LUMINOSITY, EMITTANCE EVOLUTION AND OP SCANS

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Abstract

During 2015 proton physics operation, beam size estimates were derived from the luminosities acquired during small VdM-like beam separation scans (the so called "OP scans"). This talk recalls the main results from such scans, e.g. fill-by-fill differences and emittance evolution in stable beams. In particular, it is shown that emittance shrinking due to synchrotron light damping was observed for the first time with proton beams. Furthermore, the luminosity evolution is analysed and the optimal fill length is derived based on average and expected turn-around times. A few comments on the luminosity imbalance between ATLAS and CMS and BCMS bunch-by-bunch emittances are also given.

OP SCANS

Introduction

Small beam separation scans have been used to derive an estimate of the beam size, dubbed "OP scans" as opposed to the van-der-Meer beam separation scans for luminosity calibration of the experiments. Following [1], in the presence of a beam offset, the luminosity of a colliding bunch pair is given by Eqn. 1.

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

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

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).

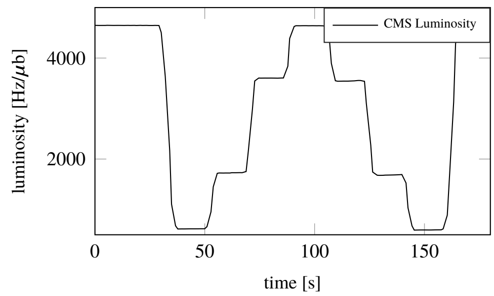

Figure 1: Luminosity evolution during an OP scan.

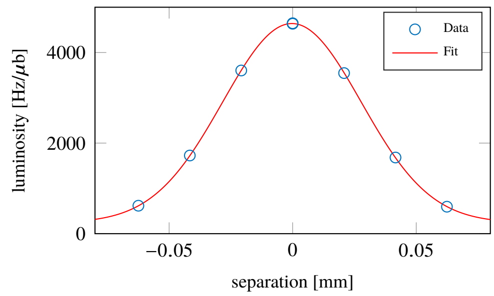

Figure 2: Fitted beam profile from an OP scan.

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

$$\begin{aligned} \Sigma_{xing} &= \sqrt{2\sigma_{xing}^2 \cos^2\left(\frac{\alpha}{2}\right) + 2\sigma_z^2 \sin^2\left(\frac{\alpha}{2}\right)} \\ &= \sqrt{\frac{2\varepsilon_{sep}\beta^*}{\gamma} \cos^2\left(\frac{\alpha}{2}\right) + 2\sigma_z^2 \sin^2\left(\frac{\alpha}{2}\right)} \end{aligned} \quad (4)$$

Scan Parameters

During 2015 proton-proton operation, OP scans were done at the start of collisions and before programmed dumps for most fills.

For the first part of the run both ATLAS (IP1) and CMS (IP5) were scanned for comparison. In October 2015 it was decided to stop scanning ATLAS for two reasons. First, instabilities were observed during the scans in the ATLAS horizontal plane. Second, the data quality of the ATLAS luminosity readings during the scans was affected by intrinsic limitations of their luminosity monitors in measuring a rapidly varying luminosity.

The final scan parameters used in 2015 are shown in Table 1. A scan with these parameters (e.g. Fig. 2) puts the experiment concerned at a low luminosity for ~1 min (e.g. Fig. 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.

Table 1: OP scan parameters.

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

Data Sources

All emittances derived from OP scans shown in this paper are based on CMS bunch-by-bunch online luminosity. Only fills after Technical Stop 2 are considered as online bunch-by-bunch luminosity at a high rate only became available then. Fills during which the CMS solenoid was not at its nominal field are excluded due to the lack of a reliable luminosity calibration.

The emittances from OP scans shown in this paper include a preliminary non-linearity correction provided by CMS [2]. Offline-corrected luminosities will be considered as soon as they become available.

For deriving the emittances, the measured $\beta^* = 0.84$ m [3] was used. In the crossing plane, a nominal crossing angle of $\alpha = 290\ \mu$rad and Gaussian bunches with a bunch length as measured by the LHC Beam Quality Monitor [4] were assumed.

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 derived from OP 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	-	15%
logitudinal bunch shape	-	10%
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.

For 4 fills with 3 individual bunches, emittances derived from OP scans have been compared to wire scanner measurements. The values were found to agree within the expected error boundaries.

