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IBS FOR RHIC OPERATION BELOW TRANSITION ENERGY AND VARIOUS RF SYSTEMS

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Introduction

Following first successful runs in RHIC at low energies for physics (Beam Energy Scan I) there is a strong interest in further low-energy RHIC operation in the range of $\gamma=4-10$ but with higher luminosity (Beam Energy Scan II). An electron cooling was proposed to increase luminosity at these low energies [1-2]. Both transverse and longitudinal Intra-beam Scattering (IBS) can be counteracted with electron cooling. In addition, the phase-space density of the hadron beams can be further increased by providing stronger cooling. Unfortunately, the defining intensity limitation for low energies in RHIC is expected to be the space charge [3]. Experimental studies of the space-charge effects and beam lifetime in RHIC were reported in Refs. [4-5]. Additional limitations at low energies and their possible mitigations were discussed in Refs. [6-7].

In Ref. [8] it was suggested that better luminosity performance may be expected by using lower frequency RF system and longer bunches compared to the baseline 28 MHz RF, which is being used for RHIC operation with heavy ions. Recently, even lower frequency RF of 4.5 MHz was proposed for future low-energy RHIC operation [9].

Although low-frequency RF systems in RHIC (either 9 or 4.5 MHz) seem to address possible limitations of beam lifetime observed at low energies, the resulting ion beam temperatures in beam rest frame get further from an equilibrium which lead to a much stronger longitudinal IBS. This would put stronger requirement on electron cooling system under consideration. However, operation below transition energy allows us to exploit an IBS feature that drives the transverse and longitudinal beam temperatures towards equilibrium by minimizing the longitudinal diffusion rate using larger longitudinal beam emittance and larger RF voltage. Such studies were performed before to explore IBS redistribution at low energies for the 28 and 56 MHz RHIC RF systems [10]. This Note presents results of similar studies for newly proposed 4.5 and 9 MHz RF systems.

IBS redistribution below transition energy

28 MHz RF system

Presently low-energy RHIC operation employs 28 MHz RF system. The maximum possible total RF gap voltage on two cavities is now 500 kV (the use of 450 kV with beam operation was demonstrated). For previous low-energy RHIC operation, ion beams were produced using the Tandem injector resulting in a relatively small longitudinal emittances delivered to RHIC. The values of the longitudinal emittance values measured in 2010 are shown in Table 1.

γ	$S_{95\%}$, eV-s/nucleon
4.1	0.25
6.2	0.33
10	0.36

Table 1. Longitudinal emittance was measured at AGS extraction in 2010 by P. Harvey.

Recently, heavy ion operation switched from the Tandems to the EBIS injector. To achieve high bunch intensities comparable to those provided previously with the Tandems several RF merges were employed in the Booster and AGS in 2012 [11]. As a result, longitudinal emittance at RHIC injection was larger than in previous runs based on the Tandem with the longitudinal emittance of $S=0.6$ eV-s/n for the bunch intensity of $N=1.6 \cdot 10^9$. Some modest improvement in the longitudinal emittance can be expected in the future with a better execution of the RF merges [11]. For low-energy RHIC operation where we are limited by the space-charge effects, the highest bunch intensity is not required and some RF merges can be dropped which should result in smaller longitudinal emittance. Thus, we assume that for bunch intensities of about $N=0.8 \cdot 10^9$ and $0.4 \cdot 10^9$ we can expect the longitudinal emittance of around 0.3 and 0.15 eV-s/n, respectively.

To take into account space-charge limitation in RHIC, for discussion in this note, we use such bunch intensity that the incoherent space-charge tune spread ΔQ_{sc} does not exceed the value of $\Delta Q_{sc}=0.05$. A discussion of the space-charge limit in a collider and corresponding beam lifetime will be reported elsewhere. Table 2 shows IBS growth rates with present 28 MHz RF system for ion beam at $\gamma=4$ keeping the space-charge tune spread constant at $\Delta Q_{sc}=0.05$ by changing ion bunch intensity. One can see that longitudinal IBS growth rate strongly increases when momentum spread becomes smaller and beam temperatures get further from an equilibrium. More RF voltage can be applied which would result in larger momentum spread. However, shorter bunch length would require further decrease of bunch intensity to keep the space-charge tune spread constant thus reducing luminosity.

