BEAM DYNAMICS LIMITS FOR LOW-ENERGY RHIC OPERATION*

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Abstract

There is a strong interest in low-energy RHIC operations in the single-beam total energy range of 2.5-25 GeV/nucleon [1-3]. Collisions in this energy range, much of which is below nominal RHIC injection energy, 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 [4]. There have been several short test runs during 2006-2008 RHIC operations to evaluate RHIC operational challenges at these low energies [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 Intra-beam Scattering (IBS), and ultimately from the space-charge limit. Here we summarize dynamic effects limiting beam lifetime and possible improvement with electron cooling (for more details see Ref. [6]).

EXPECTED PERFORMANCE

We have carried out several short test runs at an intermediate energy point of interest, $\gamma=4.9$, to benchmark projections for future low-energy RHIC operations. During the first test run with gold ions in June 2007, the beam lifetime was very short and dominated by machine nonlinearities. These nonlinearities were intentionally increased to suppress head-tail instabilities. During the latest test run in March 2008, beam lifetime was improved using a new defocusing sextupole configuration. The store length was extended from 15 minutes in 2007 to 1 hour in 2008 [5-6].

Presently, the uncertainty in the expected useful luminosity at low energies is very large. For example, the reported rate of beam-beam counter coincidence signals was about 340Hz in the March 2008 test run. However the rate of useful physics events was estimated to be only about 1Hz.

Some improvements in the useful luminosity are straightforward. For example, doubling the number of bunches (to the nominal 108) will double the event rate. Since machine performance was limited by nonlinearities, we expect some improvement in the machine performance with additional tuning. We expect that an additional 3-fold increase would be possible at energies around $\gamma=4.9$. An estimate of run time needed for the proposed low-energy physics program is given in Ref. [6].

The first luminosity improvement will come from improved control of machine nonlinearities. Transverse and longitudinal IBS growth can later be compensated by electron cooling. Electron cooling of RHIC ion beams will increase the average integrated luminosity, and will provide longer stores for physics [7]. If a critical point signature is found, a larger statistical sample (on the order of 50M events) will be requested to characterize it. RHIC low-energy electron cooling will enable acquisition of this data in a reasonable period of time.

LUMINOSITY LIMITATIONS

Intra-beam Scattering

IBS is one of the major effects contributing to RHIC heavy ion luminosity degradation, driving bunch length and transverse beam emittance growth.

IBS-driven bunch length growth causes beam losses from the RF bucket. Figures 1-2 show some results of simulations of ion beam dynamics using the BETACOOL program [8], for low-energy beam parameters in Table 1.
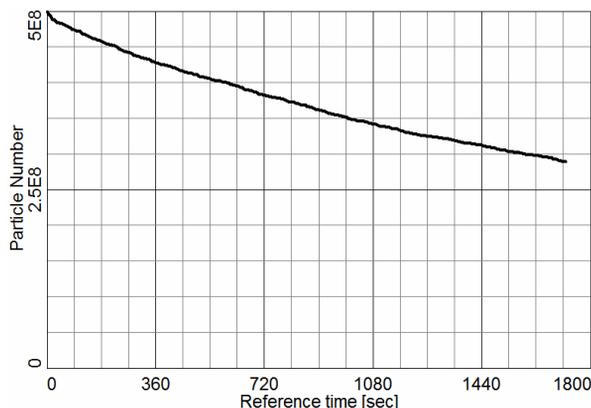

Figure 1. Simulated decrease of bunch intensity due to loss from RF bucket caused by longitudinal IBS at $\gamma=2.7$.
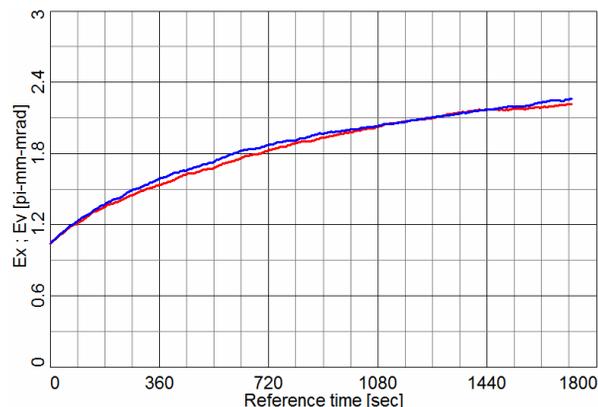

Figure 2. IBS-driven RMS un-normalized emittance growth at $\gamma=2.7$. Red curve - horizontal emittance. Blue curve - vertical emittance.

