

BEAM-BASED MEASUREMENTS OF THE CPS WIRE SCANNER PRECISION AND ACCURACY

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Abstract

During the 2013 run a systematic campaign of beam-based measurement on the CERN Proton Synchrotron wire scanners has been performed. In this work we report the conditions of the measurements, we describe the results and their interpretation. The observations are compatible with an emittance relative precision and accuracy respectively better than 2% and 5% in the vertical plane for nTOF beams. The present limitations of the system are discussed and possible solutions are presented.

INTRODUCTION

A wire scanner (WS) is a beam instrumentation device intended mainly for measuring the beam transverse normalised emittance (ϵ_n) in multi-passage machine [1–4]. Together with the bunch intensity (N_b), ϵ_n is a crucial parameter for determining the CERN injector chain performance. With precise and accurate WSs it is possible to monitor and detect issues along the machine cycle and along the different machines in the chain, allowing an overall control and optimisation of the injector complex. Due to the importance of this device, continuous efforts are spent to overcome its limitations and improve its precision, accuracy and reliability. In the following we present and discuss a beam-based measurement method to determine the CERN Proton Synchrotron (CPS) WS precision and accuracy in terms of transverse profile, rms beam size σ and ϵ_n .

The precision of a measurement system is the degree to which repeated measurements under unchanged conditions show the same results whilst the accuracy refers to the degree of closeness of the measured quantity to that quantity's actual (true) value. The precision is related to statistical errors, minimised by a proper design of the instrument, whilst the accuracy is related to systematic errors, minimised by a proper instrument's calibration.

The Signal Chain

In the CPS there are 5 rotational WSs (2 vertical and 3 horizontal). With a WS, it is possible to produce controlled beam losses by moving a thin wire (≈ 15 twisted carbon fibres for a total of $\approx 30 \mu\text{m}$ wire) across the beam (the usual wire speed, v_w , is 15 m/s, i.e. it moves at $\approx 30 \mu\text{m}/T_0$ where T_0 is the CPS revolution frequency, $\approx 2 \mu\text{s}$), Fig. 1. A portion of the secondary shower is collected by two scintillators. The scintillator photons are then transduced in an amplified current signal by a photomultiplier. From the tunnel the signal is filtered and transported to the server where is digitalised.

Considering the measurement of a single bunch, the beam profile ($p(y)$, function of the transverse position y)

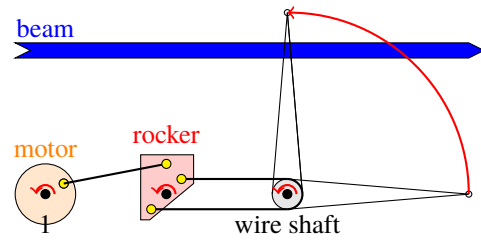


Figure 1: The CPS wire scanner.

is converted in a time signal (assuming v_w constant we have $y = v_w t + y_0$, Fig. 2). If the longitudinal bunch length is small in comparison to the T_0 (which is usually the case in the PS¹) the signal retrieved by the scintillator can be thought as a sampling with period T_0 of $p(v_w t + y_0)$ (Fig. 2).

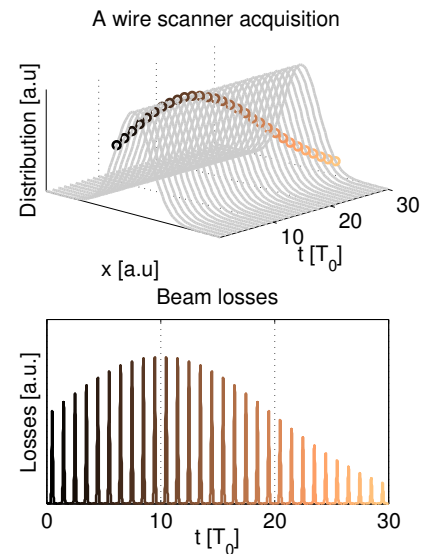


Figure 2: The bunch-wire interaction during several passages of the same bunch. At a constant WS speed of $30 \mu\text{m}/T_0$ we need ≈ 35 turns to explore 1 mm of the beam transverse profile.

If the spectrum of $p(x(t))$ is limited in the $[0, 1/2T_0]$ interval, to get back the profile information from the sampled signal a low-pass filter is used (the cable in our case will serve as filter) and finally the filtered signal is re-sampled at T_0 and digitised.

In reality the wire is not crossing the beam at constant speed but it experiences a strong acceleration ($\approx 100 \text{ g}$, i.e. the Δv_w between consecutive turns in $\approx 2 \cdot 10^{-3} \text{ m/s}$)

¹ The working principle remains valid also for bunch length comparable to T_0 .

therefore to convert back the time profile in a signal $\propto p(x)$ we need to measure the wire position in time. This is done by recording for each scan the angular position of the motor (Fig. 1) and by using a look-up table that relates the motor position to the wire position. The look-up table is measured with a dedicated calibration setup.

