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VARIATIONS IN THE CHARACTERISTICS OF THE SUPERCONDUCTING WIRE USED FOR THE ISR SUPERCONDUCING HIGH-LUMINOSITY INSERTION

by

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Summary

A total of 30.000 meters of NbTi solid multifilamentary superconductor, $I_c \sim 2500$ A at 6 T, was tested. For each stretch of wire received, measurements were made to check if the wire met the specifications. The specification and the measuring set-up are described. Systematic measurements of the critical currents, Cu : SC ratio, Ti content and wire size are discussed. A strong variation in the critical current could be correlated to a strong variation in the Ti content.

1. Introduction

Eight superconducting quadrupoles for a high-luminosity insertion in the ISR have been built by European industry according to CERN design and manufacturing specifications[1]. These quadrupoles operate with a gradient of 43 T m^{-1} and have a warm bore with a radius of 87 mm. They have just been installed in the ISR. This paper describes measurements made during the acceptance tests for the wire used in these magnets. The wire (Fig. 1) is a solid multifilamentary NbTi superconductor with rectangular cross-section and rounded edges. A solid wire was chosen because it was thought difficult to get the required dimensional tolerances[2] with a cable or a braid. Even with a solid conductor the tolerable gradient error in the quadrupoles ($\Delta g/g < 10^{-3}$ at a radius of 65 mm) makes shimming and knowledge of the wire dimensions during coil winding necessary. Because of the high voltages possible during a quench (1 kV) and the high stresses in the quadrupole coil (60 N mm^{-2}), a very good quality of insulation is required. A scheme consisting of a layer of PVA varnish with a Kapton tape glued over it was chosen[3]. During the insulation process, high temperatures may occur. A temperature above 600 K can lower the critical current of the conductor. Since the wire was produced by one manufacturer and insulated by another, this implied that the critical currents had to be checked before and after insulation. Because field changes in the quadrupole are slow (< 0.02 T s^{-1}), electromagnetic losses are small, and the filament diameter and twist pitch can be chosen rather large.

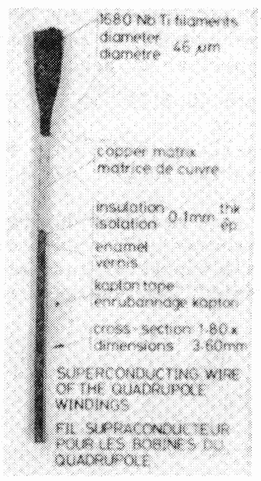

Fig. 1 Multifilamentary NbTi Superconducting Wire

A list of the main points in the specification are given below:

- Critical current (10^{-14} Ωm):

  parallel to the broad face at 5 T : $I_{c5\parallel} = 3220$ A
  " " " " " at 6 T : $I_{c6\parallel} = 2570$ A
  perpendicular to the broad face at 5 T: $I_{c5\perp} = 2480$ A
  " " " " " " at 6 T: $I_{c6\perp} = 1980$ A

- Bare dimensions : 1.80 x 3.60 mm^2 (±0.01 mm)
- Edge rounding radius : 0.5 mm
- Cu : SC ratio : 1.5 - 1.8 : 1
- Filament diameter : d ⩽ 50 μm
- Twist pitch : ⩽ 50 mm
- Resistance ratio : > 120
- Insulation thickness : 0.10 mm
- Standard deviation in the transverse dimensions of a stretch of insulated wire: 0.01 mm
- Maximum temperature during the insulation process : 580 K.

2. Measuring Methods and Devices

2.1 The critical current measuring device (Fig. 2)

The critical current must be measured parallel and perpendicular to the broad face of the conductor and at both ends, this before and after insulation.

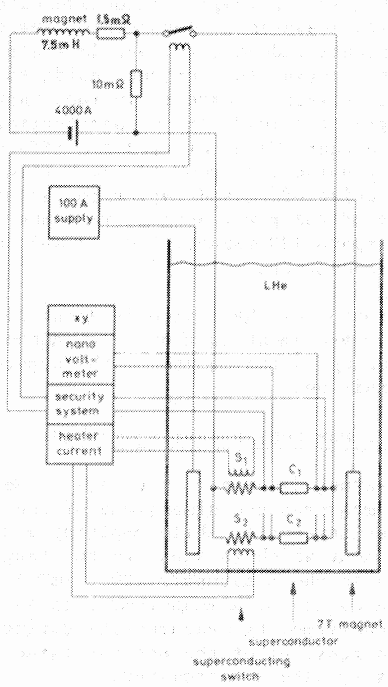

Fig. 2 Critical Current Measuring Set-up

To reduce measuring time, we designed a sample holder with two superconducting switches to be able to measure two samples at the same time. Such a switch has a resistance of 50 nΩ in the superconducting state and a resistance of 3 mΩ in the normal state and can carry more than 3500 A (Fig. 3).

