

# MODELING LONGITUDINAL BEAM PARAMETER SPREADS FOR THE HL-LHC ERA\*

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## Abstract

Roughly 2500 bunches are accelerated to collision energy during physics production in the Large Hadron Collider (LHC). Due to the beam production scheme in the injector chain, a certain spread in bunch length and intensity at injection into the LHC is unavoidable. The variation in these parameters has implications for RF capture, leakage of particles from the buckets at flat-bottom, and therefore the losses at the start of acceleration. Moreover, bunches with particularly high intensity or short length can become unstable. With the doubling of the nominal bunch charge in the High-Luminosity (HL) LHC era, these variations will become increasingly important. Beam tests have been carried out over the past few years in the LHC with beam intensities up to the HL baseline. Based on data from these studies, projections of longitudinal parameter spreads can be made for the HL-LHC era. In this contribution, the parameters of the beams injected into the LHC are examined in detail. These results are discussed within the context of beam stability and the generation of off-momentum particles at injection energy in the HL-LHC.

## INTRODUCTION

The nominal bunch intensity injected into the Large Hadron Collider (LHC) will be increased from  $1.8 \times 10^{11}$  protons per bunch (p/b) during the present run to  $2.3 \times 10^{11}$  p/b for the High-Luminosity (HL-)LHC era [1, 2], which comes with a number of challenges. Due to the limitations of the power available in the LHC radio frequency (RF) system, the beam losses at the start of the energy ramp are expected to increase [3, 4]. Furthermore, recent theoretical studies have shown that the HL-LHC beams could be near the limit of stability in the longitudinal plane [5]. Both of these challenges are strongly influenced by the exact charge and distribution of the beams that will be delivered to the HL-LHC.

Beams with the HL-LHC specifications have already been injected into the LHC during machine development (MD) sessions performed in 2024 and 2025. The bunch parameters like the bunch length and bunch intensity were measured during these sessions. In the following, the analysis of longitudinal beam parameters from these first high-intensity MD sessions are presented. The consequences for the operation of the HL-LHC in terms of beam losses and beam stability are also briefly discussed.

## BUNCH LENGTH AND INTENSITIES DURING HIGH-INTENSITY TESTS

During MD sessions in 2024 and 2025, the LHC captured trains with bunch intensities close to the HL-LHC baseline from its injector, the Super Proton Synchrotron (SPS). In addition to the standard beam for HL-LHC, these bunch intensities have been probed with the two other foreseen beam types as well: The batch compression merging and splitting (BCMS) beam, which has lower transverse emittances, and the 8 bunches 4 empty buckets (8b4e) beam type, which is an alternative to mitigate electron cloud build up, if needed [6].

The bunch length and intensity of the three different beam types for HL-LHC are represented in Fig. 1. The bunch intensity was measured using the fast beam current transformer (FBCT) in the SPS at top energy before extraction. The bunch length was found using the SPS beam quality monitor (BQM), which retrieves the linear charge density of the beam measured by a wide-band longitudinal pick-up [7]. By convention in the SPS and LHC, the bunch length is defined to be the  $4\sigma$ -equivalent to the estimated full-width at half-maximum (FWHM) of the bunch. The BQM therefore extracts the bunch length by finding the FWHM of the line-density,  $\tau_{\text{FWHM}}$ , and then scales it by  $2/\sqrt{2 \ln 2}$  to obtain the  $4\sigma$ -equivalent,  $\tau_{4\sigma}$ . The  $4\sigma$ -equivalent bunch length was used to calculate the longitudinal emittance at extraction assuming steady-state conditions. Finally, the LHC bunch length was calculated from the emittance and assuming an RF voltage of 7.9 MV, which is the baseline capture voltage in the LHC during the HL-LHC era.

The LHC Injectors Upgrade (LIU) beam parameter specifications along with their spreads are represented by the shaded areas in the plots in Fig. 1 [8]. For all three beam types, the bunch length is on the lower side of the specifications. During the high-intensity measurements, the main RF voltage at SPS extraction was limited to 8.5 MV for the standard and BCMS beams and 8.0 MV for the 8b4e trains while the LIU baseline is 10 MV. This was caused by limitations in RF power in the SPS. The longitudinal emittance was therefore lower in the MD sessions compared to the baseline for HL-LHC, even though the SPS bunch length was very close to the specified 1.65 ns. The bunch intensity, on the other hand, is within the LIU specifications with a peak-to-peak spread of  $2.0 \times 10^{11}$  p/b to  $2.6 \times 10^{11}$  p/b.

