LHC IR Upgrade Nb-Ti, 120mm Aperture Model Quadrupole Test Results at 1.8K

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Abstract **– Over the last five years, the model MQXC quadruple, a 120 mm aperture, 120 T/m, 1.8 m long, Nb-Ti version of the LHC insertion upgrade (due in 2021), has been developed at CERN. The magnet incorporates several novel concepts to extract high levels of heat flux and provide high quality field harmonics throughout the full operating current range. Existing LHC-dipole cable with new, open cable and ground insulation was used. Two, nominally identical 1.8 m long magnets were built and tested at 1.8 K at the CERN SM18 test facility. This paper compares in detail the two magnet tests and presents: quench performance, internal stresses, heat extraction simulating radiation loading in the superconducting coils, and quench protection measurements. The first set of tests highlighted the conflict between high magnet cooling capability and quench protection. The second magnet had additional instrumentation to investigate further this phenomenon. Finally we present test results from a new type of superconducting magnet protection system.**

Index Terms— **Accelerator magnets cold testing, Circuit modeling, Heat extraction, HL-LHC, Magnetic shimming, Manufacturing process, Quadrupole, Quench heaters, Quench protection system, Superconducting accelerator magnets, Superconducting coils, Tooling.**

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 Saclay 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 of the order of 500 W. This quadrupole, called MQXC [1-4] had the innovative feature of an 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 is still 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 about 8 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].

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II. MAGNET CROSS SECTION AND PARAMETER LIST

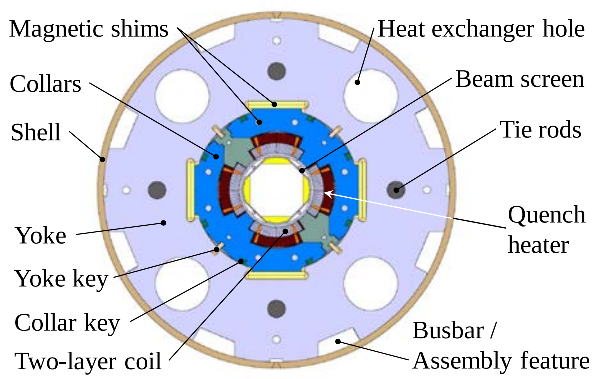

Fig. 1. MQXC cross section

In this paper, we present test results from the two model magnet tests. MQXC0 was tested during summer 2012 [8] and MQXC2 completed its first test campaign April 2013.

TABLE I
CABLES & MAGNET PARAMETER LIST FOR MQXC

Quantity	Magnet	Inner Cable	Outer cable	units
Operating current	12800			Amps
Operating gradient. HiLumi optics	118.05			G(T/m)
% short sample at operating point		79.33	76.09	%
Max field at nominal current		7.844	6.534	Tesla
Cable 100% short sample current		16137	16822	Amps
Max Gradient	147.2			G(T/m)
Field @ 100% magnet short sample		9.7984		Tesla
Nom. ramp rate +Ve & -Ve	11			A/s
Cu/SC ratio		1.65	1.95	#
Number of strands		28	36	#
Diameter of strand		1.065	0.825	mm
Operating temperature	1.9			K
Inductance / m at nominal current	4.78			mH/m
3 part Differential Inductance MQXC 1.8m model magnet, I = magnet current				
For I < 4 kA: L0 =8.46856				mH
For 4 <I<9 kA: L = L0*(1.037-2.257e-5*I+4.708E-9*I^2-3.470e-13*I^3)				mH
For I>9 kA: L = L0*(2.731 -4.573e-4 *I+3.908e-8*I^2-1.123e-12*I^3)				mH

These tests covered: training the magnet up to 1 kA above nominal operating current, quench heater delays, magnet heat extraction simulated by heaters in the midplane, a thermal cycle to see if the magnet retained its training, spot heater tests to try to measure magnet hot spot temperatures, and finally a number of tests using a novel magnet protection system which quenched the coil without quench heaters and could be applied to future LHC and other types of magnets. MQXC uses LHC dipole cable with new porous polyimide insulation, open ground insulation, self-supporting stainless steel collars, and a set of magnetic shims that can adjust the field harmonics by 2-3 units of $x10^{-4}$. The models are intended to be fully compatible with the LHC accelerator (See Fig.1), although extending the magnet length from 1.8 m to ~ 9 m would need tooling development. Table 1 lists the magnet parameters and measured cable performance of the superconducting cable used in the construction of the two model magnets.

