ACCURACY OF THE SPS TRANSVERSE EMITTANCE MONITORS

F. Roncarolo, B. Dehning, C. Fischer, J. Koopman, CERN, Geneva, Switzerland

Abstract

A campaign of studies and measurements has been carried out with the aim of establishing the SPS transverse profile monitors resolution, reproducibility and accuracy. The studies regarded systematic dependencies of the SPS Wire Scanner (WS) monitors on the operation setups and on the beam parameters, like beam intensity, bunch spacing and beam size. The emittance increase due to multiple Coulomb scattering during the linear WS operation has been measured and compared with the theoretical model prediction. Numerical simulations estimate the errors introduced by the limited resolution of the imaging systems and by excessive electronic noise of the detectors. The experimental measurements have been carried out with a wide range of beams, from the low intensity pilot bunch to the LHC nominal beam. At first the different SPS WS are compared during simultaneous measurements. The SPS IPM vertical profiles have been compared to the WS while tracking the beam emittance from 26 to 450 GeV. The IPM resolution improvements from 2003 to 2004 are pointed out.

WS MEASUREMENTS

The CERN SPS is equipped with ten WS monitors (five for each transverse plane) mounting $30\,\mu m$ diameter Carbon wires. Four of them are based on a mechanism that drives the wire *linearly* along a direction orthogonal to the beam trajectory with a maximum speed of $1\,m/s$. The remaining six monitors are based on a rotational mechanism which drives the wire at a maximum speed of $6\,m/s$.
All the WS measurements presented below were carried out with two or three instruments simultaneously, with a time jitter of $1\,ms$. For all the plots and tables which will be presented hereafter, the emittances are intended at one sigma and normalized to the beam energy.

Linear WS Calibration

The result of the simultaneous operation of two linear WS (measuring the vertical beam size) during seventeen SPS cycles is shown in Fig. 1. Each time slot (horizontal axis on the plot) refers to one cycle and consequently to the injection of new particles that do not necessary have the same emittance as in the previous cycle. Two scans per cycle are performed with each instrument: at $t = 0.5\,s$ after the protons injection the wires move in a forward direction (*IN scan*, from the bottom to the top of the beam pipe) and at $t = 1.5\,s$ they move backward (*OUT scan*). Both instruments detect a systematic emittance increase during

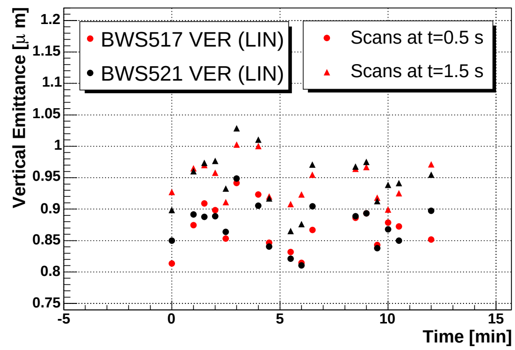


Figure 1: Comparison between two linear WS during simultaneous measurements with TOTEM beam injected every 30 s in the SPS and circulating at 26 GeV for 4.5 s.

the two scans. This is due to Coulomb scattering between the beam and the wire material, the OUT scan detects the emittance increase generated by the IN scan [3].

The standard deviation of the measured emittance increase, divided by $\sqrt{2}$ (since the increase is detected by two scans), assesses the monitors *repeatability*. In terms of beam size the repeatability results in 6 and $10\,\mu m$ for the considered instruments. The mean value of the differences between the emittances measured by the two linear monitors determines the relative WS *accuracy*. The relative average difference results well below $1\,\%$ of the small vertical emittance characterizing the measured beam ($\approx 0.9\,\mu m$).

Cross Calibration Between Linear and Rotational WS

The three rotational WS monitoring the vertical beam size have been operated in synchronization with a linear device (labelled 517V) used as a reference. Table 1 and Fig. 2 summarize the comparisons, including the one between the two linear WS described in the previous paragraph. The IN and OUT scans are analyzed separately and in the table μ, σ and σ_μ are the differences mean value, standard deviation and error on the mean ($= \sigma/\sqrt{N_m}$) over N_m measurements. The figure also refers to the "IN/OUT correction".
A post-processing of the values of the wire position during the rotational WS operation is in fact necessary. The measured angular position of the wire is projected on the transverse coordinate by an algorithm. A systematic error in the angular position arises from a low pass filter used to reduce the electronic noise on the potentiometer. Such filter introduces a delay in the time domain between the measured and the real angle, which results in an opposite

Table 1: Vertical normalized emittance differences between the linear WS labelled V517 and the other four SPS WS, separating the IN and OUT scans. (R) stands for ”Rotational” and (L) for ”Linear”.

