BNL-94090-2010-CP

Interplay of space-charge and beam-beam effects in a collider

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Presented at the 46tth ICFA Advanced Beam Dynamics Workshop
Morschach, Switzerland
September 27 – October 1, 2010

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
DOE Office of Science

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INTERPLAY OF SPACE-CHARGE AND BEAM-BEAM EFFECTS IN A COLLIDER *

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Abstract

Operation of a collider at low energy or use of cooling techniques to increase beam density may result in luminosity limitation due to the space-charge effects. Understanding of such limitation became important for Low-Energy RHIC physics program with heavy ions at the center of mass energies of 5-20 GeV/nucleon. For a collider, we are interested in a long beam lifetime, which limits the allowable space-charge tune shift. An additional complication comes from the fact that ion beams are colliding, which requires careful consideration of the interplay of direct space-charge and beam-beam effects. This paper summarizes our initial observations during experimental studies in RHIC at low energies.

INTRODUCTION

Design of several projects which envision hadron colliders operating at low energies such as NICA at JINR [1] and Electron-Nucleon Collider at FAIR [2] is under way. In Brookhaven National Laboratory (BNL), 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 energies corresponding to γ=2.7-10 [3].

In a collider the maximum achievable luminosity is typically limited by beam-beam effects. For heavy ions significant luminosity degradation, driving bunch length and transverse emittance growth, comes from Intrabeam Scattering (IBS). For Low-Energy RHIC such IBS growth can be effectively counteracted with electron cooling [4]. 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, direct space-charge force from the beam itself is expected to become the dominant limitation [5]. In fact, similar limitations may become important even in future high-energy electron-ion colliders when strong cooling is employed to boost the luminosity [6, 7].

Also, the interplay of both beam-beam and space-charge effects may impose an additional limitation on the achievable luminosity lifetime. Thus, understanding at what values of space-charge tune shift one can operate in the presence of beam-beam effects in a collider is of great interest for all of the above projects.

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Operation of RHIC for Low-Energy physics program started in 2010 which allowed us to have a first look at the combined impact of beam-beam and space-charge effects on beam lifetime experimentally.

LUMINOSITY LIMITATIONS

Space charge

In general, the space-charge force can change the oscillation frequencies of individual particles (incoherent effect) as well as frequencies of collective beam oscillations. This can lead to rather complex phenomena of space-charge driven resonances, as well as complicates response to the resonances driven by other mechanisms. These effects are mostly of concern for space-charge dominated beam transport and high-intensity storage rings operated close to the space-charge limit associated with low-order machine resonances. Although some of the effects may become important for long beam lifetime in a collider. For discussion of these effects see, for example, Refs. [8-10] and references therein.

A convenient figure of merit for direct space charge effects in circular accelerator is the incoherent direct space-charge tune shift. For a Gaussian transverse distribution, the maximum incoherent space-charge tune shift can be estimated using the following formula:

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

where F_c is a form factor which includes correction coefficients due to beam pipe image forces (the Laslett coefficients), r_p is the proton classical radius, A and Z are the atomic mass and charge numbers, 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.

When the space-charge tune shift becomes significant, the beam can overlap resonances, leading to large beam losses and poor beam lifetime. For machines where the beam spends only tens of milliseconds in the high space-charge regime, the tolerable space-charge tune shift can be as large as ΔQ_{sc}=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 [11].

Beam-beam

Each time the beams cross each other, the particles in one beam feel the electric and magnetic forces due to the particles of the other beam. For a round beam, the linear incoherent beam-beam tune shift for hadrons is:

$$\xi = -\frac{Z^2 r_p}{A}\frac{N_i}{4\pi\beta^2\gamma\varepsilon}\frac{1+\beta^2}{2} \quad . \tag{2}$$

Here we assumed colliding beams moving with the same velocity. The positive sign of β^2 corresponds to the case of the test particles and the bunch moving in opposite directions.

