BEAM SIZE ESTIMATION FROM LUMINOSITY SCANS AT THE LHC DURING 2015 PROTON PHYSICS OPERATION

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Abstract

As a complementary method for measuring the beam size for high-intensity beams at 6.5 TeV flat-top energy, beam separation scans were done regularly at the CERN Large Hadron Collider (LHC) during 2015 proton physics operation. The luminosities measured by the CMS experiment during the scans were used to derive the convoluted beam size and orbit offset bunch-by-bunch. This contribution will elaborate on the method used to derive plane-by-plane, bunch-by-bunch emittances from the scan data, including uncertainties and corrections. The measurements are then compared to beam size estimations from absolute luminosity, synchrotron light telescopes, and wire scanners. In particular, the evolution of the emittance over the course of several hours in collisions is studied and bunch-by-bunch differences are highlighted.

METHOD

In LHC 2015 proton physics operation, luminosity scans with a small beam separation have been used to derive an estimate of the beam size. Following [1], in the presence of a beam offset, the luminosity of a colliding bunch pair is given by Eqn. 1.

$$L = \frac{f_{rev} N_1 N_2 \cos\left(\frac{\alpha}{2}\right) F}{2\pi \Sigma_x \Sigma_y} \tag{1}$$

where

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

F is referred to as the *separation factor* and is the only component that changes with the beam separation d. Σ_x, Σ_y are the beam spot sizes in the x, y plane. In the crossing plane, the effect of the crossing angle has to be taken into account. Σ_d refers to the spot size in the plane in which the separation d is applied.

Following Eqns. 1 and 2 the beam spot size in each plane can be determined by scanning the separation d in steps, recording the luminosity change and fitting a Gaussian to derive Σ_d. This can be done either per beam, summing up the luminosity over all bunches, or separately for each bunch using bunch-by-bunch luminosity data. The luminosity evolution and the respective fit are shown in Figs. 1 and 2.

In order to derive the transverse emittances $\varepsilon_{X,Y}$ from the beam spot size $\Sigma_{X,Y}$, it is assumed that the beam sizes of Beam 1 and Beam 2 are identical (Eqn. 3). For deriving the emittance in the crossing plane, the longitudinal profile is assumed to be Gaussian with bunch length σ_z (Eqn. 4).

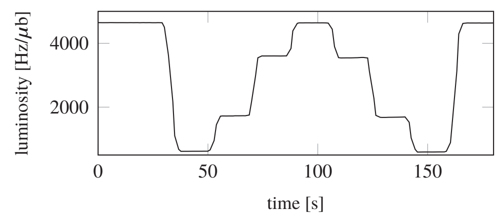

Figure 1: Luminosity evolution during a scan.

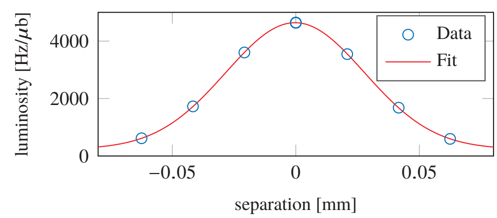

Figure 2: Fitted beam profile from a scan.

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

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

Scan Parameters

The most-commonly used scan parameters used are shown in Table 1. The scan range is given in "nominal" σ, i.e. the transverse beam size σ calculated by assuming a nominal emittance of $\varepsilon_{nominal} = 3.75\,\mu$m. Such a scan puts the experiment at a reduced luminosity for ~1 min per plane scanned.

Table 1: Scan Parameters

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

Data Sources

All results shown in this paper are based on CMS bunch-by-bunch luminosity.

Fills during which the CMS solenoid was not at its nominal field are excluded due to the lack of a reliable luminosity calibration. [2]

Error Estimations

The error sources considered and their contribution to the total error of the derived emittances are given in Table 2.

