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LHC LOW-BETA QUADRUPOLE MAGNETS: CRYOGENIC REFRIGERATION CAPACITY AND IMPROVED CONTROLS FOR LUMINOSITY OPTIMIZATION

B. Bradu, K. Brodzinski, V. Gahier, G. Ferlin, M. Younes-Cronnier
CERN, Geneva, Switzerland

Abstract

The LHC low-β quadrupole magnets, also known as "Inner Triplets", are the final focusing magnets located on each side of LHC interaction points. The current LHC Inner triplets are NbTi superconducting magnets operated in superfluid helium at 1.9 K and use a bayonet heat exchanger to extract the power deposited by the secondary particles coming from the proton collisions. The dynamic heat loads in Inner Triplet are consequently proportional to the LHC luminosity and due to the recent upgrades of LHC and its injectors, the cryogenic capacity limit can be reached around ATLAS and CMS experiments where the luminosity can go slightly beyond the LHC ultimate luminosity. First, this paper resumes the history of the Inner Triplet cryogenics with the different tests performed in the past to assess their cooling capacity. Then, the different techniques implemented in the cryogenic control system to handle the luminosity transients are detailed and finally, a new control interaction between the cryogenic system and the LHC luminosity server is detailed to optimize online the LHC luminosity.

INTRODUCTION

The Large Hadron Collider (LHC) comprises four pairs of low-β quadrupole magnets to focus the beams at the four interaction points holding the ATLAS, ALICE, CMS and LHCb experiments. Each cryogenic magnet assembly is an "inner triplet" constituted by four NbTi superconducting quadrupoles named Q1, Q2a, Q2b and Q3 for a total length of 30 m and a weight of 22 tons to provide a high quality magnetic field gradient, up to 215 T/m [1], see Fig. 1 where the Q1 cold mass is shown. The LHC Inner triplets have been designed to extract locally up to 10 W/m at 1.9 K, corresponding roughly to the heat load induced by the LHC collision debris in ATLAS and CMS for an ultimate luminosity $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2}s^{-1} (*i.e.* twice the nominal luminosity).

INNER TRIPLET CRYOGENICS CAPACITY LEGACY

The inner triplet cold masses are immersed in a pressurised static bath of superfluid helium at 1.9 K where the heat is extracted through a *bayonet heat exchanger* (BHX). The BHX is made of a copper corrugated tube [2] where saturated superfluid helium is circulating at very low pressure (~ 18 mbar) corresponding to a saturation temperature of 1.83 K, see Fig. 2. The *sub-cooling heat exchanger* (SHX), interfacing the cryogenic distribution line (QRL), allows to maximise the liquid fraction produced in the final expansion.

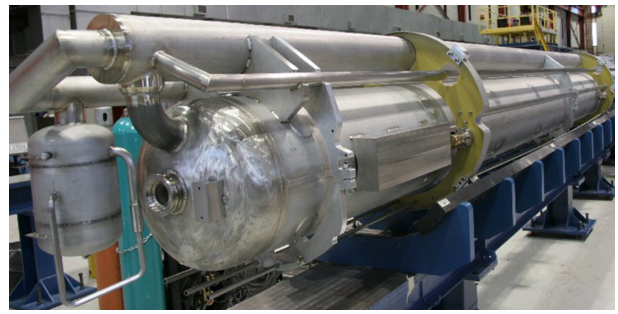

Figure 1: Q1 magnet cold mass with its overflow vessel and the bayonet heat exchanger outer shell.

Note also the presence of *overflow vessels* at the BHX extremities for liquid helium recovery. Such vessels are needed either in case of unbalance between the heat load and the liquid helium supply if the BHX cannot evaporate more helium than what is supplied, either because of an excessive gas velocity that could drive the liquid out of the BHX. If one of these phenomena occurs, it means that the cryogenic capacity limit is reached.

