CROSS-CALIBRATION OF THE LHC TRANSVERSE BEAM-PROFILE MONITORS

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Abstract

Calibration of a transverse beam profile monitor is of fundamental importance to guarantee the best possible accuracy and reliability of the instrument over time. In LHC the calibration standard for transverse-profile measurements are the wire scanners. Other profile monitors such as beam synchrotron light telescopes and interferometers are calibrated with respect to them. Additional information about single-bunch sizes can be obtained from beam-gas imaging with the LHCb vertex detector, from the transverse convolved beam sizes extracted from luminosity scans at the collision points, and from the evolution of the luminous-region parameters as reconstructed by ATLAS and CMS inner tracker detectors during such scans. For the first time at the LHC, a dedicated cross-calibration of all the above-mentioned systems was carried out with beam in 2016. Additionally, dedicated optics measurements were also performed in order to determine with the highest possible accuracy the amplitude function at the interaction points and at the position of the profile monitors. Results of these measurements are presented in this paper.

INTRODUCTION

The cross-calibration of the different emittance measurement devices and techniques was performed during a Machine Development session in Oct 2016. Ten nominal intensity proton bunches were injected and selectively blown up to obtain normalised emittances, $\epsilon_{H,V}$, in the range $\leq$ 1 up to ~6 μm rad. The van der Meer (vdM) optics with particularly large beta values at the interaction points (β^*) at 6.5 TeV per beam, was chosen for the exercise in order to minimise the contribution of the vertex resolution in the beam size measurement, $\sigma_{H,V}$, at the experiments.

WIRE SCANNER MEASUREMENT

Wire scanners (WS) [1] measure the transverse beam density profile by means of a moving thin wire, which interacts with the beam generating a cascade of secondary particles intercepted by a scintillator, coupled with a photomultiplier (PMT). The charge deposition is proportional to the local density of the beam and is used to measure the beam density profile. Figure 1 shows the evolution of the $\sigma_{H,V}$ as measured by the WS during the MD.

To avoid PMT saturation the applied voltage and the optical density filters at the scintillator output were carefully chosen. Additionally, the measured profiles were reprocessed to improve the WS precision that is limited by noise, both on the wire position and on the PMT signal readings. The reported $\sigma_{H,V}$ measurements feature a reproducibility of $\sim 5\%$ and the systematics are also estimated to be $< \ 5\%$.

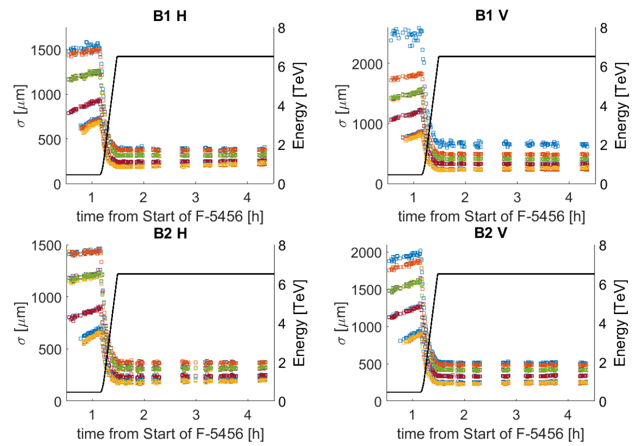

Figure 1: $\sigma_{H,V}$ evolution, bunch-by-bunch, as measured by the WS. The adiabatic shrinking of the beam size during the energy ramp is observed.

BSRT MEASUREMENT

The BSRT monitors image the visible synchrotron light generated by the beam traversing a dedicated superconducting undulator, at injection energy, and a D3 type dipole located in IR4 after $\geqslant$1 TeV. The $\sigma_{H,V}$ calculation from the BSRT measurements is extensively explained in [2]. The cross calibration process heavily relies on the WS measurement quality, the emittance range of the circulating bunches and the knowledge of the machine optical functions. In fact, three different calibration sessions were needed in 2016 [3] to cope with the different operational conditions.

