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MECHANICAL DESIGN AND TESTING OF A MAGNETICALLY COUPLED MOTION SYSTEM FOR LHC WIRE SCANNERS

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Abstract

Linear wire scanners are essential instruments for beam profile measurements in the Large Hadron Collider (LHC) at CERN. The current scanners installed in the machine have shown reliability and performance limitations in recent years. This work presents the development and validation of a bespoke motion system for the next-generation LHC wire scanners. The design replaces vacuum bellows with a planar magnetically coupled linear drive, coupled to a custom ceramic in-vacuum linear guide capable of high-velocity operation in ultra-high vacuum. A dedicated test rig has demonstrated the system's positional accuracy, rigidity, and long-term durability, with over 80,000 cycles completed without degradation. This motion technology will be integrated into the first prototype scanner for impedance verification during the 2025 year end technical stop (YETS) and offers potential for wider application in demanding vacuum environments.

INTRODUCTION

In the Large Hadron Collider (LHC), Linear Beam Wire Scanners (BWS) play a key role as the reference instrument for machine developments and are used to calibrate other profile measurement devices which provide precise bunch-by-bunch measurements at all energy levels [1].

In November 2023, as part of the Wire Scanner Consolidation Project, work began on a new generation of LHC Linear BWS. The objective of the new design is to address mechanical limitations and reliability issues of the existing scanners, for which the design predates the Large Electron–Positron (LEP) collider installation in the 1980s [2]. The long interval since the legacy design offers the opportunity to integrate modern materials and motion-system technology.

A new scanner design has now been finalised, with the first prototype scheduled for installation in the LHC during the 2025 year-end technical stop (YETS). The new design, shown in Fig. 1, differs significantly from the legacy system, largely to accommodate a new magnetically coupled driving system that eliminates the need for vacuum bellows — a frequent failure mode in current scanners [2]. This paper describes the design and development of this bespoke driving system, and the testing performed to validate its suitability for use in the LHC.

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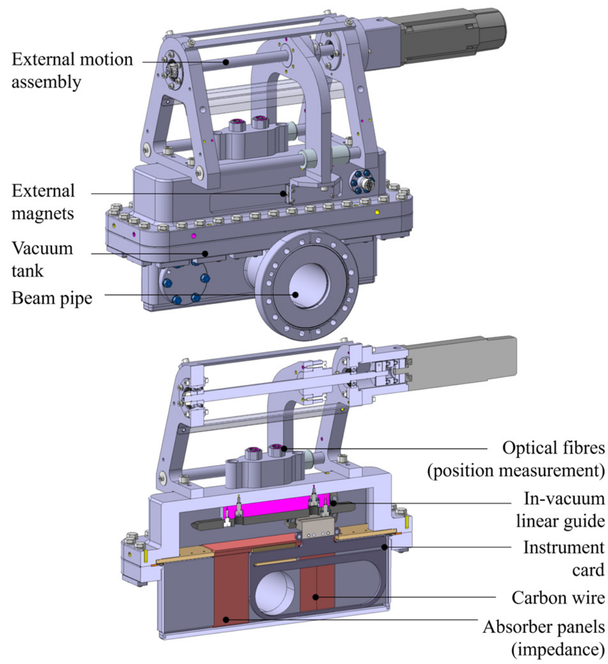

Figure 1: New LHC wire scanner prototype design.

ENGINEERING DEVELOPMENT

Commercially available magnetically coupled drive products have previously been tested at CERN for their suitability in BWS applications, with positive results [3]. These systems typically operate via a concentric magnet pairing through a thin-walled cylindrical vacuum chamber [4].

Although integration of such an off the shelf system into the new scanner was considered, it was ultimately rejected in favour of a custom-engineered solution. A cylindrical system would require a large space envelope, as the entire drive length must be mounted to the side of the chamber [2]. In addition, a key mechanical limitation of the legacy scanner would remain — the long, unsupported cantilever between the drive fixation point and the wire-measurement point, inside of vacuum, which can cause vibrations and positional uncertainty.

