IBS AND POSSIBLE LUMINOSITY IMPROVEMENT FOR RHIC OPERATION BELOW TRANSITION ENERGY *

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Abstract

There is a strong interest in low-energy RHIC collisions in the energy range below present RHIC transition energy. These collisions will help to answer one of the key questions in the field of QCD about the existence and location of a critical point on the QCD phase diagram [1-4]. For such low-energy RHIC operation, particle losses from the RF bucket are of particular concern since the longitudinal beam size is comparable to the existing RF bucket at low energies. In this paper, we explore an Intra-beam Scattering (IBS) feature below transition energy that drives the transverse and longitudinal beam temperatures towards equilibrium to see whether we can minimize longitudinal diffusion due to IBS and predict some luminosity improvement for the low-energy RHIC project.

INTRODUCTION

There have been several short test runs during 2006-2008 RHIC operations to evaluate RHIC operational challenges for energies below present injection energy [5]. Beam lifetimes observed during the test runs were limited by machine nonlinearities. This performance limit can be improved with sufficient machine tuning. The next luminosity limitation comes from transverse and longitudinal IBS, and ultimately from the space-charge limit. Detailed discussion of limiting beam dynamics effects and possible luminosity improvement with electron cooling can be found in Refs. [6-8].

Operation below transition energy allows us to exploit an IBS feature that drives the transverse and longitudinal beam temperatures towards equilibrium. Simulation studies were performed with the goal of understanding whether we can use this feature of IBS to improve the luminosity of the RHIC collider below transition energy.

IBS BELOW TRANSITION ENERGY

The longitudinal bunch emittance injected into the AGS is about or less than 0.08 eV-s/nucleon (95%). However, it is increased significantly as a result of bunch merging and the energy ramp. Recently, it was shown that the emittance increase during merging can be controlled and kept to about 0.1 eV-s/n at the AGS injection energy. But emittance growth on the ramp remains, resulting in emittances of about 0.2 eV-s/n at AGS extraction energies in a range of γ=2-4 and about 0.3 eV-s/n for typical higher extraction energies [9].

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Table 1 lists the RF bucket acceptance for the present 28 MHz RF with maximum possible total gap voltage of 500 kV for the lowest energy points of interest. Only harmonic numbers which are divisible by 9 (which satisfy both of present constraints of experiment trigger and geometry of RHIC experiments [10]) are shown.

Table 1: 28 MHz RF (500 kV total gap voltage) bucket acceptance

γ	h	RF bucket acceptance, eV-s/nucleon
2.7	387	0.1
3.2	378	0.14
4.3	369	0.23

After injection into RHIC, longitudinal IBS leads to significant intensity loss due to particle losses from the RF bucket. Achieving AGS longitudinal emittances significantly smaller than the RHIC RF bucket acceptance does not help much because the longitudinal IBS only becomes stronger resulting in strong debunching (unless electron cooling in RHIC is provided [6, 7]). Table 2 shows how the longitudinal IBS rate would increase if one would inject bunches with smaller longitudinal momentum spread.

Table 2: IBS rates ($\tau_x^{-1} \equiv d\varepsilon_x/(\varepsilon_x dt)$, $\tau_z^{-1} \equiv d\sigma_p^2/(\sigma_p^2 dt)$) for different longitudinal rms momentum spread σ_p for 28 MHz RF with 500 kV total gap voltage, RF bucket acceptance 0.1 eV-s/nucleon, γ=2.7, bunch intensity N=1×10^9, transverse beam emittance of ε=15µm (95%, normalized).

$S_{95\%}$, eV-s/nucleon	σ_p	transverse IBS τ_x^{-1}, sec^{-1}	longitudinal IBS τ_z^{-1}, sec^{-1}
0.09	0.00045	0.007	0.006
0.07	0.0004	0.0065	0.014
0.04	0.0003	0.004	0.06

However, below transition energy, IBS drives the transverse and longitudinal beam temperatures towards equilibrium (in a smooth lattice approximation). This suggests that longitudinal heating can be slowed if the longitudinal beam temperature is larger than transverse, but at the expense of transverse heating. If there is enough RF voltage, one can increase the longitudinal beam temperature by shrinking the bunch length or perhaps inject the beam with larger longitudinal emittance provided that the RF bucket acceptance is sufficiently large. One can then redistribute IBS rates between the longitudinal and transverse degrees of freedom and minimize losses from the RF bucket due to the longitudinal IBS. Experimental study of such redistribution effect due to IBS below transition energy is found, for example, in Ref. [11].

