

LUMINOSITY AND BEAM PARAMETER EVOLUTION FOR LEAD ION BEAMS IN THE LHC

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Abstract

Heavy ion beams in the LHC are subject to strong blow-up and debunching effects from intra-beam scattering and luminosity-driven beam losses. The large nuclear charge is at the origin of these effects, both in the cross sections for simple Coulomb scattering and the ultraperipheral interactions occurring in the collisions. We compare predictions from our models with data on luminosity, beam size and intensity evolution from the first heavy ion run of the LHC. This analysis has to take account of the varying capabilities of the LHC beam instrumentation between injection and collision energies.

INTRODUCTION

Quantitatively understanding the time-evolution of the luminosity of colliding heavy-ion beams (fully stripped lead nuclei, of charge $Z=82$ and nucleon number $A=208$ in the case of the LHC [1]) requires a detailed understanding of the kinetics of the particle distributions of two beams in 3 degrees of freedom [2]. The luminosity itself removes particles from the beam because of the very large cross-sections (several hundred barns, enhancement factor with respect to protons: $\sim Z^7, Z^4 \dots \sim 10^{13}$) for ultraperipheral electromagnetic processes such as photonuclear dissociation and bound-free pair production [3,4]. The change in intensity modifies the rates (scaling $\sim Z^4 / A^2 \sim 10^3$) at which the longitudinal and transverse emittances blow up due to intra-beam (multiple Coulomb) scattering (IBS), which in turn lead to further intensity loss by debunching, the diffusion of particles out of the RF bucket. At full energy, the IBS effects are expected [3] to be overcome by radiation damping ($\sim Z^5 / A^4 \approx 2$). Because some of these processes already operate during the injection period [5], the bunches of the beam already have a distribution in emittance and intensity when the beams are first put into collision. The evolutions of the two beams are coupled through the luminosity but are in general different, depending on initial conditions.

Previous approaches to this problem have employed systems of coupled ordinary differential equations for the emittances and intensities of a sufficiently large set of bunches [3,6]; this can work well but is limited by the assumption that all bunches have a Gaussian distribution. In [6] a simulation method taking account of the non-Gaussian nature of the longitudinal distribution in the IBS and luminosity-loss calculations was developed and applied successfully to luminosity data from many fills of RHIC. The predictions also made there for the LHC apply to design beam energy, $E = 2.76A \text{ TeV} = 7Z \text{ TeV}$.

For the analysis of the first Pb-Pb run of the LHC [5], we could attempt the more ambitious goal of simulating,

not only the luminosity and intensity but also the copious data available from the LHC instrumentation [7] and logging system for bunch lengths and emittances, luminous region and luminosity data from the ATLAS experiment. With the detailed dependence of IBS rates, in particular, on all these quantities, this constitutes a severe test of the theory and methodology with, in principle, no free parameters.

At half-design energy and with $\beta^* = 3.5 \text{ m}$ instead of 0.5 m , moreover, the LHC is in a different regime, with weaker luminosity burn-off, negligible radiation damping but rather stronger IBS, leading to significant debunching and luminosity decay from emittance growth—a machine more akin to RHIC [6] (before the implementation of stochastic cooling) than the full-energy LHC that we have yet to see.

SIMULATION AND DATA

Full background and details of the simulation and data analysis methods applied are given in [6,8] and we can summarise only a few essential points here. Among the enhancements of the multi-particle simulation [6] is a choice of several calculations of IBS, which give similar results in practice; those given here use a fast method [9] which integrates over the detailed LHC optics but does not include effects of vertical dispersion. The non-gaussian longitudinal distribution is modelled as in [6] and betatron coupling is assumed to distribute IBS over the two transverse phase planes.

Bunch-length data from the LHC Beam Quality Monitor (BQM) and ATLAS luminous region were rather consistent. We then used the theoretical relations with applied RF voltage to deduce energy spread and longitudinal emittance.

However deducing the transverse emittances was not straightforward. The charge per Pb bunch was $< 10\%$ that of protons and the main instruments available in the physics runs were the synchrotron light monitors (BSRT). These cycled their gating over all bunches to provide bunch-to-bunch data with a periodicity of many minutes. An elaborate time-smoothing and interpolation method was used to infer a continuous evolution in the intervals. However the absolute values of emittances derived from the BSRT calibration measurements were not consistent with the ATLAS luminosity nor with the simulation (see also [10]). An alternative calibration formula [8] was derived by requiring consistency with the ATLAS luminosity at the start of physics but retaining relative magnitudes of horizontal vs. vertical beam sizes and between beams. The simulations could then try to reproduce the evolution of an average bunch from the detailed initial conditions of a given fill.

Because of the risk of quenching magnets, it was not possible to use the wire scanners [7] to measure emittance with stored Pb beam energies beyond those of a few bunches at injection energy. The beam-gas ionization monitors [7] sometimes gave a relative measure of beam sizes but were not yet well calibrated.