		Relative Emittance Difference [%]					
		Scan IN			Scan OUT		
Monitors	N_m	μ	σ_μ	σ	μ	σ_μ	σ
414V(R)	14	4.0	1.9	7.1	-3.7	2.3	8.7
416V(R)	5	-32.7	2.1	4.7	-37.9	2.2	4.9
519V(R)	7	10.4	2.7	7.1	-0.8	4.1	10.8
521V(L)	17	0.3	0.6	2.3	0.1	0.6	2.5

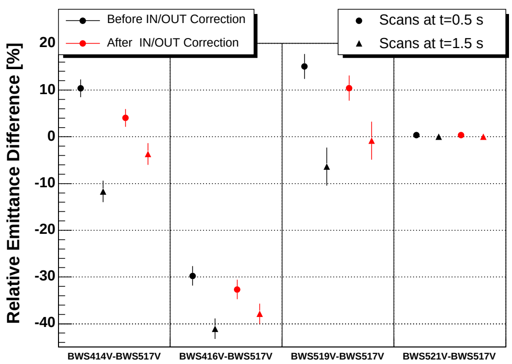


Figure 2: Normalized emittance relative differences between couples of WS monitors.

sign offset in the angular domain for opposite movement directions. Even if the wire speed is constant, the measured transverse beam size is distorted, due to the non linearity of the wire position projection on the transverse coordinate. Hence, without any off-line correction, the emittance measured during the IN scan systematically results about $10\,\%$ higher then the one measured during the OUT scan. The off-line correction reduces the error to below $3\,\%$ [2].

Reconsidering now the comparisons summary of Table 1, the error on the mean σ_μ, expression of the accuracy of this set of measurements, has a maximum value of $4\,\%$ (for the monitor labelled 519V, OUT scans). The *repeatability* of the differences follows from the repeatability of the compared instruments. With the assumption that all the monitors are characterized by the same statistical fluctuations in measuring the beam size, the repeatability would be the standard deviation of the differences divided by the square root of 2. However it is not known a priori if the repeatability of the rotational WS is equal to the one of the linear devices. Profiting of the considerations of the previous paragraph, we can take $r_{517V} = 10\,\mu m$ as the repeatability of the reference wire scanner in terms of beam size. This corresponds to a variation of $10\,nm$ of the absolute emittance. In terms of relative emittance the repeatability of BWS517V is $r_{\epsilon 517v} = 1.1\,\%$. This value, together with the statistical fluctuations of the differences between couples of instruments can be used to calculate the repeatability of the other monitors according to:

$$r_{dif,i} = r_{i-517V} = \sqrt{r^2_{\epsilon 517V} + r^2_{\epsilon i}}$$

Table 2: Repeatability in terms of beam size of the five SPS WS monitoring the vertical plane.

Monitor	**Repeatability** $[\mu m]$			
	Scan IN	Scan OUT	Average	RMS
414V (R)	29.9	36.8	33.4	4.9
416V (R)	32.6	36.8	33.4	1.0
519V (R)	33.1	50.6	41.8	12.4
517V (L)	10			
521V (L)	12.8	14.3	13.6	1.0

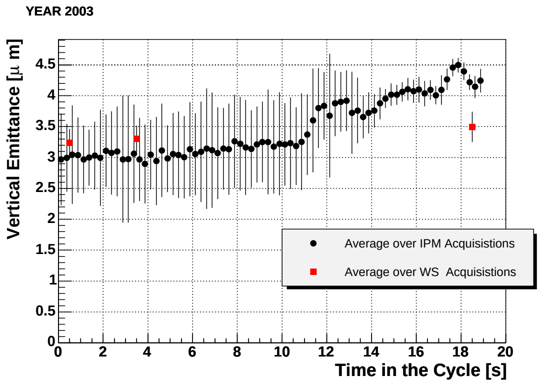
$$\Rightarrow \quad r_{\epsilon i} = \sqrt{r^2_{dif,i} - r^2_{\epsilon 517V}} \quad \text{with i=414V, 519V, 521V}$$

where the values $r_{dif,i}$ are the standard deviations σ of the differences in terms of relative emittance. From each value $r_{\epsilon i}$ the repeatability in terms of absolute beam size can be calculated, after denormalizing for the betatron function and the beam energy. The repeatability values determined for the five WS are summarized in Table 2, where the average and RMS values are calculated from the IN and OUT scans.

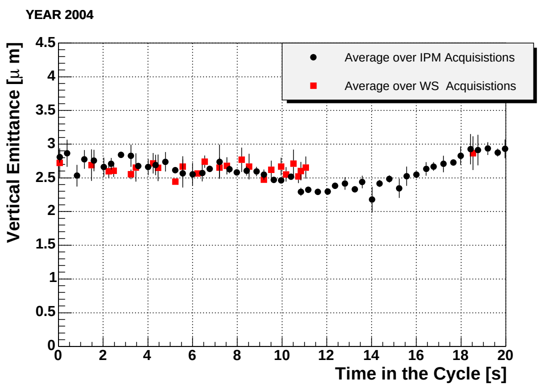
CROSS CALIBRATION BETWEEN WS AND IPM

The SPS Ionization Profile Monitor (IPM) [4], designed to monitor the vertical emittance has been calibrated with respect to the WS, after several adjustments and upgrades during the year 2003 [5]. We will present the IPM-WS comparisons in measuring all the LHC type beams accelerated in the SPS in 2004 and confront the results with the ones obtained in 2003.

