POTENTIAL FOR LUMINOSITY IMPROVEMENT FOR LOW-ENERGY RHIC OPERATION*

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Abstract

At the Brookhaven National Laboratory, a physics program, motivated by the search of the QCD phase transition critical point, requires operation of the Relativistic Heavy Ion Collider (RHIC) with heavy ions at very low beam energies corresponding to 2.5-20 GeV/n. Several physics runs were already successfully performed at these low energies. However, the luminosity is very low at lowest energies of interest (< 10 GeV/n) limited by the intra-beam scattering and space-charge, as well as by machine nonlinearities. At these low energies, electron cooling could be very effective in counteracting luminosity degradation due to the IBS, while it is less effective against other limitations. Overall potential luminosity improvement for low-energy RHIC operation from cooling is summarized for various energies, taking into account all these limitations as well as beam lifetime measured during the low-energy RHIC runs. We also explore a possibility of further luminosity improvement under the space-charge limitation.

INTRODUCTION

In Brookhaven National Laboratory (BNL), a physics program, motivated by the search of the QCD phase transition critical point, requires operation of RHIC with heavy ions at very low energies [1]. A detailed physics exploration in such a regime calls for a very high rate of collision events for energies corresponding to γ=2.7-10. However, at such low energies in RHIC the luminosity drops much faster with energy than a typical γ^2 scaling at high-energy operation, governed by the emittance and fixed machine aperture. As a result, achievable luminosity becomes extremely low for the lowest energy points of interest. Luminosity improvement for these lowest energies of RHIC operation is thus highly desired.

In a collider, the maximum achievable luminosity is typically limited by the beam-beam effects. For heavy ions significant luminosity degradation, driving bunch length and transverse emittance growth, comes from the intra-beam scattering (IBS). For low-energy RHIC such IBS growth can be counteracted with electron cooling [2].

If IBS were the only limitation, one could achieve a small hadron beam emittance and bunch length with the help of cooling, resulting in a dramatic luminosity increase. However, as a result of low energies, the direct space-charge force from the beam itself is expected to become the dominant limitation [3]. Also, the interplay of both beam-beam and space-charge effects may impose an additional limitation on the achievable lifetime [4].

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Operation of RHIC for Low-Energy physics program started in 2010 which allowed us to explore various limiting factors experimentally [5] and produce projections for future luminosity improvement.

LUMINOSITY LIMITATIONS AT LOW ENERGY

In a collider, when maximum luminosity is limited by beam-beam effects it can be expressed through the beam-beam parameter ξ (maximum tune shift for zero-amplitude particles):

$$\xi = \frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma\varepsilon} \frac{1+\beta^2}{2} \qquad (1)$$

as

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^* C_r} \frac{2\gamma\beta^3}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi, \qquad (2)$$

where β^* is the beta function at the interaction point (IP), r_p is the proton classical radius, N_i is the number of ions per bunch, A and Z are the ion atomic and charge numbers, γ, β are relativistic factors, ε is the un-normalized rms emittance, σ_s is the rms bunch length, C_r is the ring circumference, and the "hour-glass" factor $f(\sigma_s/\beta^*)$ is defined as:

$$f\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)du}{\left[1+\left(\frac{u\sigma_s}{\beta^*}\right)^2\right]}. \qquad (3)$$

If luminosity is limited by the space-charge tune shift value ΔQ_{sc}, it can be expressed as:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^*} \frac{\sqrt{2\pi}\sigma_s}{C_r^{\,2}} \gamma^3\beta^3 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q_{sc}, \qquad (4)$$

where no transverse acceptance limitation was taken into account. For a Gaussian transverse distribution, the maximum incoherent space-charge tune shift can be estimated as:

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{C_r}{\sqrt{2\pi}\sigma_s}, \qquad (5)$$

where we assumed round beam transversely and Gaussian longitudinal profile.

When in addition to the space charge there is also a limitation from the transverse acceptance (which is the case for RHIC at lowest energies of interest), even stronger drop in luminosity with energy could be expected [6]:

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$$L = 8\pi^2 \left(\frac{A}{Z^2 r_p} \right)^2 \frac{c\varepsilon}{\beta^*} \frac{\sigma_s^2}{C_r^3} \gamma^6 \beta^5 f\left(\frac{\sigma_s}{\beta^*} \right) \Delta Q_{sc}^2 . \quad (6)$$

The ratio of the space-charge to beam-beam tune spread is given by

$$\frac{\Delta Q_{sc}}{\xi} = \frac{1}{\gamma^2} \frac{C_r}{\sqrt{2\pi}\sigma_s} \frac{2}{1+\beta^2} \quad (7)$$

and is plotted in Fig. 1 for a typical rms length of ion bunches in RHIC with the 28 MHz RF at low energies (σ_s=1-2 m). One can see that the space-charge spread dominates for energies of the most interest for the low-energy RHIC physics program.