At the beginning of the LHC project in 1998, the inner triplets were initially designed to handle a total heat load of 172 W at 1.9 K over the 30 m, including 10 W of static heat loads with a maximum local dynamic heat load of 10 W/m in the Q1 magnet [2]. After several developments, prototyping and tests on the BHX both at Fermilab and at CERN, the inner triplet cryogenic capacity was re-evaluated at 316 W in 2001, including 34 W of static heat loads considering the cold mass temperature just below 2 K for the ultimate conditions [3]. Finally, in 2005, the installed cryogenic capacity was specified at 425 W at 1.9 K for the inner triplets around ATLAS and CMS considering that the BHX was slightly increased [4].

In 2006, the in-situ pressure test at 25 bar of one inner triplet led to the damage of its BHX. A global consolidation was consequently performed in 2007 on all inner triplets with modifications of the BHX dimensions, see Table 1 and Fig. 3. The reduction of the new bayonet geometry impacted the cryogenic capacities of inner triplets. However, no specific tests were performed at that time to asses precisely the new cryogenic limits.

CRYOGENICS CAPACITY TESTS

Capacity tests were performed by the cryogenic operation team in 2017 and 2019 to evaluate the local cryogenic capacity limits of the inner triplets and so the maximum

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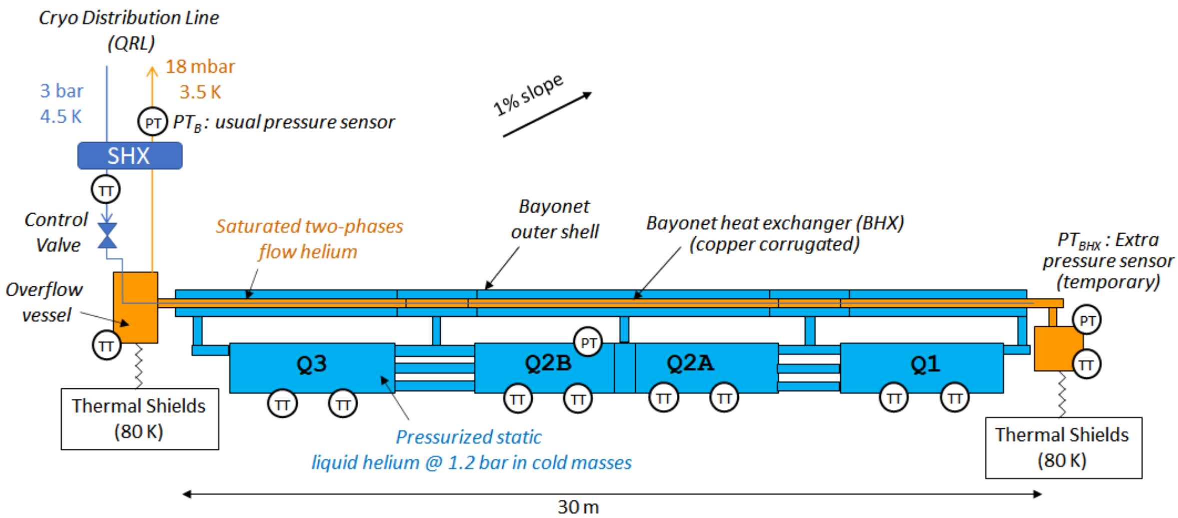

Figure 2: Inner Triplet cryogenic process flow diagram.

Table 1: Bayonet Heat Exchanger Geometry [in mm]

	Proto (2001)	**Installed** (2005)	**Consolidated** (2007)
Outer/inner Diam.	97/86	97.6/90.4	95/83
Wall thick.	0.7	0.8	1.0
Corrug. depth	5.0	3.6	6.0
Corrug. pitch	12.4	9.1	12.6