The drive system developed for the new scanner implements a permanent magnet (PM) based planar linear magnetic coupling (PLMC) [2]. A pair of externally driven planar magnet arrays are coupled with a second pair inside the vacuum chamber. The inner arrays are mounted on an in-vacuum linear guide, to which a card supporting the scanning wire is directly attached. Both the coupling and the linear guide have been designed specifically for this application, with the aim of providing repeatable and reliable scans. This new drive system is shown in Fig. 2.

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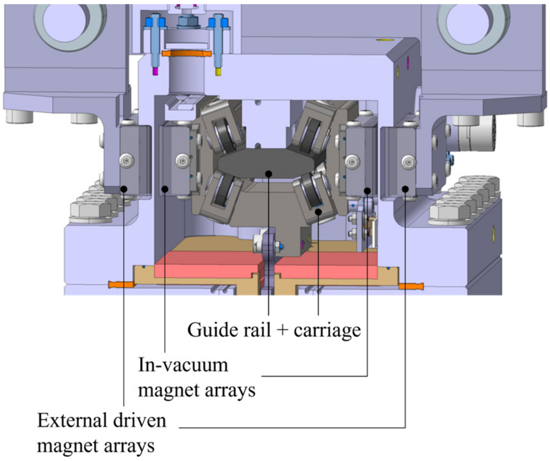

Figure 2: Sectioned view of the new scanner drive system.

In-Vacuum Linear Guide

Resolving the unsupported-cantilever issue required an in-vacuum linear guide to optimise the motion profile. The restrictive operating conditions of the LHC scanners meant that no commercially available guide met the following requirements:

- Ultra-high vacuum (UHV): 1×10^{-11} mbar
- Bake-out temperature: >150 °C
- Peak operating speed: 1 m/s
- Stroke: 133 mm
- Lifetime over one operational run: 20,000 cycles
- Positional resolution: < 15 µm
- No polymers or liquid lubricants

All rejections from suppliers cited the inability to guarantee the required lifetime or velocity without lubrication. A research and development collaboration with Ceratec Technical Ceramics BV (Netherlands) was initiated to develop a suitable guide. The first prototype consisted of a titanium carriage with silicon nitride (Si_3N_4) bearings with PEEK cages, running on a Si_3N_4 rail. The bearings were preloaded onto the rail via thin sections of the titanium carriage, which acted as mechanical springs to provide a smooth motion profile.

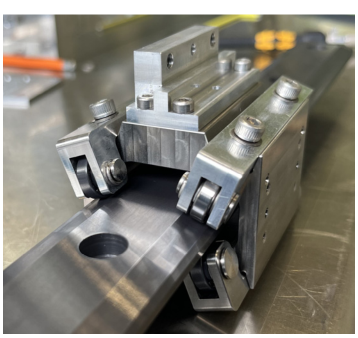

Figure 3: Image of 2nd iteration ceramic linear guide.

Following initial testing, the guide was modified to the second iteration shown in Fig. 3. This version replaced the mechanical spring sections with solid carriage arms, preloaded to the rail using disc springs. The change increased the carriage strength and resilience to lateral loading. This was in response to the first design deforming during magnet installation due to unbalanced attraction forces. The new arrangement also allows the preload to be tuned, balancing rigidity and friction as required, then fixed for operation using set screws.

Magnetic Coupling

The PLMC prototype array produced for testing is shown in Fig. 4. The arrays underwent an optimisation campaign to identify the best magnet arrangement within the available envelope. Each array consists of six alternating-polarity Samarium–Cobalt (Sm_2Co_{17}) rectangular magnets mounted on a ferrous yoke.

