# Performance Assessment of Pre-series Fast Beam Wire Scanner Prototypes for the Upgrade of the CERN LHC Injector Complex

J.L. Sirvent, L. Garcia, G. Trad, J. Tassan-Viol, J. Emery, P. Andersson, F. Roncarolo, W. Andrazza, D. Gudkov, R. Veness, B. Dehning

The European Organization for Nuclear Research (CERN). Geneva, Switzerland.

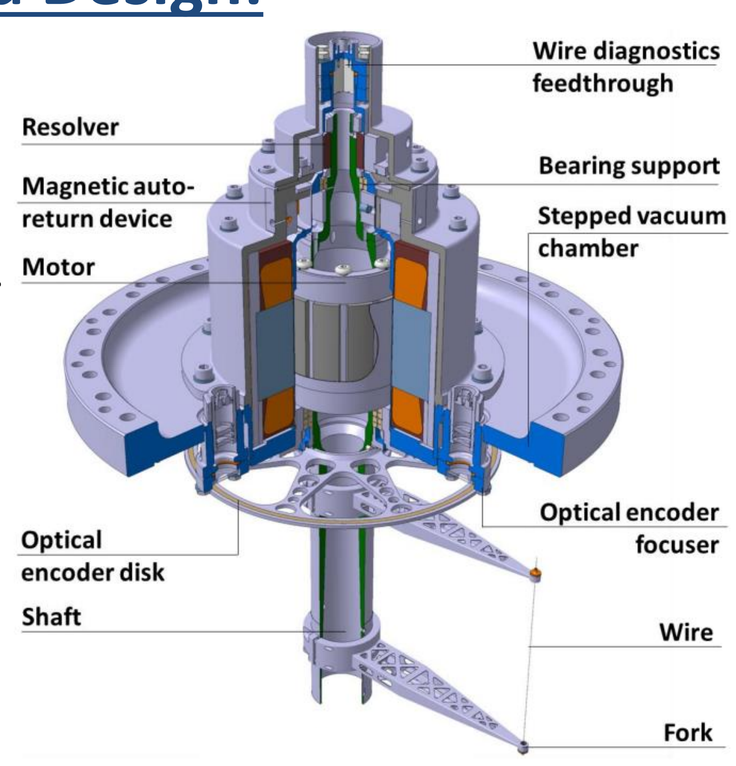
***Abstract:*** *The High Luminosity Upgrade of the Large Hadron Collider (HL-LHC) will feature higher intensity beams in the whole injector chain. This upgraded scenario requires that normalized transverse emittance be measured with a precision better than 5%. For beam wire scanners at CERN, this translates into a required wire position incertitude in the order of a few micrometres. A new generation of beam wire scanner (BWS), for transversal beam profile monitoring, is under development on the framework of the LHC Injector Upgrade (LIU) project at CERN. Two pre-series prototypes have been built and installed in the SPS and PSB, 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.*

## Motivations for an Upgraded Design:

- **Higher speed needed** for HL-LHC beams intensity.
- Nominal speed required 20m/s (wire integrity).
- **Emittance precision < 5%** (2.5% beam width).
- C. **Wire** position measurement **incertitude ~ 5 um**.
- Requirements not met with current BWS generation.

### Design Features:

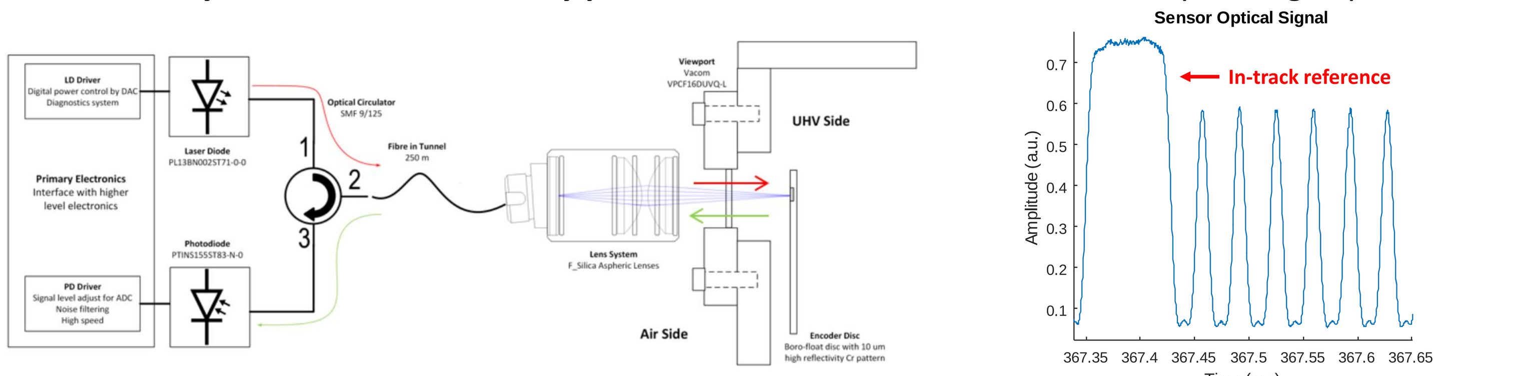
- **Common** baseline **design for all** CERN machines.
- **Mobile parts in-vacuum** with a shared shaft .
- Direct drive with trough **magnetic coupling**.
- Passive **magnetic auto-return** device (for safety).
- High accuracy passive **fibre-optic position sensors**.
- Kinematic unit **optimized for design acceleration**.