The periodicity of the beam-beam interaction and the fact that beam-beam force has a nonlinear dependence on the particle amplitude causes two important effects: an excitation of the nonlinear resonances and a tune dependence on particles amplitude. As a result, one has to consider the full tune spread within the beam similar to the tune spread due to direct space charge. The beam-beam interactions are very complex phenomena and, similar to direct space charge, involve both incoherent and coherent effects.

If the beam-beam tune shift parameter ξ exceeds some threshold value, beam-beam-driven diffusion can significantly increase the transverse emittance. In hadron colliders, the total achieved tune spread due to beam-beam interactions is much smaller than in electron machines, which is believed to be due to a negligible effect of strong damping mechanism through synchrotron radiation which counteracts beam-beam diffusion in electron machines. The largest total tune spread due to several beam-beam interactions per turn which was achieved in Tevatron is about 0.03.

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

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

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”.

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

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

For RHIC parameters, the maximum achievable luminosity is expected to be limited by space charge tune shift for energies corresponding to $\gamma < 11$ and by beam-beam for higher energies [5]. For low energies where space charge dominates, luminosity and event rates scale with γ^3, without taking into account limitation due to the transverse acceptance.

A mostly unexplored effect at this moment is the interplay of direct space-charge and beam-beam effects, which takes place when beams with significant space-charge tune spread collide. In such a case, in its most simple manifestation beam-beam can excite resonances which will be crossed as a result of space-charge tune spread. We started to explore these effects in dedicated Accelerator Physics Experiments (APEX) and during 2010 RHIC physics Run at low energies which are briefly summarized in next section.

RHIC EXPERIENCE

Experiments with protons

An experimental investigation of the interplay of beam-beam and space-charge effects in RHIC started with APEX experiments in May 2009 using protons beams at γ=25. In these experiments the beam-beam parameter per interaction was up to ξ=0.01 (with a maximum of two interaction points) and a space-charge tune spread up to ΔQ_{sc}=0.03 (either horizontal or vertical).

For discussions in this paper both beam-beam and space-charge tune shift values are calculated using the simple formulas in Eq. (1)-(2), with bunch intensity and bunch length taken from the wall current monitor measurements while values of transverse emittance are taken from the ionization profile monitor (IPM) measurements. Although IPM records values of both horizontal and vertical emittance, as well as emittances of bunches in one collider ring could be different from the other, throughout this paper we assume that horizontal and vertical emittances are approximately the same (which was true for most of the measurements), unless specified otherwise.

Figure 1 shows time evolution of the vertical emittance of bunches in the Yellow and Blue RHIC rings before and after beams were put into collisions. Rapid peeling of large amplitude particles right after the beams were put into collisions was observed, which was attributed to the excitation of beam-beam resonances. Resulting reduction of beam intensity is shown in Fig. 2.

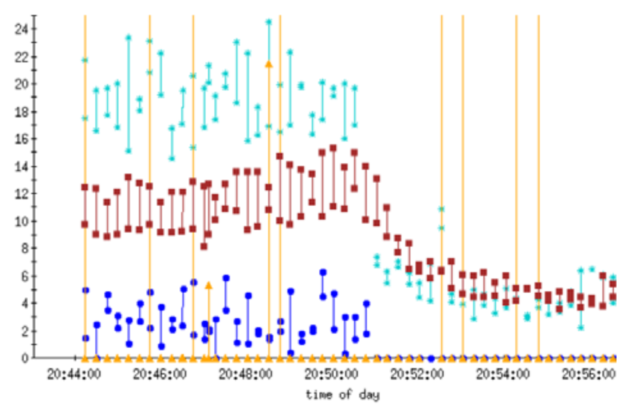

Figure 1: Time evolution of beam emittance. Vertical axis - emittance values (95% normalized, mm mrad); horizontal axis – time. Brown rectangles and light blue star symbols show emittances in separate collider rings.