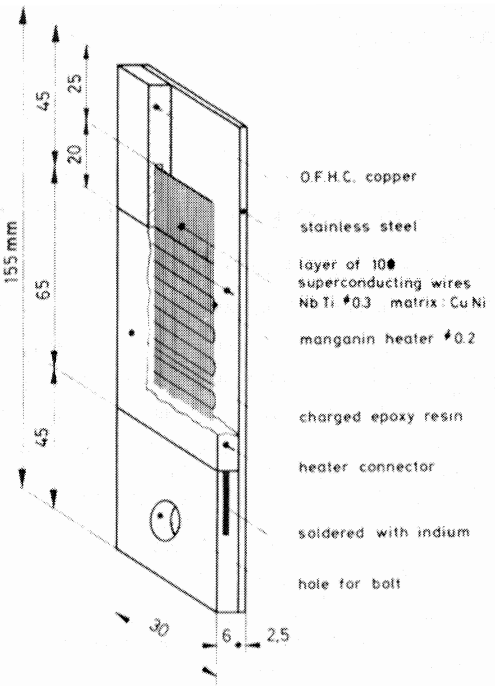

Fig. 3 Superconducting Switch

The samples are soldered with indium to a copper sample holder over a length of at least 10 cm to make sure that all current goes into the superconducting filaments. The length over which the critical current is measured is about 40 mm. The critical current is defined at 10^{-14} Ωm, corresponding to a voltage of 0.15 - 0.20 μV over the sample. Inductive effects can make an accurate measurement impossible. Changing fields and currents induce a voltage in the potential leads by redistributing the current inside the superconductor. This effect is especially important near the transition region and leads to an underestimation of the critical current. We eliminated the effect by making point-by-point measurements, each time waiting until the inductive effects disappeared. To eliminate current ripple of the power supply, we placed a large inductance (a spare ISR magnet, L = 7.5 mH) in series with the superconductor.

The resolution of the device is about 0.03μV. The accuracy of a measurement is about 2 %, although this can vary depending on the length of the superconducting to normal transition.

2.2 The wire dimensions measuring method

The apparatus, described in detail in Ref. 4, automatically measures the dimensions of the insulated wire at regular intervals, while applying a pressure during measurement which is equal to the tangential precompression in the quadrupole (20 N mm^{-2}) during winding. The accuracy of a measurement is ±3 μm. This accuracy was confirmed by measurements during coil winding. The dimensions of the non-insulated wire are measured manually with a micrometer.

2.3 Cu : SC ratio

The wire is weighed and its volume measured by water displacement. The copper is then etched away and the superconducting filaments weighed alone. From these two measurements and knowing the specific weight of copper, the Cu : SC ratio can be calculated. By assuming values for the specific weight of Nb and Ti, it is possible to determine the alloy composition. The accuracy of Cu : SC ratio determination is ±0.01. The Nb and Ti content can be calculated with a precision of better than 1 % assuming that no other substances are present.

3. Results and Discussion

3.1 Systematic measurements of critical current, Cu : SC ratio, Ti content, resistance ratio and wire dimensions

Thirty-one stretches of wire (conductor "0" was a prototype), varying in length from 500 - 2400 m, were received. Figure 4 has been made up from the results of the measurements on the ends of the bare wire. If the values at the beginning and on the ends of a conductor are the same, only one point is drawn. It should be noted, however, that at the beginning of production, a fall in the critical current of almost 1000 A can be correlated to the Ti content, dropping from 50 - 51 % to 47.5 %. Later on (conductor No. >10), the Ti content never drops below 49.5 % and the variation in the critical current must be attributed to other reasons. We never noticed a significant change in the critical current due to the insulation process. Often $(I_{c5\perp} - I_{c6\perp})/I_{c6\perp}$ changed little when the critical current changed. Sometimes, great differences occurred at the beginning and the end of the wire.

The values of the "anisotropy", $I_{c6\parallel}/I_{c6\perp}$, were found to lie between 1.03 and 1.21. A step in the Cu : SC ratio (conductor No. ≥14) was due to a change in the manufacturing process. The resistance ratio of the conductor between room temperature and the superconductor transition temperature was found to lie between 120 and 300.

The dimensions of the bare wire were measured every 50 m and those of the insulated wire every 5 m. Figure 5 shows as an example the measurement of the width of the first 12 km of insulated wire. Each point represents the mean of about 50 measurements. From this, the standard deviation in the width is calculated. The insulation thickness is calculated by subtracting the width of the bare wire from the insulated wire and dividing by 2.