Unfortunately, to produce a sufficiently large momentum spread with the 28 MHz RF requires more RF voltage than is presently available, in the assumption that transverse beam emittances will be close to typical values at RHIC injection energy. The maximum possible total RF gap voltage on two cavities is now 500 kV. Table 3 shows that 1 MV of 28 MHz RF would allow us to accommodate large incoming longitudinal emittances, up to 0.145 eV-s/nucleon for the lowest point of interest with γ=2.7, and provide sufficiently large longitudinal beam temperature. Alternatively, for a small longitudinal emittance of 0.1 eV-s/nucleon, an RF voltage of 1 MV would allow us to shrink the bunch length and increase rms momentum spread σ_p to 0.00058 which is close to the values needed to stop longitudinal IBS heating (Table 3).

Table 3: IBS rates for the 28 MHz RF with 1 MV total gap voltage, bucket acceptance 0.145 eV-s/nucleon, γ=2.7, bunch intensity $N=1\times10^9$ and transverse beam emittance ε=15µm (95%, normalized).

$S_{95\%}$, eV-s/nucleon	σ_p	transverse IBS τ_x^{-1}, sec^{-1}	longitudinal IBS τ_z^{-1}, sec^{-1}
0.11	0.0006	0.001	0
0.13	0.00065	0.009	-0.0015

The idea of employing IBS redistribution below transition energy to minimize longitudinal IBS is rather simple. But for RHIC applications we are interested in maximizing the luminosity. Here the bunch length growth, intensity loss due to debunching, and transverse emittance growth are all important. Therefore, it is essential to understand whether stopping longitudinal IBS at the expense of the transverse emittance growth improves luminosity. Beam dynamics simulations were performed with the BETACOOL code [12] for both the present 28 MHz RF and for a planned 56 MHz RF. Since the 28 MHz RF maximum available voltage is limited to 500 kV while simulations showed that we would need up to 1 MV, we only summarize results for the 56 MHz RF.

OPERATION WITH 56 MHZ FOR LOW ENERGIES

An upgrade of the RHIC storage RF system with a 56 MHz superconducting cavity is presently underway [13]. With 2.5 MV voltage this cavity will provide a large bucket acceptance and will significantly improve RHIC performance at top energy both for heavy ions and protons [14].

For low-energy operation we can find harmonic numbers which allow use of this SRF cavity at fixed RF frequency. Table 4 shows several energies available for a fixed RF frequency of 56.2989 MHz by choosing an appropriate RF harmonic. Only harmonics which are divisible by 9 are shown (for constraints see Ref. [10]).

Table 4: Harmonic numbers and corresponding energies with fixed RF frequency of 56.2989 MHz (with 2.5 MV RF voltage).

γ	h	RF bucket acceptance, eV-s/nucleon
6.4	729	0.34
4.6	738	0.2
3.8	747	0.14
3.3	756	0.12
3.0	765	0.1
2.7	774	0.08

The bunch length with the 56 MHz RF will be shorter than with the 28 MHz RF which will provide a larger momentum spread for the same longitudinal emittance. This is beneficial both for IBS redistribution (as discussed in the previous section) and useful luminosity within the detector vertex.

Two approaches are being considered to address long bunch length in the AGS [15]. The first is "quad pumping" technique with which coherent longitudinal oscillations are excited in the AGS, and the bunch is extracted to RHIC when the bunch length is at its minimum. Another approach is to inject first into the 28 MHz RF (bucket length 36 ns) and then adiabatically bring on the 56 MHz RF voltage to shorten the bunch length. In the latter case, only selected 56 MHz RF harmonics could be used which requires further consideration.

For injection in the 28 MHz RF with a bucket length of 36 ns, one would like to have longitudinal emittance below 0.14 eV-s/nucleon for γ <3.5 (see Table 5). On the other hand, it may be beneficial to have longitudinal emittances of 0.2 eV-s/nucleon or larger for γ > 4.3, to ensure small longitudinal IBS growth during accumulation process. To inject 56 bunches in both RHIC rings before adiabatically turning on the 56 MHz RF will take about 100 s. We therefore want the longitudinal IBS growth times to be significantly less than this to reduce debunching during accumulation.

Table 5 shows IBS growth rates for different longitudinal emittances of incoming bunches at several energies. Calculations of IBS rates were done with an assumption that the transverse emittance of the incoming bunch is 15µm (95%, normalized) at any energy. If the transverse emittance is larger at lower energy points, the ratio between the transverse and longitudinal beam temperatures will be different and IBS rates will need to be recalculated. Note that for the case of γ=6.4 (Table 5) an attempt to increase longitudinal emittance to reduce longitudinal IBS resulted in beam temperatures close to equilibrium. As a result, both the longitudinal and transverse IBS growth rates became very small. Such operational condition would be ideal. Unfortunately, significant debunching will occur in this case since the longitudinal emittance of 0.4 eV-s/n is already close to the RF bucket acceptance at this energy.

