The Motorized Alignment Jacks for the LHC Low Beta Quadrupoles

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The LHC low beta quadrupoles, whose alignment tolerances are very tight, will be located in areas with a strong radiation field. They will have to be re-aligned remotely, by motorized jacks, according to the feedback of alignment sensors located on each magnet. In order to carry out these remote displacements, it has been decided to motorize the jacks designed to support all of the LHC cryomagnets. Two adapters, which allow plugging stepper motors on radial and vertical axes of the jacks, have been developed through collaboration between RRCAT, DAE, INDIA and CERN. This paper describes the functional requirements concerning the motorized jacks, details of the adapters and motors, engineering design, their production, and the results of the repositioning tests carried out.

1. INTRODUCTION

The Alignment tolerances for the LHC insertions are particularly stringent regarding the low beta quadrupoles (Q1, Q2 and Q3) of inner triplets for the four experiments ATLAS, ALICE, CMS and LHCb, which induce strict positioning tolerances, in a severe environment (high radiation fluxes). Each triplet consists of three different quadrupole elements, weighing from 15 to 18 tons, totaling 24 low beta magnets in 8 triplets of the four experiments. A minimum incremental motion of 0.01 mm is required on all vertical and horizontal movements. The good operational characteristics of the alignment jacks designed for ARC magnets of LHC prompted their use in the low beta section also [1]. Some modifications in the LHC jacks were made to meet the specific requirements of the inner triplets. Magnets Q1 and Q3, which are short in length, are considered totally rigid and Q2, which is longer, needs a correction of vertical sag between support points. Wire Positioning System (WPS) and Hydrostatic Levelling System (HLS) are used to get the position of the magnet in five degrees of freedom with a submicrometric resolution [2]. Each of these magnets is supported on three alignment jacks, and the eight long quadrupoles also have a fourth central support for correction of vertical sag. Thus a total of 72 motorized alignment jacks and 8 Central motorized central supports are required. The jacks dedicated to the longitudinal adjustment of the quadrupoles, along the beam line, are referred to as “longitudinal jacks”, whereas the jacks dedicated to the radial adjustment of the quadrupoles are referred to as “radial jacks”. The additional vertical adjustment jack placed to control and correct the vertical self-weight deformation of the long quadrupoles is referred to as “central jack”. Each of these jacks has a motorized vertical motion and only the radial jacks have motorized transverse motion (providing motion in roughly “horizontal direction”). Distinction is made between longitudinal jacks and radial jacks based on the fundamental machine alignment requirement, which is not so strict in the longitudinal direction.

A total of 80 jacks, all having vertical motorization and 48 also having transverse motorization, have been manufactured and are ready for installation.

2. FUNCTIONAL REQUIREMENTS

2.1. General Layout

The alignment & supporting of the quadrupoles is achieved by a tripod configuration of jacks, similar to the ARC magnets, making use of three alignment jacks, each having a controlled motion in the vertical as well as in one transversal direction in the horizontal plane, whereas the other transversal horizontal motion is free, see Figure 1. A suitable layout and orientation of the three jacks yields the required degrees of control and freedom for the alignment.

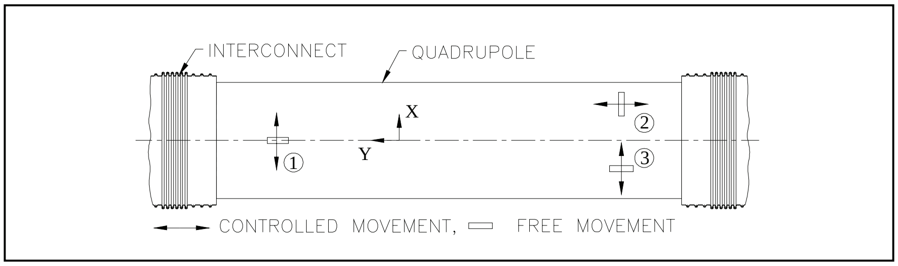

Figure 1: Top view of a quadrupole magnet Q1 or Q3: alignment jacks at position 1, 2 and 3. Vertical motion is motorized at all the three locations. Transverse motion is motorized at location 1 and 3.