EMITTANCE

Start of collisions

In Fig. 3, we show the convoluted emittances from OP scans, ATLAS and CMS online absolute luminosity and the Synchrotron Radiation Telescope (BSRT, [5]) at the start of collisions. Since OP scans were done manually and not consistently at the same time after declaring Stable Beams, all OP scans less than 2 h into Stable Beams are considered to be "at the start".

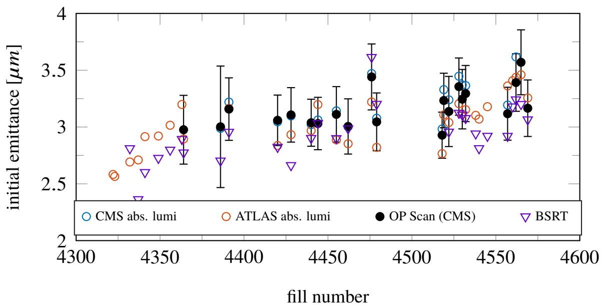

Figure 3: Convoluted emittances at the start of collisions.

Evolution in collisions

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

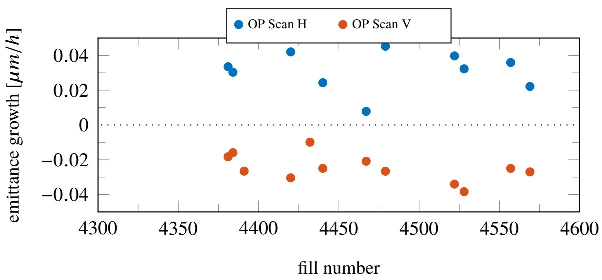

Figure 4: Emittance evolution from OP scans.

As shown in Fig. 5, the convoluted emittances from absolute luminosities and OP scans were constant within error expectations. The BSRT measurements indicate a small shrinkage of the convoluted emittance. This discrepancy is mainly originated from disagreements in the horizontal plane.

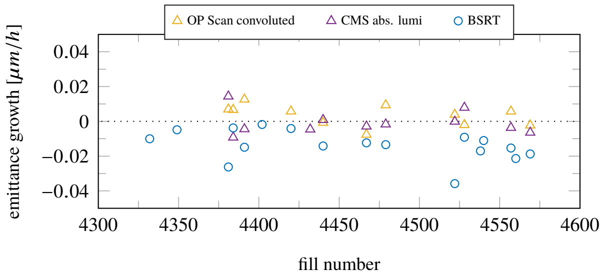

Figure 5: Convoluted emittance evolution in collisions.

BCMS Beams

In October 2015, beams produced according to the BCMS technique [7] were injected into the LHC. For fill 4555, the LHC was filled with 601 BCMS bunches (589 colliding in IP 1 and 5). This fill was ramped up and brought into collisions for ~2.5 h, with two sets of OP scans done in CMS at the start and at the end of collisions. The average emittances derived from these scans are shown in Table 3.

Note that the emittances at the start of collisions are ~0.5 μm lower than the average emittances of standard beams in 2015. Within ~2 h of collisions, the vertical emittance was found to be constant, while the horizontal showed a growth of ~0.2 μm, which is substantially larger than the growth observed for standard beams (see Fig. 4).

Table 3: BCMS beam emittances derived from OP scans. The train with selective emittance blow-up was excluded from the average.

Time in collisions	horizontal	vertical
14 min	2.3 μm	2.5 μm
132 min	2.5 μm	2.5 μm

Bunch-by-bunch emittance differences have also been studied for this test fill. As shown in Fig. 6, the emittances were blown up in the vertical plane for the first train. For the other trains emittance spreads of up to 1 μm have been observed. Also, the first bunch of the second train in a SPS batch had an increased emittance (Fig. 7). It is to be noted that the smallest bunches had a transverse emittance of ~2 μm, which is a significant improvement with respect to the standard beams.

While this study is based on a single BCMS test fill, we suggest to further investigate the BCMS option. In particular, possibilities to reduce the extra emittance growth throughout the cycle with respect to the nominal beams need to be studied.