3.2 Measurement of thermal and mechanical properties of the wire

On some conductors, thermal and mechanical measurements were performed. As an example, we list some mechanical properties of conductor No. 27 at 300 K:

- Yield strength (0.2 %) : 270 N mm^{-2}
- Elastic modulus : 9.8 x 10^4 N mm^{-2}
- Ultimate tensile stress : 570 N mm^{-2}
- Microhardness (HV 50 g) : 76 - 127.

Thermal properties were measured during the selection of the insulation process[3]. These measurements were performed with little blocks of insulated wire impregnated with epoxy resin. The results are:

- Thermal conductivity perpendicular to broad face (4.3 K) : 0.4 W m^{-1} K^{-1}
- Thermal conductivity of the insulation (4.3 K) : 0.04 W m^{-1} K^{-1}
- Thermal contraction perpendicular to the broad face of the conductor (300 - 4.2 K) : 4.6 x 10^{-3} .

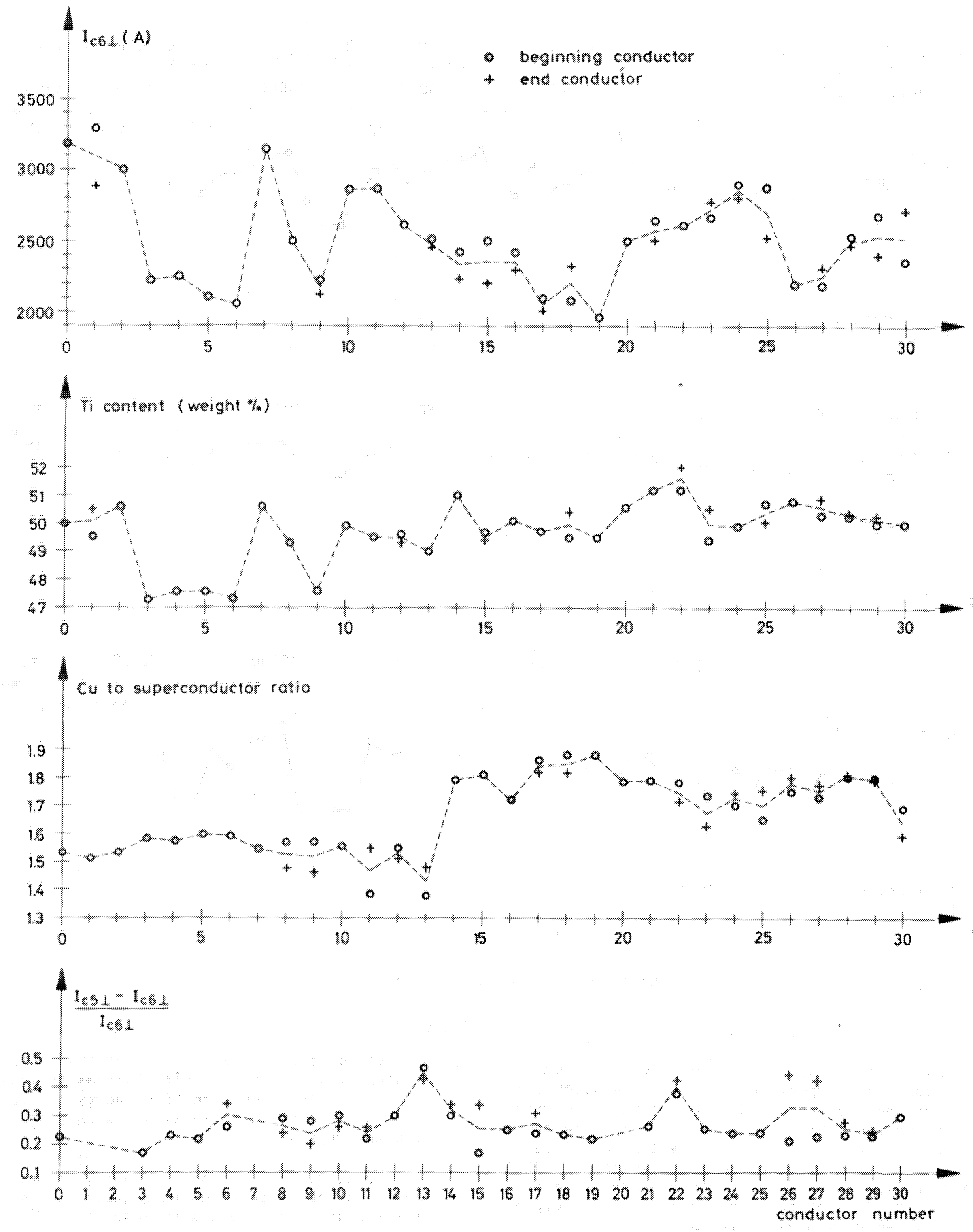

