PERFORMANCE ASSESSMENT OF WIRE-SCANNERS AT CERN

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Abstract

This article describes the current fast wire-scanner devices installed in circular accelerators at CERN with an emphasis on the error studies carried out during the last two runs. At present the wire-scanners have similar acquisition systems but are varied in terms of mechanics. Several measurement campaigns were performed aimed at establishing optimal operational settings and to identify and assess systematic errors. In several cases the results led to direct performance improvements while in others this helped in defining the requirements for new detectors.

WIRE-SCANNERS AT CERN

Wire-scanners are the reference devices for beam emittance measurements in the Large Hadron Collider (LHC) and its injectors. They are also used for calibrating "online" instruments, such as Ionization Profile Monitor (BGI) or Synchrotron Radiation Monitor (BSR), when applicable. It is therefore essential for them to be accurate and reliable with any error sources well understood.

Beam characteristics, sampling conditions and infrastructure differ a great deal all along the accelerator chain, and the wire-scanner systems are adapted to handle these differences. In the LHC, the devices are linear with a constant speed of 1 ms^{-1}. In the Super Proton Synchrotron (SPS), both linear scanners with a speed around 1 ms^{-1} and rotational ones with nominal speed of 6 ms^{-1} are used. In the Proton Synchrotron (PS) and Proton Synchrotron Booster (PSB), all devices are rotational fast wire-scanners with speeds of 10 or 15 ms^{-1}.

WIRE-SCANNERS ERROR SOURCES

Providing an accurate measurement of the beam emittance from this instrument depends on the accuracy of the wire position determination, the linearity of the signal chain measuring the secondary particles generated while the wire crosses the beam and the stability conditions of the beam. In this paper we will concentrate on the studies and improvements performed on the wire-scanner and its acquisition chain during the last two runs to guarantee the correct usage of the instrument and reduce as much as possible any systematic errors.

Identified error sources are mechanical uncertainties, electronics drifts and noise, non-linear behaviour of the photomultipliers, timing errors and limitations of the fitting algorithm. Errors due to beam instabilities are not discussed in this article, although they do affect the measurement results provided by the devices to the end users.

These error sources are summarized in Fig. 1, linking them to their origin in the wire-scanner system, and grouping them by how they affect the measurement.

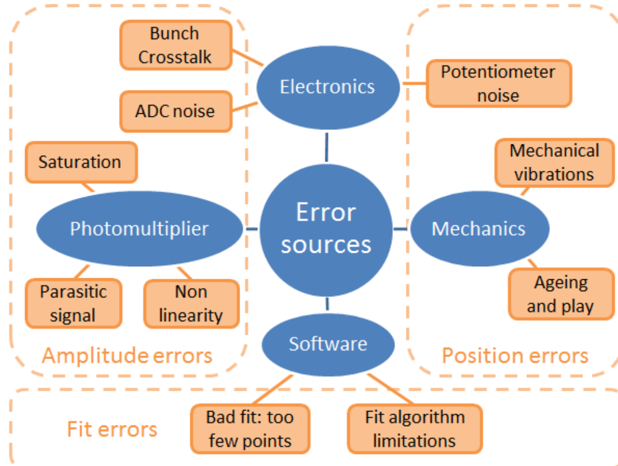

Figure 1: In blue, the different layers of the measurement chain. In orange, the potential sources of error linked to each layer.

POSITION ERRORS

In this section, we focus on the sources of uncertainty linked to the actual position of the wire when it crosses the beam. These errors need particular attention, as they immediately affect the accuracy of the profile width measurement. While with the LHC and SPS scanners the determination of the wire position with the measurement device is relatively straightforward, the rotational scanners of the PS and PSB have complex kinematic introducing large mechanical play which needs calibration before the installation in the accelerators on a dedicated calibration bench [1].

Mechanical Issues

In the current design of rotational wire-scanners for the PS and PSB, shown in Fig. 2, the number of fixed and moving rotation axes makes the wire scanner subject to mechanical play. At the same time, the large accelerations applied to the system will create vibrations of moving elements.