The bunch intensity threshold for longitudinal instabilities increases with the bunch length [9, 10]. How these parameters correlate with each other from the injectors could therefore become important for beam stability in the LHC.

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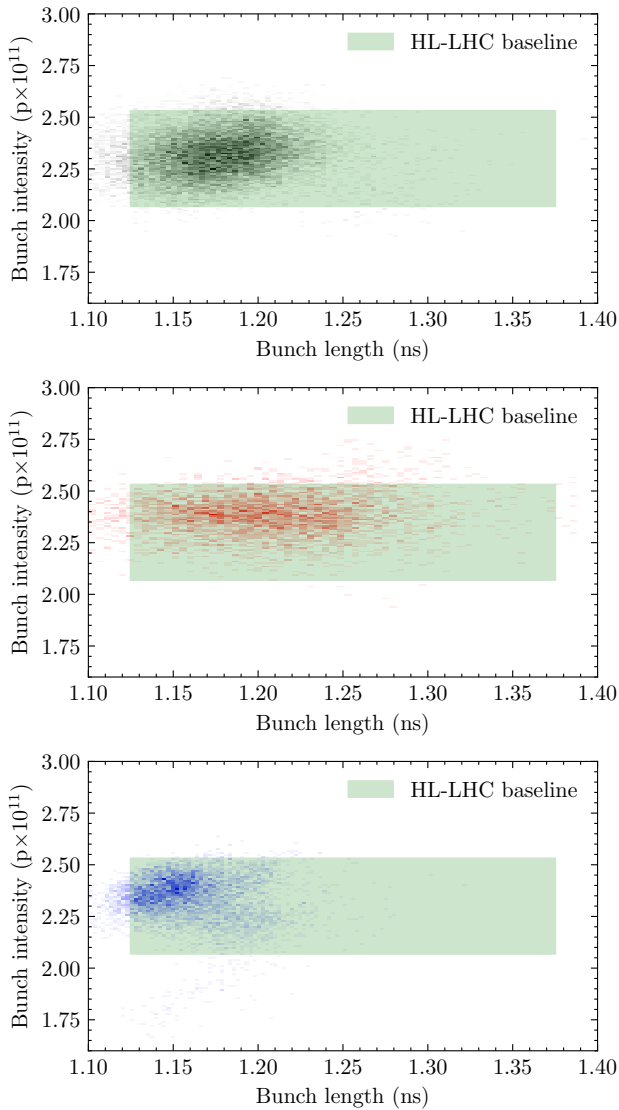


Figure 1: Bunch intensity as a function of the filamented bunch length in the LHC for the standard (top), BCMS (middle) and 8b4e (bottom) beam types.

The correlation coefficient between the bunch length and intensity was therefore determined for the three beam types. The standard beam had a coefficient of 0.11 while the BCMS and 8b4e beams had coefficients of 0.09 and  $-0.06$  respectively. Hence, no significant correlation was found between the two parameters.

## ESTIMATING LONGITUDINAL HALOS

The halo population of the beam in the longitudinal plane is another important parameter for HL-LHC. The halo content affects the amount of uncaptured particles generated at the bunch-to-bucket capture and has an impact on the stability of the bunches. The beam distribution  $F$  of a single proton bunch in the synchrotrons at CERN is typically described by the binomial distribution given as [11]

$$F(H) = F_0 \left(1 - \frac{H}{H_0}\right)^\mu. \quad (1)$$

In the equation,  $H$  is the longitudinal Hamiltonian,  $H_0$  is the Hamiltonian value enclosing all particles in the bunch,  $F_0$  is a normalization factor and  $\mu$  is known as the binomial exponent. The population of the longitudinal halo is described by the binomial exponent, with a larger exponent corresponding to more populated tails. In the past, the line density corresponding to this distribution was approximated by

$$\lambda(t) = \lambda_0 \left(1 - 4 \frac{t^2}{\tau_{\text{full}}^2}\right)^{\mu+1/2}, \quad (2)$$

