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D. Leroy, J.Krzywinski*, L. Oberli, R. Perin,
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The paper reports on the magnet quench behaviour and the field measurements at low and high magnetic induction. Measurements of the losses in the superconducting cables and the quenching field at various field ramp rates are used to investigate the temperature margin in superfluid helium under steady state losses.

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Abstract--Superconducting twin-aperture dipole model magnets for the CERN future superconducting collider (LHC) have been built in industry and tested at CERN. They make use of high aspect ratio superconducting cables wound on a 50 mm Ø bore. The twin-aperture dipoles have reached 10 T bore field, which is the highest field obtained in an accelerator type dipole up to now.

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I. INTRODUCTION

CERN is proceeding with the design of a new high energy collider, the Large Hadron Collider (LHC), consisting of a double ring which enables the circulation of counter-rotating beams of particles of the same sign. This machine is to be installed in the existing 27 km long tunnel of LEP, the electron-positron collider in operation at CERN since 1989 [1].

To fit into the available tunnel space and permit the collider to reach the highest energy at a reasonable cost, the magnets are designed following the two-in-one concept, originally proposed at Brookhaven National Laboratory. In this concept, the two magnetic apertures are placed in a common yoke and cryostat assembly leading to smaller cross-sectional dimensions and to a more economical solution.

The technology of accelerator superconducting magnets has been applied with extraordinary success on a large scale in the Tevatron and HERA projects. The excellent results obtained with dipole prototypes for the SSC confirm that superconducting magnet technology is now mature for operational fields up to 6.6 T. The demand for higher fields continues to be motivated by economy of space, capital investment and operation cost. The aim for the LHC is to reach a machine operational field in the range of 9 to 10 T. These high field levels can be obtained by lowering the operational temperature to ~1.9 K. Superfluid helium which presents the advantage of a high heat conductivity, must penetrate the insulated coils to cool the conductors so as to improve the enthalpy of the conductor. This is of special importance in a collider of high luminosity and high energy, since beam losses in the machine could possibly lead to a power deposited in the coils of 10 mW/cm^3 in the most exposed dipole.

CERN has an important R&D programme covering development of superconducting cables, construction of short models and full length prototype magnets in collaboration with several European Institutions, laboratories and industrial firms. An effort towards building LHC model dipoles is also carried out in Japan.

This report describes the results obtained with 1 m long models which have been made in industry. In order to test different design ideas, the four magnets were built with a number of technical variants concerning the type of cable and electrical insulation, details in coils, material, shape and assembly method of the collars and the material of the outer shrinking cylinder [2].

Preliminary results have been reported in [2]. This report deals particularly with the tests performed on two magnets called MTA-JS and MTA-H.

II. SUPERCONDUCTING CABLES USED IN MTA1 MODELS

A. Cable geometries

A basic choice for the LHC dipoles was made for coils with two layers of superconducting cables, which implies the use of cables of large width and two types of strands to optimize the use of the superconducting material. The inner layer cable has 26 strands of 1.29 mm diameter and a 2.04/2.50•17 mm^2 cross section. The cable for the outer layer has 40 strands of 0.84 mm diameter and a 1.30/1.67•17 mm^2 section. The outer layer which has an aspect ratio of 11.4 has presented some problems of mechanical stability and burrs on the thin edge of 1.30 mm due to the high compaction factor. To overcome these difficulties, the cables fabricated by one of the suppliers had one strand in two coated with Sn and the thin edge soldered during fabrication. This technique gives good stability for winding and allows penetration of helium between the strands. This solution was adopted for the models at an early stage of the programme. Developments in cabling technique and winding tests have later shown that it is not necessary to solder the cables to obtain good mechanical stability. The transposition pitch of the cable varies from 120 to 130 mm for the inner cable and from 100 to 132 mm for the outer cable. Twist pitch of the strands before cabling is 25 mm. The unsoldered cables have a Sn Ag coating on the strands. The Sn coating has a better thermal transfer to superfluid helium [3] and is less sensitive to oxidation. Of course, there is a risk of higher eddy current losses than on uncoated strands, but the coating ensures a more uniform and reproducible behaviour.

