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Abstract - Power tests and magnetic measurements have been performed on various 1 m long LHC dipole model magnets. Single and twin aperture magnets were energised up to peak fields above 9 Tesla. Subjects studied are quench behaviour, improvements in the test facility, and losses in the superconductors.

The field quality was measured with rotating coils immersed directly in the 1.8 K bath of the vertical cryostat. The design of these coils as well as the achieved measurement precision will be presented. Preliminary measurements of the persistent currents show an unexpected time dependent decay of the field harmonics.

I. INTRODUCTION

The R&D program for high field superconducting magnets required for the CERN LHC accelerator project includes the development and testing of 1m long 10 T Model Twin Aperture magnets (MTA1). The results of the tests of three MTA1 models are presented in ref. [1]. The program will now consist of mechanical modifications and improvements to these magnets and construction of new ones in order to push their performance towards higher fields and to finalize the design of the full length magnets.

The main subject of this report is to describe the methods used in the tests and some observation during testing. The test station used previously for the measurements of single aperture 9 T magnets [2] had to be improved to obtain faster turnover and to be able to measure the field quality with harmonic coils. Moreover, the instrumentation to analyse the behaviour of the magnets was improved.

The experience gained will be used to design the facilities needed for the acceptance tests of the several thousand LHC twin aperture magnets.

II. IMPROVEMENTS OF THE TEST FACILITY

In view of the increasing pace of the tests, the vertical cryostat assembly was improved in the following ways:

- The power junctions between the vapour cooled current leads and the magnet's cables are made by clamping a layer of pure indium between the two cables. The compression at cryogenic temperature is ensured by invar washers. Compared to soldered joints, a considerable time is saved during mounting and demounting whilst the resistance can be kept in the range of 2 n Ω for a 15 kA joint.
- Tight passages, inserted into the 6 cm thick epoxy-glass plate lying between the He I and II baths, are equipped

with standard flat cable connectors on both sides. They allow rapid connections between more than 200 instrumentation leads.

Excessive temperature gradients during cool-down and warm-up are avoided by distributing the cooling gas with passive deflectors between the free channels present in the magnet and cryostat assemblies. The differences between the temperature of the external surface of the magnet and the average temperature of the coils deduced by resistance measurements are continuously monitored. On any transverse section of the magnet, the highest difference is estimated to be below 10 K when the cool-down from room temperature to 4.2 K takes about 40 hours.

III. QUENCHES OF TWIN APERTURE MODELS

At 1.8 K, the magnets reach 8.7 T after about 5 quenches and have a maximum field of 9.05 T corresponding to 92% of short sample limit [1]. The three tested models are characterized by training. They reach the short sample limit of 7.9 T at 4.3 K. The LHC dipole magnet consists of two dipoles in a common magnetic yoke electrically connected in series.

During the tests, the voltage differences between the two poles of the same aperture and between the two apertures of the same magnet are used for quench detection and triggering of active protections. Fig. 1 shows a typical behaviour seen on most quenches during training of the MTA1 magnets. A voltage peak of about 1 ms and ranging from 20 to 100 mV appears, before the resistive transition, on the difference between apertures and is seen much smaller on the difference between the two poles of the quenching aperture. During the

Fig. 1 Quench detection signals showing a voltage peak appearing on both poles of the same aperture before the onset of a resistive transition.

first powering of a magnet, displays on an oscilloscope show similar characteristic peaks, the amplitude of which is insufficient to provoke a quench. Other detection methods are under study to investigate the sources of these voltage peaks in the near future.

For the tests in the laboratory, a 20 mΩ resistor located outside the cryostat allows to extract about 75% of the stored energy to protect the quenching magnet. The 200 volts or more applied to the magnet provokes a fast transition of the complete winding in less than 40 ms as has been measured by temperature probes distributed in the apertures. This allows to keep thermal stresses and internal voltages to safe values: maximum temperatures calculated by the $\int I^2 \cdot dt$ method (MIITS) are kept always below 90 K. Heaters are foreseen to protect the LHC full length magnets.

In the initial seconds after a quench, an enthalpy increase of 2 to 3 kW is measured on the liquid helium II bath by means of carbon sensor calorimetry. An estimate of 2500 cm² of effective surface for the heat transfer from the magnet's winding to the superfluid helium leads to transfer power of about 1 W/cm².

