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DESIGN OF A HIGH-PRECISION LIFTING SYSTEM FOR THE HL-LHC HEAVY COMPONENTS IN THE INTERACTION REGION

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Abstract

Given the high radiation level and the tight alignment tolerances, the HL-LHC interaction region components are designed to be realigned remotely using motorized supporting jacks, as human interventions in these zones must be limited to the strict minimum.

A position adjustment system will allow a vertical and horizontal displacement of each jack support by at least +/-2.5 mm with a resolution of less than 10 µm. The weight of the supported elements, up to 170 kN and transverse loads reaching 30 kN, will have to be remotely moved by means of mechanical actuators. The system will be exposed to a cumulated radiation dose of up to 2 MGy during the 15 years of lifetime [1].

To comply with these requirements, an extensive design effort has been initiated at CERN to study the possible system layouts. This includes the prototyping of various solutions, studying subsystems through dedicated test setups and using simulations to obtain a clear understanding of the mechanical principles at play.

This paper reports on the work undertaken to design the high-precision lifting system, the various mechanical analysis carried out, and their main outcome. It reviews the proposed solutions and their expected alignment performance.

SYSTEM INTEGRATION REQUIREMENT

The heavy components of the HL-LHC interaction region are designed to be supported on standardized HL-LHC jacks, closely derived from the original design of the LHC supporting jacks [2].

These jacks are based on the concept of a tilting-column with two bearings on each end (see Fig. 1). They allow the accurate positioning within a range of +/-10 mm of the top bearing in one direction of the horizontal plane, while the other horizontal position is left free to move.

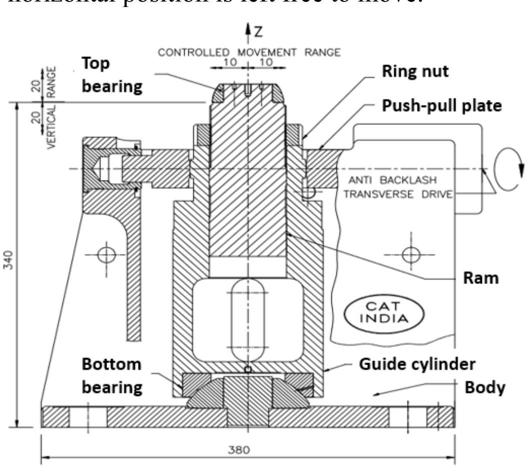

Figure 1: Transverse cross section of the LHC jack [2].

Like in the LHC, the heavy accelerator components are designed to be supported on three jacks located on two support planes on both ends of the component (see Fig. 2).

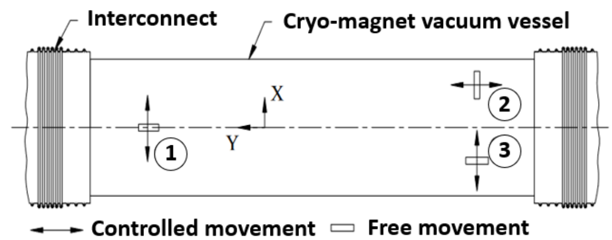

Figure 2: Top view of a cryomagnet - supporting jacks at position 1, 2 and 3 – adapted from [1].

Jacks 1 and 3 will permit the accurate positioning of the component in the radial (X) direction while jack 2 will determine the position in the longitudinal direction (Y).

The height (Z) of the component can be controlled on each jack by lifting the ram inside the guide cylinder, following which the ring nut is adjusted to retain the chosen height (see Fig. 1).

In the HL-LHC interaction region, the ram will be permanently supported by the motorized lifting system. Thanks to this, the height can be adjusted remotely without a manual intervention underground. Consequently, the lifting system must fit inside the bottom cavity of the guide cylinder to allow actuation of the ram from below.