To assess the BSRT performance, comparison of the $\epsilon_{H,V}$ measured by the BSRT and WS is presented for two different scenarios both at the injection energy and 6.5 TeV. The first scenario uses the operational calibration (Old) based on the modeled β functions and $\epsilon_{H,V}$ ranging from ~ 2 to 6 μm rad. In the second, the BSRT was re-calibrated using the β values measured during this MD and profiting of the wide range of injected $\epsilon_{H,V}$ ranging from ~ 0.8 to 6 μm rad.

Table 1 summarizes the error distributions. Systematics up to $20 - 30\%$ on the $\epsilon_{H,V}$ are observed using the Old calibration. Recalibration is thus mandatory to obtain reli-

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able measurements since it improves greatly the accuracy of the measurements and the agreement with the WS. A small deviation from the expected linear behavior is nevertheless observed for very small bunches indicating that for $\sigma_{H,V} < 200\mu m$ ($\epsilon_{H,V} < 1.5$ μm rad) the assumption of a Gaussian optical resolution of the system does not properly describe the results. This is predicted in [2] and presents the major limitation of a diffraction limited optical system.

An attempt to directly map the measured $\sigma_{H,V}$ by the BSRT and by the WS scaled by $\frac{\beta_{BSRT}}{\beta_{WS}}$ was carried out and resulted in a new "non linear" calibration function leading to some measurement precision improvement as quoted in Table 1. Future studies will investigate its applicability for the operational beams in 2017.

Table 1: Parameters (Centroid $\bar{\Delta}$ and Standard Deviation σ_{Δ}) of the Relative Discrepancy the $\epsilon_{H,V}$ Measured by the WS and the BSRT

	Calibration	[%]	Beam 1 H	Beam 1 V	Beam 2 H	Beam 2 V
450 GeV	Old	$\bar{\Delta}$	-16.1	3.55	-0.9	-10.4
		σ_{Δ}	2.27	3.9	2.8	2.3
	New	$\bar{\Delta}$	1.79	0.1	0.5	1
		σ_{Δ}	3.3	4.1	3.6	2.8
6.5 TeV	Old	$\bar{\Delta}$	18.7	32.3	5.4	-3.9
		σ_{Δ}	9.2	18.6	10.9	6.2
	New	$\bar{\Delta}$	-0.2	-1.2	-1.5	-0.11
		σ_{Δ}	11.3	8.5	10.6	6.3
	Non Linear	$\bar{\Delta}$	0.45	0.8	0.2	0.5
		σ_{Δ}	5	7.1	8.1	3.6

EMITTANCE FROM BEAM-GAS INTERACTIONS AT LHCB

Using the Beam-Gas Imaging (BGI) method [4], a unique capability of the LHCb experiment [5], the beam width can be reconstructed and used to calculate the transverse emittance. Each LHC beam is visible through the collision of protons in the beam with the residual gas molecules. The interaction vertices are reconstructed by the VErtex LOcator (VELO) subdetector placed around the interaction point, allowing the measurement of the beam shape.

During the MD helium gas was injected inside the VELO vacuum chamber to increase the sample size. The reconstruction of interaction vertices is performed using standard LHCb algorithms [6]. The observed vertex distribution is fitted with a convolution of the true beam shape and the measured vertex position resolution [7, 8]. Both single and double Gaussian models are used, giving compatible results for the standard deviation of the beam shape.

Figure 2 correlates the $\epsilon_{H,V}$ obtained using the BGI and the WS methods during the stable beams period. The intercept, p_0, quantifies the offset between both measurements. A deviation from unity in the slope, p_1, indicates a systematic error in either the measurement of the value of β or the beam width at LHCb and/or the WS. A considerable discrepancy between BGI and WS measurements is seen only in the horizontal plane for beam 1. Correlations of the $\sigma_{H,V}$ as reconstructed by LHCb and variables like the longitudinal vertex position and the beam slope do not show any systematic behaviour. Currently, the reason for the discrepancy is not understood. All other comparisons show an agreement within 10%.

