ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR55

MODELLING INTRA-BEAM SCATTERING IN THE LHC FOR LONGITUDINAL BEAM LOSS STUDIES*

M. Zampetakis†, K. Iliakis, B. E. Karlsen-Baeck[1], H. Timko
CERN, Geneva, Switzerland
[1]also at the Department of Physics, Sapienza Università di Roma, Rome, Italy

Abstract

In the Large Hadron Collider (LHC), intra-beam scattering (IBS) is one of the main drivers of longitudinal emittance growth during the long injection plateau. With the halo of the longitudinal bunch distribution being close to the separatrix, IBS consequently drives beam losses by pushing particles outside the RF bucket at the flat-bottom. As IBS and beam losses impose a requirement on the minimum RF bucket size, this mechanism has an important impact on the RF power requirements for the High Luminosity (HL-) LHC. In this contribution, the effect of IBS is introduced in the Beam Longitudinal Dynamics (BLonD) tracking code. This numerical model is then benchmarked against analytical estimates, as well as against beam measurements performed in the LHC. The impact of IBS-driven losses on the RF power requirements is discussed through the correlation between the time spent at flat-bottom and the average bunch length, which translates into start-of-ramp losses.

INTRODUCTION

The complete filling of the two rings of the Large Hadron Collider (LHC) requires approximately one hour. During this long injection plateau at the constant energy of 450 GeV, effects such as Intra-Beam Scattering (IBS), RF phase noise [1] and transients of the beam phase loop at every injection lead to longitudinal emittance blow-up. With the halo of the longitudinal bunch distribution being close to the separatrix, these effects consequently drive beam losses by slowly pushing particles outside of the RF bucket. Such particles drift asynchronously until the start of the energy ramp, after which most of them are lost.

Consequently, flat-bottom losses impose a requirement on the minimum RF bucket size, determining also the RF power requirements at injection. In the High Luminosity (HL-) LHC era, where the nominal injected bunch intensity will be as high as $2.3{\times}10^{11}$ protons per bunch (p/b) [2], the current RF system of LHC [3] is expected to be pushed to its limits in terms of RF power [4]. Thus, understanding the impact of the IBS-driven losses on the RF power requirements is vital.

To perform simulations including IBS, a numerical model is introduced in the Beam Longitudinal Dynamics (BLonD) tracking code [5] to simulate the IBS effect on a macro-particle distribution, in the form of an additional energy kick. This model is then benchmarked against analytical estimates, as well as beam measurements performed in the LHC. The measured correlation between time spent at flat-bottom and bunch length at the start of the ramp is discussed in view of start-of-ramp losses.

IBS MODEL IMPLEMENTATION

The IBS module newly implemented in the BLonD tracking code is based on a numerical model that was first introduced in [6, 7] and later used for various studies and in different regimes [8–10]. This model assumes that the transverse and longitudinal degrees of freedom are independent and that the particle distributions in the transverse planes remain always Gaussian. In addition, the IBS kick is weighted with respect to the longitudinal line density to account for non-Gaussian longitudinal distributions as observed in LHC [11–13].

In the case of BLonD, where the macro-particle tracking acts only on the longitudinal distribution, the IBS kick can be applied exclusively in the longitudinal plane. Every turn, each particle receives a change on its energy in the form of an energy kick that depends on the optics of the ring, the beam parameters and the particle's longitudinal position. This kick has the following form:

$$\delta(\Delta E) = r\sigma_{\Delta E}\sqrt{2T_s^{\mathrm{IBS}}T_{\mathrm{rev}}\sigma_\tau\sqrt{\pi}\rho(t)}, \qquad (1)$$

where r is a Gaussian random number with zero mean and unit standard deviation, T_{rev} is the revolution period, $\sigma_{\Delta E}$ is the standard deviation of the energy spread ΔE, σ_τ is the 1σ bunch length, ρ is the longitudinal line density and T_s^{IBS} is the IBS growth rate in the longitudinal plane. To calculate the IBS growth rates, the method of Nagaitsev [14] was chosen. This method originates from the quantum IBS model of Bjorken and Mtingwa [15], but expresses the IBS integrals in terms of the complete elliptic integrals of the second kind for better efficiency. On the other hand, it neglects the vertical dispersion, which is acceptable as a first order approximation.