The jack, (Figure 2), is composed of a mainframe body whose base plate is fixed to the tunnel floor by means of two bolts (solid shims are used underneath in some locations). The horizontal movement is obtained by controlled tilting of a vertical column, the so-called guide cylinder, by shifting a cylindrical feature on the column with two moving parallel planes of the so called push-pull ring. The push-pull ring is moved by an integral anti-backlash nut device. The vertical movement is obtained by changing the height of the column by moving a ram inside a cylinder. Considering the limited number of alignment operations in the LHC lifetime, an important choice, aimed at reducing the cost of the jacks, was to provide the vertical adjustment by using a removable auxiliary jack (not presented in this paper) inserted concentrically within the guide cylinder. The lifting and relieving of the quadrupole weight is achieved by operating the auxiliary jack and the setting of the vertical position is achieved by manual adjustment of the ring nut.

For the inner triplet use, auxiliary jack is used for the first phase of manual vertical alignment. A motorized adaptor (described later) is inserted in the same guide cylinder cavity for obtaining the remote operation. The transverse movement is motorized with the help of an adaptor, which takes care of quick mounting and dismounting requirement and acts as a rigid coupling between the motor and the jack drive-nut.

2.2. Functional requirements

The motorized jacks are used for the remote alignment of the low beta quadrupoles. The functional requirements of the motorized jacks are given in Table-I below. Range of motorized displacements is controlled to prevent damage to the interconnects between the adjacent magnets. Weight and plugging/unplugging time of the adaptors are controlled as the adaptors will need to be removed for clearing the passage and for re-centralization on expiry of the motorized range in a high radiation environment (16kGray/year). The range of manual adjustment is same as that for the ARC magnets.

No major change in the design of ARC magnet was desired to take advantage of the manufacturing set-up of the series ARC jacks and the extensive experience with their testing & performance.

Table I: Functional specifications

	Requirements of motorized movement	**Value**
1	Range of the effective motorized displacement on each axis	± 2 mm
2	Minimum effective displacement	0.01 mm
3	Load capacity	100 kN
4	Weight of one adaptor	< 15 kg
5	Plugging / Unplugging time for one adaptor	< 10 minutes

2.3. Design

The design of the ARC magnet jacks [1] was modified in order to enhance its stiffness and to incorporate necessary engineering features for motorization.

The impediment to obtaining a small incremental motion of the alignment jack is the treacherous nature of friction. Value of static coefficient of friction and the differing values of static and dynamic coefficient of friction greatly affect the design. The nature of friction is such that it has a higher static value (high limiting value, μ_{Static}) and a lower dynamic value (reduces with velocity, however, taken here as independent of velocity, $\mu_{Dynamic}$). Taking the case of horizontal movement of the magnets, the elastic body of movement device acts like a spring, while applying external force on the magnet. The magnet does not move until the force is greater than the force of static friction, $\mu_{Static}mg$ (m being the mass of the magnet and g acceleration due to gravity). Once the external force exceeds $\mu_{Static}mg$ then the magnet moves suddenly (as $\mu_{Dynamic}mg$ is smaller) and the component accelerates and once set in motion; and its motion governed by:

$$F_{ext}=m.a$$

In this case of aligning a magnet, the prime mover (motor) will be continually displaced till a displacement is seen at the position sensors. This displacement will have two parts one that will go into deforming the body to generate the force to overcome high static friction and the second part of actual motion. However, when the motion of the motor is stopped, the spring body may still be deformed and motion also continues afterwards.