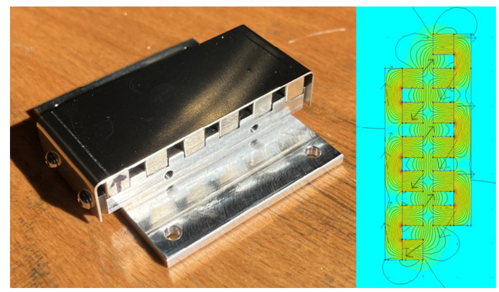

Figure 4: Assembled magnet array (left) and simulated displaced coupled array field map (right).

This design provides high predicted magnetic rigidity when the coupled arrays are displaced along the scanning direction. The two pairs of arrays are coupled through a 1 mm thick section of the stainless steel (SS) vacuum chamber, see Fig. 2. The total separation between the magnet arrays inside and outside of vacuum is 4 mm, which includes 1 mm each of vacuum and air gaps, and an additional 0.5 mm of a SS sheet on each array to secure the magnets to the yoke, and protect them during assembly and operation, as seen in Fig. 4. This gap has been optimised to find a compromise between rigidity and attraction force.

The scanner uses arrays mounted on either side of the linear carriage, balancing the attraction forces and preventing excessive bearing loads, as seen in Fig. 2. The carriage is designed to withstand this bidirectional pulling force with negligible displacement and stress.

TESTING

To validate the motion system for the new scanner, a dedicated test rig was produced, shown in Fig. 5. On the rig, the magnetic coupling and guide assembly are implemented exactly as on the instrument, except the inner (in-vacuum) parts operate in air. The outer (air-side) components are driven by a ball screw and linear guide, representative of the final design. Removable 1 mm SS panels, not shown here, can be fitted to the rig to simulate the vacuum chamber wall. With this rig, three key characteristics of the developed technology were tested:

Coupling Rigidity The inner carriage was fixed to the rig frame via a force sensor, while the outer carriage was displaced using push screws. Position was measured with a dial gauge in 0.1 mm steps; the force sensor output was used to construct a rigidity profile for comparison with simulation, repeated at different air gaps.

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Coupling Slack Magnetic encoders on the inner and outer carriages recorded real-time positions during scans, allowing the profiles to be compared to quantify the slack.

Linear Guide Lifetime The motion profiles were logged to assess the guide performance over time and detect any degradation under high cycle counts.

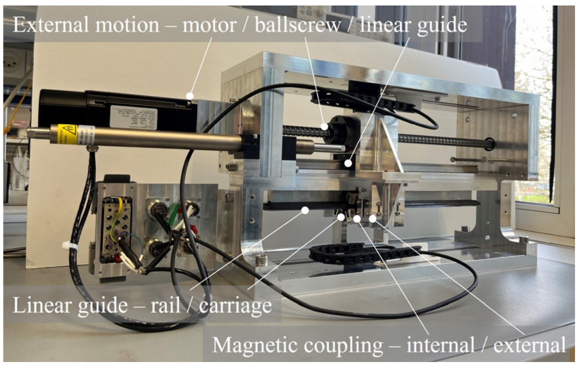

Figure 5: Image of finished test rig.

RESULTS AND DISCUSSION

Coupling Rigidity Figure 6 shows the measured force in the scanning direction versus displacement at two gap sizes. For the chosen 4 mm, a steep increase in attraction force is observed for small displacements, giving a rigidity of ≈45 N/mm. Comparisons with simulation show a ≈20 % reduction in the measured data, likely due to variations in supplied magnet strength and inherent limitations in the modelling. The root cause is still under investigation.

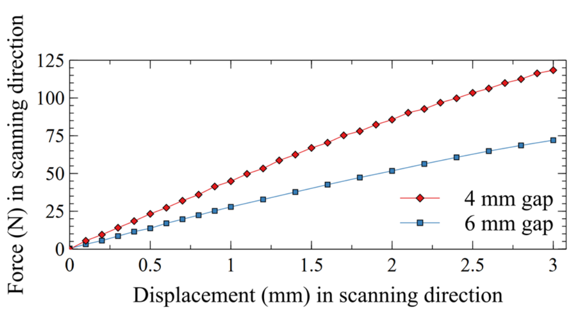

Figure 6: Rigidity plot for 4 and 6 mm air gap couplings.

