BUNCH-BY-BUNCH ANALYSIS OF THE LHC HEAVY-ION LUMINOSITY

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Abstract

After the first run in 2010 [1], the LHC continued its heavy-ion operation with collisions of lead nuclei in late 2011. The beam dynamics of the high intensity lead beams are strongly influenced by intra-beam scattering (IBS), especially on the injection plateau. Each train injected from the SPS spends a different time at injection, introducing significant changes from train to train. Within the trains there is an even larger spread imprinted by the SPS injection plateau. This results in a spread of the luminosity produced in each bunch crossing. The particle losses during collisions are dominated by nuclear electromagnetic processes, leading to a non-exponential intensity decay during the fill and short luminosity lifetime at $3.5Z$ TeV. The luminosity, emittance, intensity and bunch length evolution of the 2011 run was analysed bunch-by-bunch and compared with simulations. Based on this analysis, estimates of the potential luminosity performance at $6.5Z$ TeV, after the present shutdown, are given.

SIMULATION

All simulations presented in this paper are done with the so-called Collider Time Evolution (CTE) program [2]. This program performs a 6D tracking of initial particle coordinates taking into account intra-beam scattering (IBS), burn off from luminosity production, radiation damping and quantum excitation. It requires data on the initial beams, like the particle type, no. of particles per bunch, N_b, transverse emittances, $\varepsilon_{N,x,y}$, bunch length, σ_z, total RF voltage, V_{RF}, that are taken from measurements in the following.

BUNCH-BY-BUNCH DIFFERENCES

In heavy-ion operation of the LHC, the lead ions from the source have to pass LINAC3, LEIR (Low Energy Ion Ring), the PS (Proton Synchrotron) and the SPS (Super Proton Synchrotron) to be fully stripped and pre-accelerated up to $450Z$ GeV at the exit of the SPS before they are injected into the LHC. In each pre-accelerator a certain number of bunches will be accumulated from the previous machine before their energy ramp and transfer to the next. The bunches injected earliest have to wait at the low injection energy, where they are more strongly affected by IBS (which scales with $\propto \gamma^{-3}$) [3] than those arriving later. Thus IBS introduces significant bunch-by-bunch differences in emittance growth and particle losses. The filling scheme used in 2011 implied that this effect happens

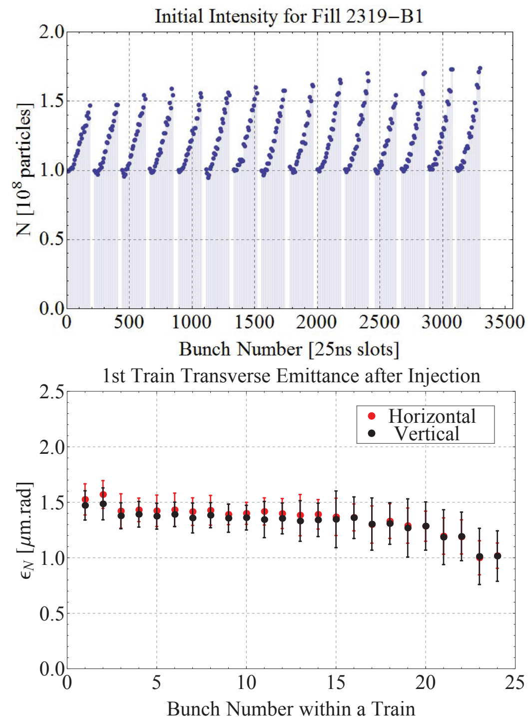

Figure 1: Initial intensity (top) and emittance (bottom) data after injection into the LHC.

mainly in the SPS and LHC while forming trains and the whole beam, respectively.

In Figure 1 the intensity and transverse emittances are shown right after injection to the LHC as a function of the bunch number. The intensity plot shows the whole beam of 15 trains (injections from the SPS) with 24 bunches each. The emittance data is only displayed for the first injected train. In both cases a clear pattern within the trains is observable arising from the IBS at the injection plateau of the SPS.

Beams at Injection

Figure 2 shows the measured (dots) evolution of four single bunches at the injection plateau of the LHC compared to the results of the simulation (lines, corresponding colours). The simulated emittance growth and particle losses due to debunching shown in the plots are in good agreement with the measured data. Also the growth in the longitudinal and vertical plane, which are not displayed here, are predicted well.

The particles lose about 7% of their intensity and double their horizontal emittance within 30 min, about the time required to fill both rings of the LHC with ions and there-