When actuating force, $F_{ext} = k.x$ (k is stiffness N/mm of the jack and x its overall deformation consisting of all energy storage elements in the chain), is more than $\mu_{Static}mg$, and the mass accelerates as follows-

$$m.a = (\mu_{Static}mg - k.x - mg\mu_{Dynamic})$$ – Causative force starts reducing as ($\mu_{Static}mg - k.x$), x being displacement from the initial position, a is acceleration

$$m.v(dv/dx)= -kx + mg(\mu_{static} - \mu_{Dynamic})$$

Integrating both sides

$$mv^2/2 = \{-(k.x^2/2)+ mg(\mu_{static} - \mu_{Dynamic}).x\} + C$$

Now, at x=0 (when the motion starts), v=0; this gives C=0. The equation of motion is a second order equation and has two solutions. The velocity is zero for the initial condition and it is again zero as follows:

$$v = -(k.x^2/2) + mg(\mu_{static} - \mu_{Dynamic}).x = 0$$

The magnet will stop (v = 0) after going a distance given by

$$\mathbf{x = 2.mg(\mu_{static} - \mu_{Dynamic})/k}$$

This gives the minimum effective movement, x, based on the mass, m, being moved, stiffness of the jack being k. Co-efficient of static friction being μ_{static}, and that of dynamic friction being $\mu_{Dynamic}$. This analysis highlights the importance of keeping friction as well as difference (μ_{static} - $\mu_{Dynamic}$) low and keeping stiffness of the moving arrangement high. A high stiffness also guarantees stability of position over time.

2.4. Engineering design

The jacks and adaptor units are designed for high stiffness commensurate with the observed values of static and dynamic coefficient of friction. A provision is made in the design to enhance the stiffness, if required after the installation of the jacks.

2.4.1. Vertical adaptor

The vertical adaptor is a compact precision lifting device having a load capacity of 10 tons and setting resolution better than 0.01 mm. The adaptor fits in the jack cavity, provides a precision lifting mechanism and interfacing features with jack and motor, Figure-2, 3. Three prototypes of vertical adaptor based on different concepts viz. wedges-on-rollers, screw driven by gear train and using a polyurethane (PU) block as hydraulic fluid were developed. As expected, the adaptor based on wedges with flat roller cages and HSS (High Speed Steel) raceways had a more difficult manufacturing and were expensive, though accurate in adjustment. The second concept using simple screw needed a high torque for operation. The third concept making use of a PU cylindrical block as a hydraulic fluid was easier to manufacture. PU based concept was selected for implementation after thorough testing of adaptors based on the three different concepts. As PU comes in many variations, a particular brand of PU was selected based on a test campaign launched at CERN to test the PU blocks' capability to resist permanent volume change under stress and its capability to regain its shape when stress is removed [2]. The PU has a property of high volumetric change with respect to temperature; hence it was necessary to control temperature during its dimensional measurements close to the operating temperature. As the range is only ±2 mm, a procedure involving use of height adjusting tool of the RAM of the jacks, is developed for utilizing full range of movement. A small range is specified so as not to make over-travel which may result in damage to interconnects of magnet.

A pre-series of eight adaptors were made to qualify the design and manufacturing processes involved. The testing of pre-series also helped in evolving geometry optimization in vertical adaptor for assembly under severely restricted access to longitudinal jack.