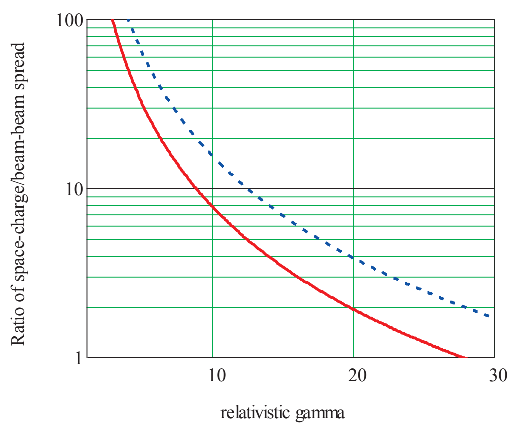

Figure 1: Ratio of the space-charge tune spread to beam-beam spread at low energies in RHIC for rms bunch length 2 m (red) and 1 m (blue, upper dash line).

SPACE-CHARGE LIMIT IN A COLLIDER

From the Equations (4)-(6), one can see that maximum achievable luminosity is limited by the value of the space-charge tune spread. Contrary to the low-energy high-intensity circular machine where this value is associated with a collective instability of the beam due to the lowest order resonances and is thus referred to as the space-charge limit (see Refs. [7-8], for example), in a collider we are interested in a long beam lifetime which sets much smaller limit on this value. In addition, interplay with the beam-beam resonances may become important and should be taken into account as well [4].

A particle within the beam can experience amplitude growth and be lost if its tunes get inside the stopband of the imperfection resonance. In general, since the growth rate associated with the resonance depends on the tune spread within the beam, the strength of the resonance and its order, one can accommodate smaller tune spread when interested in longer beam lifetime. For example, without taking into account amplitude dependent space-charge detuning and possible resonance correction, if one is interested only in tens of msec of beam lifetime then only lowest order resonances need to be avoided, which allows to achieve the space-charge tune spread of ΔQ_{sc} =0.2-0.5. Beam lifetimes in access of a few minutes have been achieved with the tune spread of about 0.1 [9]. In LEAR, it was possible to accommodate the space-charge tune shifts of about 0.1 with a proper choice of the working point and with the help of electron cooling [10]. However for RHIC, we are interested in the beam lifetimes much longer than just a few minutes. As a result, for the present projection of luminosity improvement we limit the tune shift value to only ΔQ_{sc} = 0.05, based on our experience at RHIC.

RHIC EXPERIENCE

First low-energy RHIC runs for physics were successfully performed in 2010 at γ=6.1 and γ=4.1 and in 2011 at γ=10.5. In addition, attempts were made to operate RHIC at such low energy as γ=2.7.

In the discussion which follows we rely on the values of emittance measured with the ionization profile monitor [5]. The initial space-charge tune shift values during operation at γ=4.1 could have been close to 0.1. The short beam lifetime was attributed to a combination of several effects [5, 11]. For slightly higher energy of γ=6.1 significantly better lifetime was measured for comparable space-charge tune shifts. However, we did not observe beam lifetime better than half an hour for the space-charge tune spread of 0.05 or larger, compared to the beam lifetimes of several hours measured for the tune spreads in the range of 0.02-0.035.

In addition, significant effects on the beam lifetime were observed when beams were put into collisions. For the space-charge tune spread larger than 0.05 it appeared difficult to find sufficient space free from dangerous resonances on the tune diagram to avoid effects of beam-beam on the lifetime. When the space-charge tune spread is modest (0.03-05) and beam-beam parameter is much smaller than the space-charge tune spread, one may expect to find the working point where effects of beam-beam are minimized. Such an experiment with heavy ions was performed in RHIC in 2011 with the space-charge tune spreads of 0.02-0.035 by moving the working point close to an integer. Almost no effect on beam lifetime was observed after beams were put into collisions.

