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PERFORMANCE ASSESSMENT OF PRE-SERIES FAST BEAM WIRE SCANNER PROTOTYPES FOR THE UPGRADE OF THE CERN LHC INJECTOR COMPLEX

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Abstract

A new generation of beam wire scanner (BWS), for transversal beam profile monitoring, is under development on the framework of the LHC Injector Upgrade project at CERN. Two pre-series prototypes have been built and installed in the Super Proton Synchrotron and Proton Synchrotron Booster, to assess the performance of the upgraded BWS concept.

This contribution shows the outcome of the measurement campaigns carried out on the first BWS prototypes, both in the laboratory and with proton beams. An evaluation of a high dynamic range acquisition system for the measurement of the secondary showers produced by the beam-wire interaction is also presented.

INTRODUCTION

The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) will feature higher intensity proton beams in the whole injector chain. In addition, this upgraded scenario requires that the normalized transverse emittance of these beams be measured with a precision better than 5%. For beam wire scanners, the reference transverse beam profile monitors at CERN, this translates into a required wire position measurement uncertainty of a few micrometers.

The performance of the current operational beam wire scanners at CERN is limited by electronic noise on the signal from their position sensitive potentiometers, by the reproducibility of their motion mechanics and by the dynamic range of the acquisition system measuring the resulting secondary showers. The current wire position measurement uncertainty is in the order of ±100µm for the fast rotating scanners in the Proton Synchrotron (PS) and its Booster (PSB) at a speed of $15ms^{-1}$ [1], ±30µm for the rotating scanners ($6ms^{-1}$) in the Super Proton Synchrotron (SPS) and ±18µm for the linear scanners ($1ms^{-1}$) installed in the SPS and LHC [2]. The linear scanners are limited for use with low intensity beams as at higher intensity the deposited energy can lead to sublimation of the carbon wires used. In addition, all of these systems use bellows for motion transfer to the in-vacuum mechanics, this represent reliability issues when performing thousands of scans per year. The current scanners cannot therefore fulfill the HL-LHC specifications in terms of reliability and precision.

The need for higher measurement reproducibility at higher speeds has motivated the design of an innovative high precision beam wire scanner for the LHC Injectors Upgrade (LIU) project [3]. The upgraded concept is based on a rotational architecture with a frameless motor, where all mobile parts are located in vacuum on a shared shaft, eliminating the need of bellows. The wire position is determined through a high accuracy optical encoder [4], see schematic of Fig. 1. The secondary showers produced through the beam-wire interaction will be acquired using a high dynamic range acquisition system to eliminate the tedious set-up of operational parameters when switching between different beam configurations [5].

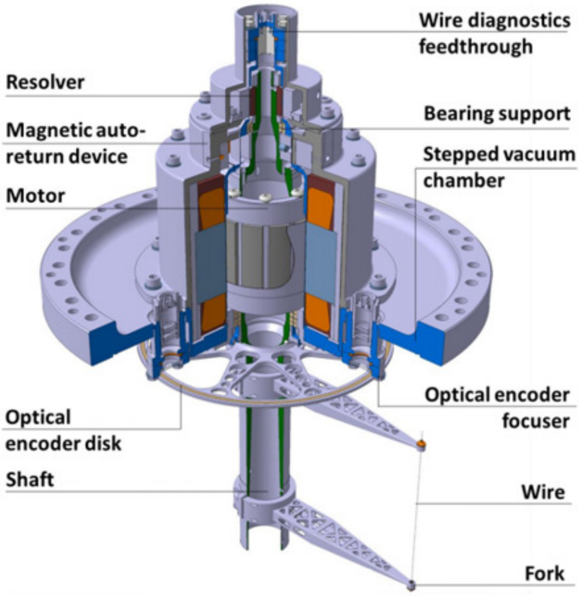

Figure 1: LIU beam wire scanner schematic.