LIU Beam Wire Scanner with components in detail [6]

## High precision optical position sensor:

- **Radiation hard passive encoder sensor:** Based on 9/125 SMF and operating at 1310nm.
- **Encoder Glass disk:** 20um pitch track of reflective (10um) and transparent (10um) sections.
- **Operation:** One fibre per sensor, light focused on disk (20um MFD), reflections coupled back.
- **Redundancy and online eccentricity position error correction:** Two sensors operating in parallel.




Optical position sensor working principle and signal received with disk rotation

## Calibration bench for prototype characterization:

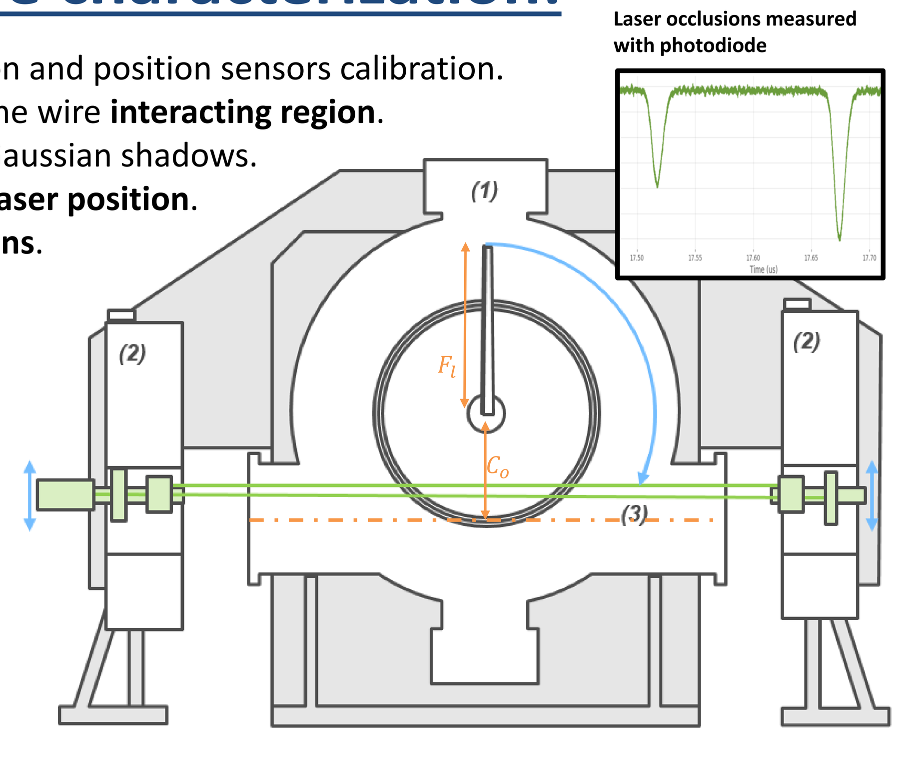
- **An optical bench** is used for the instrument characterization and position sensors calibration.
- **Two parallel beams** (2.94mm separation) are **focused** on the wire **interacting region**.
- **Interaction point** defined as the **centre** between the two Gaussian shadows.
- **Sensors position** at Wire/Laser interception **compared to laser position**.
- The measurements are **repeated** for **different laser positions**.
- Angular to projected **wire trajectory is reconstructed.**
- The **trajectory is fitted with an analytical approximation.**

