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# DEVELOPMENT AND QUALIFICATION OF MICROMETRE RESOLUTION MOTORIZED ACTUATORS FOR THE HIGH LUMINOSITY LARGE HADRON COLLIDER FULL REMOTE ALIGNMENT SYSTEM

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*Abstract*

In the framework of the High-Luminosity Large Hadron Collider project at CERN, a Full Remote Alignment System (FRAS) is under development, integrating a range of solutions for the remote positioning of accelerator components. An important component of FRAS is the motorized actuator allowing the remote adjustment of accelerator components with a micrometre resolution. These actuators need to fulfill multiple requirements to comply with safety rules, and be highly reliable and maintenance free as thus are located in a harsh environment.

The integration of the safety functions required for the FRAS was crucial, with the motorized actuators able to provide an absolute position monitoring of the available stroke, integrating electrical end-stops and having an embedded mechanical stop as a hardware safety layer. In addition, the design has been elaborated to allow a rapid, in-situ re-adjustment of the nominal stroke in order to cope with potential readjustment requirements, following long-term drifts caused by ground motion.

This paper describes the design approach, prototyping and qualification of these motorized actuators.

## INTRODUCTION

The High-Luminosity-Large Hadron Collider (HL-LHC) project is an upgrade of the current LHC that aims to increase its integrated luminosity by a factor of 10. In order to achieve such a luminosity, components of the Long Straight Sections (LSS) will be replaced around the two major detectors (ATLAS and CMS), representing a major modification of 1.2 km of beam line [1, 2].

The increased luminosity will generate higher radiation levels in the LSS and prevent from an easy and safe access in the area. In order to reach the required physics performance, the LSS components will have to be aligned within +/- 0.3 mm (1 sigma) over a 450 m length. The alignment will be performed by the Full Remote Alignment System (FRAS) [3, 4]. It consists of a set of sensors and actuators allowing a micrometre position monitoring and remote adjustment of the accelerator components.

To perform their adjustment, the heaviest components, like magnets, will be installed on a set of 3 standardised jacks (each jack providing 2 degrees of freedom of adjustment). The following chapters describe the design, prototyping and qualification of the radial and vertical motorized adapters used for the accurate adjustment of each jack position.

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## SYSTEM CRITICALITY DUE TO REMOTE OPERATION

During the alignment operations in HL-LHC, the available stroke of the vacuum interconnection bellows linking adjacent components of the beam lines must be taken into account before a relative movement. As the FRAS will be operated remotely, a safety strategy has been implemented to protect the machine from unexpected relative movements that could lead to major failures. Two safety functions, representing the major challenges in the adapters design, have been assigned to the motorised adapters:

- They shall provide at anytime the absolute position of the adapter within its stroke, to control that the displacement at the level of the bellows is performed within the limits of ±2.5 mm.
- A mechanical end-stop shall block any motion if the nominal stroke of ±2.5 mm is exceeded. This additional feature represents a challenge regarding the developed force of the adapters (up to 17 500 kg).

## MOTORISED ADAPTERS DESIGN

### Vertical Position Adjustment

Each vertical adapter has been designed to withstand loads up to 17.5 T, to fit into small jack adapter volume (Figure 1). The compactness of the overall design was one of the major challenges which is why a quasi-hydraulic actuation solution has been selected. The main concept relies on the deformation of a polyurethane pastille in the actuator head. A pushing finger driven by a self-locking thread-nut system deforms radially the pastille taking the full chamber space and lifting the piston to adjust the jack position as per an hydraulic cylinder (see Figure 2). This system, already used today in the LHC, provides a micrometre position adjustment.

### Radial Position Adjustment

For the radial actuation, the motion is performed by the jack mechanism itself, consisting of a screw-nut actuation system linked to a high-ratio worm gear (see Figure 1). Hence, the radial motorized adapter role is to provide a high resolution rotary motion and to measure it in an absolute way. The global stroke of the actuator to perform the ±2.5 mm final motion corresponds to 58 revolutions.

