DEVELOPMENT AND TESTING OF HIGH FIELD, HIGH CURRENT DENSITY SOLENOIDS AND MAGNETS, WOUND WITH STABILIZED FILAMENTARY Nb_3-Sn CABLE AND REACTED AFTER WINDING

by

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ABSTRACT SUMMARY

First, the successful development and testing of a 2.6 cm inner diameter, high field and high current density solenoid, wound with a Cu-stabilized, fine filamentary Nb_3-Sn cable, and reacted after winding, is described. At an overall current density in the winding of 352 $\frac{A}{mm^2}$, corresponding to a current density of 565 $\frac{A}{mm^2}$ in the non-insulated cable, a maximum field of B_m = 8.8 T had been obtained without any training.

Based on this very positive result, a 0.9 m-long, 10 cm-warm bore, beam line quadrupole magnet, wound with the same cable, is actually being assembled.

The nominal parameters are : field gradient 74 $\frac{T}{m}$, maximum field in the winding B_m = 7.4 T at an overall current density in the winding of 300 $\frac{A}{mm^2}$.

The very specific technological and design aspects of this magnet, related to the "wind and react" technique, such as the conductor insulation, coil winding technique, execution of connections etc, will be discussed.

Actually, the four coils for the quadrupole magnet have been manufactured and the assembly of the magnet started. We expect to perform the first tests early next year.

i) Introduction

As a result of intensive development efforts during the past years, fine filamentary Nb_3-Sn superconductors are now available as compacted conductors or cables, with the possibility of adding or incorporating a certain percentage of stabilizing copper in different ways.

There is an obvious interest in the application of filamentary Nb_3-Sn superconductors to magnets used in high energy elementary particle physics : apart from the intrinsic advantage of Nb_3-Sn superconductors with respect to Nb-Ti ones, consisting in much higher magnetic fields at comparable current densities - it can roughly been stated that filamentary Nb_3-Sn superconductors will at 8 T carry the same overall current density as Nb-Ti at 4.5 ... 5 T - it has also the advantage of a much higher critical temperature of T_K = 18 K (at B = 0 T) and of a very small filament size of 2 ... 3 µm.

Using equation (1) to determine the allowed temperature rise ΔT (I, B, T_K) for Nb_3-Sn and Nb-Ti at an assumed operating temperature of 4.6 K :

$$\Delta T = (T_K - 4.6) \{1 - (\frac{I.B}{I_m B_m})^{0.5}\} \qquad (1)$$

and assuming that a magnet is designed for $I = 0.7.I_m$, $B = 0.7.B_m$, one obtains :

for Nb-Ti → ΔT = 1.62 K ;
for Nb_3-Sn → ΔT = 4.0 K.

This means that beam line and accelerator magnets and solenoids, wound with filamentary Nb_3-Sn, would be considerably more safe against quenches due to heat generation in the conductor by eddy currents, energy deposit due to radiation induced by primary and secondary particles, as well as heat leaks in general.

Furthermore, the very small filament diameter of Nb_3-Sn superconductors, of ∿ 2 ... 3 µm provides high intrinsic stability, reduces training and minimizes persistent diamagnetic current effects.

The price to be paid for a successful application of this superconductor is the more complex technology and materials to be used for the "wind and react" technique, the only one which can be successfully applied to the design of beam line and accelerator magnets with very small bending radii of the windings.

ii) The solenoid

A 2.3/9.0 cm diameter, 5 cm high test solenoid, with several features similar or equal to those encountered in windings of superconducting magnets, had been made and successfully tested by end 1978.

A cable, manufactured by the Vacuumschmelze Co, Hanau, Germany, according to Fig. 1 has been used. The 1.1 x 2.2 mm^2 cable consists of a central stabilizing 0.4 x 1.5 mm^2-Cu strip, surrounded by a Ta-barrier and some binding copper ; around this central part twelve 0.4 mm ∅ strands are transposed, two of stabilizing Cu, again Ta-and Cu-clad and coated with Sn, and ten superconducting bronze-Nb composites. After reaction each superconducting strand will contain 3721 ∿ 3µm wide Nb_3-Sn rings.

