Magnetization Measurements on LHC Superconducting Strands

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Abstract—**When using superconducting magnets in particle accelerators like the LHC, persistent currents in the superconductor often determine the field quality at injection, where the magnetic field is low. This paper describes magnetization measurements made on LHC cable strands at the Technical University of Vienna and the Institute of Physics of the Polish Academy of Sciences in collaboration with CERN. Measurements were performed at T=2K and T=4.2K on more than 50 strands of 7 different manufacturers with NbTi filament diameter between 5 and 7 micrometer. Two different measurement set-ups were used: vibrating sample magnetometer, with a sample length of about 8mm, and an integrating coil magnetometer, with sample length of about 1m. The two methods were compared by measuring the same sample. Low field evidence of proximity effect is discussed. Statistics like ratio of the width of the magnetization loop at 4.2K and 2K, and the initial slope dM/dB after cooldown are presented. Decrease of the magnetization with time, of the order of 2% per hour, was observed in some samples.**

I. INTRODUCTION

The proton collider ring LHC [1] which is under construction uses superconducting magnets operating at a temperature of 1.9K to guide the particles. Protons are injected at low fields in the magnets. Persistent current magnetization in the NbTi filaments of the superconducting magnet cable can cause important magnetic field distortions in these conditions, since the magnetization is high when the field is low.

In addition variation in the magnetization during production by a manufacturer might induce random field errors in the magnets which decrease machine performance. Since there will be more than one cable manufacturer there will certainly be a difference between average magnetization values for each of them. Interfilament proximity coupling could make the magnetization higher at low fields, which could have an influence on the performance of certain magnets in the machine. Therefore a collaboration was started between CERN, the University of Technology of Vienna and the Institute of Physics of the Polish Academy of Sciences in order to study the magnetization characteristics of the superconducting strands of the magnet cables.

In addition a slow drift in time in the field errors was observed in LHC dipoles [2]. Although this is thought to be an effect mainly due to current redistribution in the cable, part of this drift could originate in the strand.

Typical characteristics of the strands of the LHC main dipole are shown in Table I.

Table I

TYPICAL CHARACTERISTICS OF LHC MAIN DIPOLE STRANDS. THE INNER LAYER STRAND IS SLIGHTLY LARGER THAN THE OUTER LAYER STRAND.

Parameter	Strand 1	Strand 2	Unit
Strand diameter	1.065	0.825	mm
Filament diameter	7	6	µm
Number of filaments	8800	6400	
Twist pitch	18	15	mm
Nb/Ti ratio	53:47	53:47	(by weight)
Cu:Sc ratio	1.65	1.95	(by volume)
Nb-NbTi ratio	0.04	0.04	(by volume)

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II. MEASURING METHODS

Two different magnetization measurement setups were used. The Institute of Physics used a vibrating sample magnetometer, while the University of Technology used an integrating coil magnetometer. Both are described below.

A. Integrating Coil Magnetometer Setup

This setup is described in detail in [3]. We therefore only recall the principal of operation and the calibration method. It consists of a magnet, a pickup system and an integration unit (Fig. 1). Magnetization is measured by slowly varying the external field and measuring the difference in the voltage induced in two pickup coils, one with and one without sample. Integrating the signal gives a voltage proportional to the sample magnetic moment. The sample is in the form of a

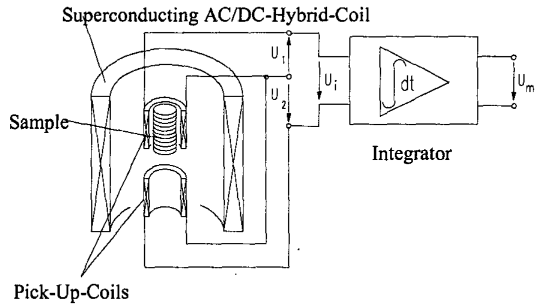
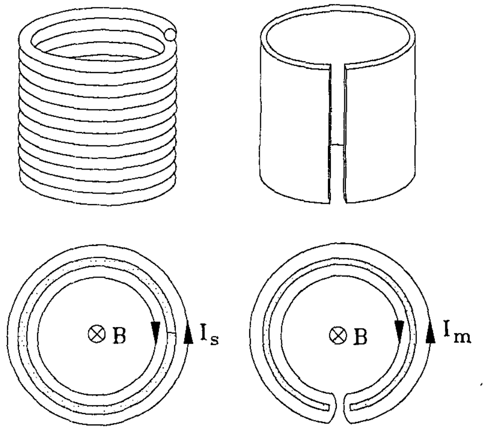


Fig. 1 Sketch of Integrating coil magnetometer setup [3].



a) Sample b) Nb–Foil

Fig. 2.Sample geometry (a) and Nb-foil (b) used for calibration [3]. The Nb sheet has a form such that its magnetization currents are similar to those the sample.

little coil(Fig. 2a). Calibration is performed with a Nb sheet (Fig. 2b) in the superconducting state utilising the diamagnetic properties of the Meisner state of Nb.

