OPERATIONAL EXPERIENCE WITH LUMINOSITY SCANS FOR BEAM SIZE ESTIMATION IN 2016 LHC PROTON PHYSICS OPERATION

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Abstract

Luminosity scans were regularly performed at the CERN Large Hadron Collider (LHC) as of 2015 as a complementary method for measuring the beam size. The CMS experiment provides bunch-by-bunch luminosities at sufficient rates to allow evaluation of bunch-by-bunch beam sizes, and the scans are performed in the horizontal and vertical plane separately. Closed orbit differences between bunches can also be derived by this analysis.

During 2016 LHC operation, these scans were also done in an automated manner on a regular basis, and the analysis was improved to significantly reduce the systematic uncertainty, especially in the crossing plane. This contribution first highlights the recent improvements to the analysis and elaborates on their impact. The measured beam sizes during 2016 proton physics operation are then shown and compared to measurements from synchrotron light telescopes and estimates based on the absolute luminosities of the LHC experiments.

INTRODUCTION

In LHC 2016 proton physics operation luminosity scans with a small beam separation (“Emittance Scans”) have been used to derive an estimate of the beam size, as already in 2015 [1].

For Gaussian Beams, in the presence of a beam offset, the luminosity of a colliding bunch pair is given by Eq. 1 [2].

$$\mathcal{L} = \frac{f_{rev} N_1 N_2 \mathcal{S}}{2\pi \Sigma_x \Sigma_y} \tag{1}$$

where

$$\mathcal{S} = \exp\left(\frac{-d^2}{2\Sigma_d^2}\right) \tag{2}$$

$N_{1,2}$ are the bunch intensities, f_{rev} is the revolution frequency, and $\mathcal{S}$ is the *separation factor*, the only component that changes with the beam separation d. Σ_x, Σ_y are the convoluted beam sizes in the x, y plane (including the effect of the crossing angle α in the crossing plane). Σ_d is the convoluted beam size in the plane in which the separation d was applied.

Following Eqs. 1 and 2, the convoluted beam sizes Σ_x, Σ_y can be determined by scanning the separation d in steps, recording the luminosity change and fitting a Gaussian to derive Σ_d (Fig. 1).

To derive the transverse emittances $\varepsilon_{x,y}$ from the convoluted beam sizes $\Sigma_{x,y}$, it is assumed that the beam sizes of Beam 1 and Beam 2 are equal (Eq. 3). For deriving the emittance in the crossing plane, the longitudinal profile is assumed to be Gaussian with bunch length σ_z (Eq. 4).

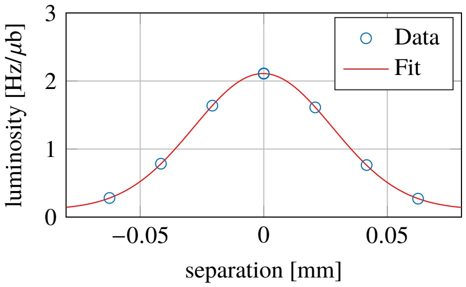

Figure 1: Fitted beam profile from a scan.

$$\Sigma_{sep} = \sqrt{2}\sigma_{sep} = \sqrt{\frac{2\varepsilon_{sep}\beta^*}{\gamma}} \tag{3}$$

$$\Sigma_{xing} = \sqrt{\frac{2\varepsilon_{xing}\beta^*}{\gamma}\cos^2\left(\frac{\alpha}{2}\right) + 2\sigma_z^2\sin^2\left(\frac{\alpha}{2}\right)} \tag{4}$$

NON-GAUSSIAN BUNCHES

In the nominal LHC cycle, the bunch length is increased artificially during the energy ramp by injecting RF phase noise [3]. As a side effect, this changes the longitudinal bunch profile from a Gaussian to a more “round” distribution [4].

If the longitudinal distribution is not Gaussian, the simple factorization as in Eq. 4 is no longer valid for the crossing plane. While still assuming a Gaussian distribution in the transverse dimensions, the luminosity during a scan of the separation d in the crossing plane fulfills Eq. 5.

$$\mathcal{L} \propto \exp\left(\frac{-d^2}{4\sigma_{xing}^2}\right) \cdot C(d) \tag{5}$$

$$C(d) = \int_{-\infty}^{\infty} \mathrm{d}s\,(d_1 * d_2)(2s)\,\exp\left(\frac{-s\sin\left(\frac{\alpha}{2}\right)\left(s\sin\left(\frac{\alpha}{2}\right) - d\right)}{\sigma_{xing}^2}\right) \tag{6}$$

where α is the crossing angle, $d_{1,2}$ are the longitudinal distributions for beam 1 and beam 2, respectively, and $*$ denotes a convolution.