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Table 1: Characteristics of the strands used in the models

Firm	Strand Diameter (mm)	Number of Filaments	Filament Diameter (μm)	Nb Barrier	Cu/Sc Ratio	J_c (A/mm^2) at 10^{-14} Ωm before cabling	
						6T 4.2 K	8T 4.2 K
A	0.835	1230	14	No	1.8	2020	
B	0.825	2550	9.5	Yes	1.96	2270	
B	1.272	3060	15	Yes	1.75		1080
C	1.29	900	25	No	1.91		980

B. Electrical characteristics of strands & cables

The superconducting alloy is NbTi with 46.5 % Nb. Table 1 gives the measured characteristics of the strands used in the models.The quantities ordered for the models were too small to permit the firms to adjust the C_u/S_c ratios which are larger than the specified values of 1.8 for 0.84 mm strand and 1.6 for 1.29 mm strand.

Measurements have been performed in SACLAY at temperatures lower than 4.2 K [4], on strands after cabling (at 1μV/cm) (Table 2). From these measurements it appears that the current densities are higher by 10 % in the strands of diameter 0.84 mm than in those of 1.29 mm.

Fig. 1 shows typical current densities versus temperature for a strand of 1.29 mm. It can be seen that

$$J_c\ (8T, 4.2\ K) = J_c\ (10.8\ T, 2\ K)$$

giving at high field a shift of 2.8 T when the temperature is reduced from 4.2 K to 2 K.

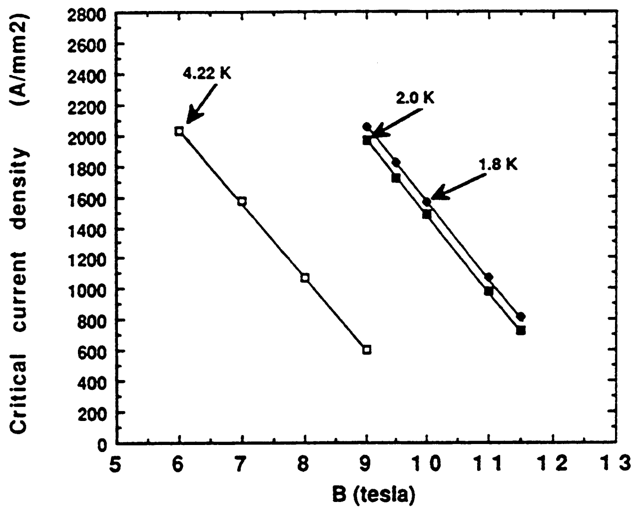


Fig. 1: Current density for a strand of 1.29 mm

Table 2: Critical current densities in strands at 1 μV/cm

	T = 4.22 K			T = 2 K			T = 1.8			
B (T)	6	7	8	9	10	11	9	10	11	dJ_c/dB
B 1.272 mm	2081	1575	1041	1997	1472	977	-	1563	1076	514
C 1.29 mm	2030	1572	1068	1959	1488	980	2048	1567	1073	494
B 0.825 mm	-	1779	1207	2234	1667	1089	2357	1784	1212	572

Table 3: Short sample in cables at 10^{-14} Ωm on overall section of cable at 4.2 K

Firm	Cable type	I_c (A)	B	n	RRR	ΣI_c strand at 6T	I_c cable/ΣI_c strand	B_o, quench in magnet
A	outer	16040	6 T	24	75	16350	0.981	10.40 T
C	inner	11620	8 T	35	81	11280	1.029	9.91 T
B	inner	11940	8 T	35	135	12350	0.967	10.03 T

Measurements of the critical currents have been performed at BNL [5]. Table 3 gives the results and compares them to the critical measurements on strands after cabling. The results are within 3 % using the empirical rule that the critical current in field perpendicular to a cable, taking into account the self field, is approximated by the sum of the critical currents on the strands after cabling without taking into account the self field on the strands. At BNL, it was found that the cables used in the models did not present any training during the short sample measurement.

Verifications have shown that the cable performance is not affected by a heat treatment of 5 hours at 160°C, simulating the coil curing procedure. At the start of the development on LHC superconducting cables, the design value of current density at 11 T, 2 K was 1190 A/mm^2. It seems that this goal is difficult to achieve with 5 μm filament diameter and the performance specification for LHC cable will be reviewed.

III. DESCRIPTION OF THE TESTED MAGNETS

A description of the MTA twin-aperture model magnets can be found in [2] and [6]. In order to understand their behaviour their main characteristics are recalled below. Two of the MTA magnets have been disassembled in order to make observations and modifications and are being reassembled.

A. The twin-aperture models (MTA1)

The coil consists of two layers, each with a different aspect ratio cable made of NbTi composites. To obtain a good field homogeneity, the inner layer is subdivided into four blocks of conductors, the outer into two blocks. The longitudinal spacers are made of copper. The upper spacer of the inner layer has holes to provide helium passage to "fish bones" spacers located between the two layers. The electrical insulation consists of a 25 μm Kapton™ layer (50% overlap) and a B-stage pre-impregnated fibre glass layer spaced by 2 mm. The fibre glass has a density of 125 gm/m2 and contains not more than 23% B-stage epoxy.