B. Vibrating Sample Magnetometer Setup

The measurements of magnetization versus field at 2 K (pressure of 26 mm Hg) and at 4.2 K (liquid helium temperature) were performed using a Vibrating Sample Magnetometer (VSM), Princeton Applied Research PAR Model 4500 with cryostat Model 153 and Varian 12-inch electromagnet. The maximum of applied magnetic field was 1.6 T. The current of this normal electromagnet is supplied by a Danfysik Magnet Power Supply, Model 853, stability class ±3 ppm (30 minutes) and ±10 ppm (8 hours). The temperature of the sample is measured by a Cernox Resistance Temperature Sensor with accuracy of 5 mK. The temperature stability at 4.2 K is about 70 mK. At temperature of 2 K the measurement of the helium vapour pressure is additionally performed. In optimal conditions temperature stability at 2 K is about 70 mK. The equipment accuracy is such that the absolute value of magnetization is better than ±2 %. For calibration of the magnetometer a nickel standard sample is used. The applied magnetic field was perpendicular to the wire.

C. Samples

Samples were taken from cable strands for LHC dipole cables. They came from 7 different manufacturers. The NbTi filament diameter varied from 4.7 to 8 μm.

The samples measured in the vibrating sample magnetometer consist of one piece of wire with a length of about 8 mm. This is shorter than the twist pitch of the filaments (~20mm). The mass of these samples is about 0.055 g.

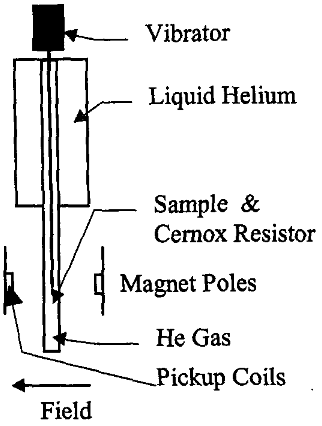


Fig. 3. Sketch of vibrating sample magnetometer setup.

The samples measured in the integrating coil magnetometer are small coils with a much longer length of strand (ca 90cm). It was therefore possible with these samples to also measure the magnetization due to interfilament coupling.

D. Measuring Procedure

The magnetization was in general measured at a temperature of 4.2K and 2K. The magnetization data were normalized to the volume of sample (strand) calculated from the mass and the density of wire (magnetic polarization in Tesla).

The following procedure was used:

(1) The field was cycled between approximately +1.5T and -1.5T and the magnetization was measured during the cycle. This we call "the hysteresis loop" (Fig. 5).

(2) After zero field cooling the magnetization was measured for field increasing from 0 to about 0.5 T (the so-

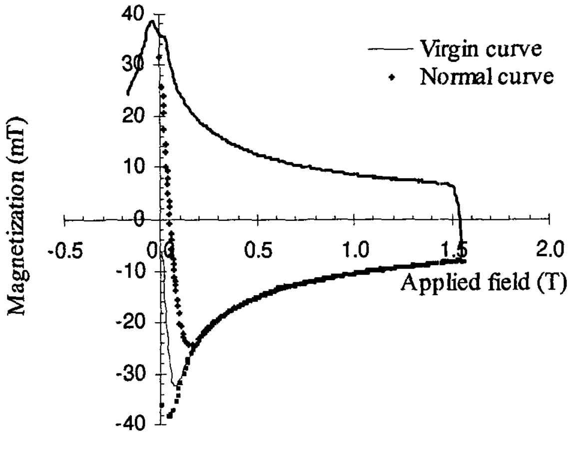


Fig. 4. Magnetization of the reference sample 01D95276AE at T=2K illustrating two different typical measurement cycles: the "virgin curve" after cooldown in zero field, and the "normal cycle" of the magnetization in increasing field after a field decrease to zero field

called "virgin curve").

(3) After magnetizing the sample to about 1.5 T and decreasing magnetic field to zero value the magnetization was measured for increasing magnetic field. This we call the "normal cycle" (Fig. 4) since it is similar to the cycle that the main magnets in LHC will carry out.

In the vibrating sample magnetometer the external field changed with a rate of about 1.3mT/s, while the integrating coil magnetometer used rates of 10, 20, and 50mT/s.