It is worth noting that $\alpha = 0$ yields $C(d) = \text{const.}$ and the separation dependency reduces to the *separation factor* as shown in Eqs. 2, 3. This shows that the longitudinal distribution only affects scans in the crossing plane, while the separation plane remains unchanged.

If the longitudinal distribution is measured for both beams, the convolution and the integration in Eq. 6 can be done numerically, and a non-linear regression of Eq. 5 to the measured scan points yields σ_{xing}.

Simulations

To benchmark this approach, emittance scans have been simulated for bunches with a transverse Gaussian, but longitudinal $\cos^2$ distribution in different machine configurations and emittances. The simulated data was then analyzed using this method, and compared to the Gaussian approximation based on full-width half-maximum (FWHM) and true RMS bunch length measurements.

Table 1: Reconstruction of emittances from simulated luminosity scans with a longitudinal $\cos^2$ distribution. The r.m.s. bunch length was 7.5 cm.

2015 machine parameters
$\beta^* = 45$ cm, $\alpha = \pm 145\ \mu$rad

Method	Reconstructed Emittances	
	$\varepsilon_{ref} = 2\ \mu$m	$\varepsilon_{ref} = 3.5\ \mu$m
Gaussian fit, FWHM bunch length	1.65 μm	3.13 μm
Gaussian fit, r.m.s. bunch length	2.03 μm	3.52 μm
Using measured longitudinal profile	2.00 μm	3.50 μm

2016 machine parameters
$\beta^* = 40$ cm, $\alpha = \pm 185\ \mu$rad

Method	Reconstructed Emittances	
	$\varepsilon_{ref} = 2\ \mu$m	$\varepsilon_{ref} = 3.5\ \mu$m
Gaussian fit, FWHM bunch length	0.90 μm	2.37 μm
Gaussian fit, r.m.s. bunch length	2.17 μm	3.63 μm
Using measured longitudinal profile	2.00 μm	3.50 μm

Results are compiled in Table 1. In 2015, the Gaussian approach using a FWHM bunch length measurement was used and a systematic error 15% was assumed in the crossing plane [1]. For the machine configuration used in 2016, using measured longitudinal bunch profiles became crucial, in particular when measuring low-emittance beams.

Machine Studies

To directly probe the impact of a changing longitudinal distribution, emittance scans were done during the commissioning of the longitudinal bunch flattening [5].

During these tests, a sinusoidal RF phase modulation was applied to flatten the longitudinal bunch distribution to compensate for the shrinking caused by synchrotron radiation damping. The distribution was measured before and after, the change is show in Fig. 2.

Before and after the flattening, an emittance scan was done in the crossing plane. Results are shown in Fig. 3, and compared to the yield of Eq. 5 considering the change in longitudinal distribution and intensity, but no change in transverse emittance. The agreement shows that the longitudinal distribution is well accounted for.

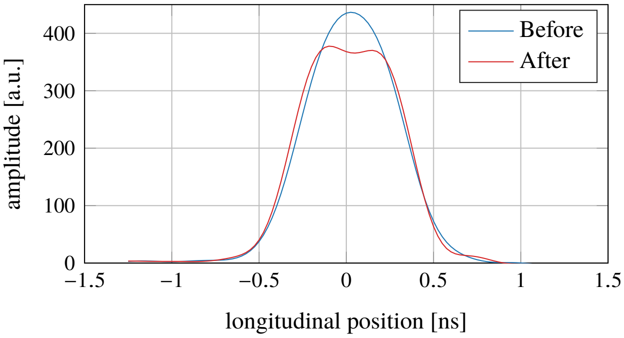

Figure 2: The measured longitudinal profile before and after the flattening.

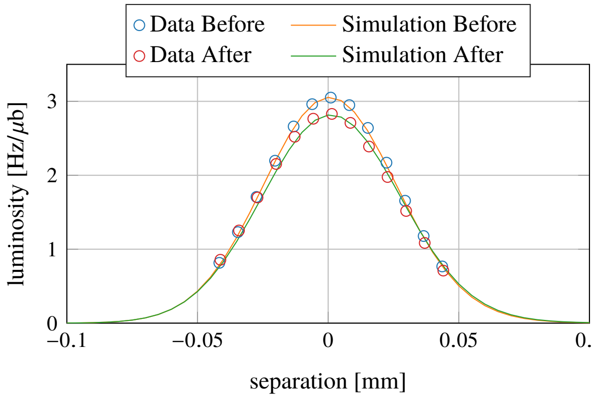

Figure 3: The scan data and the simulation based on the measured profiles. The effects of the bunch profile change are well reproduced. The transverse emittances of the two simulated scans are identical.

