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THE LARGE HADRON COLLIDER'S BEAM WIRE SCANNER CONSOLIDATION

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Abstract

To serve the needs of the High Luminosity Large Hadron Collider (HL-LHC) era, a consolidation of the beam wire scanner has been initiated. The instrument is a crucial tool for measuring the transverse beam profile by moving a thin carbon wire across the beam. It can only withstand a fraction of the LHC's nominal beam intensity but provides a reference to calibrate other instruments that operate non-invasively at higher beam intensities. Since the start of the LHC, the scanners have provided hundreds of thousands of measurements, but the design has technical limitations that need to be addressed to provide the required reliability and performance for the HL-LHC runs. The initial consolidation phase involved testing the injector's acquisition and control electronics in the LHC to assess its suitability for the specific beam conditions. As part of this process, we updated the mechatronic and motion controller. Beam test campaign has revealed higher performance w.r.t the existing system and a higher adaptability to varying beam conditions. Simultaneously, we are developing a novel actuator that uses a permanent magnets-based coupling replacing the standard bellows and long arm that limits the performance and induces vibrations. Before testing this new concept with beam, we have developed a calibration bench to evaluate the mechanism's precision and accuracy of the wire position determination. This contribution presents the 2023 beam and laboratory tests as well as the electromechanical developments.

LHC WIRE-SCANNERS

From the beginning of the Large Hadron Collider (LHC), eight wire scanners systems (BWS) with linear motion are in operation to characterize a fraction of the total beam intensity. These scanners provide reference measurements for machine developments and calibrate non-invasive instruments suitable at all beam intensities [1]. So far, these systems have accumulated more than 225k measurements, providing reliable data for over 15 years [2–5]. Driven by a mechanism originally designed for LEP [6, 7] visible on Fig. 1, the carbon wire is accelerated up to a velocity of 1 m/s through the beam. A scintillator followed by inter-changeable neutral density filters and a photo-multiplier evaluates the intensity of the secondary particles generated by the beam-wire interaction.

The linear motion was chosen over the rotary type due to higher precision in the carbon wire position determination and higher data points per beam sigma due to lower velocity. This velocity is safe to characterize beams with $2.7 \cdot 10^{13}$ protons at 450 GeV and $1.5 \cdot 10^{12}$ at 6.8 TeV [8]. These levels are sufficient for operational purposes and to cross-calibrate other instruments [9, 10].

After a few years of operation, early failures of some key electronic components were observed [11], leading to system unavailability until parts were replaced. These limitations were addressed with the electronics dedicated to a rotary system for the LHC injectors [12], under development at that time. The improved electronics, developed as part of the LHC injector upgrade [13], has been in operation since 2021, providing higher reliability and performance compared to previous generations [14]. More recently, the mechanism of the LHC BWS has shown reliability limitations during intensive operation, causing failures (e.g. vacuum leaks) and machine downtime.

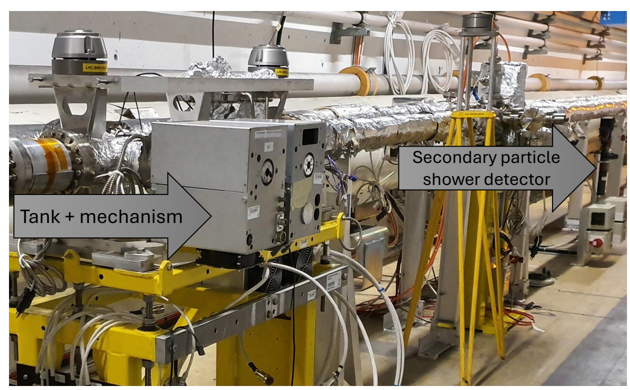

Figure 1: Beam wire-scanners on LHC Beam 1 line.