III. Magnet Test

A. *Training & test overview*

The MQXC2 magnet reached nominal current after five training quenches, identical to the first model MQXC0 [8].

TABLE II

TRAINING HISTORY FOR MQXC2				TRAINING HISTORY FOR MQXC0	
Event #	Training Amps	De-Training Amps	Quench location	Training Amps	Quench location
4	**10850**		coil 3, outer layer	**11385**	coil 3, outer layer
5	**11485**		coil 3, outer layer	**11860**	coil 4 outer layer
6	**11733**		3 outer layer jump?	**12300**	coil 1 inner layer
7	**12146**		coil 3, outer layer	**12226**	coil 3, outer layer
8	**12404**		coil 7 outer layer	**12538**	coil 2 outer layer
9	**12802**		coil 8 outer layer	**13249**	coil 3 inner layer
10	**12911**		coil 3, outer layer		
28		**12218**	coil 8 outer layer		
29	**12791**		coil 8 outer layer		
37	**13118**		coil 3, outer layer		
38	**13459**		3 outer , & joint		
44		**13366**	coil 7 outer layer		
45	**13450**		coil 3, outer layer	*Thermal Cycle*	
63		**12652**	coil 3, outer layer		
64	**13001**		coil 3, outer layer		
82		**12500**	coil 7 outer layer		
83	**13436**		coil 3 joint then outer		
86	**13625**		coil 3, outer layer		
93		**13158**	coil 8 outer layer		
94	**13740**		coil 7 outer layer		

The first 4 quenches were close to or in the layer jump area of coil 3, and then quenches began moving between coils. After the thermal cycle MQXC2 needed one quench to return to nominal current. In Table II, we see several de-training quenches. One was due to the thermal cycle. The other 4 occurred just after violent events, induced during testing the heat extraction and new protection system CLIQ [9].

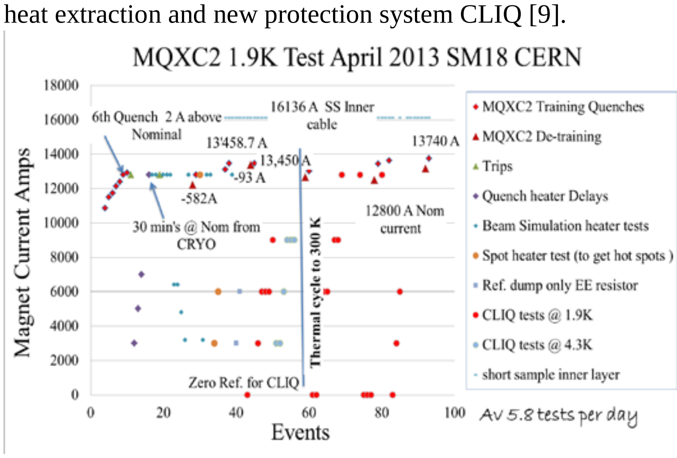

Fig. 2. Three weeks test overview, one week thermal cycle.

The average increase in current during training was 344A. The maximum training current achieved so far is 13,740 A, 85.2% short sample at 1.9 K inner cable, 940A over nominal operating current. During the next test campaign, the magnet will be trained to plateau. The majority of the testing was: quench heater delays, heat extraction, attempts to measure cable hot spots, and testing the new protection system CLIQ (Fig. 2).

B. *Quench heater delays*

The quench heaters were designed for a max current of 80A. Unfortunately the test equipment only delivered 40A then later after reconfiguring, we reached 66 A in a few tests.

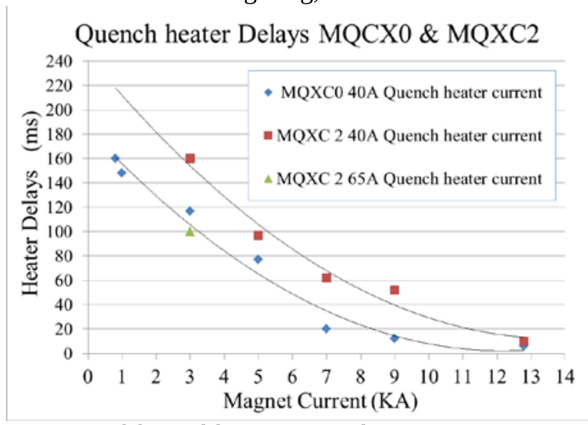

Fig. 3. Quench heater delays MQXC0 and MQXC2 at 40A

At nominal current the quench heater delay was similar in both MQXC0 and MQXC2. However at lower current MQXC2 has a consistently longer delay, as shown in Fig.3. The difference is due to a modification in the ground insulation. The delay is only part of the story for the quench heaters. Finally we are looking to quench a large volume of conductor and develop sufficient coil resistance to limit hot spot temperatures in the coils. In the next set of tests the dump resistor will be delayed to reveal the resistance developed in the coils, and so the full effectiveness of the quench heaters.