STICK SLIP AND SYSTEM STIFFNESS REQUIREMENTS

The Principle of Frictional Stick-Slip

The so-called « stick-slip » describes the oscillatory motion affecting most common materials when they are sliding. For example it commonly occurs when rubbing a wet finger on the edge of a crystal glass or when dragging a chair on the floor. The amplitude of the sliding motion is directly dependent on the materials in contact and the system stiffness. With a simple demonstration, based on the conservation of energy [3], it can be shown that the stick slip amplitude for a sliding system is:

$$d = \frac{2.N.(\mu_s - \mu_d)}{k} = \frac{N.(\mu_s - \mu_{stop})}{k} \quad (1)$$

With N being the normal force at the sliding interface, μ_s, μ_d, μ_{stop} respectively the static, dynamic and rest friction coefficient, and k the system stiffness along the sliding direction. In our case, this amplitude defines the alignment resolution of the system. This highlights the importance of good material selection for loaded sliding surfaces and the need for sufficient system stiffness along the alignment direction.

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Material Friction Testing

To select suitable interface materials and to define the required system stiffness accordingly, a friction testing campaign has been conducted at CERN in early 2021 to quantify the static and rest friction coefficients for selected materials [4]. This setup was based on the friction of two disk samples and the measurement of the friction load before and after the sliding occurred (see Fig. 3).

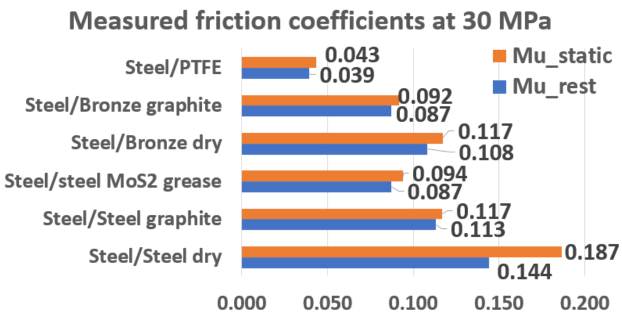

Figure 3: Measured friction coefficients at 30 MPa interface pressure for selected materials.

While the absolute value of friction coefficients is important to determine the system actuation load, it is the scatter between the static and rest friction coefficient that defines if the system is sensitive to stick slip.

Among the candidate materials tested, PTFE has the lowest friction coefficients and lowest friction coefficient scatter. It is however notoriously subject to radiation degradation and creep and so it cannot be used for our application. The steel/bronze couple, even at dry state, shows an interestingly low scatter of friction coefficients while being less susceptible to galling. So whenever possible, we will use this material combination lubricated with graphite for sliding interfaces.

System Stiffness Requirement

The supporting jacks will be subjected to transverse loads coming from the LHC operational conditions (vacuum, cryogenics) and neighbouring accelerator components. For the superconducting magnets of HL-LHC, this transverse force was evaluated to be up to 27 kN [5]. At this transverse load, a static friction force of 6 kN is expected at the ram/guide cylinder interface [6]. Considering the friction test results (Fig. 3) the residual force after sliding is expected around 4.5 kN. From Eq. (1) we can then compute that the required vertical stiffness must be at least 150 kN/mm to get a resolution below 0.01 mm.

THE LIFTING LEVER DESIGN

Lever System Design

A first design was conceived on the principle of a simple lever system. By carefully choosing the position of the fulcrum, this principle allows both a good control over the displacement and a low actuation force.

The design solution is based on a lever resting on a cylindrical bearing. The distance between the bearing centre and the lifting point is 40 mm, respectively 280 mm to the application point of the actuation load, thus giving a displacement reduction ratio of 7:1 (see Fig. 4).

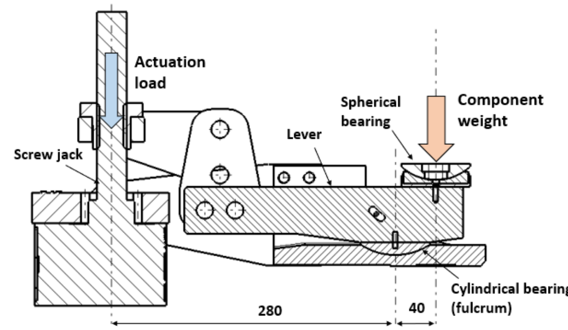

Figure 4: Cross section of the lifting lever solution.

