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STUDIES ON STOCHASTIC COOLING OF HEAVY IONS IN THE LHC

M. Schaumann*, CERN, Geneva, Switzerland and RWTH Aachen, Aachen, Germany
J.M.Jowett, B. Salvant, M. Wendt, CERN, Geneva, Switzerland
M. Blaskiewicz, S. Verdú-Andrés, BNL, Upton, NY, USA

Abstract

Future high luminosity heavy-ion operation of the LHC will be dominated by very rapid luminosity decay due to the large collision cross-section and, to a lesser extent, emittance growth from intra-beam scattering (IBS) due to the high bunch intensities. A stochastic cooling system could reduce the emittance far below its initial value and reduce the losses from debunching during collisions, allowing more of the initial beam intensity to be converted into integrated luminosity before the beams are dumped. We review the status of this proposal, system and hardware properties and potential locations for the equipment in the tunnel.

MOTIVATION

The ALICE collaboration has plans for a major upgrade during the second long LHC shutdown, LS2, currently scheduled for 2018, to allow for peak luminosities of 6–7 times the design value ($\mathcal{L} = 1 \times 10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). As in past years, ATLAS and CMS will also be taking data during heavy-ion operation, leading to high burn-off rates with 3 experiments in collision and, consequently, short fills.

The planned upgrades of the injector complex [1] are expected to significantly increase luminosity [2] but may be insufficient to provide the requested $10\,\mathrm{nb}^{-1}$ in Pb-Pb collisions during the HL-LHC era.

At RHIC, 3D stochastic cooling of bunched Au and U beams has been very successful [3,4]. The emittance growth and the debunching component of the losses during collisions were substantially reduced, improving luminosity lifetime and lengthening fills. It is natural to consider a similar approach to cooling the LHC heavy-ion beams [5,6].

LUMINOSITY ESTIMATES

In this paper, the luminosity and beam evolution are simulated with the Collider Time Evolution (CTE) program [7], used regularly for LHC. CTE performs a 6D tracking of initial particle coordinates, taking into account intra-beam scattering (IBS), radiation damping and beam population burn-off by collisions. Stochastic cooling is included as in [5]. The initial beams are specified by the particle type, no. of particles per bunch, N_b, transverse emittances, ϵ_n, RMS bunch length, σ_z, total RF voltage, V_{RF}. System properties (bandwidth, gains) for stochastic cooling are also required.

A wide spectrum of intensities and emittances is imprinted on the LHC Pb bunches during the accumulation of bunch trains in the injector chain, resulting in a large spread of single bunch luminosities and lifetimes in collision [8]. The following estimates are based on the parameters of three typical Pb bunches in an SPS train, as in 2013 (Table 1).

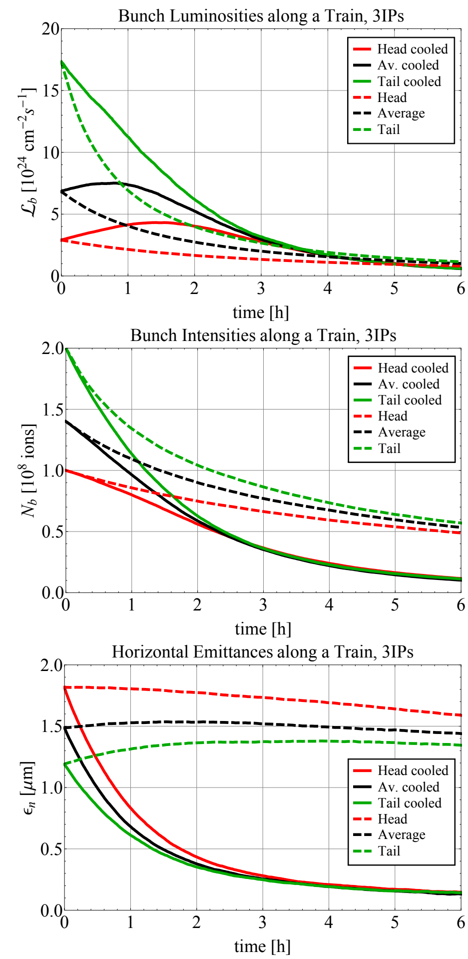

Figure 1: Beam and luminosity evolution with and without cooling for the three bunches from Table 1.