$S_{95\%}$, eV-s/nucleon	σ_p	σ_s , m	$N, \times 10^8$	transverse IBS τ_x^{-1} , sec ⁻¹	longitudinal IBS τ_z^{-1} , sec ⁻¹
0.3	0.00053	2.4	8	0.001	0.001
0.2	0.00044	2.0	7	0.00075	0.003
0.15	0.00037	1.7	6	0.0005	0.006

Table 2. IBS growth rates ($\tau_x^{-1}=d\epsilon_x/\epsilon_x dt$, $\tau_z^{-1}=d\sigma_p^2/\sigma_p^2 dt$) for different longitudinal momentum spread (beam temperature) for the 28 MHz RF with total gap voltage of 150 kV, $\gamma=4.1$ and transverse beam emittance of $\epsilon=15$ μm (95%, normalized).

In this Note, we use convention of 95% longitudinal emittance S defined as:

$$S_{95\%} = 6\pi \frac{mc^2}{c} (\beta\gamma) \sigma_p \sigma_z, \quad (1)$$

where m is the rest mass per nucleon, σ_z is rms bunch length and σ_p is rms momentum spread.

Small momentum spread and longitudinal heating due to IBS

Choosing lower frequency RF system and thus longer bunches will reduce space-charge tune spread value. This will allow to cool beam transversely which in turn should allow us to reduce beta-function at the interaction point resulting in higher luminosity [8]. In addition, transverse cooling will enable larger transverse acceptance which should provide better beam lifetime for the same space-charge tune spread value, as observed experimentally [4-5]. However, longer ion bunch will have smaller momentum spread and thus stronger longitudinal IBS growth rates.

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 stopped (at least initially) if the longitudinal beam temperature is close or larger than transverse.

If there is enough RF voltage, one can increase longitudinal beam temperature by shrinking the bunch length or perhaps inject the beam with larger longitudinal emittance (provided that RF bucket acceptance is sufficiently large). By doing so, one can redistribute IBS between the longitudinal and transverse degrees of freedom and minimize losses from the RF bucket due to the longitudinal IBS [10].

If longitudinal beam temperature is smaller than transverse, the longitudinal heating rate (diffusion coefficient) can be approximated by:

$$\frac{d\sigma_p^2}{dt} = \frac{r_i^2 c N_i \Lambda_c}{8\beta^3 \gamma^3 \varepsilon_{x,un}^{3/2} \langle \beta_x^{1/2} \rangle \sigma_s} \left(1 - \sqrt{\frac{\Delta_z}{\Delta_x}} \right), \quad (2)$$

where r_i is the classical radius of ion, N_i is number of ions in the bunch, Λ_c is the Coulomb logarithm, σ_s is the RMS bunch length, σ_p is the RMS momentum spread, $\beta_x \approx \beta_y$ is the average beta-function around the ring, $\varepsilon_x \approx \varepsilon_y$ is the transverse beam emittance (rms, un-normalized), and Δ_z and Δ_x are the longitudinal and transverse rms velocity spread of ion beam in beam rest frame, respectively. An expression in Eq. (2) roughly describes the longitudinal heating rate when $\Delta_z/\Delta_x < 1$. It is valid only for the case of smooth-lattice approximation and round beam and is similar to the relaxation coefficient for anisotropic plasma (in such a regime with the longitudinal heating one gets transverse cooling in the other plane). In the limit of very small longitudinal velocity spread when Δ_z/Δ_x goes to zero one recovers longitudinal diffusion coefficient typically used for the high-energy approximation [12]. More accurate expressions for such diffusion coefficient with anisotropic velocity distribution can be found, for example, in Refs. [13-15]. Here we use approximate scaling in Eq. (2) for illustrative purpose only to demonstrate why one gets very strong longitudinal IBS growth rate when beam temperatures deviate from equilibrium with decreasing longitudinal momentum spread. In the Tables in this Note we show results of numerical simulations of IBS growth rates with the BETACOOL code [16] using realistic RHIC lattice without approximations.

Below we summarise results of IBS redistribution study and required RF voltage for the proposed low-frequency RF systems of 9 and 4.5 MHz.

