Se.C.R.E.T.S. : A Stability Experiment on the Role of segregated Copper in Nb3Sn Cable-in-Conduit Conductors

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Abstract— **In Se.C.R.E.T.S. (Segregated Copper Ratio Experiments on Transient Stability), the stability performance under transverse field transient is compared for two Nb_3Sn cable-in-conduit conductors which differ only because of the different distribution of the stabilizing copper, either included in the Nb_3Sn strand cross section or segregated as bundled copper wires. If the segregated copper is found to be effective for stability purposes, the copper fraction in the Nb_3Sn strands can be substantially reduced, with dramatic cost advantage for the high field fusion magnets. The experiment is assembled in the SULTAN facility at CRPP, with 11 T background field and superimposed transverse pulsed field to generate the transient disturbance. The layout of the conductor, the winding sample and the assembly procedure are described. The instrumentation and the test program are planned to provide results to be easily extrapolated to the ITER conductors.**

Index terms—**Nb_3Sn cable-in-conduit, transient stability, copper segregation**

I. INTRODUCTION

Since the early sixty's, it is known that some low resistivity, normal metal stabilizer must be attached to the superconducting material to obtain in a wound conductor a performance similar to the bulk superconductor. The required amount of stabilizer for cryogenic stabilization was assessed [1] for bath cooled conductors through the steady state ratio of the heat removal rate to the generated power (Stekly parameter). Later, this power balance was extended as a design criterion to the transient stability of forced flow conductors, see for example [2].

In monolithic conductors (large composites and soldered cables) the stabilizer is fully bonded to the superconductor. In cable-in-conduit conductors, the stabilizer cross section can be adjusted either varying the copper ratio in the superconducting strands or adding a number of copper wires (segregated copper) bundled with the superconducting strands. On sight, the first option sounds preferable, as it offers a safe electrical contact between superconductor and stabilizer. However, it may have a severe financial penalty in the case of Nb_3Sn strand, whose market price is driven by the complexity and risk of the assembly and manufacturing procedures, rather than by the cost of the components. For this reason, the price of Nb_3Sn strand is roughly independent on its copper fraction. Using segregated copper in a cable-in-conduit conductor may turn into a dramatic cost saving for a large Nb_3Sn coil [3].

The stability models used in the past for multistrand cables assumed that the current distribution, as well as the disturbance energy, is homogeneous over the conductor cross section, i.e. no interstrand current sharing is required. A number of recent experimental results, see for example [4-5], showed that current re-distribution among adjacent superconducting strands occurs on a time scale shorter than 1 ms and is a major mechanism for stability against transient, localized disturbances in multistrand cables: effective current sharing starts at interstrand resistance (defined as resistance between two strands in a cable multiplied by the cable length) $< 10^{-6}$ Ω·m. In the same way, it may be inferred that the segregated copper wires are effective for stability, i.e. the current in the stabilizer shares homogeneously between the copper inside the Nb_3Sn strands and the segregated copper wires, despite the contact resistance at the wire crossovers.

In "Se.C.R.E.T.S." (Segregated Copper Ratio Experiment on Transient Stability), the effectiveness of the bundled copper wires for stability against transverse field transients is assessed by the crucial comparison of the performance of two cable-in-conduit conductors made of Cr plated Nb_3Sn strands.

II. DESCRIPTION OF THE EXPERIMENT

A winding made of two Nb_3Sn cable-in-conduit conductors is fitted in the bore of the SULTAN test facility at CRPP, with DC magnetic field up to ≈ 11 *T*, DC operating current up to 12 *kA* ($J_{non\text{-}Cu}$ up to 400 A/mm^2) and cooling by supercritical Helium with adjustable temperature and mass

