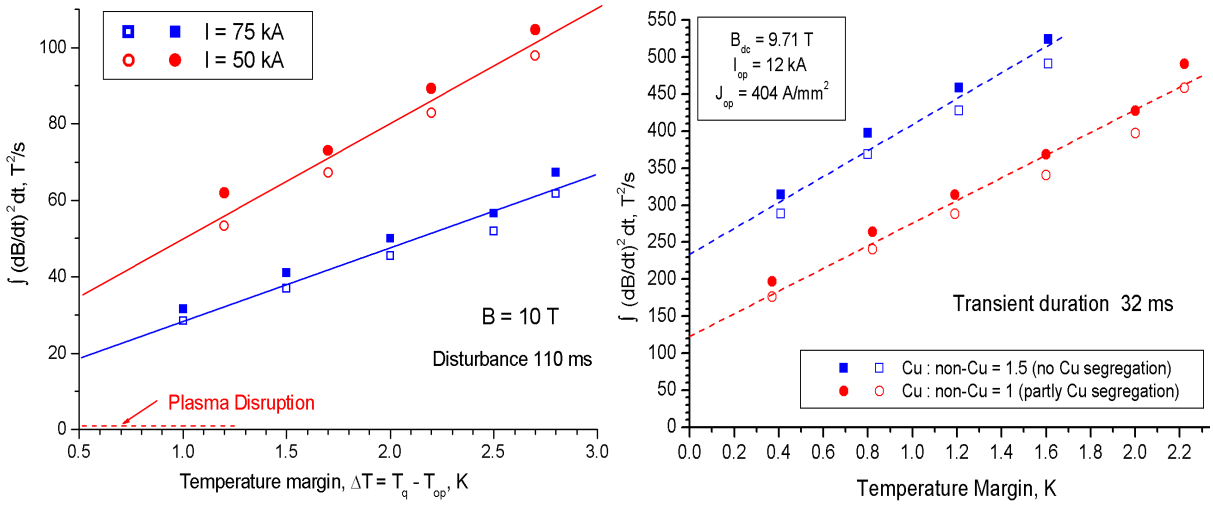

FIG. 1. Transient field stability results on a Nb_3Sn CS model coil conductor(left) and on two Nb_3Sn subsize conductors identical except the location of the stabilizer(right)

During the test in SULTAN of a model coil conductor, large field transients, well above the plasma disruption events, have been applied under relevant operating conditions, proving, see Fig 1 left, that a very marginal temperature margin is necessary to withstand a field transient like the plasma disruption [4]. 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 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 result, see Fig. 1 right, proved that, although the segregated copper marginally contributes to transient stability, the Cu:non-Cu = 1 is largely sufficient for the ITER stability requirement [3].

Dropping the Cu:non-Cu ratio from 1.5 to 1 means to reduce by 20% the amount of strand to be procured, by keeping unchanged the “non-Cu” current carrying cross section. Besides the advantage in the procurement time scale, a large cost economy, of the order of 100 M€, is also obtained as the market price of the Nb_3Sn strand does not depend on the Cu:non-Cu ratio. The evidence that large field transient can be withstood with marginal temperature increase can be used to either reduce the overall margin (i.e. the conductor price) or to re-allocate the margin for other unexpected effects observed in the conductor and model coil test [5].

3. Stability and Heat Transfer Coefficient

The ability to effectively transfer heat from the superconducting strand to the coolant is a key feature of the cable-in-conduit conductors. The heat transfer coefficient, h, together with the stabilizer cross section, A_{cu}, and the wet perimeter, p_w, determine the “limiting” current, I_{lim},

$$I_{\lim} = \sqrt{A_{cu}\, p_w\, h\,(T_c - T_{op}) / r_{Cu}}$$

i.e. the maximum operating current at which an instantaneous disturbance (energy input) can be recovered without causing an irreversible runaway [6]. Above I_{lim}, any small disturbance, e.g. a microscopic strand movement in the cable, may cause a sudden take-off (quench) and the conductor is said to be “unstable” or to have “unstable” transition.

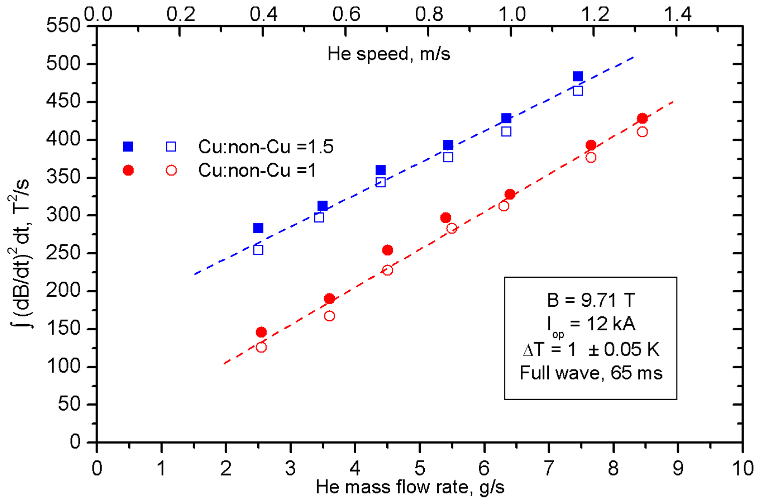

FIG. 2. Transient field stability results on two Nb_3Sn CICC as a function of the coolant speed

