EXPERIMENTAL STUDIES OF IBS IN RHIC AND COMPARISON WITH THEORY *

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Abstract

A high-energy electron cooling system is presently being developed to overcome emittance growth due to Intra-beam Scattering (IBS) in RHIC. A critical item for choosing appropriate parameters of the cooler is an accurate description of the IBS. The analytic models were verified vs dedicated IBS measurements. Analysis of the 2004 data with the Au ions showed very good agreement for the longitudinal growth rates but significant disagreement with exact IBS models for the transverse growth rates. Experimental measurements were improved for the 2005 run with the Cu ions. Here, we present comparison of the 2005 data with theoretical models.

INTRODUCTION

Present performance of the RHIC collider with heavy ions is limited by the process of Intra-Beam Scattering (IBS) within the beam. To achieve required luminosities for the future upgrade of the RHIC complex [1] an Electron cooling system was proposed [2]. For electron cooling it is extremely important to make sure that the models of IBS, used in our cooling simulations, are in a good agreement with experimentally measured growth rates.

With the dedicated IBS measurements performed in 2004 for Au and in 2005 for Cu ions it was intended to increase the accuracy and parameter range of previous IBS experiments [3]. For this purpose, bunches of various intensity and emittance were injected, and growth rates of both the horizontal and vertical emittance and the bunch length were recorded with the Ionization Profile Monitor (IPM) [6] and the Wall Current Monitor (WCM), respectively. Other effects which may obscure comparison, like the beam-beam collisions, were turned off. Experiments were done with the RF harmonic h=360 allowing growth of the longitudinal profile without losses from the bucket.

Although, agreement for the longitudinal growth rate was very good for the 2004 measurements with the Au ions, the growth of the transverse emittance had some uncertainties [4]. The measured transverse emittance growth was larger than the one predicted by simulation using Martini's model [5] of IBS with the exact designed RHIC lattice. As a result of the 2004 studies, a fudge factor was introduced for the transverse growth rate of IBS so that simulations would agree with the measurements. This was done to make sure that we do not underestimate IBS growth rate for the design of our cooling system [7].

Following the 2004 measurements several simulation studies were done trying to understand a possible source of the disagreement, including IBS growth for the lattice with different average dispersion functions, FODO approximation for the lattice vs. realistic RHIC lattice with straight-section insertions, dispersion mismatch and others [8]. As a result of these studies, our conclusion was that the disagreement for the transverse growth rate is most likely related to the uncertainties in the 2004 measurements rather than due to the effects described above.

The latest 2005 data with the Cu ions showed very good agreement between the measurements and Martini's model [5] of IBS for the designed RHIC lattice without any approximation. Comparison of the 2005 data with the theoretical models for the IBS is presented in this paper.

GENERAL MODELS

A theory of IBS for proton beams was proposed by Piwinski [9], who calculated the beam growth rates in all three dimensions. In the original theory, growth rates were estimated as an average around the circumference of the ring. For this purpose, the ring lattice functions were also averaged. This model was later extended by a CERN team in collaboration with Piwinski to include variations of the lattice function around the ring. An improved model was later described in a detailed report by Martini [5] and is referred here as Martini's model. Similar results were also obtained with a completely different approach of S-matrix formalism by Bjorken and Mtingwa [10].

Both Martini's and Bjorken-Mtingwa's models require numerical evaluation of the integrals at each of the lattice elements, which may be time consuming. As a result, a variety of approximate models were developed over the years which allow a quick estimate of the IBS rates. However, since we are concerned with accurate description of each of the effects in our cooling simulations using the BETACOOL code [11], we do not use the approximate models.

The models by Martini and Bjorken-Mtingwa were benchmarked vs one another within the BETACOOL code for various types of the lattices and found to be in a very good agreement. For our numerical studies of cooling as well as for comparison with the experimental data we use the Martini's model [5, 11]. We also use the designed lattice of RHIC which includes the derivatives of the lattice functions.

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PARAMETERS OF THE EXPERIMENT

For the 2005 data with Cu ions dedicated IBS measurements were done at both the injection beam energy of 11.2 GeV/n and the full energy of 100 GeV/n. The transition energy corresponds to $\gamma_t = 23$ GeV. At injection, the growth rates were measured both with and without the horizontal-vertical coupling. At 100 GeV/n beam energy the growth of the emittance and bunch length was measured for a fully coupled motion. Since standard operation in RHIC is at beam energy of 100 GeV/n close to full coupling we limit the present discussion of the data to this energy.

