POTENTIAL OF STOCHASTIC COOLING OF HEAVY IONS IN THE LHC

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Abstract

The dynamics of the high intensity lead beams in the LHC are strongly influenced by intra-beam scattering (IBS), leading to significant emittance growth and particle losses at all energies. Particle losses during collisions are dominated by nuclear electromagnetic processes and the debunching effect arising from the influence of IBS, resulting in a non-exponential intensity decay during the fill and short luminosity lifetimes. In the LHC heavy ion runs, 3 experiments will be taking data and the average fill duration will be rather short as a consequence of the high burn-off rate. The achievements with stochastic cooling at RHIC suggest that such a system at LHC could substantially reduce the emittance growth and the debunching component during injection and collisions. The luminosity lifetime and fill length could be improved to optimize the use of the limited run time of 4 weeks per year. This paper discusses the first results of a feasibility study to use stochastic cooling on the lead ion beams in the LHC. The present and expected future performance without cooling is presented and compared to preliminary simulations estimating the improvements if stochastic cooling is applied.

SIMULATION

The simulations presented in this paper are done with two related simulation programs [1, 2]: the Collider Time Evolution (CTE) program [2], used regularly for LHC, was built on a previous version of [1]. These programs perform a 6D tracking of initial particle coordinates, taking into account intra-beam scattering (IBS) and beam population burn-off from luminosity production. Moreover, [2] additionally takes into account radiation damping and quantum excitation. On the other hand, [1] includes a treatment of stochastic cooling.

Both require data on the initial beams, like the particle type, no. of particles per bunch, N_b, transverse emittances, $\varepsilon_{N,x,y}$, rms bunch length, σ_z, total RF voltage, V_{RF}, that are taken from measurements in the following. The program in [1] also requires the definition of the stochastic cooling system to be used (bandwidth, gains).

LHC HEAVY-ION BEAMS

The lead ion bunches cannot be injected into the LHC directly from the source. The particles have to pass several pre-accelerators (LINAC3, LEIR (Low Energy Ion Ring), PS (Proton Synchrotron), SPS (Super Proton Synchrotron)) to be fully stripped and pre-accelerated up to the LHC injection energy of $450Z$ GeV.

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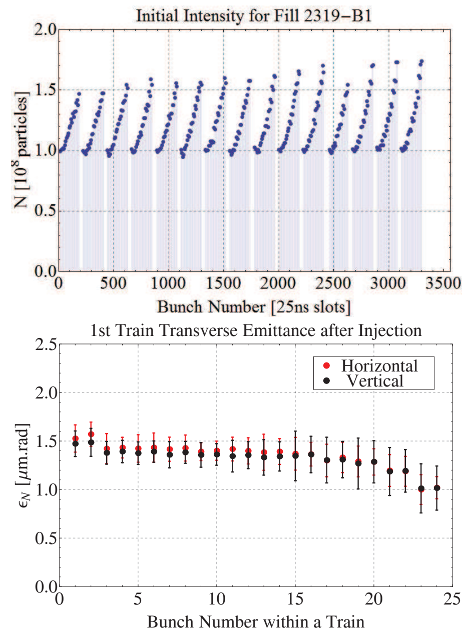

Figure 1: Initial intensity (top) and emittance (bottom) data after injection into the LHC.

Table 1: Typical Bunch Parameters in 2013

Parameter		head	average	tail
N_b	[10^8 ions]	1	1.4	2
$\varepsilon_n = \varepsilon\gamma$	[μm rad]	1.2	1.5	1.8
σ_z	[m]	0.08	0.10	0.11

Bunch-by-Bunch Differences

Because of the shorter length of the machines down the chain, a certain number of bunches will be accumulated in each pre-accelerator 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 and intensity. This effect occurs mainly while forming trains in the SPS and again when assembling them into the full beam in the LHC.

In Fig. 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 are 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. Table 1 summarises the parameters of 3 typical bunches along a train.