The heat transfer coefficient strongly depends on the helium turbulence at the strand surface (Dittus-Bölter correlation), however in the ITER design criteria, a low value of *h* is retained, corresponding to the quasi-stagnant helium condition (600 – 1000 $W/K{\cdot}m^2$). In the ITER Nb_3Sn CICC, we never observed an unstable transition, even at reduced stabilizer cross section, also due to the broad transition (low *n* index [7]) and hence large ?$T = T_c - T_{cs}$. However, the impact of the helium speed (and hence *h*) on the ability of the Nb_3Sn CICC to recover after an energy input was observed in the transient field stability experiment [3], see Fig.2, where the disturbance duration (65 ms) is longer than for a strand movement (< 10 ms).

In NbTi CICCs, unstable transitions are observed above a threshold current density which can be assessed as J_{lim}. Below J_{lim}, blue dots in see Fig.3, the CICC results scale satisfactorily compared to the strand J_c (green lines). Above J_{lim}, the CICC performance (red dots = I_q) deviates progressively from the strand data. The only difference between the two CICCs in Fig. 3 is the strand coating: the CICC with low resistivity coating (SnAg) has a higher threshold for unstable transition, 800 vs. 550 A/mm^2, which is an evidence of a more effective interstrand current sharing (on the other hand, the CICC with SnAg coating has much higher ac loss and hence a very poor transient field stability [8]).

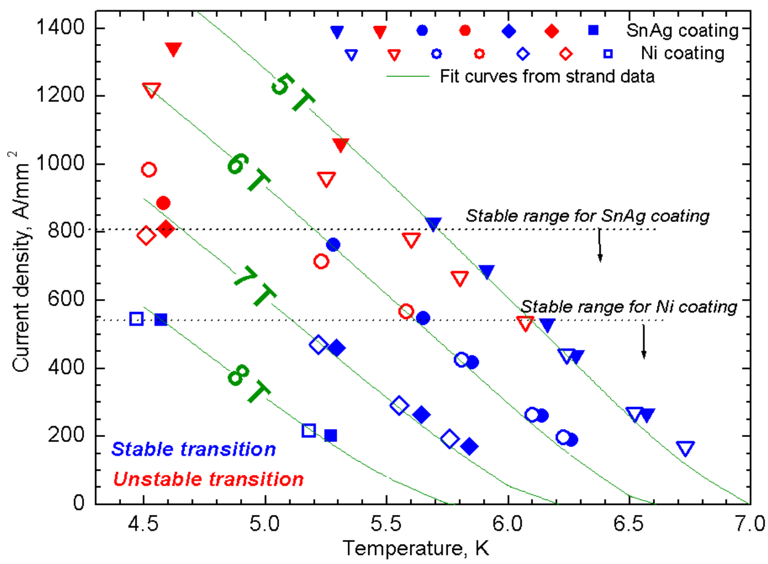

FIG. 3. DC performance of two NbTi CICCs without central hole, identical except the strand coating, revealing the threshold between stable and unstable transition

The presence of a pressure release channel in the CICC drastically reduces the coolant speed in the strand bundle area for the same overall mass flow rate. The impact on the stability is dramatic. A NbTi full size ITER conductor (with central hole) tested in SULTAN in 2002 showed a threshold for stable to unstable transition, i.e. J_{lim}, in the range of 150 A/mm^2 [9] compared to the 550- 800 A/mm^2 observed in the conductor without central hole. The effect of the coolant speed on h and hence on J_{lim} is much stronger than the Cu to non-Cu ratio. In fact, the conductor with central hole and J_{lim} ~ 150 A/mm^2 has Cu:non-Cu ~ 1.9, compared to Cu:non-Cu ~ 1.05 in the conductor without central hole and J_{lim} ~ 550 A/mm^2 (both conductors have the same void fraction and Ni strand coating).

5. AC Loss

The coupling loss characterization of a superconductor is aimed to identify the coupling loss constant, nτ, to be used in the loss formulae. In large multistage CICCs, several induced current loops of different size overlap with multiple time constants. The extrapolation of the coupling loss from a low frequency range (e.g. the charge and discharge of a large coil) to a short time scale event (e.g. plasma disruption and initiation) may lead to large errors as the loops with large time constant are fully screened in short time scale events. In SULTAN, the ac loss can be measured over a broad range of frequency, from 0.03 to 6 Hz by combined calorimetric and magnetization methods [10].