In this paper, we illustrate the processes with two sample fills from the 2010 heavy-ion run. In one of them, Fill 1511 (Figure 1), the simulation model works well; in the other, Fill 1494 (Figure 2), it does not. The reasons for this are connected with the intermittent presence of a noise source of unidentified origin [11] which, when its frequency spectrum overlaps betatron sidebands, can lead

to a significant additional emittance growth, most often in vertical, for Beam 2. No attempt is made to model this in our present simulation. Its absence during Fill 1511 accounts for the good detailed agreement. During Fill 1494, it appears to switch on and off twice and the agreement with the simulation is lost.

Note that, in Fill 1511, because of the initial conditions, the behaviour of the transverse emittances was very different between beams and planes but is nevertheless accounted for in detail by the physical effects included in the simulation.

Analyses of a number of other, quite different, fills, both proton and Pb ion, can be found in [8].

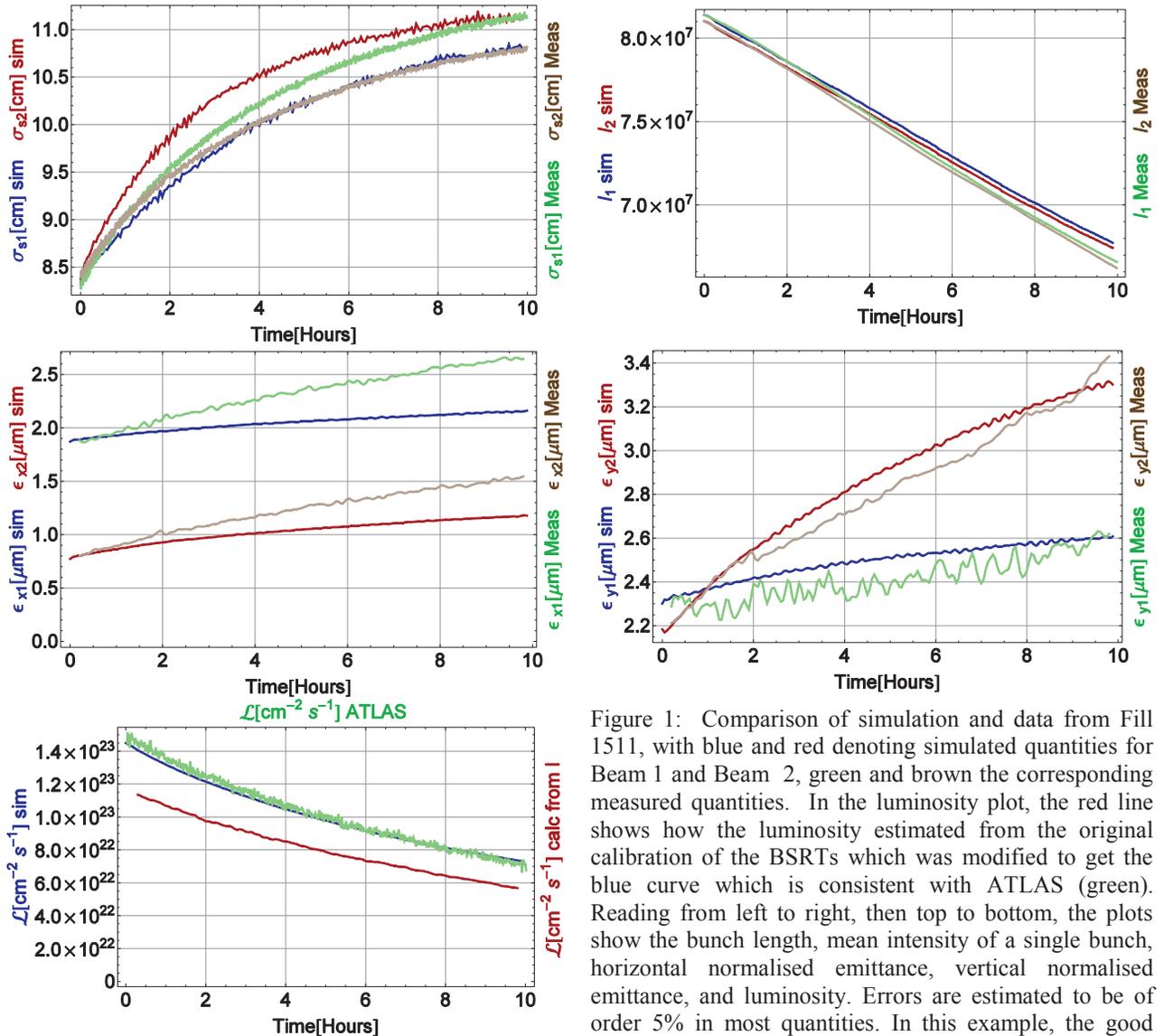


Figure 1: Comparison of simulation and data from Fill 1511, with blue and red denoting simulated quantities for Beam 1 and Beam 2, green and brown the corresponding measured quantities. In the luminosity plot, the red line shows how the luminosity estimated from the original calibration of the BSRTs which was modified to get the blue curve which is consistent with ATLAS (green). Reading from left to right, then top to bottom, the plots show the bunch length, mean intensity of a single bunch, horizontal normalised emittance, vertical normalised emittance, and luminosity. Errors are estimated to be of order 5% in most quantities. In this example, the good detailed agreement *at all later times* between measured and simulated quantities suggests that the BSRT emittance calibration derived by fitting the 4 separate initial emittances to the *initial* ATLAS luminosity and luminous region is correct.

