A FIRST LOOK AT THE IMPACT OF BEAM-BEAM EFFECTS ON THE EMITTANCE SCAN OBSERVABLES IN THE LARGE HADRON COLLIDER

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Abstract

During the operation of the Large Hadron Collider (LHC), regular beam separation (emittance) scans are essential for accurately determining beam emittance and give valuable observables for monitoring the stability of luminometers. These scans provide a critical insight into beam quality and detector performance. In this study, we investigate how beam-beam interactions influence emittance scan observables by combining numerical simulations and experimental data, and discuss the resulting implications for measurement accuracy.

INTRODUCTION

Beam separation scans, commonly referred to as emittance scans, are a standard tool in LHC operations serving two complementary purposes: on the machine side, they provide a direct measurement of the transverse beam emittance [1], while for the experiments they offer a means to monitor the stability of luminometers across fills [2]. The absolute luminosity calibration is performed during dedicated van der Meer (vdM) scans, where beam conditions are optimized for maximum measurement precision [3]. Emittance scans, conducted under nominal physics conditions, face a much more complex systematic landscape — in particular, the presence of long-range beam-beam interactions from 2460 circulating bunches introduces bunch-to-bunch variations entirely absent in the low-intensity vdM regime. Previous studies have already established that beam-beam effects introduce measurable biases to luminosity observables, including contributions to the apparent non-linearity and fill-to-fill stability of experimental luminometers [4]. However, those studies were limited to single-bunch or simplified multi-bunch models, motivating the full treatment presented here.

Quantifying these beam-beam contributions is a necessary step toward making emittance scans a more reliable tool for both purposes. However, a full treatment at realistic LHC conditions requires simultaneous modelling of head-on and long-range interactions across the entire bunch population with a realistic lattice description.

Recent developments in pyTRAIN [5] now allow this to be studied. In this paper we present a first look at how beam-beam interactions shape emittance scan observables, using a nominal Run 3 fill 10875 as a reference case. We find that while significant progress is possible, the current framework reveals important limitations, in particular the absence of full bunch distribution information, that will need to be addressed before beam-beam corrections to luminosity observables can be made practical.

SIMULATION SETUP

Simulations are performed using pyTRAIN [5], a multi-bunch beam-beam simulation code that tracks beam parameters turn by turn using a realistic LHC lattice model and filling patterns with bunch trains. The parameters used in this study are summarised in Table 1 and are based on fill 10875, with conditions corresponding to the third emittance scan of the fill, using the lattice model `R2025aRP_A18cmC18cmA10mL200cm_Flat.madx`.

Table 1: Simulation Parameters

Parameter	Value
Number of bunches	2460
Median intensity	1.1×10^{11}
Median emittance (x)	2.35 µm
Median emittance (y)	2.0 µm
β^* (crossing-angle plane)	0.6 m
β^* (non-crossing plane)	0.18 m
Tune (x)	62.315
Tune (y)	60.322
Chromaticity	15
Octupoles K	-12
ATLAS/CMS half crossing angle	160 µrad

Benchmark Against COMBI

The pyTRAIN simulation is benchmarked against COMBI [6], a strong-strong macro-particle tracking code which, by virtue of simulating the full particle distribution, captures non-Gaussian effects and beam shape distortions not accessible to pyTRAIN. The benchmark is performed using single-bunch separation scans at vdM-like parameters ($\xi = 3.24 \times 10^{-3}$). In pyTRAIN the real vdM lattice model is used, while COMBI applies linear phase advance transformations turn by turn. Results for the simulated β^* change at IP5 during the horizontal scan, expressed as $(\sigma_{BB}/\sigma_0)^2$ to allow direct comparison between the RMS beam size from COMBI and the β^* from pyTRAIN, are shown in Fig. 1. The two codes are in good agreement at larger separations where the linearised beam-beam approximation in pyTRAIN holds well; differences at small separation are expected, as the beams overlap more and a larger portion of the transverse distribution is exposed to the non-linear regime of the beam-beam force.

