

Commissioning of the Low- β Triplets of the Large Hadron Collider

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Abstract—The low- β triplets of the Large Hadron Collider were designed and constructed by a world-wide collaboration officially formed in 1998. Over the course of the following years the collaboration worked to produce the triplet components, including four 215 T/m, 70 mm aperture quadrupoles, a DFBX distribution feedbox, and at the low luminosity interaction points a cold D1 beam separation dipole. In 2005 the first triplet was installed in the LHC tunnel, and at the end of 2007 hardware commissioning of the first triplets started. As of August 2008 five triplets have been successfully powered. This paper documents the processes and experience gained during the commissioning phase of the LHC.

Index Terms—LHC, InnerTriplets, quadrupole

I. INTRODUCTION

THE low- β triplet systems located on either side of each interaction point (IP) of the Large Hadron Collider (LHC) are composed of four main quadrupole magnets (MQX), a beam separation dipole magnet (MBX), five corrector magnet assemblies (MCBX (2), MCBXA, MQSX, MCSOX), and a distribution feed box (DFBX) that supplies cryogenic, power, and instrumentation connections for all of the elements (Fig. 1). The triplet system design, prototyping, and production was completed through a collaboration of institutes and industries in Japan, the United States, and Europe [1, 2, 3].

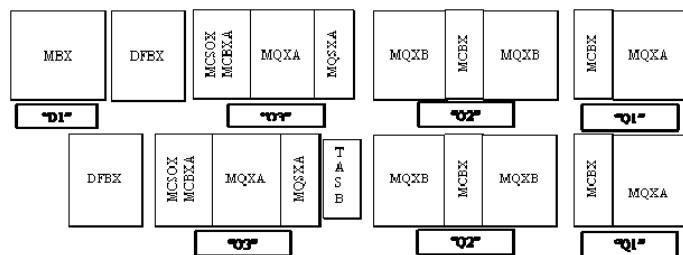


Fig. 1. Superconducting magnets and related components for the low luminosity interaction points (top) and the high luminosity interaction points (bottom) of the LHC.

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The conductor used throughout the magnetic elements is Nb-Ti, in Rutherford-type cables for the MBX and MQX and ‘ribbon’ cable for the correctors. Powering is provided for the MQX through three nested power converters while the MBX is run on a separate large converter. The steering dipole and skew quadrupole correctors are run by individual bipolar 600 A power converters; the smaller correctors through individual 120 A circuits.

The transition from cryogenic to room temperature powering components is made at the DFBX, through four or six pair (depending on whether the D1 is superconducting (MBX) or conventional (MBW)) of 7.5 kA HTS leads for the main circuits, and fourteen 600 A and ten 120 A vapor cooled conventional leads for the rest.

All triplet superconducting magnetic elements operate at 1.9 K; the DFBX also provides connections to all cryogenic utilities including the steady state 1.9 K supply and return, shield flows, and connections for cool-down and warm-up and other transient conditions.

The first triplet installation in the LHC tunnel started in December 2005 at the left side of IP8 and the hardware commissioning of this triplet began in November 2006.

II. MECHANICAL COMMISSIONING

As for all components of the LHC, the triplet systems undergo a thorough and systematic check before being brought up to full power. In the case of the triplets, these tests revealed several flaws that needed time for replacement and/or tuning of the triplet systems.

In November 2006 a pressure test, one of the first safety tests associated with commissioning of any installed LHC component, revealed a production flaw in the joint at the end of the copper corrugation used as a heat exchanger in the quadrupole magnets. This heat exchanger is larger than those in the rest of the LHC due to the high local dynamic heat load seen during operation from particle debris generated by collisions at the IPs. Under normal operation, the corrugation provides a channel for sub-atmospheric helium II to flow, and a wall across which heat exchange can occur with the magnet pressurized helium II bath. Nominally the magnet bath operates at 1 bar; however, pressures of up to 17 bar are used during cool-down, and the quench relief valves are set at 18 bar. The magnet helium vessels are thus designed to 20 bar, and require a safety test pressure of 25 bar. During the pressure test at IP8 Left, the corrugation collapsed at about

12 bar. During the next two months tests were run at both Fermilab and CERN, and new corrugations acquired. Replacement of the new heat exchanger corrugation started in late January 2007.