Fortunately, for such rather modest space-charge tune spread it was possible to find a working point in the machine where the effect of beam-beam resonances was minimized [12]. An example of a beam lifetime measurement in a subsequent APEX study in June 2009 with a better working point is shown in Fig. 3. Although the effect of beam-beam on lifetime was still observed, the dramatic situation shown in Figs. 1-2 was avoided.

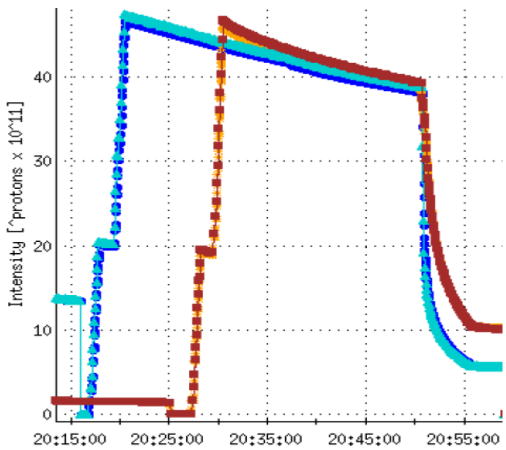

Figure 2: Measurements of total beam intensity loss corresponding to Fig.1 ($\Delta Q_{sc,y}$=0.03, total ξ=0.01).

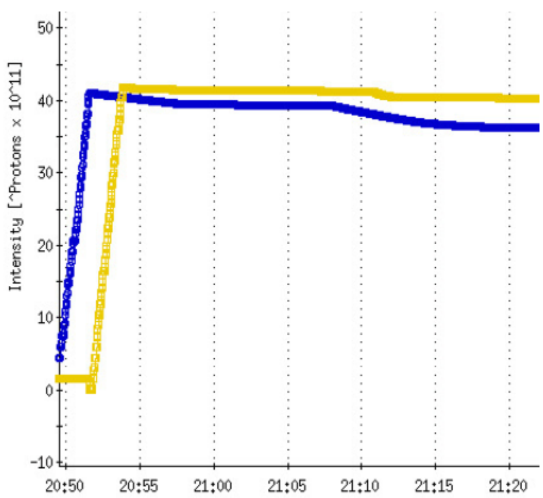

Figure 3: Beam intensity loss during June 2009 RHIC APEX for proton beams for a working point where strong beam-beam resonances were avoided ($\Delta Q_{sc,y}$=0.02, total for two IP's ξ=0.014).

Although of general interest, the regime of large and comparable space-charge and beam-beam tune spread which we had with protons at γ=25 is not directly relevant for Low-Energy RHIC program. For this regime of interest dominant limitation comes from the space charge due to low energies. Such regime was studied with Au ions in 2010.

Experiments with Au ions

In 2010 experimental studies continued during RHIC operation with Au ion beams at low energies γ=4-10. Since due to very low energies the space-charge tune spread was much larger than the beam-beam parameter, it was expected that beam-beam effects should be relatively small, and one should be able to accommodate relatively large space-charge tune spreads.

In March 2010, APEX experiments were done at typical injection energy for heavy ions at γ=10 with a space-charge tune shift of about ΔQ_{sc}=0.03. Before beams were put into collisions the beam lifetime was 1600-2000s, which could be further improved with additional machine tuning. In the past, during dedicated measurement of IBS growth rates in RHIC, beam lifetime of more than 2 hours was measured for comparable space-charge tune shifts of 0.02-0.03.

When beams were put into collisions the lifetime of individual bunches was affected despite the fact that beam-beam tune shift was rather small ξ=0.002. Our attempts to produce beams with larger space-charge tune shifts at this energy by injecting bunches with smaller bunch length were unsuccessful due to insufficient RF voltage in RHIC needed for the longitudinal matching. As a result, the regime with higher space charge was studied in the experiments which followed at lower energy.

