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LABORATORY AND BEAM BASED STUDIES FOR ASSESSING THE PERFORMANCE OF THE NEW FAST WIRE SCANNERS FOR THE CERN INJECTOR COMPLEX

J. Emery*, P. Andersson, W. Andreazza, J. M. Fernandez, A. Goldblatt, D. Gudkov, F. Roncarolo
J. L. Sirvent, J. Tassan-Viol, R. Veness, CERN, Geneva, Switzerland

Abstract

At CERN, fast beam wire scanners serve as reference transverse profile monitors in all synchrotrons. As part of the LHC Injector Upgrade project, a new generation of scanners has been designed to improve system reliability, precision and accuracy in view of higher brightness beams. This paper will discuss the performance achieved during both laboratory calibration and prototype testing with beam. The beam measurements performed in 2018 demonstrated excellent system reliability and reproducibility, while calibration in the laboratory showed that an accuracy below 10µm can be achieved on the wire position determination.

INTRODUCTION

Fast Beam Wire Scanner (BWS) systems are commonly used in synchrotrons to monitor transverse beam sizes. They are based on kinematic units designed to move very thin wires at high speed through a particle beam. The wire-beam interaction generates a shower of secondary particles that is typically measured by a scintillator coupled to a photomultiplier tube. The correlation between the wire position and the intensity of the secondary particles shower allows the determination of the transverse beam size.
As part of the LHC injectors Upgrade (LIU) project at CERN, the 17 BWS systems presently installed in the CERN PSB, PS and SPS, historically using 3 different designs, will be replaced by a single, new generation of device that will be start to be commissioned towards the end of 2020.

The new design aims at combining the movement accuracy of presently used linear systems that are limited in speed [1] with the high speed of rotative scanners [2, 3]. In addition the new design (see Fig. 1) will be made more robust by not including any moving vacuum bellows, a common source of failure on its predecessors. All moving parts (motor, resolver, optical encoder and fork) are on the same shaft on the vacuum side, while the motor stator coils are on the air side. A thin, magnetically permeable membrane allows magnetic energy transmission from stator to motor without the need for a vacuum feedthrough.

The use of a *direct drive* system, where the motor is directly coupled to the parts to actuate, leads to lower mass, lower friction and reduced mechanical play. With this arrangement, the angular position of the fork is driven without the translation stage or gearbox used on older systems, thus yielding enhanced accuracy and precision.

* jonathan.emery@cern.ch

Wire Position Determination

The shaft angle, and thus the wire position, is measured by an optical encoder based on a reflective disk engraved with anti-reflective marks. The encoding of the marks during disk rotation gives the incremental angular position. The absolute angle is calculated from the encoding of specific reference marks. An extensive description of the optical encoder design can be found in [4].
Even though the mechanical design was optimized for high stiffness and low mechanical play [5,6], a laboratory bench is systematically used to verify the transverse wire position as a function of the angular position of the shaft for different wire speeds. This calibration allows any fork or wire deformation during the scan to be corrected.

Secondary Particles Detection

The beam-induced shower of secondary particles generated as the wire interacts with the beam will be measured by a scintillator located downstream of the beam-wire interaction point. In the current systems this scintillator is coupled to a Photo-Multiplier Tube (PMT), with selectable neutral density filters placed between the scintillator and the PMT to cover the signal generated by the wide variety of beams in the LHC injectors. For the LIU systems, the single PMT combined with neutral density filters, has been was replaced with four PMTs linked to the same scintillator each with a fixed neutral density filter [4]. All 4 PMT signals are then digitised in parallel. Depending on the beam parameters, there will be always one optimal PMT which is not saturated and with enough signal to noise, that can be selected by software after the acquisition, eliminating the need to choose an appropriate optical density filter before each measurement. The new PMT setup includes custom

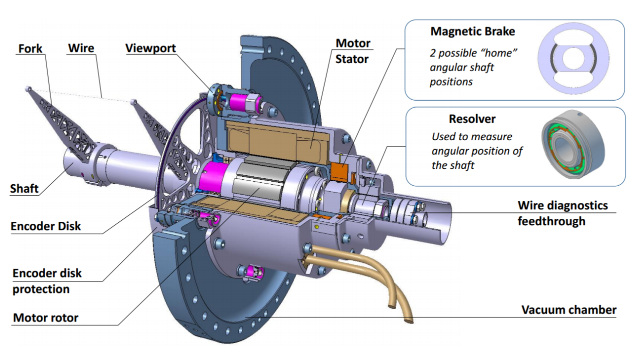

Figure 1: LIU wirescanner electro-mechanical mechanism and movement encoders.

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made powering boards (Fig. 2), designed to maximise the number of charges the tube can detect per unit time without saturating. This detection technique has been extensively tested and optimized in the laboratory [4].