Unfortunately, the failure at the lower test pressure masked a more serious flaw revealed during the March 2007 pressure test at IP5 Left. During the ramp to test pressure, at 19 bar the internal supports of the Q1 magnet cryostat failed due to the longitudinal pressure load caused by the asymmetry of the ends of the magnet helium volume; the end closest to the interaction point has no bellows, while the end away from the interaction point includes multiple large bellows.

Further inspection showed that the Q3 cryostat supports had also been damaged due to similar loads though in the opposite direction; in addition later inspection showed that the onset of failure was seen in the Q1 supports from the original test at IP8L. In addition smaller separate problems were discovered in the DFBX design.

A means to react the longitudinal loads properly, in a manner consistent with installation in the tunnel was required. Joint efforts at CERN and Fermilab, with input from LBNL, BNL, and KEK developed several potential solutions. At a meeting in late April 2007 it was decided to pursue and fully develop the “cartouche” solution, a re-entrant cylinder and rod utilizing the differential thermal contraction of Invar and aluminum to create an extremely rigid system to react loads while following the relative motion of the cold mass to the vacuum vessel during cool-down. Design details were finalized and procurements started immediately through both CERN and Fermilab; the first pieces arrived at CERN in late May; and by mid-June proof testing was complete. In early July the first retrofitted triplet at point 8R was successfully pressure tested in the tunnel. By the end of August 2007, through the extensive efforts of all personnel, the consolidation of all magnets and DFBX were completed. The remaining pressure tests were all successfully completed in accordance with the overall LHC commissioning planning, the eighth and last triplet at point 5L in March 2008.

III. CRYOGENIC SYSTEM

A. Cryogenic Schemes

The cryogenic distribution system of the triplets and DFBX are similar to the LHC stand alone magnets and DFB systems, respectively [4], and can be operated independently from the rest of the LHC arc magnets. Supercritical helium supplies the DFBX liquid helium bath and the triplet magnets through a cool-down valve from the LHC sector common header C. The DFBX liquid helium bath is separated from the triplet and D1 superfluid helium baths at 1.9 K by lambda plugs. Saturated superfluid helium from header B flows through the corrugated copper heat exchanger: in the quadrupoles this heat exchanger is external to the magnet but inside the cryostat; in the D1 the heat exchanger is inside the magnet yoke similar to the remainder of the LHC. The heat exchanger is sized to extract the static and dynamic heat deposited in the helium pressurized superfluid bath. The measured static heat load in a triplet is 46 W, in good agreement with design calculations; at

nominal luminosity and energy the dynamic load will be close to 200 W.

Figure 2 shows the flow schematic of the DFBX, triplet and D1 for low intensity LHC interaction points (IP2 and IP8). For clarity, the thermal shield, beam screen, plug-in module (PIM), and quench relief circuits are not shown. Quench relief valves prevent the magnet pressures from exceeding 18 bar, relieving the extra pressure to header D (also used as the cryogenic recovery line).

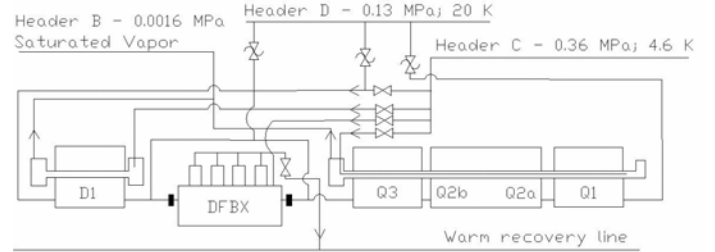


Fig. 2. Flow schematic of the triplet, D1 and DFBX at IP2 and IP8.