First, the coupling strength was measured to be $dQ_{min} = 0.006$ with a tune separation of 0.008, which we call a fully coupled motion. This allows us to use standard treatment of IBS for uncoupled motion and then assume that the horizontal growth rate is equally shared between the horizontal and vertical dimension. Otherwise, in a general case without full coupling, one has to use the IBS formalism for the coupled motion developed by Piwinski [9] or, recently, by Lebedev [12].

Six bunches of different intensity were injected and accelerated to a beam energy of 100 GeV/n in both rings ("yellow" and "blue"). Different intensities in the bunches also resulted in different emittances. This allowed us to verify a scaling of the IBS growth rate with the intensity and emittance. The bunch intensities in the "blue" ring are shown in Fig. 1.

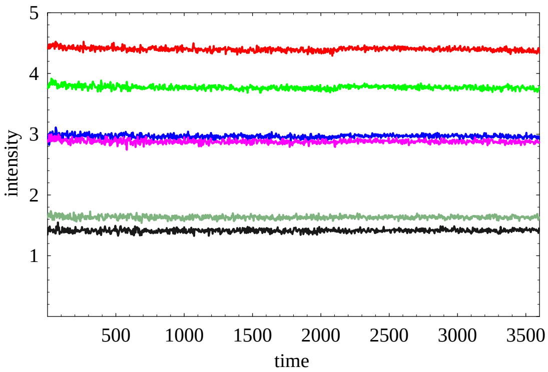

Figure 1: Bunch intensities [$\times 10^9$] vs time [sec].

For standard RHIC operation one uses RF cavity with harmonic h=2520 which corresponds to a very small acceptance. As a result, there is a significant beam loss from the bucket due to IBS. Also, there is a possibility of emittance growth due to the beam-beam collisions. To insure an accurate benchmarking of the IBS models, the measurements were done with h=360 ($U_{rf} = 300$ kV) so that there were no losses from the bucket due to IBS. The beam-beam collisions were turned off.

The growth of the longitudinal bunch length was measured for each individual bunch using the Wall Current Monitor. The horizontal and vertical emittances for each individual bunch were measured with the Ionization Profile Monitor [6]. In both the vertical and horizontal directions nice Gaussian profiles were observed. The emittance values were reconstructed from the measured rms of the distributions and known beta function values at the location of the horizontal and vertical IPM's.

COMPARISON WITH EXPERIMENTAL DATA

Figure 2 shows comparison of simulations vs measurements for the growth of the horizontal and vertical emittance for the bunch intensity of 2.9$\cdot 10^9$ Cu ions.

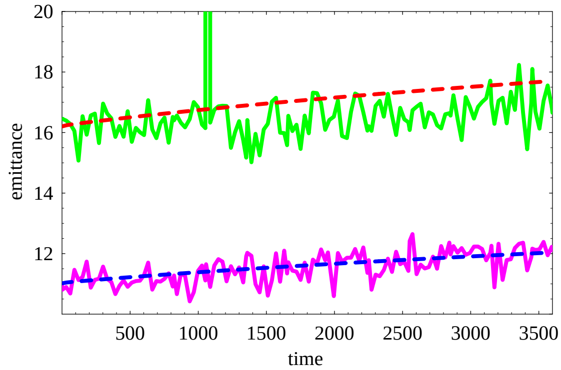

Figure 2: Horizontal and vertical 95% normalized emittance [μm] vs time [sec] for bunch intensity 2.9$\times 10^9$ Cu ions. Measured emittance: top green curve (horizontal), bottom pink curve (vertical). BETACOOL simulation using Martini's model: top red dash line (horizontal), blue dash line (vertical).

Analysis of the emittance and bunch length growth for different bunches in both rings showed that the measured growth rates scale correctly with the bunch intensity and the value of the initial emittance, as shown for the two intensities in Fig. 3 and Fig. 4 for the bunch length and horizontal emittance, respectively.