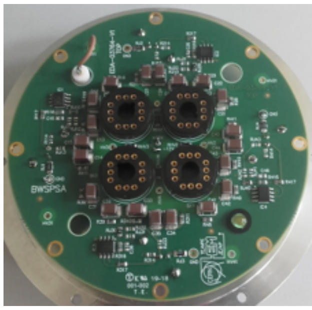

Figure 2: Custom made power board for the four-PMTs used to couple to the scintillator detector.

LABORATORY STUDIES

The precision and accuracy of the wire position determination has been extensively studied by means of a laboratory test bench [3, 7] in which a laser is used to simulate the particle beam at different transverse positions. By varying the laser position and performing multiple wire-scans, the transverse position of the wire as a function of the encoded shaft angle can be experimentally measured. The instance the wire reaches the laser beam is determined by measurement of the missing laser power due to the laser-wire interaction using a photo-diode. This kind of calibration is essential for the overall *accuracy*, since it allows any residual mechanical play or deformation of the fork or wire during the scan to be determined.

In addition, the test bench is used to systematically check the *precision* with which the wire position is measured. This is achieved by quantifying the residuals of the calibration points with respect to the polynomial function expected from geometry.

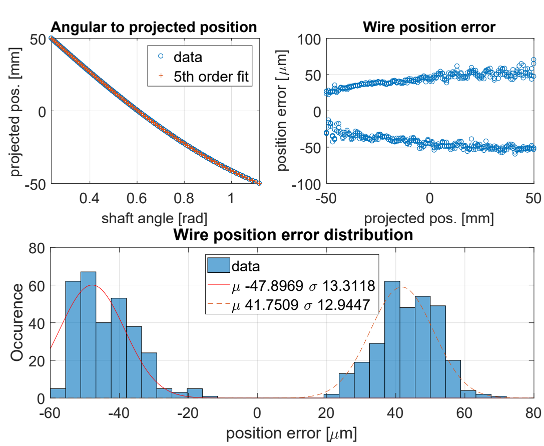

Figure 3: Calibration data example (fitting IN and OUT data with a single function).

The result of a calibration example can be seen in Fig. 3. The top left plot shows the calibration curve with the 5^{th} order polynomial used to predict the projected wire position from the encoded angle obtained from the optical disc. In this case a single fit has been performed on the whole set of data, i.e. two scans with opposite directions (IN and OUT) for each laser position. The distribution of the residuals between the projected wire position (bottom plot) and their variation as function of the laser (wire) position (top right plot) reveal a systematic residual offset between the IN and OUT scans. This offset, the *INOUT slack* is proportional to the wire speed and is very likely to be caused by the wire (or fork) bending under the angular acceleration force. For this reason, fitting the calibration data with different functions for the IN and OUT directions can increase the precision and accuracy of the final measurement. A summary of the calibration results for the first 8 scanners tested is shown in Table 1. It can be seen that the RMS value of the residuals to the fit, i.e. the projected wire position determination precision, is always below $6\mu m$.

Table 1: Summary of Calibration Results for the 8 PSB Scanners

	Residuals RMS [μm]			**INOUT Slack [μm]**		
V [rad/s]	**55**	**110**	**133**	**55**	**110**	**133**
Device #						
CR03	2.04	3.27	5	32	92	115
CR04	1.38	1.55	3.84	28	76	100
CR05	1.45	2.30	4.05	30	87	110
CR06	4.29	2.56	4.76	31	87	113
CR07	3.15	3.50	4.80	29	80	106
CR08	2.35	2.28	5.89	31	88	110
CR09	0.72	1.95	2.56	42	120	150
CR10	1.99	2.69	3.94	32	88	110
AVG	2.2	2.5	4.4	31.9	89.8	114.3
STD	1.0	0.6	0.9	4.0	12.4	14.2

A series of calibrations performed on the same system both with and without pumping the calibration tank to vacuum levels similar to the operational ones, did not result in significant differences to the calibration results. It was therefore decided to perform the standard calibration of all other devices at atmospheric pressure.

Impact of the Control System

The proper design and programming of the BWS control electronics plays a key role in the final system precision. For instance, a smooth feedback control, ensuring the wire travels at the desired speed at the requested moment, allows fork and wire deformations and vibrations during the scan to be minimized. In addition, the control system reproducibility minimizes the uncertainty of the calibration when applied during operation.