OPERATIONAL SETUP

Emittance scans were done regularly at the start of collisions and at the end of each fill at the CMS experiment. The results presented are based on the CMS bunch-by-bunch online luminosity. During one machine study fill, results from ATLAS and CMS were compared and agreements better than 5 % were found [6].

The operational scan parameters were based on the values established in 2015 [1], and are shown in Table 2. The scan range is given in "nominal" σ (assuming a nominal emittance of $\varepsilon = 3.5\ \mu$m). Such a scan puts the experiment at a reduced luminosity for ~1 min per plane scanned.

Table 2: Scan Parameters

Number of separation steps	7
Integration time per step	10 s
Maximum beam separation	3 σ (nominal)

2016 EMITTANCE MEASUREMENTS

Convoluted Emittances

The average convoluted transverse emittances from emittance scans are shown Fig. 4 and compared to the other emittance measurements at the LHC.

At the beginning of the year, the average transverse emittance at the start of collisions was 3.6 ± 0.5 μm. As of LHC fill 5079, the “Batch Compression Merging and Splitting” (BCMS) [7] beam production scheme was used operationally, reducing the initial emittance to 2.0 ± 0.3 μm.

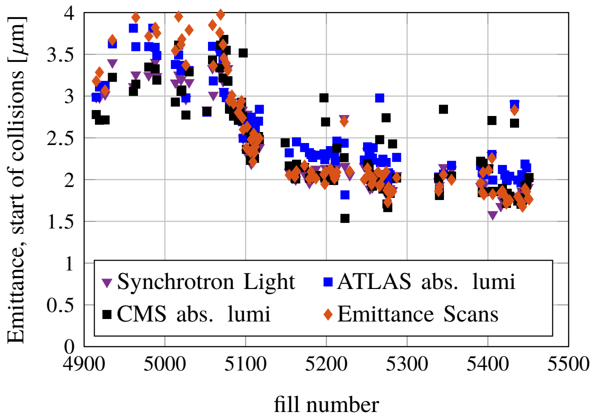

Figure 4: The average convoluted emittances at the start of collisions in 2016.

Emittances per Plane

A difference between the ATLAS and CMS luminosities has been observed throughout 2016 LHC operation. As the beams cross in different planes in the two experiments, non-round beams can cause such an imbalance [8] via the crossing angle.

The horizontal and vertical emittances at the start of collisions are shown in Fig. 5. It should be noted that, for a large part of the year, the horizontal emittance was larger than the vertical one at the start of collisions. This is consistent with the luminosity ratio observed [8].

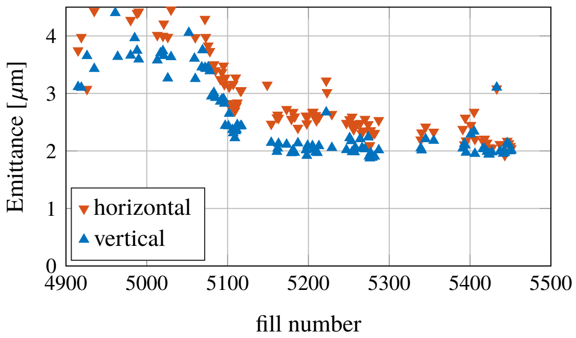

Figure 5: The average horizontal and vertical emittances at the start of collisions in 2016.

CONCLUSIONS

Emittance scans were used throughout 2016 as a complementary, independent tool for measuring the transverse emittance in collisions. The operational parameters were the same as in 2015.

With the beam and machine parameters used in 2016, the present approach of measuring the bunch length with a full-width half-maximum algorithm and then assuming all planes to be Gaussian lead to systematic errors of up to ~50 % in the crossing plane. To mitigate this, the analysis was refined to take into account measured longitudinal profiles. This new approach has been validated in simulations and machine studies.

The measured convoluted transverse emittances were 3.6 ± 0.5 μm before the introduction of the “BCMS” beam production scheme in the injectors and 2.0 ± 0.3 μm thereafter. For a large part of the year, the horizontal emittance was larger than the vertical. This is in agreement with the data from beam instrumentation and the ATLAS and CMS absolute luminosities.

ACKNOWLEDGEMENTS

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