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MECHANICAL CONSOLIDATION OF THE LHC INNER TRIPLET MAGNET SUPPORTING SYSTEM FOR REMOTE ALIGNMENT

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Abstract

Given the high radiation area and the tight alignment tolerances, the LHC inner triplet magnets were designed to be realigned remotely using motorized supporting jacks.

However, during run 2 the LHC triplet realignment system started to show an unexpected behavior with erratic load variations on the magnet supporting jacks when operated. It was then decided to freeze any further realignment of the LHC triplet magnet for the remainder of the run.

Subsequently a project team was setup at CERN to understand better the conditions leading to such unexpected behaviour and to study and propose a technical consolidation for the realignment system of the LHC triplet magnet. A fully instrumented magnet string using LHC triplet spare magnets was assembled and used at CERN to provide a realistic test bench for this study.

This paper reports on the work undertaken to study the triplet magnet overall realignment kinematic, the findings on the readjustment system malfunction and details the consolidation solution implemented for the next LHC run.

INTRODUCTION

Inner Triplet Layout

The inner triplet string is composed of three superconducting quadrupole magnets (Q1, Q2 and Q3) and their electrical feed box (DFBX), each installed in a specific cryostat. These are linked together through flexible interconnections.

In order to cope with the longitudinal loads due to vacuum forces, between magnets and then to the DFBX which is anchored to the ground, the magnet vacuum vessels are rigidly linked by tie-rods placed outside of the interconnection bellows (see Fig.1).

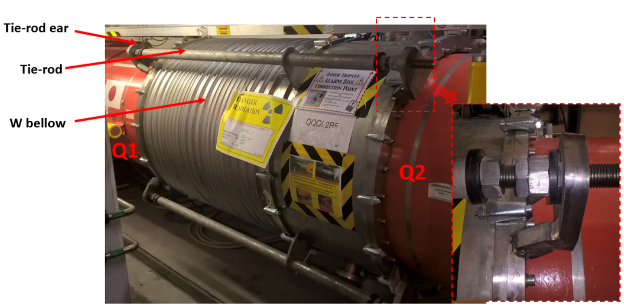

Figure 1: As-installed view of the Q1-Q2 interconnection.

The Inner Triplet Support Jacks

Each triplet magnet is positioned on supporting jacks which allow a precise magnet positioning in the vertical and radial direction (Fig. 2).

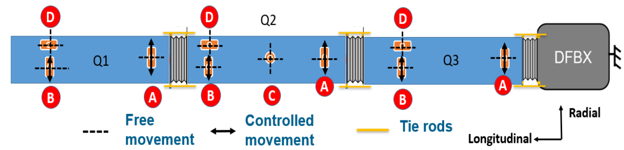

Figure 2: Schematic top view of the triplet jack installation and supporting scheme.

The LHC jacks are based on a tilting column principle that allow a guided horizontal translation of the magnet of +/- 12 mm by mean of tightening/untightening of a dedicated guiding nut [1]. In the other horizontal direction, the same tilting principle allows a translation of +/- 12 mm, but it is not guided and translation is free by design.

In the case of the LHC inner triplet, these jacks are fitted with motors to allow a precise radial and vertical position control and remote realignment [2].

REALIGNMENT SYSTEM ISSUE

In 2012, a first alignment issue was found on the jack Q2D when a tentative vertical realignment was made of the triplet 5R (Fig. 3).

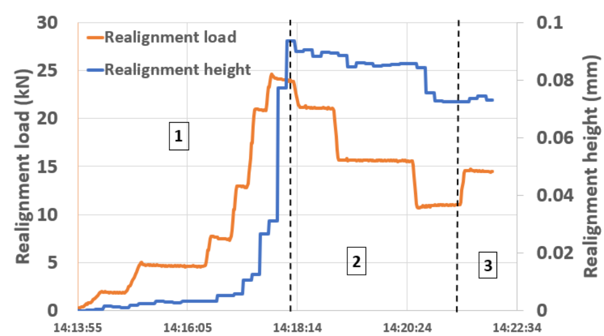

Figure 3: Realignment height vs load – 5R Jack Q2D.

The realignment system was slowly lifted with a progressive load transfer from the LHC jack onto the alignment system (Fig. 3 label 1). Noticeable cryostat lifting started at a realignment system load of 21 kN.

Since the final alignment height was overshot, descent orders were sent to the realignment system (Fig. 3 label 2). The load on the realignment system then decreased to about 11 kN with no correlated cryostat movement.