During the ongoing LIU BWS calibration campaign it was possible to compare two different control systems. The first is based on a commercial DSpace setup [8] adopted since the

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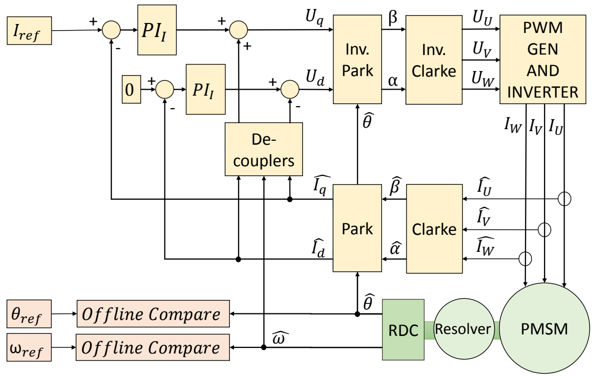

Figure 4: Motor control architecture with only motor current feedback and no position and speed feedback [9].

early mechanical design validations. The second is the first prototype of the final custom made CERN electronics that will be interfaced to the standard accelerator control system. The comparison was done by calibrating the same BWS unit with the two different control systems programmed to reach the same nominal speed of 110 rad s^{-1}. Some 330 scans per control system were performed to obtain the final calibration tables. The final comparison is shown in Table 2, demonstrating the enhanced precision of the custom made system.

This improvement can be explained by the main conceptual difference between the controllers, with the custom made controller programmed without position and speed feedback only kept the motor current feedback. This simplification is meant to increase reliability and minimize the motion instabilities while ensuring smoothly applied forces. The online actions of the controller are limited to the minimum necessary, avoiding abrupt corrections of the position and speed during the motion. To achieve the desired speed and position, the trajectory is pre-calculated using the system model.
Such a controller architecture is shown in Fig. 4. By means of mathematical transforms, the feedback follows the rotor displacement and controls the applied torque which is proportional to the current I_q. More details can be found in [9]. A drawback of not having a position feedback is the uncertainty on the shaft angle after a scan, which was observed to be about 0.2 rad. This uncertainty can be mitigated by adapting the starting time of the next scan.

Table 2: Residuals to the Polynomial Fit and INOUT Slack in [µm] at a Sominal Speed of 110 [rad/s] With Two Different Control Systems

Control system	Residuals RMS	INOUT Slack
DSpace	4.57	79.6
CERN custom made	2.16	75.7

BWS PROTOTYPE TESTS WITH BEAM

Three prototype systems, one each in the PSB, PS and SPS, were already installed and extensively tested over the last few years. The SPS prototype was the first to be installed and its validation with various beam types was already presented in [10]. The PSB and PS prototypes were mostly tested in 2018. They both used the new multi-PMT detector to monitor the secondary showers, for which a result example is shown in Fig. 5. For this LHC type beam at the PS top energy, one PMT channel (CH1) is saturated whereas both CH2 and CH3 allow the transverse profile to be reconstructed with a relative agreement of 1 % in the measured beam size.

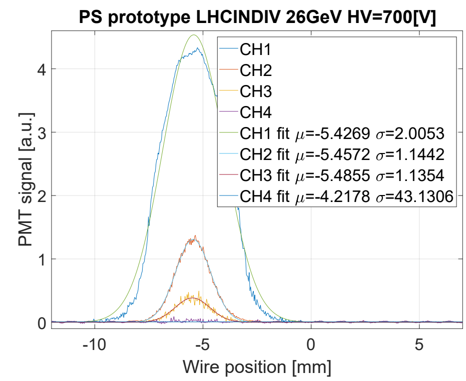

Figure 5: Beam profile as measured in the PS with the new BWS and a 4-PMT detector.

Various measurement campaigns allowed the system's precision to be successfully verified while measuring beam types differing in energy, intensity and size. Table 3 contains a summary of beam measurement results which were systematically analyzed.

Table 3: Summary Table of BWS Beam Measurements

Beam Type	P [GeV/c]	Scans	Beam Size	RMS
PSB/LHC25	1.4	275	2.5	1.6%
PSB/LHC25	1.4	141	2.5	0.88%
PS/LHCINDIV	26	26	1.4	2.7%
PS/BCMS	1.4	507	2.9-3.5	0.8%
PS/SFTPRO	1.4-14	64	7-2.5	0.8%
PS/TOF	3.3	37	10	0.6%
PS/TOF	12.7	37	6	0.4%
SPS/COAST	270	56	0.7-0.9	2.3%
SPS/BCMS48	26	17	2.5	1.3%

During some of the measurement campaigns it was possible to compare the performance of the prototype with the existing operational systems. An example is shown in Fig. 6, which is the result of a series of measurements on the same PSB beam type for different intensities. When assuming a linear dependence of the beam size on the intensity, the residuals to a linear fit confirm the improved precision of the new system with the new system giving a reproducibility of

