IBS SIMULATIONS WITH DIFFERENT RF CONFIGURATIONS IN RHIC*

C. Liu#, A. Fedotov, M. Minty, V. Ptitsyn, Collider Accelerator Department,
Brookhaven National Lab, Upton, NY, USA

Abstract

This report focuses on transverse and longitudinal emittance growth of polarized proton beam due to Intra-Beam Scattering (IBS) at RHIC. Simulations are presented which give guidance on the configuration of the RF systems to mitigate IBS-induced emittance growth. In addition, simulated growth rates are compared with measured emittances at injection, which show better agreement in longitudinal than transverse dimension. The results in this report will help us better understand the emittance evolution at injection for current RHIC operations and for future operations (eRHIC).

IBS OVERVIEW

The IBS are small angle coulomb scattering between particles, which would cause beam dimensions in phase space to grow. Many theories of IBS have been developed in the past [1-5]. These theories show that when the beam energy is below the transition energy, an equilibrium beam distribution exists so that particles only exchange energy between the transverse and longitudinal dimensions. While with beam energies above the transition energy, the beam distribution expand in all dimensions. At RHIC, the injection energy of the proton beam (24 GeV) is above the transition energy (~21 GeV). The growth rates increase with the beam phase space density, charge state, and decrease with beam energy. In addition, the energy spread itself also affects the growth rates.

A detailed comparison between various IBS models and measurements in RHIC was reported in Refs. [6-8] for heavy ion beams. The study in this report is focused on analysis of IBS-induced emittance growth for proton beams in RHIC.

SIMULATION CODE AND INPUTS

The simulation was performed with code BETACOOL [9]. Of many simulation functions provided by BETACOOL, only IBS calculation is performed for our case.

The accelerating RF in RHIC was switched from 28 MHz to 9 MHz cavity in 2010 for better matching of the longitudinal emittance of the incoming beam from AGS and the RF bucket in RHIC. The eRHIC ring-ring design requires 330 bunches [10,11].. Therefore, the ion beam needs to be accelerated by 28 MHz cavities and then can be re-bucketed in higher harmonic cavities. Under this circumstance, it is interesting to compare the IBS growth rates and emittance evolution with these two RF configurations.

The particle distribution in 3D space are assumed Gaussian. The transverse emittance was adjusted to match the values measured by the Ionization Profile Monitors (IPMs). The longitudinal energy spread is needed with the RF configurations as inputs to define the longitudinal emittance. The RF configuration was set according to the operational conditions. The beam energy spread is given by [12]

$$\frac{\sigma_p}{p} = \left(-\frac{heV\cos\phi_s\, S^2 f_0^2}{18\pi\eta E_s^3\beta^2}\right)^{1/4}$$

where h is the harmonic number, V is the cavity voltage, ϕ_s is the synchronous phase, S is the 95% longitudinal emittance, f_0 is the revolution frequency, η is the slip factor, E_s is the beam energy, β is the Lorentz factor.

The 95% longitudinal emittance is estimated to be ~ 1 $eV \cdot s$ from AGS. With 9 MHz cavity at 19 kV, $\frac{\sigma_p}{p} = 4.5 * 10^{-4}$. With 28 MHz cavity at 120 kV, $\frac{\sigma_p}{p} = 9.3 * 10^{-4}$.

The Martini model was chosen for the IBS rates calculation. First the integral was evaluated numerically, and then the coulomb logarithm was chosen to match the previously calculated growth rates for fast calculation of the growth rates [13]. The Mad-X Twiss output of pp15-e0 lattice [14] was imported in BETACOOL for simulation.

SIMULATION

The beam parameters for the two simulation scenarios are listed in Table 1.

Table 1: Beam Parameters for IBS Simulation of Proton Beam at Injection

Parameters	Unit	9 MHz	28 MHz
N_p	10^{11}	2	2
$\varepsilon_x/\varepsilon_y$ (95%)	μm	11.1/9.2	11.1/9.2
σ_z	cm	128.1	88.5
Cavity voltage	kV	19	120
σ_p/p	10^{-4}	4.5	9.3

IBS Simulation and Comparison with Experiments with 9 MHz Cavity

RHIC was first assumed as a well-decoupled machine in this case of simulation. The un-normalized transverse emittances were adjusted so that the normalized 95% emittances match with the measured emittances by IPMs shown in Fig. 3. The energy spread was also adjusted started from the theoretical value from the previous section so that the bunch length matches the rms value

*Work performed under Contract No. DE-AC02-98CH1-886 with the auspices of the DOE of United States.
#cliu1@bnl.gov

measured by Wall Current Monitor (WCM) [15]. The 28 MHz cavity was on with 100 kV voltage for Landau damping. The measurement precision of IPMs has been improved over the years. Therefore, measurement data was chosen from 100 GeV polarized proton run in 2015 for comparison with simulations.

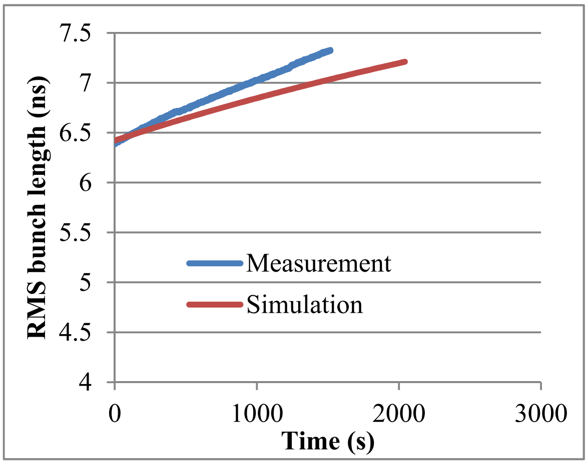

Figure 1: Comparison between measured and simulated bunch length evolution over ~30 minutes.