C. *Measuring hot spot in the magnet*

Most magnet hot spot temperatures are calculated using a conservative adiabatic approach. However with the high heat extraction needed for the MQXC magnet design we decided to try to measure the hot spot temperatures. We developed a spot heater that was tested at 4 K and 2 K that was then mounted on the layer jump in the inner high field turn. This was powered with a pulsed power supply containing a 10 mF, capacitor charged to 80 V, a set of voltage taps either side of the heater and a fast 2 to 3 ms response CCS type temperature sensor was also mounted near the heater [10].

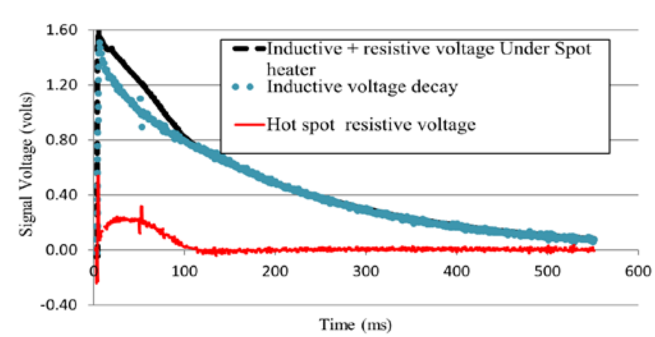

Fig. 4. Magnet current 9kA, spot heater induces quench recovery due to cooling after 100 ms. Dump delay 2 ms after breaching 100mV threshold.

Unfortunately the wiring to the temperature sensor was damaged during the magnet collaring process and we lost both temperature sensors. Using the voltage signals from the taps both sides of the heater, we hoped to estimate the hot spot in the cable from the copper resistivity. The main protection for the magnet during the tests is energy extraction using the dump resistor. When the dump is switched into the circuit the voltage noise conceals the signal from the small hot spot section of cable so we decided to delay the switching of the dump resistor as a function of the magnet current to reduce this noise. However at high currents to be able to protect the magnet we could not delay the switch. Consequently we can only see clearly events under 9 kA. In Fig.4, we measured voltages in the section of cable under the spot heater. In this example, due to the cooling, the quenched volume recovers. The dump resistor dominates this event. For long magnets protected with quench heaters we rely on the coil resistance generated to spread the heat and reduce the current. More testing is needed to confirm that the quench heater can develop sufficient resistance to protect the long magnets. Firing heaters at the full 80A we hope will improve protection results.

D. Brief summary of other results from MQXC0 & MQXC2.

During cool-down the temperature difference between the top and bottom of the magnet was maintained at 180 K. The magnetic field was only measured at room temperature, revealing an error of a few units [11-12]. We will fully map at high current the field quality in the next test campaign. The differential inductance was measured at 11 A/s and 50 A/s both identical to MQXC0 values, see Table I & [8]. Eddy current measurements revealed similar MQXC2 losses between 1 kA to 5.5 kA loss P [J]=230+1.25 x dI/dt [A/s] & 5.5 kA to 10 kA [J]=130+1.25 x dI/dt [A/s], MQXC0 [J]= 265.8 + 1.49x dI/dt [A/s], losses are mainly due to inter-strand coupling losses [8]. MQXC2 RRR was on average 252.7±98, MQXC0 average was 228.0±6; the differences could be due to cables histories. The joint resistances: MQXC0 0.35 nΩ with a standard deviation of 81 pΩ, MQXC2 0.582 nΩ with a standard deviation of 968 pΩ. An average of 5.8 tests per day were performed, 1.9K temperature recovery was achieved after 2hrs cooling.