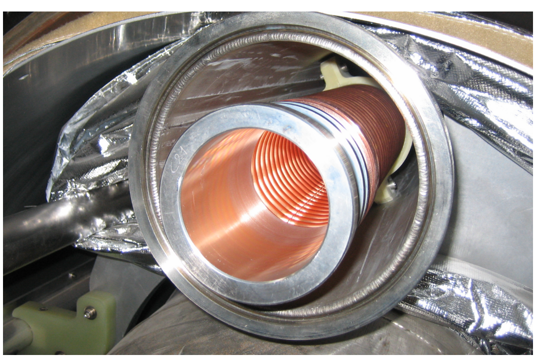

Figure 3: Inner Triplet bayonet heat exchanger after consolidation in 2007 in its outer shell.

luminosity that can be achieved by ATLAS and CMS. These tests consist in increasing progressively the power of the electrical heaters located on the cold masses to mimic the heat loads induced by the collision debris until observing liquid in the overflow vessel. The measurements were giving a maximum total dynamic heat load of 270 W corresponding to the ultimate luminosity of $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2}s^{-1}, value confirmed during the LHC operation over 2018.

More recently, in April 2021, one inner triplet (L1) was equipped temporarily with an extra pressure sensor (PT_{BHX}) to measure precisely the pressure inside the BHX to better estimate the helium saturation temperature (TT_{sat}). Unfortunately, this sensor can be used only for capacity tests without beams due to the radiations at this location during the LHC physics operation. It is also important to note that each inner triplet has some specificities (elevation, valve, sensor accuracy, etc.) and the operation conditions can also play a significant role in the cryogenic limits (maximum allowed temperatures, saturation pressure, gas velocity, flash rate, heat load repartition, etc.).

During these new capacity tests, the new pressure sensor PT_{BHX} showed a higher pressure than expected due to an extra pressure drop inside the sub-cooling heat exchanger (SHX) that was then confirmed by CFD simulations. As consequence, the triplets were always regulated at a temperature very close to the saturation temperature, provoking an early overflow in the BHX when the heat load and the helium flows were increasing. It was then decided to redo the capacity tests with a higher ΔT between the cold mass temperature and the saturation temperature calculated from the pressure sensor PT_B located after the SHX that was underestimated ($\Delta T = TT_{max} - TT_{sat}$ was increased from 100 mK to 130 mK). Moreover, the heat loads provided by the electrical heaters along the inner triplets were distributed more in agreement with the simulations of heat deposition by the collision debris around ATLAS and CMS. As a result, a total dynamic heat loads of 340 W representing a theoretical luminosity of $\mathcal{L} = 2.5 \cdot 10^{34}$ cm^{-2}s^{-1} was extracted in this inner triplet, see Fig. 4.

CRYOGENICS CONTROLS AND HIGH LUMINOSITY TEST

Since 2016, a sophisticated cryogenic regulation, combining feedback and feedforward controls, has been setup in the inner triplet cooling loops to manage the very fast heat load transient when the collisions start in ATLAS and CMS [5].

Nevertheless, several overflows occurred between 2016 and 2018 in some inner triplets and the operation teams had to manage some delicate cryogenic and beam adjustments

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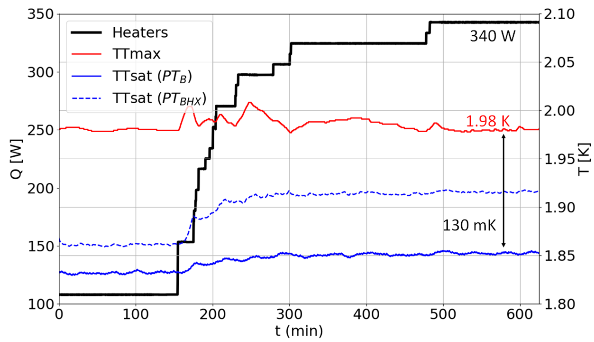

Figure 4: ITL1 capacity test in April 2021.

to reduce temporarily the luminosity allowing the recovery of the cryogenic system without dumping the beams.