PERFORMANCE EXPECTED WITH COOLING

Electron cooling was proposed to increase the luminosity of RHIC operation for heavy ion beam energies below 10 GeV/nucleon. The role of electron cooling for the lowest energy points is to counteract IBS: this prevents transverse emittance growth and intensity loss from the RF bucket due to the longitudinal IBS. As the energy is increased, the space-charge effect on the hadron beam becomes smaller which permits cooling of the transverse or longitudinal emittances of the hadron beams as well, allowing in turn to reduce the β* [2].

In RHIC operation at γ=6.1, the dominant limitation was consistent with the IBS, so that applying electron cooling for this energy would compensate both transverse and longitudinal emittance growth, minimize beam losses from the RF bucket and on the transverse acceptance, and significantly increase the integrated luminosity. However, during RHIC operation at γ=4.1, measured fast time component of the beam lifetime decay was much shorter than expected from the IBS and was attributed to other effects [5, 11]. As a result, beam lifetime at γ=4.1 and below has to be significantly improved first in order to expect substantial luminosity gains from electron cooling.

Since space charge prevents cooling of beam emittance or bunch length at lowest energies, an approach of operation with longer bunch length was recently explored [12]. The bunch length was increased by using the 9 MHz RF system instead of the 28 MHz RF, which would allow us to cool transverse emittance by the same amount the bunch length was increased (keeping the space-charge tune shift constant), allowing to reduce the β^* by having smaller beam size in the triplets. This resulted in an additional factor in luminosity improvement on top of the factors reported earlier [13].

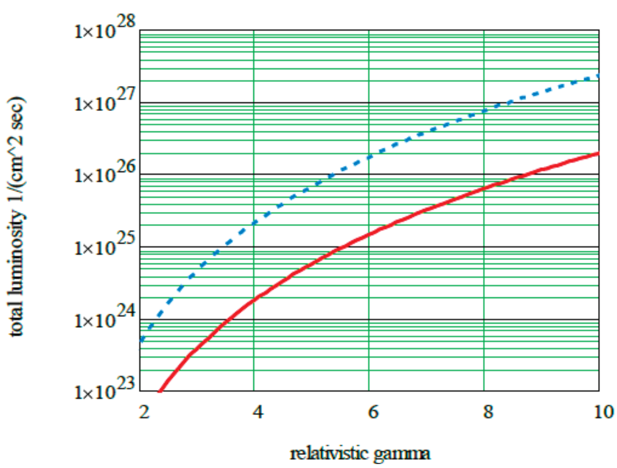

Figure 2: Projection of average total luminosity (without vertex cut) for 111 bunches of Au ions in RHIC for the space-charge tune spread of ΔQ_{sc}=0.05: 1) blue dash upper curve - with electron cooling and long bunches (9 MHz RF); 2) red solid lower curve – without cooling and nominal bunch length (28 MHz RF).

Overall expected luminosity improvement as a function of energy is shown in Fig. 2, where we assumed that the maximum luminosity with cooling can be kept constant. In reality, some luminosity degradation is expected and careful compensation of ion losses on recombination as well as optimization between cooling and beam lifetime is required [13]. The maximum luminosity without cooling was divided by a factor of 3 to account for luminosity lifetime due to the IBS and time between refills. One can see that about 10-fold improvement from cooling may be expected for the total luminosity without the vertex cut. However, for RHIC application, the question of useful luminosity within limited detector vertex cut becomes of most interest. The question of detector vertex cut was investigated in Ref. [12]. It was found that, although improvement factor is reduced when the vertex cut is decreased, the luminosity gain by going to longer bunch could be is still significant.

We note that the use of longer bunches can help to boost luminosity even without electron cooling. In such a case, having longer bunch allows us to put higher intensity per bunch which can boost the maximum luminosity dramatically. Unfortunately, without the help of cooling, an increased bunch intensity results in very large IBS growth rates with the fast beam losses from the RF bucket and on the transverse acceptance. As a result, luminosity lifetime becomes extremely short so that such approach requires also very short physics stores. Simulations of various approaches, including the case without cooling, were performed, and results for the luminosity lifetime can be found in Ref. [12].

SUMMARY

Low-energy RHIC physics program would greatly benefit from luminosity increase at low energies. Here we discussed beam dynamics limits based on experience with the RHIC operation, and a possible improvement from electron cooling, including operation with longer bunches at the space-charge limit in a collider.

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