Once obtained the measured profile, $\tilde{p}(y)$, is fitted with a 5 parameters (k_1, k_2, A, σ, μ) function

$$f(y) = k_1 + k_2x + \frac{A}{\sigma\sqrt{2\pi}} e^{-\frac{(y-\mu)^2}{2\sigma^2}} \quad (1)$$

where σ is the rms beam size at the wire position.

To preserve the information of the profile the signal treatment has to be linear in the dynamic of interest (typically the photomultiplier working point has to be optimised to work in its linear region) and the low-pass frequency response has to be flat in the spectrum of $p(y(t))$.

Operational Conditions

As we explained, the WS is sampling the beam transverse profile. Therefore, if the beam is changing its distribution during the measurement, the recovered beam σ is meaningless. In addition to the hypotheses of linearity (mainly the photomultiplier) and equalisation of the signal chain (mainly the cable) we have to verify that the beam distribution is stationary during the measurement (negligible effect due to the motion of the beam centroid, the acceleration, the variation of the optics function, the filamentation...). Furthermore we need to verify that the losses on the scintillator are dominated by the ones induced by the beam-wire interaction.

METHODS

In general, the precision and the accuracy of an instrument can be evaluated using a prototype (an object with known properties) or instruments with known and higher precision and accuracy. In our case we have neither a prototype beam nor a better instrument. We will show in the following how we can use the beam-based measurements to evaluate the WS performance by using two vertical PS WS (in section 64, V64, and section 85, V85) at the same time.

Measuring Precision

To evaluate the precision of the WS we can measure the same unknown ensemble of beam σ (assumed normally distributed) with two WSs. If the precision of the two WSs is the same, we can compute it using correlation studies (principal component analysis, PCA). For n beam pulses we obtain a $n \times 2$ matrix, M . Each column of the matrix represent the measured beam σ in V64 and V85 for n different pulses. The σ 's have a coherent component (due to the fact that there is a pulse-by-pulse σ jitter) and an incoherent component (due to the WS finite precision). From PCA, the variance of the incoherent component is the smaller eigenvalue of the covariance of M .

Measuring Accuracy

Assuming that the distribution is stationary during the measurement, the normalised beam profile measured by V64 and V85 has to be the same and has to be symmetric. Within the single pulse the comparison between the two profiles is dominated by the WS precision. But if we average on all pulses acquired (> 50 pulses), the difference of the two profiles and the asymmetry of the single profile is a measurement of the systematic error due to the finite accuracy of the instrument. Moreover, knowing that the β -beating of the PS is within 1% [5], we can compare the beam σ ration in section 64 and 85 with the expected value obtained from the machine optics.

RESULTS

We measured the nTOF beam at flattop energy ($p = 20$ GeV/c) with V64 and V85 (we neglected parasitic vertical dispersion). We measured an average beam σ of 2.6 and 1.9 mm in V64 and V85 respectively. By correlation studies (PCA) we observed a relative precision of the WS of 0.57% and an intrinsic shot-by-shot variation of 0.92% (Fig. 3).

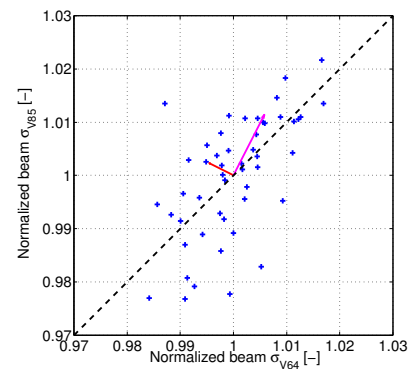


Figure 3: The correlation study (PCA) on the beam σ in V64 and V85.

Concerning the WS accuracy, the first consideration is on the direct comparison of the normalised beam profiles observed from V64 and V85. The profiles are averaged for the different beam pulses to determine the systematic error of the measurement. Within the WS accuracy we expect to see the same symmetric profile in the two WSs. The obtained results are shown in (Fig. 4). It is possible to show that the observed systematic error of the reconstructed profile is compatible with the precision of the WS calibration. In V85 the reconstruction of the profile appears less accurate (asymmetry) due to the smaller β -function at its position. In addition to the accuracy of the profile we studied the accuracy in the beam σ determination following two approaches: (1) beam-based measurements and (2) numerical simulation starting from the precision of the calibration curve. Concerning the first approach, we studied the ratio of the beam size in the two WSs and compared it to the expected ratio from

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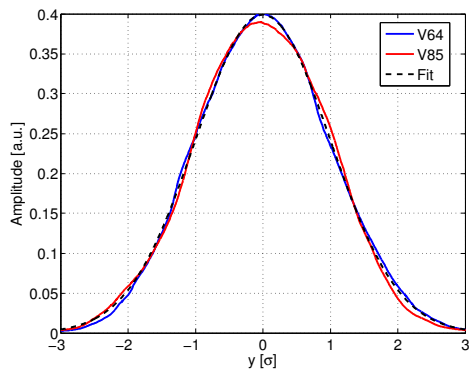


Figure 4: The averaged and normalised beam profiles in V64 and V85.