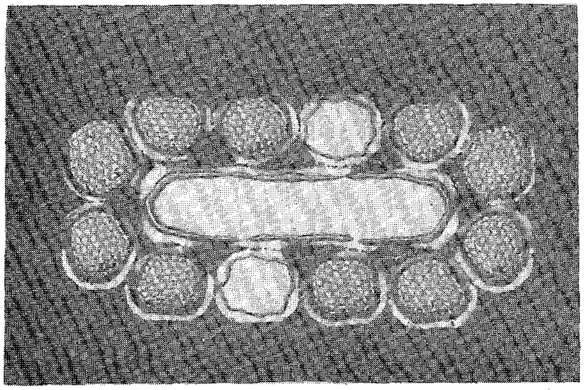

Figure 1

The cable is transposed and the filaments in each composite are twisted. The percentage of various parts in this cable, referred to the total cross-section, are: stabilizing Cu 27.2 %, binding Cu and Ta 6.5 %, Nb_3-Sn superconductor 13 %, bronze 51 %, Sn 2.3 %.

The problem of an adequate conductor insulation, to withstand the high temperatures of the reaction process, had been successfully solved by using quartz-glass fibres made by the "Quarz & Silice Co" in Paris, France. The fibres are made with a special glue yielding a low carbon content after reaction (0.03 %). The braiding of the insulation has been done by the "Isola Co", Breitenbach, Switzerland.

During the winding process it turned out to be necessary to "impregnate" the insulation with paraffin, in order to avoid mechanical damage to the insulation.

The reaction diagram according to Fig. 2 shows two steps related to paraffin extraction from the winding at 75 ... 80°C and at 270°C under vacuum.

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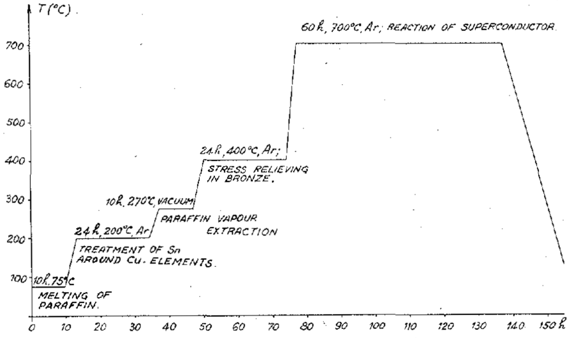

Figure 2

Two further important features of the test solenoid : the coil ends and the connections to the lower end of the current leads. Due to the extreme brittleness of the Nb_3Sn cable after reaction, the coil ends were made of In-clad Nb-Ti superconductor, sandwiched to the Nb_3-Sn cable and soldered with an In-Sn alloy over a length of ∿ 10 cm ; contact resistances below 10^{-8} Ω were obtained at 4.2 K.

The end connections, made of Nb-Ti were In-Sn soldered to grooved and In-clad copper rods, forming the lower current lead end (Fig. 3).

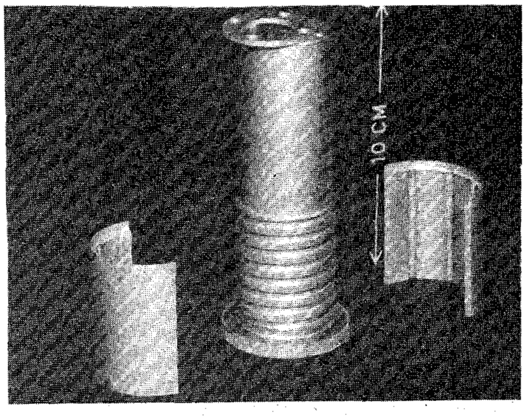

Figure 3

The completely wound and reacted solenoid had been impregnated with epoxy resin, mounted into a stainless steel shell, equiped with sensors, Hall plates etc, and mounted into a vertical cryostat (Fig. 4).