The first 3 turns of the inner layer in the ends are spaced by 3 mm G11 spacers to distribute the field and to avoid electrical shorts. Between each conductor in the ends, there is a wedged support made of a sandwich of G11 and Kapton to ensure mechanical contact over the surface of the conductors. Before curing, a moderate axial pre-stress is put in the ends, the length being defined and fixed by the tooling. The layer jump which allows the inner cable to go to the level of the outer layer before being soldered to the outer layer cable has a 2 mm thick Cu sheet soldered for stabilisation.

The coils have been wound successfully in industry. The most critical point is the first turn of the inner layer which has a radius of 6.5 mm where the cable tends to be opened. The conductor positioning in the ends can be realized with a precision of ± 0.5 mm and ± 1° angle. The Young's modulus of the coils in the straight part is around 15000 N/mm^2.

B. Collaring

The four poles are assembled in common collars in which they are pre-stressed at average room temperature with an azimuthal pressure around 50 N/mm^2. The collars are made in Al alloy 5083G35 or Al 2014T6. The highest stress in the collars occurs near the rods in the horizontal plane which sustain a force of 3400 N/mm for the lateral rods and 6800 N/mm for the central rod. In the MTA-JS, the lateral rods which require a higher pre-stress on the coils for their insertion during collaring, have been replaced by keys. The collaring of the coils in the common collars is made in three steps: insertion of lateral rods at a diameter reduced by 0.2 mm with respect to the nominal insertion of central rod followed by the final insertion of the lateral rods. The relaxation of the Al collars has been reduced by partially pulling on the sides of the collars.

C. Iron yoke & outer cylinder

The iron yoke surrounding the twin collar coils is split into two parts at the vertical symmetry plane of the magnet. The two iron inserts between collars and yoke reduce the quadrupolar component in the twin-aperture dipole. Between the collars and the iron yoke, shims are provided to accommodate the height and the width of the collared coils to the dimensions of the yoke. The iron yokes are compressed onto the collars and fixed by clamps. The iron gap is open at room temperature. The outer cylinder made of stainless steel or Al alloy has a pre-stress at room temperature such that at cooldown, the iron gap is closed with a compression of 3000 N/mm on the mating forces of the yoke parts and the collars and yoke are in close contact in the horizontal plane.

D. Axial forces

The axial forces of 700 kN at 10 T are taken by the outer cylinder via a 55 mm thick common stainless steel plate. This end-plate undergoes a deflection of 1 mm at its central part at 10 T. Shims are provided between the end plate and the outer cylinder to adjust the axial pre-stress on the coils. Different compressions of the ends were tried for two magnets, without apparent effects on the training behaviour.

IV. BEHAVIOUR AT 4.3 K

All the tested magnets have reached their short sample limit at 4.3 K, one after four quenches, for the others the quenches at 4.3 K were consecutive to the training at 1.8 K. The field obtained is of about 7.9 T, giving transverse forces of 350 t/m in the coils. The axial forces amount to 10.9 tons per aperture.

The pick-up coil system [7] localizes the quenches at short sample limit at the maximum angle of the inner layer, and in the central part, at the location of the peak field as expected from 2D calculations.

V. MEASUREMENTS PERFORMED AT 1.8 K

The magnets are tested in a vertical cryostat in which the temperature can be adjusted between 1.75 K and 2.16 K. The tests at superfluid helium last two to three weeks. Another week is needed to complete a thermal cycle to investigate retraining behaviour. All quenches are performed with maximum energy extraction to a dump resistance outside the cryostat. More than half of the initial stored energy remains and is dissipated homogeneously in the winding, where the hot spot temperature remains typically below 100 K.

The instrumentation for magnetic measurements and measuring the conductor losses is described in [8], and pick-up coils for localization of the transition are now systematically used for all types of quenches.

The tests include the following items.

- Training, instrumented as far as possible to localize the quenches and measure the movements of the structure with strain and displacement gauges.
- Measurements of the losses in the conductor as a function of ramp rate.
- Measurements of the degradation of performance due to ramp rate.

  (These last two measurements allow estimations of the temperature margin of the conductor and of the possible effect of particle beam losses.)
- Measurement of the D.C. resistance of the coils and of the connections between layers or poles with an accuracy to better than 10 µV at 10 kA.
- Magnetic measurements. Among others, preliminary studies of the effect of persistent currents.
- Studies of the behaviour of the heaters to spread the quench throughout the full winding.