E. Coil stress measurements

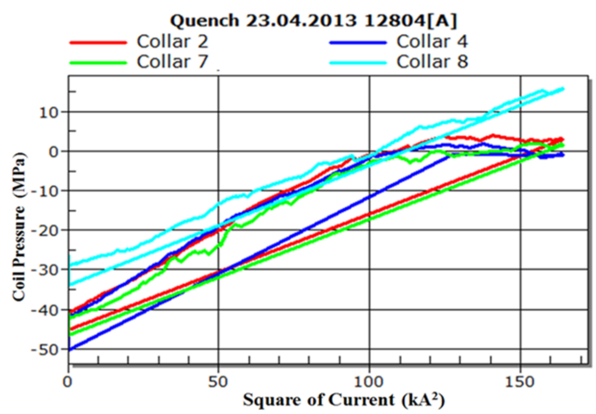

Fig.5. Example stress measurements on all poles, inner and outer layers. Collar 4 unloading at 149 kA^2 (12.2kA). Heater induced quench @ 12.8 kA (164 kA^2).

The stresses of the inner and outer layers for all four poles were continually measured throughout the testing. The unloading of collar 4 on coil 7 inner layer did not result in training quenches. Most training was in the outer layers. In Fig.5, the straight line is pressure reduction in coil 7 inner layer; we see a clear flattening out of the pressure at 11.2 kA. Then a heater induced quench at 12.8 kA, the ragged line is the hysteresis of the fast reloading of stress as the magnet current drops to zero.

F. Heat Extraction simulating beam heating

Steady-state heat extraction from the magnet was measured using the so-called Beam Simulation Heaters (BSHs). They consist of flat heaters located between the mid-plane cables for the whole magnet length, allowing to transfer heat to such cables which are the most exposed to beam loss [13]. The testing procedure consists of energizing the magnet to nominal 12.8 kA, then stepwise increasing the power in the BSH by 10% steps until a quench occurs.

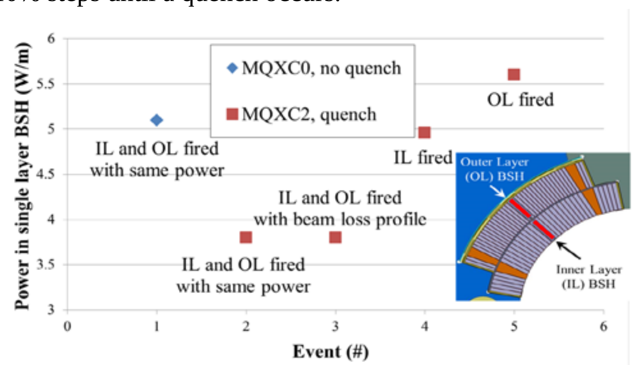

Fig. 6. Power deposited in Beam Simulation Heaters (BSH), at 1.9 K and at the nominal current of 12.8 kA. Different heating configurations are compared.

Fig. 6 summarizes the heat extraction tests carried out at 1.9 K at a current of 12.8 kA. The y-axis refers to the power deposited in the Inner Layer (IL) BSH of one coil (see insert), except for event 5 where the power was deposited in the Outer Layer (OL) BSH. The first event refers to MQXC0. It withstood a power deposition of 5.1 W/m without quenching, while firing both IL and OL BSHs with the same power. However part of the heat is short circuited to the bath via He II micro-channels through the cable insulation. First calculations estimate that 50 mW/cm^3 reach the cables [8]. Such heat extraction is about four times larger than the 12 mW/cm^3 threshold estimated for the LHC magnets.

In the same conditions, MQXC2 featured a smaller heat extraction (event 2). This is probably due to a change of the midplane insulation, which was modified to avoid short circuit between cables. Event 3 reproduces the radial profile of the beam induced heat deposit, i.e. 3 times more power in the IL than in the OL BSH. No differences were observed with respect to event 2. An improved heat extraction is measured instead when the boundary conditions are drastically changed. This is the case of firing only the IL or the OL BSH (events 4 and 5), and demonstrates a good heat extraction through the open ground insulation. Quenches were located in high field zones.

A more detailed analysis of the results, where a numerical model is used to reproduce the coil thermal behavior, is reported in [15-19].

IV. Coupling-Loss Induced Quench System

An innovative magnet protection system was tested on the MQXC magnet, based on a capacitive discharge system injecting AC current into the middle of the magnet and inducing an oscillation change in its transport current. The resulting fast change of the magnetic field induces high inter-filament and inter-strand coupling losses, which, in turn, develop heat directly inside the cables. This coupling-loss induced quench (CLIQ) system, described in detail in [9] and [19] has the capability to initiate the quench in a large portion of the coil winding pack, thus distributing more homogeneously the energy dissipated during the quench process and quickly reducing the magnet current.