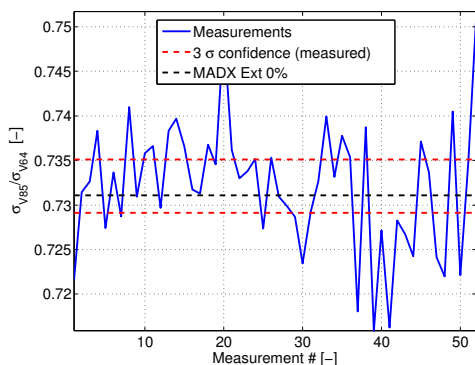


Figure 5: Measured and expected (black) ratio of the beam size in V64 and V85.

the optical considerations. The measured ratio is fully compatible with the present knowledge of the machine optics [5] (Fig. 5). This information does not give a complete response of the WS accuracy since it is based on the beam σ ratio and not directly on the beam σ . Nevertheless starting from the known precision of the calibration curves ($\approx 30 \mu\text{m}$) we can estimate with numerical simulations its effect on the WS relative accuracy. The results of the simulations are plotted in Fig. 6. For the nTOF beam at top energy we expect an accuracy better than 0.1%. If we assume a very small emittance beam $\epsilon_n = 0.5 \mu\text{m}$ (beam $\sigma=0.46 \text{ mm}$ for $\beta = 12$ and for the relativistic factors $\beta_r \gamma_r = 28$) the expected relative accuracy of the beam σ increases up to 1%. To determine the precision and the accuracy in the ϵ_n we have to consider, in addition to the beam σ , all other possible sources of error. It is possible to show that in linear approximation

$$\frac{\Delta\epsilon}{\epsilon} = K_\beta \frac{\Delta\beta}{\beta} + K_{\gamma_r} \frac{\Delta\gamma_r}{\gamma_r} + K_D \frac{\Delta D}{D} + K_\delta \frac{\Delta\delta}{\delta} + K_\sigma \frac{\Delta\sigma}{\sigma}$$

where $K_\beta = -1$, $K_{\gamma_r} = \frac{\gamma_r^2}{\gamma_r^2 - 1}$, $K_D = K_\delta = \frac{2D^2\delta^2}{D^2\delta^2 - \sigma^2}$ and $K_\sigma = 2 - K_D$ where D and δ represent respectively the dispersion on the relative momentum spread of the beam.

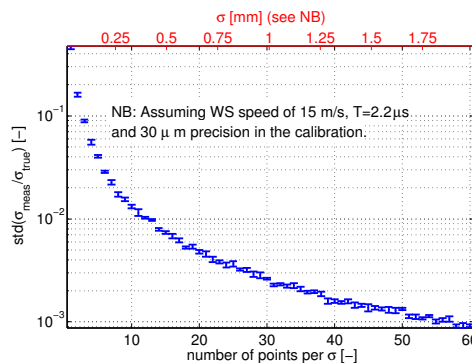


Figure 6: Simulated relative accuracy on the relative beam σ starting from the measured precision of the calibration curve of $30 \mu\text{m}$.

In the vertical plane we assume $D=0 \text{ m}$. The β and γ_r will contribute only to the accuracy and not to the precision since they are a constant input for the determination of the ϵ_n and are not directly measured for each WS scan. Assuming our observed precision of 0.6% on the beam σ we obtain a precision of 1.2% on the ϵ_n . Assuming an accuracy of 1, 0, and 1% respectively on the β , γ_r and σ we obtain an accuracy of $\approx 2.25\%$ on ϵ_n .

In the horizontal plane the situation is more complex due to the possible unstable condition when $D\delta \approx \sigma$ (see K_D expression) and the dispersive contribution to the transverse profile. To overcome the latter problem a deconvolution algorithm will be implemented relaxing the present hypothesis of Gaussian longitudinal distributions for the determination of the beam σ .

CONCLUSION

In this work, we reported the conditions and the results of the 2013 measurement campaign of the CPS WSs. The observations are compatible with an emittance relative precision and accuracy respectively better than 2% and 5% in the vertical plane for nTOF beams. The authors acknowledge the precious help of our PS-OP colleagues during the measurements.

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