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Testing Results for Nb-Ti, 120-mm-Aperture, Low-B Quadrupole Models for the LHC High-Luminosity Insertion

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The design and construction of a 120 mm wide-aperture, Nb-Ti superconducting quadrupole magnet for the LHC insertion region is part of a study towards a luminosity upgrade of the LHC at CERN, envisaged for 2020-22. The main challenges for this accelerator quality magnet are to operate reliably with the high heat and radiation loads that are predicted in the insertion magnet regions. Calculations give approximately 500 Watts over the 30-m-long string of insertion magnets, while today LHC is operating for a nominal heat load of 12 Watts. To extract this heat, the model magnets incorporate new features: Open cable insulation, open ground insulation, open magnet structure, and a quench heater that has open channels to help extract the steady state heat load. This paper presents results from tests at room temperature and 1.8 K for the initial model magnet. We report magnet training, transfer function and field quality measurements, quench heater performance, and heat extraction studies using imbedded heaters to simulate the deposited beam heating profile.

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***Abstract*—The design and construction of a 120 mm wide-aperture, Nb-Ti superconducting quadrupole magnet for the LHC insertion region is part of a study towards a luminosity upgrade of the LHC at CERN, envisaged for 2020-22. The main challenges for this accelerator quality magnet are to operate reliably with the high heat and radiation loads that are predicted in the insertion magnet regions. Calculations give approximately 500 Watts over the 30-m-long string of insertion magnets, while today LHC is operating for a nominal heat load of 12 Watts. To extract this heat, the model magnets incorporate new features: Open cable insulation, open ground insulation, open magnet structure, and a quench heater that has open channels to help extract the steady state heat load. This paper presents results from tests at room temperature and 1.8 K for the initial model magnet. We report magnet training, transfer function and field quality measurements, quench heater performance, and heat extraction studies using imbedded heaters to simulate the deposited beam heating profile.**

Index Terms—**Cold testing, Heat extraction, HL-LHC, Manufacturing process, Magnetic shimming, Superconducting accelerator magnets, Quadrupole, Tooling, Quench heaters.**

I. Introduction

FOR the phase-1 luminosity upgrade of the Large Hadron Collider at CERN, a development program was started in 2007 in collaboration with CEA Sacly to develop a (Nb-Ti) 120 mm aperture quadrupole with a gradient of 120 T/m and the ability to extract very high heat loads on the order of 500 W. This quadrupole, called MQXC [1-4] had the innovative feature of a insulation scheme allowing a direct path from the helium bath to the superconducting strands [5]. Subsequently it was decided to move directly to the phase-2 insertion design requiring Nb_3Sn technology and larger apertures. MQXC was needed for a backup technology in case the Nb_3Sn magnet could not achieve the design targets and reliability within a relatively short time scale of about10 years. Moreover, the high heat load technology for the Nb-Ti magnet is a feature required for future magnets in the matching sections, namely the separation dipoles D1 and D2, the two/in/one quadrupole Q4 and several correctors [6,7].

In this paper, we describe the final assembly of the first 1.8-m-long model magnet, MQXC(0), that was assembled at CERN; we also describe the test setup, the measurement of the room temperature field harmonics, as well as results in terms of training, quench performance, and quench location. Measurements of the splice resistances, the RRR of the coils, inductance, and AC losses are also given. The test was also dedicated to the protection of the magnet with the investigations on the quench heaters efficiency. Special tests were carried out to study heat extraction, with encouraging results.

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II. Overview of Magnet Assembly

The coil layers, made up of two different cables, are wound and cured to size individually [4]. Inner and outer layers are assembled together with the quench heater between the two coil layers. The coils are measured and the ends are shimmed so that the coil pressure gradually reduces (at room temperature) from the 80 MPa in the straight section to 30 MPa at the coil extremity. The four poles are sorted to optimize the coil mid-plain position.

During the assembly of the 1.8-m-long MQXC(0), the coils are placed vertically around a spring-loaded, collapsible mandrel and held in place with straps. The cooling sheets were mounted on the coils and pass through the ground insulation providing an open path to extract heat from the coil to the 1.9 K helium bath. Full-length heaters are placed between poles in order to simulate the beam-induced heat load. The full-length collaring shoes are then placed on top of the ground insulation to protect it from being damaged by the collars during collaring.

