OBSERVATION AND SIMULATION OF BEAM-BEAM INDUCED EMITTANCE GROWTH IN RHIC*

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Abstract

In the recent years the peak luminosity of the RHIC polarized proton run has been improved. However, as a consequence, the luminosity lifetime is reduced. The beam emittance growth during the beam storage is a main contributor to the luminosity lifetime reduction, and it seems to be caused mainly by the beam-beam effect during collision. A simulation study of the emittance growth is performed with RHIC machine parameters using the LIFETRAC code [1]. The initial results of this study were reported in an earlier paper [2]. We present, in this paper, an in depth investigation of the emittance growth for a range of beam-beam parameters and bunch lengths. The simulation results are also compared to the available data from experimental measurements.

INTRODUCTION

With the increase of the beam intensity, the peak luminosity of the RHIC polarized proton operations has improved by factors 2 and 3 during 2005 and 2006 runs, respectively [3]. At the same time, for fills with the highest peak luminosity, the average luminosity lifetime in storage has reduced from 28 hours to 15 hours. If the luminosity lifetime continues to decline along with the increase of the peak luminosity, the average luminosity will reach a maximum, which falls short of the RHIC design goal. This would be a serious obstacle to improving machine performance, especially, in the RHIC enhanced design, which calls for at least another factor of 2 improvement in the average luminosity [4].

The two major factors affecting the luminosity lifetime are the beam intensity lifetime and the beam emittance growth. The RHIC experience shows the beam emittance growth is the most important, since for high luminosity fills with the luminosity lifetime of 15 hours, a typical beam intensity lifetime is better than 50 hours, whereas the emittance growth is about 4.5% per hour. The beam emittance growth could be caused by the rf (radio frequency) noise, the beam vibration, magnet non-linearity, bad vacuum, etc. The most noticeable causes that are closely related to the beam intensity are IBS (intra-beam scattering) and beam-beam collision effects. It has been shown that the normalized transverse emittance, the longitudinal emittance, and the form factor at Tevatron and RHIC are all similar. The typical transverse emittance growth at Tevatron is 2.7% per hour at the bunch intensity of 2.7×10^{11} [5,6], whereas RHIC sees typical 4.5% per hour emittance growth at the bunch intensity of 1.3×10^{11} in 2006 run, and even 0.9×10^{11} in 2005 run. Therefore, it seems that the beam-beam effect is more important than IBS in the observed beam emittance growth at RHIC.

From 2005 run to 2006 run, the RHIC proton beam bunch intensity was increased from 0.9×10^{11} to 1.3×10^{11} [3], and the number of IPs (interaction points) was reduced from 3 to 2 (we plan to keep IP=2 for the foreseeable future). With comparable beam emittance at the early store, the beam-beam parameter is about the same in the 2005 and 2006 runs, despite the 45% increase of the bunch intensity in 2006. The beam emittance growth at store is better correlated with the beam-beam parameter, rather than the bunch intensity. Moreover, the luminosity lifetime is also well correlated with the beam-beam parameter. This indicates that the emittance growth in store and the luminosity lifetime reduction might be mainly caused by the beam-beam collisions.

OBSERVATION OF BEAM EMITTANCE GROWTH DURING STORAGE IN RHIC

The RHIC proton beam emittance at store is calculated from the ZDC (Zero degree calorimeter) coincidence rates measured at the two major experiments, PHENIX and STAR. The ZDC is a luminosity detector installed at all experiments for the evaluation of the machine performance. For beam emittance, the IPM (ionization profile monitor), the polarimeter target (thin carbon film), and the experimental vernier scan are also used to verify and compare. The 95% normalized beam emittances, from 1.5 hours to 5.5 hours from the acceleration ramp event, have been evaluated for all fills in 2005 and 2006 runs. Specifically, the luminosity at 1.5 hours after accramp is considered as the peak luminosity, and the average lifetime during the next 4 hours is taken as the luminosity lifetime. Likewise, the emittance growth rate is defined as the average growth rate during the same 4 hours.