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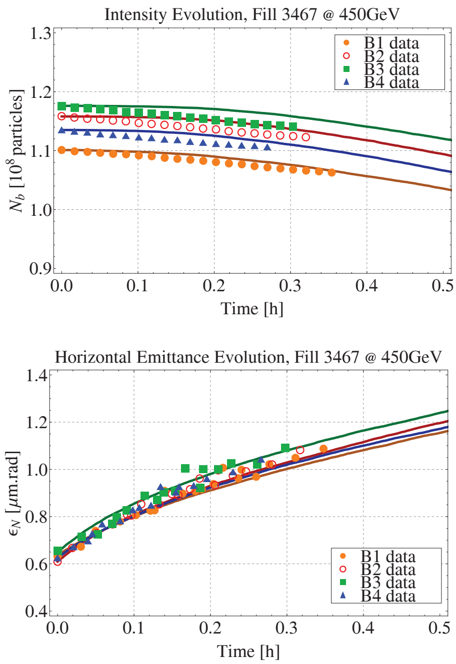

Figure 2: Intensity (top) and emittance (bottom) evolution at injection for 4 single bunches. Dots: measurement, lines: simulation.

Beams at Injection

It takes about 30 min to fill both rings of the LHC with ions. This implies that the first injected train has to wait this time before being ramped. As can be seen from Fig. 2, where the measured (dots) evolution of four single bunches at the injection plateau of the LHC are compared to simulation results done with [2] (lines, corresponding colours). Typical bunches lose about 7% of their intensity and double their horizontal emittance within 30 min.

The measured emittance growth and particle losses due to debunching (no collisions present) shown in the plots are well reproduced by the simulation. Also the growth in the longitudinal and vertical plane, which are not displayed here, are predicted well.

IBS leads to emittance growth mainly in parts of the machine with non-zero dispersion. The dominant growth of the horizontal emittance is transferred to the vertical plane by betatron coupling. Since both vertical dispersion and coupling are small in the LHC, so is the vertical emittance growth.

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 Fig. 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. Note

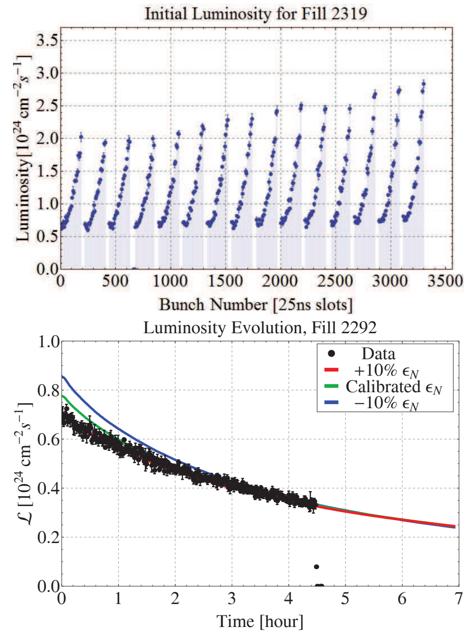

Figure 3: Bunch-by-bunch luminosity at the start of collisions (top) and evolution of a single bunch compared to simulation (bottom).

that the filling pattern of the LHC is such that the leading bunches of trains in the two rings collide with each other. An overall slope connecting the last bunches of each train can now clearly be seen, indicating 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 others but their integrated luminosity is also higher. In the bottom plot of Fig. 3, the evolution of $\mathcal{L}$ as a function of time in collisions is shown for a typical bunch from 2011.

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 show the best agreement with the red curve for all parameters, computed for an initial ε_N which is $10\,\%$ higher than the calibrated value.

EXPECTATION AT 7Z TeV

In normal heavy-ion operation three experiments (ALICE, ATLAS, CMS) take data during the physics runs, leading to a high burn-off rate and short beam lifetimes. In 2011 the average fill length was about 6 hours, while peak luminosities of $\mathcal{L} = 0.5 \times 10^{27}\text{cm}^{-2}\,\text{s}^{-1}$ (half the design luminosity) at $3.5Z$ TeV were reached with 358 bunches per beam. After the long shutdown the energy will be upgraded to $6.5Z$ TeV and later to $7Z$ TeV, naturally leading to even stronger burn-off rates.

Figure 4 shows the expected evolution of the bunch luminosity in ALICE at $7Z$ TeV determined with [2]. It is

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evident that the luminosity decay will be significantly faster if 3 experiments (blue) are in collisions, compared to a single experiment (red). For the case of 3 colliding IPs the luminosity decays to half of its initial value in only about 2 h, which compares unfavourably with turnaround times of about 3 h.

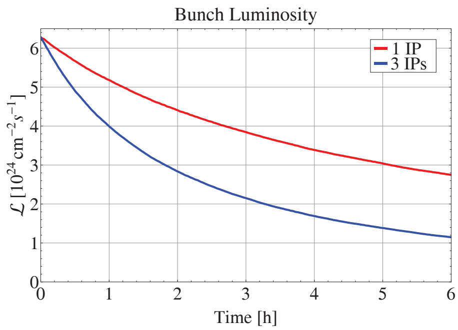

Figure 4: Bunch luminosity at $7Z$ TeV for 1 (red) and 3 (blue) colliding IPs.