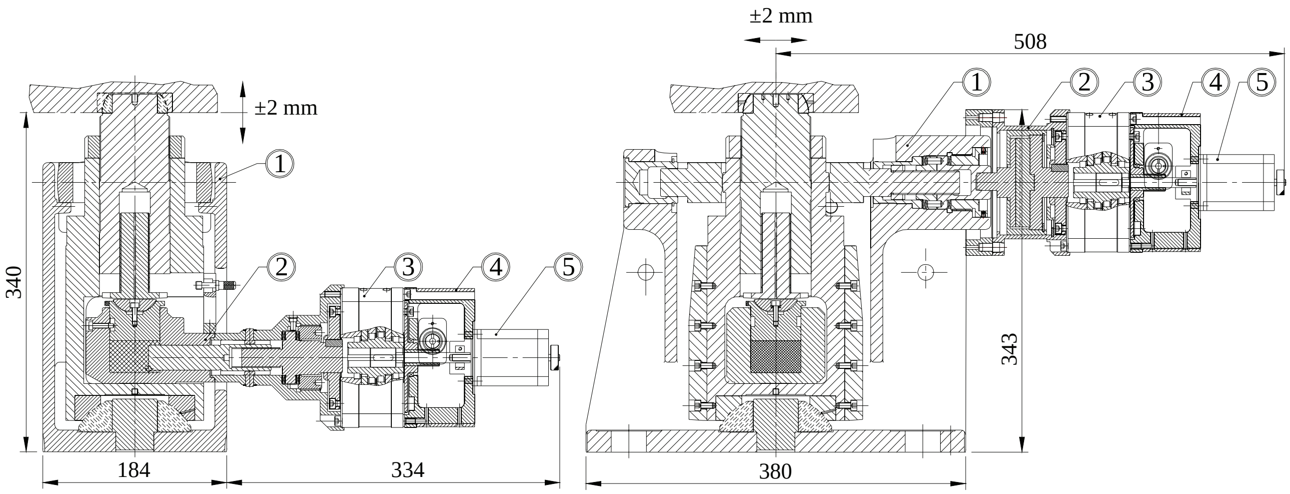

Figure 2: Details of motorization of vertical motion on the left and transverse motion on the right. Numbered components are as follows; 1- Jack, 2 - Adaptor, 3 - Gear-head, 4 - Limit switch unit, 5 - Stepper motor. The range of motorized movement is shown as ± 2 mm.

2.4.2. Transverse adaptor

Transverse adaptor, shown in Figure-2, is designed to allow mounting of the motor with ease and with minimum disturbance to the set position of the magnet. It provides an Oldham coupling, chosen for its high torsional stiffness, between the pentagon socket of the jack and the gear head out-put shaft to take care of eccentricity and also axial distance variations.

For the mounting of adaptors, possible viewing angles have been considered so that the mounting is done in one go to minimize the dose to the person.

2.5. Assembly and testing of the pre-series

The vertical and transverse adaptors are assembled with the jacks, and two stepper motors - one each for vertical and transverse movement- are coupled to these adaptors, see Figure 2 and 3. Three such jacks support each magnet, except that the longitudinal jack does not have a transverse motorized motion. The integrated alignment system consisting of jacks, pre-series vertical & transverse adaptors supplied by RRCAT, and motors & its control unit provided by CERN, was successfully tested on a dedicated test set-up under a RRCAT-CERN joint test campaign in June 2005 at CERN.

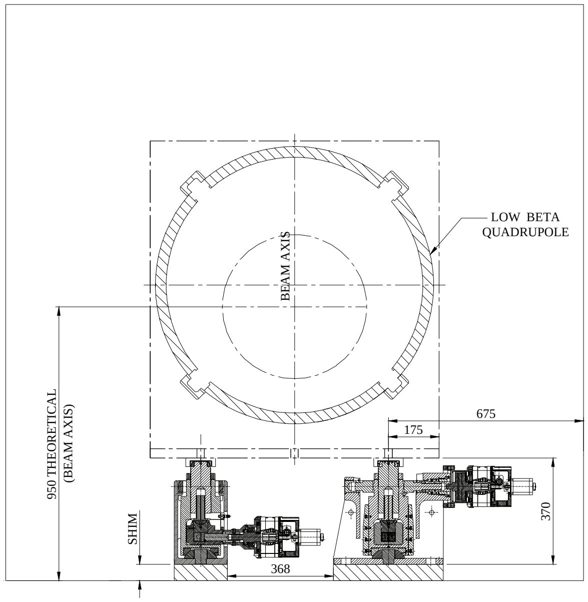

Figure 3: End view of quadrupole on the motorized jacks

Figure 4: Test facility.