To further improve the magnet cooling, the collaring shoes are also perforated with openings of about 30% of the surface area. The 3-mm-thick Nippon stainless steel collars (with a ±0.01 mm tolerance) are stacked around the aperture and spaced to give a 3.3% open gap between the collars to extract heat. Eight holes in the collars at 30° can be filled with magnetic shims. The aperture is fitted with its eight full-length keys using a collaring press. After this operation, the mandrel is removed. After welding the end flanges on to the collared aperture, the joints are soldered in the joint-box.

The collared aperture is then placed vertically in the yoking tooling. The yoke laminations are stacked with an identical system as used for the LHC main quadrupole assembly. The obtained yoke packing factor has been 99.6%; higher than expected 98%. The magnet is completed with the placement of the yoke end flange and mounting the four 80 mm diameter tie rods.

During collaring, one of the magnet cables that exit a coil had three strands accidentally cut. It was not possible to repair without dismantling the aperture. Since this damage is only marginally affecting the performance, and being in a low field region, it has been decided to continue without repairing the cable.

III. Field measurements at Room Temperature

In order to allow a longitudinal scan of the entire magnetic length including the ends, the magnet was fitted with an aluminum tube of 70 mm inner diameter, with a total length of 3 meters. The so-called QIMM system [8] was applied, which had served for the qualification of the LHC main quadrupole cold masses. The measurement mole was positioned in three locations denoted as 0, +750 and -750 mm, corresponding to the distance from the magnet center to the center position of the mole, which has 68 mm outer diameter and coils at 27 mm radius. The search coil length is 750 mm. Three different currents were used in these series of measurements, 10, 15 and 20 A. Fig. 1 compares the measured field multipoles for the collared coil and the slightly improved values for the full magnet with its magnetic yoke.

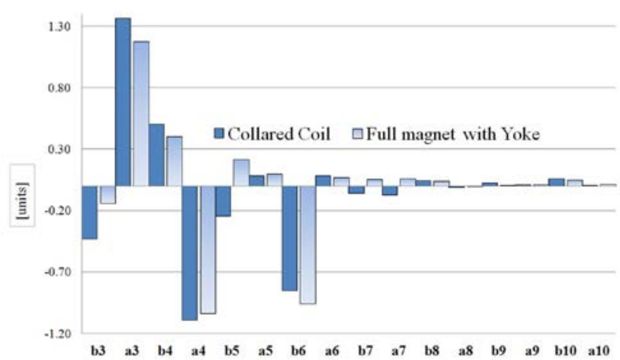

Fig 1. Harmonic Multipoles (a_n, b_n in units of 10-4). Measured with 10 A, 15A & 20A excitation magnet current. Measured at a reference radius of 27 mm.

The field quality has been measured at room temperature. Results are shown in Table I: a systematic b_6 of about 1 unit is present, when the measured results are scaled to 40 mm ref. radius. Non-allowed multipoles are pretty good, with only two components (a_3 and a_4) above one unit. A magnetic shimming [3] has been proposed to improve field quality. Eight 8-mm-diameter holes, located in the collars, at 105 mm from the magnet center and at 30° from the coil mid-plane can be filled with magnetic rods. The impact of a single rod on the multipoles in absence of saturation is shown in Table II (according to the angular position the same multipole can be varied by two different quantities, which are given in Table II). The aim is to correct non-allowed multipoles larger than 1 unit, which may arise from assembly or coil asymmetries. The technique is able to correct several units of 3rd order, and a few units of 4th order.

TABLE I
MULTIPOLES IN THE STRAIGHT PART OF THE MAGNET, MEASURED AT ROOM TEMPERATURE (UNITS AT R_{REF}=27 MM & SCALED TO R=40MM)

Measurment at R=27mm			Scaled to R=40mm	
Order	an	bn	an	bn
3	1.176	0.139	1.74	0.21
4	-1.035	0.403	-2.27	0.88
6	0.1	0.216	0.48	1.04
10	0.014	0.051	0.32	1.18

The agreement with measurements, carried out at room temperature is within 20%. There is a small side effect on b_6, each rod giving about 0.06 units, which is negligible.