In reality, the impact of IBS affects all three planes and its strength depends on the iterative evolution of the total volume of the beam. That is, the evolution of the longitudinal plane affects the transverse planes and vice versa. BLonD tracks only longitudinal macro-particle distributions, and to respect the 3-dimensional nature of IBS, the transverse emittances are evolved analytically using the following simple differential equation [14–16]:

$$\frac{d\varepsilon_{x,y}}{dt} = T_{x,y}^{\mathrm{IBS}}\varepsilon_{x,y}, \qquad (2)$$

* work supported by the HL-LHC project
† michail.zampetakis@cern.ch

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR55

where $\varepsilon_{x,y}$ are the transverse emittances and $T_{x,y}^{\mathrm{IBS}}$ the IBS growth rates.

Benchmarking of the IBS Module

To benchmark the IBS module, tracking simulations performed with BlonD were compared with analytical estimations using Nagaitsev's method [14]. The simulation parameters were chosen to be close to the operational parameters of 2023 of the LHC at flat-bottom energy, as shown in Table 1. Since all analytical models make this assumption, a Gaussian distribution consisting of 10^5 macro-particles was used. The simulation time corresponded to about 5 minutes (3.5×10^6 turns).

Table 1: Benchmarking Simulation Parameters

Parameters	
Energy, E	450 GeV
RF Voltage, V_{RF}	5 MV
Intensity, N_b	1.6×10^{11} p/b
Bunch length, $\tau_{4\sigma}$	1.2 ns
Norm. emittances, $\varepsilon_{x,y}^N$	1.8 µm

The results of this comparison are presented in Fig. 1 in terms of evolution of the relative horizontal (blue), vertical (green) and longitudinal (red) emittances. The analytical estimates are indicated with dark full lines, while the results produced from BLonD with light dashed lines. Excellent agreement is observed in the longitudinal plane and, as a consequence, in the transverse planes, too.

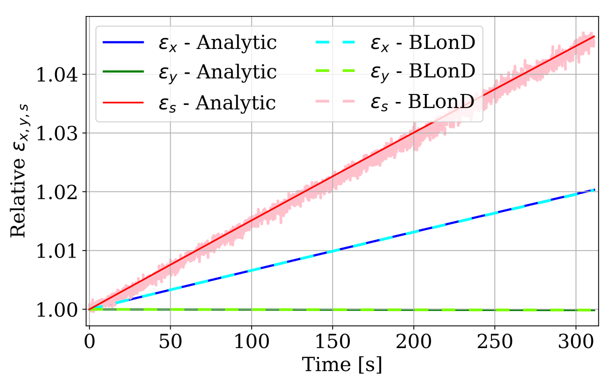

Figure 1: Comparison of the relative horizontal (blue), vertical (green) and longitudinal (red) emittances between analytical IBS calculations (dark full lines) and tracking simulations using BLonD (light dashed lines) in the LHC.

The longitudinal emittance ε_s is directly proportional to bunch length and energy spread. For an estimation of the longitudinal emittance growth due to IBS, both the energy spread ΔE and bunch length $\tau_{4\sigma}$ were evolved through time using exactly the same growth rates. By construction, the analytical calculations produced exactly the same growth for both planes, as shown in Fig. 2 with the dark color markers. However, tracking simulations (light colors) showed a bunch

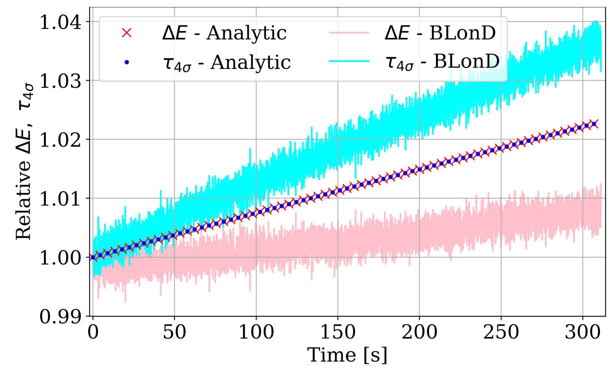

Figure 2: Comparison of the relative 4σ bunch length (blue) and energy spread (red) between analytical IBS calculations (dots and crosses, respectively) and tracking simulations using BLonD (light lines) for LHC parameters.

length growth that is approximately 4 times larger than the growth of the energy spread.