The longitudinal bunch length evolution from simulation and measurement are both shown in Fig. 1 for comparison. The relative difference of bunch length between measurement and simulation is about 4% in half an hour.

The transverse emittance evolution is shown below (Fig. 2).

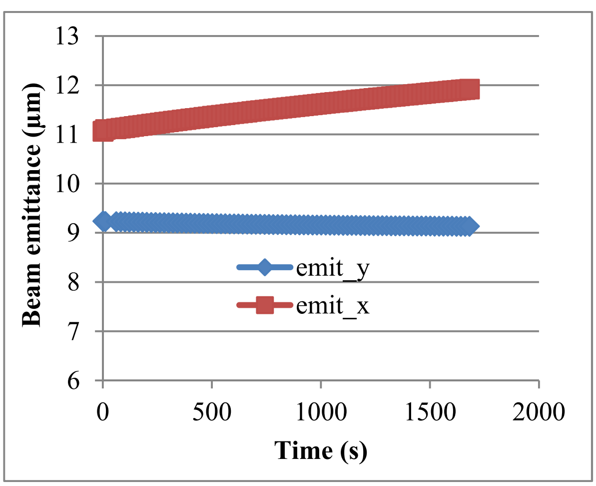

Figure 2: Transverse emittance evolution simulated by BETACOOL for the decoupled case with 9 MHz RF system; the horizontal emittance is in red and vertical emittance in blue.

From the simulation, the horizontal growth rate is 3.35E-5[$1/s$], the vertical growth rate is -3.48E-6[$1/s$], and the longitudinal growth rate is 1.47E-4 [$1/s$] for the decoupled case.

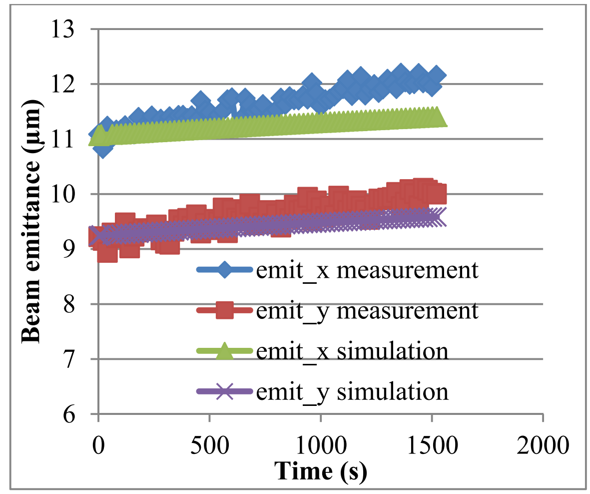

Figure 3: Transverse emittances measured by IPMs at injection and simulated transverse emittance evolution for coupled case with 9 MHz cavity.

If one assumes full coupling between horizontal and vertical planes in the simulation, the horizontal growth rate is 1.53E-5[$1/s$], the vertical growth rate is 1.83E-5[$1/s$], and the longitudinal growth rate is 1.47E-4[$1/s$]. With full coupled machine, the transverse growth rates are average of the rates in both planes in the case of no coupling. The evolutions of bunch length are the same for coupled and decoupled cases.

The measurement of proton beam emittance at injection about half an hour was taken during Run-15 100 GeV polarized proton program. The measured transverse emittances by IPMs are shown in Fig. 3, with the beam emittance evolution simulated for the coupled case for comparison. The IPM profile measurements and corresponding Gaussian fits are in a good agreement for this set of measurement.

In both coupled and decoupled cases, we observed noticeable discrepancy of transverse emittance evolution between simulation and measurement.

IBS Simulation with 28 MHz Cavity

For proton beam at injection with 28 MHz RF system, the transverse emittances are kept the same as for the case with 9 MHz cavity. The energy spread was set twice as much as that for 9 MHz case based on the theoretical calculation in the previous section.

From the simulation, the horizontal growth rate is 2.85E-5[$1/s$], the vertical growth rate is 3.42E-5[$1/s$], and the longitudinal growth rate is 2.89E-5[$1/s$]. Compared with the growth rates with 9 MHz RF system coupled case (Table 2), the transverse rates with 28 MHz RF system are higher while the longitudinal rate is lower.

ISBN 978-3-95450-182-3

Table 2: Comparison of Growth Rates from Simulation with 9 MHz and 28 MHz Cavity with Transversely Coupled Machine

Rates	$\frac{1}{\varepsilon_x}\frac{d\varepsilon_x}{dt}$	$\frac{1}{\varepsilon_y}\frac{d\varepsilon_y}{dt}$	$\frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt}$
Unit	10^{-5}/s	10^{-5}/s	10^{-5}/s
9 MHz	1.53	1.83	14.7
28 MHz	2.85	3.42	2.89

Discussion

The IBS growth rate is proportional to $\frac{NZ^4}{A^2}$, therefore the rates for Au beam is about 10 times higher than that of proton beam. With comparable noise contribution to the emittance evolution, IBS contribution is dominating for Au beam, but not for proton beam. Therefore, the agreement between simulated and measured emittance with IBS is better for Au beam than for proton beam [16].

SUMMARY

In this report, the simulation of IBS effects on RHIC polarized proton beam and the comparison with experiment at injection was presented. With 9 MHz cavity, the simulated longitudinal growth rate is higher, the transverse growth rate is lower than those with 28 MHz cavity due to the smaller energy spread. The coupling of RHIC is visible from the evolution of transverse emittance. The growth rates from simulation are generally lower than those from measurements, especially so in transverse planes. There are other causes for the observed emittance growth other than IBS. Experimental studies [17] on beam emittance in RHIC has been carried out in the past and will resume in the future.

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