TABLE II
MAGNETIC SHIMMING, MODEL VERSUS MEASUREMENTS

	Model	Measurements	
		μ	σ
c_{3A}	2.41	2.14	0.01
c_{3B}	1.30	1.13	0.02
c_{4A}	0.85	0.74	0.01
c_{4B}	0.15	0.13	0.02
c_{5A}	0.25	0.22	0.01

Field targets are set at high field, whereas these magnets are nearly transparent at injection: therefore, the technique has to work with full saturation. Simulations show that at nominal current the effect is reduced by about a factor two, i.e. it is still sizeable and usable for correction.

IV. Test Results

A. Cool-down to 1.9 K, RRR, and Joint Resistance.

After inserting the magnet into the test cryostat we repeated the electrical checks. The cool-down was controlled setting a large 200 K temperature difference between the top and bottom of the magnet. It took about 12 hours to cool and fill with liquid. During cool-down we measured each coil resistance to obtain a RRR values. The joint resistances have an average of 0.35 nΩ with a standard deviation of 81 pΩ. The RRR averages for the inner and outer cable are 225 and 231, respectively measured during cooling. In both cases this is within specifications.

B. Training to nominal current

The quench protection thresholds were set to 50 mV with 10 ms verification time. Nominal current is 12.8 kA, short sample around 16 kA, so we selected a 50 mΩ protection dump resistor to keep voltage below 800 V. The quench heaters were not connected for the first set of tests since the energy extraction is enough to protect the magnet. The first training quench was at 11.39 kA, corresponding to 71% of short sample with the helium bath at 1.92 K. After three further quenches the current reached the nominal 12.8 kA. A plateau of 30 minutes was then performed before triggering a dump. The quench location moved between coils for each successive quench (see Table III).

C. Coil resistance during a quench.

In order to investigate if the quench heaters can quench a sufficiently large volume of superconductor, so that the magnet can survives without a dump resistor. Sufficient coil resistance during quench is the key protection parameter.

TABLE III
QUENCH HISTORY FOR THE MQXC(0)

Quench #	%ss	(Amps)	Coil	Stored Energy [KJ]	Miits	Helium bath temp (°K)
1	71.2%	11385	coil 3, Layer2	518	12.80	1.92
2	74.1%	11859.8	coil 4, layer 2	562	12.94	1.79
3	76.9%	12300	coil 1, layer 1	605	13.12	1.94
4	76.4%	12226	coil 3, layer2	602	13.28	1.86
Reached 12800A without quenching plateau for 30 minuets.						
Dump	31.3%	5000	coil 2, layer 2	100	2.61	1.93
5	78.4%	12538	coil 4 layer 2	628	13.53	1.95
6	82.8%	13249	coil 1, layer2	701	15.13	1.87

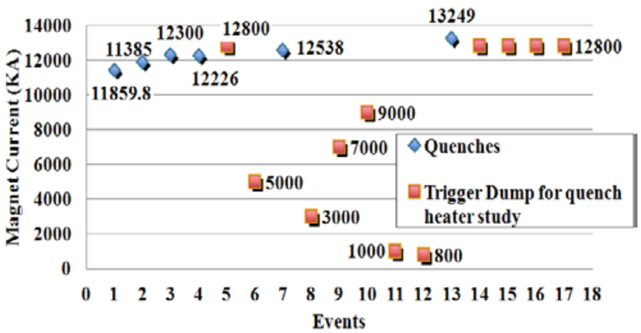

Fig 3.Test history of (natural) quenches and heater-triggered events.

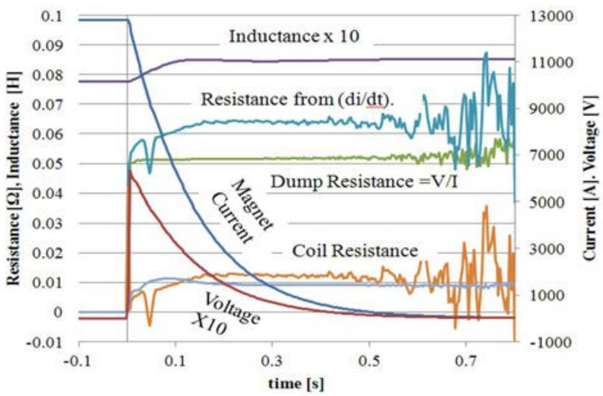

Fig. 4: Resistance versus time during the dump of the current on external resistor at nominal current.