in the LHC with  $\tau_{\text{full}}$  being the full bunch length. This formula is derived using the short-bunch approximation ( $\tau_{\text{full}} \ll T_{\text{rf}}$ ). However, as the bunches are comparable or longer than half the bucket length ( $T_{\text{rf}} = 2.5$  ns), this approximation does not yield accurate results. The complete formula for the binomial line density, taking into account the nonlinear part of the RF potential, is given as

$$\lambda(t) = \lambda_0 \left(1 - \frac{\sin(\omega_{\text{rf}} t)^2}{\sin(\omega_{\text{rf}} \tau_{\text{full}})^2}\right)^{\mu+1/2}, \quad (3)$$

with  $\omega_{\text{rf}}$  being the RF angular frequency. Note that, in both equations, the effect of potential-well distortion is not taken into account. A comparison of the two expressions for the line density is shown in Fig. 2 for a bunch in the LHC of length  $\tau_{4\sigma} = 1.25$  ns and a binomial exponent of  $\mu = 1.5$ .

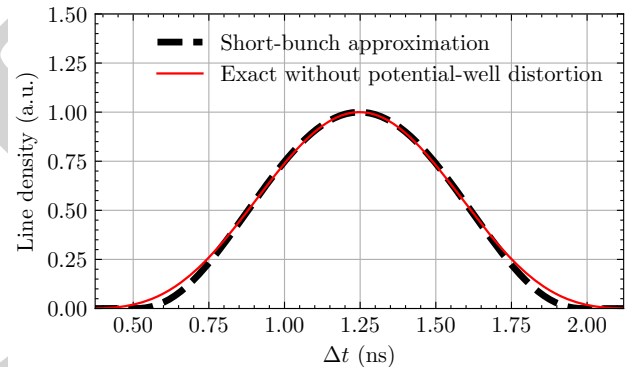


Figure 2: Comparison of the exact binomial line density (red) with the short-bunch approximation (black) with typical LHC parameters.

Using the short-bunch approximation is accurate for the core of the bunch. However, the tails of the exact expression is larger than the approximate form for the same value of the binomial exponent, as can be observed in Fig. 2.

Figure 3 depicts the bunch length and binomial exponent resulting from using Eq. (2) to fit line densities produced using Eq. (3). The full bunch length  $\tau_{\text{full}}$  used for Eq. (3) was scanned from 0.2 ns to 1.5 ns, keeping the binomial exponent at  $\mu = 1.5$ . The fitted full bunch length using Eq. (2) is accurate for short bunches, as the approximation still holds (see Fig. 3 (top)). For longer bunches, the full bunch length is overestimated. Figure 3 (bottom) represents the ratio between the binomial exponent of the exact line density  $\mu_2$  and that of the fit using the approximation  $\mu_1$ .

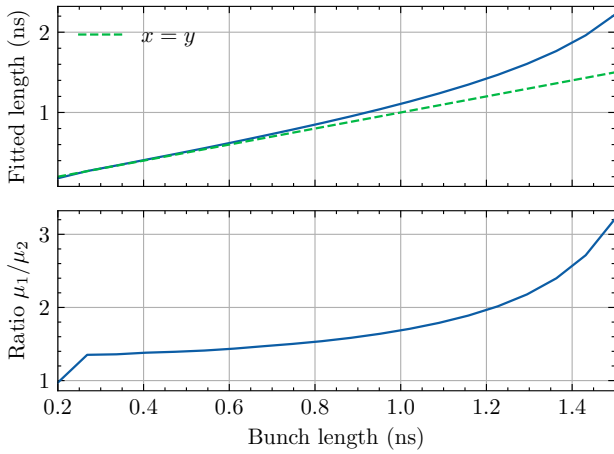


Figure 3: Fitted full bunch length (top) and the ratio of the binomial exponents  $\mu_1$  and  $\mu_2$  (bottom), using the short-bunch approximation and as a function of the exact full bunch length, respectively.

The figure shows that the tails are overestimated when using the approximate expression in Eq. (2) and becomes less accurate with longer bunches.

### Longitudinal Tails at HL-LHC Bunch Intensities

For the analysis of the beam parameter spread, the binomial exponent was estimated from the line densities measured in the LHC during one of the high-intensity MD sessions with standard beams at  $2.3 \times 10^{11}$  p/b. The transfer function from the pick-up to the scope was used to correct each measured profile and Eq. (3) was then used to fit them. The result from this procedure is represented in Fig. 4, and the mean values and standard deviations are found in Table 1.