$$Y = C_o - F_l \cos(\pi - \alpha_{Sensor} + Phase)$$

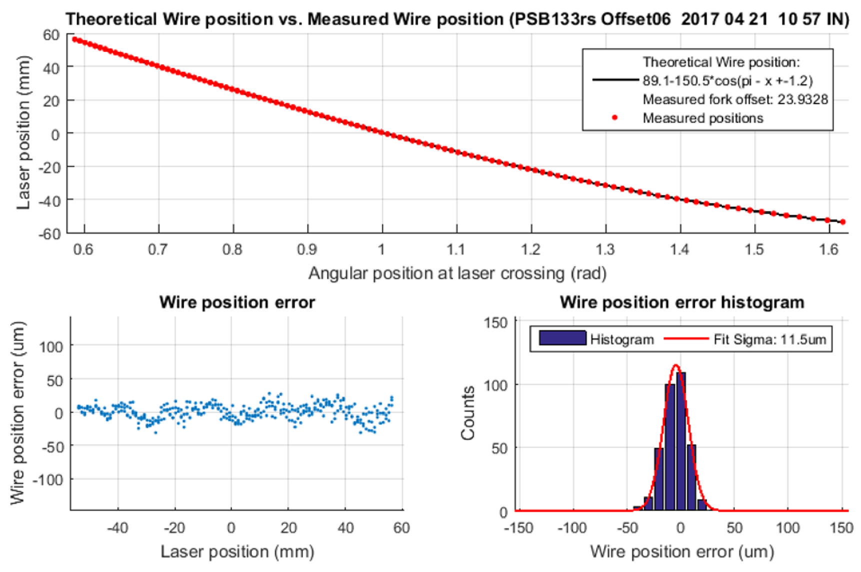
- **Residuals** studied to **determine** systematic and random **position errors** (scanner accuracy and precision).

| Speed | 8 m/s | 20 m/s |
|---|---|---|
| Residuals Spread | 5.5 um | 11.5 um |
| Accuracy | 10 um | |
| Precision | 2.5 um | 6 um |

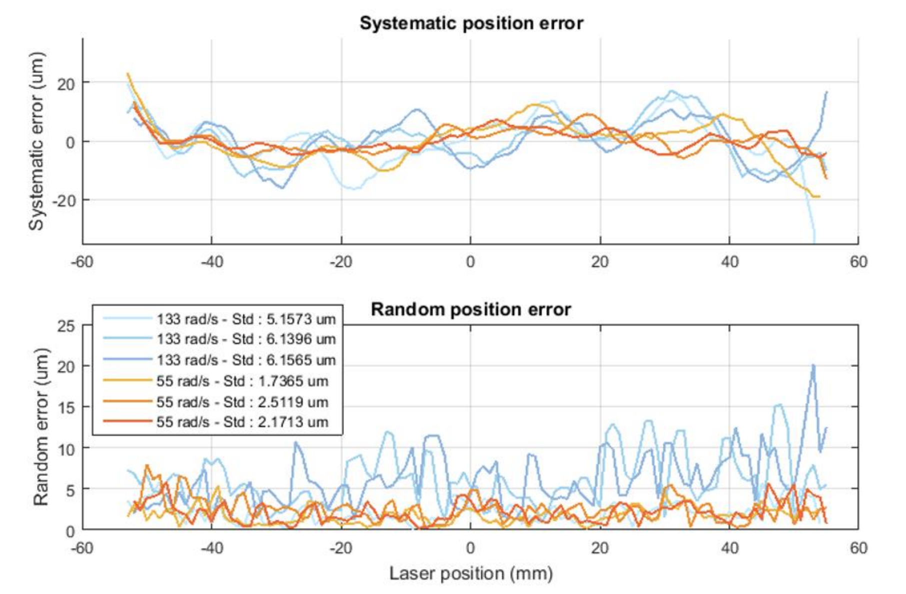
Scanner characterisation with calibration bench




PSB calibration bench schematic showing scanner tank (1), mobile stages (2), optical system (on green) and beam/wire interaction point (3).




Scanner calibration at 20m/s and fit residuals analysis.




Systematic and random position errors for calibrations at 8 and 20m/s

## PSB Prototype Performance with Proton Beams:

### Infrastructure for BWS prototype:

- Two acquisition systems (Standard, Q-PMT).
- ICECAL_V3 Front-end for HDR evaluation.

