ACCURACY OF PROFILE MONITORS AND LHC EMITTANCE MEASUREMENTS

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Abstract

The monitoring and controlling of the beam transverse emittance is essential to allow high luminosity performances in a collider operation. The profile monitors in the LHC injection chain are exploited to determine their precision. A fit strategy was developed to reduce the fitting procedure error and make it negligible compared to instrumentation errors. The method proved to be robust against non-Gaussian tails and can estimate the fraction of non-Gaussian distributed beam intensity. The procedure was applied to the 2003 SPS Wire Scanner measurements with different kind of LHC type beams. The reproducibility and accuracy of the six available monitors was determined by making synchronized measurements on the same proton beam. Some instrumental errors were discovered and corrected to the three per cent level. The demanding small LHC transverse emittances were determined under different beam conditions in terms of intensity, bunch spacing and length in the PS Booster, PS and SPS.

DATA PROCESSING

Dedicated software has been developed to make an off line treatment of the data acquired from all the CERN transverse profile monitors. The algorithm is written using the C++ programming language and is linked to the ROOT package libraries [1]. The analysis aim is to measure the beam transverse emittance and to specify additional information which characterize the significance of the results.

At first an error is assigned to each profile data point; this is later used to evaluate the χ^2 . The fitting routine is based on the χ^2 minimization.

The statistical uncertainty of a signal can be defined as proportional to the square root of the signal amplitude, when the largest uncertainty is caused by the number of incoming events. However, in the case of particle beam profiles, for which the tails regions can be affected by electronics noise and background, the error does not only depend on the number of events.

The error bars have been defined as the RMS of four contiguous measurements. If $y_i, i = 1 \ldots 4$ are four contiguous acquisitions with mean value $\overline{y}$, their error bars are defined as the RMS of the four measurements,

$$\epsilon_i = \sqrt{\frac{1}{4}\sum_{i=1}^{4}(y_i - \overline{y})^2} \tag{1}$$

This assumption is true in the tails regions and in a profile peak region, while overestimates the error in the profile regions whin a gradient dY/dX different from zero. This drawback proved to not bias the analysis accuracy. The profile is then fitted with a Gaussian function plus an offset:

$$f(x) = A + \frac{B}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}}. \tag{2}$$

where μ is giving an estimate of the beam position, and σ of the beam size. A is the profile offset, and B a parameter proportional to the profile amplitude. The resulting $\overline{\chi_0^2}$ (which is normalized for the degrees of freedom) is introduced in the following equation in order to evaluate the probability of getting a $\overline{\chi^2} \leq \overline{\chi_0^2}$ for a given number of degrees of freedom d:

$$P_d(\overline{\chi^2} \leq \overline{\chi_0^2}) = \frac{2}{2^{d/2}\Gamma(d/2)} \int_{\overline{\chi_0^2}}^{\infty} x^{d-1} e^{-x^2/2} dx \tag{3}$$

where

$$\Gamma(d/2) = \int_0^{\infty} e^{-t} t^{(d/2-1)} dt$$

is called *Gamma Function*. The probability in Eq. (3) is also called *confidence (or significance)* level. The confidence level of the parametrization is taken as the indicator of the appropriate fit. If the confidence level is not considered acceptable (the limit value is normally set to 60%), a second fit is performed only considering the acquisitions with amplitude above a threshold. The threshold is increased until when the confidence level is accepted.

For instance, Fig. 1 shows the acquired data and two approximating functions: one fitting all the data (blue) and one fitting only the data above a threshold level with an acceptable confidence level (green). Fig. 2 displays the errors given to each measurement before the fitting and the residuals between each measurement and the second approximating function. The integral of this latter quantity is used to specify the non-Gaussian level of the beam. The residuals of the data above the threshold are very small and not considered in the integral calculation.

Fig. 3 shows the beam size σ as function of the varying threshold. When fitting all the data points, the parametrization overestimates the width of the distribution. Excluding the points below a threshold leads to lower values of the Gaussian width σ. The threshold is increased up to $15.5\,\%$ of the peak, where the confidence level is accepted. For the given example the relative difference in the normalized emittances measured with the two different parametrization exceeds $60 \cdot 10^{-2}$. The core of the beam is well fitted by a Gaussian distribution, but the residuals integral is $\approx 9\,\%$ of the profile integral. This value indicates the presence of tails.