E. Comparison of the Vibrating Sample and Integrating Coil Magnetometer results on the Same Sample

Since the two measuring setups, samples and calibration methods were different we compared the results of a magnetization measurements by the two methods on a reference strand (01D95276AE). The samples were taken next to each other from this strand. The two measurements are compared in Fig. 5. The difference on the width of the magnetization loop is only 3.5% at 2K.

III. RESULTS

We use SI units throughout, that is: $B=\mu_0(H+M)$. Usually we use $\mu_0 M$ (in Tesla or mT) to give the magnetization. The width of the hysteresis loop, that is the difference in magnetization between the up and down branch at a given field, is often called "2M".

Most factors which influence the magnetization can be derived from the Bean model [4]. According to this the magnetization of a strand in the hysteresis loop is:

$$M=\frac{2}{3\pi}\lambda J_c d \text{ or alternatively } M=\frac{2}{3\pi}\frac{\lambda^{3/2}}{\sqrt{N_f}}J_c D \qquad (1).$$

Here M is the magnetic moment per unit volume, λ is the ratio of the superconductor to strand volume. J_c the critical current density, N_f the number of filaments, d is the filament diameter and D the strand diameter.

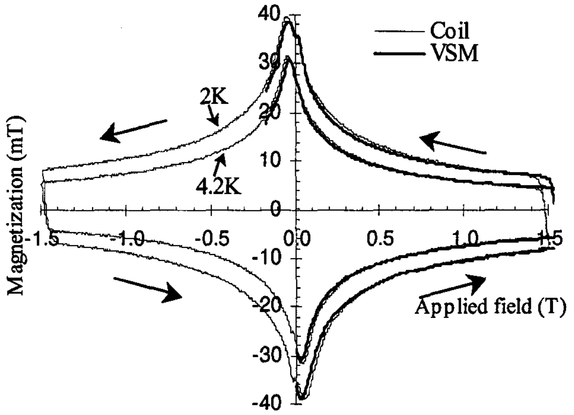


Fig. 5. Comparison of a magnetization measurement made on reference strand 01D95276AE by the two setups.

A. Width of the Magnetization Hysteresis Loop

Since we want to make an estimation of how the magnetization varies between different manufacturers, we choose to look at the differences in the width of the magnetization loop at a field of 0.5 T. This field was chosen since it is close to the field in the LHC dipole windings, when injecting protons in the machine. Table II shows the results for a series of strands with characteristics very close to those of Table I. Interesting is that the standard deviation in 2M/λd, which is proportional to J_c according to (1), is almost as large as for the one for the width of the hysteresis loop (2M) at B= 0.5T for both strand types. This indicates that the variation in magnetization is mainly due to the variation of J_c at low field.

The maximum difference between manufacturer average magnetization values at 2K was 7% for strand 1 and 6% for strand 2. The standard deviation from the average for a manufacturer was estimated for 3 manufactures where a significant number (7-9) of samples were available and varied between 3.3 and 6.5%. We found that samples having the same transport current J_c at 11T and 1.9K could have a magnetization at 0.5T and T = 2K which differed by as much as 10% for the same manufacturer.

B. Evidence of Proximity Coupling

Filament proximity coupling can occur [5] in strands, if the filaments are very close together and the field is low. Interfilament distances are typically 1μm in the measured strands. The effect of filament coupling is to increase the magnetic moment of the strand, and thus the apparent amount of superconductor in the strand. To detect coupling we performed measurements on the initial magnetization increase at T=2K and T=4.2K after cooldown of the sample in zero field. The expected magnetization is then $\mu_0 M = -2\lambda B$ where B is the applied field. If proximity coupling takes place one expects this value to increase. Indeed average

Table II

AVERAGE AND STANDARD DEVIATION OF THE MAGNETIZATION HYSTERESIS LOOP WIDTH AT B=0.5T

	Strand type 1 23 samples		Strand type 2 22 samples	
	Average	Standard deviation	Average	Standard deviation
T = 2K				
2M (mT)	26.97	6.7%	20.31	4.6%
2M/λ (mT)	71.03	6.0%	59.98	4.0%
2M/λd(mT/μm)	10.25	5.8%	10.01	4.2%
T= 4.2K				
2M (mT)	18.36	10.1%	13.78	7.9%
2M/λ (mT)	48.33	9.2%	40.66	6.7%
2M/λd(mT/μm)	6.98	9.0%	6.78	6.2%
M(2K)/M(4.2K)	1.47	5.4%	1.48	5.4%