The lever is actuated by a commercial worm gear jack with a maximum actuation load of 30 kN which results in a maximum actuation load of 210 kN at the component level. The component weight is supported on a bronze spherical bearing. Both, the cylindrical and spherical bronze bearings are lubricated with dry graphite to limit the stick-slip on these highly loaded interfaces. Finite element simulations show a vertical system stiffness of 600 kN/mm, and a maximum Von-Mises equivalent stress on the lever of 270 MPa under a load of 200 kN.

Lever Prototype Testing

A prototype for this lever-based solution has been produced and tested (see Fig. 5).

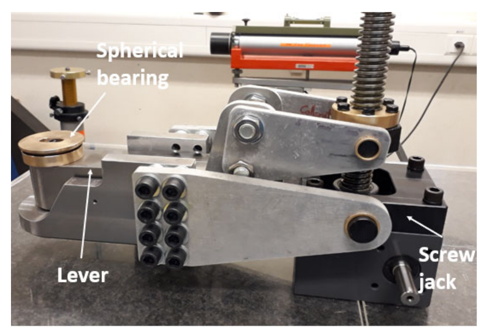

Figure 5: Prototype of the lifting lever design.

A 200 kN magnet was used for the purpose of testing (Fig. 6). Actuation loads of up to 100 kN were possible within the alignment range with a measured alignment resolution of about 5 μm.

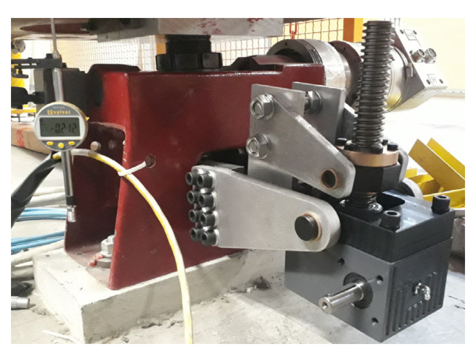

Figure 6: Prototype lever inserted in the magnet jack.

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HYDROSTATIC ELASTOMER DESIGN

Based on the extensive operational experience with the LHC design [7], a solution using the hydrostatic deformation of an elastomer body was also proposed. Among the possible elastomers, thermoplastic polyurethane (TPU) has shown to be radiation resistant, while it is being considered uncompressible since it allows very big elastic deformation while having a low shear modulus. These materials have been used successfully within the LHC alignment systems, with the advantage over fluids of limiting the risk of hydraulic leaks which would eventually lead to a loss of control over the components vertical position.

The TPU cylinder pad (ϕ50 mm – 30 mm high) is enclosed within a cavity with the component load applied from the top through a vertical piston. A pushing finger (ϕ 25 mm) is then gradually inserted horizontally inside the cavity and deforms the TPU pad which in turn pushes the vertical piston in a controlled way. Given the large alignment range requested, a test bench was setup at CERN to measure the ability of the TPU pad to allow alignment within a wide range of deformation and to measure the required actuation force (see Fig. 7).

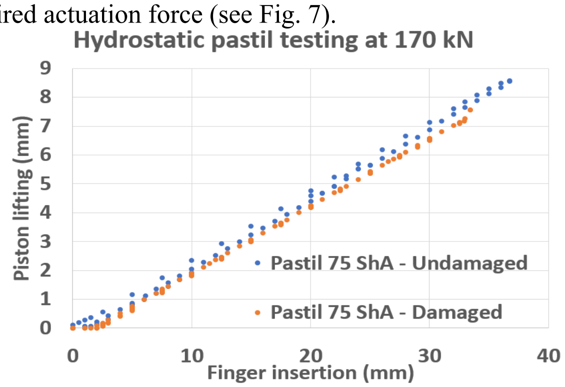

Figure 7: Testing of the 75 ShA TPU pad at deep finger insertion and high loads.