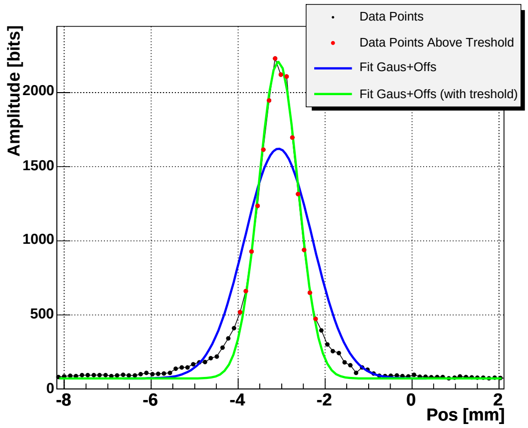

Figure 1: Beam profile from the SPS WS.

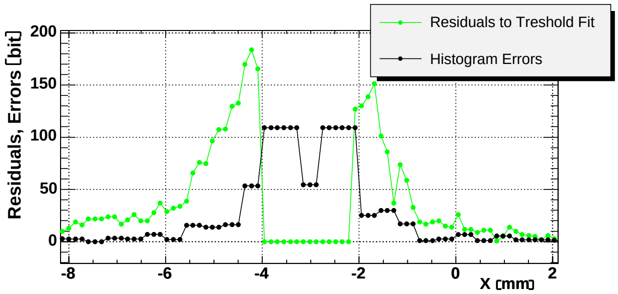

Figure 2: Graph of the errors assigned to the acquisitions of the data shown in Fig. 1 (black) and graph of the residuals between the data and the parametrization with threshold (green).

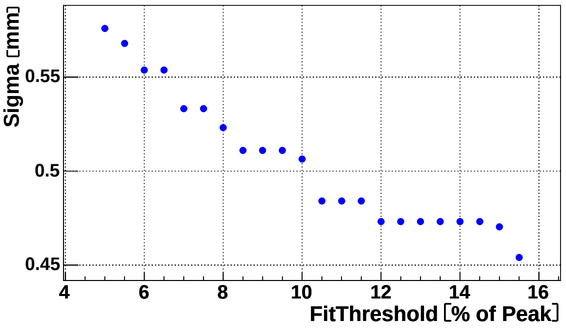

Figure 3: Variation of the evaluated beam size while changing the fit threshold.

SPS WIRE SCANNERS

The SPS ring is equipped with twelve wire scanner monitors [2]. Half of them move linearly through the beam with a maximum speed of $1\,m/s$. The other six are rotational instruments, the wire is moving at a maximum speed of $6\,m/s$. Their direction, at the beam's location, has an angle with respect to the orthogonal to the particles' trajectory, of about 20°. The shower of secondary particles, produced by the wire-beam interaction, is detected by a scintillating material coupled to a photomultiplier tube.

Correction of Systematic Errors

The wires' movement can be from the outer part of the ring to the inner (*IN Scan*) or opposite (*OUT scan*). During the operation of the six rotating devices, systematic difference in the measured beam size, using the two opposite direction, was discovered and investigated. The discrepancy is related to a low pass filter integrated in the position readout electronics. The filter introduces a delay in the time domain while reading the absolute angular position of the motor. Such effect causes an error in the calculation of the wire location in the transverse plane [3]. The error develops as an offset angle which has opposite sign for the two movement directions. A correction is now implemented, by estimating an angle such that the beam appears in the same position during two scans with opposite directions. Fig. 4 shows the "IN-OUT" beam size relative difference as function of the absolute beam size. Before the correction the average difference is $\approx 10\cdot 10^{-2}$, while after it is below $3\cdot 10^{-2}$. The plot illustrates the average of 136 profile measurements, performed with all the rotational devices.

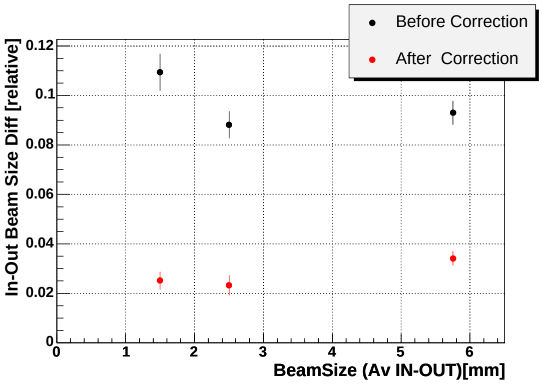

Figure 4: Relative difference in the beam size of the "IN" and "OUT" SPS wire scanners scans, as function of the absolute beam size (before and after the correction)

Relative Comparisons

In order to estimate the accuracy of the SPS wire scanners several measurements have been devoted to estimate the normalized emittance by detecting the transverse beam size with all the available monitors. The scans were performed in synchronization, each time at the same instant during the the beam injection in the SPS. The emittance blow up due to the multiple Coulomb scattering generated by the beam-wire interaction would alter the particles' distribution and cause asymmetric profiles. However this effect is negligible for the LHC beam in the SPS [3], even when using several monitors on the same beam.