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ISBN 978-3-95450-122-9

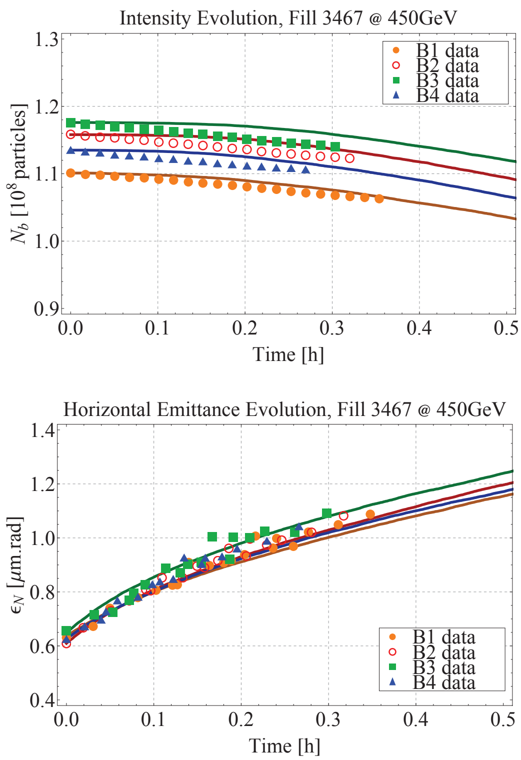

Figure 2: Intensity (top) and emittance (bottom) evolution at injection for 4 single bunches. Dots: measurement, lines: simulation.

fore the time the first injected train has to wait before being ramped to $E = 3.5Z$ TeV. Bunches injected later are accelerated earlier in their evolution curve to arrive at top energy with smaller ε_N and higher N_b.

Colliding Beams

The bunch-by-bunch differences in N_b, ε_N and σ_z explained above translate into a significant spread in luminosity, $\mathcal{L}$, from one bunch crossing to another, as can be seen in Figure 3 (top), where the initial bunch luminosities measured by the ATLAS experiment directly after the start of collisions are displayed. The measured bunch luminosity changes by up to a factor of six inside one train. The visible pattern is dominated by the differences in N_b, since $\mathcal{L}$ is proportional to the product of the intensities of the two bunches. Note that the filling pattern of the LHC is such that the leading bunches of trains in the two rings collide with each other. Since the bunch-by-bunch differences in ε_N are inversely correlated to N_b, the variations seen in Figure 1 are amplified in Figure 3. An overlying slope connecting the last bunches of each train can now clearly be seen, which indicates the variations established during the time the trains sit at injection energy in the LHC.

Following the differences in the initial luminosity the bunches also suffer from different luminosity lifetimes: bunches with high initial values show a much faster luminosity decay than other, however their integrated luminosity is also higher. In the bottom plot of Figure 3 the evolution of $\mathcal{L}$ as a function of time in collisions is shown for a

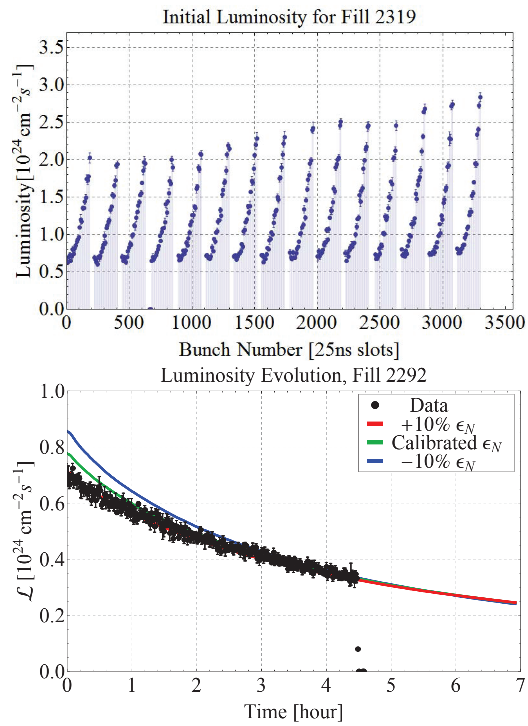

Figure 3: Bunch-by-bunch luminosity at the start of collisions (top) and evolution of a single bunch compared to simulation (bottom).

typical bunch from 2011. Figure 4 shows its N_b, $\varepsilon_{N,x}$ and longitudinal full-width half-maximum ($FWHM$) evolution. The $FWHM$ is a measure of the bunch length σ_z.

The black points indicate the measurement, but since the absolute calibration of ε_N is difficult (though required as simulation input), the other curves (red, green, blue) show three simulation attempts with varying initial ε_N. The data shows the best agreement with the red curve for all parameters, computed for an initial ε_N which is 10 % higher than the calibrated value. The agreement of the data with the red curve is good, except that the simulation predicts slightly faster losses of N_b, which might be explained by a discrepancy of the longitudinal beam profiles. The simulation assumes Gaussian profiles, whereas the real profile is known to look more like a water-bag distribution with almost no tails. The particles in the tails will be the first to be lost due to the debunching effect of IBS. A bunch with Gaussian longitudinal profile (as assumed in the simulation) will lose more particles compared to a distribution with fewer particles in the tails.