CONSOLIDATION

The consolidation aims to prepare the BWS for the HL-LHC with enhanced overall reliability and performance and to be ready for higher beam intensities and smaller beam sizes. Through this renovation, we also aim to prepare the wire scanner for future upgrades. R&D (not covered here) includes the study of low-density materials and smaller cross-sections [15]. By achieving the consolidation objectives, we will significantly reduce instrument downtime while enhancing accuracy and precision. These improvements will ensure compatibility with HL-LHC beams [16]. Table 1 summarizes key parameters of the operational system in place today (column OP), the intermediate system equipped with the consolidated electronics (column LIU), and the fully consolidated system (column HL).

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Table 1: Designs Parameters

Parameter	OP[a]	LIU[a]	HL[a]
Wire velocity m/s	1.1	0.85	>=1.1
Wire stroke mm	133	133	133
Beam ϵ_n [b]	3.75	3.75	2.5
Beam σ 450 GeV ~ µm	800	800	670 [c]
Beam σ 6.8 TeV ~ µm	200	200	150 [c]
Precision µm [c]	20	10	5
bakeout temp. °C	80	150	150
lifetime in kcycles [d]	10	25	80
motorisation [e]	dc	pmsm	pmsm
transmission	belt	direct	direct
position encoder	resistive	inductive	optical

[a] from design reports [16]
[b] OP: Operational, LIU: intermediate, HL: final system
[c] forecast by scaling from $_n$ difference
[c] Estimated physical beam size precision
[d] Mechanism lifetime before servicing (by design)
[e] dc: direct current motor, pmsm: permanent magnet synchronous motor

The mechatronic system must accelerate the wire to a nominal velocity of 1 m/s, with the wire position measured every LHC turn (89 µs). This wire speed—slower than in the LHC injectors—allows sampling of many profile points at injection. However, it makes profile reconstruction challenging at top energy, where beam sizes can be as low as 200 µm. Since slowing the wire further would limit the maximum measurable beam intensity without breaking wires, monitoring the wire position with high accuracy is crucial.

The consolidation was planned in two phases, defined and optimized to cope with various factors including LHC master schedule, budget, and resources.

1. **Control and DAQ electronics** validation before LHC Long Shutdown 3 (LS3). For this phase, the operational electromechanism was modified (only outside vacuum parts) and the new electronics and SW adapted to control and readout linear scanner systems.

2. **Final electromechanical design**. This involves the design of a novel actuators solving the present systems reliability and mechanical stability issues. If planning allows an installation in the LHC before LS3, the full validation in the laboratory will be complemented by beam tests.

Four consolidated systems are expected to be operational after LS3, along with four legacy systems. After a phase of cross-comparison, an additional four consolidated scanners will replace the remaining legacy systems.

PHASE 1 - CONTROL AND DAQ ELECTRONICS TESTS

The secondary particle shower evaluation and the scanner controller hardware are identical to the electronics for the rotary scanner [14] developed during the LIU project [13]. Software modifications were required for both the accelerator control infrastructure linkage and the scanner controller's internal operations. Figure 2 shows the system architecture with the mechanism and detector (left) and the acquisition and scanner controller (right).

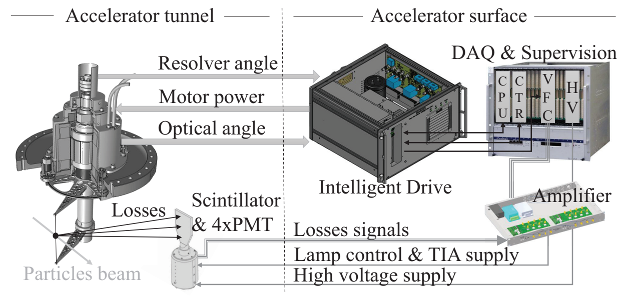

Figure 2: Wire-scanner system architecture.

The new electronics uses FPGA-based motion control fully developed at CERN for this instrument. The electronics are situated far away from radiation, requiring careful design of the motion controller [17] and power stage filtering to reduce perturbations on long cables. Various sensors, including a high-precision optical encoder [18], are integrated into the controller.