Table 1: Typical Bunch Parameters in 2013

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

The benefit of a cooling system with a bandwidth $W = $ 5–20 GHz is shown in Fig. 1, where the single bunch-pair luminosity, intensity and emittance evolution through a 6 h fill is plotted. The dashed lines show the evolution without, the solid lines with, cooling.

Cooling shrinks the emittance, colliding beams more efficiently and reducing the fraction of the original stored beam that has to be dumped at the end of a fill. The luminosity

* Michaela.Schaumann@cern.ch

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efficiency, $\eta_{\mathcal{L}}$, can be defined as the ratio of the integrated luminosity achieved per fill, $\mathcal{L}_{\text{int}}$, summed over all experiments, to its potential maximum, when all particles of the beam with the smaller total intensity, N, have been collided:

$$\eta_{\mathcal{L}} = \frac{\sum_{\text{IP}} \mathcal{L}_{\text{int}}}{\mathcal{L}_{\text{int,max}}} = \frac{\sigma_c \sum_{\text{IP}} \mathcal{L}_{\text{int}}}{\min(N_1, N_2)}, \qquad (1)$$

where σ_c is the total collision cross-section. Typical good fills of the 2011 Pb-Pb run at beam energy $E_b = 3.5Z$ TeV (and the 2012 p-p runs at $E_b = 4$ TeV) had $\eta_{\mathcal{L}} \simeq$ 15–20%. Predicted performance at $E_b = 7Z$ TeV without cooling in a standard 6 h Pb-Pb fill is $\eta_{\mathcal{L}} \simeq 60\%$. Stochastic cooling could increase it to 88%, an increase in integrated luminosity per experiment approaching 50%.

HARDWARE CONSIDERATIONS

The space required for the full 3D system is proportional to the number of cavity modules. Following the RHIC system, one has to expect a requirement of 12–15 m per plane and beam. The only place in the LHC tunnel where some 40 m might be found is in IR4, where the RF, feedback and many beam instrumentation systems are located.

For optimal mixing the kicker-to-pickup distance should be large, while the pickup-to-kicker distance should be small, to preserve the relation between measured signal and beam condition. As a compromise, and also to match the signal and beam travel times, the pickups ($L_{\text{PU}} \simeq 1$ m) could be placed $\simeq 3/8$ of a turn downstream of the kickers, i.e., in IR7 for Beam 1 and in IR1 for Beam 2. The betatron phase advance between pickup and kicker should be about $(n + 1/2)\pi$ for optimal transverse cooling efficiency.

For frequencies up to 20 GHz, the cavity apertures have to be as small as 1–2 cm in diameter; as in RHIC, this requires a special design allowing the devices to open at injection, when the beams are large, and close at top energy for cooling operation. Studies based on the currently expected optics for after LS2, have shown that an aperture of 1 cm could be possible, if the cavities are located just behind the IR4 dispersion suppressors, where the β-functions in both planes are sufficiently small. However the separation of beam pipes may be marginal and requires further study.

The frequency spacing of the cavity modules should approximately fulfil $\Delta f \approx c/(4\sigma_z)$. For an average RMS bunch length of $\sigma_z = 0.1$ m, $\Delta f \simeq 750$ MHz. So, for a system with a bandwidth of $W = 20 - 5$ GHz $= 15$ GHz about 20 cavity modules are required. Clearly, the smaller the bandwidth, the smaller the frequency coverage of the system and the less efficient the cooling.

The required RMS longitudinal voltages are 2–3 kV per cavity, the voltages required for the transverse planes are of the order of a few tens volts.

