TESTING OF THE LHC MAGNETS IN CRYOGENIC CONDITIONS: CURRENT EXPERIENCE AND NEAR FUTURE OUTLOOK

V. Chohan, M. Buzio, G. De Rijk, J. Miles, P. Pugnat, V. Remondino, S. Sanfilippo, A. Siemko, N. Smirnov, B. Vullierme, L. Walckiers, CERN, Geneva, Switzerland

Abstract

For the Large Hadron Collider under construction at CERN, a necessary and primordial condition prior to its installation is that all the main twin-aperture dipole and quadrupole magnets are tested in the 1.9 K cryogenic conditions. These tests are not feasible at the manufacturers and hence, are carried out at CERN at a purpose built facility on the site. This presentation will give an overall view of the issues related to the operation of the test facility. In particular, it will give the goals that need to be met to ensure the magnet integrity and performance and the context & constraints on the test programme. Results accumulated from the tested magnets and the ensuing tests stream-lining will be presented, together with some explanations and hard limits. Finally, some improvements planned for efficient operation will be given within the confines of the testing programme as was foreseen and the project goals and deadlines.

GOALS & MEANS

The rate of the cold tests of the dipole and quadupole magnets is currently increasing to meet the magnets delivery. In parallel the construction & commissioning of all the 12 purpose-built test benches was completed in May 2004. The goals are to cryogenically and electrically test the 1732 cryo-magnets: 1232 Dipoles to operate at 8.33 T nominal field and 386 standard cell Short Straight Sections (SSS) equipped with quadrupoles of 223 T/m nominal gradient. These values translate to a current of 11850 A. In addition 114 insertion region SSS's will require more specialised testing schemes [1]. All dipole & quadrupole magnets are tested for field quality at room temperature at the manufacturers but the cryogenic and electrical integrity for the LHC requirements can only be tested at CERN due to the cryogenic needs. We envisage to measure the field quality of a sufficient sample of all these magnets at cold in order to correlate these with the factory measurements done at room temperature and to accumulate enough knowledge on the dynamic effects expected to perturb significantly the LHC injection. The SSS testing is in early stages while significant progress has been made for the dipoles through close scrutiny and reviews to arrive at a relatively stable but necessary tests programme, dealt briefly in this paper.

During 2003, the delivery rate of the dipole cold masses increased steadily and was matched by the setting up of the round-the-clock tests operation, operation of the cryogenic infrastructure, callout equipment support, structured supervision for operation and so forth. Eight test stands out of the twelve foreseen were in completed phase of construction by end-2003. As that year progressed, the dipole tests programme was thoroughly examined several times to a stream-lined level of today, with completed training programme and the field quality measurement for 95 dipoles by the end-2003. The year 2004 has seen further progress and to date ~170 additional dipoles have been tested cryogenically and electrically, with only a sample of these tested for field quality.

THE COLD TESTS PROGRAMME

Tests Phases & Cryogenics

The cryogenic system currently cools down the magnets from ambient to 90 K in 12 h by circulating gaseous helium through a heat exchanger cooled with liquid nitrogen. The 2nd phase to reach 1.9 K takes further 14 h. The warm-up phase duration is nominally 12 h [2].

Cryogenic infrastructure permits us to have at the same time only one magnet in each of the two cool-down phases (300K-90 K, 90 K-1.9 K) and one magnet in the warm-up phase (last quench to 300 K). In addition, the cryogenic limits us to 3 dipoles being cold at 1.9 K, with a further capacity constraint of not exceeding 9 recoveries of high field quenches or initial cooling from 4.2 K to 1.9 K per 24 h. All these requirements impose significant sequencing constraints in the testing regime with multiple benches and different stages of connections, cool-downs, cold tests, warm-ups and disconnections. A detailed study at end-2003 of the duration of the various phases of the test cycle was carried out and showed that an average of 240 h were needed for the full test cycle instead of the nominal 108 h foreseen.

The nominal cold test duration without field quality measurements of 28 h is based on two high field quenches: this is the minimum needed to detect insulation breakdowns in nominal conditions of the Lorentz forces and the thermal gradient. The training quenches take place only after the preparatory 11 hrs that are required to measure the leakage current at 3.5 kV, verification of the proper functioning of the protection heaters and setting-up of the instrumentation, particularly, for quench localisation and magnetic measurements. After high field training, the presently stream-lined magnetic measurements are launched, lasting about 6 hrs and give the magnet strength and field multi-poles in static conditions as well as during the nominal current ramp for the LHC from injection to the collision energy.