9 MHz RF system

For the 9 MHz RF, the longitudinal emittance $S=0.15$ eV-s/n and bunch intensity $N=5 \cdot 10^8$ resulting IBS growth rates are shown in Table 3. Small initial values of the space-charge tune spread indicate that cooling of transverse emittance by at least a factor of two should be possible, which will increase transverse acceptance and should improve beam lifetime.

RF Voltage, kV	σ_p	σ_s , m	ΔQ_{sc}	transverse IBS τ_x^{-1} , sec ⁻¹	longitudinal IBS τ_z^{-1} , sec ⁻¹
25	0.00018	3.6	0.02	-0.00036	0.023
50	0.00021	3.0	0.024	-0.00029	0.018
100	0.00026	2.5	0.03	-0.00011	0.011

Table 3. IBS rates ($\tau_x^{-1}=d\varepsilon_x/\varepsilon_x dt$, $\tau_z^{-1}=d\sigma_p^2/\sigma_p^2 dt$) for $S=0.15$ eV-s/n, bunch intensity $N=5e8$ for the 9 MHz RF, $\gamma=4.1$ and transverse beam emittance of $\varepsilon=15$ μm (95%, normalized).

One can see that even with 100 kV RF voltage longitudinal IBS growth times are very short which requires very fast cooling to counteract such IBS. Requirement on electron cooling can be

relaxed if we can operate with larger longitudinal emittance which also requires larger RF acceptance and thus RF voltage. This is shown in Table 4 for several longitudinal emittances.

S_{95} , eV-s/n	RF bucket acceptance A_s , eV-s/n	RF, kV	σ_p	σ_s , m	ΔQ_{sc}	transverse IBS τ_x^{-1} , sec $^{-1}$	longitudinal IBS τ_z^{-1} , sec $^{-1}$
0.3	0.5	100	0.00036	3.6	0.02	0.00017	0.0027
0.3	0.6	150	0.0004	3.24	0.022	0.00027	0.002
0.4	0.7	200	0.00049	3.5	0.021	0.0004	0.0008

Table 4. IBS rates ($\tau_x^{-1}=d\epsilon_x/\epsilon_x dt$, $\tau_z^{-1}=d\sigma_p^2/\sigma_p^2 dt$) for $S=0.15$ eV-s/n, bunch intensity $N=5e8$ for the 9 MHz RF, $\gamma=4.1$ and transverse beam emittance of $\epsilon=15$ μm (95%, normalized).

From Table 4 one can see that longitudinal IBS growth rate can be strongly minimized with large longitudinal emittance of $S=0.4$ eV-s/n which also requires large RF voltage of about 200 kV. For the RF voltage of 150 kV one can already achieve reasonably weak IBS growth rates. The IBS-driven luminosity lifetime is shown in Figs. 1-2 for parameters from Table 4. With electron cooling such IBS-driven luminosity lifetime could be strongly improved.