IMPEDANCE

The small aperture of the series of cavities means that the impedances of (a) the cavities themselves, (b) the transition to these small apertures, and (c) the longitudinal and transverse resonant modes in the surrounding tank, need to be carefully minimized with the cavities both open and closed. Preliminary simulations, optimized to obtain the effective impedance of the current RHIC kicker (one tank with 5 cavity modules at different frequencies), indicate that the low frequency impedance is dominated by (a) and can be modelled as bellow corrugations [9] (Fig. 2). The kicker impedance in open position is ∼ 2 mΩ in the longitudinal plane and 20 kΩ/m in the plane of plate separation. A large number of these cavities would then represent a non-negligible fraction of the total longitudinal LHC impedance (currently 0.1 Ω) and transverse LHC impedance (currently 2 MΩ/m at injection) [10]. Further studies should be performed in order to assess the resonant modes trapped in the large tank, as well as to optimise the RHIC design for use in the LHC.

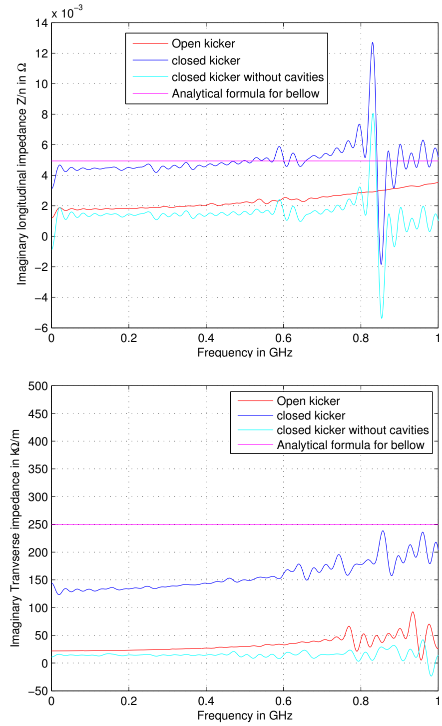

Figure 2: Longitudinal and transverse simulated impedances of RHIC kicker open (red), closed (blue), closed with cavities filled by metal (cyan) and the formula in [9] (magenta).

FEASIBILITY TEST

To demonstrate that stochastic cooling can work for heavy-ions in the LHC, a test with a minimal cooling system is in preparation for 2015/16. Existing Schottky pickups centred on 4.8 GHz would be used to measure the beam signal (see below). A single longitudinal cavity at the same frequency would be installed in IR4 to apply the correction to Beam 1. A preliminary cavity design is available, with parameters scaled from the longitudinal kicker in RHIC (Table 2).

Table 2: Preliminary Test Cavity Parameters

f	R/Q	Q_{load}	V_{RMS}	t_{fill}
4.8 GHz	142 Ω	2150	6 kV	143 ns

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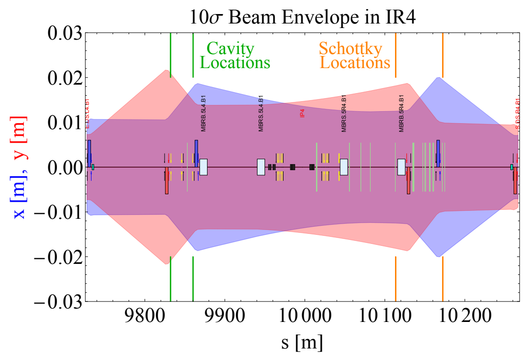

Figure 3: IR4 layout and 10σ transverse beam envelopes at injection energy.

The voltage of 6 kV corresponds to the longitudinal voltage excited along the beam axis of the kicker for a maximum input power of 40 W from the amplifier. Its small aperture of about 4 cm diameter would not meet the impedance requirements for p-p operation so the cavity should be installed in a technical stop preceding the Pb-Pb operation and removed afterwards. Short term installations in the beam pipe are possible in certain prepared locations, highlighted in green in Fig. 3.

Unlike the RHIC transverse cavity design, or a future system for LHC operation, the cavity for this test would have a fixed aperture, constraining the inner radius to be compatible with the beam size at injection. Figure 3 displays the 10σ beam envelopes at injection energy in the horizontal (blue) and vertical (red) plane in IR4, overlaid with a schematic of the main beam line elements along the central orbit, the Schottky pickup positions are highlighted in orange. While either pickup can be chosen for the experiment, the margin is greater at the right-hand cavity location.