Discussion on the Longitudinal Beam Profiles

One of the main difficulties that one may face in IBS simulations for LHC, is the non-Gaussian shape of the longitudinal beam profiles. The IBS kick introduced in BLonD considers non-Gaussian longitudinal beam profiles and weights the IBS kick depending on the position of each particle with respect to the line density. However, this kick has a diffusive nature that follows a random Gaussian distribution. This means that the longitudinal distribution will eventually become Gaussian with time. This is not compatible with what has been observed at flat-bottom in LHC [12, 13] where the profiles are best described with a binomial distribution of $\mu = 1.5 - 2$, or with past studies showing that IBS tends to populate more the tails of the distribution [17, 18].

To investigate this discrepancy, a simulation similar to the previous case has been performed. The key difference is that now the generated distribution is a binomial distribution with an exponent of $\mu = 2$. The initial beam profile is indicated with red crosses in Fig. 3, while the corresponding Gaussian fit is plotted as a red line. For comparison, the beam profiles from an IBS simulation with a duration of 15 minutes are shown in blue. Results confirm that indeed the distribution tends to become Gaussian which may lead to wrong predictions for the RF power limitations. Alternatives like the modified kinetic IBS kick [19] or a Particle-in-Cell (PIC) IBS code should be considered for more accurate beam profile evolution.

COMPARISON WITH MEASUREMENTS

To benchmark the IBS implementation against measurements, the bunch length as a function of time was analyzed for a single bunch at flat-bottom in the LHC. The bunch had an intensity of 2.42×10^{11} p, an initial bunch length of $\tau_{4\sigma} = 1.22$ ns, and normalized horizontal and vertical emittances of $\varepsilon_x^N = 1.90$ µm and $\varepsilon_y^N = 1.97$ µm, respectively. The RF voltage during the measurement was 4 MV. Figure 4

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR55

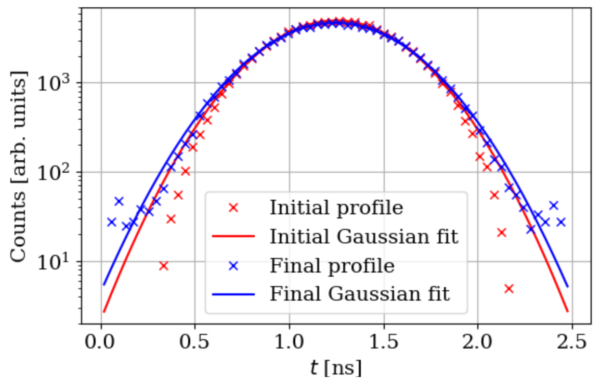

Figure 3: Comparison of initial and final longitudinal profiles after a duration of about 15 minutes, indicated with red and blue crosses, respectively, under the influence of the introduced IBS kick. For reference, Gaussian fits are also shown with full lines.

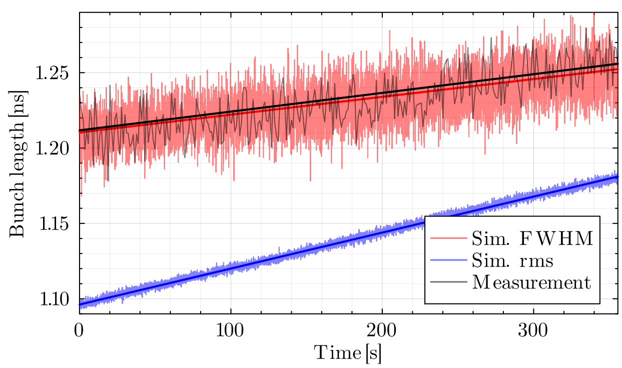

Figure 4: Comparison of the simulated FWHM (red), rms (blue) and measured (black) bunch length evolution from the BQM in beam 2 in the LHC. Linear fits are indicated with darker solid lines.

shows the measured full-width at half-maximum (FWHM) bunch length (black) via the Beam Quality Monitor (BQM) for a duration of 6 minutes. Using a linear fit on this data, a growth rate of (111.7 ± 2.2) ps/h is extracted.