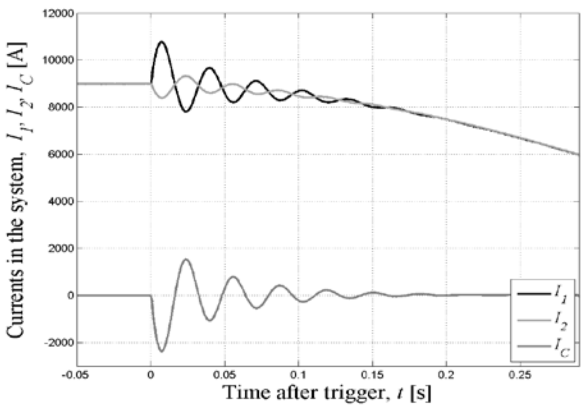

Fig.7. Measured current discharged by the CLIQ system, I_C, measured current I_2, and calculated current I_1=I_2-I_C, after the triggering of the CLIQ system when I_0=9 kA.

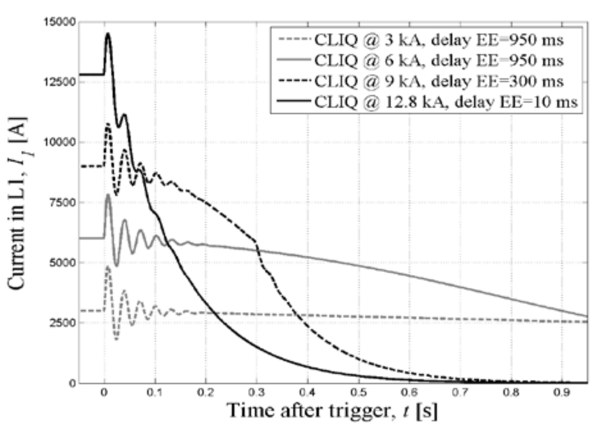

Fig.8. Comparison between the current I_1=I_2-I_C after the triggering of the CLIQ system with 28.2 mF at different current levels (U_0=500 V). For clarity we only plot one half of the magnet circuit, in the Y-axis L1 refers to this side where the current in the coils is initially positive.

The four MQXC poles were powered in series. The CLIQ system, featuring a 28.2 mF, 500 V capacitor bank, discharged a current through a current lead connected between one pole and the other three, thus injecting a current with opposite polarity in the two sides of the magnet. Fig. 7 shows the measured current discharged by the CLIQ system and the resulting current in the two magnet sides. The current change in the three series poles is about 3 times smaller than the current in the single pole due to the larger impedance of this branch. The coupling losses induced in the magnet cable were large enough to develop a quench resistance of about 25 mΩ after 300 ms. Fig. 8 shows the current profiles measured in four separate CLIQ tests at different current levels. In this early stage of the testing of the system, an energy-extraction system was triggered with a delay short enough to assure the magnet protection in case of a failure of the CLIQ system. The test results show that the quench resistance developed by the CLIQ system was large enough to effectively discharge the current of the magnet and protect it against damage due to overheating. Several tens of quenches have been induced using the new proposed method showing excellent reproducibility. A more detailed analysis of its performance is presented in [9]. The CLIQ system is very promising because it has the potential to effectively reduce the hot-spot temperature in a magnet by rapidly quenching a large fraction of superconductor, thus allowing a more homogeneous heat distribution in the magnet cables. It deposits more heat in the inner region of the magnet, where a natural quench is more likely to occur. Its robust electrical design makes it preferable to other protection systems, such as quench heaters, which bear significant risk of insulation beak-down. The CLIQ system can be implemented as an effective back-up solution on a magnet with failing quench heaters without the need of expensive repair work. Alternatively, the CLIQ system may be used together with conventional quench heaters in a high-performance hybrid protection system [14].

V. Conclusion

The second MQXC model has been tested at CERN at 1.9ºK. It reached nominal operating current 12.8 kA in five quenches. Heat extraction tests show that the magnet is able to withstand the predicted heat loads with margin. Quench protection is still a concern due to the high heat extraction capability in the coils. Further testing is planned: to further explore the quench heater performance, training the magnet up to a plateau, and completing the magnetic field measurements on the second model magnet MQXC2. A new Coupling-Loss Induced Quench System "CLIQ" has been tested, and demonstrated good potential to replace the classic quench heater technique in many future superconducting systems.

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