Table 2: Errors on Emittances From Luminosity Scans

Error source	**separation plane**	**crossing plane**
luminosity non-linearity	5%	5%
β^*	3%	3%
dynamic β^*	2%	2%
beam-beam kick	2%	2%
crossing angle	-	10%
logitudinal bunch shape	-	15%
combined error	6.5 %	19.1%

It is to be noted that the predominant error sources (crossing angle and longitudinal bunch shape) only affect the absolute emittances derived in the crossing plane (horizontal plane in CMS). The separation plane and bunch-by-bunch relative differences are not affected. Also, only the non-linearity due to pile-up effects and the longitudinal bunch shape are expected to change over the course of a fill, and therefore to possibly affect the time evolution of the emittance.

RESULTS

Emittances

In Fig. 3, we show the convoluted average emittances from luminosity scans, ATLAS and CMS online absolute luminosity and the Synchrotron Radiation Telescope (BSRT, [3]) at the start of collisions.

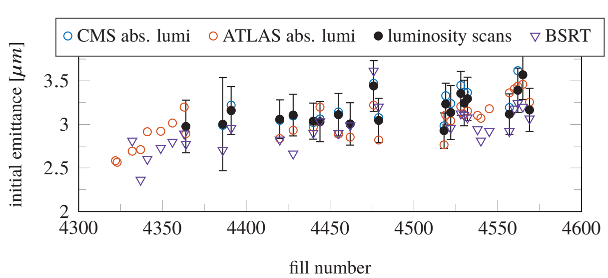

Figure 3: Convoluted average emittances derived from luminosity scans and absolute luminosities at the start of collisions.

In Fig. 4, the bunch-by-bunch emittances for a typical LHC fill derived from luminosity scans are shown. It is to be noted that the error band is dominated by systematic effects which do not affect the relative bunch-by-bunch values. This is illustrated by Fig. 5, where it is shown that for bunch-by-bunch differences in the convoluted emittance, data from luminosity scans and the absolute luminosities from the ATLAS and CMS experiments are in very good agreement.

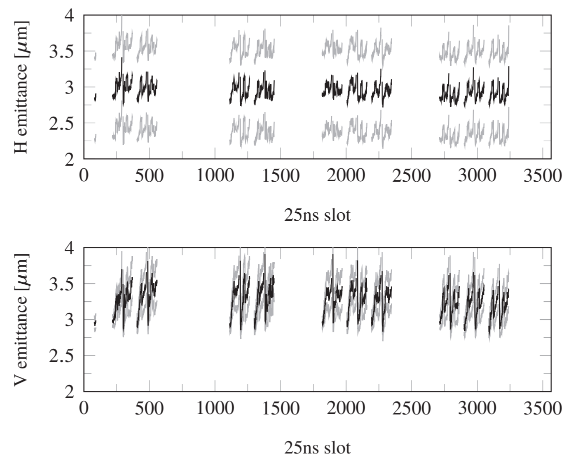

Figure 4: Emittances derived from a luminosity scan for LHC fill 4440, ~2 h into collisions (grey: error band).

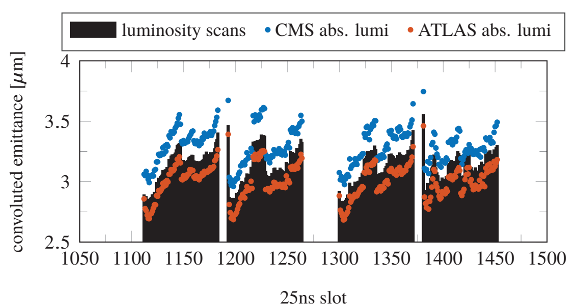

Figure 5: Comparison of convoluted emittances for two 144 bunch batches of LHC fill 4440.

Emittance evolution in collisions

The emittance evolution in collisions has been analyzed for fills with at least 2 luminosity scans. Results for the vertical (CMS separation) plane are shown in Fig. 6. It is to be highlighted that for the first time in a proton-proton collider, consistent shrinkage of the emittance was observed, detected by both luminosity scans and the BSRT. This is consistent with the high synchrotron radiation damping at 6.5 TeV [4].