B. Cryogenic Operation

Although the operating procedure of the triplets is based on the logic used for the arc magnets, special attention was given to the cool-down and warm-up criteria. Aside from the specifics of the triplet cryogenic scheme, special attention was taken to prevent damage of the PIMs due to differential thermal contraction of components in the triplet assembly. A typical cool-down time for the triplets is of the order of one week, and is typically staged. The quadrupole and dipole magnets are first cooled down to 20 K as permitted by the sector cooling capacity. Once the DFBX check out is completed, the magnet cool-down is resumed together with the cool-down of the DFBX.

After validation of the quality assurance of each of the circuits through the system, the DFBX is filled with liquid helium. Specific criteria on the helium liquid level, lead temperatures and pressure allow the cryogenic operation and magnet powering phases (cryo-start and cryo-maintain).

C. DFBX Description

Figure 3 shows a typical cross section of a DFBX. As previously mentioned, the DFBX provide power to the triplets and the cold D1 through HTS and vapor cooled low current leads. The DFBX cryo-instrumentation and valves allow the user to monitor and control the pressure, temperature, liquid level, and cryo-heaters. About 60 different control loops are used with either PLC or local control loops to operate the cryogenic system. Electrical flag heaters controlled by local thermo-couples are installed on each vapor-cooled and HTS current lead.

The individual cooling of each of the 7.5 kA HTS power leads is controlled by an electro-valve, which uses as process variable a temperature sensor located on the cold side of the HTS lead. In order to permit the proper HTS operation and to limit the heat load to the DFBX the valves regulates at 50 K.

The 600 A and 120 A current leads are vapor-cooled by the boil-off generated inside the liquid helium tank. The

individual cooling of each vapor cooled lead uses similar valve control loops and was originally expected to be controlled by a mass-flowmeter. However in the final implementation this was not possible, and a consolidation effort followed.

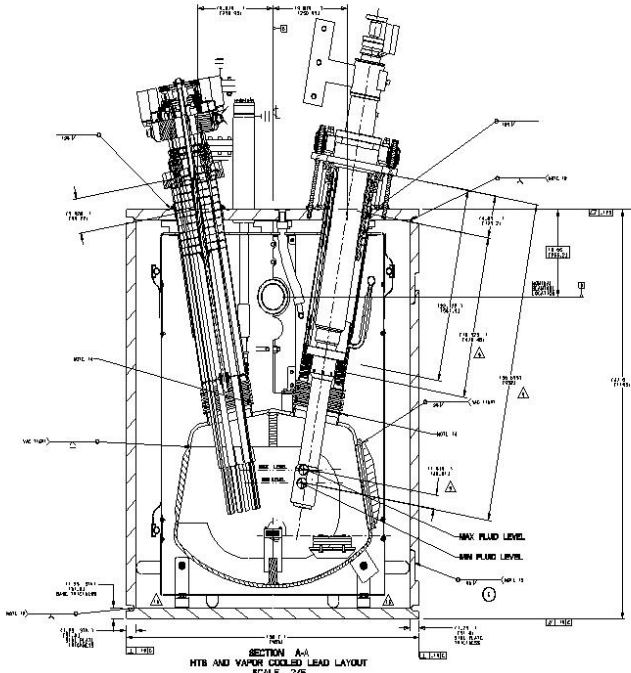


Fig. 3. DFBX cross section showing vapor-cooled and HTS current leads.

D. DFBX Consolidations

Two major consolidations were required to operate the DFBX vapor-cooled leads:

- 1) No temperature sensors were specified on the vapor cooled leads, inside the liquid helium tank, as a variable to be used to control the lead flow. New platinum temperature sensors installed outside the DFBX vacuum vessel at the interface of each lead now provide this data. In addition the read-out of these sensors on the 600 A current leads needed to be filtered to reduce signal noise.
- 2) During the first DFBX cool-down, condensation was observed at the base of the four low current lead chimneys and on the G10 tubes when cold helium was flowing through; therefore a bracket heater was mounted on each of the chimney flanges. A local temperature sensor installed on each chimney is used as the control variable to maintain the temperature above the dew point.