### Test conditions:

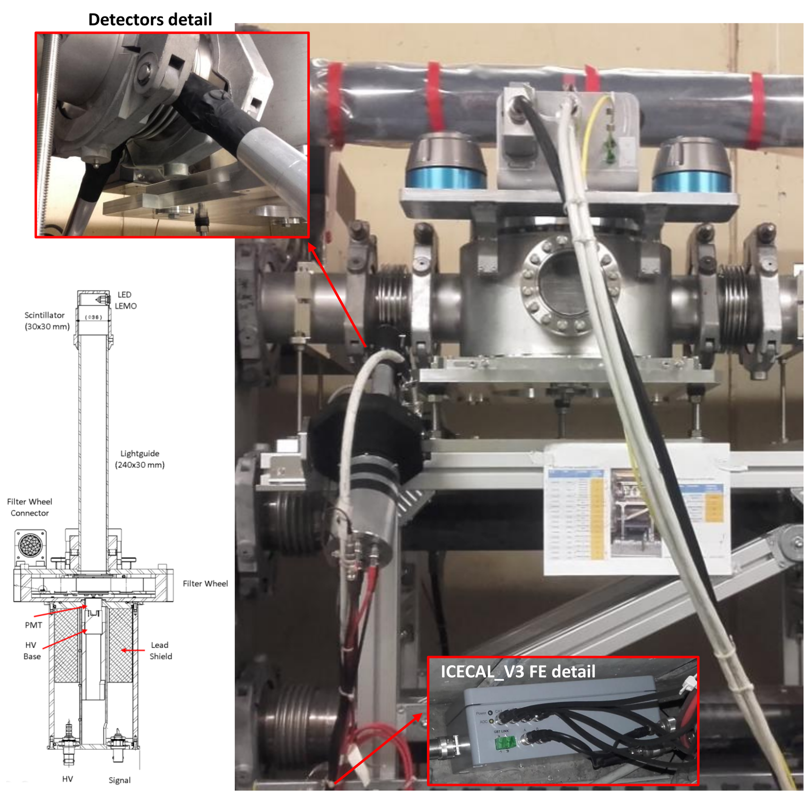
- Single bunch LHC25 at 1.4GeV, 180e11Protons.
- Single bunch ISOLDE cycle, 820e11 Protons.
- Prototype scanner BR3.BWS.4L1.H (20m/s)
- Reference scanner BR3.BWS.2L1.H (15m/s)
- Scans done over different injections.
- Bunch Interceptions per scan > 200-700.

### Analysis and processing:

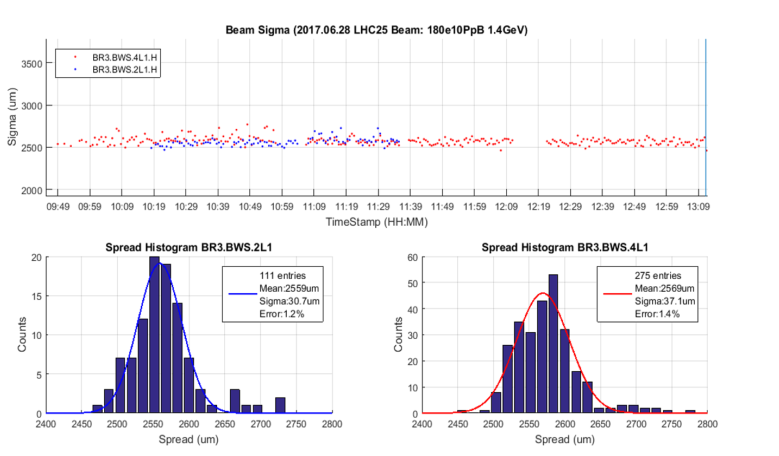
- Beam profile averaged over multiple turns.
- Beam width measurements scatter compared.
- Results subject to shot-by-shot variations.