The parameters defining the condition of the measurement were then produced in simulation. The simulated bunch length evolution is shown in Fig. 4, following an average growth rate of (214.8 ± 0.3) ps/h from the rms fit and (106.3 ± 2.4) ps/h from the FWHM fit. The FWHM fit has 5 % difference from the measurement, already showing very good agreement considering that RF phase noise, another source of longitudinal emittance blow-up in the LHC, is not included in the simulation. Another observation to make from Fig. 4 is the difference between the FWHM and rms bunch length growth rate. IBS changes the shape of the distribution [17, 18] and there is a significant difference in growth rate between the two fitting methods, which must be taken into account when comparing with measurements. In general, further measurements should be taken to increase the confidence in the benchmark and to verify the bunch shape evolution. Furthermore, RF noise should be included in the IBS simulation, which will be needed for estimates of RF power limitations.

IBS-DRIVEN LOSSES

During Run 2, an empiric correlation was found between the average bunch length during the start of the ramp and the maximum Beam Loss Monitor (BLM) ratio-to-dump threshold during the ramp in the LHC [20].

The bunch length observed before the ramp depends on how the bunches filament right after injection due to the SPS and LHC RF buckets aspect ratio difference, as well as errors in energy and phase of the injected beam. Furthermore, both IBS and RF noise contribute to bunch lengthening due to the long flat-bottom. This effect can be observed in Fig. 5, which shows the average bunch length as a function of the weighted time spent at flat-bottom. Here, the weighted time t_w, with respect to bunch intensity, is given by:

$$t_\mathrm{w} = \frac{\sum_i N_b^{(i)} t_b^{(i)}}{\sum_i N_b^{(i)}}, \tag{3}$$

where $N_b^{(i)}$ and $t_b^{(i)}$ are the injected intensity and time spent at flat-bottom of bunch number i, respectively. In Fig. 5 one can see that for fills where the bunches spent a long time at flat-bottom had also significantly longer bunches, which translates into more losses [21].

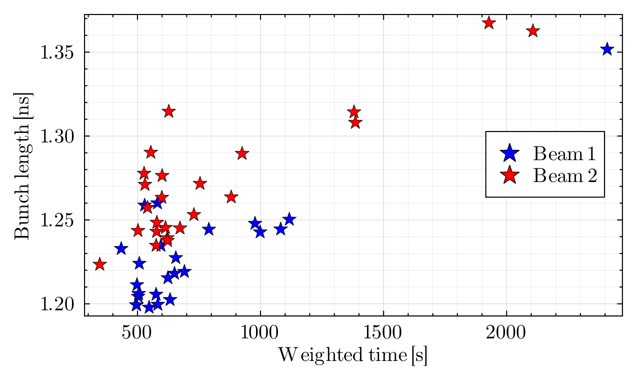

Figure 5: The average bunch length before the ramp as a function of the weighted time of the beam spent at flat-bottom.

CONCLUSIONS AND FUTURE PLANS

A new IBS module has been implemented in the longitudinal macro-particle tracking of BLonD. In this model, the longitudinal emittance growth is introduced through an energy kick, while the transverse emittances are evolved analytically in time. Benchmarks with analytical calculations showed excellent agreement in all three planes, but the non-Gaussian shape of LHC flat-bottom profiles might be better modelled through expanded IBS models. Preliminary benchmarks of the model against measurements in the LHC show promising results, but further measurements will be made to increase the confidence in the model. Previous measurements indicate that IBS and RF noise [1] along the flat-bottom can significantly contribute to longitudinal emittance blow-up, leading to start-of-ramp losses.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR55

REFERENCES

[1] T. Mastoridis *et al.*, "Radio frequency noise effects on the CERN Large Hadron Collider beam diffusion", *Phys. Rev. ST Accel. Beams*, vol. 14, no. 9, p. 092802, 2011. doi:10.1103/PhysRevSTAB.14.092802

[2] O. Aberle *et al*. "High-Luminosity Large Hadron Collider (HL-LHC): Technical design report", *CERN Yellow Reports: Monographs*, CERN, Geneva, Switzerland, Rep. CERN-2020-010, 2020. doi:10.23731/CYRM-2020-0010

[3] D. Boussard and T. Linnecar, "The LHC Superconducting RF System", in Proc. *Joint Cryogenic Engineering Conf. and International Cryogenic Materials Conf.*, Montreal, Canada, 1999, https://cds.cern.ch/record/410377