VI. THE MAGNETS AT 1.8 K

A. Training curves

Fig. 2 shows the training curve of the MTA-JS magnet. The longitudinal compression was decreased after the first test, without apparent effect on the behaviour.The magnet was assembled with the iron yoke open at room temperature but closed at low temperature. It went to just above 10 T after a long training. Letting the magnet slowly warm-up near to full field gave a value of 9.91 T as the short sample limit at 2.1 K.

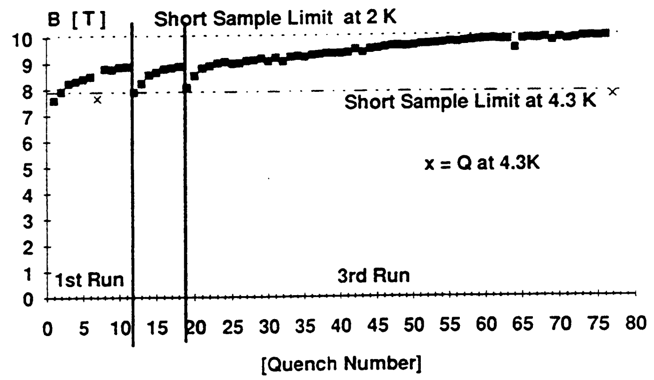


Fig. 2: Training of the MTA-JS magnet

The MTA-H coil-collar assembly was first tested without the iron yoke and shrinking cylinder : the collars were free to deform under the e.m. forces. The first two quenches were made at 4.3 K and the next one at 1.8 K for a field 0.7 T higher (Fig. 3). The magnet reached the short sample limit at 4.3 K after this training.

The same MTA-H magnet improved appreciably when equipped with its iron yoke, even taking into account the different field-current relationship. The shimming of the iron yoke was adjusted so that the vertical gap between the halves

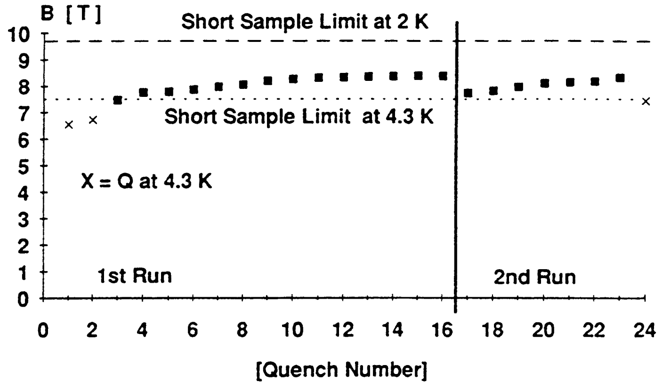


Fig. 3 : Training of the MTA-H magnet without its iron yoke

was not closed at low temperature, with the full force of the external shrinking cylinder transferred to the collars at the mid plane. It had reached 9.8 T when it was decided to stop the training (Fig. 4). The second quench of the next run was at 9.2 T. The last two quenches at 4.3 K are at the short sample limit : their values differ by less than 0.02 T and the pick-up coil system localizes them in the inner turn of the inner layer, central part.

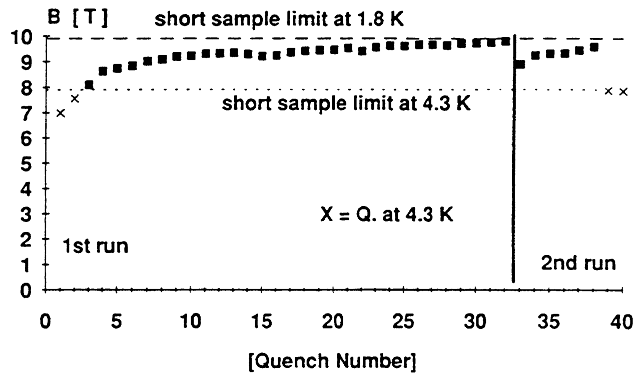


Fig. 4 : Training of the MTA-H magnet with the iron yoke mounted

B. Location of the quenches

The quenches in the first models have shown voltage peaks that initiate the resistive transition [8]. These peaks have suggested sudden movements of the conductors due to the e.m. forces, that could be localized by pick-up coils connected to the quench recorder.

The resulting work is extensively described in [7].The stored signals, of about 100 µsec duration, allow quench location along the magnet axis. When the transition is not consecutive to a movement detectable by a voltage peak, it nevertheless induces a slower flux change. Modelling this change by a magnetic moment allows tentatively to localize the quench in the transverse plane of the winding.