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TABLE 1. CONDUCTOR LAYOUT

	Conductor A	Conductor B
Cable configuration	3 x 3 x 4 x 4	(1+7) x 4 x 4
N of strands	144	112
N of Cu cores	Ø	16
Strand diameter	0.81 mm	0.82 mm
Cu:non-Cu	1.45-1.54	1.02
Cu-core diameter	-	1.1 mm
non-Cu cross section	29.68 mm2	29.57 mm2
Cu cross section	44.52 mm2	44.77 mm2
Overall perimeter	0.366 m	0.343 m
SC strand perimeter	0.366 m	0.288 m
Twist pitches, mm	10,48,87,120,160	10, 61, 120,160
Nb3Sn strand/m	0.66 kg/m	0.52 kg/m
Steel wrapping	25 x 0.065 mm, 14 mm pitch	
Jacket wall thickness	1. 01 ± 0.02mm	
Void fraction	≈ 37 %	
Conductor diameter	14.54 ± 0.03 mm	
Cable space diameter	12.54 ± 0.03 mm	

flow rate up to 11 *g/s*. A set of pulsed field coils provides the transverse field disturbance for stability experiments.

A. The cable-in-conduit conductors

Two conductor sections, A and B, each about 50 m long, are prepared with different cable layouts. Conductor A is a typical last but one cable stage of the high field ITER Model Coil conductor (CS1), with all the stabilizing copper included in the superconducting strand cross section at Cu:non-Cu = 1.5 [6]. Conductor B has the same Cu and non-Cu overall cross section, but the Cu:non-Cu ratio is reduced to 1 in the superconducting strands and the first cable stage is built by a ring of 7 strands around a copper core, see Fig.1 and Table 1.

The Nb_3Sn strand for conductor A is identical to the ITER Model Coil strand [6]. For conductor B, the same supplier (VNIINM, Moscow) provided the strand with different Cu:non-Cu ratio and the same non-Cu J_c. All the strands are Cr plated by the same vendor (VNIIKP, Moscow). The cable sections are jacketed by butt weld and pull-through method into a 316 L stainless steel pipe with identical geometry. The qualification tests of the conductors (ac losses, contact resistance and I_c vs. axial strain) as well as the results of the manufacturing quality assurance, are reported in [7].

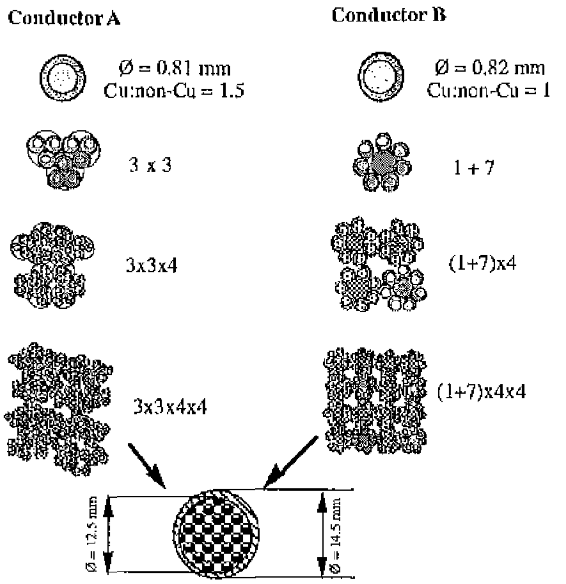

Fig. 1 Layout and cross section of the two cable-in-conduit conductors

B. The winding

Two conductor sections, ≈ 16 m long, are joined at one end and wound as a bifilar, single layer solenoid at OSWALD, Germany. The He inlet is placed at the joint. The He outlets are at the winding termination. The diameter of the winding is 400 mm. The conductors are encased in a half round groove machined on a steel cylinder. A overlapped mica-glass tape is wrapped on the conductor before heat treatment. The 2 x 11 turns are spaced and bolted to the steel cylinder by a number of clamps, see Fig.2. After the heat treatment, the conductors with the mica-glass insulation had a resistance to ground in the range of 10 MΩ. The insulation was replaced by a half overlapped kapton tape with identical thickness. The winding is not impregnated to allow free access between the clamps for instrumentation, heaters and pulsed coils. The length of the winding is about 1 m, excluding joint and termination.