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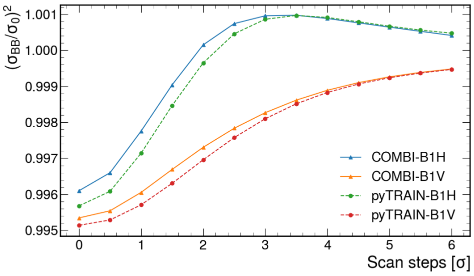

Figure 1: Comparison of the squared beam size $(\sigma_{BB}/\sigma_0)^2$, equivalent to the β^* change, at IP5 during a single-bunch horizontal separation scan at vdM-like parameters ($\xi = 3.24 \times 10^{-3}$). COMBI results are shown as the ratio of the RMS beam size with (σ_{BB}) and without (σ_0) the beam-beam kick, while pyTRAIN results are obtained from the matched β^* before applying beam-beam kicks, used for normalisation.

RECONSTRUCTED LUMINOSITY

Luminosity is reconstructed and compared to the online CMS luminosity measurement on a per-bunch basis using two approaches. The first reconstructs the luminosity directly from the bunch sizes extracted from the fit to the luminosity scan curve, requiring no external calibration constant. The second reconstructs the luminosity from pyTRAIN simulated beam parameters combined with BSRT measured emittances. The pyTRAIN-based median value is 8 % lower than the online CMS measurement. The BSRT is calibrated typically once per year and can drift between the calibration session and the fill under study [7], which is the most likely source of this discrepancy.

The relative difference per bunch with respect to the CMS measurement is shown for both calculations in Fig. 2. While the scan-based calculation is closer in absolute value to the CMS measurement, the pyTRAIN-based calculation exhibits a slightly smaller bunch-to-bunch spread. This suggests that the beam-beam effects driving the bunch-to-bunch luminosity variations are better captured by the pyTRAIN simulation, as the scan-based approach does not account for the variation of the β^* and the beam-beam induced offset throughout the scan steps.

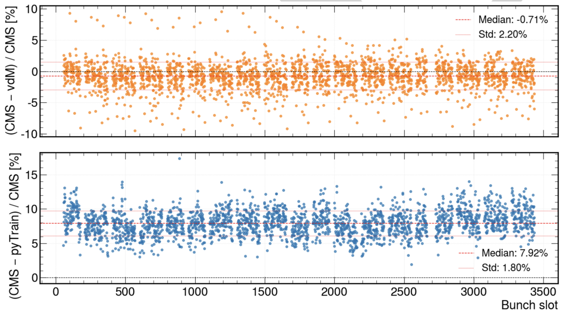

Figure 2: Relative difference per bunch between the reconstructed luminosity and the online CMS measurement, for the scan-curve-based calculation (upper) and the pyTRAIN-based calculation (lower).

The bunch-to-bunch structure within trains is investigated in Fig. 3, where five example trains are overlaid. Several features are visible. PACMAN bunches, located at the boundaries between batches, exhibit significantly lower luminosity due to a beam-beam induced offset of around 1 μm — approximately ten times larger than for mid-train bunches. Within each batch, the 5th bunch carries higher luminosity owing to its above-average intensity. A luminosity slope of around −5 % is also present across each batch, arising from two competing contributions: a −2 % effect from the intensity product and a +4 % effect from emittance growth along the train.

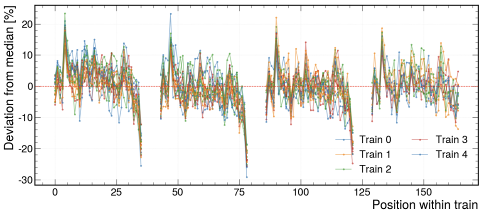

Figure 3: Luminosity pattern within bunch trains (overlaid).

