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SPECIAL TECHNIQUES IN THE FABRICATION OF COILS
OF HIGH PRECISION SUPERCONDUCTING QUADRUPOLE MAGNETS FOR
THE CERN-ISR HIGH-LUMINOSITY INSERTION

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ABSTRACT

This paper describes two measuring devices specially conceived in view of the fabrication by industry of the coils of the eight superconducting quadrupole magnets for the CERN ISR high-luminosity insertion. The first device is an automatic bench for the precise measurement of the SC wire dimensions. Measurements are performed under a pressure of 20 MPa and with an accuracy of ± 0.003 mm. The second device allows the immediate detection of any short-circuit which may occur during winding. It is based on the continuous monitoring and recording of the d.c. resistance of the whole length of the SC wire during all winding and impregnation processes.

1. INTRODUCTION

One of the intersections of the CERN Intersecting Storage Rings (ISR) will be equipped in 1980 with eight superconducting quadrupole magnets. By this means, luminosity at this intersection will be increased by a factor of about 6.¹ The main parameters of these magnets are:

- Effective length - 4 magnets :	1.15 m
- 4 magnets :	0.65 m
- Inner diameter of main coils :	232 mm
- Nominal gradient :	42.7 T/m
- Peak field in windings :	5.4 T
- Nominal current :	1600 A
- Stored energy (for L = 1.15 m) :	500 kJ

The required tolerance on the gradient is $1 \cdot 10^{-3}$ over the whole beam region.

As shown in Fig. 1, each coil consists of three blocks of conductor of respectively 4, 9 and 16 azimuthal layers of 10 turns each. To obtain the required field accuracy, the centre of each block must be positioned to within ± 0.05 mm. The superconducting wire is a 1.80 mm $\times$ 3.60 mm rectangular composite of NbTi filaments in a copper matrix. Its insulation consists of a PVA enamel layer coated with a polyimide film glued by ester-imide resin.² The insulation thickness is 0.10 mm.

Fig. 1. Cross-section of a coil

The tolerances on the dimensions of the wire (± 0.01 mm) and of its insulation (± 0.03 mm) are too large to satisfy directly the tolerances on the position of the blocks of conductor: the dimensions of each stretch of wire must be precisely measured over its whole length. It is not sufficient, however, to use a conventional measuring instrument because, during winding and impregnation, the wire in the coil is subjected to a tangential pre-compression of 20 MPa and its dimensions, in fact those of the insulation, decrease by 0.01 mm to 0.02 mm. For this reason, a special measuring bench, which applies the same pressure on the wire

during measurements, has been developed and is described in this paper.

The second device described in this paper concerns the detection of short-circuits during coil fabrication. Interturn or ground short-circuits in SC magnets with such a high stored energy may cause local burning of the coils: the magnet would have to be repaired and the whole high luminosity insertion would remain inoperative for several months. The wire insulation and the winding process have been carefully studied in order to avoid such short-circuits, but the necessary small thickness of the insulation, the high pre-compression applied to the coil and the ever possible human error during coil fabrication mean that it would be unreasonable to place absolute confidence in the insulation. In an industrial production of SC magnets, it is essential to be able to detect a short-circuit as soon as it occurs and then repair it before continuing with the winding operation.

2. BENCH FOR THE MEASUREMENT OF THE SC WIRE DIMENSIONS

2.1 Basic requirements

The design of this bench was made to satisfy the following four requirements:

- an accuracy in the range of 0.005 mm,
- a pressure of 20 MPa must be applied on the wire during measurements,
- integrity of the wire and its insulation must be safeguarded,
- a large number of measurements must be performed taking into account the variation of the dimensions over the length of the wire.

Approximately 26 km of SC wire, needed for the fabrication of the coils, have to be measured.

Moreover, preliminary tests showed that under a 20 MPa pressure, the insulation creeps during 1 to 2 s. For all these reasons, it was decided to perform periodic measurements on the wire, fixed in position, in a completely automatic way and to treat the results statistically.

2.2 Description

A general view of the measuring bench is shown in Fig. 2 and details of the wire dimension measuring device are shown in Fig. 3.

- ① control console
- ② spool of wire to be measured
- ③ wire dimension measuring device
- ④ spool of measured wire

Fig. 2. General view of the measuring bench

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Fig. 3. Details of the wire dimension measuring device

During measurements, the SC wire is gripped between two hemi-spherical pads by means of two articulated arms actuated by a pneumatic jack. This jack applies the required pressure on the wire. The measurement is performed by an inductive linear transducer precise to ± 0.001 mm and the overall accuracy is ± 0.003 mm. Calibration can be checked by means of a set of gauges.

A wheel of a 10 cm developed length rolls on the wire and measures its length by incrementing an electronic counter at each turn. This counter is used to stop the wire and initiate the measurements each time its content is incremented by a preset value corresponding to the distance between two measurements.