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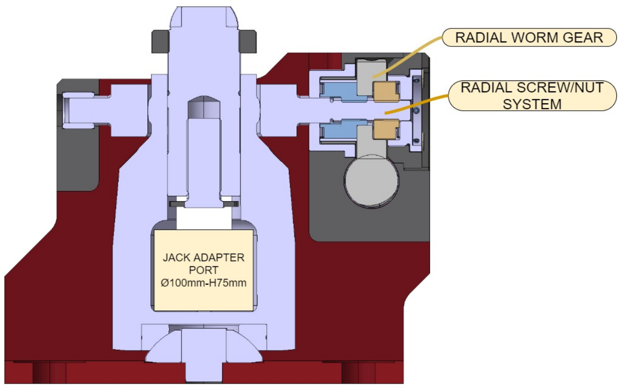


Figure 1: Cross-Section of the HL-LHC jack.

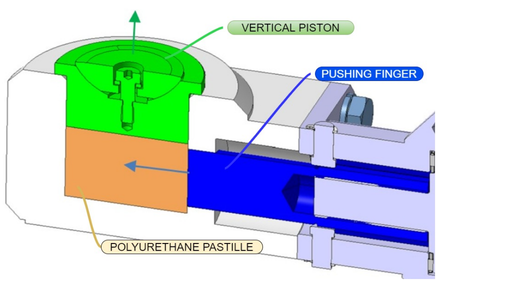


Figure 2: Vertical adapter head based on polyurethane pastille deformation.

### *Stroke Position Monitoring and Nominal Position Adjustment*

Both adapters are designed to provide a jack head (see Figure 3) movement stroke of ±2.5 mm (either radially or vertically). This value shall not be exceeded under any circumstances. To do so, a stroke monitoring feedback loop is embedded in the design of each motorized adapter. Using an additional worm gear reduction constrained by a spring, each adapter is equipped with a "feedback axis" rotating by 360° for a full actuation stroke. This so called feedback axis (Figure 4) is equipped with a resolver operating in an absolute regime (one rotation matched to the full stroke of the jack) and electrical end-switches to prevent any over-stroke movements.

Even if the motorized adapter stroke has been limited for remote operation to prevent too important shifts, the situation where the stroke limits are reached might appear. Such situation caused for example by the floor motion, could lead to the necessity of modifying the nominal position of each motorized adapter.

Due to this additional constrain, the motorized adapters have been designed in a way, that the nominal position of the motorized stroke of ±2.5 mm can be manually adjusted within a higher range of ±5 mm. Hence, both actuators mechanisms allow for a quick and manual adjustment of their motorized range during technical stops if required (Figure 5).

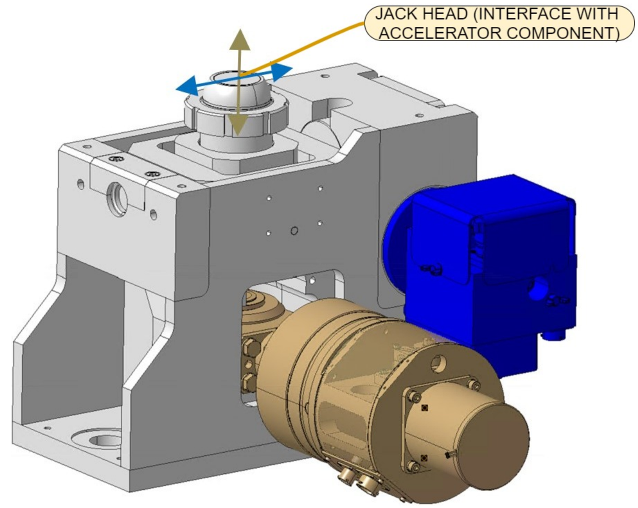


Figure 3: Jack equipped with radial and vertical motorized adapters.

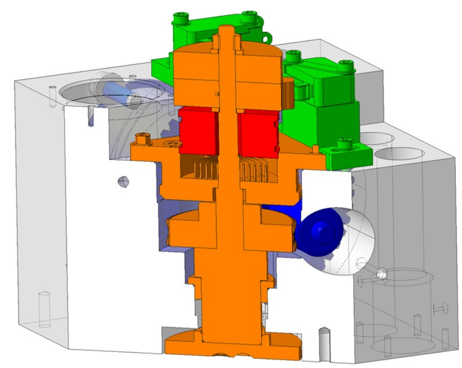

Figure 4: Stroke monitoring system with output axis [Blue], feedback axis [Orange], resolver [Red] and electrical End Switches [Green].