Beam Dynamics in High-Intensity Circular Machines

Table 1. Parameters of RHIC low-energy gold ion beam used in IBS simulations for Figs. 1-2.

γ	2.7
Number of ions per bunch, 10^9	0.5
Initial transverse 95% normalized emittance, mm-mrad	15
RMS momentum spread	0.0005
RF harmonic	387

Table 2. Incoherent space-charge tune shifts for different energy points.

γ	h	$\varepsilon_{95\%,n}$ μm	N_i, $\cdot 10^9$ (bunch intensity)	ΔQ_G	ΔQ_{fb}
2.7	387	15	0.5	0.12	0.07
3.4	375	15	1	0.15	0.08
4.4	369	15	1	0.1	0.05
4.7	366	15	1	0.07	0.04
6.6	360	15	1	0.04	0.02

Space charge tune shift

For a Gaussian transverse distribution, the maximum incoherent space-charge tune shift can be estimated using the following formula:

$$\Delta Q = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{F_c}{B_f},\qquad(1)$$

where F_c is a form factor which includes correction coefficients due to beam pipe image forces (the Laslett coefficients), N_i is the number of ions per bunch, ε is the un-normalized RMS emittance and B_f is the bunching factor (mean/peak line density). Here we assume $F_c = 1$.

For low-energy RHIC operations, the present RF bucket acceptance is relatively small due to limited RF voltage. The injected ion beam longitudinal emittance is comparable to or larger than the RF bucket acceptance. As a result, the RF bucket is completely filled after injection. For the estimate of the space-charge tune shift ΔQ_{fb} in this full bucket case, we assume a parabolic ion beam profile. Table 2 compares this to the space-charge tune shift ΔQ_G for a Gaussian longitudinal profile for different energies of interest.

When the space-charge tune shift becomes significant, the beam can overlap resonances, leading to significant beam losses and poor lifetime. For machines where beam spends only tens of milliseconds in the high space-charge regime, the tolerable space-charge tune shift can be as large as $\Delta Q=0.2$-0.5. However, for a long storage time, the acceptable tune shifts are much smaller. Beam lifetimes of a few minutes have been achieved with tune

shifts of about 0.1 [9, 10]. For RHIC, we are interested in much longer lifetimes, so we use a space-charge tune shift of 0.05-0.07 as a limit for our estimates.

Beam-beam and luminosity limits

If the beam-beam tune shift parameter ξ exceeds some threshold value, beam-beam-driven diffusion can significantly increase transverse emittance. An acceptable beam-beam parameter per single Interaction Point (IP) in hadron colliders is 0.005-0.01.

When the single-bunch luminosity is limited by the beam-beam effect it can be expressed in terms of ξ as:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^* C_r} \frac{2\gamma\beta^2}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi,\qquad(2)$$

where C_r is the ring circumference, β^* is the beta-function at the IP, σ_s is the RMS bunch length, and the factor $f(\sigma_s/\beta^*)$ describes the "hourglass effect". For low-energy RHIC operations we presently use $\beta^*=10m\gg\sigma_s$, so we neglect the hourglass effect by approximating $f(\sigma_s/\beta^*)=1$.

When the single-bunch luminosity is limited by the space-charge tune shift ΔQ, it can be expressed as:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^*} \frac{B_f}{C_r} \gamma^3\beta^2 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q.\qquad(3)$$

Figure 3 shows the limits for single bunch luminosity due to space charge with $\Delta Q = 0.05$ (red line) and beam-beam with $\xi = 0.01$ (blue dash line). For the plot we used RHIC beam parameters for Au ions with $\beta^*=10m$, $N_i=1\cdot 10^9$, and B_f of 28 MHz RF bucket completely filled with a parabolic density distribution. For parameters listed above, the maximum achievable single bunch luminosity is limited by space charge tune shift for $\gamma<11$, while for $\gamma>11$ the luminosity will be limited by beam-beam. In the energies where space charge dominates, luminosity and event rates scale with γ^3.
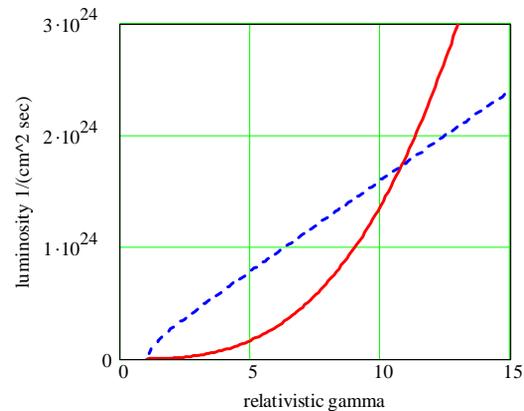