The electron cloud, IBS, and beam-beam are the three most plausible factors that might cause beam emittance growth and also closely associated with the beam intensity. However, as shown in [3], at RHIC the electron cloud takes place at the beam injection and acceleration, and it is reduced rapidly to a minimum in early store. Therefore, the electron cloud is not a main cause of the emittance growth in store. The IBS is proportional to 3-D bunch density. At RHIC the correlation of the transverse emittance growth and the bunch density has not been observed in the proton runs 2005 and 2006. For instance, the bunch intensity in 2006 is 45% higher than that in 2005, but comparable emittance growth rate has been seen.

At RHIC, the emittance growth rates of colliding beams are always observed to be much higher than non-

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colliding beams. In Fig.1, a non-colliding beam is compared to a colliding beam. During 4 hours at 100 GeV, the bunch intensity and vertical emittance of the non-colliding beam (blue) remained almost constant until working point changes at 3.5 hours. In contrast, the rates of intensity reduction and emittance increase of the colliding beam (red) were almost constant.

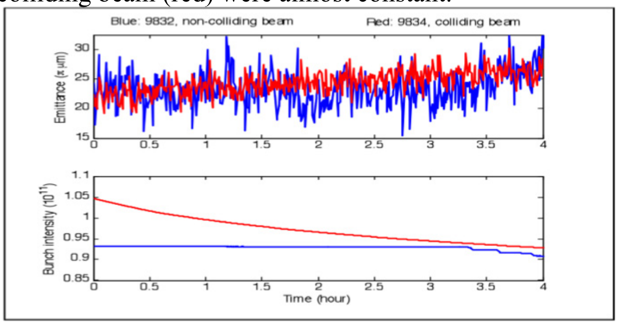

Figure 1: Yellow beam bunch intensity and the Yellow vertical emittance measured by the IPM of a non-colliding beam (blue) and a colliding beam (red), at the storage.

The average beam emittance growth rate $\Delta\varepsilon/\varepsilon$ is plotted versus the bunch intensity and beam-beam parameter in Fig. 2 for the 2005 and 2006 runs. It is observed that the emittance growth rate is not correlated with the bunch intensity, but somewhat correlated with the beam-beam parameters, despite the large difference between the bunch intensities in 2005 and 2006 runs.

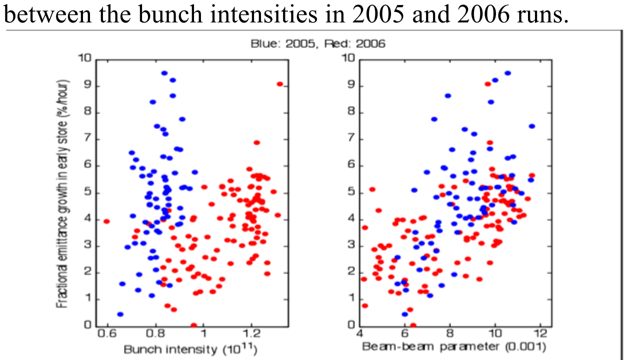

Figure 2: Emittance growth rate vs. bunch intensity and beam-beam parameters in 2005 (blue) and 2006 (red) run.

The luminosity lifetime, observed from the experimental coincident hadron collisions, is also well correlated to the beam-beam parameter for the 2005 and 2006 runs, as shown in Fig.3. It was about 28 hours for the beam-beam parameter of 0.004 or less, but reduced to 15 hours at the beam-beam parameter of 0.012.

The RHIC enhanced design goal calls for doubling the average luminosity in RHIC polarized proton runs. To double the peak luminosity, assuming constant beam emittance and the same number of IPs, the bunch intensity must be increased to 2×10^{11} protons [4]. The peak beam-beam parameter would reach 0.02. Without improvement in the beam-beam induced emittance growth, the luminosity lifetime might be reduced to about 7 hours. This would limit improvements to the average luminosity, and makes a better understanding of the beam-beam effect on the emittance growth essential.