[4] H. Timko *et al.*, "Advances on LHC RF Power Limitation Studies at Injection", in *Proc. HB'23*, Geneva, Switzerland, 2023, pp. 567–570. doi:10.18429/JACoW-HB2023-THBP39

[5] H. Timko *et al.*, "Beam longitudinal dynamics simulation studies", *Phys. Rev. Accel. Beams*, vol. 26, no. 11, p. 114602, 2023. doi:10.1103/PhysRevAccelBeams.26.114602

[6] M. Blaskiewicz and J. M. Brennan, "Bunched Beam Stochastic Cooling Simulations and Comparison with Data", in *Proc. COOL'07*, Bad Kreuznach, Germany, 2007, paper WEM2I05, pp. 125–129.

[7] M. Blaskiewicz, J. M. Brennan, and F. Severino, "Operational Stochastic Cooling in the Relativistic Heavy-Ion Collider", *Phys. Rev. Lett.*, vol. 100, p. 174802, 2008. doi:10.1103/PhysRevLett.100.174802

[8] R. Bruce, J. M. Jowett, M. Blaskiewicz, and W. Fischer, "Time evolution of the luminosity of colliding heavy-ion beams in BNL Relativistic Heavy Ion Collider and CERN Large Hadron Collider", *Phys. Rev. ST Accel. Beams*, vol. 13, no. 9, p. 091001, 2010. doi:10.1103/PhysRevSTAB.13.091001

[9] M. Zampetakis *et al.*, "Interplay of space charge, intrabeam scattering and synchrotron radiation in the Compact Linear Collider damping rings", *Phys. Rev. Accel. Beams*, to be published. doi:10.48550/arXiv.2308.02196

[10] M. Zampetakis, "Numerical Models and Interplay of Intrabeam Scattering with Incoherent Effects in High Brightness Circular Accelerators", PhD Thesis, Department of Physics, University of Crete, Heraklion, Greece, 2024.

[11] M. Hostettler, "LHC Luminosity Performance", PhD Thesis, Bern U., Bern, Switzerland, 2018, https://cds.cern.ch/record/2319396

[12] H. Timko *et al.*, "LHC Longitudinal Beam Dynamics during Run 2", in *Proc. 9th LHC Operations Evian Workshop*, Evian Les Bains, France, 2019, pp. 245–251, https://cds.cern.ch/record/2750299

[13] T. Argyropoulos, private communication.

[14] S. Nagaitsev, "Intrabeam scattering formulas for fast numerical evaluation", *Phys. Rev. ST Accel. Beams*, vol. 8, p. 064403, 2005. doi:10.1103/PhysRevSTAB.8.064403

[15] J. D. Bjorken and S. K. Mtingwa, "Intrabeam Scattering," *Part. Accel.*, vol.13, p.115143, 1983, https://cds.cern.ch/record/140304

[16] A. Piwinski, "Intra-beam Scattering", in *9th International Conference on High-Energy Accelerators*, SLAC, Stanford, CA, USA, 1974, pp. 405–409. doi:10.5170/CERN-1992-001.226

[17] S. Papadopoulou *et al.*, "Impact of non-Gaussian beam profiles in the performance of hadron colliders", *Phys. Rev. Accel. Beams*, vol. 23, no. 10, p. 101004, 2020. doi:10.1103/PhysRevAccelBeams.23.101004

[18] S. Papadopoulou, "Bunch characteristics evolution for lepton and hadron rings under the influence of the Intra-beam scattering effect", PhD Thesis, Department of Physics, University of Crete, Heraklion, Greece, 2019.

[19] M. Zampetakis *et al.*, "Interplay of space charge and intrabeam scattering in the LHC ion injector chain", arXiv:2310.03504 [physics.acc-ph], submitted for publication. doi:10.48550/arXiv.2310.03504

[20] L. Medina *et al.*, "Optimal injection voltage in the LHC", *Nucl. Instrum. Methods Phys. Res., A*, vol. 1039, pp. 166994, 2022. doi:10.1016/j.nima.2022.166994

[21] B. E. Karlsen-Baeck *et al.*, "Correlating Start-of-ramp Losses with Beam Observables at Flat-bottom in the LHC", presented at IPAC'24, Nashville, TN, USA, 2024, paper MOPC11, this conference.