Unlike the previous measurements with the SPS WS, where the different monitors have been compared simultaneously on the same beam, the comparison between IPM and WS has been carried out over long periods. In such a way it was possible to assess the IPM repeatability with different gain settings and its reproducibility with different beam conditions. During the considered periods the beam emittances measured by the IPM and the WS are determined by averaging a number of profiles. The averages which will be presented in the plots and tables are computed from all the profiles at a fixed time in the cycle for several cycles. The error bars on the plots indicate the error on the mean. The cross calibration has been carried out during the acceleration in the SPS of the LHC *pilot*, the *75 ns bunch spacing* and the *LHC nominal* beams, differing in intensity and bunch spacing and beam size. Fig. 3 displays the vertical emittance as function of time in the cycle, as measured by the IPM and WS monitors with the nominal LHC beam in 2003 and 2004. The particles circulate at 26 GeV until $t = 10.8\,s$, when the acceleration starts. The energy flat-top at 450 GeV begins at $t = 18.5\,s$. In 2003 the IPM overestimated of about $17\,\%$ the emittance measured at top energy by the WS. The discrepancy dropped below $2\,\%$ in 2004. This demonstrates the improved resolution obtained after the upgrade of the imaging system [5]. Table 3 summarizes the IPM-WS comparisons carried out in 2004



(a)



(b)

Figure 3: Vertical normalized emittance measured by the IPM with LHC nominal beam and comparison with the WS: (a) year 2003, (b) year 2004.

with the three different beams. Fig. 4 displays the absolute difference between the beam size σ_{IPM} measured by the IPM and the expected value at the IPM location σ_{WS}, derived from the WS measurements. The difference is plotted as function of σ_{WS} for the various measured beams. The largest discrepancy between IPM and WS is with the smallest beam, the pilot bunch at 450 GeV. Expressing the IPM *beam size error* as $\delta\sigma = \sqrt{\sigma_{IPM}^2 - \sigma_{WS}^2}$, $\delta\sigma$ resulted in about 350 μm in 2003 and 250 μm in 2004. For an expected beam size of 224 μm at the IPM location (see last line in Table 3), the IPM *beam size overestimation* ($\sigma_{IPM} - \sigma_{WS}$) was about 240 μm in 2003 and decreased to 140 μm in 2004. These two values are very close to the $\mu m/pixel$ factors achieved in the two years with the different optical imaging systems.

SUMMARY AND OUTLOOK

During the acceleration in the SPS of low intensity, low emittance beams the wire scanner monitors were operated simultaneously. The linear WS, have been considered as a reference and the rotational compared to them. The systematic difference between two linear WS is below 1 % in terms of normalized emittance. The difference between the rotational and linear monitors emittance varies from 3 to 38 % (in terms of normalized emittance). The SPS Ionization Profile Monitor has been optimized and tested under several beam conditions and the measured normalized vertical emittance has been compared with the one measured with the WS. The IPM overestimates the width of low intensity, low emittance beams. Such effect is attributed to the limited resolution of the imaging system. Improvements were observed in the year 2004 with respect to the year 2003, but the relative disagreement between IPM and WS remains above 20 % in terms of normalized emittance when the beam size at the IPM location is below 400 μm.

Table 3: IPM resolution with different beam conditions and comparison with parallel wire scanner measurements. Measurements taken during the SPS 2004 run. σ^e_{IPM} is the beam size expected at the IPM location, derived by the WS measurements.

Beam	E_b $[GeV]$	σ^m_{IPM} $[mm]$	σ^e_{IPM} $[mm]$	ϵ_{IPM} $[\mu m]$	ϵ_{WS} $[\mu m]$	$\Delta\epsilon$ $[\%]$
LHC	26	3.097	3.085	2.770	2.750	0.7
Nomin.	450	0.762	0.755	2.900	2.850	1.8
75 ns	26	2.209	2.201	1.410	1.400	0.7
	450	0.583	0.535	1.700	1.430	18.9
Pilot	26	0.985	0.911	0.280	0.240	16.7
	450	0.361	0.224	0.650	0.250	160.0

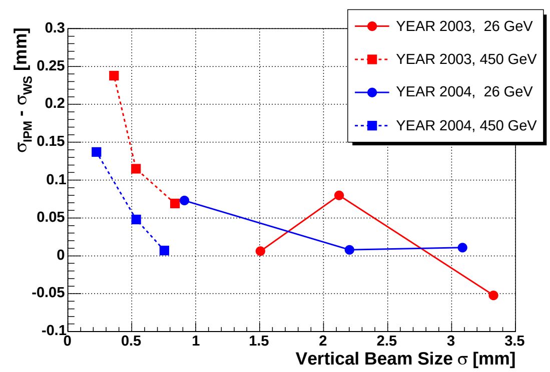


Figure 4: Comparison between IPM and WS derived from all the available measurements, in terms of beam size differences.

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