Fig. 5 depicts an example of such measurements. The normalized vertical emittance is plotted as function of the su-

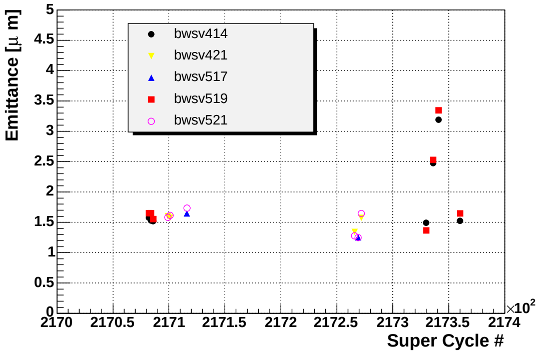

Figure 5: Normalized vertical emittance tracked by five different wire scanners in the LHC, as function of the super cycle number.

Monitors	Mean [%]	Spread [%]	Error on the Mean [%]
v519-v414	4.81	2.25	0.92
v521-v421	1.87	2.34	1.17
v521-v517	2.49	2.67	1.39

Table 1: Relative emittance differences as measured in Fig. 5

per cycle number, as measured by five wire scanners in synchronization. The measurements were done on the $75\,ns$ bunch spacing LHC beam. The emittance variation is very well tracked by different monitors.

Table 1 resumes the relative differences in the normalized emittances shown in Fig. 5. It was possible to compare three couples of monitors. The mean difference indicates a systematic discrepancy which can be for instance related to uncertainties on the optical functions. The error on the mean ($= RMS/\sqrt{N_{meas}}$) attests the significance of the systematic discrepancy. The spread (RMS) gives an indication of the instruments non reproducibility. Taking the average value of the spread ($\approx\ 2.4\,\%$) and dividing by $\sqrt{2}$ (being each difference relative to two instruments), it is possible to estimate the non reproducibility of a single monitor as $\approx\ 1.7\,\%$. Although more studies are needed, these results are very encouraging.

TRANSVERSE EMITTANCE TRACKING IN THE LHC PRE-ACCELERATORS

The data treatment strategies described above have been also implemented to analyze the beam profiles generated with the CERN PS Booster and PS. Several studies were performed during the year 2003 using the Fast Flying wire systems [4] installed in the two accelerators. In the PSB it was also possible to compare the results with the ones of three wire grids installed along an extraction line.

Such measurements campaigns allowed the tracking of the transverse emittance of the protons beams during acceleration to LHC and under different beam conditions [5]. For instance, Fig. 6 shows the vertical emittance evolution of the LHC ”pilot bunch” ($5 \cdot 10^9$ protons) from the PSB top energy to the energy of the injection from the SPS to the LHC. Here the error bars express the spread of each set of measurements, which were not taken in the same periods and therefore suffer beam size oscillations in addition to the instruments’ systematic and statistical errors.

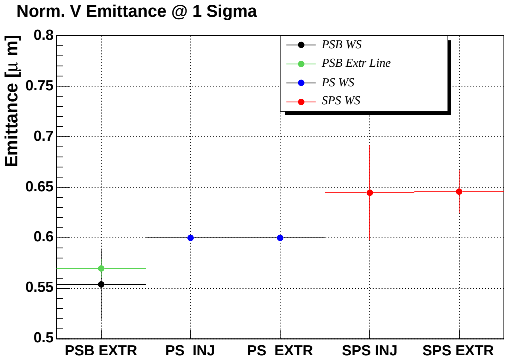

Figure 6: Vertical emittance evolution of the ”pilot” bunch in the LHC pre-accelerators.

CONCLUSIONS

A new set of analysis tools has been developed to study the reproducibility and accuracy of the transverse profile monitors exploited at CERN. In this paper we presented the analysis method and showed how its application to the CERN wire scanner monitors served to depict their accuracy. Relative comparisons between the SPS monitors showed systematic differences below $5\,\%$ with statistical fluctuations below $1.5\,\%$. The proper calibration of these instruments brought to the characterization of the beam transverse emittance during the acceleration to LHC.

Acknowledgments

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