For CICCs of Cr coated Nb_3Sn strands with void fraction about 36%, the loss curve in linear and logarithmic scale is shown in Fig. 4. For field changes on a time scale shorter than 4 – 5 s (f > 0.2 Hz), the coupling loss is very small, substantially restricted to the interfilament loss, with nτ of the order of 1 to 3 ms. This result is independent on the loading history. On the opposite, the energy loss for slow time varying field, with time scale of the order of 10 to 1000 seconds (e.g. the coil charge) is large, with not really predictable nτ. After cyclic operation, the interstrand resistance increases and the large current loops may vanish locally, in the most heavily loaded sections of the winding. However, in average, the overall decrease of the coil loss after many load cycles may be not dramatic.

In NbTi, the effect of strand coating on the ac loss is investigated as a function of the load history, see Fig. 5. The two CICC samples with 336 strands are identical, except the strand coating, either Ni or low resistivity SnAg. The results indicate that the Ni coating is the best choice, with low ac loss, weakly changing upon the initial load cycles. In the SnAg coated sample, the ac loss is initially very large and keeps decreasing after a large number of cycles.

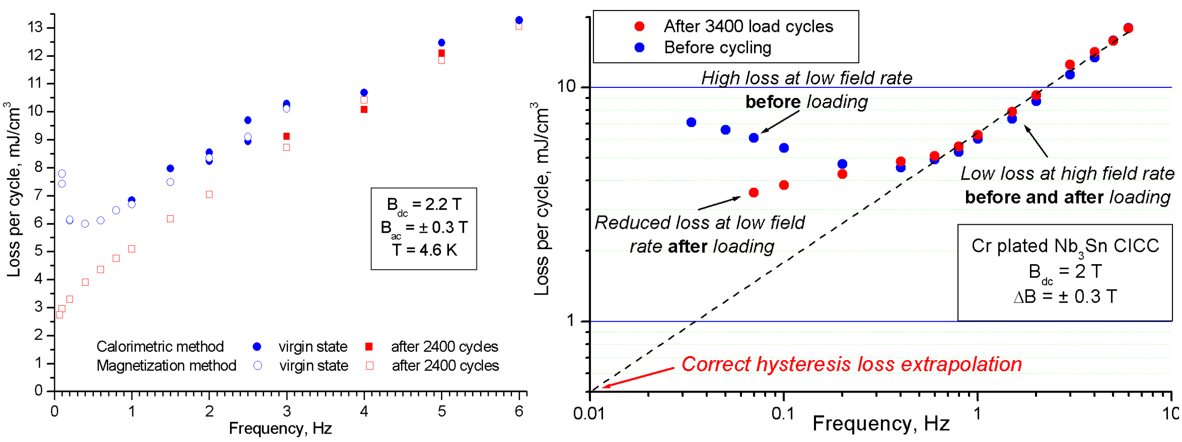

FIG. 4. AC loss in linear (left) and logarithmic scale (right) for Cr coated Nb_3Sn CICC under different load conditions

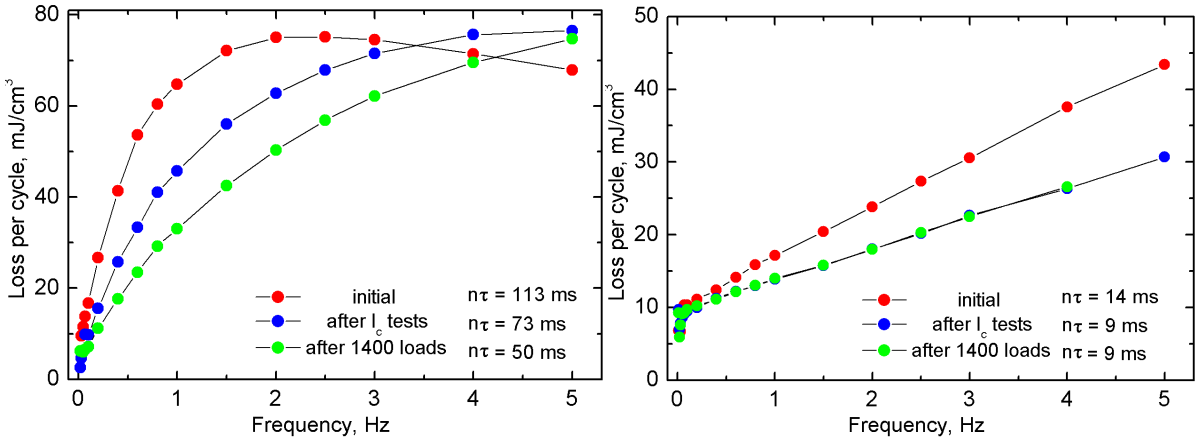

FIG. 5. AC loss of two NbTi CICC with either SnAg coating (left) or Ni coating (right) at different steps of the load history

6. Conclusion

The results obtained in several R&D tasks carried out in the SULTAN test facility have improved the knowledge of the ITER conductor behavior under realistic operating conditions. A refinement of the design criteria, leading to higher reliability and reduced cost, is obtained in the field of transient field stability (margin for plasma disruption), ac loss (actual loss constant to be retained for critical, fast events) and limiting current (impact of coolant speed on stability).

7. References

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