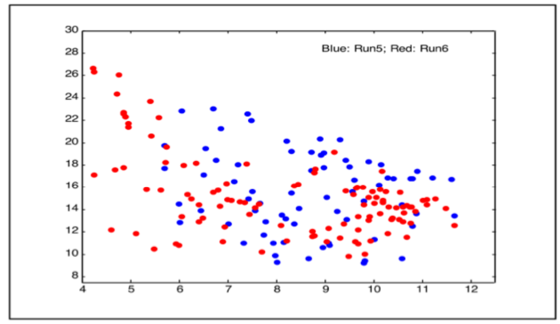

Figure 3: Luminosity lifetime, averaged during 4 hours in early storage, of 2005 run (blue) and 2006 run (red) as function of the beam-beam parameter.

SIMULATION OF BEAM EMITTANCE GROWTH IN RHIC

The parameters relevant to the simulation are derived from beam measurements during RHIC 2006 100GeV polarized proton operations. The important parameters and initial conditions used in this simulation study and the preliminary results were reported in reference [2]. In general, the accuracy and precision of the simulation results are dependent of the number of macro-particles and random number generator used for the simulation. In this study 10^3 to 10^7 macro-particles were tested and the results convergence was found to be at 10^4. Therefore, a Gaussian distribution of 10^4 macro-particles was used for the initial distribution. The results are averaged over all 10^4 particles and 10^5 turns.

A set of 12 simulations was performed with different beam-beam parameter, or tune shifts, ξ ranging from 0.000 to 0.018 with the same initial normalized emittance of 15πμm-rad. Fig. 4 shows the emittance evolution as derived from these simulations. The slopes of the emittance growth curves increase rapidly for $\xi > 0.012$.

The emittance growth rate versus beam-beam parameter obtained from the simulation is displayed in Fig. 5 along with the RHIC experimental data from Fig. 2. The green lines represent the mean value and the standard deviation of the simulated data. The black line is a linear fit to the simulation data. The simulation result is close to the average value of experimental data, but slightly higher than the lower limit observed in the RHIC operations.

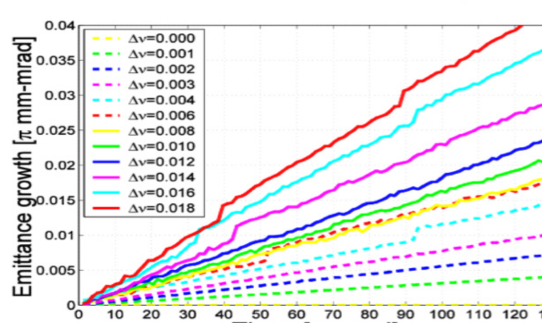

Figure 4: Emittance evolution of beams with different beam-beam parameter values, ξ, as function of time.

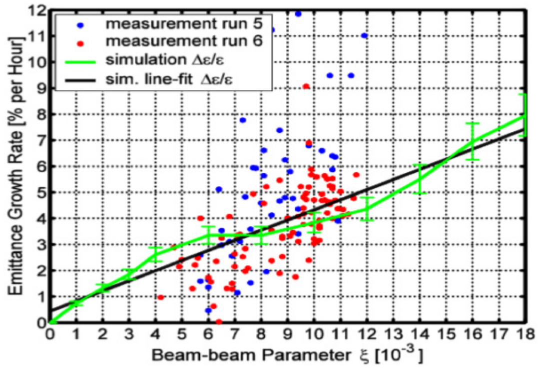

Figure 5: Simulated emittance growth rate and measured beam emittance growth (2005 and 2006 runs) versus beam-beam parameter.

The simulation tracks the emittance growth for only the initial 2.13 minutes after the beams are brought to collision. Therefore, the emittance growth rate in the simulation overestimates the observed data, which is averaged over 4 hours.