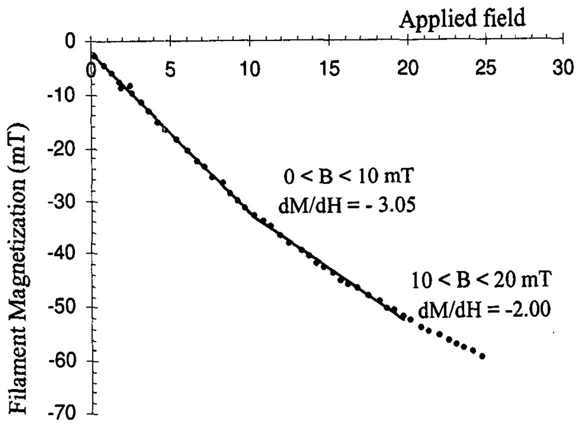


Fig. 6. Typical evidence of coupling is shown here at the start of the virgin magnetization curve. The initial slope (-3.05) is larger than the expected value (-2). In this case the coupling seems to vanish near an applied field of 10mT.

values of $\mu_0M/\lambda B$ change from -2.33 at 4.2K to -3.23 at 2K (Fig. 6, Table III). The field below which coupling is apparent is around 10mT.

C. Relaxation Measurements

Magnetization measurements as function of time, were performed with the vibrating sample magnetometer on the reference strand (Fig. 7) and on another sample. This was done in a magnetic field of about 0.5 Tesla at 2 and at 4.2 K, both for the increasing and decreasing branch of the hysteresis loop. The measurements were performed as follows:

(1) for increasing field ("up"):

At fixed temperature the field was decreased to -1.6 T, increased to 0 T and next increased to about 0.5 T. The increase of magnetic field was stopped and the change of magnetization was measured for more than one hour.

(2) decreasing branch ("down"):

At fixed temperature the field was decreased to -1.6 T, increased to 1.6 T and next decreased to about 0.5 T. In the field of 0.5 Tesla the decrease of magnetic field was stopped and the change of magnetization was measured for more than one hour.

The results show a decay, which becomes proportional with *ln(t)* after a 100 seconds or so and which is larger at 4.2K than at 2K. The second sample showed similar decay rates but the decay at 4.2K was only slightly larger than at 2K. The decay rate changed somewhat for up and down cycles.

Table III

THE MEASURED SLOPE $d(\mu_0M/\lambda)/dB$ OF THE VIRGIN MAGNETIZATION CURVE. DERIVED FROM MEASUREMENTS BETWEEN 0 TO 5mT.

Parameter	Value at 2K	Value at 4.2K
Number of samples	36	18
Minimum value of slope	-3.63	-2.47
Maximum value of slope	-2.73	-2.15
Average virgin of slope	-3.23	-2.33
Standard deviation of slope	0.20	0.09

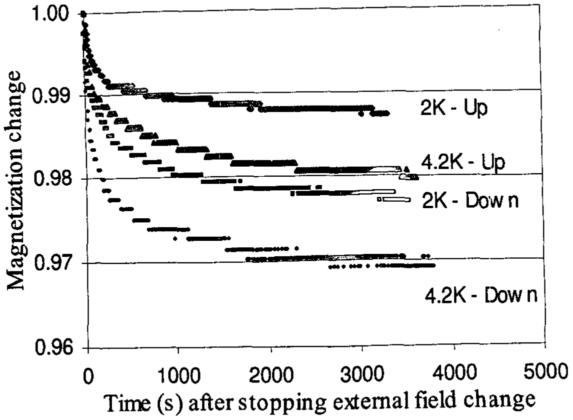


Fig. 7. Decay of the magnetization of the reference strand 01D95276AE.

IV. CONCLUSION

The production of these strands has taken place in a development phase, during which manufacturers have tried to increase current density and made other changes to the strands. Therefore variation in the magnetization properties for a given manufacturer cannot be compared to final cable production where the manufacturer must keep all strand properties as constant as possible. In final production maximum difference in magnetization at low field between manufacturers will probably be lower than 10%. We expect the standard deviation in the average magnetization of a given manufacturer to be lower than we have measured here, since it was dominated by the variation in J_c. A value within the specification limits of 4.5% seems readily attainable.

There is clear evidence of interfilament coupling at a temperature of 2K up to an applied field of about 10mT. Due to the low values of applied field where it occurs, this has only a small influence on the field errors of the superconducting magnets of LHC.

The magnetization decay found as function of time. 2-3 percent in one hour, is not negligible, but smaller then the typically 10% decay observed in LHC model magnets.

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