The winding is manufactured according to the wind-and-react method. The heat treatment is carried out in Ar atmosphere (575 C / 150 hrs, 650 C /200 hrs). A number of specimens for strand I_c, conductor ac losses and I_c vs. strain, are also included in the heat treatment. After heat treatment, all the bolts are replaced. The joint and termination are finished after the heat treatment.

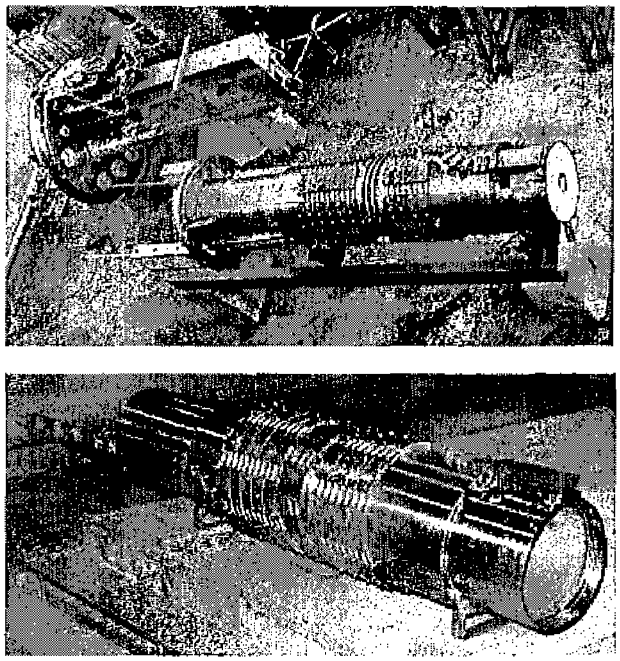

Fig. 2 The winding before the heat treatment (below) and with current leads and flange for insertion in the SULTAN facility (above)

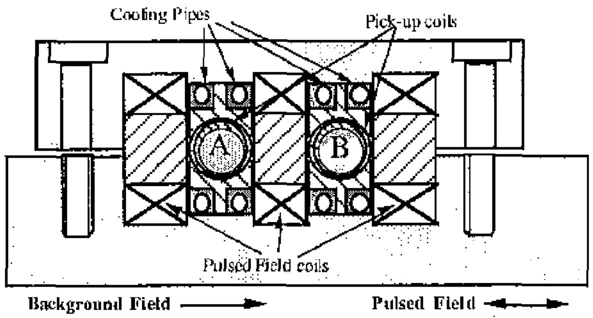

Fig. 3 Detail cross section at the pulsed coils location

C. *The pulsed field coils*

The transverse pulsed field for the stability test is provided by a set of three bent race-track coils (designed and manufactured at Univ. of Twente), wound with a copper wire, covering about 300 mm of conductor length. The windings are potted and attached to a steel clamp, which is bolted to the main cylinder after heat treatment, see Fig. 3 and 4. A number of cooling pipes are attached to the pulsed coils to intercept the heat generated after a shot and prevent heating by conduction of the cable-in-conduit conductors.

The average pulsed field over the conductor cross section is, with a ± 500 *A*, ± 100 *V* power supply, up to ± 0.78 *T*, with ±10% homogeneity. The actual operating range depends on the duration of the pulsed field shot (hot spot limit on the race-track coils) and on the dI/dt (self-inductance ≈ 1.4 *mHy*). The shots simulating the plasma disruption have an amplitude up to ≈ 0.5 *T* and a time scale 0.3-0.5 *s*. Smaller amplitude ΔB, say ± 0.1 *T*, can be swept in sinus mode for duration up to 10 *s*, over a frequency range 0.1 – 5 *Hz*. Faster pulse field shots can be obtained using the discharge of a capacitor, with a resonating frequency about 20 *Hz* (one cycle about 50 *ms*).