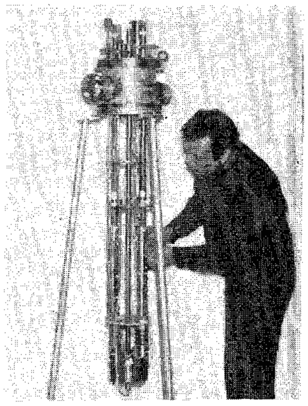

Figure 4

Test results are shown in Fig. 5 : a critical current of I_k = 1370 A has repeatedly been reached without any training. The corresponding maximum field in the winding was B_{max} = 8.75 T, the average current density in the 1.1 x 2.2 mm^2 cable, 565 $\frac{A}{mm^2}$ or 352 $\frac{A}{mm^2}$ over the total cross-section of the insulated cable.

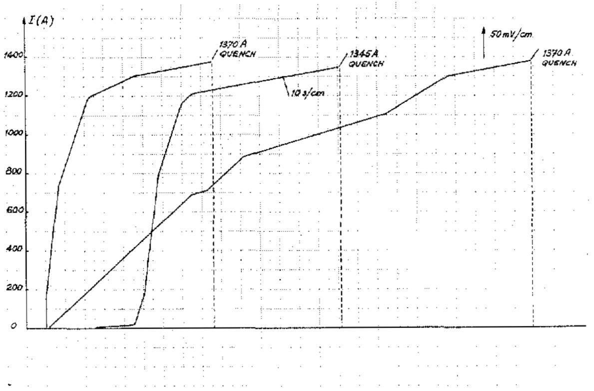

Figure 5

iii) The superconducting quadrupole magnet

Based on the very encouraging results obtained with the test solenoid, we decided to build a 0.9 m long, 10 cm useful warm bore, beam line quadrupole magnet to be wound with the same 1.1 x 2.2 mm^2 Nb_3-Sn superconducting cable. In order to shorten the design and manufacturing time, we have chosen to build a high field version of the 55 $\frac{T}{m}$ field gradient, 5 T-maximum field superconducting quadrupole called "CASTOR", wound with compacted, Cu-stabilized Nb-Ti superconductor, successfully tested in 1972 {1} and since installed and operational in one of the CERN 400 GeV SPS secondary beam line.

By doing so, we could re-use most of "Castor"'s infrastructure, such as the He, N_2 and vacuum tanks of the cryostat, the current leads and the mechanical clamping system for the active part.

It should, however, be stressed, that the "wind and react" technique of the Nb_3-Sn superconductor imposes a novel and more sophisticated technology for the manufacturing of the winding active part, as explained below.

The active part cross-section is shown in Fig. 6 : each pole winding consists of two parts with 6 layers and 60 turns and 16 layers and 160 turns respectively.

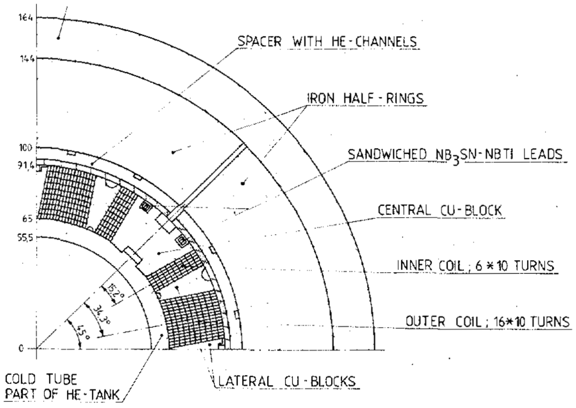

Figure 6

The insulated and paraffin "impregnated" Nb_3-Sn cable is wound around the central and lateral Cu-blocks, and the completed winding is compressed by the two lateral end blocks ; all blocks have an Al_2O_3 sprayed ground insulation (Fig. 7). The central and lateral blocks are cut and mounted with a specific clearence in order to allow for the different thermal expansion and contraction coefficients of the superconductor, copper and stainless steel between 700°C (reaction temperature) and 4.2 K.

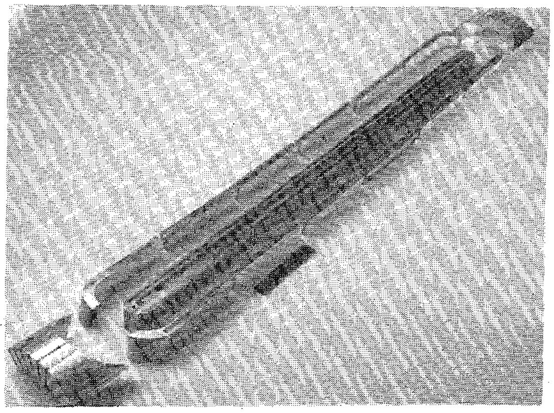

Figure 7

The magnet is of the cold iron type : two 4 cm thick split rings of soft iron surround the four windings, mounted onto a stainless steel tube, forming part of the He tank.