To prevent such a situation, the cryogenic control system is now computing in real-time an *inner triplet cryogenic capacity* that is sent to the LHC luminosity server to delay the luminosity increase during the levelling process and to aware operators. This indicator is calculated from the distance observed between the pressure and temperature sensor values in each inner triplet and their nominal expected values. A value close to 0% means that the inner triplet operates closes to its nominal cryogenic conditions, a warning level of 60% means that the cryogenic conditions are becoming critical indicating that the luminosity must not be increased anymore and 100% means that the cryogenic system cannot continue to operate in such a situation and the luminosity must be decreased (separation of the beams is needed).

A dedicated test was performed in November 2022 to increase slowly the luminosity beyond the LHC ultimate value in order to validate the cryogenic capacities in real conditions. Note that ATLAS and CMS were not ready yet to handle this very high luminosity due to the too high pile-up but they can accept it for a short period. This high luminosity test results are shown in Fig. 5 where one can see that the luminosity was first increased until the cryogenic limit of on one inner triplet (L5) at $\mathcal{L} = 2.6 \cdot 10^{34}$ cm^{-2}s^{-1}. A second attempt was performed after the cryogenic system recovery with a luminosity maintained between 2.35 and 2.5$\cdot 10^{34}$ cm^{-2}s^{-1} during one hour with success. Nevertheless, first signs of overflows were noticed in the L5 again and this value cannot be retained for a standard smooth operation of LHC. Finally, it was decided that the inner triplet could be operated up to a dynamic heat load of 325 W, corresponding to a maximum luminosity of $2.4 \cdot 10^{34}$ cm^{-2}s^{-1} for the rest of the Run 3, providing that ATLAS and CMS experiments can handle the corresponding pile-up.

CONCLUSION

The inner triplet cryogenic system is a key parameter to ensure a high luminosity in the LHC as it must extract the dynamic heat loads induced by the collision debris. Inner triplet bayonet heat exchangers have been tested, modified, and consolidated over time and the cryogenic capacity was recently re-evaluated. The inner triplet cryogenic capacity

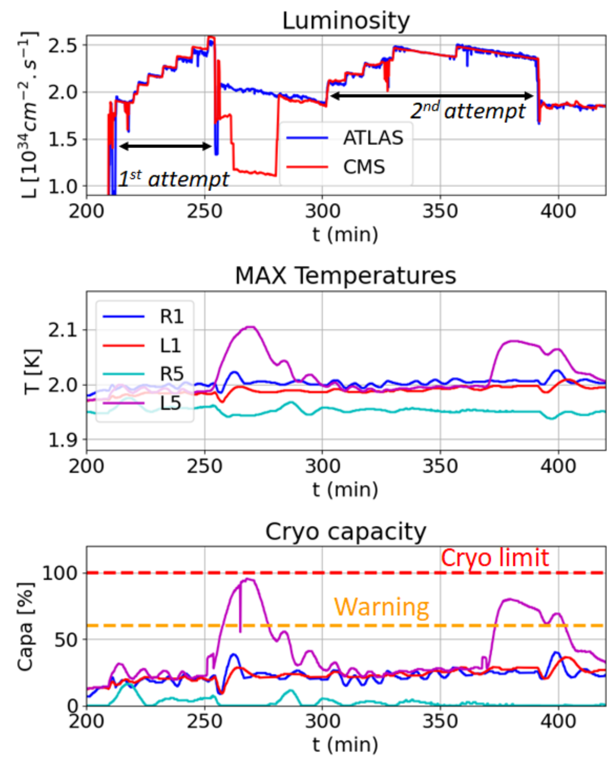

Figure 5: High luminosity test in November 2022.

limit is not only coming from the BHX but also from the pressure drop induced by the SHX. A dynamic heat load between 285 W and 325 W was finally retained for the LHC physics operation during the Run 3 until the end of 2025, before HL-LHC era. This value corresponds to a range of luminosity between 2.1 and $2.4 \cdot 10^{34}$ cm^{-2}s^{-1}.

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