| 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% |

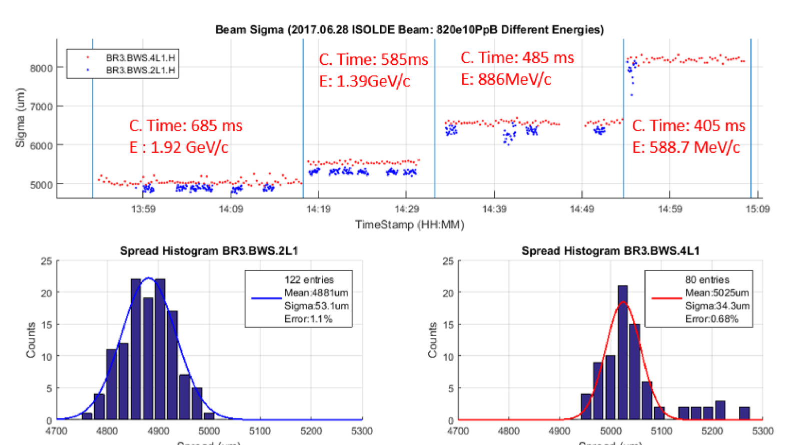
Beam width and measurement spread for both scanners.




BWS prototype (BR3.BWS.4L1.H) installed on PSB tunnel.




Beam profile measurements for LHC25 Beam at 1.4GeV

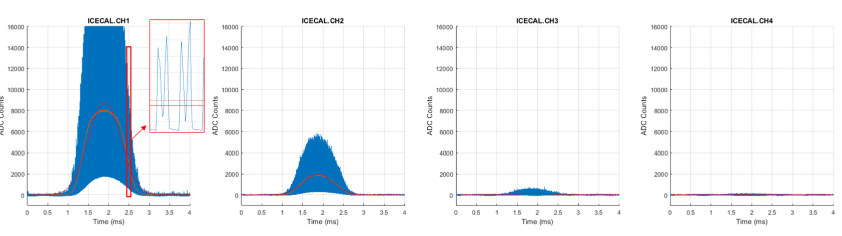



Beam profile measurements during the ISOLDE beam cycle

## High dynamic range secondary shower acquisition system:

### Q-PMT detector:

- **Four PMT** operating in parallel.
- **Different ND filters** per detector.
- PMTs **characterized** with **custom** HV **bases**.
- Working points scaled down by 1/10.
- **Indented for single configuration** with all beams



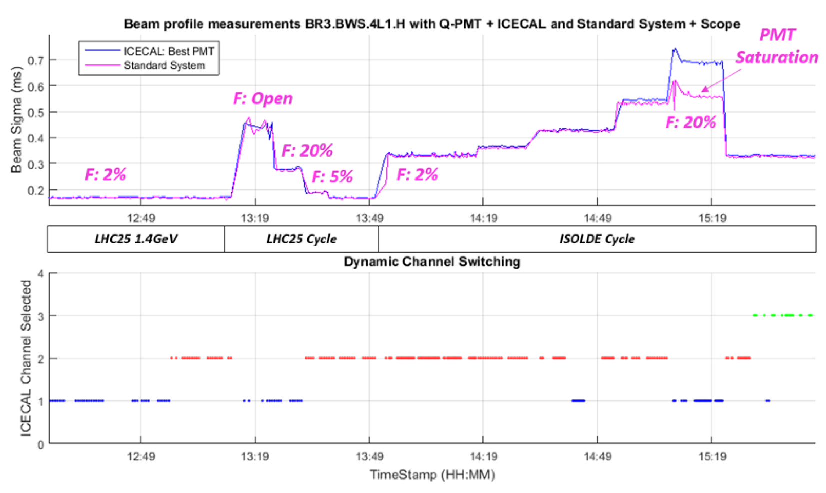
Q-PMT profiles acquired with ICECAL_V3 Front-End

### In-Tunnel acquisitions with front-end:

- Evaluated on PSB but intended for SPS/LHC
- Quad-channel 40MHz integrator ASIC.
- Low noise **acquisition close to detectors**.
- **Expected** QPMT-FE combined **dynamics ~1e6**.