The test was conducted with increasing loads of up to 250 kN of vertical force on the pad (hydrostatic pressure of 127 MPa) with satisfactory results. As shown in Fig. 7, the piston lift is both very linear with respect to the finger insertion and reproducible upon loading and unloading. A TPU pad was purposefully damaged to simulate crack due to ageing and was re-tested with similar results (orange points in Fig. 7).

At ultimate finger insertion, the finger actuation force is 58 kN. This exceeds the theoretical hydrostatic force of 42 kN by 16 kN and shows that pushing the pad to big deformations requires a pushing force larger than the hydrostatic force. This is typically not the case for conventional fluid-based hydraulic systems where the actuation force is constant and always equal to the hydrostatic pressure. A uni-axial compressibility test was carried out on the TPU pad and the bulk modulus was measured in the order of 2.4 GPa for a 75 ShA TPU and 2.9 GPa for a 90 ShA TPU. This was confirmed by the measured linear slope of the piston-to-finger displacement of 0.23 mm/mm instead of 0.25 mm/mm if the pad was strictly incompressible (Fig. 7).

This compressibility adds however an additional vertical system flexibility in the order of 160 kN/mm. This is above the required stiffness necessary to comply with the resolution requirement (150 kN/mm). However, the actual resolution in extreme loading conditions with the full system should be assessed by further dedicated tests.

Since the TPU pad is enclosed in a cavity, any thermal expansion can only translate into a vertical piston translation. For TPU, thermal expansion coefficients up to 200 µm/m/K^{-1} were reported. With the current TPU pad dimensions of this would amount to 18 µm/K.

A prototype was designed based on a worm gear principle with a reduction ratio of 107:1 (Fig. 8). It will actuate an M18 screw to produce the required pushing force on the finger of 60 kN. The system transfer function is then 35 µm of vertical piston displacement per input shaft turn.

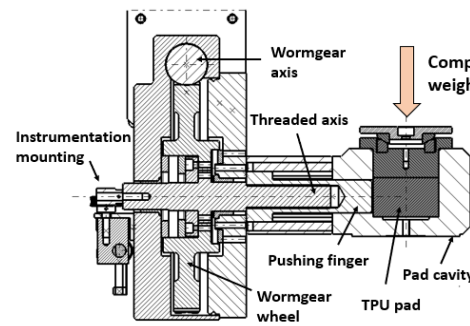

Figure 8: Cross-section of the prototype TPU pad design.

A prototype has been assembled (see Fig. 9) and has been tested on the test magnet (Fig. 4) with positive results. Loads up to 100 kN were successfully lifted with a resolution inferior to 5 µm

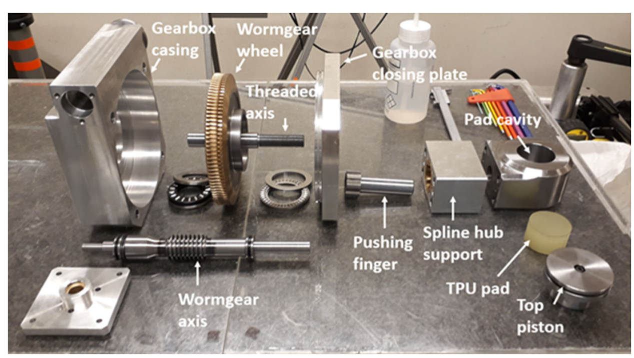

Figure 9: TPU pad prototype upon assembly.

CONCLUSION

The need for a lifting solution allowing the positioning of heavy elements with a 10 µm resolution has driven an extensive design and validation effort at CERN. Among the numerous alignment solutions considered, the lever and hydrostatic elastomer pad have been prototyped and tested with positive results. Further testing should now aim at validating the system's radiation and ageing resistance before choosing the most appropriate design for series production.

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