A polymer-based scintillator coupled with four photomultipliers (PMT) evaluates the losses generated by the wire interacting with the beam. Each PMT has different neutral density filters to cover larger dynamic ranges and a custom powering scheme to reduce the time between measurements [19]. The acquisition chain features high-speed digitizers coupled to FPGA-based on-demand digital integration to adapt to different accelerators and beam schemes [20].

The software architecture has been developed with two layers. The first layer independently controls the motion controller and the particles detection while the second layer combines the two data sources, applies calibration and presents the interface to external systems [21]. Only minimal changes were necessary to adapt this software to the LHC system, as the adaptation to the new electromechanics occurs within the controller's FPGA.

Actuator Upgrade for the Liu Electronics

The electromechanical system was partially upgraded to become compatible with the controller of the rotary systems [14] to profit from its higher reliability, greater versatility and upgraded acquisition scheme. Figure 3 shows the mechanism in operation (left) and partial upgrade (right). The motor was changed to a permanent magnets-based synchronous motor (PMSM) with an angular encoder and a ball screw instead of slippery coupling. The compensation springs to balance the vacuum force were removed and compensated by the extra friction of the pre-loaded ball screw. The scanner controller was adapted to a rotational speed four times higher, multiturn operation and additional non-linearity introduced by higher frictions compared to the rotary system. With this design, the electronics and acquisition system were tested in

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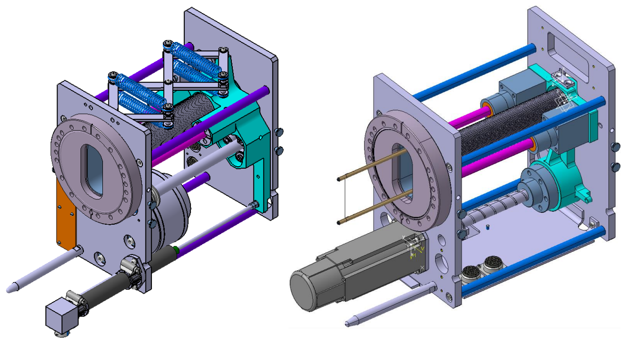

Figure 3: legacy mechanism (left), partial upgrade (right).

the LHC, but it eventually became evident that the mechanism would not meet all the consolidation requirements.

Beam Tests in the LHC

Two BWS systems, mechanically modified (outside vacuum part only) to be compatible with the new electronics were installed to measure the horizontal profiles of the two LHC beams [22].

Various set of experiments were completed to validate the new control electronics and DAQ chain. The measurement results were compared to the legacy systems, closely located and operated at the same time. To date, the most representative set of measurements [23] was obtained during a dedicated LHC fill using three bunches with different emittances, measured at both injection and top energy.

Figure 4 shows the beam size measure difference between the legacy and new systems during the Machine Development (MD) number 9545 at injection energy (FB, left) and Top energy (FT, right). Both systems obtain matching results with a relative difference in the order of $\pm 2.5\%$ and no more than 25 µm of absolute difference. Figure 5 shows the averages for both systems of the IN beam scan measurement minus the OUT beam scan measurement taking place a few seconds apart. While both systems present compatible results with a max average of 10 µm, the new system presents lower statistical errors and better coherence between FB and FT. The overall dataset confirms very coherent results between legacy and new systems. Nevertheless, the new system has a very high potential for improvement by optimizing

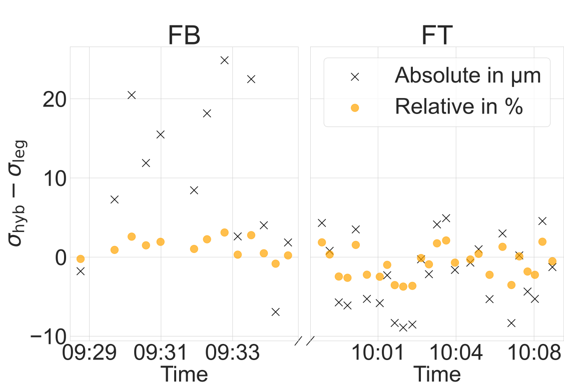

Figure 4: Difference in beam size between systems.