LUMINOSITY

The luminosity lifetime in 2015 proton physics operation was observed to be much higher than in 2012, while the peak luminosity was 30 % lower. This is a consequence of the 2015 machine configuration with lower bunch brightness and a higher flat-top energy. The key parameters are compared

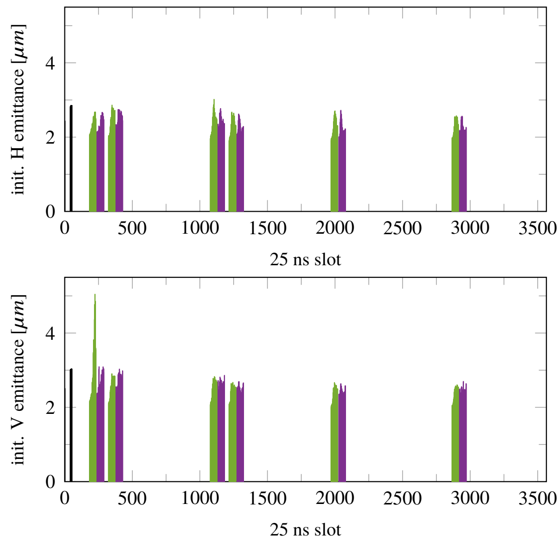

Figure 6: BCMS beam emittances from OP scans at the start of collisions.

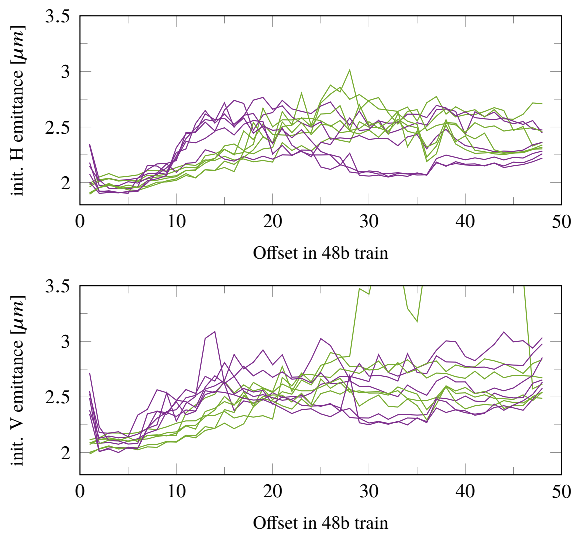

Figure 7: BCMS beam emittances from OP scans at the start of collisions by offset in the train, color coding as in Fig. 6

in Table 4. Within 10 h of collisions, the luminosity decayed to ~80 % of the initial value for a typical 2015 fill, and to ~40 % in 2012 (Fig. 8).

With the convoluted emittance being almost constant as a consequence of the synchrotron radiation damping, the luminosity decay in 2015 was strongly dominated by intensity burn-off [6].

Optimum Fill Length

The method presented in [8] to determine the optimal fill length to increase the overall integrated luminosity was applied to the CMS luminosity. Only fills with more than 1000 bunches which were in collisions for more than 12 h were taken into account.

Table 4: Beam parameters and luminosity at the start of collisions for typical "good" fills. The 2015 values refer to the final step of the intensity ramp-up.

	2012	**2015**
Energy	4 TeV	6.5 TeV
Bunch Intensity	1.7 ppb	1.2 ppb
Emittance	2.4 μrad	3 μrad
Number of Bunches	1374	2244
Peak Luminosity	7500 Hz/μb	5000 Hz/μb
Luminosity Lifetime	5 h	30 h

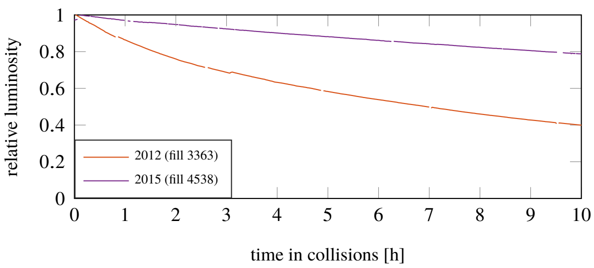

Figure 8: Relative Luminosity decay in 2012 and 2015.

The time from dumping one fill to having the next fill in collisions is referred to as the "turnaround time". As shown in Fig. 9, for the most probable turnaround time of 6.5 h [9], the optimum time spent in collisions is found to be 25 h. For the shortest turnaround time (3 h), the optimum time in collisions is 16 h.

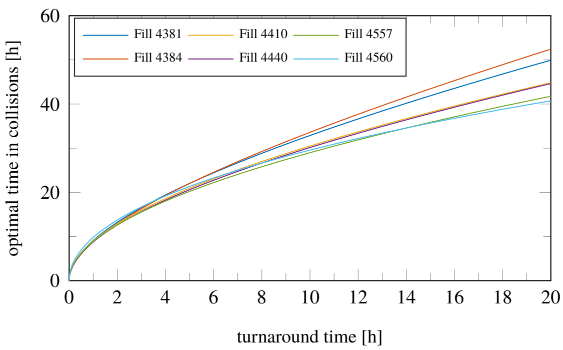

Figure 9: Optimum time spent in collisions.