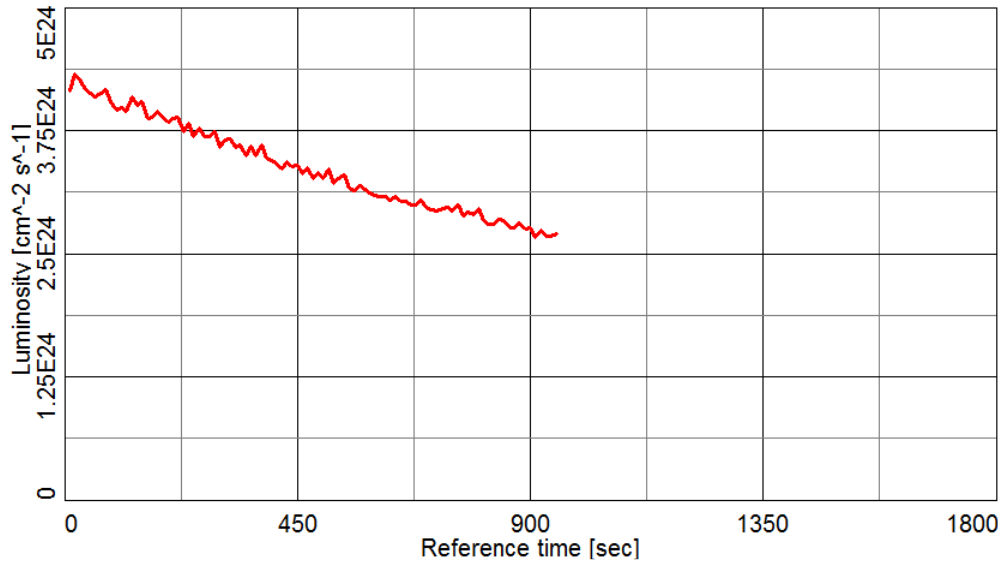


Figure 1. Luminosity lifetime (due to transverse and longitudinal IBS, including particle losses from the RF bucket) at $\gamma=4.1$, for initial beam parameters in Table 4 with the 200 kV of 9 MHz RF and longitudinal emittance $S=0.4$ eV-s/n.

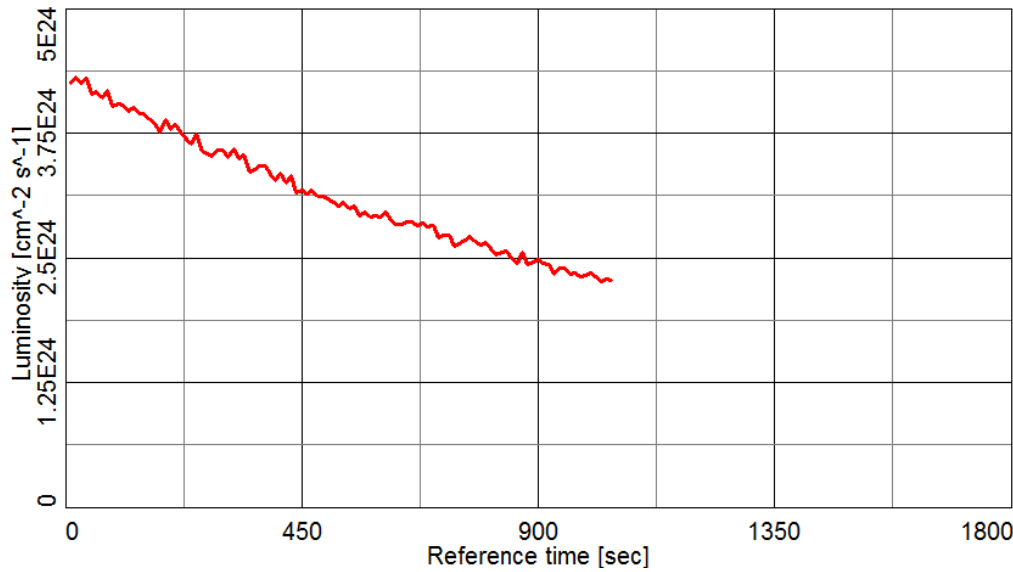


Figure 2. Luminosity lifetime (due to transverse and longitudinal IBS) at $\gamma=4.1$, for initial beam parameters in Table 4 with 150 kV of 9 MHz RF and $S=0.3$ eV-s/n.

It appears that about 150 kV of the RF voltage is required for the 9 MHz system to make longitudinal IBS growth rate reasonably small. For RF voltage of 100 kV, an acceptance of the RF bucket is not sufficient for making use of large longitudinal emittance to control IBS growth rates.

4.5 MHz RF system

Since 4.5 MHz RF system corresponds to a harmonic $h=60$ of the particle revolution frequency in RHIC, we can have only 60 colliding bunches in each ring. To provide the same initial luminosity as for the 9 MHz RF with 120 bunches, intensity per bunch should be increased for the 4.5 MHz RF. Below we use bunch intensity of $N=7.5 \cdot 10^8$ for the 4.5 MHz compared to $N=5 \cdot 10^8$ for the 9 MHz RF to compensate for the number of bunches and longer bunch length, compared to the 9 MHz RF.