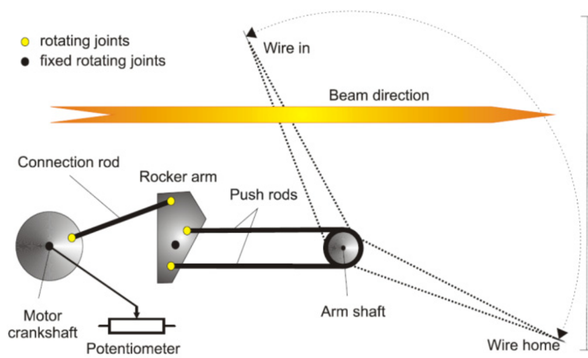

Figure 2: schematic of a PS and PSB rotational wire scanner.

ISBN 978-3-95450-127-4

Motion model optimization is currently underway to reduce mechanical vibrations by smoothing the acceleration phase and maintaining a constant speed while the wire crosses the beam, and a whole new mechanical design has been made for the next generation of wire-scanners [2] [3].

Potentiometer Reading Noise

For the linear wire-scanner used in the LHC, the sampling noise of the potentiometer signal whilst in the parking position has a standard deviation of 6 ADC bins, which corresponds to an interval of confidence (2σ) of +/- 54 μm. As the typical beam size σ_{beam} in the LHC ranges from 240 μm to 1.7 mm, some processing is needed to reduce this noise and improve the position accuracy. 5-tap averaging filters are therefore used, reducing the error range to +/- 18 μm.

For rotational wire-scanners, the reading noise on the ADC is smaller. In SPS, its standard deviation is only 0.5 bins, thus having an error range of 0.187 mrad, i.e. around +/-33 μm in the center of the vacuum tank. In PS, the reading noise standard deviation is around 1.5 bins, leading to an error of +/-90 μm in the center of the tank.

Position Sensor Calibration

For the current generation of rotational PS and PSB wire-scanners, the relationship between potentiometer position and projected wire position is a complex function, subject to many mechanical plays, requiring offline calibration. A calibration bench has been designed [1], from which a series of measurements is run to extract calibration tables and an interval of confidence for each scanner.

The calibration is performed by moving a laser/photodiode system and recording the photodiode signal versus angular position while the wire is scanning. The laser is mounted on a stepping motor with a known position from the centre of the vacuum tank, with the light split into two beams with a fixed distance between them of 2.80 mm. As the wire crosses the laser beam it produces two dips in the photodiode response for which the potentiometer value can be extracted.

Initially, the calibration procedure consisted of displacing the laser and its sensor in steps of 5 mm, measuring three times at each known position. Translation tables were then built by interpolating the averages. The introduction of new bellows to extend the lifetime of the wire-scanners in the machine in 2011 allowed increasing the number of scans for the calibration, which now uses steps of 0.5 mm. In parallel, new fitting algorithms were incorporated to profit from the smaller calibration steps. Different fitting routines including trigonometric formulas are being studied to further improve the reliability of the calibration.

The calibration set-up used has the advantage of eliminating systematic errors but the calibration is not perfect, as seen by the spread on measurements obtained for the same laser position. The calibration errors depend on many factors including the mechanical reproducibility, laser alignment precision, distance between calibrated positions, number of measurements per position and fitting or interpolation algorithm.

The statistical precision of the calibration is obtained by applying the calibration tables to the measured potentiometer values. The distance between dips in the photodiode response should then be a constant corresponding to the laser beam separation. Latest calibrations give an average laser beam distance of 2.80 mm with an rms of 0.08 mm.

In order to check the calibration of installed wire-scanners, the operation crew performed a set of measurements with closed-orbit bumps at the beginning of each run. These measurements have been particularly important in the SPS (see Fig. 3) where the theoretical position tables are now corrected by linear calibration factors that are different for IN and OUT scans. Similar measurements repeated the following year turned out to be reproducible and the correction remains valid indicating a systematic mechanical effect.