This setup has a very narrow bandwidth. Since the cooling time $T_{\mathrm{cool}} \propto N_{\mathrm{b}}/W$, the cooling is slow ($T_{\mathrm{cool}} \simeq 15\,\mathrm{h}$) and the expected effect is small. Therefore, the reduction of the bunch length should be measured on a low intensity test bunch with respect to a non-cooled witness bunch featuring the same beam properties.

Longitudinal Schottky Signals

Each particle (ion) of charge Ze in a bunched beam follows synchrotron oscillations of the frequency f_s ($\ll f_{\mathrm{rev}}$), having random amplitude and phase. This results in a time difference with respect to the synchronous particle, circulating with f_{rev}, thus causes a phase modulation of each particle of the bunched beam. The longitudinal Schottky spectrum appears as a set of synchrotron satellite lines spaced by f_s around each revolution harmonic hf_{rev}.

Figure 4 shows longitudinal and transverse Schottky signals of two harmonics around $hf_{\mathrm{rev}} \approx 4.8$ GHz of a Pb beam detected by a broadband Schottky pickup in the LHC in different operating conditions. The narrow peaks of the longitudinal harmonics express the coherent signal contents, i.e., the amplitude is $\propto N$. The "hump" below the peak displays the incoherent longitudinal Schottky signal. Because of the random phase, the amplitude is reduced to $\propto \sqrt{N}$. The individual synchrotron frequency satellite lines become only visible if zoomed in closely.

With a few minor modifications the detection of the longitudinal Schottky signals can be improved to provide the desired signals for the feasibility test. For instance, performing solely as longitudinal Schottky pickup by obtaining the sum-signal from the two adjacent slotted-waveguide couplers and operating at a different harmonic in the range $4.6\,\mathrm{GHz} < hf_{\mathrm{rev}} < 5.0\,\mathrm{GHz}$ could improve the signal level.

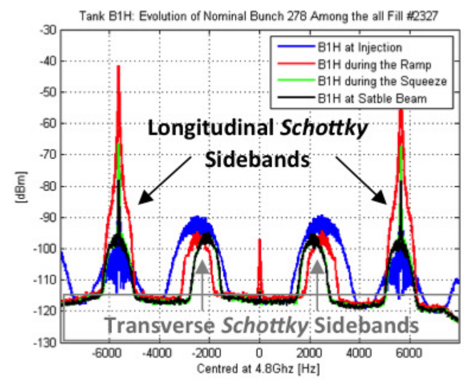

Figure 4: Longitudinal and transverse side bands of the detected LHC Schottky signal with 1.1×10^8 Pb^{82+} ions.

CONCLUSIONS

A stochastic cooling system in the LHC could dramatically shrink the emittance of heavy-ion beams as they collide and thereby approach the theoretical maximum integrated luminosity per fill without recourse to elaborate optics or crossing schemes. First simulations have shown very promising results, but some key problems remain to be solved. Design of a proof-of-principle demonstration of longitudinal stochastic cooling in the LHC is under way.

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REFERENCES

[1] D. Manglunki *et al.*, WEPEA060, IPAC13 (2013).
[2] M. Schaumann, TUPRO014, these proceedings.
[3] M. Blaskiewicz *et al.*, Phys.Rev.Lett., 105:094801 (2010).
[4] Y. Luo *et al.*, TUPFI082, IPAC13 (2013).
[5] M. Blaskiewicz *et al.*, TUYA03, IPAC11 (2011).
[6] M. Schaumann *et al.*, TUPM1HA02, COOL'13 (2013).
[7] R. Bruce *et al.*, Phys. Rev. ST AB 13, 091001 (2010).
[8] M. Schaumann *et al.*, TUPFI025, IPAC13 (2013).
[9] K-Y. Ng, PAC'87, 1051 (1987).
[10] N. Mounet, EPFL PhD thesis 5305 (2012).