The active part is clamped by 5 cm-wide, 4 cm-thick pre-stressed rings of an Al-alloy ; the rings are mounted at room temperature. Due to the higher contraction of these rings during cool down, the winding is always under adequate compression, even when energized and exposed to considerable electromagnetic forces.

Fig. 8 shows the coil winding around a horizontal cylinder with pressing side plates. Figs. 9 and 10 show the straight and end parts of a 10 turn layer.

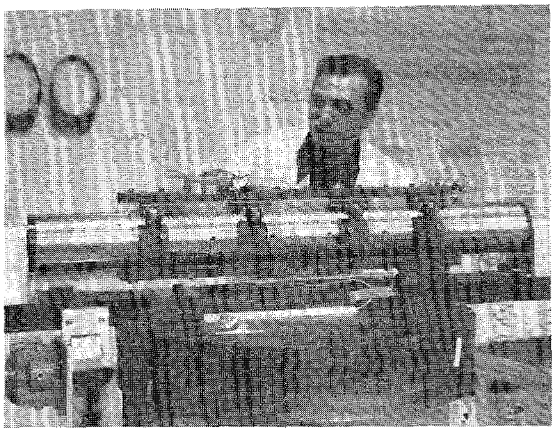

Figure 8

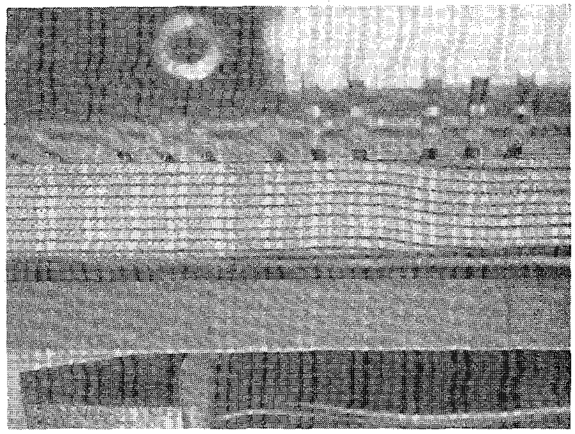

Figure 9

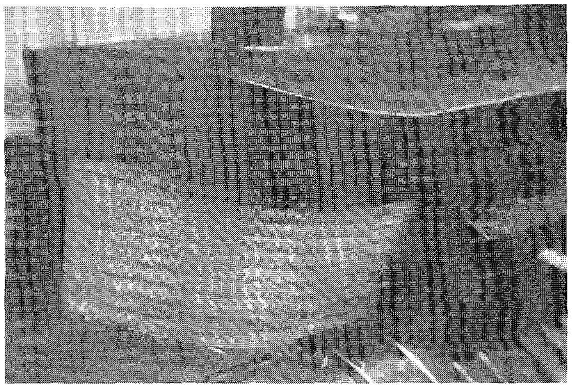

Figure 10

Figure 11 shows the completed winding of one pole prior to reaction.

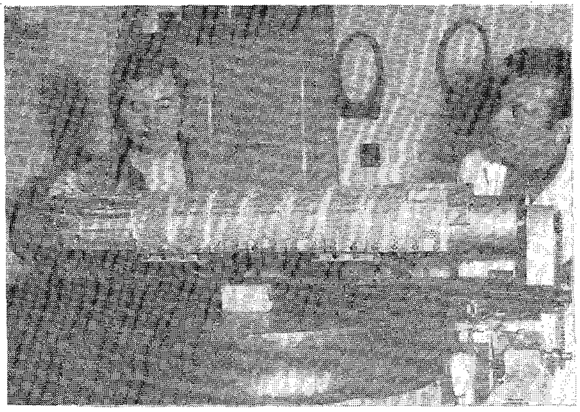

Figure 11

Figure 12 shows the coil after reaction. Ground insulation is being applied and one can recognize the coil end connections, made of two parallel Nb-Ti conductors, sandwiched and soldered to the Nb_3-Sn cable. The coil is then placed into a precise mould and impregnated with epoxy resin.