A special test consisted of ramping to nominal, open the switch and disconnect the power supply and dumping the current into the external resistor. In a similar test, the Nb3Sn quadrupole HQ developed a resistance (quenched) due to the fast initial ramp rate [9]. In our case, we see a very limited development of resistance of about 10 mΩ, see Fig. 4. The coil resistance is estimated through a local fit of I versus t with an exponential – the time constant is the inductance divided by the resistance at that time:

$$R_{Coil} = ((L_{diff} \cdot dI/dt) / I) - (I/V)_{circuit}$$

D. *Differential Inductance measurement (L_{diff}).*

The inductance measurement is performed by ramping up and down from 80 A to 12800 A at the nominal ramp-rate of 11 A/s. The inductance was deduced for the inner and outer layers of coil 1 to 3 separately, for the inner and outer layer of coil 4 combined and for the full magnet, see results in Fig.5.

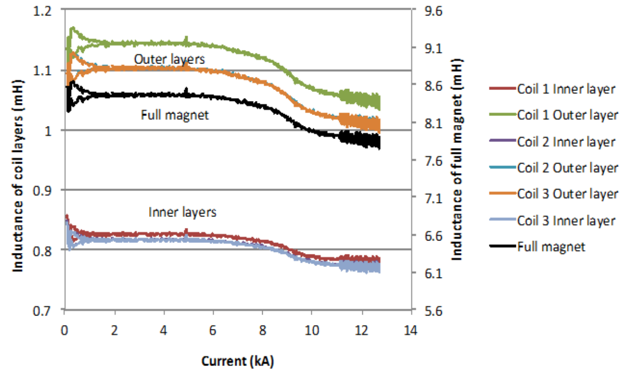

Fig 5. Measured differential inductance of the full magnet plotted on the right y-axis, which is scaled to the left axis by a factor of 8.

We see a hysteresis mainly between 80 A and 2 kA due to the magnetization of the filaments. Estimates through ROXIE [10] model are in good agreement with the measurements for the full magnet and show that the coil inductance is constant up to about 5 kA. Above 5 kA the inductance decreases due to saturation in the magnetic yoke.

When summing the inductance of the separate parts, the values do not add up to the full magnet inductance, because the voltage taps were wrongly installed forming a pickup coil and hence reducing the measured inductance. Additionally, inductances of 0.07 to 0.17 mH were measured with the voltage taps across inter-layer joints and inter-coil joints, which also indicate that voltages were picked up. In a next measurement the voltage taps will be changed such that the pick-up voltage is minimised.

E. *Quench heater performance*

The quench heaters are powered with a capacitor bank of 14.2 mF, charged with 400 V and with initial current of 40 A per circuit. This circuit has one heater element touching one side of all coils. A second circuit touches the other side of all coils, and is the reserve protection.

Heaters have been fired to estimate the delay of the induced quench. Time delay between heater firing and quench onset are given in Fig. 6, as a function of the operational current. At nominal current of 12.8 kA, one has a very short delay smaller than 10 ms.

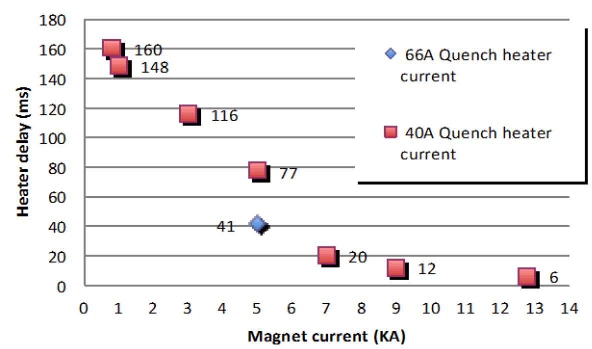

Fig. 6: Quench heater delays

The heaters were powered with 40 A, i.e. 50% of the design nominal value 80 A. We have some evidence that the magnet developed insufficient resistance to quench, recovering in about 0.1 s. At 5 kA we used 66 A in the heater circuit with no improvement.