This method seems promising. The longitudinal localization, able to distinguish among seven regions, is straightforward and works both for sharp movements or for quenches that are not due to training. The localization in the transverse plane is for the moment tentative, particularly in the ends of the winding where the magnetic moment can be three-dimensional. Fig. 5 shows the position of the pick-up coils in the magnet winding.

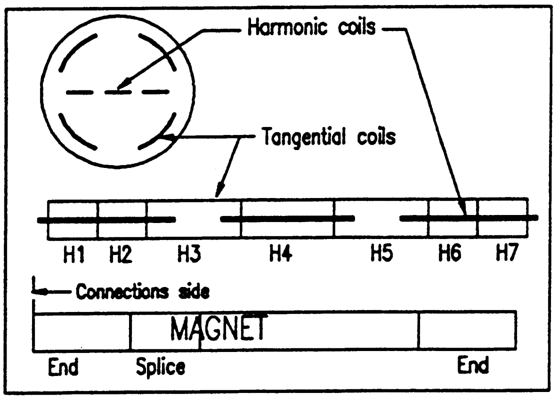


Fig 5 : Position of the pick-up coils to localize quenches in the magnet winding

Table 4 summarises the deduced location of training quenches at 1.8 K for the three series of the above mentioned tests.

- The distribution of the quenches among the four poles is detected by means of voltage taps.
- The distribution among the seven lengths of the pick-up coils enables longitudinal localization. Some of the columns group several locations since a few quenches are seen on several coils simultaneously, or because the tests were performed with a smaller number of coils.
- The number of localized quenches is lower than the total number of quenches, due to instrumentation problems.

The first two runs of the MTA-JS are not included because the method of localization had not at that time been tried. The results from two other magnets are added : the MTA-A and the single aperture MSA-K [9]. The search for the position in the transverse plane localizes most of the quenches in the first turn of the inner layer.

Table 4: Measured Location of quenches among the four poles for the twin-aperture models, and as a function of longitudinal position

<table>
<tr><th></th><th>MAT-JS</th><th>MTA-H without yoke</th><th colspan="2">MTA-H with yoke</th><th colspan="2">MTA-A</th><th>MSA-K</th></tr>
<tr><td>Pole 1</td><td>31</td><td>1</td><td colspan="2">14</td><td colspan="2">12</td><td>-</td></tr>
<tr><td>Pole 2</td><td>11</td><td>2</td><td colspan="2">2</td><td colspan="2">16</td><td>-</td></tr>
<tr><td>Pole 3</td><td>9</td><td>15</td><td colspan="2">17</td><td colspan="2">7</td><td>-</td></tr>
<tr><td>Pole 4</td><td>7</td><td>3</td><td colspan="2">3</td><td colspan="2">3</td><td>-</td></tr>
<tr><td>H1Conn. end</td><td rowspan="3">19</td><td rowspan="3">15</td><td>0</td><td rowspan="3">5</td><td rowspan="3">2</td><td rowspan="4">3</td><td>13</td></tr>
<tr><td>H2</td><td>3</td><td>3</td></tr>
<tr><td>H3, Splice</td><td>10</td><td>1</td></tr>
<tr><td>H4</td><td rowspan="2">9</td><td rowspan="2">1</td><td>2</td><td></td><td rowspan="2">5</td><td>1</td></tr>
<tr><td>H5</td><td>4</td><td rowspan="2">3</td><td></td><td>2</td></tr>
<tr><td>H6</td><td rowspan="2">14</td><td rowspan="2">3</td><td>11</td><td colspan="2" rowspan="2">no coil</td><td>0</td></tr>
<tr><td>H7 end</td><td>0</td><td></td><td>14</td></tr>
</table>

The single aperture MSA-K was equipped with voltage taps between each block of the inner layer, and on the connections between the two layers. One third of all quenches start simultaneously in the middle block of the inner layer and in the outer layer. The pick-up coils detect a sharp movement initiating all these quenches in one end (H1). A longitudinal sliding of one layer against the other would be compatible with these observations.

C. The effect of the structure

When a quench is consecutive to a 'peak', signature of a movement, it is followed by oscillations. They are heavily damped in the case of the MTA-H with its iron yoke, less damped in the case of the MTA-JS having the iron gap closed. Almost no damping is observed with the free coil-collar structure of the MTA-H without its iron yoke. The same vibration frequencies are observed during the three tests : 2.8, 4.2 and 6.4 kHz.