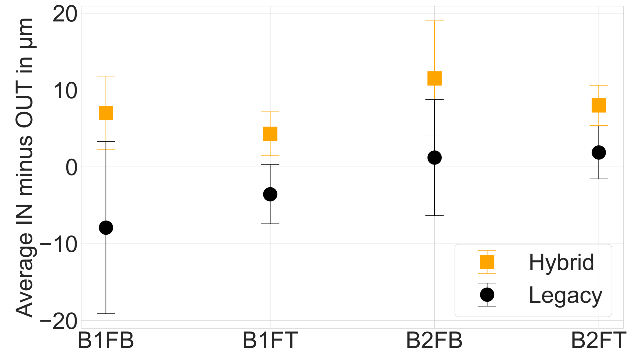

Figure 5: MD#9545 beam size IN - OUT difference.

its operational measurement point and by taking advantage of its four parallel PMT acquisitions.

PHASE 2 - UPGRADED ELECTROMECHANICS

The next step in consolidating the BWS systems focuses on developing an improved electromechanical system to ensure high reliability, availability, and accuracy. Key design challenges, briefly discussed below, relate to wire position determination, improving or avoiding movable vacuum bellows[1] and optimizing the overall electromechanics to minimize mechanical play and vibrations[2]. This last point involves studying novel actuators and refining the control system—for example, to enhance motion control stability.

Bellow-Free Actuator Study

We have started investigating a bellow-free actuator using a commercial tubular-type permanent-magnet (PM) linear magnetic coupling (TLMC) [24]. This type of link is made of permanent magnets that attract each other through a thin membrane, replacing the vacuum bellow-based actuation. To have enough accuracy, this type of link requires an in-vacuum encoder. The developments completed so far are documented in [25], which demonstrates how the design can be optimized by: 1) Modeling the link using a second-order transfer function 2) applying a motion pattern that minimises the resonance peak of the link. These methods can significantly reduce vibrations of the inner part. Figure 6 illustrates the beneficial effect of the time-optimal trajectory that strongly attenuates the main resonance of the inner part motion.

Mechatronic Concept

Another branch of developments focuses on designing and prototyping a bellow-free instrument built around an in-vacuum linear guide and a planar magnetic link. The new concept is based on a removable card with the wire (see Fig.7 center) that slides inside a thin vacuum vessel (bottom) by means of an in-vacuum rail that is actuated with

[1] Due to the steadily increasing usage rate over the years, numerous vacuum leaks have occurred at the bellows level with the current design.

[2] The cantilever arm holding the wire forks limits performance. It's susceptible to misalignment and vibrations, which affect wire position accuracy.

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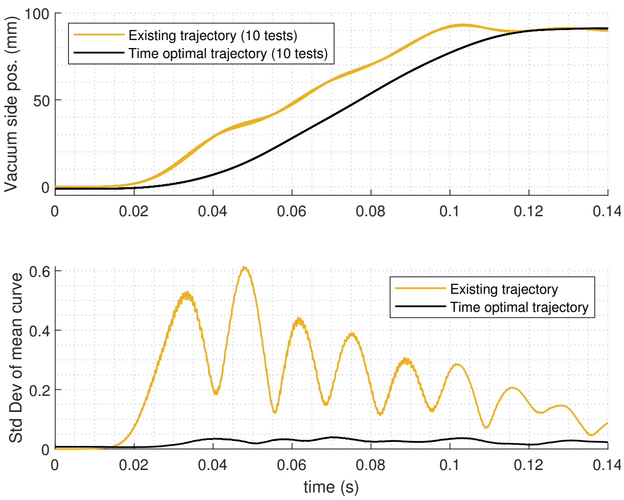

Figure 6: TMLC in-vacuum part actuated with a time-optimal trajectory strongly attenuating the main resonance.

permanent magnets links through a thin wall (top). The integration into the LHC environment is being carefully evaluated, considering radiation compatibility, outgassing, and electromagnetic coupling with the circulating beam. The latter can lead to thin wire heating to the point of breakage, a phenomenon observed for years on rotary systems of the CERN SPS [26–28].