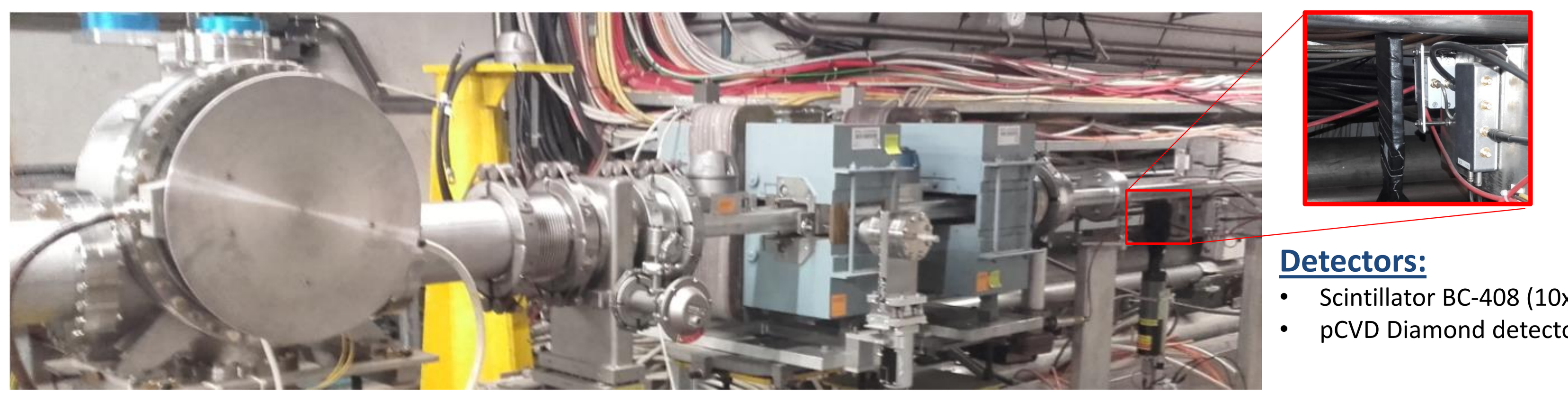
### Operation during Beam Test:

- Single configuration for LHC25/ISOLDE cycles.
- **Dynamic channel selection** in post-processing.
- Secondaries dynamics varied by 1e3.
- System **virtually free of PMT saturation**.




Standard and Q-PMT profile measurements for BR3.BWS.4L1.H

## SPS Prototype Performance with Proton Beams:



Beam Wire Scanner prototype (BWS.51740.V) installed on SPS tunnel

### Detectors:

- Scintillator BC-408 (10x10x1 cm)
- pCVD Diamond detector (1cm2)

### Tests conditions:

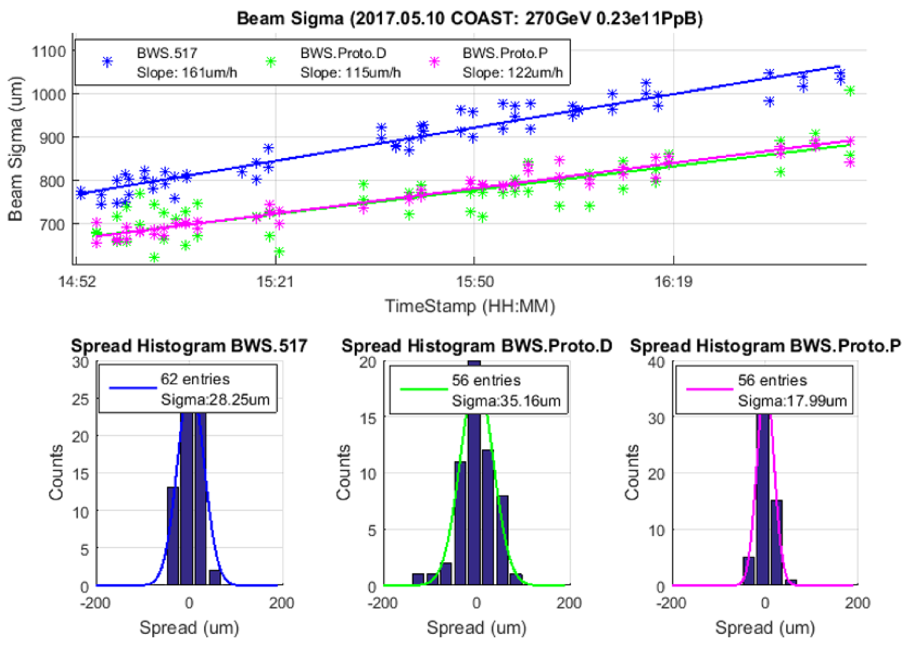
- **Single bunch** (0.23e11 Protons) at **270GeV**.
- Beam/Wire **interceptions** every **23us** (SPS rev. period)
- Beam **continuously circulating** during various hours.
- **Emittance** (and beam sigma) **growth** with time.
- **Prototype** scanner **BWS.51740.V** scans at **20m/s**.
- **Reference** scanner **BWS.51731.V** scans at **1m/s**.