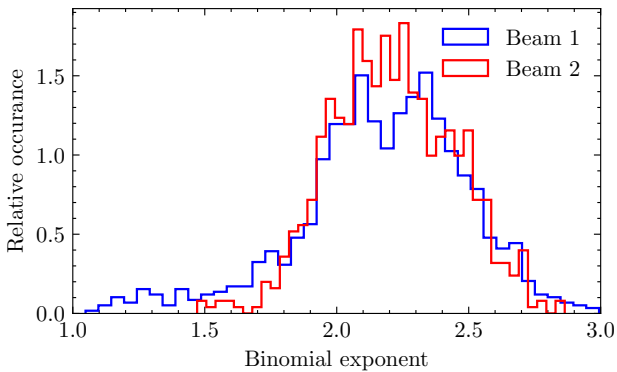


Figure 4: Estimated binomial exponent distribution from high-intensity MD with standard beam trains. The bunch intensity was  $2.3 \times 10^{11}$  p/b.

Table 1: Estimated binomial parameters from measurements of bunches with HL-LHC bunch intensities.

	Binomial $\mu$	Bunch length
Beam 1	$2.17 \pm 0.32$	$(1.29 \pm 0.05)$ ns
Beam 2	$2.21 \pm 0.23$	$(1.33 \pm 0.06)$ ns

The longitudinal halo arriving to the LHC has long been considered to correspond to  $\mu = 1.5$ . However, one can

see that the halos for the beams at HL-LHC intensities are more populated. This finding is also supported by the studies of uncaptured particles at LHC injection. In Ref. [4], the longitudinal halo was inferred from simulations of the bunch-to-bucket transfer, while varying the  $\mu$  of the beam to fit the data. It was found that for the HL-LHC intensity beams, a binomial exponent slightly larger than 2 would best fit the measurement data. Hence, both the profile measurements and the estimates of uncaptured beam indicate that the longitudinal tails are more populated with HL-LHC intensity bunches than what was assumed for operational beams during the current physics run.

The distribution of the  $4\sigma$ -equivalent bunch length estimated using the same data is represented in Fig. 5. The bunches were captured with a voltage of 6.0 MV, which is the reason why they are longer than in Fig. 1 (top). Scaling the bunch lengths in Fig. 1 (top) from 7.9 MV to 6.0 MV in the LHC, yields an expected bunch length of  $(1.28 \pm 0.04)$  ns. This is slightly shorter than the values summarized in Table 1. Hence, the bunches blew up slightly in emittance after filamentation, likely due to the voltage mismatch between the SPS and LHC.

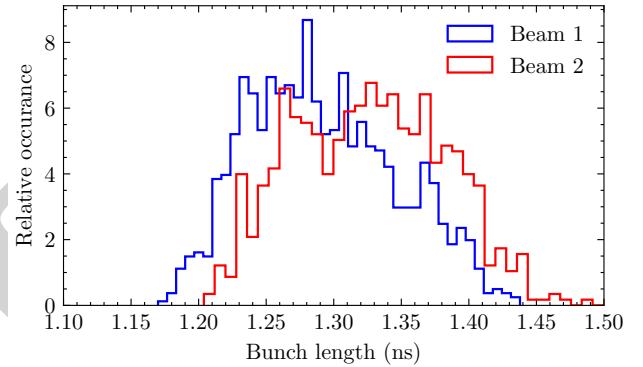


Figure 5: Estimated bunch length distribution from high-intensity MD with standard beam trains after filamentation in the LHC. The bunch intensity was  $2.3 \times 10^{11}$  p/b.

## CONCLUSIONS

Bunch trains with parameters close the HL-LHC baseline were captured for the first time in 2024 and 2025. A systematic analysis of the bunch length and intensity of these beams shows that there is no significant correlation between the two once they reach the LHC. This is an important check, as a negative correlation would increase the risk of unstable bunches in the longitudinal plane for HL-LHC.

Analysis was performed on the longitudinal line density measurements taken during these high-intensity MD sessions. The high-intensity bunches have, on average, more populated longitudinal tails than what was assumed in the past for operational beams. This will impact the amount of uncaptured beam during injection into the HL-LHC. However, this will have a limited effect on RF voltage requirements, as studies have shown that the acceptable amount of off-momentum beam losses at the start of the ramp can be increased [12].

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