IV. ELECTRICAL COMMISSIONING

The triplet system is powered with 13 (IP1/5) or 14 (IP2/8) electrical circuits: the main quadrupole circuit (Q1, Q2 and Q3 magnets), the D1 circuit (when appropriate), seven 600 A, and five 120 A orbit corrector circuits. The main quadrupole circuit consists of three power converters connected in parallel (Fig. 4). The power converter labeled as RQX powers all of the magnets while RTQX1 powers Q1 and RTQX2 powers Q2 magnets only. The D1 and all the orbit corrector circuits are powered by individual power converters.

Each electrical circuit can be divided into warm and cold

electrical circuit components. Warm electrical components are the power converters (PC), protection electronics, warm buses and diagnostic and protection cables up to the DFBX. Cold

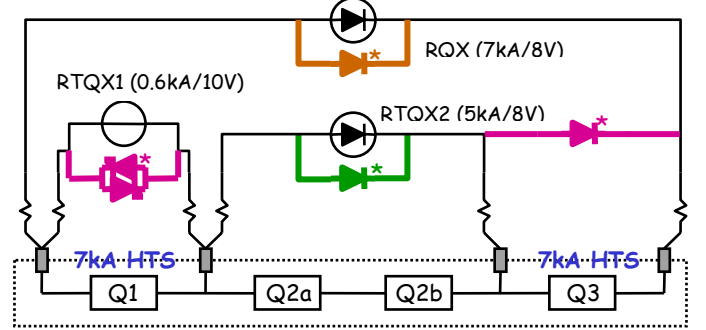


Fig. 4. The triplet is powered with three PC connected in parallel. The current is measured with current transducer (DCCT) right next to the PC. The current is fed through four HTS current leads. For properly protecting the magnets and the power converters additional bypass diode was added to the circuit across Q3 and a two directional thyristor based bypass across Q1.

components include the current leads, superconducting buses, the magnets and the cold part of the diagnostic and protection cables.

The protection system has two major elements: the Power Interlock System (PIC) and the Quench Protection System (QPS). The main magnets are protected with quench heaters while the correctors are protected with 50 mΩ dump resistors fully integrated into the PC system.

Commissioning of each circuit starts with only the warm components. After successful checking of each individual component, the warm buses are short circuited and the whole system is checked out. The final test involves holding nominal current for 24 hours to assure no hidden malfunction exists.

Cold powering starts after cryo-start and cryo-maintain are achieved. The Electrical Quality Assurance (ELQA) team checks the continuity of all of diagnostic and protection cables, and after completion of HV stand off tests, the warm buses are connected to the current leads. The QPS team performs the Individual System Tests (IST), which is the first time when the quench heaters are energized.

Powering tests are performed using a program known as the Sequencer. The Sequencer is a semi-automated program that executes an ordered list of steps described and approved in previously written procedures. However, after certain steps are performed, the Sequencer cannot continue to the next step before the results are approved by the experts. The Sequencer also allows for collection of all results in an on-line data base.

Most of the cold powering tests have to go through: i) Power Converter Configuration (PCC), ii) Power Interlock test (PIC), iii) Powering to Injection current (PLI) and iv) Powering to Nominal current (PNO) tests. Each of these tests contains several steps which were carefully designed to reveal any malfunction of the system. A typical system test of the triplet main circuits can be completed within three days, while a orbit corrector can be tested in half a day.

Cold commissioning of the triplet circuits started in April 2008. To date, five out of eight quadrupole circuits have been commissioned. Corrector circuit commissioning was delayed due to current lead regulation issues described in the previous

section, and only one set of correctors has been commissioned.

To date all cold commissioning has been successful and no spontaneous quenches have occurred during commissioning of the magnets. In order to test the integrity of the cryogenic components at low temperature and high pressure conditions a heater discharge event was performed while the quadrupoles at 5R were operating at nominal current. The temperatures and pressures measured in the magnet cryostats are shown in Fig. 5. The highest temperature was just slightly above 12 K. The pressure increased up to 18 bar, when the relief valve opened and stayed open for 20 seconds. The recovery time and overall performance was as expected.