SPS PROTOTYPE PERFORMANCE

The precision validation of the SPS BWS prototype [6] (BWS.51740.V) was carried out by measuring a single bunch with $2.3x10^{10}$ protons, during a period in which it was accelerated to 270 GeV and left circulating for several hours. Due to beam dynamic aspects, this beam suffers an emittance increase during this time and negligible beam intensity losses.

A standard linear scanner (BWS.51731.V) was operated in parallel with the prototype for performance comparison. The linear scanner performed scans at $1ms^{-1}$, while the nominal speed of the prototype was $20ms^{-1}$. With the circulating bunch interacting with the wire every 23µs (the SPS revolution period) and the prototype running 20 times faster than the linear scanner, the number of times the bunch intercepts the wire (points per sigma) is reduced for the prototype, thus providing less information for the Gaussian fitting routine used on the resulting profile.

Whereas the linear scanner was equipped with a CERN standard scintillator/photo-multiplier (PM) detector for measuring the secondary shower, the prototype was equipped with both a scintillator-PM system and an experimental pCVD diamond system.

The beam emittance uncertainty for each scanner was determined from the residuals around a linear fit applied to the emitance growth in time (Fig. 2). The normalized emittance was calculated from the sigma value of a Gaussian fit applied to each measured profile, the accelerator optics and the beam energy. The normalized emittance measured by both scanners is the same, however, the absolute sigma values differ for both scanners due to the accelerator optics (beta functions are different for each scanner location). The measurement results are summarized in Table 1.

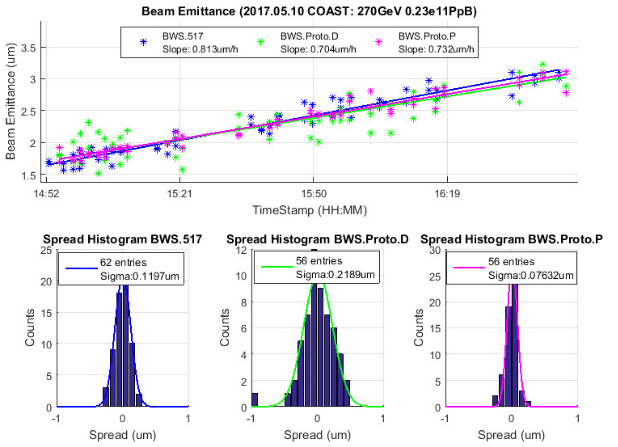

Figure 2: Beam emittance evolution and measurement spread for the linear scanner BWS.51731.V (blue traces) and the rotational prototype BWS.51740.V using a scintillator-PM (magenta traces) and a diamond detector (green traces).

Table 1: SPS BWS Performance Summary on Beam Test with a COAST (single bunch $2.3x10^{10}$ protons at 270GeV)

Scanner	**BWS.51731.V**	**BWS.51740.V**	
		PMT	**Diam.**
Speed	1	20	
Points per σ	39	1.7	
Sigma (µm)	900 ± 28	800 ± 18	800 ± 35
(σ %)	3.0 %	2.3 %	4.3 %
Emit. (µm)	2.5 ± 0.12	2.5 ± 0.07	2.5 ± 0.22
(σ %)	4.7%	3.0 %	8.7 %
Centroid (σ µm)	94	48	66

Despite the drastic decrease in the number of points per sigma of the prototype, due to its increased speed with respect to the linear scanner, it nevertheless showed a 1.5 times lower spread on the beam width determination and a factor 2 precision improvement on the beam centroid measurement. This is ultimately translated into a higher reproducibility on the emittance calculation.

When normalizing to the same number of points per sigma as the linear scanner, and with a factor of 2 lower wire position uncertainty, the beam width precision is improved by a factor 2.

Due to its limited detection area (10 by 10 mm^2) the diamond detector profiles were highly influenced by statistical noise that degraded its performance. The operational scanner also featured a systematic difference on the beam centroid measurement of 1mm between IN and OUT scans that was not observed on the prototype scanner.