The legacy mechanism relies on a motion guiding system outside vacuum. In contrast, the magnetically coupled actuation configuration requires an in-vacuum inner part with a low-friction guide to ensure high accuracy.
Collaboration with industry has led to the on-going development of a guiding technology based on high-precision fully ceramic rail and wheels. This innovation aims to ensure precise operation for tens of thousands of cycles. A pre-study shows we may operate the new concept without an in-vacuum encoder and rely on position prediction [25]. Nevertheless, a high-precision in-vacuum wire position sensor should be considered as an option to enhance the ultimate system performance. This approach was developed for the LIU project [18], using a continuous laser beam focused on an in-vacuum optical disk. A similar method is currently

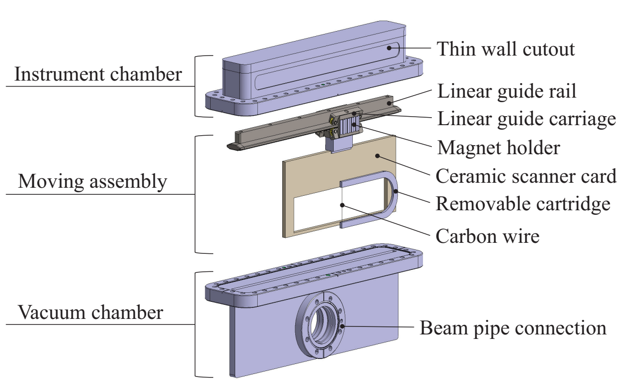

Figure 7: Magnetically coupled wire-scanner concept.

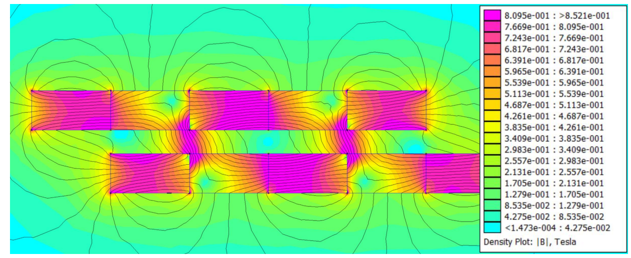

Figure 8: Magnetic flux density plot of the planar link concept with longitudinally magnetised permanent magnets.

being pursued for this project, which aims to integrate an in-vacuum linear ruler engraved with reflective patterns.

Planar Permanent-Magnet Based Linear Coupling

To actuate the scanner card, a planar permanent-magnet-based linear coupling (PLMC) was preferred w.r.t. a tubular-type permanent-magnet linear magnetic coupling (TLMC). The TLMC stands off the axis of the beam and therefore requires long arms to hold the carbon wire.

The PLMC is an in-house design around a custom made rail placed very close to the wire. Various magnetic link topologies were modeled using Finite Element Analysis (FEA), similarly as in [24] to benchmark various options and select the most appropriate. Figure 8 shows the magnetic density plot of a permanent-based magnetic link with longitudinal magnetisation to the displacement plane. The misalignment between the upper and lower parts generates horizontal force. The FEA is performed to compute the force versus position misalignment and benchmark the solutions using absolute maximal force and force rigidity figures.

CONCLUSION

The consolidation of the wire scanner is progressing steadily to meet the new requirements for the HL-LHC era. We have successfully assessed and validated the secondary particle shower acquisition chain and scanner controller electronics for LHC beams. Our team is currently prototyping a new scanner mechanism, incorporating an innovative card concept featuring an in-vacuum rail, an optical encoder near the carbon wire, and actuation via a planar magnetic link.

In early 2025, we plan to assess the accuracy and precision of this concept using a bench setup that simulates the particle beam with a laser. This setup will allow us to quantify the carbon wire position determination using a novel in-vacuum linear rule coupled with our custom-designed intelligent drive electronics. Based on the results of these assessments, we will target a potential installation of a prototype in the LHC by the end of 2025.

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