To minimize the stray field on the SULTAN coils, the pulsed field windings are placed at locations symmetric with respect to the center of SULTAN, with the field orientation parallel to the background field. The stray field amplitude on the high field coils is ≤ 3% of the pulse field amplitude at the cable-in-conduit cross section.

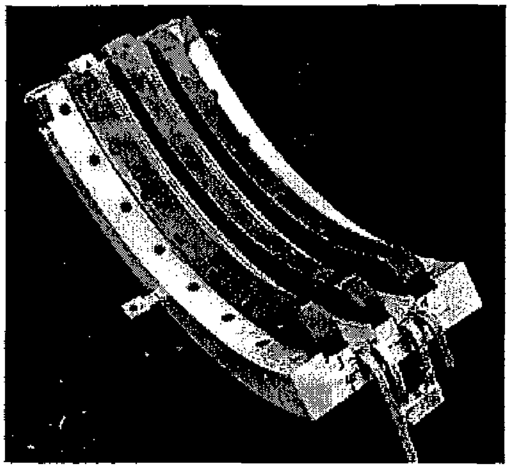

Fig. 4 The pulsed coils, pre-assembled with the steel clamp and the upper cooling pipes

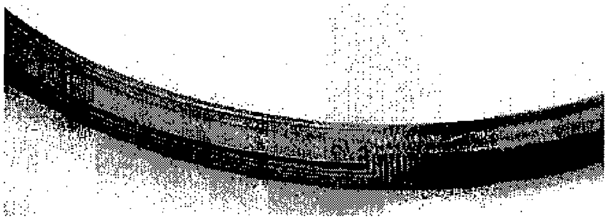

Fig.5 Detail of a pick-up coil, obtained by machining the toroidal, Cu plated surface of a glass-epoxy shell

The cable-in-conduit conductors are surrounded by saddle shaped pick-up coils to detect the magnetization. The 8 turns of the pick-up coils are spaced to carry out two-dimensional flux integration [8]. To fit the toroidal surface of the conductors, the pick-up coils are manufactured by high precision machining a copper plated glass-epoxy shell, see Fig.5.

D. *Instrumentation and test program*

The background field produced by the SULTAN split coils, up to 11.3 T, has a saddle shape in axial direction. The difference between the peak field (at the 3rd turn) and the field at the center of the winding is –6%. A 12 kA dc current source provides non-Cu operating current density up to 400 $\mathrm{A/mm^2}$ (compared to 160 $\mathrm{A/mm^2}$ in the high grade ITER CS and 324 $\mathrm{A/mm^2}$ in the ITER TF). A 80 W heater controls the inlet temperature over a broad range. Throttle valves at both outlets adjust the mass flow rate in the two conductors. The temperature sensors, see Fig. 6, are in contact with the coolant (the jacket is locally opened). Voltage taps are attached both in the highest field section and at the location of the pulsed coils.

The test program includes the dc test of both conductors with T_{cs} measurements vs. background field and operating current. The Lorentz forces on the winding load one conductor in tension and the other in compression. As both conductors are tightly clamped to the bulk steel cylinder, the longitudinal strain, ε, is expected to be the same. A test

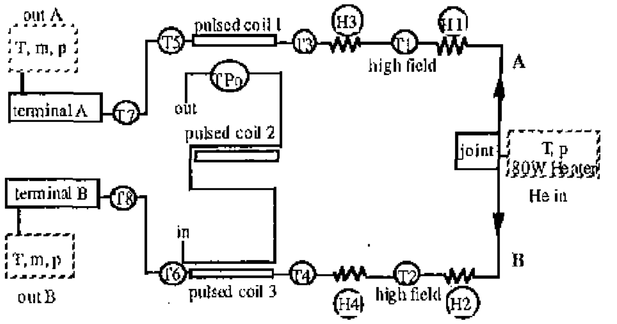

Fig. 6 Schema of cooling, heaters and thermometers location

with reverse polarity of the sample current will be done to verify the assumption. Small heaters are placed on each conductor before the high field sections and the pulsed field, see Fig. 6, to unbalance (if necessary) the operating temperature and obtain dc characterization for both conductors.