Some 90 pre-series dipoles were tested up to end-2003 with an extended programme. They required an average of 3.2 quenches to reach 9 T (12850 A). For series production, it was foreseen to arrive at 9 T in 2 quenches. In fact, the manufacturing contract stipulates that a dipole should attain 9 T after a maximum of 8 quenches. For pre-series magnets needing more than 5 quenches to attain 9 T, a thermal cycle and a second run of tests were prescribed. On average, these additional tests added 18 hours to the total duration. Furthermore, 27 hours were desirable for special tests or were due to the logistics of shafts insertion/removal, as required for the quench localisation and magnetic measurement.

One must also include the magnet connections and removals in overall bench occupancy for cold tests. The duration for the removal and connection of the dipoles to the Cryogenic Feed Boxes (CFB) lasted about 60 hours in 2003 because of the restrictions in the associated industrial support contract for this work. The situation has significantly improved since and will reduce to 24 hours per magnet once these difficulties are resolved. The connection phase of work also includes the verification of the instrumentation present in the dipole and the measurement of the leakage current to ground at 500 V. Several unacceptable current leaks were found and repaired on the test stands whenever possible, i.e., in the instrumentation feed box (IFS) bringing the instrumentation and the protection heaters taps outside the cryostat. A thorough leak search is performed afterwards on both the cold mass helium enclosure and the outer vacuum chamber ensuring the thermal isolation of the cryostat. The finding and consecutive repair of numerous leaks resulted in an averaged loss of 17 hours but gave the relevant experience for improved future efficiency.

Test rates

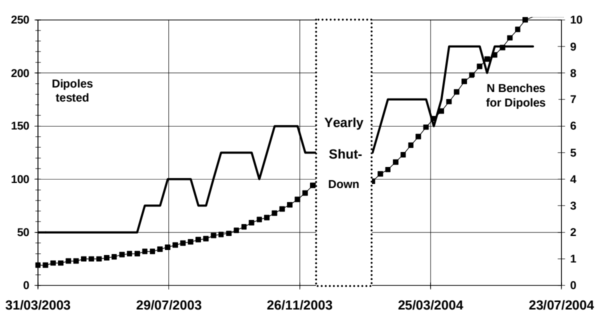

Figure 1: Test rate and dipole test benches availability from March 2003 to June 2004.

Fig. 1 shows the test rate obtained so far together with the benches available for the dipoles. The stream-lining proposed at end-2003 and implemented in 2004 in limiting the training of well performing magnets to 2 quenches up to 12000 A (8.4 T), the sampling approach in field quality evaluation [3] and the use of proficient tools in operation [4], [5] & methodologies of working explain the substantial progress in 2004. A typical performance of one dipole tested per bench per week is often surpassed for weeks without technical problems.

Improvements foreseen

The following steps are underway during or by the end of 2004 to enable the overall test cycle to be completed in the nominal 108 hours.

- Round the clock work & including weekends for the dipole removals & connections as well as for the field quality equipment insertions/removals
- Improvements in Cooling-Warming-Unit (CWU) for the removal of water accumulated over several tests in the super insulation of the CFB's.
- Equipping the vacuum chamber pumps with automatic removal of the water accumulated in the super insulation.
- Increase in the mass-flow rate of gaseous helium from 100 g/s to 150 g/s for each of the 2 circulation compressors.
- Installation of a 3rd 150 g/s circulation compressor for redundancy during the cool-down and warm-up.

Test rates desired

The completion of these improvements is essential to reach the desired test rate using 9 of the 12 test benches operated with reasonable sequencing, yielding 2 tested dipoles and standard cell SSS per day and on the basis of 9 slices of 12 hours per magnet:

- Installation / Removal: 2x12 h
- Set-up/pumping: 12 h
- Cool-down to 1.9 K: 12 +14 h
- Cold tests with Training+ Mag.M'ments: 34 h
- Warm-up: 12 h

A 20 % margin exists on the cold test duration if one assumes that most dipoles will not need more than 2 high field quenches.

The three remaining test benches will be dedicated either for magnets requiring further testing or the 114 dispersion and matching section SSS's. The above figures do not permit any mishaps in test equipment and operation if LHC installation deadlines are to be met. This then leads us to a constant vigil in the tests programme and further streamlining, if feasible.

BRIEF OVERVIEW OF TESTS RESULTS

Electrical and training performance

Table 1 illustrates as an example some 33 dipoles out of 98 with non-conformities of varying degrees of importance. Training quenches giving rise to poor performance are always located in the coil ends. Of the accepted magnets, all attained 9 T in the first run. 36 of the accepted dipoles were powered during a second run after a thermal cycle to room temperature. As expected, these dipoles generally reached the equivalent current value of the first quench of the first run without a quench. However 35 % of them did not reach the value of the second quench of that first run. Therefore, it is expected that some magnet training at the commissioning of the LHC will occur for magnets that did not reach the nominal 8.3 T at their first current excitation.