The two tests of the MTA-H, with and without iron yoke, confirm that no problem is expected from friction between collars and yoke halves which have to move with respect to each others during cool-down. The two in one structure is most probably not responsible for the long training of the LHC models :

- two single aperture magnets suffer also from a similar training,
- the majority of the quenches below the short sample limit are in the ends, and are consecutive to a detectable movement,
- the results of the Twin Aperture Prototype give a further confirmation [6].

The superconducting cable allows a field of 10 T to be reached, which was attained in one of the twin aperture models. Studies are pursued to understand whether increasing the thermal transfer would nevertheless decrease the training, as it would at the same time decrease the degradation due to beam losses. In this respect, the compactness of the winding presents difficulties: the filling factor is now about 98 %.

The MTA-H magnet was assembled to have the full stress of the shrinking cylinder on the collars at low temperature. The ends were responsible for most of the quenches below 9.3 T. This method of clamping therefore seems promising.

VII. CONDUCTOR LOSSES DUE TO RAMP RATE

Loss measurements are performed in order to investigate the dissipation during charging and discharging the dipoles. The magnet undergoes a current cycle: 2.9 kA, 11 kA, 2.9 kA with constant ramp rate. The losses are deduced from the measured differences between the stored and extracted energies.

Fig. 6 shows the measured loss for several dipoles after correction for the resistive loss in the connections between the layers. The resistance of these connections is measured at about 4 nΩ at high field. Large differences in the gradient of the curve are attributed to differences in the interstrand coupling losses. This is mainly due to different values of the contact resistance between crossing strands. One of the magnets (plot K) had a smaller cable width (15 mm) than the others (17 mm).

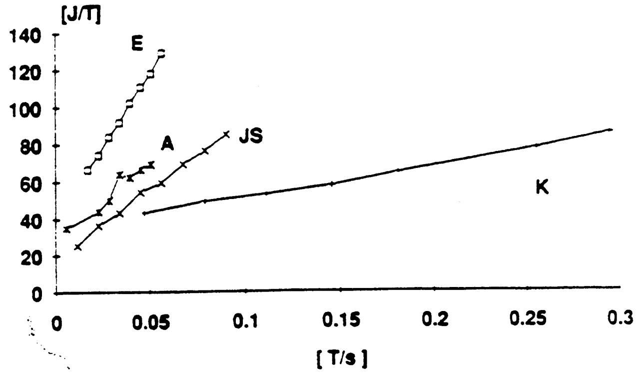


Fig. 6: Energy lost (joule/tesla), scaled to one aperture as function of the field ramp rate for 4 different magnets

Quenches as a function of the ramp rate (Fig. 7) are performed to gain knowledge about the cooling of the cables. Although at high ramp rates, the small duration of the ramp does not allow steady state conditions to be reached, the degradation of the quench current due to beam losses can still be estimated. For this, it is necessary that the quench starts in the block where the beam losses are expected to be maximum. This is likely to be true as the inter-strand coupling losses are also maximum in the midplane due to the high dB/dt perpendicular to the wide side of the cable. In fact, the quenches at ramp rates above 0.1 T/s are generally detected to be in the mid-plane, inner layer.

If the quench can be precisely localized, the temperature inside the winding can be deduced by its relationship with the short sample limit. From the curves of Fig. 7, it can be seen that the temperature of the winding smoothly increases through the lambda point; these magnets have the same stability whether the winding temperature is above or below this point.

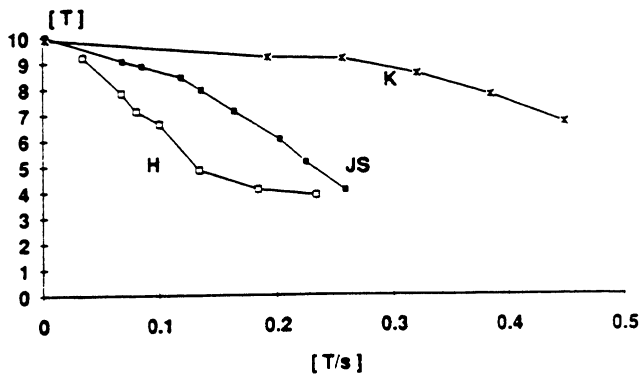


Fig. 7: Quench field as a function of the field ramp rate for several magnets. The bath temperature is at 2 K. The ramp is always started at 2 T

The variation of quench field also depends on the bath temperature. A degradation is noticeable above 1.9 K which corresponds to the maximum thermal conductivity of helium (Fig. 8).