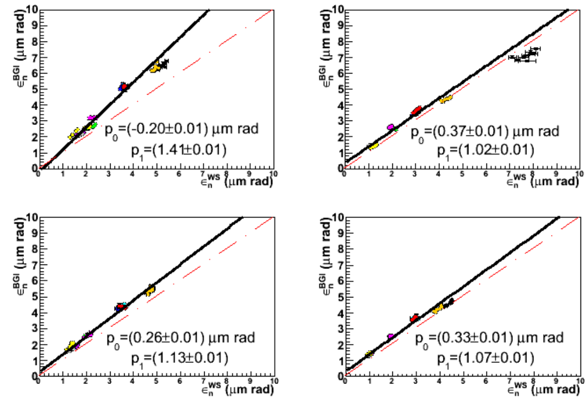

Figure 2: Emittance from BGI vs wire scanners. The figure has to be redone with the latest values of the measured betas

EMITTANCE FROM ONLINE LUMINOSITY MEASUREMENT

The emittance scan analysis [9] was applied to the bunch-by-bunch online luminosity measurements during the transverse beam scans. In the vdM optics no crossing angle is present at ATLAS and CMS, and hence any contribution of the longitudinal distribution vanishes. The first of the 3 scan pairs had to be excluded due to an interference with the LHC orbit feedback system. Within the statistical errors derived from the fits and the systematic errors of ~6 % e.g. due to uncertainties in $\beta*$ and non-Gaussian bunch profiles the results from the ATLAS and CMS scans are consistent.

The results are compared to the WS measurements in Fig. 3 showing maximum differences of −4%/+12%, which is consistent within the expected systematic and statistical errors.

EMITTANCE FROM CMS OFFLINE LUMINOSITY MEASUREMENT

Pixel Luminosity Telescope (PLT) [10] is one of the CMS online luminometers based on silicon pixel sensors used to measure the emittance during the transverse beam scans in the CMS experiment. Accumulated rates as a function of the displacement were fit using the “CMS vdM fitting framework". A double Gaussian function is chosen because it gives the most accurate agreement with the transverse profiles shapes. The beam width extracted from the fit was translated into emittance. Beam-beam correction and length scale corrections are applied. The source data used in this offline analysis is identical to the online data, as pileup corrections are already included in the online publication. Agreement

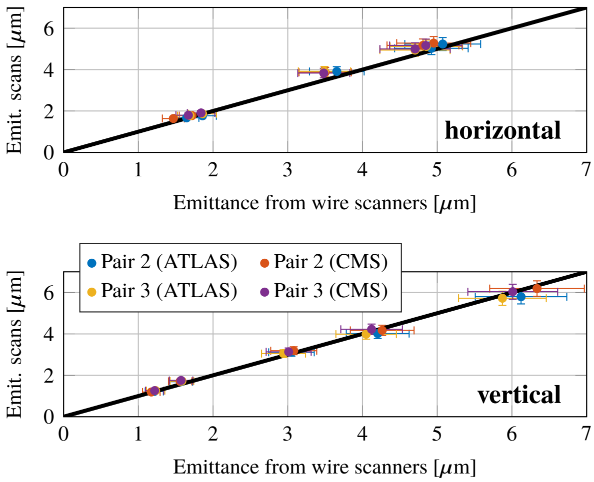

Figure 3: $\epsilon_{H,V}$ from the emittance scan analysis compared to the WS measurements. The diagonal is unity.

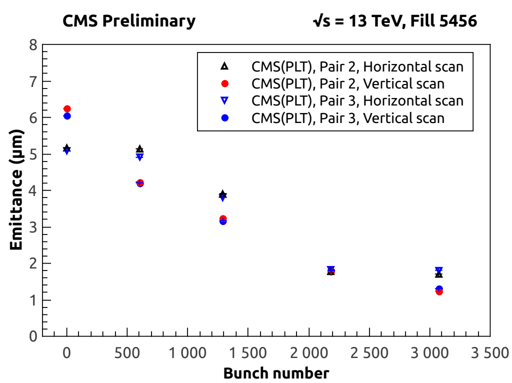

Figure 4: Off-line $\epsilon_{H,V}$ measured from the emittance scan analysis by CMS using the PLT data.

in emittance between online and offline analyses is 4% in vertical and 5% in horizontal scans.