Assembly of motorized jacks was integrated with the low beta string for the testing. The adaptors were mounted on the low beta modified jacks installed under magnet Q1 (tests could not be carried out on the heaviest magnet Q2 due to scheduling problems as it still had interconnects on one end). Q1 has a total weight of 15t while Q2 has a total weight of 18t. All the 3 jacks were laid on the ground with no additional fixation.

The vertical and transverse adaptors were also tested under Q2 for a range of ± 1 mm with the magnet placed on the standard PMPS jacks in String low beta in building181.

The displacements were monitored using WPS sensors (Wire Positioning System) with a sub-micrometric resolution, located on one side of each cradle. Each sensor monitors horizontal and vertical distance with respect to a stretched wire considered as the reference.

Motor displacements were performed by the control/command unit which allows sending direct commands via RS232 bus to the motor (relative displacements with the choice of the direction, clock wise or anti clock wise, and the number of steps or continuous displacements).

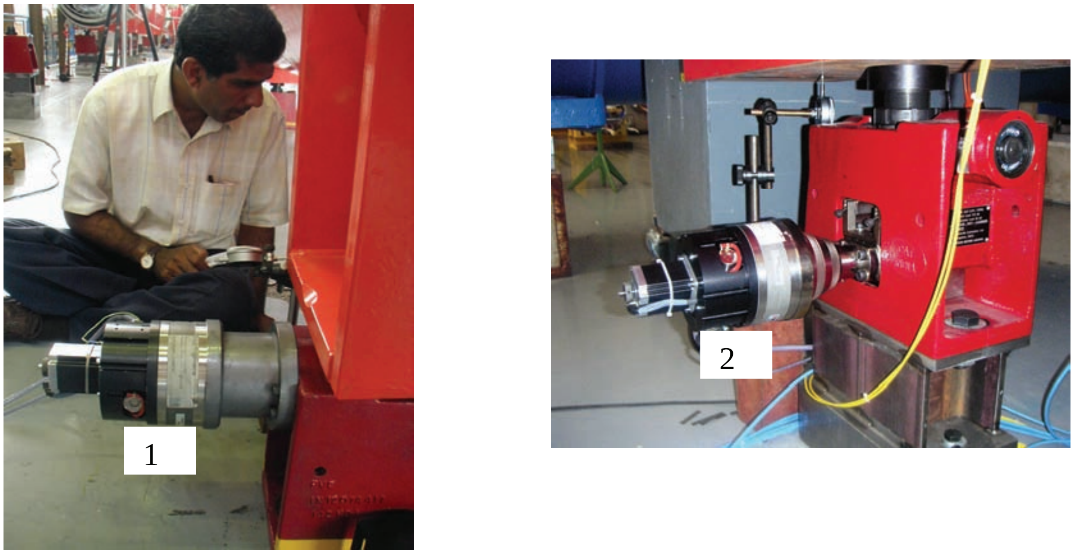

Figure 5: motorization of radial axis (1: radial adapter + motor) and vertical axis (2: vertical adaptor + motor)

Test for vertical resolution has been carried out on the jack with the heaviest load above. The resolution has been tested at the middle and extreme positions of the range,.

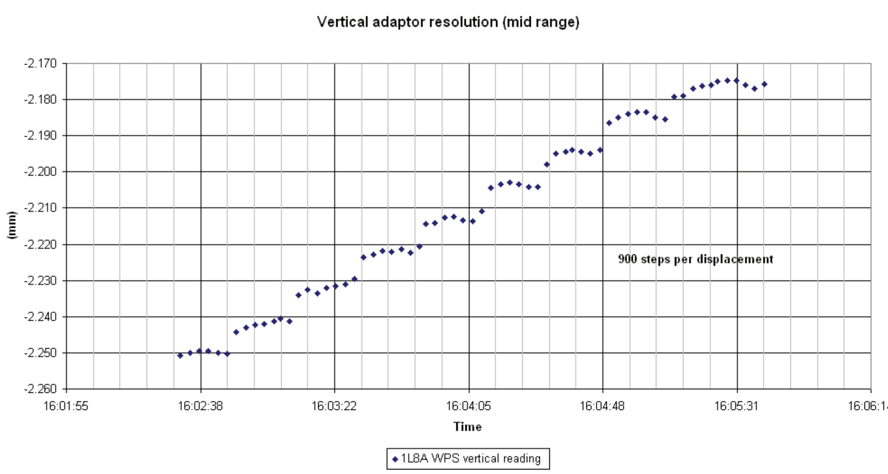

Figure 6: WPS readings of the vertical resolution, which is within the requirements all along the range of the adaptor.