PROJECTIONS FOR AFTER LS1

After the current long shutdown (LS1) the LHC will run at a higher energy of $6.5Z$ TeV. This will make it possible to also decrease the β^*-function at the interaction point from 1 m, which was used in 2011, to the design value of 0.5 m. To estimate the gain in peak luminosity at the beginning of collisions, the bunch-by-bunch luminosities of all physics fills in 2011 were used to compute a model

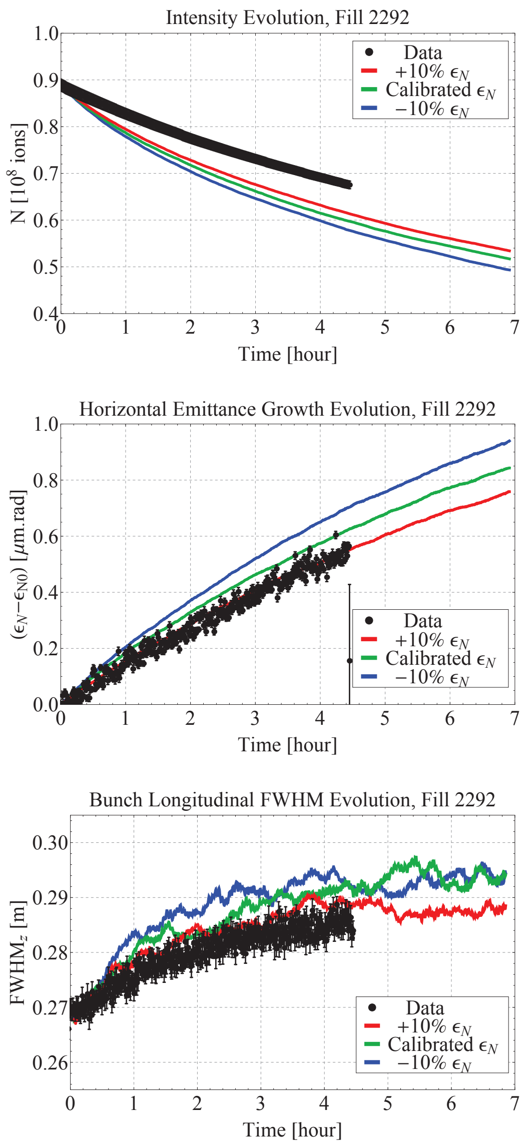

Figure 4: Evolution of a singe bunch compared to simulation. Top: intensity, middle: emittance, bottom: longitudinal FWHM.

which can predict the peak luminosity of a bunch as a function of its position inside the beam. This model is shown in red in the top plot of Figure 5, the blue dots compare this model to the data of the last fill of the run. In the bottom plot this model was scaled to the new parameters expected after LS1, assuming the same filling scheme and beam properties as in 2011, leading to a peak luminosity of $\mathcal{L} = 1.8 \times 10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is 1.8 times above the design value.

In the 2013 proton-lead run [4] average Pb intensities of $N_b = 1.6 \times 10^8$ with average $\varepsilon_N = 1.3\,\mu\mathrm{m}$ were injected into the LHC, compared to $N_b = 1.2 \times 10^8$ and $\varepsilon_N = 1.5\,\mu\mathrm{m}$ in 2011, an improvement from the injector side of about 30 % in intensity (cf, design $N_b = 7 \times 10^7$).

The filling scheme used in 2011 had a bunch spacing of 200 ns between bunches of the same train. This could be reduced to a scheme with alternating 200 ns and 100 ns spacing after LS1 to increase the number of circulating bunches.

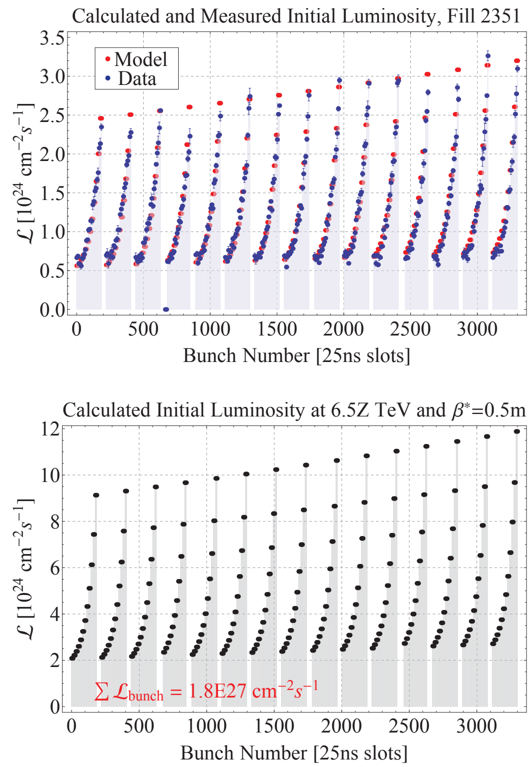

Figure 5: Bunch-by-bunch model ($E = 3.5Z$ TeV, top) and estimate ($E = 6.5$ TeV bottom) of the initial luminosity.

Nevertheless, thanks to the performance of the injectors it will easily be possible to reach luminosities $\mathcal{L} > 2 \times 10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ after the current shutdown. However, as an interim measure, it may be necessary to level luminosity at a lower value because of rate limitations of the experiments. This will reduce the otherwise very rapid luminosity decay and yield similar integrated luminosity. With an upgrade of the SPS injection kickers planned in LS2 2018 [5], shorter bunch spacings and still higher luminosities can be expected.

Acknowledgements: This work is supported by the Wolfgang-Gentner-Programme of the BMBF (Federal Ministry of Education and Research, Germany).

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ISBN 978-3-95450-122-9