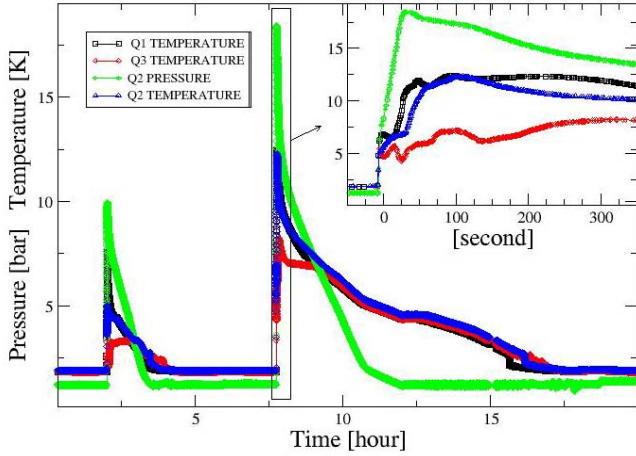


Fig. 5. Temperatures and pressure in the 5R triplet after heater discharge tests. The first one was at medium current ($I(Q1, Q3) = 3000A$, $I(Q2) = 5000A$). The second event corresponds to magnets at slightly higher than nominal current values. The upper plot is a zoom of the second event.

Figure 6 shows the D1 magnet temperatures after a heater discharge event. Both the triplet and the D1 magnets were powered, the D1 to 1000A, the Q1 and Q3 to 3000A and the Q2 to 5000A. Although D1 and the triplet are hydraulically connected the temperature rise in D1 due to a quench in the quadrupoles is insignificant.

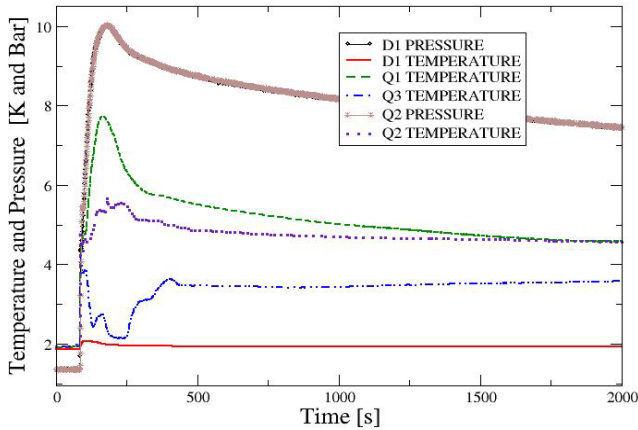


Fig. 6. Temperature and pressure after a heater discharge event. In which both the triplet and the D1 magnets were powered. D1 current was at 1000A, Q1 and Q3 was at 3000A and Q2 was at 5000A.

Calculating the quench integral values during heater discharge tests is useful to evaluate system behavior. Due to

the triplet powering scheme (Fig. 4.) the measured current at the PC does not directly correspond to the magnet current. In a case of a heater discharge, some fraction of the current bypasses the current measurement location by going through the bypass diodes and thyristors (Fig. 7 RQX and RTQX2 curves) which makes it impossible to directly measure the current decay in Q1 and Q3 magnets. In order to measure Q1 and Q3 magnet currents after the discharge, we have to use the voltage signals of the resistive section of the current leads, but the low resolution of these signals is such that the measured quench integral error is larger. The results are summarized in Table I. The measured values are in good agreement with previously measured values performed on the test benches.