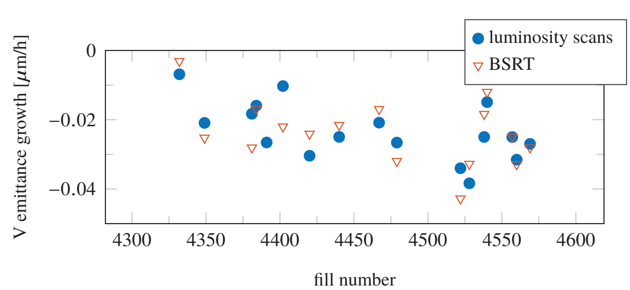

Figure 6: Emittance evolution from luminosity scans and the BSRT in the vertical (CMS separation) plane.

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Bunch-by-Bunch Orbit Observations

By considering the position of the peaks from the bunch-by-bunch Gaussian fits, differences in the separation on a bunch pair level resulting from different closed orbits can be observed. Such differences are expected as the number of long-range beam-beam encounters is different among bunches due to the filling schemes of the LHC [5].

In Fig. 7, we show the number of long-range beam-beam encounters per bunch in the LHC high-luminosity experiments for LHC fill 4440. For this fill, both beams of the LHC were filled symetrically with batches of 144 bunches, consisting of two trains of 72 bunches each. The bunch spacing was 25 ns. Bunches in the beginning and in the end of each train are missing some long-range encounters ("PACMAN" bunches, [6]).

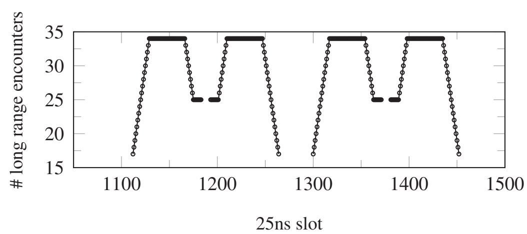

Figure 7: Number of long-range encounters for two 144 bunch batches of LHC fill 4440.

Fig. 8 shows the bunch-by-bunch peak positions in the vertical plane as measured by a luminosity scan in LHC fill 4440, grouped by 144 bunch batches. It is evident that the PACMAN bunches in the beginning and in the end of each 72 bunch train have different closed orbits, resulting in a different bunch pair separation. Also, two batches are not colliding in the LHCb experiment, with a clearly visible impact on the closed orbit.

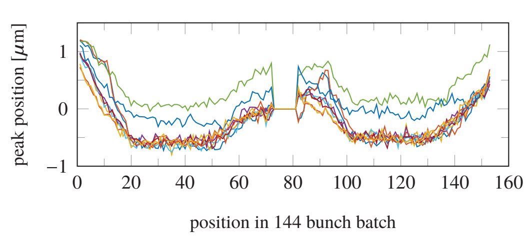

Figure 8: Vertical peak positions by position in a batch for LHC fill 4440. The two outlier batches (green and blue) are not colliding in the LHCb experiment.

The TRAIN code [7] can simulate self-consistent closed orbits on a bunch-by-bunch level under the presence of long-range beam-beam effects. Preliminary simulations taking into account the measured intensity spread for LHC fill 4440 show a promising agreement to the data.

CONCLUSIONS

During the LHC 2015 proton-proton physics operation, luminosity scans were used as a complementary emittance measurement in collisions. With the most common parameters, such a scan takes ~1 min per plane scanned. The results are very accurate in the separation plane of experiment scanned, while in the crossing plane a systematic error is introduced by the crossing angle and the longitudinal distribution.

The convoluted transverse emittance at the start of collisions was on average ~3 μm with a spread of typically ~0.5 μm among the bunches. In collisions, emittance shrinking was observed in the vertical plane for the first time in a hadron accelerator. The convoluted emittance was constant within the accuracy of the measurement.

Additionally, bunch-by-bunch differences in closed orbits have been observed using the data collected during the luminosity scans. This is due to the different number of long-range encounters and was reproduced by simulations.

FUTURE WORK

We propose to continue doing the luminosity scans presented in this paper at the LHC during 2016 proton-proton operation, as they not only provide a complementary bunch-by-bunch emittance estimation, but also allow to observe bunch-by-bunch beam-beam effects. Ideally scans should be done before any programmed beam dump and at the start of collisions.

The systematic effects in the crossing plane will be subject to further studies, and possibilities to correct for them will be investigated.

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