The realignment load was down to around 11 kN, so the realignment sequence was aborted, and a lift order was sent to recover some load on the realignment system (Fig. 3 label 3).

Subsequent tunnel inspections showed that the jack Q2D was tilted to a blocking position in the longitudinal direction (Fig. 4) and was in contact with its frame.

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A longitudinal movement of the Q2 magnet was then manually carried out thanks to the interconnection tie-rods in order to recover some jack clearance. As a result, the jack recovered its alignment capabilities.

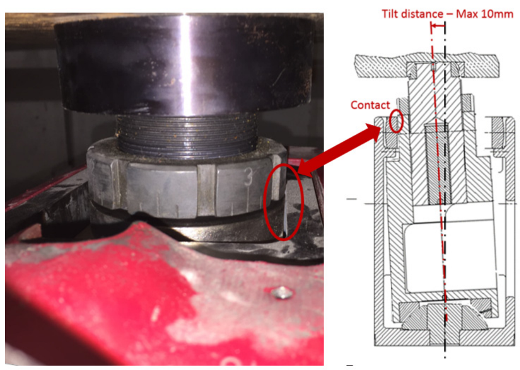

Figure 4: (left) Triplet 5R Jack Q2B in contact (right) schematic cross-section of the jack.

In 2017, during another realignment campaign, a vertical realignment displayed a similar abnormal load/displacement pattern that appeared simultaneously on triplet 5R jack Q1A and triplet 5L jack Q1D.

Further underground inspections showed that, six out of eight triplet strings had at least one realignment jack in contact with its frame on the Q1 magnet (similar to Fig. 4). This showed that the Q1 magnets were all subjected to a longitudinal movement greater than their allowable jack design capability of +/- 12 mm leading to an unwanted internal contact.

SUBSYSTEM TESTING

To investigate any malfunction of a subsystem, dedicated tests were performed on the triplet magnet interconnection tie-rod ear as well as a standalone supporting jack (Fig. 5).

Figure 5: Dedicated testing of (left) standalone jack test (right) tie rod ear stiffness.

The jack was put in contact with its frame, similar to the situation witnessed in the tunnel and was progressively loaded transversely on a dedicated test bench (Fig. 5 left). It was then operated for a vertical realignment operation and the operating load was measured with a load cell. Early results showed that when loaded transversely, a large friction load was to be overcome to get a vertical jack motion [3]. However, no measurable stick slip was witnessed, the jack movement remained smooth within a 0.01 mm resolution. These results were consistent with the pattern seen on Fig. 4.

Later, the tie rod ears of the spare triplet magnets were loaded up to 20 kN each to measure their respective longitudinal deflection in operation (see Fig. 5 right). The longitudinal deflection at the level of a single tie rod was in the order of 3.5 mm [4]. Cumulating the displacement due to the tie-rod ear deflections, the Q1 magnet longitudinal movement under vacuum was expected to be in the order of 17.5 mm before reaching a steady state situation. This is more than the 12 mm of jack design capacity.

BENCH SETUP FOR THE TRIPLET STRING TEST

In order to better characterize the working conditions and realignment kinematics of the triplet string a test bench was setup on the surface by using LHC spare magnets (Fig. 6).

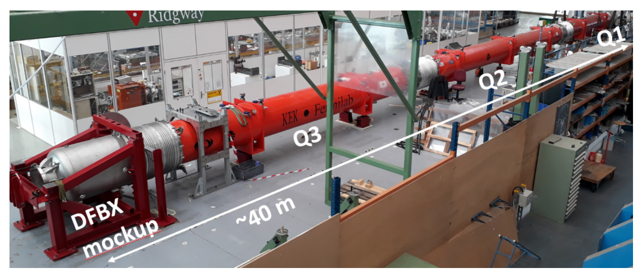

Figure 6: Layout of the triplet string test in 2019.

This setup was designed to be vacuum pumped as this is the dominant contribution to the longitudinal displacement. Although we know that cryogenic circuit pressure and temperature have an impact on the triplet kinematics this is expected to be less significant.

The string was equipped with dedicated sensors to study the vacuum load path and magnet realignment kinematics. Each magnet was monitored for vertical and radial movements with a wire positioning system (WPS) similar to the LHC tunnel installation [5].

The magnet longitudinal movements were monitored using capacitive sensors and the load resting on each jack was monitored with dedicated load cells. Each interconnection tie rod (see Fig. 1) was equipped with strain gauges to measure the applied load (see Fig. 7).