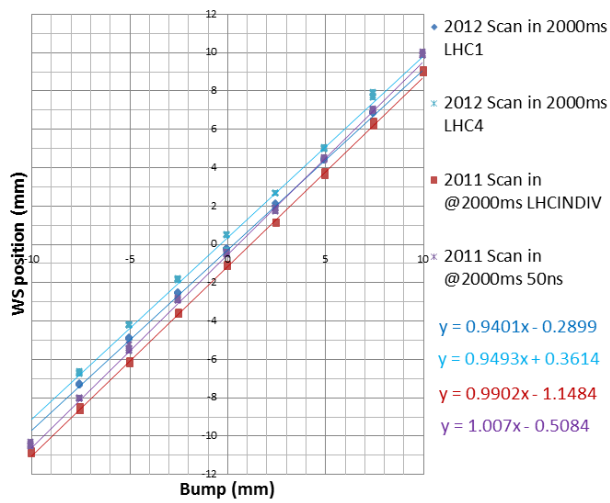

Figure 3: 2011 and 2012 SPS position calibration with closed orbit bumps.

AMPLITUDE ERRORS

Photomultiplier Saturation

Photomultipliers usually have a very good response time (around 2 ns) and are therefore suitable for high-frequency acquisition such as the 40 MHz required for bunch-by-bunch measurement in the SPS or LHC.

The detection of saturation in the photomultiplier has been one of most difficult issues to deal with during the everyday use of the wire-scanner. The current acquisition electronics use a logarithmic amplifier and ADC to sample the signal transmitted from the photomultiplier, allowing it to cover a large dynamic range and saturation of the photomultiplier itself may be hidden.

Saturation occurs when the incoming light intensity to the photomultiplier is too high. After some tens of microseconds, no more local charges are available in the supply capacitors and the measured intensity drops quickly even if the incoming light continues to increase.

ISBN 978-3-95450-127-4

Several studies on the photomultiplier behaviour have been carried out in all machines to determine linearity limits and compare them with laboratory tests.

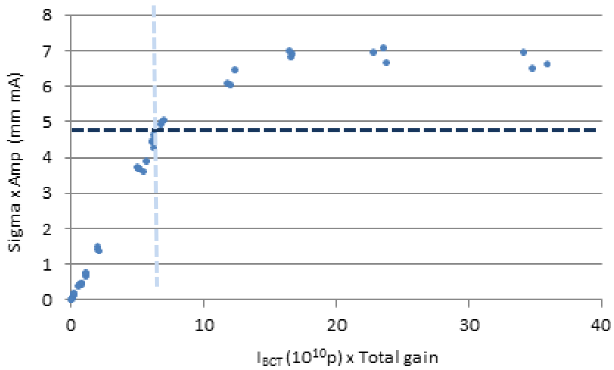

Figure 4: Photomultiplier response versus beam intensity.

The total area under the Gaussian curve representing the beam profile should be proportional to the intensity of the beam, but as shown in Fig. 4, this proportionality is only maintained up to a certain point. This point is the upper limit of the working range in terms of beam intensity times the total photomultiplier gain.

The linearity of the photomultiplier response to the incoming light depends almost entirely on the intensity and energy of the beam since the recharge time is an order of magnitude higher than the beam crossing time. Thus, another series of measurements were performed to establish an empirical threshold defining the limits of the intensity signal exiting the photomultiplier before reaching saturation. Based on the acquired profile, the front-end software computes the total intensity transmitted from the photomultiplier and provides the application software with an indication of the current signal level with respect to the saturation threshold.

Parasitic Photomultiplier Signal

The first studies performed in the PS and PSB and later in the LHC showed that the effect of the optical filters installed before the photomultiplier to limit the incoming light had a transmission much higher than expected. This was actually due to the direct impact of the secondary particle shower on the photomultiplier. This effect reduced the working range even when the optical filters were properly adjusted for the light produced by the scintillator and meant that beams with high intensity could hardly be measured without photomultiplier saturation.

This problem has been solved by either installing smaller photomultipliers which could be shielded with a few cm of lead in the PS and PSB or, in the SPS, by moving the photomultiplier further away from the beam. The parasitic contribution of the secondary shower on the photomultiplier signal in the LHC is between 1 and 3% compared to the total scintillator light intensity. This could be the dominant contribution, depending on the scintillator light attenuation.

Photomultiplier Gain Settings

The detection of the saturation was still not enough to operate the instrument in an easy, reliable fashion. Further studies on the influence of the photomultiplier working point on the beam size proved that the best range of use is when using the largest possible optical attenuation with the corresponding maximal photomultiplier gain below saturation, even if the electronic noise is slightly increased [4].