EMITTANCE SCANS

Before simulating the separation scan, initial transverse offsets are determined iteratively, correcting each plane in sequence to account for the mutual dependence between planes. This procedure is analogous to the luminosity optimization performed during LHC operation, where the transverse position of the beams is adjusted iteratively by introducing small offsets in each plane to locate the luminosity peak. In the simulation, only the median offset across all bunches is corrected; this reflects the actual operational constraint, as the orbit feedback system can only act on the average beam position and has no means to correct individual bunch offsets. In emittance scans, the initial median offset measured at the level of 1–3 μm is reduced to a residual of order 0.05 μm. Without this correction, the luminosity would be substantially lower, by about 10 %.

The residual separation and the corresponding β^* changes during the scan are shown in Figs. 4 and 5, comparing the single-bunch and full-beam cases. The β^* variation relative to the value at the start of the scan remains at the percent level across all scan steps, with the largest deviations observed at small separation where the beam-beam force is strongest. However, in absolute terms the difference between the single-bunch and full-beam cases is more significant: in the horizontal (non-crossing) plane the difference remains below 1 %, while in the vertical (crossing-angle) plane it exceeds 3 %. The bunch-to-bunch spread in the full-beam case also exhibits the same asymmetry, remaining below 0.5 % in the horizontal plane while exceeding 1% in the vertical plane. This asymmetry between the horizontal and vertical planes is a result of the cumulative effect of all long-range beam-beam interactions, which add up differently in the two planes. The beam-beam induced offset differs by 0.1–0.2 μm between the two cases across all scan steps. This is significant given that the absolute offset in the single-bunch case is itself within 0.2 μm. Moreover, while the single-bunch offset is well-constrained, the full-beam spread across bunches is considerably larger, ranging from -0.25 μm to $+1.5$ μm, driven by the varying long-range interaction pattern of each bunch depending on its position within the train. Furthermore, in the full-beam case the bunch-to-bunch spread of the residual offset in the non-scanning plane reaches a similar magnitude to that in the scanning plane, an effect entirely absent in the single-bunch simulation, which highlights the importance of modelling the complete multi-bunch interaction pattern.

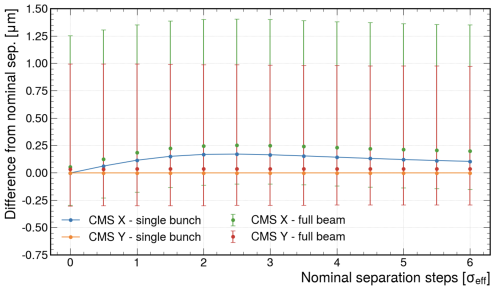

Figure 4: Median of residual separation in both transverse directions during the H (non-crossing) plane scan at IP5 for single-bunch (blue) and full beam (orange). Errorbars indicate the spread across all bunches.

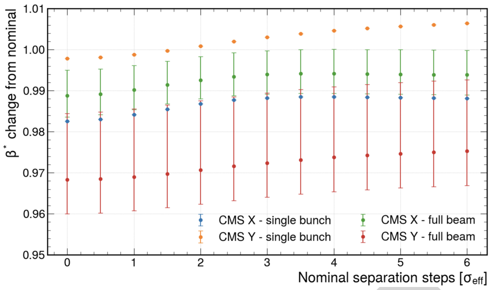

Figure 5: Median of β^* change in both transverse directions during the H (non-crossing) plane scan at IP5 for single-bunch (blue) and full beam (orange). Errorbars indicate the spread across all bunches.

Luminosity During the Separation Scan

The luminosity change from head-on (HO) and long-range (LR) beam-beam interactions as a function of separation scan step is shown in Fig. 6 for both H and V plane scans, with each curve corresponding to an individual bunch. At small separation the effect is similar across all bunches, while the spread grows significantly with increasing separation. In the horizontal (non-crossing) plane no strong dependence on the position within the train is observed. In the vertical (crossing-angle) plane, however, a clear systematic trend emerges: bunches later in the train show a smaller luminosity change at large separation amplitudes, as visible from the colorbar indicating the position within the train. This dependence reflects the varying long-range interaction pattern accumulated by each bunch depending on its position within the filling scheme.