SIMULATION WITH SHORTER BUNCHES

Compared with other hadron colliders, such as the Tevatron [5,6], the SPS proton-antiproton collider [7,8], and HERA [9], the observed emittance growth during the beam collision at RHIC is the largest for comparable beam-beam parameters. During several RHIC runs, the working points for Blue and Yellow beams at store have been repeatedly adjusted, swapped, and fine-tuned. No systematic change of the emittance growth has been observed by the IPM in either horizontal or vertical directions. However, it is noticed that the RHIC proton bunch is the longest among the hadron colliders. The bunch lengths are 14ns in early store at RHIC, 6.8 ns at Tevatron, ~3 ns at SPS, and ~2.6 ns at HERA.

With the beam-beam interaction, incoherent betatron tune shift may develop which increases the bunch tails. Emittance growth may take place if the beam-beam force is strong enough to induce non-linear oscillations. This is similar to a proposed mechanism for electron cloud induced beam emittance growth [10], and longer bunches may be more vulnerable to this effect.

The RHIC upgrade plan calls for shorter bunches in the store, mainly due to the consideration of improving the experimental vertex and also to prevent particle leakage from the rf bucket [11]. There are two steps in the RHIC upgrade plan. The first is to use a 9 MHz rf system to match the beam injected from the AGS into the RHIC, followed by the existing 28 MHz system for store. The second step would use a 56 MHz superconducting cavity during the store. The RHIC proton bunch length will become 7.8 ns and 4 ns for the 9 MHz and 56 MHz plans, respectively. The 9 MHz rf system is being commissioned during the RHIC 2009 run.

A set of LIFETRAC simulations was performed with RMS bunch lengths ranging from 20 cm to 100 cm, i.e., the full bunch durations of 2.7 ns to 13.3 ns, respectively. The lattice and simulation parameters (see Reference [2]) are kept the same in order to make a direct comparison. The simulated emittance growth rate as a function of bunch length is shown by the blue curve in Fig. 6. In the range of RMS bunch length relevant to RHIC, the emittance growth rate as function of σ_{RMS} is obtained from polynomial curve fit: $\Delta\varepsilon/\varepsilon = 0.01324\ \sigma_{RMS}^3 - 0.0727\ \sigma_{RMS}^2 + 0.101\sigma_{RMS} - 0.003$, which is shown by the red curve. The simulation, shows that for the RMS bunch length < 80 cm, the emittance growth rate is reduced to 3.4% per hour for the 9MHz upgrade and to 2.1% per hour for the 56MHz upgrade, corresponding to 10% and 50% improvements from the current RHIC operation, respectively.

The simulation provides a plausible explanation of the large emittance growth rate observed at RHIC, compared with other hadron colliders. It also suggests smaller emittance growth rate for the current RHIC rf upgrade plans, which will result in shorter bunches at store.

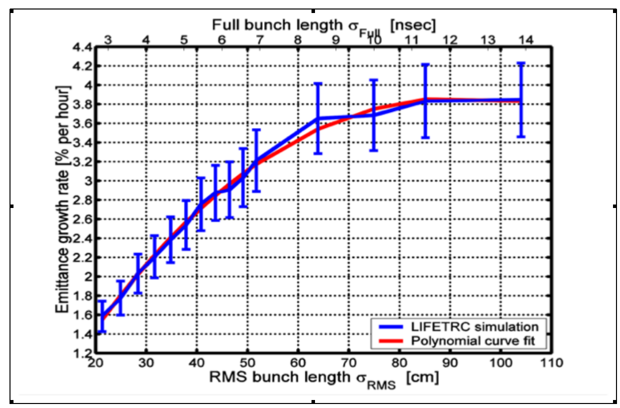

Figure 6: The emittance growth rate as a function of RMS bunch length (bottom scale) and as a function of full bunch length (top scale).

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