The test for transverse resolution has been carried out on the jack in the worst conditions with longitudinal jack in an extreme position (away from the drive location).

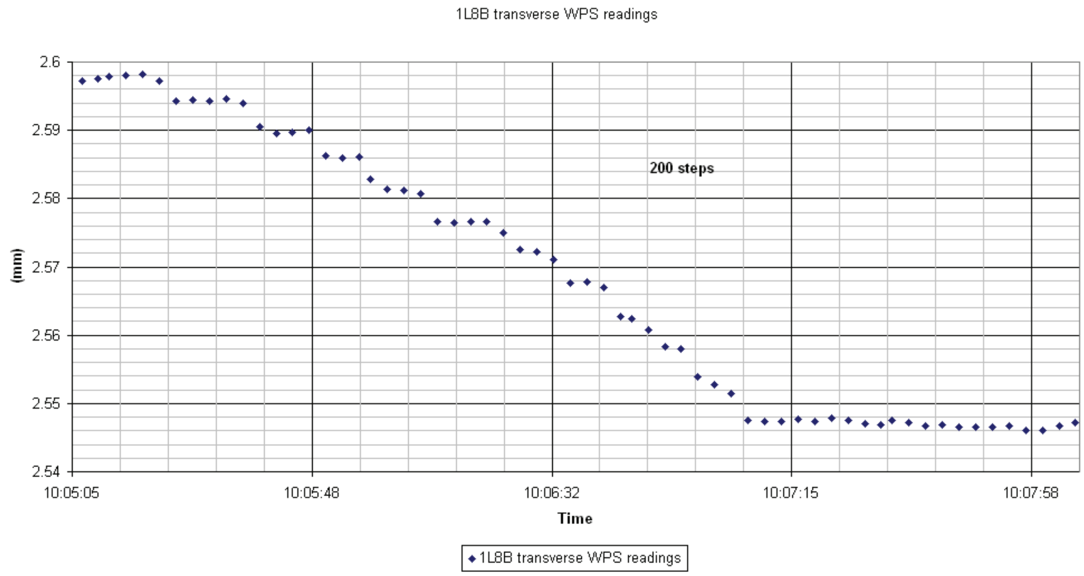

Figure 7: WPS readings of the transverse resolution. The resolution is within the requirements all along the range of the radial adaptor.

The backlash for this jack is about 8° (1500 steps are necessary to displace the motor again if there is a change in the direction). The backlash is constant all along the range per jack (apart from modifications due to age) and it does not affect the set position as it is beyond the self-locking screw. The load capacity of the motorised jacks was tested under a load of 110% of rated load in India by RRCAT. The plugging and unplugging of one motorization (adaptor + motor) takes about 3 minutes to fix it on one jack. The major difficulty is to fix the motor on the adaptor, but this operation will be performed in the mechanical workshop.

3. CONCLUSION

It is concluded as a result of this work motorized jacks for remote positioning of the LHC low beta quadrupoles were successfully developed after the pre-series testing confirmed their performance. The positional tolerances, high radiation environment, need to find out economic solutions in view of the large numbers required and extremely limited space made the work quite challenging. The use of polyurethane block for such a precision lifting requirement is not quite intuitive and is remarkable. The series production of the 80 jacks and 128 adaptors for their motorization was completed in Indian industry under the control of RRCAT and the jacks and adaptors were supplied to CERN according to the LHC schedule requirement.

4. ACKNOWLEDGMENTS

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