S_{95} , eV-s/n	RF bucket acceptance A_s , eV-s/n	RF Voltage, kV	σ_p	σ_s , m	ΔQ_{sc}	transverse IBS τ_x^{-1} , sec ⁻¹	longitudinal IBS τ_z^{-1} , sec ⁻¹
0.15	0.46	10	0.00012	5.35	0.02	-0.0007	0.064
0.4	0.8	30	0.00026	6.6	0.016	-0.00006	0.006
0.4	1.0	50	0.00029	5.8	0.019	0.00001	0.005
0.5	1.3	80	0.00036	5.8	0.019	0.00016	0.0026

Table 5. IBS rates ($\tau_x^{-1}=d\epsilon_x/\epsilon_x dt$, $\tau_z^{-1}=d\sigma_p^2/\sigma_p^2 dt$) for bunch intensity of $N=7.5e8$ for 4.5 MHz RF, $\gamma=4.1$ and transverse beam emittance of $\epsilon=15$ μm (95%, normalized).

From Table 5 one can see that relatively large longitudinal emittance and RF voltage are required to minimize longitudinal IBS rates and achieve luminosity lifetime comparable to the one with the 9 MHz RF system. Figure 3 shows luminosity lifetime (mostly due to longitudinal IBS and losses from the RF bucket) for the longitudinal emittance of $S=0.5$ eV-s/n and RF voltage of 80 kV for the 4.5 MHz system.

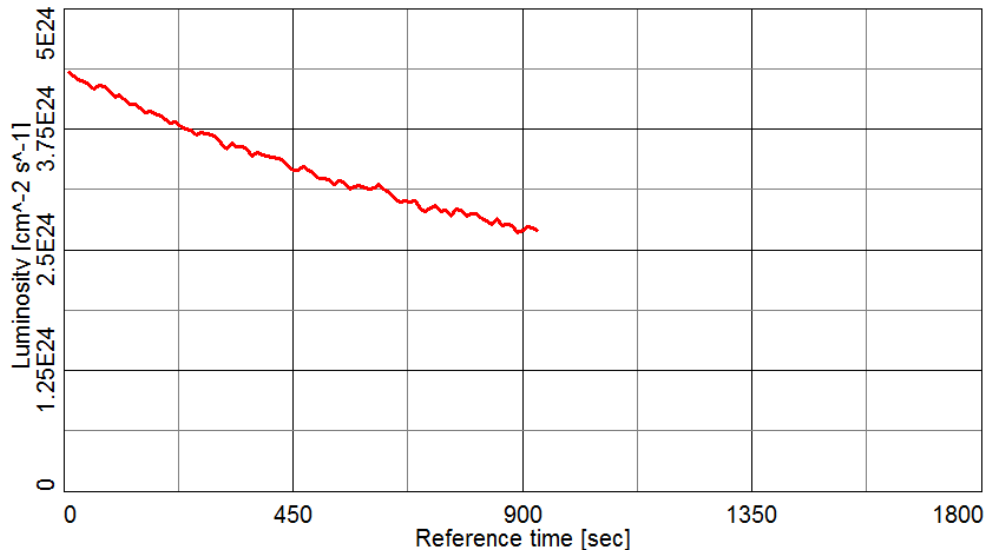


Figure 3. Luminosity lifetime (due to transverse and longitudinal IBS) at $\gamma=4.1$, for initial beam parameters in Table 5 with 80 kV RF voltage for the 4.5 MHz system and $S=0.5$ eV-s/n.

Summary

Low-frequency RF systems in RHIC (either 9 or 4.5 MHz) seem to offer possible remedies for some beam lifetime limitations observed at low energies in RHIC. However, for long ion bunches the resulting ion beam temperatures in beam rest frame get further from an equilibrium which leads to a strong longitudinal IBS. This can be mitigated to some extent by using larger longitudinal emittance and RF voltage.

In simulations, a reasonably good luminosity lifetime due to IBS and comparable luminosities were obtained by using large value of longitudinal emittance which in turn requires large RF voltage of about 150 kV and 80 kV for the 9 and 4.5 MHz RF, respectively. Any of these new RF systems with such voltages seem to be a good choice for RHIC operation with longer bunches and electron cooling.

Electron cooling should improve luminosity for these scenarios significantly by counteracting longitudinal IBS and by providing cooling of transverse emittance which in turn should allow us to reduce the beta-function at the interaction point.

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