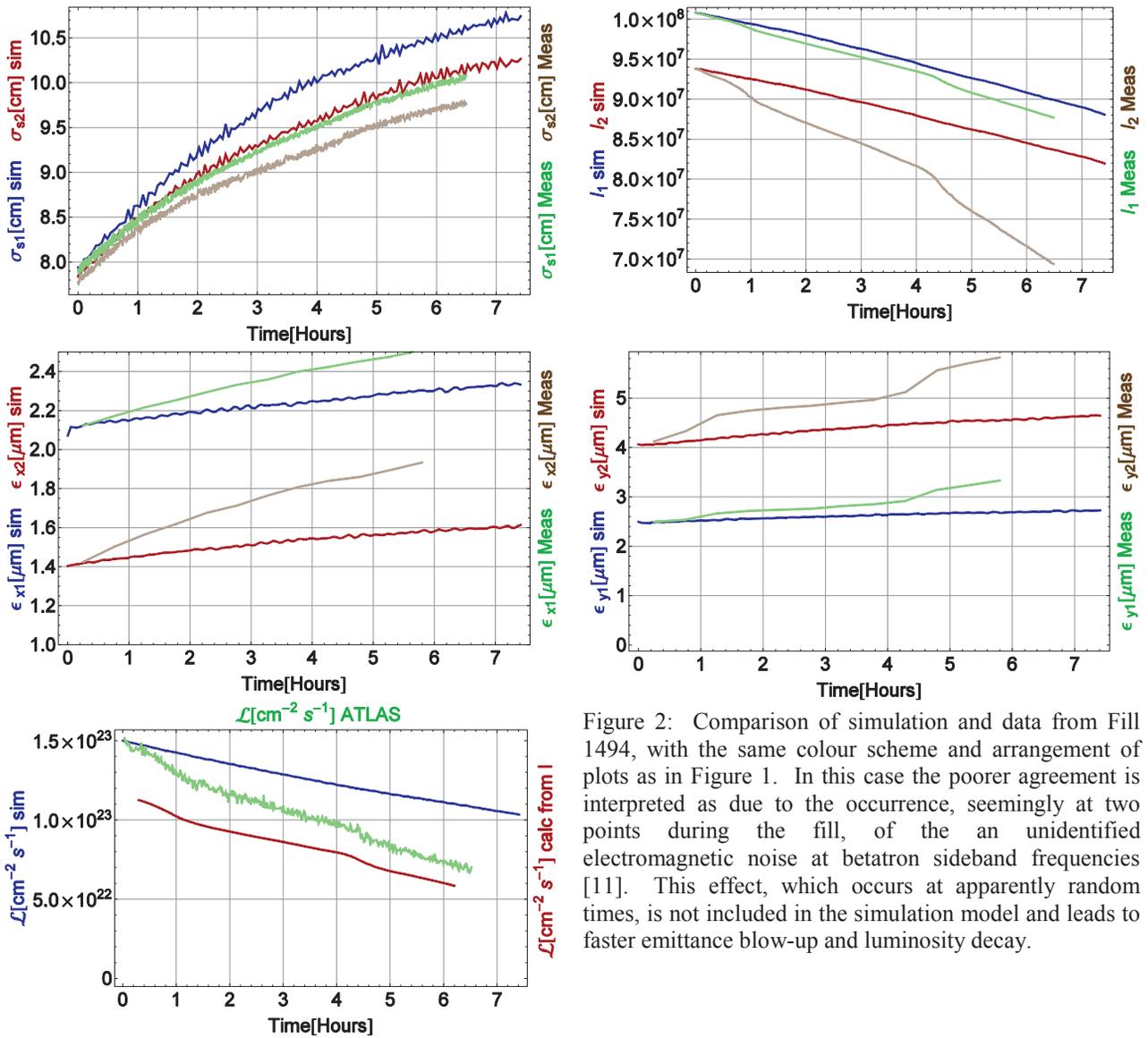


Figure 2: Comparison of simulation and data from Fill 1494, with the same colour scheme and arrangement of plots as in Figure 1. In this case the poorer agreement is interpreted as due to the occurrence, seemingly at two points during the fill, of an unidentified electromagnetic noise at betatron sideband frequencies [11]. This effect, which occurs at apparently random times, is not included in the simulation model and leads to faster emittance blow-up and luminosity decay.

CONCLUSIONS

At least when the intermittent noise excitation is absent, modelling of the evolution of heavy-ion beam parameters and luminosity under the influence of (mainly) IBS growth and debunching and losses from collisions can account in some detail for LHC heavy ion fill data.

A cooling system [12] to reduce the emittance growth and debunching could be of substantial benefit for the heavy-ion integrated luminosity in the LHC.

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