The spool of wire to be measured (2 in Fig. 2) is mounted on an axis on which there are a disk-brake and an electromagnetic brake. The disk-brake locks the spool and prevents the wire from moving during measurements. For safety reasons, it acts when the supply current is cut (fail-safe). The electromagnetic brake sets the tension of the wire when it is moving.

After measurement, the wire is wound on a spool (4 in Fig. 2) equipped with an electromagnetic clutch driven by a low-speed motor. The motor runs continuously and the electromagnetic clutch sets the tension of the wire during measurements (5 to 10 kg).

A computer restarts the movement of the wire after recording the measurements and displays these results on a C.R.T. display unit. This computer also gives mean values, standard deviations and graphic display of the measurements over the length of each stretch of wire. For safety reasons:

- i) the wire is tightly guided by several sets of rollers until very near the jaws of the apparatus,
- ii) with the exception of the pads on these jaws, no metallic piece is in contact with the wire, and
- iii) the interlock system prevents the wire from being moved when this could present a risk.

2.3 Performance

Up to now, approximately half of the 26 km of wire has already been measured without causing the slightest damage to the insulation. These lengths of wire were measured at intervals of 5 m at a rate of 100 measurements per hour. One length was measured twice to check the reproducibility and the validity of the statistical

method; the difference between the mean values was within 0.001 mm. A periodic calibration with the reference gauges guarantees the ± 0.003 mm overall accuracy.

3. SHORT-CIRCUIT DETECTION SYSTEM

3.1 Principle

This system is based on the change of the d.c. resistance ($\approx 3.5 \Omega/\text{km}$) of the stretch of wire used to wind a coil, caused by an interturn short-circuit. This change is very small (1/300 to 1/1000 depending on the length of the wire) and changes due to ambient temperature variation (0.004°C^{-1}) may be of the same order of magnitude. Furthermore, since the wire resistance is measured by the voltage drop when carrying constant current, parasitic induced voltage can also cause problems. Discrimination between a short-circuit and other parasitic signals is possible by considering their time dependence. A graphic record (Fig. 5) shows clearly the occurrence of a short-circuit which gives a quick, but then stable, decrease of the d.c. resistance, in contrast to changes due to temperature variations which are slow and continuous, and to parasitic inductions which are fast but never present a plateau.

3.2 Description

A schematic diagram of the short-circuit detection system is shown in Fig. 4.

Fig. 4. Principle of the short-circuit detection system

A current regulated at 1 A circulates through the wire from the inner wire end of the coil in progress to the other wire end on the spool. The voltage drop due to this current is put in opposition with a reference voltage generated by a digital-to-analog converter (10 V in 1000 steps). The difference is amplified and recorded (Fig. 5).

The step caused by a short-circuit covers approximately 1/5 of the strip chart width. This width corresponds to a change of temperature of 1 to 4°C depending on the length of the wire. When the pen of the recorder reaches certain limits near the edge of the strip chart, a comparator increments a counter which in turn increments the D.A.C. (by four steps) in such a way as to keep the pen between these limits on the strip chart. The system is also used during the whole impregnation process and works very well despite a warming up of the coil to 120°C .

Fig. 5. Example of recording from the short-circuit detection system

Besides the recording, acoustic and visual warnings are triggered off by fast variations of the measured voltage, thus allowing an immediate detection of any short-circuit occurring during the winding process without watching continuously the recording.

In addition to the interturn short-circuit detection unit, another unit with coil-to-ground short-circuit and wire insulation defect detection systems is provided. Each system has acoustic and visual warnings. A coil-to-ground short-circuit increases the voltage on the recorder and can, therefore, be distinguished from an interturn short-circuit. The insulation defects are detected by four small brushes rubbing on each face of the wire along the unrolling line.

Furthermore, at each turn of the winding machine, a second track displays on the strip chart a positive or negative pulse depending on the sense of rotation of the winder. This feature makes it possible to follow the coil progress, to count the number of turns and also to get a display of the unwinding operations, which generally indicate that there have been some difficulties in the winding process.

Figure 6 shows the short-circuit detection system.

Fig. 6. Short-circuit detection system

2.3 Performance

Compared to a prototype version, which was successfully used during the winding of the four coils of the prototype magnet³ and only had a 100 mA current and 20 steps, this improved version is much easier to handle. The increased current gives a better signal/noise ratio, and spurious warnings due to parasitic induction signals are much less frequent, even in the industrial environment in which the coils are now being produced. The increased number of steps corresponding to a temperature variation 25 times larger allows the new version to be used during impregnation without making any modifications. No maintenance is required by the coil manufacturer; in case of failure of a unit, it can be immediately replaced by a spare one.

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