Coupling Slack Figure 7 shows the displacement profiles of the inner and outer parts of the coupling, along with the positional difference between them. As expected, a measured slack is present, necessary to initiate an acceleration, but the in-vacuum part closely follows the driven external part. Within the ≈ ±35 mm wire-in-beam zones, the slack remains below ±0.4 mm. The position measurement is assumed independent of this slack, as the final instrument will use an in-vacuum incremental optical encoder to reconstruct the beam profile. The graph shows the reproducibility of the slack within ±0.1 mm across 29 scans.

The position difference plot has revealed a harmonic vibration around 37 Hz. There is a risk that these vibrations could excite the wire and introduce errors. A calibration campaign using a laser to simulate the particle beam is under way to assess the true impact. In parallel, the motion profile is being optimised through adjustments to the motor control input to damp the oscillations throughout the scan.

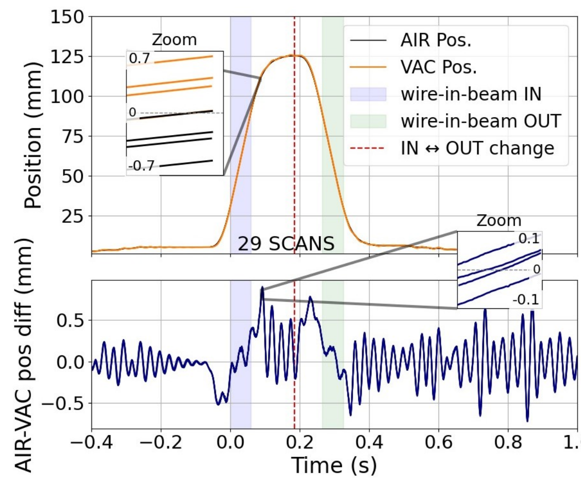

Figure 7: Plots showing the position and position difference of the inner and outer parts of the coupling.

Initial results show the new scanner achieves better accuracy compared to the existing scanners, despite the observed vibrations [2]. The expected accuracy of the wire position determination for the new scanner is 15–20 µm.

Linear Guide Lifetime During the first test phase, the rig completed over 80,000 scans – more than four full operational runs – far exceeding the required lifetime. The reproducibility of the slack remained stable throughout the campaign, indicating negligible degradation. For example, analysis of 10,000 scans between cycles 20,000 and 30,000 showed a maximum peak-to-peak variation of 0.2 mm over the whole scanner stroke, confirming system stability.

Inspection of the guide after the campaign revealed residue along the rail, assumed to originate from the bearing cages. Dismounted bearings showed increased rolling resistance, but this added friction did not affect the motion profile or cause blockage. Alternative bearings are currently under test: Full-complement Si_3N_4; Hybrid with SS races and Si_3N_4 balls; Full Si_3N_4 with SS cages. The last configuration is expected to outperform the others and will be implemented on the first installed prototype. The final phase of endurance testing will be conducted under vacuum, which should confirm that ambient-air operation did not affect the lifetime results.

CONCLUSION

A bespoke planar magnetically coupled drive system with an in-vacuum linear guide has been developed for the new LHC wire scanner, eliminating the need for vacuum bellows - a recurring failure mode in the legacy design. Testing on a dedicated rig confirmed the system meets positional accuracy, rigidity, and lifetime requirements, with over 80,000 scans completed without performance degradation. Although a coupling vibration was observed during scanning, the new scanner is expected to improve wire-position determination accuracy to 15–20 µm. The new motion technology is scheduled for integration into the first prototype scanner, installed in the LHC during YETS 2025. The results of this campaign will guide the next iterations of the design and prepare the system for series production foreseen during the third LHC Long Shutdown (LS3).

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