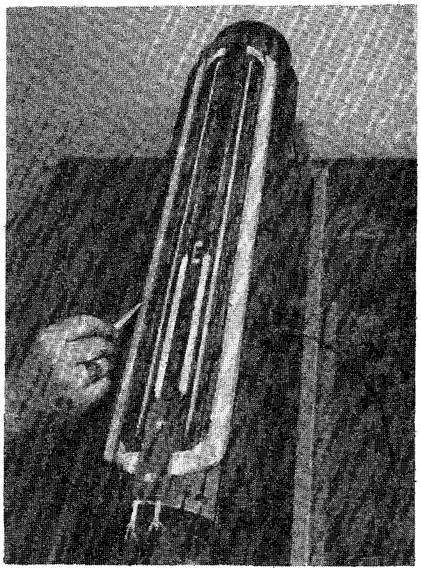

Figure 12

Figure 13 shows the completely impregnated coil, with geometrical tolerances better than ± 0.05 mm.

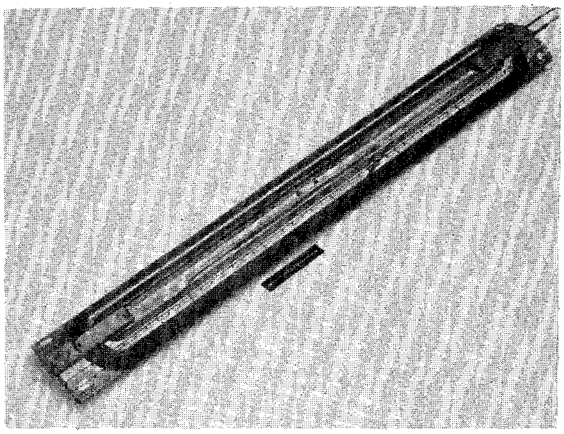

Figure 13

Figure 14 shows the results of short sample, critical current measurements according to an original loop induction method {2} whereby the samples were reacted with every single cable length required to wind one pole.

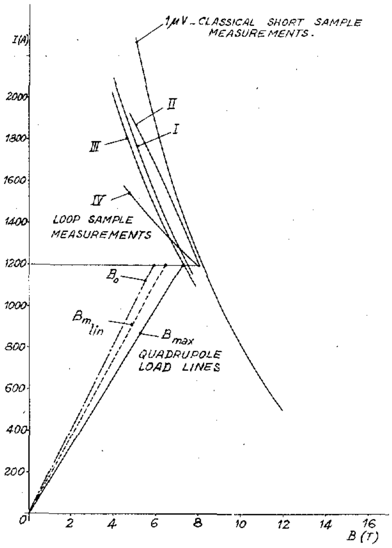

Figure 14

Also shown are the expected quadrupole magnet load lines for the useful field in the aperture B_o, the maximum field in the magnet linear part $B_{m_{lin}}$ and the maximum field in the coil ends B_{max}, to reach 7.4 T at an overall current density in the winding of 300 $\frac{A}{mm^2}$ and 4.2 K.

The corresponding excitation current amounts to I_n = 1150 A, the stored energy of the quadrupole to E = 185 kWs.

The windings of a first dummy pole wound with a 1.1 x 2.2 mm^2 Cu and bronze cable started in September 1979. At present, all excitation coils have been completed and the magnet assembly started. We hope to complete the magnet and begin our tests by March 1981.

iv) Acknowledgement

Fruitful discussions with Mr. D. Leroy are acknowledged.

Litterature :

{1} D. Leroy : A low energy, high precision superconducting quadrupole for high energy beams.

Publ. in the Proceedings of the Fourth Conference on Magnet Technology, Brookhaven, 1972.

{2} D. Hagedorn : Simple and economical method to measure the quality of joints between superconducting wires at high currents ; CERN, SPS/EMA/Note 78-22 of 15.1.1979.