It is worth noticing that at this high energies radiation damping has become strong enough to act as a natural cooling system and partly counteract IBS. For a bunch with average properties (see Table 1) at $7Z$ TeV, as in Fig. 4, the transverse radiation damping time is $T_{\mathrm{rad},x} = 12.7\,\mathrm{h}$, the horizontal IBS growth time $T_{\mathrm{IBS},x} = 7.6\,\mathrm{h}$. This effect is included in the simulations shown in Fig. 4.

STOCHASTIC COOLING ESTIMATES

In the previous sections, we saw that the ion beams in the LHC suffer from strong IBS at all energies, leading to significant emittance growth particle loss. The installation of a stochastic cooling system could help against this to increase the fill length and thus the integrated luminosity.

Assuming 2013 average Pb bunch parameters (Table 1) and a nominal energy spread of $\Delta p/p = 1.1\times10^{-4}$, a cooling system with a bandwidth of $W = 5-20\,\mathrm{GHz}$ is necessary to achieve reasonable short cooling times (Eq. 8.1 of [4]):

$$T_{\mathrm{cool}} = \frac{N_b C_{\mathrm{LHC}}}{4\sigma_z W}\left[\frac{M+U}{(1-\tilde{M}^{-2})^2}\right] \approx 1.8\,\mathrm{h}, \qquad (1)$$

where C_{LHC} is the circumference of the LHC, σ_z the RMS bunch length (to get the total length of the bunch the factor 4 is introduced). The mixing factor M is the number of turns it takes for a particle of RMS momentum error to move by one sample length T_s with respect to the nominal particle with $\Delta p/p = 0$. Using the slip factor $\eta = 1/\gamma_T^2 - 1/\gamma^2$ (where γ is the relativistic Lorentz factor and γ_T this factor at transition energy), $\Delta p/p$, the revolution frequency f_{rev} and the centre frequency of the cooling system, the mixing can be estimated to be $M \approx 10$. $\tilde{M}^{-2} \rightarrow 0$ was assumed in the calculation, referring to the perfect situation of no (undesired) mixing between the pickup and kicker. The noise to signal ratio was set to $U = 0.01$, since compared to M this factor is usually small and has only little influence on the result. Taking a system similar to that installed at RHIC, with a kicker consisting of 16 cavities, a RMS peak voltage of around $V_{cavity} = 2\,\mathrm{kV}$ would be required per cavity for the longitudinal plane. The voltage requirement for the transverse cavities is usually smaller.

Figure 5 (top) shows a comparison of simulations with (solid lines) and without (dashed lines) stochastic cooling for one experiment in collisions determined with [1]. The luminosity evolution of three typical LHC lead bunches, indicating the spread between bunches within a train (bunch parameters given in Table 1), are displayed. The simulation does not include radiation damping and assumes no coupling between the transverse planes. In this configuration, the cooling improved the integrated luminosity by about a factor 2, mainly because the emittance growth was turned into damping. The bottom plot of Fig. 5 evaluates the influence of cooling systems with different bandwidths on the example of the average bunch in Table 1.

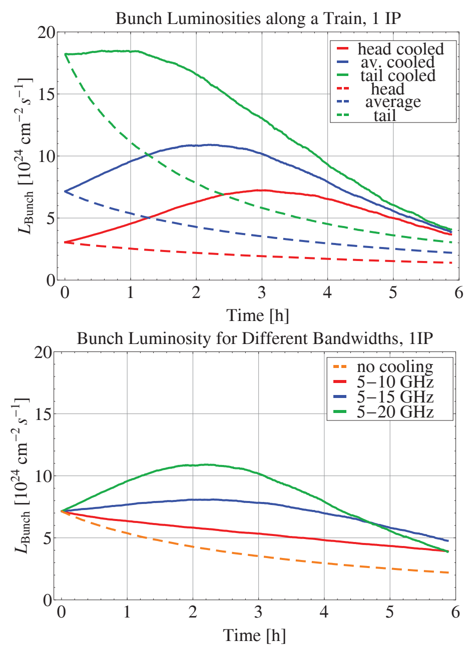

Figure 5: Top: Bunch luminosity for 3 typical bunches with and without cooling. Bottom: Average bunch from top plot for systems with different bandwidth.

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