IV. ENERGY DISSIPATED AND STORED IN THE MAGNETS

A new method has been developed to perform high precision electrical measurements to determine simultaneously the stored energy or inductance, the energy loss, and the d.c. resistance. These quantities can be measured both on the whole magnet and on parts of the magnet as long as these parts are provided with voltage taps.

In this method, the magnet is subjected to a current cycle $I_1 \Rightarrow I_2 \Rightarrow I_1$. To reduce the influence of noise and ripple on the magnet, both the integrated voltage and current are continuously measured with sampling time t_{int} of 0.05 to 5 s resulting in incremental data $\sum \int U dt$ and $\sum \int I dt$.

The stored energy and energy loss are calculated by assuming:

$$\int U I dt = (\int U dt \int I dt) / t_{int} \quad (\text{true for small } t_{int}),$$

so that, for half a cycle:

$$E_{st/loss} = \frac{1}{2t_{int}} (\sum \int U^{up} dt \int I^{up} dt \pm \sum \int U^{down} dt \int I^{down} dt)$$

with the plus sign for the energy loss and the minus sign for the stored energy. An example of measurements of the energy loss as a function of the ramp rate is shown in Fig. 2. At 12 As⁻¹, corresponding to acceleration foreseen for LHC, the power density dissipated in the winding is then of about 0.03 mW/cm³.

These measurements are precise to within 10⁻³ for the stored energy and 10⁻⁴ times the stored energy for the energy loss.

The incremental integrated values of the current and the voltage are used to determine best fit polynomial functions $I_{fit}(t)$ and $U_{fit}(t)$ both for the ramp up and the ramp down. From these fits the inductance as a function of the current is calculated by:

$$L(I) = \left(\frac{U(I)_{fit}^{up}}{2I_{fit}^{up}(I)} \right) + \left(\frac{U(I)_{fit}^{do}}{2I_{fit}^{do}(I)} \right)$$

with absolute and relative accuracies better than 10⁻³ and 10⁻⁴ respectively. The d.c. resistance is calculated by measuring the voltage at several currents after current and voltage stabilization. This stabilization process can take more than 10 min, as shown in Fig. 3.

V. SYSTEM USED FOR MAGNETIC MEASUREMENT

The magnetic field is measured with harmonic coils directly immersed in the helium II bath. The motor and angular encoder are located at room temperature, on top of the cryostat, and a 1.5 m long shaft connects them to the coil assembly at 1.8 K. Coils are centred in the magnet aperture by a 10 mm ball at the bottom and a low friction sleeve bearing at the top of the magnet. Tightness between helium I

Fig. 2 Energy loss as a function of the ramp rate for current ramps between 2.88 and 10.97 kA (2 T and 7.5 T). The energy stored during these ramps is 290.98 kJ.

Fig. 3 Voltage during 500 s after a current ramp to 0 A with 12 A/s (at $t = 0$ s $U = 62$ mV)

and II baths is ensured by two low friction sleeve bearings and silicone grease filling the passage of the micro-coaxial signal cables (1 mm diameter). Two identical systems are used to measure both apertures of the magnets. Moreover two kinds of coils with different measuring radii, $R_{\max} = 23$ mm and 16.5 mm, have been used on the same single aperture 9 T model magnet.

The coil assembly spaced longitudinally along the support shaft is composed of three identical sets of 30 cm long coils measuring separately the centre and the ends of the 1 m model magnets. Each set is made of three coils (Fig. 4); the two outer coils are used to measure the harmonic content of the field when bucked with the central coil.

The coils are wound on a very precise core made of machinable glass ceramic. Their surfaces have been calibrated at LN2 temperature, showing a decrease of 0.32% compared to measurements at room temperature. These surfaces are around 0.12 m² and the bucking ratio amounts to several hundreds.

VI. PRECISION OBTAINED FOR THE MAGNETIC MEASUREMENTS

The systematic errors due to the measuring system were estimated by two different means:

- a first estimation is done by turning the coupling between angular encoder and coils shaft by 180°,
- the two external coils of the coil sets allow a measurement, with 180° phase shift, of the same part of the magnet's aperture. Part of the differences obtained can be attributed to off-centring of the symmetry axis of the coils set with respect to the rotation axis and can be deduced by calculation.

These estimations allow us to conclude that there is no systematic error greater than the reproducibility obtained in the measurements.

Fig. 5 summarises the reproducibilities, peak to peak differences over a dozen measurements, obtained in three different conditions : measurement with the 23 mm coil and with the 16.5 mm coil at fields above 5 T, measurement with the 23 mm coil at room temperature (0.05 T). The design aperture of LHC, 17 mm, is taken as a reference radius.