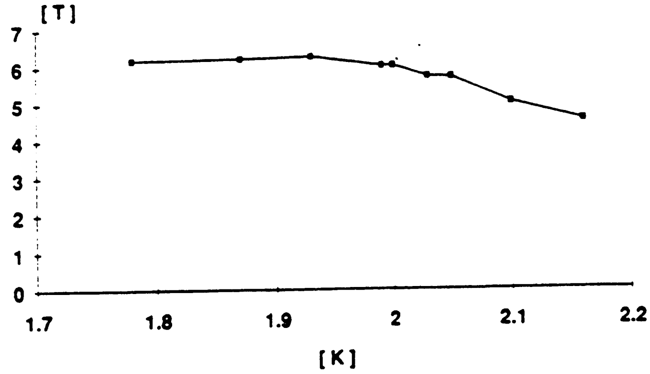


Fig. 8: Quench field as a function of the temperature for the MTA-JS. The ramp of 0.1 T/s is always started at 2 T.

VIII. MAGNETIC MEASUREMENTS

The multipole content at medium and high magnetic fields corresponds well with computation [6], and the harmonics that do not belong to the magnet symmetry are within specifications. A normal quadrupole component is present in such a twin aperture structure. A different behaviour of this component with respect to excitation is observed between the MTA-JS, iron yoke gap closed at low temperature, and the MTA-H, with a remaining vertical gap when cold (Fig. 9).

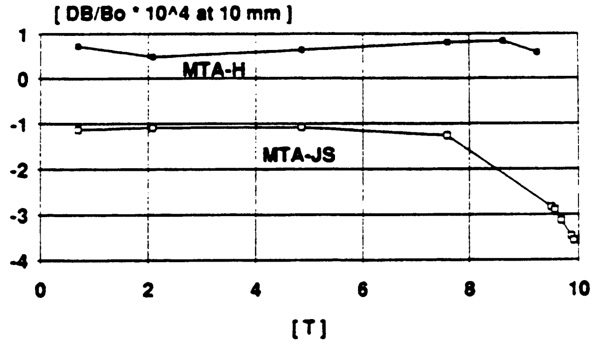


Fig. 9: Quadrupole component for the MTA-JS (yoke gap closed at low temperature), and the MTA-H (yoke gap open at low temperature)

As already reported [8], the normal sextupole component at field values near LHC injection shows a rapid increase, during typically 10 minutes, followed by a slow variation during several hours. Depending on cycling conditions, this later variation with time is sometimes too small to be measured. A similar behaviour is observed on higher harmonics.

The value obtained after the fast rise has stabilised is attributed to filament magnetization. Measurements fit well with calculation, at different fields, and at both 4.3 and 1.8 K for the sextupole and the decapole components [10].

The first increase of the sextupole term has the following characteristics (Fig. 10).

- It fits better an exponential than a logarithmic decay, and at the same current, the time constant is about the same, irrespective of the magnet, of the cycling conditions, or of the temperature. This time constant is of about 300 sec at a field of 0.55 T corresponding to LHC injection.
- It does not depend on temperature, or variation of temperature.
- Its amplitude depends on cycling conditions, but weakly on the cable used (see section II for a description of the cables).
- A measurement at four different locations, one end and both central parts of both apertures, give similar results.

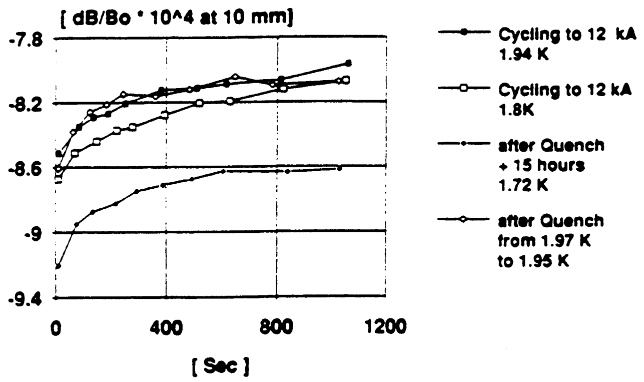


Fig. 10: Sextupole component as a function of time for four different cycling conditions

Some of these characteristics seem to exclude an effect of flux creep in the filaments. More complete measurements are needed before reaching to a conclusion.

After 15 minutes at a field corresponding to LHC injection, a ramp of 1.4 mT/s provokes a bump of less than 10^{-5} on the sextupole component expressed as field error at 10 mm aperture. The instrumentation does not allow this measurement to be performed reliably at the maximum foreseen beam acceleration rate of 8 mT/s.