PSB PROTOTYPE STUDIES

Instrument Laboratory Characterization

The wire position accuracy and precision of the BWS was determined by means of an optical bench. The system consists of a mobile laser that is displaced along the BWS scanning axis. For each laser position, the angular information given by the optical position sensor is determined at the moment of the wire/laser interception. Repeating this process for different laser positions the angular-to-projected transformation of the wire trajectory can be determined.

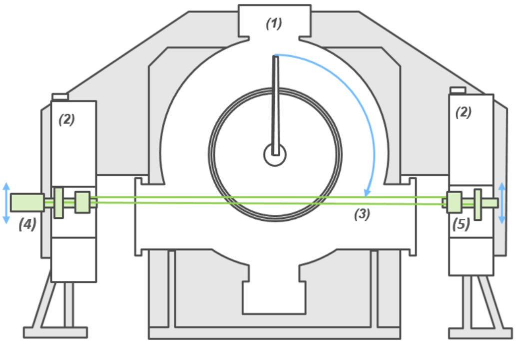

Figure 3: PSB calibration bench schematic showing scanner tank (1), mobile stages (2) and optical system (on green) with laser (4) and photo-diode (5). Wire trajectory (in blue) and interaction point (3) are also displayed.

The optical system consists of a Gaussian 532nm laser followed by a focusing lens and a beam displacer mounted on a mobile stage. These elements generate two parallel beams separated by a known and constant distance (2.94mm) that are focused on the laser/wire interaction region. On the other side of the scanner tank, a second mobile stage contains similar beam displacer which combines both beams for entry into a single photo-diode (see Fig. 3). As the carbon wire passes through each of the parallel laser beams, it generates a Gaussian dip in the photo-diode response. The angular interaction point is defined as the mid-point between the two dips observed.

The scanner was characterized along ±50mm from the central beam position at both $8ms^{-1}$ and $20ms^{-1}$. The measurements were then fitted with an analytical approximation based on the scanner geometry, with the wire position uncertainty expressed as the spread in the fit residuals.

The complete calibration analysis resulted in a position uncertainty of 6µm and 11.5µm for $8ms^{-1}$ and $20ms^{-1}$ respectively (see Fig. 4).

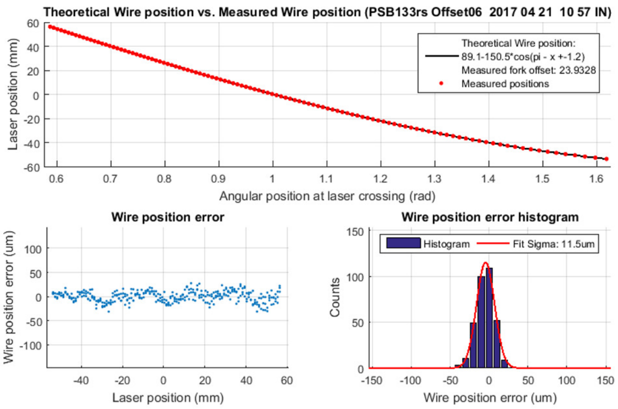

Figure 4: PSB calibration results at 20m/s.

The measured wire position exhibited an oscillatory behavior around the analytical approximation, reproducible over successive calibrations. These systematic oscillations were dependent on the scan speed, which suggests some kind of mechanical vibration or wire oscillation during the scan.

The accuracy and precision of the wire position measurement can be determined through a deeper analysis of the fit residuals. Systematic deviations from the analytical motion curve define the accuracy of the instrument and random errors its precision.