Fig. 4 Critical Current, Cu : SC ratio, Ti content

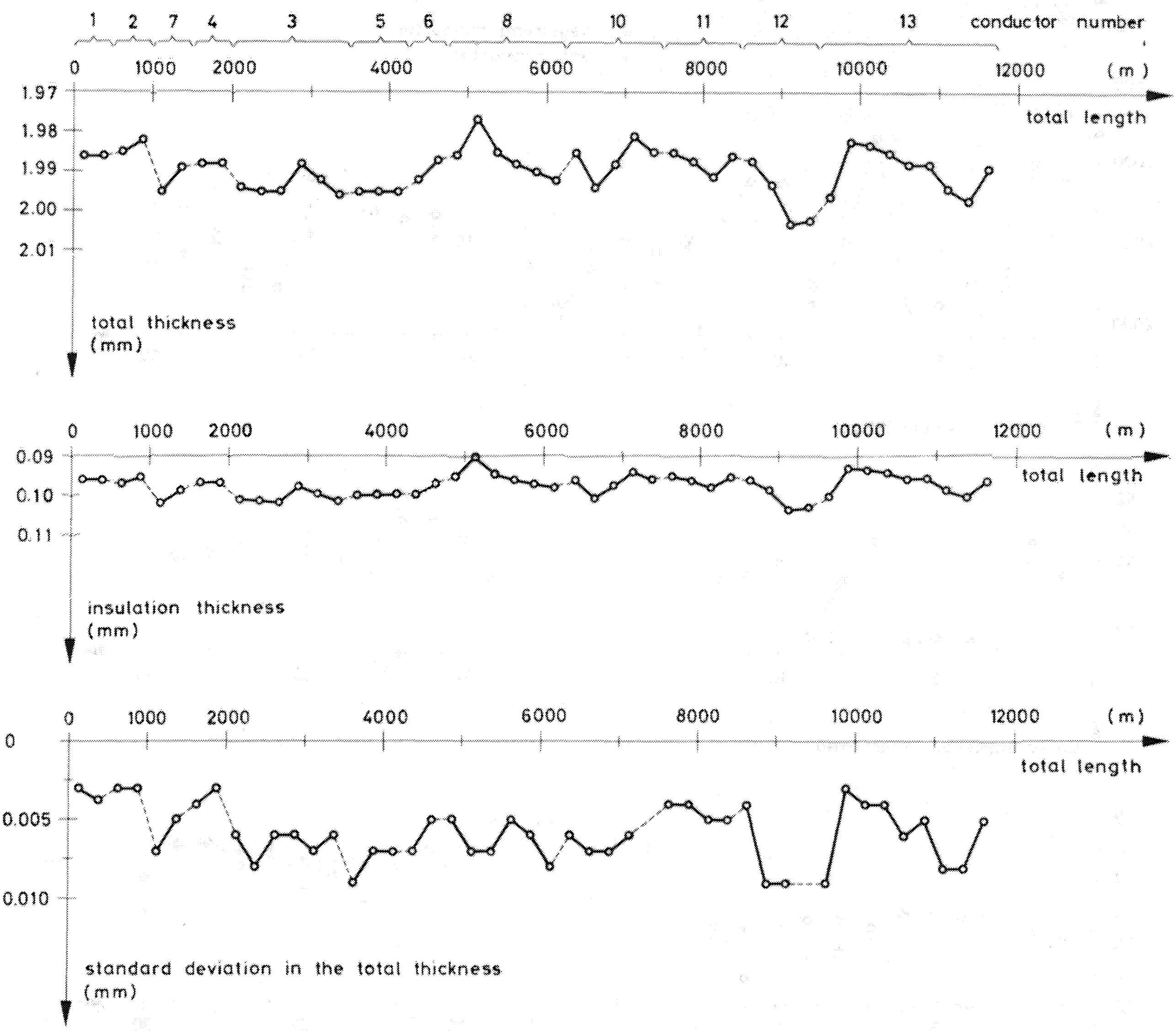

Fig. 5 Width of the Insulated Wire

4. Conclusion

A 30 km length of solid superconductor has been produced according to specifications. Two manufacturers were involved, one for the production of the bare wire and one for the insulation. Systematic acceptance tests were performed on the bare conductor and on the insulated conductor. A critical current variation of 1000 A at the beginning of production could be correlated to a variation in the Ti content. The width of the superconductor, insulated with a PVA varnish and a layer of Kapton, was measured every 5 m. The variation in the mean dimensions of the insulated stretches of wire was less than 0.02 mm. The standard deviation in the dimensions of each separate insulated stretch was less than 0.01 mm.

References

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