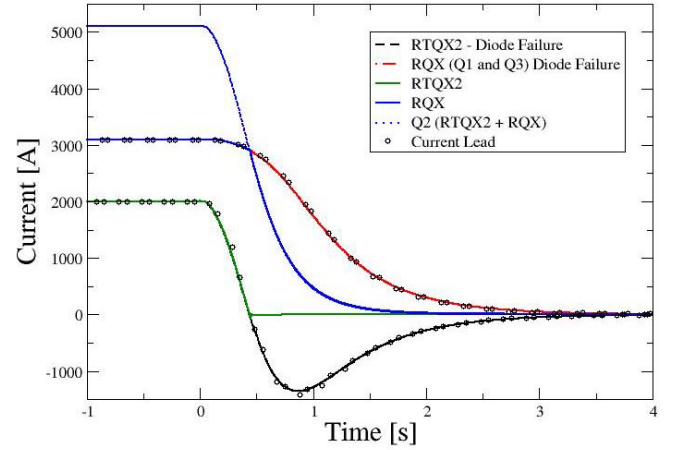


Fig. 7. Current decay is shown after a heater discharge event in two cases: a normal case labeled as RQX and RTQX2 and an abnormal case labeled as RQX – Diode failure and RTQX2 – Diode Failure. The circular symbols represent the current measurement using current lead voltage signals. The measured current values by DCCT (in a Diode Failure case) and by using the current lead signals showed a good agreement.

TABLE I MARGIN REQUIREMENTS

Magnet	Current [A]	QI [MIITs]
Q1,Q3	3100	8.3
Q2	5100	9.8
Q1,Q3	6800	10.6
Q2	11400	14.2

Figure 7 also includes a special event where reverse current was observed through the RTQX2 PC. In this case, by accident the thyristor based protection was not connected and after a heater discharge the bypass diode across the RTQX2 PC was compromised (see RQX and RTQX2 – diode failure curves). Fortunately the recovery effort after this event was small, but at this time the measured current at RQX was equal with the currents of Q1 and Q3 magnets, thus we were able to compare them to measurements from the current lead voltages and use the data as shown in the figure.

Electrical commissioning of the triplets has revealed only two issues worth mentioning. During a heater discharge event,

immediately after putting a small amount of current into the magnets, we observed an anomalous heater voltage discharge curve (Fig. 8.). After detailed debugging of the entire heater circuit, it was found that a faulty connector was breaking down by shorting the output of the Heater Power Converter (HPC). This consequently compromised the HPC. It was replaced and the connector repaired.

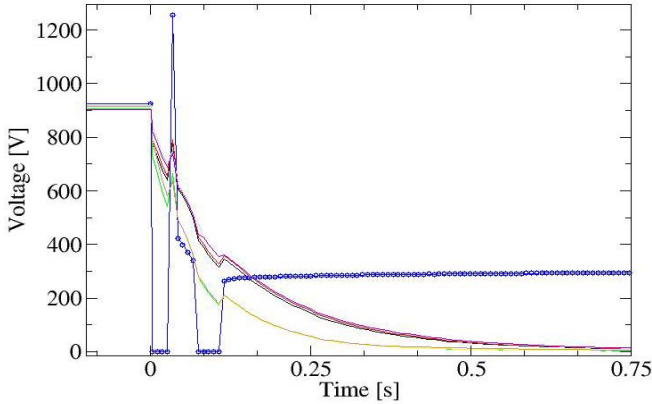


Fig. 8. Heater discharge voltage curves are shown. Besides the characteristic heated decay times of the two different heater designs (KEK 20 Ω and Fermilab 11 Ω quench heaters) one of the heaters exhibited an anomalous discharge curve.

Secondly, by design the triplet quadrupole circuit is the only electrical circuit in the LHC where, in case of loss of the cooling water for the PC, the QPS activates the heaters with the purpose of reducing the risk of damage of the bypass diodes. After experiencing a special malfunction of the system, which resulted in the quench heaters being discharged 14 days in a row twice a day, this feature has been abandoned and modifications introduced which prevent excessive heater firing while maintaining system safety.

V. CONCLUSION

As of this writing five of the eight triplets of the LHC have been commissioned. Although faults have been found in portions of the system, concerted efforts of all collaborators have lead to the quick implementation of any required repairs and ultimately the successful commissioning of the triplets themselves.

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