The key test for SeCRETS is the stability test under pulsed field. After setting background field and dc operating current, the temperature is adjusted to obtain the same temperature margin, ΔT, in both conductor and pulsed field shots are applied with increasing amplitude till one conductor quenches. Afterwards, ΔT is increased in the weaker conductor to allow further testing of the stronger conductor. The test is repeated for several settings of operating current density and two time-scale of pulsed field, say 50 and 200 ms. The relative performance of the two conductors can be assessed by the ratio of the limiting current [2],

$$\frac{I_{lim}^{A}}{I_{lim}^{B}} = \sqrt{\frac{p^{A} A_{Cu}^{A}}{p^{B} A_{Cu}^{B}}} \qquad (1)$$

If the segregated copper fully contributes to stability, the ratio in (1), using the data in Table 1, is expected 1.03, i.e. the two conductors have about the same stability performance. Considering only the copper included in the Nb_3Sn strands, conductor A is expected, according to (1), to have 38% better performance than B.

Another object of the SeCRETS test is the assessment of the minimum ΔT required to withstand plasma disruption. The field profile and time scale of a plasma disruption can be reproduced by the pulsed field coils. After setting the background field and the ITER relevant operating current density, the "plasma disruption" is applied and the temperature margin is decreased till a quench occurs.

The ac losses can be measured as a function of the background field and operating current. A small, sinusoidal ΔB, say ± 0.1 T, is applied over a broad range of frequency, for a duration up to 10 s. The ac losses are measured by gas flow calorimetry, see for example [9], and, at low frequency, by pick-up coil magnetization and V·I. The fact that the ac losses may be slightly different in A and B is part of the game, as this is also a result of the different conductor layout due to the copper segregation.

An annular array of six Hall sensors is attached at three locations to both conductors to monitor the current distribution and its evolution. A linear array of Hall sensors is also placed at the conductor edge to investigate the occurrence of boundary induced coupling currents, far away from the pulsed field region [10]. The ability of the two conductors to re-distribute the current among superconducting strands and the segregated copper is part of the game (as well as the ac loss) for the comparison of the two layouts. The initial current distribution, when the pulse field is applied, is monitored at three different locations: as the joints have the same layout and the current rate is the same in the two conductor, the initial current distribution is also expected to be similar in A and B.

III. STATUS AND SCHEDULE

The SeCRETS project started about mid 98. The conductor procurement (through VNIINM and VNIIKP) was completed by the end of 98. The winding was carried out at OSWALD GmbH in March 99 and heat treatment was completed at ANSALDO, Italy, in June 99. The instrumentation, assembly of the pulsed coils, current leads, structural support, etc. has been completed at CRPP in September 99. The assembly in the SULTAN facility has been delayed to complete a number of tests on conductor short samples. Warming up of the facility is underway and the cool-down of SeCRETS is planned by the end of 99. The test period is expected to last four months, with results available in spring 2000.

IV. CONCLUSION

The effectiveness of the segregated copper for stability in cable-in-conduit conductors of Cr coated Nb_3Sn strands is investigated by a crucial experiment with direct comparison of the stability performance of two conductors identical except the location of the copper stabilizer. The results of the experiment will allow modifications of the conductor design with a substantial cost reduction for the large Nb_3Sn conductors of the fusion magnets.

The test program includes also the assessment of the actual temperature margin required to withstand plasma disruption, providing another essential input for the design and cost optimization of the fusion conductor.

The assembly of the experiment is completed. The test will be carried out next winter.

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