Table 1: Examples of rejected & accepted magnets & non-conformities

Examples of Rejected Dipoles & reasons	
2002	Insulation fault in QHeaters at cold.
1005	Unacceptable performance – Cold welds in the cable.
1019	Short circuit in QHeater YT112/ ground.
3004	Coil D2 locally burnt due to insulation fault.
3003	Short circuits in QHeaters YT221/coil and YT221/ground.
1026 & 2023	Unacceptable training performance.
Examples of accepted Dipoles & types of non-conformities observed	
▪	Continuity failure of Q Heater YT222 during cold tests.
▪	Insulation Break of Q Heater YT212/ground at cold at 1900V.
▪	Vtap failure @ cold on IFS box – Repaired.
▪	Leakage curr. of Q Heater YT222 circuit on IFS box – Repaired.
▪	Q. heater circuit opened @the IFS box – Repaired.
▪	Q. heater circuit opened @the IFS box – Repaired.
▪	Electrical fault on the IFS cable (TT821) – Repaired.
▪	Several with insufficient training performance
▪	The quench performance at 4.52 K below expectation. *(Hence, install in a place with low beam loss and temperature margin)*
▪	Insulation fault detected at cold on IFS box – Repaired.
▪	Insulation fault detected at cold on Vtaps – Repaired.
▪	Several with Leak at the foot of the cryostat - Repaired.
▪	Vtaps opened up after the final warm-up
▪	Several with Temperature sensor out of order (*Use as it is)*

Field quality in cryogenic conditions

Field quality measurements are technically delicate. Following the analyses of data accumulated on the pre-series dipoles [3], it is envisaged to do field quality measurements only on ~30% of the dipoles, enough to enable the control of the remaining dipole production. Measurements are carried out in all accelerator conditions at several current levels, in particular at the injection plateau (760 A, 0.54 T) and at nominal collision plateau (11850 A). To date, the field quality of 112 dipoles has been measured using 15-m long rotating coils [6]. The population was made up of dipoles with three different cross-sections: 29 dipoles with the initial one, 73 magnets with the second (small change of the copper wedge dimensions) and 10 magnets with a third one (additional insulation layer in the coil mid-plane). Early in production, the conflicting requests of good field quality and sufficient pre-stress resulted in the average sextupole and decapole contributions largely outside the specifications [7], leading to the two times change in the coil cross-section. The streamlining of the average dipole symmetry multipoles (b3, b5, b7) is now considered to be satisfactory [7].

The reproducibility from magnet to magnet of the integrated transfer function (Field/current relationship) is currently considered the most difficult to meet with the planned beam orbit correction scheme. Fig. 2 shows the evolution during production of the integrated transfer function of the dipole field, measured at the collision plateau. The average of the integrated transfer function falls within the permissible window. The higher transfer function measured at the beginning of the production originates from the non nominal shimming of the early dipoles. The spread observed among the magnets tested at cold amounts to 6 10^{-4} at collision, staying close to the specified [8] r.m.s. limit of 8 10^{-4} and correlates with the differences observed in the collared coils transfer function between the manufacturers [7].

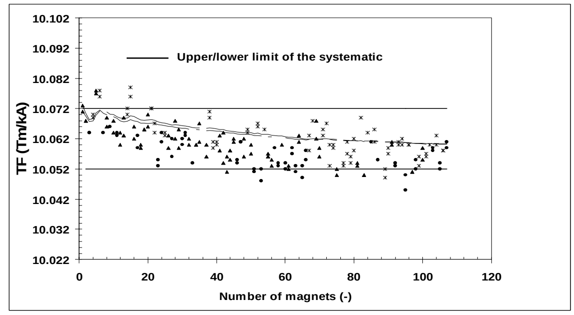

Figure 2: Integrated transfer function measured at nominal field as compared to the upper/lower limits for the systematic [8].The solid lines are the cumulated average for aperture 1 and aperture 2.

The measured systematic skew and even normal multipoles are within the targets at both operation fields. The normal sextupole b_5 at injection is on the upper edge of the target and the normal sextupole b_3 (at nominal field) and the b_7-multipole are outside the specifications [8] because the number of dipoles measured at cold with the third cross-section in which these defects are corrected is not yet sufficient to influence the statistics collected so far. The random part of the multipoles is within the targets imposed by the beam dynamics apart from the sextupole, decapole and b_7-multipole which are larger or at the limit of the specifications. This originates from the mixture of the different cross-sections and the use of the non nominal shims in first pre-series dipoles to compensate for the variations in coil sizes.

CONCLUSIONS

The LHC Magnet Tests are now fully underway with a stream-lined dipole tests programme & strict deadlines. These may even be somewhat mitigated if the quench characteristics improve as the dipole production progresses, as well as the other cited improvements in cryogenics.

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