The vacuum was then cycled several times under various configurations to study the kinematic behaviour of the triplet string.

RESULTS OF THE TRIPLET STRING TEST

As installed, the jack Q1D of the triplet string had an initial longitudinal clearance of around 12.6 mm.

On initial vacuum pumping, the magnet Q1 moved back by 9.5 mm. Overnight the building air temperature had decreased by about 5°C so the next morning the magnet was found to have moved further back by 1.5 mm due to thermal contraction of the magnet string.

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Subsequently a series of magnet radial realignment manoeuvres produced some friction release in the jacks [6], which eventually closed the residual clearance and left the Q1D jack in contact with its frame (similar to Fig. 4).

It was then concluded that the interconnect tie-rod system as installed was indeed not stiff enough to prevent a large longitudinal movement of the Q1 magnet in operating conditions. With time, because of temperature variation and friction release, this brought one of the Q1 magnet jack in contact with its body and some transverse vacuum load was then supported by the jack body itself. When operated in this situation, with a transverse load on the jack head, large friction effects within the jacks impair their magnet vertical realignment capabilities. In the different situation tested, vertical realignment was however always possible provided the friction force was overcome, with no measurable stick slip effect. The radial realignment was always possible and was seemingly unaffected in the various situations tested on our setup.

STUDY OF A SYSTEM CONSOLIDATION

Following the understanding of the alignment issue, a consolidation solution was devised to stiffen the triplet longitudinally and avoid making a major modification of the system kinematic. It was proposed to add additional tie rods at the level of the interconnection to increase the stiffness of the present tie-rods (and tie-rod ears in particular) which was confirmed to be insufficient.

With two additional tie-rods on each interconnection (see Fig. 7), the system longitudinal stiffness increased by 35%. This is expected to be sufficient to avoid bringing the tilting column in contact with the frame of the jacks, thus allowing realignment as designed originally.

It was confirmed through dedicated realignment tests that the added transverse stiffness was negligible, and the interconnection bellows remain the main contributors.

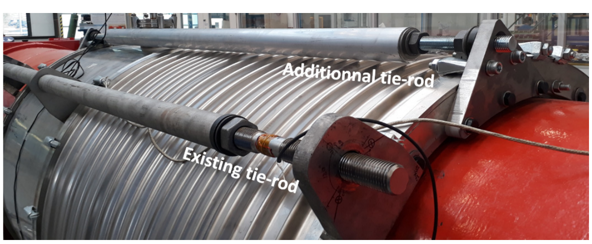

Figure 7: Prototype of additional tie-rod (autumn 2019).

IMPLEMENTATION IN THE LHC

The additional tie-rods have been implemented on all LHC triplets during the long shutdown 2 in summer 2020 (see Fig. 8).

After cycling the insulation vacuum, the overall triplet longitudinal stiffness was found to have increased as expected (see Fig. 9).

After the complete magnet cooldown, the LHC jacks are still within their operating range and have retrieved their realignment functionality before the LHC run 3.

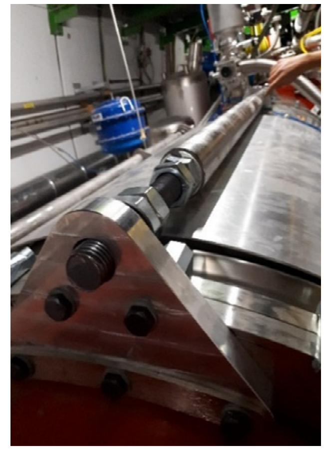

Figure 8: Additional tie-rod implementation in the LHC.

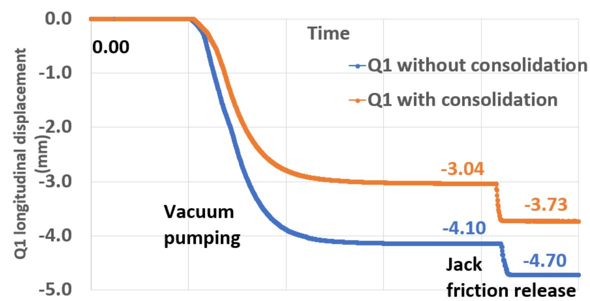

Figure 9: Comparison of the longitudinal travel of Q1R5.

CONCLUSION

Following a readjustment system malfunction for the inner triplet magnets, several tests were performed to refine our understanding of the system and the issue.

A consolidation solution was devised and implemented with a successful outcome.

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