Digital Acquisition Noise

Noise was measured on the 14-bit Digital Acquisition Boards used in LHC and SPS bunch by bunch measurements, showing a standard deviation of less than 5 ADC bins, representing 2.5 mV on a scale from -2V to 2V. This translates to a relative error around 0.25% if the photomultiplier gain is properly set to use about half of the +/-8000 range of ADC units.

Cross-Talk Between Bunches

In the bunch by bunch mode, where wire-scanner particle shower measurement is gated for a single bunch acquisition, a part of the signal comes from the preceding bunch. This crosstalk has been estimated in LHC to be about 2.5% for 50 ns bunch spacing and 8% for 25 ns bunch spacing [5], while it is around 20% for 25 ns spacing in SPS which can be explained by the low pass filtering effect of the different configurations of the pre-amplifier and twice longer signal cables.

TIMING ERRORS

For measurements in the PS machine, the optimal setting of the scanner start timing is particularly important because of RF gymnastics occurring during the magnetic cycle. The LHC beam in the PS, for example, is stable only during a few milliseconds before extraction at 26 GeV. In order to check the time when the wire is crossing the beam, an external signal initiated from the machine timing electronics is acquired at the same time as the profile. The application can thus display the beam profile with respect to both beam position and time.

FITTING ERRORS

The main reason for fitting errors is having too few points in the Gaussian curve to obtain good result. Experience shows that fitting algorithms need at least 3 points per σ of the Gaussian curve to perform well [6].

In the SPS, the precision error is significant due to the small beam size at wire-scanner locations, especially when measuring the high energy beams. In order to reduce this error, it was proposed to use the bunch by bunch measurement, and provide an average profile constructed from the bunch profile overlaying all bunches and taking into account the actual position of the wire for each bunch within the turn.

ISBN 978-3-95450-127-4

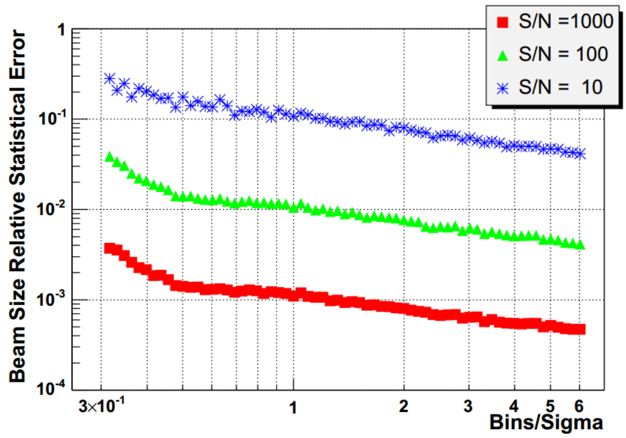

Figure 5: Beam size error as a function of the number of samples per sigma for various values of signal-to-noise ratio (S/N).

Considering only the range with more than 3 measurements per σ, Figure 5 shows that a noise of 1% on the signal amplitude leads to an error around 0.6%.

These curves also show that, for a high level of noise (10%), at least 4 measurements per σ are needed to achieve an accuracy of 5% on the fitting.

CONCLUSION AND PERSPECTIVES

Wire-scanners are deployed at CERN in the LHC and all its injector chain and need to cover a large range of beam characteristics (size, energy and intensity). Actions have been taken to correct systematic errors using calibration techniques and defining empirical optimal ranges with respect to intensity and photomultiplier gain. Some improvements are still needed for the SPS to achieve the expected accuracy and precision.

A new generation of rotational wire-scanner is now also under development [3] and a prototype will be installed in SPS for the next run (2014). Mechanical uncertainties with the new design have been thoroughly studied in [2]. It will use an optical position sensor to replace the potentiometer, with diamond detectors considered to replace the photomultipliers.

ACKNOWLEDGEMENT

We would like to thank the operational teams of PS, PSB and SPS for their measurement campaigns with wire-scanners, which specifically provided the data to study these error sources.

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ISBN 978-3-95450-127-4