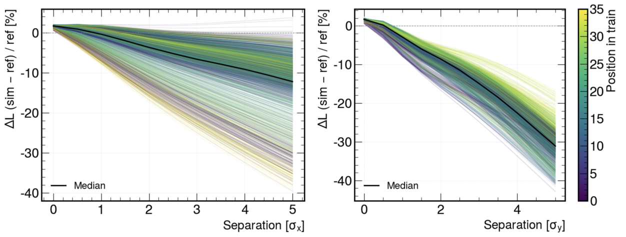

Figure 6: Luminosity change from head-on and long-range beam-beam interactions as a function of separation scan step for each individual bunch, shown for the horizontal (left) and vertical (right) plane scans. The colour indicates the position of the bunch within the train.

Reconstructed σ_{vis} Equivalent

The visible cross-section σ_{vis} is reconstructed from the pyTRAIN simulated beam parameters for each bunch. In the single-bunch case, the beam-beam effect on σ_{vis} is small, with deviations from the reference value in the range of 0 to 0.5 %. When long-range interactions are included in the full-beam simulation, the picture changes significantly: the deviation spans from -1 % to $+0.3$ %, with a clear bunch-position dependence. Inter-train bunches show systematically lower σ_{vis}, while PACMAN bunches at the batch boundaries show higher values, reflecting their distinct long-range interaction history.

These results should be interpreted with caution, as the absence of full distribution information in pyTRAIN limits the accuracy of the σ_{vis} reconstruction. Nevertheless, the clear difference between the single-bunch and full-beam cases demonstrates that long-range beam-beam interactions have a non-negligible impact on emittance scan observables, motivating further studies with more complete simulation tools.

CONCLUSION

We have presented a first study of beam-beam effects on emittance scan observables at the LHC using pyTRAIN with a realistic lattice model and filling pattern. Single-bunch models are shown to be insufficient at nominal LHC conditions, with long-range interactions driving significant bunch-to-bunch variations in the beam-beam induced offset, β^*, luminosity response, and σ_{vis} during the scan.

However, since pyTRAIN tracks mean beam parameters rather than the full particle distribution, non-Gaussian effects and beam shape distortions are not accounted for. Addressing this limitation will be necessary before beam-beam corrections to luminosity observables from emittance scans can be made practical.

REFERENCES

[1] M. Hostettler, K. Fuchsberger, G. Papotti, and Y. Papaphilippou, *Luminosity scans for beam diagnostics*, Phys. Rev. Accel. Beams **21**, 102801 (2018), `doi:10.1103/PhysRevAccelBeams.21.102801`

[2] O. Karacheban, P. Tsrunchev, and on behalf of CMS, “Emittance scans for CMS luminosity calibration,” EPJ Web Conf.,

vol. 201, p. 04001, 2019. doi:10.1051/epjconf/201920104001

[3] C. Rubbia, *Measurement of the luminosity of $p\bar{p}$ collider with a (generalized) Van der Meer Method*, CERN Technical Report, CERN, Geneva (1977). https://cds.cern.ch/record/1025746

[4] J. Wańczyk *et al.*, "Luminosity scans for beam diagnostics," PoS **EPS-HEP2023**, 624 (2024). doi:10.22323/1.449.0624

[5] M. Hostettler, X. Buffat, T. Persson, T. Pieloni, and J. Wenninger, "pyTRAIN – a modern TRAIN implementation," Apr. 2026. doi:10.48550/arXiv.2604.18466

[6] T. Pieloni, "A study of beam-beam effects in hadron colliders with a large number of bunches," Ph.D. thesis, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, 2008. doi:10.5075/epfl-thesis-4211

[7] G. Trad, "Development and optimisation of the SPS and LHC beam diagnostics based on synchrotron radiation monitors," Ph.D. thesis, U. Grenoble Alpes, Grenoble, France, and CERN, Geneva, Switzerland, 2015. https://repository.cern/records/sq3ve-y4e50