ATLAS and CMS Luminosity Imbalance

Throughout 2015 the online luminosity published by ATLAS was consistently higher than the CMS online luminosity. The difference was on average ~9 % at the start of collisions and ~4 % after several hours in collisions (Fig. 10).

Possible geometric sources of luminosity imbalance are the evolution of the transverse emittances (form factor), beam-beam induced dynamic β^* [10] and differences in the crossing angles [11]. Observations on the special μ-scan fill (fill 4435) indicate a geometric imbalance in favor of ATLAS at a ~2 % level.

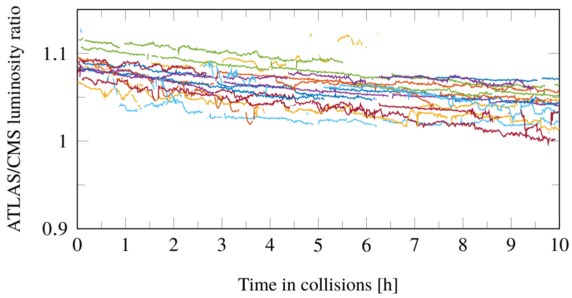

Figure 10: ATLAS and CMS online luminosity ratio.

Thanks to the van-der-Meer scans in 2015, both ATLAS and CMS derived new calibrations for their luminosity monitors. Corrections with respect to the previously published values were available only in December 2015. The ATLAS luminosity was high by 3.3 % with a residual error of 5 % on the calibration. The CMS online luminosity monitor was found to have a non-linearity leading to a luminosity reading low by ~4 % for nominal bunches at the start of collisions.

By applying these scaling factors to the luminosity, the observed imbalance is reduced to ~1 % at the start of collisions (Fig. 11).

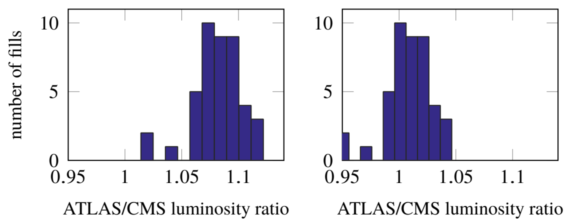

Figure 11: ATLAS to CMS luminosity ratio at the start of collisions before (left) and after (right) applying the most recent experiment calibrations as scaling factors.

CONCLUSIONS

OP scans have been performed throughout 2015 as a complementary emittance measurement in collisions. The final strategy was to do scans in CMS only, with a total of ~1 min integration time per plane.

In 2015, the convoluted transverse emittance was on average ~3 μm at the start of collisions. In collisions, emittance shrinking was observed in the vertical plane. The convoluted emittance was constant within the accuracy of the measurement. A single test fill with BCMS beams showed a transverse emittance of ~2.5 μm at the start of collisions.

The peak luminosity by the end of 2015 was ~5000 Hz/μb with an excellent luminosity life time (> 30 h). The luminosity decay was strongly dominated by the intensity decay due to luminosity burn-off. The optimal fill length was found to be ~25 h for an average preparation time of 6.5 h.

The discrepancy observed between the ATLAS and CMS online luminosities experiments throughout 2015 was resolved to ~1 % after scaling the luminosities according to the most recent calibration.

FUTURE WORK

We propose to continue doing OP scans in CMS during 2016 proton-proton operation. Ideally scans should be done before any programmed beam dump and at the start of collisions, at a rate to be discussed with CMS. A new luminosity scan application currently under development will allow an online analysis resulting in bunch-by-bunch emittances.

The BCMS beams look promising in terms of the lower initial emittance, provided that the emittance can be preserved throughout the cycle. For conclusive studies on this, more test fills are required to gather more statistics on the conditions and behaviour of the BCMS beams in the LHC.

ACKNOWLEDGEMENTS

The authors would like to thank F. Antoniou, A. Dabrowski, W. Herr, W. Kozanecki, M. Kuhn, P. Lujan, Y. Papaphilippou, T. Pieloni, M. Solfaroli, D. P. Stickland, G. Trad and J. Wenninger for their support and many fruitful discussions.

Also, the help of the LHC shift crews carrying out the OP scans throughout the year is warmly acknowledged.

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