Fig. 4 Cross-section of the three coils sets used for the magnetic measurements.

TABLE 1
TYPICAL FIELD ERRORS, EXPRESSED IN 10⁻⁴ UNITS AT 17 mm
RADIUS, MEASURED IN THE CENTRAL PART OF ONE PARTICULAR
APERTURE OF A MTA1 MAGNET AT 7 T

	b_n	a_n
2	3.64	1.36
3	4.25	1.23
4	0.75	0.26
5	0.89	0.22
6	- 0.13	- 0.02
7	4.33	0.03
8	0.09	0.16
9	1.95	- 0.09
10	- 0.10	0.11
11	1.17	- 0.10
12	- 0.03	0.03
13	- 0.10	0.04
14	- 0.01	0.01
15	0.21	0.02

The measurement of the skew term is generally the less reproducible. In that type of measurement, the skew terms are indeed sensitive to the offset of the integrator.

The reproducibility obtained with the 23 mm coil is probably limited by the quality of the mechanism rotating the coil: angular encoder and shaft torsion, or imperfect rotation in a field having non negligible harmonics even for high orders. The field errors measured are of the order of magnitude expected for the LHC series magnets [3].

At low field, the sensitivity of the electronics clearly limits the reproducibility which, expressed in flux values, amounts to maximum differences of 0.6 $\mu\text{V} \cdot \text{s}$ for the quadrupole ($n = 2$) and closely follows a 1/n law giving 0.06 $\mu\text{V} \cdot \text{s}$ for $n = 19$.

The electronic sensitivity again limits the reproducibility obtained with the 16.5 mm coil for harmonics $n > 10$. For lower harmonics, the reproducibility is seen to be the same as that obtained with the 23 mm coil. A coil radius of about 16 mm allows measurements with a sensitivity well below the random errors preliminarily estimated for the magnets [3].

VII. SERIES MEASUREMENTS OF THE LHC MAGNETS

Measurements are important during the construction of twin aperture superconducting magnets since parallelism between the field directions of the two apertures, or positioning of the axis of twin quadrupole magnets with respect to each other, are adjustable only during magnet assembly. Shimming of the coil-collar structure can also diminish unwanted harmonics. Although less sensitive than methods based on A.C. excitations, the rotating coil method gives enough precision for these room temperature measurements (Fig. 5) and allows measurements in coils mounted inside their magnetic yoke.

All LHC magnets will undergo power tests at 2 K. Their beam aperture will be equipped with an anti-cryostat of 35 mm

Fig. 5 Diagram summarising the random field errors expected for the LHC magnets and the sensitivities obtained with measuring coils of 16.5 mm and 23 mm of radial aperture.

inner diameter. Our experience described here shows that room temperature coils with a 16 mm radius will allow sufficient precision for the series magnetic measurements.

VIII. TIME DEPENDENCE OF PERSISTENT CURRENT

Fig. 6 gives the variation with time of the sextupole component after ramping the field to 2 T with a ramp rate of about 2 mT/s. Similar variations were observed for higher symmetrical harmonics.

It clearly shows an initial increase exponentially decaying with a time constant of about 120 s. This time constant is of the order of the one measured on the voltage across the magnet after current stabilization (Fig. 3). Similar short term variations were measured with several types of conductors used for different magnets: filament size between 10 and 20 μ , cables with and without fully soldered strands (see [1] for description of the magnets).

This initial increase shown in Fig. 6 is followed by a decrease best fitted by a logarithmic time dependent decay, as measured on other types of superconducting dipoles [4, 5]. It is then believed to be of another nature and needs further investigation.

Provisional measurements indicate that it is possible to diminish this effect by either a small current overshoot or by remaining at constant excitation at a lower field value.

Fig. 6 Variation with time of the sextupole field errors over 1 hour at 2 T. The magnet was previously cycled between 7.5 T and 0 T.

IX. CONCLUSIONS

The test facility built for the MTA development program is now able to measure up to two magnets per month. The energy dissipation in the magnet is measured with a precision of 10⁻⁴ times the stored energy.

Useful information has been obtained for the design of measuring facilities for the several thousand magnets needed for the LHC accelerator. A radial aperture of 16 mm was checked to be sufficient for high resolution field quality measurements. Preliminary results show that the variation with time of the field harmonics due to persistent currents in the superconducting cable is not excessive and can be handled.

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