The Fig. 5 shows the systematic and random fit errors for several calibrations at different speeds. This shows a position dependent systematic error (accuracy) of ±10µm, resulting from these suspected oscillations, with a frequency dependent on the scan speed. The measurement spread at each position (precision), is strongly dependent on the scan speed with a standard deviation of 2.5µm and 6.2µm for 8ms^{-1} and 20ms^{-1} respectively

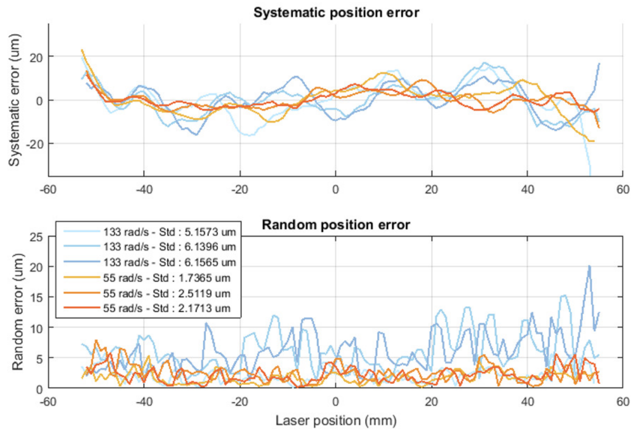

Figure 5: Analysis of fit residuals for several calibrations at 8 (orange) and 20 (blue) m/s.

A set of 100 scans performed at a fixed laser position gave a projected precision of about 3µm for 8ms^{-1} and 6µm for 20ms^{-1} confirming the previous analysis.

Studies carried out under vacuum and ambient air conditions provided similar results in terms of accuracy, however, the measurement precision for each laser position was a factor of 2 better with no vacuum at nominal speeds. The in-vacuum degradation could be linked to vibrations induced by the vacuum pump. The overall results are summarized in Table 2.

Table 2: PSB BWS Instrument Characterization

Speed (m/s)	8		20	
Conditions	Air	Vac.	Air	Vac.
Post-Calibration position error (um)	5.5	6	11.5	11.6
Accuracy (µm)	10			
Precision (µm)	2.5	2.7	6	11

Performance with LHC and ISOLDE Beams

The PSB prototype (BR3.BWS4L1.H) [7] was equipped with a standard scintillator-PM system and was tested with both, a nominal LHC beam ($1.8x10^{12}$ protons) and ISOLDE beams ($8.2x10^{12}$ protons). The operational scanner BR3.BWS.2L1.H was used for comparison.

The standard-PM signal of the prototype was digitally treated to emulate the operational scanner electronics, averaging the beam profile over multiple turns.

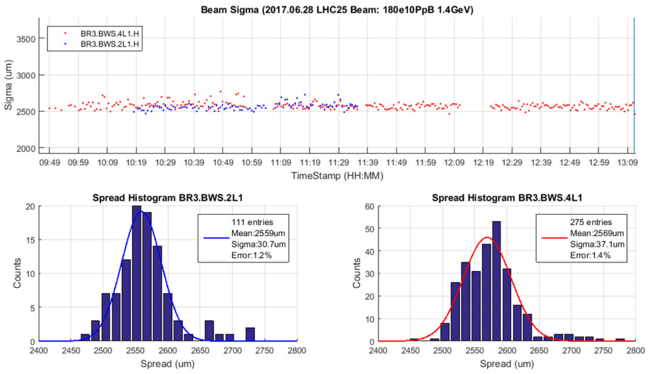

Figure 6: Beam sigma measured by PSB prototype (red) and reference (blue) scanners. LHC25ns at 1.4GeV.

As shown on Fig. 6, operational and prototype scanner measure similar beam widths, as expected since the accelerator optics are similar on both locations. The comparable measurement spread shown in both beams (always around 1% of the beam size) can be explained by the high number of points per sigma (200-700 in both scanners) and the averaging effect of the acquisition. While beam width variations over consecutive injections seem not to contribute on the beam width measurement spread, further studies are required for confirmation. The mean beam width and incertitude is shown in Table 3 for each measurement period.