Table 5: Initial longitudinal τ_z^{-1} and transverse τ_x^{-1} IBS rates ($\tau_x^{-1} \equiv d\varepsilon_x/(\varepsilon_x dt)$, $\tau_z^{-1} \equiv d\sigma_p^2/(\sigma_p^2 dt)$) for different longitudinal emittance ($S_{95\%}$) for 28 MHz RF with 500 kV total gap voltage. Bunch intensity $N=1\times10^9$, transverse beam emittance ε=15μm (95%, normalized).

γ	h	$S_{95\%}$, eV-s/n	τ_x^{-1}, sec^{-1}	τ_z^{-1}, sec^{-1}
2.7	387	0.1	0.007	0.004
3.2	378	0.1	0.004	0.006
		0.14	0.0044	0.002
4.3	369	0.1	0.0015	0.013
		0.14	0.0018	0.005
		0.2	0.002	0.0016
6.4	363	0.1	0.0002	0.016
		0.2	0.0006	0.003
		0.4	0.0007	0.0006

LUMINOSITY PERFORMANCE

Figures 1-2 show a comparison between independent operation with the 28 MHz and 56 MHz RF for γ=6.3. For other energies and more details see Ref. [15]. Although small, some advantage in luminosity performance can be seen in Fig. 1. Figure 2 shows that one can gain about a factor of two in vertex luminosity since the bunch length is smaller for 56 MHz. Simulations shown in Figs. 1-2 do not include beam loss on transverse acceptance. For actual expected luminosity gain, an optimum scenario between the transverse and longitudinal IBS could be established for specific initial beam parameters, and simulations should be repeated including beam loss on the transverse acceptance. As discussed in the previous section, the most realistic scenario for operation seems to be simultaneous operation with both 28 and 56 MHz RF systems.

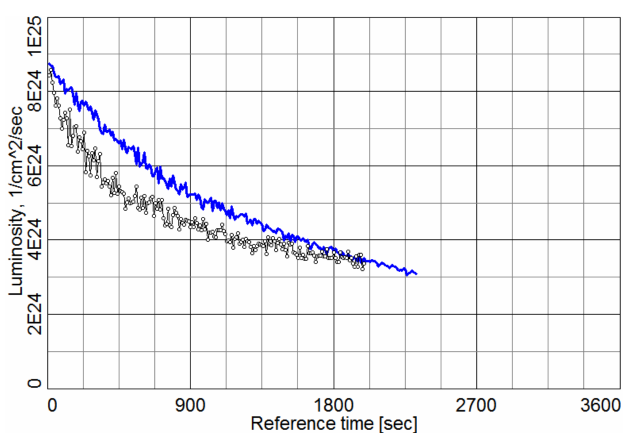

Figure 1: Simulation of full luminosity for 56 bunches γ=6.3 (β*=10m, ε=15μm, $N=1\times10^9$, $S_{95\%}$=0.2eV-s/n): 1) blue upper curve – 56 MHz RF (2.5 MV); 2) black lower curve – 28 MHz RF (0.5 MV).

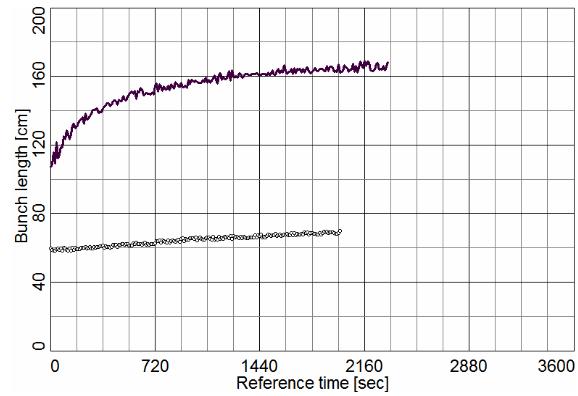

Figure 2: RMS bunch length at γ=6.3 (ε=15μm, $S_{95\%}$=0.2eV-s/n, $N=1\times10^9$): 1) upper curve – 28 MHz RF (0.5 MV gap voltage); 2) lower curve – 56 MHz RF (2.5 MV).

SUMMARY

IBS redistribution below transition energy was explored to understand possible benefits for low-energy RHIC operation. A proposed 56 MHz RF upgrade may provide the RF voltage needed to minimize longitudinal growth rates due to IBS.

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