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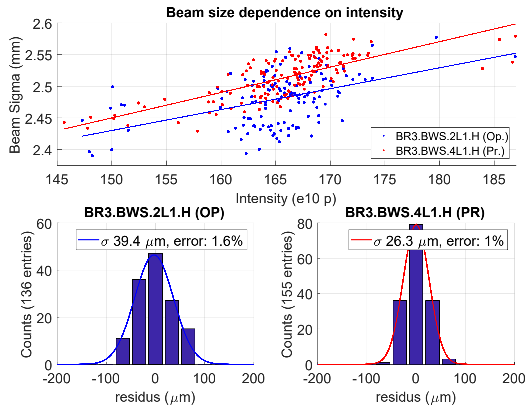

Figure 6: Comparison between old (blue) and new generation (red) wire-scanners in the PSB.

26μm on the beam size compared to 39μm for the old system (the different absolute beam size is due to the different beta functions).

The most tested prototype was the one operated in the PS accelerator in 2018, which was based on the final mechanical design and using a metallic optical encoder disk instead of the fragile glass disk adopted in earlier designs. It also allowed the prototype custom made electronics to be tested for the first time in an accelerator environment towards the end of the 2018 run, with the full system exploited by the PS operation team to characterize LIU beams [11]. Figure 7 presents a comparison of the beam emittance measured by the LIU prototype and the existing system during several PS cycles in which the beam intensity was varied over a relative wide range (*beam brightness* studies). This example shows again the excellent agreement between old and new systems. The measurements' spread (errors bars on the plot) is in this case heavily affected by the beam shot-to-shot emittance variation. The spread of the new scanner measurements resulted to be slightly worse than the old system, the reason for which has not been understood yet and could be related ot a not fully optimized profile reconstruction analysis. The PS

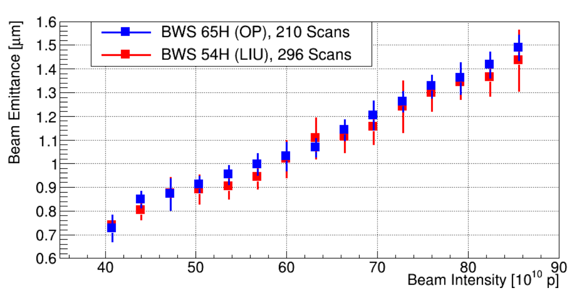

Figure 7: Transverse beam emittance of the PS beam at different intensities, as measured by the LIU scanner (red) and the existing operational scanner (blue).

prototype accuracy was also studied during a set of *dispersion measurements* in which the horizontal beam position was changed, cycle after cycle, over more than 25 mm. The correlation between the beam position measured by Beam Position Monitors (BPM) and the position of the maximum in the profile from the LIU BWS and the residuals of the BWS measurements to the linear fit are shown in Fig. 8. This set of measurements allows assessing the scaling error between BWS and BPM to be of the order of 2 % and the uncertainty on the beam position determination by BWS to be below 70 μm.

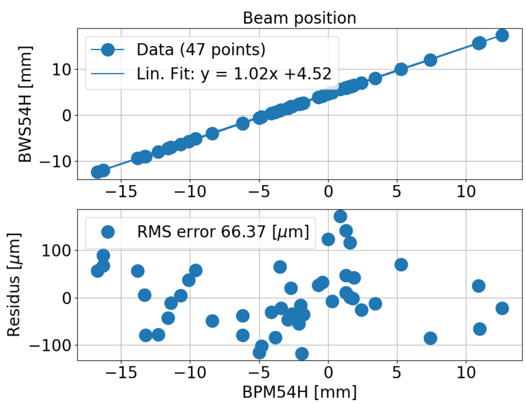

Figure 8: PS beam position as measured by standard Beam Position Monitors and the new LIU BWS (top) and residuals of the BWS measurements to the linear fit (bottom).

SUMMARY

The new generation of CERN wire-scanners, developed within the LIU project, features a completely new mechanical design, control electronics and data acquisition system. After multiple prototype studies 17 units will be installed and made operational in the PSB, PS and SPS accelerators in 2020-21. The new design was validated both in the laboratory and with prototypes in all three machines.

In the laboratory, a laser based test bench showed the wire position precision to be better than 6 μm for all speeds on the 8 units calibrated to date. To reach these values, the IN and OUT scans have to be processed individually to take into account systematic wire position offsets that are probably generated by deformations due to the acceleration forces during the scan.

The first tests of the custom made control system proved that a control logic only including a motor current feedback based on a torque-current lookup table minimizes motion instabilities and vibrations.

Finally, the extensive tests performed in the LHC injectors with prototype scanners validated the system over a large variety of beam parameters, giving us confidence that these systems will live-up to expectations when they become fully operational in 2020-21.

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