Figure 3. Single-bunch luminosity limitation 1) solid red line – by space-charge with $\Delta Q=0.05$ 2) blue dash line - by beam-beam parameter $\xi=0.01$ per IP.

PERFORMANCE WITH COOLING

If IBS is the only limitation, we could achieve small hadron beam emittances and bunch lengths with electron

cooling. Unfortunately, at the lowest energy points in the RHIC low-energy program, space charge is the defining limitation as shown in the previous section. Thus at the lowest energy points, the role of electron cooling is reduced to counteracting IBS and preventing emittance growth and intensity loss from the RF bucket. For higher energies, electron cooling would reduce emittance to the level allowable by the space-charge limit. This would allow us to reduce the beam size at the interaction points and provide larger luminosity.
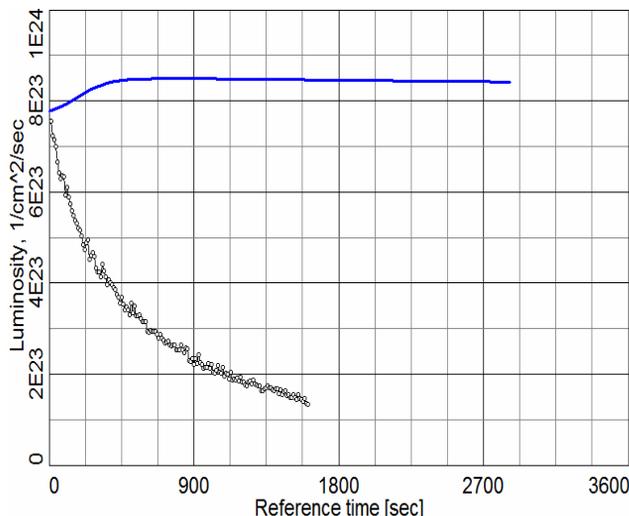

Figure 4. Simulation of luminosity with (blue line) and without (black dots) electron cooling at γ=2.7.

Figure 4 shows a simulation of luminosity evolution with and without electron cooling for γ=2.7. Simulations are done for ion bunch intensity N_i=0.5•10^9, initial 95% normalized emittance of 15 mm-mrad, RMS momentum spread σ_p=5•10^{-4}, RMS bunch length σ_s=1.9 m, and 56 bunches. Without cooling there is significant particle loss from the RF bucket and emittance increase due to transverse IBS. This results in a rapid luminosity drop limiting the store length and requiring machine refilling every 10-15 minutes. Electron cooling keeps transverse emittances constant and counteracts longitudinal IBS effects.

We can summarize [6] that electron cooling would offer long stores for physics and a 3-fold increase in average luminosity for low-energy points (γ=2.7-5). For higher energies ($\gamma > 5$), it would provide for about a 6-fold increase in average luminosity. Note that if hard space-charge limit is not reached, electron cooling can provide additional factors in luminosity improvement on top of the factor 3-6 quoted above [6].

Electron beam parameters needed for electron cooling in RHIC at these low energies (γ=2.7-7) are easily achievable with a DC electron beam cooler [6, 7]. We have also considered cooling scenarios with bunch electron beams. The main problem for bunched electron beam is transport of electron bunches without significant degradation of the electron beam emittance and energy

spread. Two approaches to an RF-gun-based cooler have been considered and found promising [6].

OTHER LUMINOSITY IMPROVEMENTS

An additional luminosity improvement is possible by operating RHIC in a "top-off" mode, with replacement of one to four RHIC bunches every AGS cycle. This approach requires some modification of RHIC injection and extraction kickers, however it appears feasible [11].

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. 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 a high RF voltage. Simulations show that additional luminosity improvements may be possible with high RF voltage from a 56 MHz superconducting RF cavity that is presently under development for RHIC [12].

ACKNOWLEDGMENTS

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