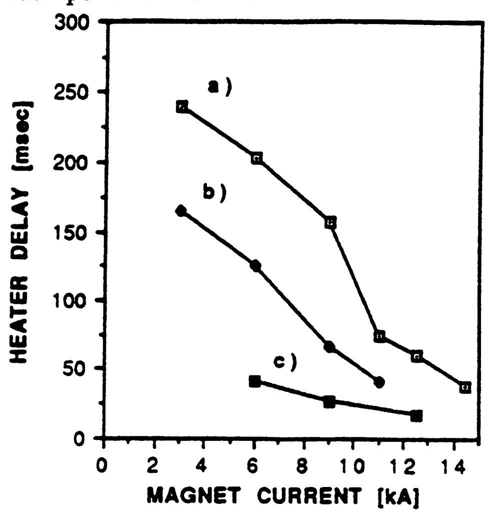
IX. BEHAVIOUR OF THE HEATERS

Models were provided with quench protection heaters consisting of AISI 302 type stainless steel strips, 12 mm wide and 25 μm thick, with Kapton as electrical insulation. Two quench heaters per aperture, each comprising two strips in parallel, are placed against the outer layer shell of the dipoles, covering 10 turns of each pole along the entire length of the magnet (40 turns are thus triggered in case of a quench). The overall thickness of the quench heater is made up from 25 μm of Kapton base, the 25 μm heater strip glued to the base through a 40 μm thick acrylic adhesive layer and a cover in 75 μm Kapton™ on the winding side.

Tests were made triggering quenches in the dipole models by firing the heaters, in order to investigate the performance of the present design. The LHC dipole prototypes (full length magnets) require protection heaters to quench safely without attaining limiting temperatures and voltages which may threaten the magnet structure. Thus, it is important to know what the heater delay will be (heater delay being defined as the time from the heater firing until the conductors underneath it quench) at different magnet current levels and with different power dissipation in the resistive strips.

Heaters are fired using a capacitor power supply triggered by the quench detection signal. This power supply has four independent units, each one of 7.2 mF, and normally these operate at a common 400 V potential. The total heater resistance is 1.8 Ω at 1.8 K. The time constant of the discharge process is normally around 150 msec.

The dependence of heater delay on the magnet current appears in Fig. 1. Two of the curves correspond to measurements at 1.8 K for initial heater strip power of 1.8 and 11.5 kW respectively. The third curve was obtained at 4.3 K for a heater power of 1.8 kW.



	a)	b)	c)
Heater initial power [kW]	1.8	1.8	11.5
Bath temperature [K]	1.8	4.3	1.8

Fig. 11: Heater delay as a function of magnet current

Fig. 12 shows heater delay as a function of the initial power dissipated in the heater at two different temperatures. The current through the magnet is 9 kA, which is at present the reference current used for heater calibrations.

The values presented here correspond to tests performed on the heater initiating the quench after the longest delay. Differences in delay between the slowest and the most rapid acting heater are in the worst case of the order of 40%.

Scaling these results to full length dipole magnets by computer simulation indicates that reliable active protection during quench can be provided using heater strips together with bypass diodes.

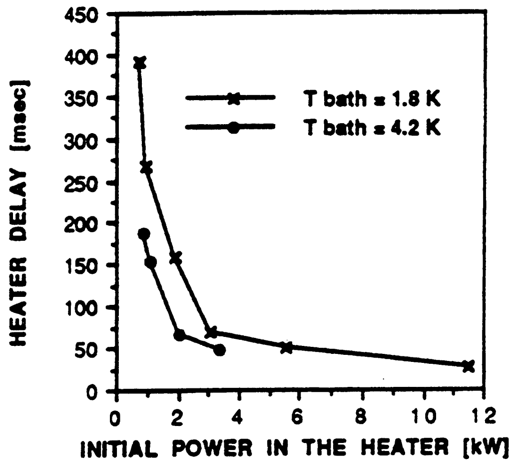


Fig 12: Heater delay vs initial power in the heater. The current in the magnet is of 9 kA, corresponding to a 6.2 T field

X. CONCLUSION

The models for LHC are the first accelerator type magnets that have reached a 10 T central field. They suffer from a long training but not due to their twin-aperture configuration. They fulfil the specifications for the field quality. According to calculations, the heaters propagate the quench in the winding fast enough to protect the full length magnets in superfluid helium. Dedicated instrumentation is now currently in use to localize the quenches and measure the eddy current losses in the conductors. These magnets have the same stability whether the winding temperature is above or below the lambda point. Most of the training quenches are located in the coil ends and their possible causes are being identified. New model magnets, modified to take into account these findings, are being built.

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