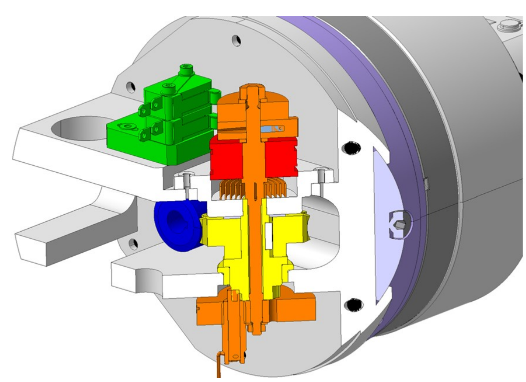

Figure 5: Stroke monitoring system with output axis [Blue], feedback axis [Orange], resolver [Red] and electrical End Switches [Green].

### *Mechanical End-Stop*

In addition to the electrical end-stops (electrical end-switches) and the absolute stroke position monitoring, a mechanical end stop is included in both adapter designs. This additional protection layer need has been specified

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in the FRAS Software Functional Specification [5]. The mechanical end-stop is the last protection barrier against over-stroke movement, in case of a failure of the motion interlock of the electrical end-switches. Unlike classic design, this mechanical end-stop has to be adjustable in case of a stroke-adjustment operation. Hence, the system is based on the feedback axis that contains a programming wheel. This wheel, after over-passing the electrical end-switches, triggers a mechanism that immediately locks the motor axis, preventing any motion of the input pinion linked to the stepper motor axis (Figure 6).

The use of a two-stages triggering system allows reducing the pressure on the feedback axis and consequently reducing the friction on the axis that could degrade the global system backlash.

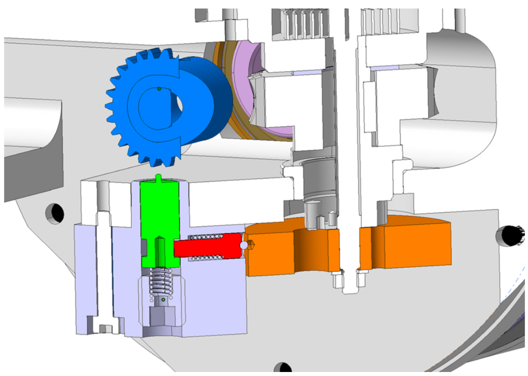

Figure 6: Mechanical end-stop and triggering system composed of programming wheel [Orange], primary axis [Red] and locking axis [Green].

## QUALIFICATION TESTS

In order to verify the performances of the various safety functions, a series of qualification tests has been performed on both adapters. It has been decomposed by adapters functions in order to obtain a step by step validation.

Currently, a set of 2 radial and 3 vertical adapters passed the individual tests that are described in the next chapters. In the future, a real use case on a test magnet, equipped as for HL-LHC is foreseen.

### *Test Configuration*

In order to measure the adapters performance, two tests configurations, adapted to both vertical and radial adapters, has been designed.

- On the Vertical adapter, the measurement is performed on the piston, called “pushing finger”, that shall normally be in contact with the polyurethane pastille (see Figure 2). A micrometric dial gauge has been installed on this piston to compare the stepper motor steps, the resolver reading and the real displacement (see Figure 7).
- On the Radial adapter, the measurement is performed on the output shaft that is at the interface between adapter and HL-LHC Jack. A rotating encoder is used in that case to perform the position reading (see Figure 8).

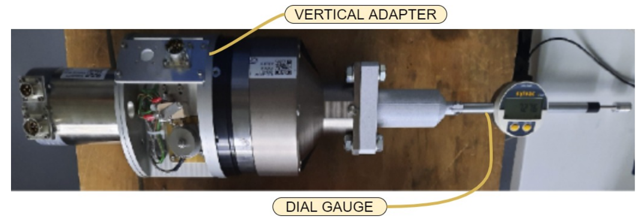


Figure 7: Vertical adapter in test configuration with a micrometric dial-gauge.