Table 3: PSB Beam Width Measurements Summary for Operational and Prototype Scanner

Beam Type	**BR3.BWS.2L1**	**BR3.BWS.4L1**
LHC25 1.4GeV	2559 ± 31, 1.2%	2569 ± 37, 1.4%
ISO 588 MeV/c	8021 ± 125, 1.6%	8245 ± 52, 0.6%
ISO 886 MeV/c	6354 ± 88, 1.4%	6571 ± 46, 0.7%
ISO 1.39 GeV/c	5302 ± 44, 0.8%	5538 ± 38, 0.7%
ISO 1.92 GeV/c	4880 ± 53, 1.1%	5025 ± 34, 0.7%

Studies of a High Dynamic Range Acquisition System for the Measurement of the Secondary Showers

For the measurement of the secondary particle shower, resulting from the beam-wire interaction, operational BWS systems are equipped with big organic BC-408 scintillator blocks coupled to a wheel of selectable neutral density filters followed by a single PMT. In this configuration the operators need to find the correct working point (filter setting and PMT gain) to avoid PMT saturation while matching the PMT output to the dynamic range of the digitization electronics. Incorrect settings strongly influence the measurement quality, it often results in poor signal to noise ratio or PMT non-linearity when near saturation.

To avoid this setting dependency in the future systems, a quad-PMT (Q-PMT) detector system was tested. On this detector, each of the four PMT is intended to operate at different photon intensity levels. The Q-PMT signals were acquired using radiation tolerant front-end electronics located in the tunnel [5], these are based on a quad-channel 40MHz integrator ASIC (ICECAL). Data from all four channels were collected simultaneously with the best working point automatically selected in post processing by choosing the highest amplitude channel which presented no ADC clipping.

Standard scintillator-PM and Q-PMT systems were used simultaneously to acquire the profiles of the prototype scanner for ISOLDE and LHC beams throughout the PSB acceleration cycle. Under such conditions, due to the beam dynamics, the effective scintillator light intensity varied by 3 orders of magnitude. Fig. 7 shows the beam sigma, in time, measured with both standard and QPMT systems. Whereas the standard system required many filter changes for suitable operation (changes are high-lighted on the plot) and featured PM saturation for several measurements, the Q-PMT system allowed operation with no tunable parameters during the complete acceleration cycles of both beam types measured.

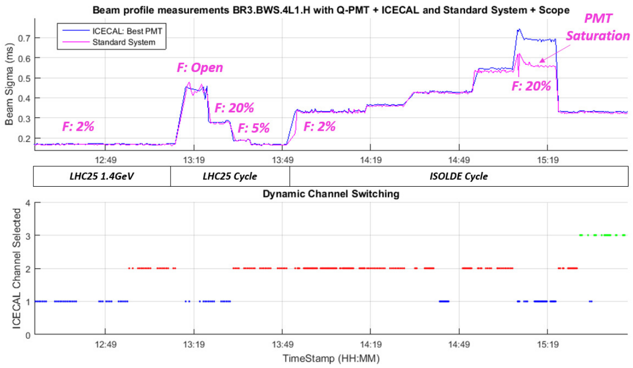

Figure 7: Top: Beam sigma measured by standard (magenta) and Q-PMT systems (blue). Bottom: Q-PMT channel selection in post-processing.

SUMMARY

The next generation of fast wire scanners at CERN are aimed to provide reliable operation with highly reproducible beam profile measurements at scanning speeds up to $20ms^{-1}$. Laboratory measurements have shown that a wire position precision of 6µm is obtainable at this maximum speed with an overall accuracy of ±10µm. The SPS beam tests have shown that the performance of the upgraded systems is comparable to that of the slow linear scanners despite 20 times less points per sigma. The beam width uncertainty in the SPS prototype was shown to be smaller than 2.5%, fulfilling the LIU requirements for emittance determination with < 5% uncertainty. Initial beam tests in the PSB have shown that the prototype scanners gives a slightly better precision than operational systems, well below the 2.5% specified by the LIU.

Test of a high dynamic range acquisition system based on a Q-PMT requiring no parameter tuning successfully demonstrated the applicability of such a system for secondary shower measurements covering several orders of magnitude.

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