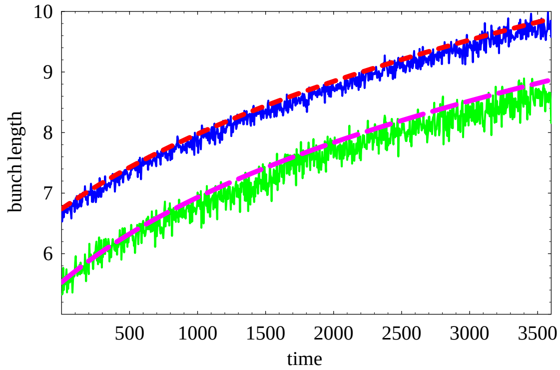

Figure 3: Growth of FWHM bunch length [ns] vs time [sec] for two bunch intensities: 2.9$\times 10^9$ (upper curve) and 1.4$\times 10^9$ (lower curve) Cu ions. Dash lines - simulations.

Since the growth of the transverse emittance is very weak on this time scale it may appear that even using the

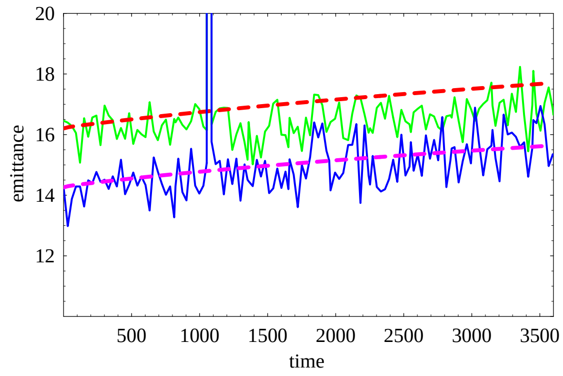

Figure 4: Horizontal 95% normalized emittance [μm] vs time [sec] for two bunch intensities: 2.9×10^9 (upper curve) and 1.4×10^9 Cu ions. Dash lines - simulations; solid lines - measurements.

"enhanced" (50% higher than expected from exact Martini's model) transverse growth rate in simulations, which we needed before for a good agreement with the 2004 data, would result in a close agreement with the measurements. However, plotting such "enhanced" IBS together with the exact model (see Fig. 5) shows that for the present data the simulations based on Martini's model agree much better with the data. We believe that such a good agreement is due to the fact that we reduced previous uncertainties to a minimum. For example, compared to the assumptions used in the analysis of the 2004 data, we now measured both the horizontal and vertical emittance and thus do not need any assumption of whether they are equal or not. We also measured the strength of the coupling.

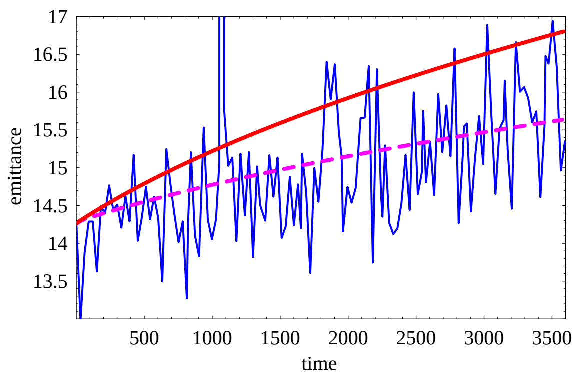

Figure 5: Horizontal 95% normalized emittance [μm] vs time [sec]. Exact Martini's model: pink (dash) line; 50% higher "enhanced" transverse growth rate: red (solid) line. Measurements: blue solid line.

IBS FOR ION BEAM DISTRIBUTION UNDER ELECTRON COOLING

Standard models of IBS discussed in this paper are based on the growth rates of the rms beam parameters for the Gaussian distribution. However, as a result of electron cooling, the core of beam distribution is cooled much faster than the tails. The IBS theory was recently reformulated for a bi-Gaussian distribution by Parzen [13]. A treatment of IBS, which depends on individual particle amplitude was proposed by Burov [14], with an analytic formulation done for a Gaussian distribution in approximation that the longitudinal rms velocity in beam frame is much smaller than the transverse. Also, a simplified "core-tail" model, based on a different diffusion coefficients for beam core and tails was proposed [15].

Numerical approach to the IBS for non-Gaussian distribution was also presented [4, 16]. A treatment of IBS based on kinetic approach [16] was implemented in BETACOOL [17] and is presently being benchmarked with other models. Recently, the bi-Gaussian profiles were recorded to provide experimental data for the benchmarking of the IBS models [18].

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