F. Heat extraction tests using Beam Simulation Heaters.

The deposited beam heating profile was reproduced by flat heaters placed in the midplane between two poles, i.e., where the highest beam loss heat deposition is expected [11]. These heaters act on inner and outer layers. The same power was deposited, uniformly along the magnet length. Once the magnet current had been set to 12800 A, the heater power was stepwise increased. At a bath temperature of 1.97 K a power of 6.3 W/m was extracted from one coil for half an hour without experiencing resistive transition, whereas a quench occurred in the inner layer with a heat deposit of 7.7 W/m. At a bath temperature of 1.87 K a maximum power of 10.2 W/m was extracted from one coil, whereas the total power deposited in the 1.8 m long magnet was 67.7 W.

A numerical model is used to analyze the coil thermal behavior. It is based on the coupled mechanisms of steady-state heat extraction through the bulk of the dielectric insulation and through micro-channels between the insulation tapes [12].

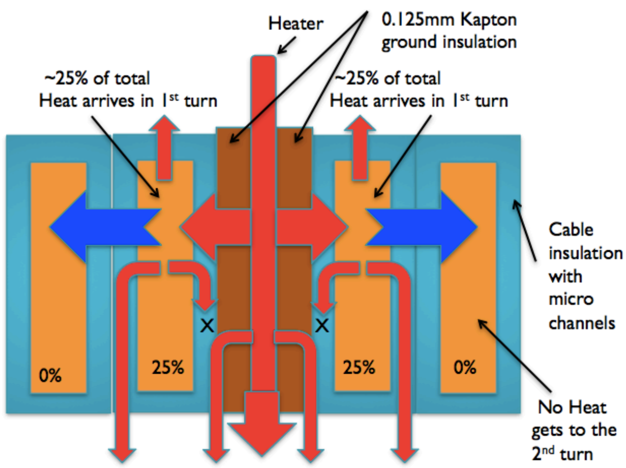

Fig. 2: Heat flow schematic from heater to cable then out to 1.9K bath.

The first calculations support the idea that a non-negligible amount of the heat deposited in the beam simulation heaters is short circuited to the bath through superfluid helium micro-channels. The remaining part, representing around 50% of the deposited heat, reaches the cables adjacent to the heaters and is subsequently extracted through their electrical insulation. It can be assumed that the amount of heat reaching the second cables away from the heater is negligible, as suggested from the dedicated thermal tests reported in [13]. In the above mentioned assumptions we can estimate that 50 mW/cm^3 can be removed without quenching the coil, at a bath temperature of 1.87 K. Such heat extraction is about 4 times larger than the 12 mW/cm^3 [14,15] estimated for the standard insulation, not far from what expected from simulations and measurements.

It must be noted that beam losses deposit heat directly inside the cable. Therefore we expect the heat extraction through the cable insulation to be more effective in case of beam losses than in our test, where the incoming heat blocked some helium channels. The assessment of these results will require further experimental and theoretical investigations.

G. Eddy-currentl losses

The eddy-current losses were characterized by averaging 10 cycles up and down between 100 A and 10 kA at ramp-rates up to 250 A/s The energy expressed in joules during one cycle is computed as the integration over time of the product of the current by the voltage across the full magnet. The loss is then the difference of energy before and after the cycle. The measured loss are P = 1.49 X + 265.8 where X denotes the ramp-rate in A/s. The maximum achieved ramp rate was 300 A/s, which did not quench the magnet. Ramp-rate quench studies will be done during the next test campaign.

V. Conclusion

A Nb-Ti, 1.8-meter long, 120 mm aperture, model quadrupole magnet, designed for high heat load extraction has been tested at CERN at 1.9 K. It reached nominal operating current of 12.8 kA within four training quenches. The room temperature field measurements reports field quality of a few units. The efficiency of magnetic shimming has been proved with room temperature measurements. The highlight of the test is the ability of the coil to operating at nominal current (80% margin on the load-line) with a 50 mW/cm3 of heat deposition. This validates the improved heat extraction of the insulation scheme proposed in [5].

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