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

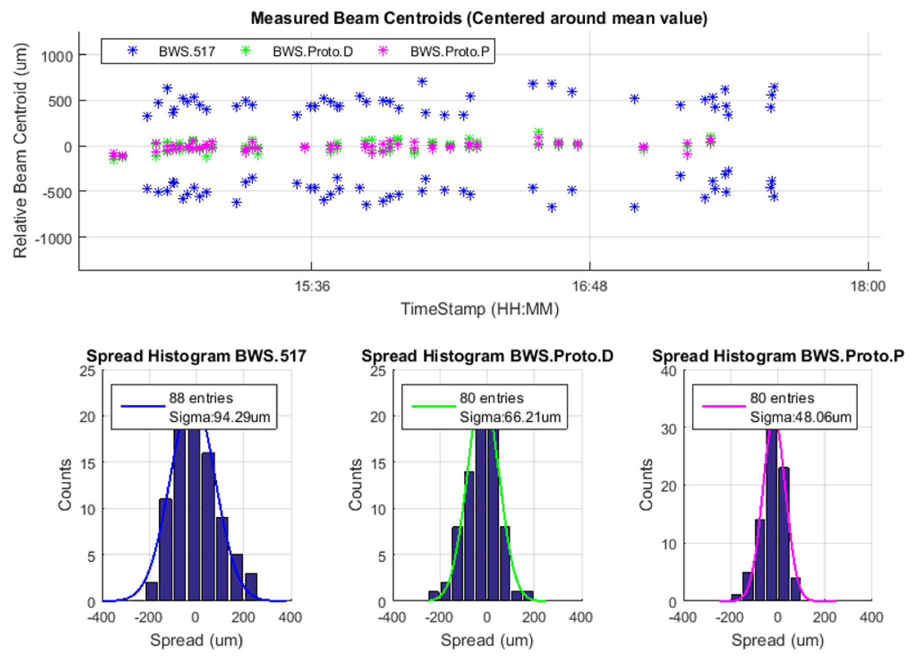
Performance summary for scanners under tests

### Analysis and processing:

- Single bunch profiles **parametrized as Gaussian**.
- Beam **width precision**: Spread **around linear growth**.
- Beam **centroid precision**: Spread **around mean value**.




Beam profile measurements of prototype and reference scanners




Beam centroid measured by prototype and reference scanners

## Summary:

Prototypes characterization determined a wire position **precision of 6 um with 10 um accuracy**. The SPS beam tests shown that the prototype performance is comparable with operational linear scanners despite a 20 times number of points per sigma, resulting in a **beam width incertitude smaller than 2.5% and 5% in emittance**. PSB beam tests leaded to a precision slightly better than operational systems, ~0.7% sigma incertitude with ISOLDE beams. The high dynamic range acquisition system based on a Q-PMT detector demonstrated its applicability covering several orders of magnitude.

## References:

[1] J. Koopman, A.G. Ollacarizqueta and Lokhovitskiy, "Fast wire scanner Calibration", in *Proc. DIPAC'09*, Basel, Switzerland, May 2009, paper TUPB05, pp. 170-173.
[2] G. Baud *et al.,* "Performance assessment of wire scanners at CERN", in *Proc. IBIC'13*, Oxford, UK., Sept. 2013, pp. 449-502.
[3] J. Coupard *et al.,* "LHC Injectors Upgrade Technical Design Report: Volume 1 Protons", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337, Dec. 2014
[4] J. Emery *et al.,* "A fast and accurate wire scanner instrument for the CERN accelerators to cope with severe environmental constraints and increased demand for availability", *in Proc. IEEE CCA'14*, Juan Les Antibes, France, Oct. 2014, pp. 1139-1145
[5] J.L. Sirvent, "Beam Secondary Shower Acquisition Design for the CERN high Accuracy Wire Scanner", Ph.D. thesis, Universitat de Barcelona, Barcelona, Spain, unpublished.
[6] R. Veness *et al.,* "Experience from the construction of a new fast wire scanner prototype for the CERN-SPS and its optimisation for installation in the CERN-PS Booster", in *Proc. IBIC'15*, Melbourne, Australia, Sept. 2015, paper TUPB061, pp. 479-482.
[7] R. Veness *et al.,* "Installation and test of pre-series wire scanners for the LHC injector upgrade project at CERN", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper MOPAB121, pp. 412-414.

Contact: jsirvent@cern.ch

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