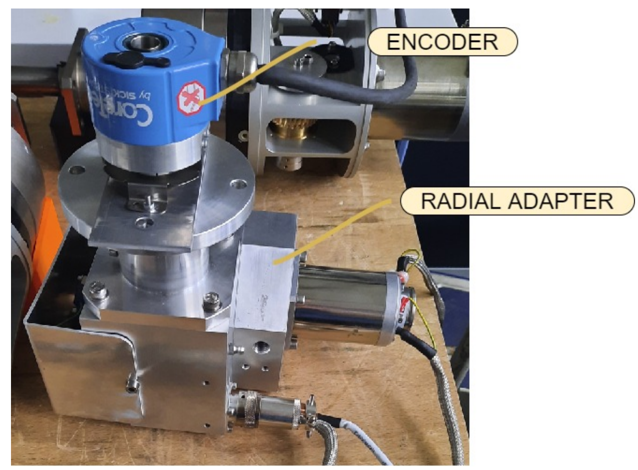


Figure 8: Radial adapter in test configuration with an absolute encoder on the output shaft.

### *Stroke Monitoring Parameters*

Several stroke monitoring parameters have been determined by the tests conducted on the Vertical and Radial adapters:

- The repeatability of the system along the full stroke, reaching several times with the same orientation some referenced positions (based on motor step counting);
- The total system backlash has been computed over 50 cycles, going back and forward to the same position (by using as the reference the stepper motor steps measurements);
- The global position error value has been determined by comparison with the external measurement system (Figures 7 and 8).

Tests results are summarized in Tables 1 and 2 for both adapters. Note that all defect values are extrapolated to the jack head motion - see Figure 3. Consequently, the presented values are already affected by the reduction ratio between measurement point and jack head.

### *Mechanical End-Stop*

The mechanical end-stop system has also been tested.

Before the machining of the adapter prototypes, a mockup containing only the programming wheel and the motor

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Table 1: Position Parameters for the Vertical Adapter

| PARAMETER | SPECIFICATION | RESULT |
|---|---|---|
| Total Stroke [mm] | 5 ± 0.05 | 4.952 |
| Repeatability [µm] | 0.5 | 0.05 |
| Backlash [µm] | 1 | 0.02 |
| Absolute position [µm] | 20 | 6 |

Table 2: Position Parameters for the Radial Adapter

| PARAMETER | SPECIFICATION | RESULT |
|---|---|---|
| Total Stroke [mm] | 5 ± 0.05 | 4.971 |
| Repeatability [µm] | 0.5 | 0.05 |
| Backlash [µm] | 1 | 0.25 |
| Absolute position [µm] | 20 | 10 |

axis has been assembled (see Figure 9). In order to verify the reliability of the system, its triggering has been performed up to 75 times without any failures. It confirmed an instantaneous locking of the motor axis even with the stepper motor at full speed. In normal operation, the triggering of this safety system is treated as a critical issue, and would lead to the replacement or the inspection of the full adapter in order to perform a global system failure analysis.

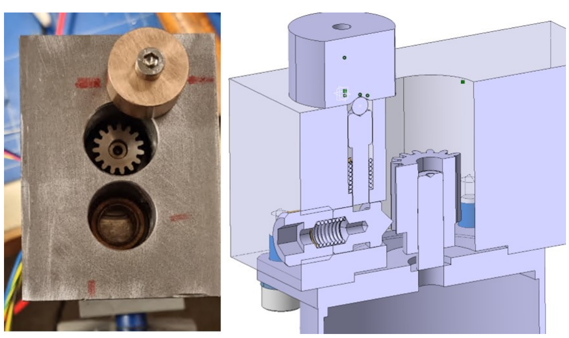
Figure 9: Mechanical end-stop triggering test configuration.

A set of tests on the final design has also been performed on both vertical and radial adapters to confirm the implementation of the design on the full assembly. Tested at nominal motor speed, both adapters showed an instantaneous stopping of the motion. This validates the additional safety layer performed by the mechanical stop. Moreover, only the motor pinion was slightly damaged by this test so the system can be reused in other designs even in applications where the actuation rate would be higher.

## CONCLUSION

The individual tests of the vertical and radial motorized adapters have shown very good results with an accurate reading of the actuator position and an appropriate triggering of the safety functions.

Additional qualification steps must still be performed on the full magnet set-up, to crosscheck the operation of the motorized adapters and jacks supporting a real component. The aim of this step will be to check that adapters properties are still compliant under nominal load and that motorized adapters allow an accurate adjustment of the component, providing correct stroke measurements used for the bellows protection. As the design is now validated, the radial adapter concept will be extrapolated for the position adjustment of smaller accelerator components in the frame of the FRAS. In that case, a Universal Adjustment Platform (UAP) [6], already developed at CERN, will be motorised with the same type of actuator.

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