OPTICS MEASUREMENTS

The calculation of the beta functions at the points of interest have been done using two different techniques: segment-by-segment (SbS) and k-modulation (KMOD). The accuracy of the SbS method [11, 12] depends on the initial size of the error bar, which is then propagated analytically through the different optics elements [13], and on the location of the Beam Position Monitors (BPM) delimiting the segment. This fact can be observed in Table 2 where β^* error bar reaches a relative value of 40% in LHCb because of a very large initial error due to a lack of measurements in the BPM closest to the IP.

The KMOD method [14–17] gives a more precise measurement of the β-function as can be seen in Table 4 were both methods are compared for the different instruments.

A limitation of the KMOD technique in the reconstruction of the β^* was found when analyzing the results presented in Table 3 [18]. This constraint was especially remarkable in IP5 and in consequence, the calculated horizontal β function was not accurate with respect to the rest of the AC-dipole

Table 2: Summary of SbS β^* Measurements at the IPs

β [m]	IP1	IP5	IP8
Closest BPM left	45 ± 2	41.2 ± 0.4	135.1 ± 0.3
IP	19 ± 3	20 ± 3	25 ± 10
Closest BPM right	40.4 ± 0.2	47 ± 1	46 ± 1

Table 3: Summary of KMOD β^* Measurements at the IPs

	Beam 1		Beam 2	
IP	β^* hor [m]	β^* ver [m]	β^* hor [m]	β^* ver [m]
IP1	17.4 ± 0.01	18.1± 0.02	17.7 ± 0.02	17.2 ± 0.02
IP5	- ± -	19.6 ± 0.02	- ± -	18.6 ± 0.01
IP8	23.9 ± 0.05	22.2 ± 0.04	21.9 ± 0.03	21.7 ± 0.03

Table 4: Summary of β^* Measurements at the Different Elements

Instruments	$\beta_{x(\mathrm{KMOD})}$	$\beta_{y(\mathrm{KMOD})}$	$\beta_{x(\mathrm{SbS})}$	$\beta_{x(\mathrm{SbS})}$
BWS.5R4.B1	191.1 ± 0.2	371.0 ± 0.5	194 ± 13	373 ± 16
MBRS.5R4.B1	192.5 ± 0.2	330.2 ± 0.5	197 ± 9	324 ± 21
BWS.5L4.B2	200.8 ± 0.2	387.3 ± 0.3	196 ± 17	403 ± 22
MBRS.5L4.B2	204.0 ± 0.2	314.8 ± 0.2	197 ± 10	341 ± 15

measurements [19](beating ≈ 40%). Note that here only the error from the tune uncertainty is included. Errors from quadrupole misalignment and fringe fields, which are of the order of 2.5% were not take into account. By comparing the results presented in the tables it can be certainly concluded that the methods are consistent with each other.

CONCLUSIONS

Many different emittance measurement sources are available at the LHC but they were never before cross-calibrated against the WS to make quantitative estimations of the systematic errors for the different systems. The presented methods agree within 10% with the WS data, except for BGI ϵ_H^{B1}; a ~40% disagreement not yet understood is observed.

The BSRT performance assessment disclosed the importance of the re-calibration using the measured β-function and a wide range of $\epsilon_{H,V}$ down to very small values. An important outcome of this MD is that from now on the measurement of the β-function at the IR4 devices will become part of the optics commissioning, which was not the case until now, to deliver the most precise BSRT measurements during physics production.

The use of $\epsilon_{H,V}$ below 1 μm rad for the first time, allowed the discovery of a new non-linear better-precision BSRT vs WS cross-calibration function, as compared to a traditional linear calibration. Its implementation for the physics production optics will be studied.

Finally, a new optics will have to be selected for the next cross-calibration session in order to overcome the issues encountered with the KMOD technique in the IPs, which compromised the use of the KMOD results.

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