For larger space-charge tune spread it appeared more difficult to find sufficient space free from dangerous resonances on the tune diagram to achieve long beam lifetime even without beam-beam. The impact of beam-beam on the beam lifetime made the situation significantly worse.

Low-energy RHIC operation in May-June 2010 at γ=6.1 and γ=4.1 provided measurements of beam lifetime with higher space-charge tune shifts, different transverse acceptance limitation by collimators, different synchrotron tunes and different values of RF voltage. All these effects are important to understand beam lifetime in RHIC at low energies. Below we present only an overall summary of some typical observations and conditions which led to measured beam lifetime rather than trying to provide detailed description of each individual experiment.

Table 1 shows calculated space-charge tune shifts at the start of the measurement and the corresponding beam lifetime when beams were not colliding. Other effects which are different for different energies are indicated under comments. Also, values of the synchrotron tune Q_s are provided for the lowest energies since they become large and could be important for understanding of beam lifetime due to the mechanisms related to synchrotron modulation. Generally, for the calculation of tune shift values we assume equal horizontal and vertical emittances unless values measured with IPM were significantly different.

Table 1: Beam lifetime for low-energy gold ion beam for different space-charge tune shifts without collisions.

ΔQ_{sc} (x,y)	τ [s]	γ	Comments
0.03	2000	10	5σ acceptance
0.05, 0.04	1600	6.1	3σ acceptance
0.09, 0.06	700	6.1	3σ acceptance, Q_s=0.006
0.1	70	4.1	2.2σ acceptance, Q_s=0.013

Beam lifetime values reported in Tables 1- 4 are the result of fitting the measured intensity decay for individual bunches. In many cases, especially for beams under collisions, intensity is better fitted with two time constants: fast and slow. In such a case, only the fast component of time decay constant is reported in the Tables. Detailed discussion of fitting results requires a full description of the settings of each individual measurement, which is outside the scope of present paper and will be discussed elsewhere.

Table 2 shows the calculated space-charge tune shifts and corresponding beam lifetime after beams were put into collisions. We should note that the effect of beam-beam was different for the bunches which were injected first in one of the collider's rings compared to the bunches which were injected later in the other collider ring. Bunches in the ring which were injected first suffered a stronger beam-beam effect which is consistent with typical observation for beams colliding with unequal emittances. In this case, by the time beams were injected in the second collider ring and put into collision, the emittance of the beam in the first ring had already grown.

Table 2: Beam lifetime for low-energy gold ion beam for different space-charge tune shifts with collisions.

ΔQ_{sc}	τ [s]	γ	Comments
0.03	600	10	5σ acceptance
0.05	400	6.1	3σ acceptance
0.1	260	6.1	3σ acceptance, Q_s=0.006
0.1	70	4.1	2.2σ acceptance, Q_s=0.013

Figure 4 and Table 1 show that without collisions beam lifetime of individual bunches at γ=6.1 was pretty good. Even for the space-charge tune shifts close to 0.1 (high-intensity bunches) the lifetime was about 700 sec. On the other hand, for the same space-charge tune shifts of about 0.1 initial beam lifetime without collisions was much worse at γ=4.1 compared γ=6.1, as shown in Fig. 5.

Significant limitation of dynamic aperture at γ=4.1 was expected due to large measured sextupole component in dipole magnets when they operate at low currents needed for this energy [13]. As a result, sextupole correctors were used to improve the beam lifetime. At the same time it was found that the use of octupoles to compensate the amplitude-dependent tune spread is essential as well. However, measured values of sextupole errors in the dipoles at the slightly higher energy of γ=6.1 are approximately the same, and thus similar limitation in the dynamic aperture could be expected. What was significantly different at these two low energies was the synchrotron tune Q_s, which leads to tune modulation with nonzero chromaticity, and can contribute to the resonance trapping mechanism and beam loss, for example.

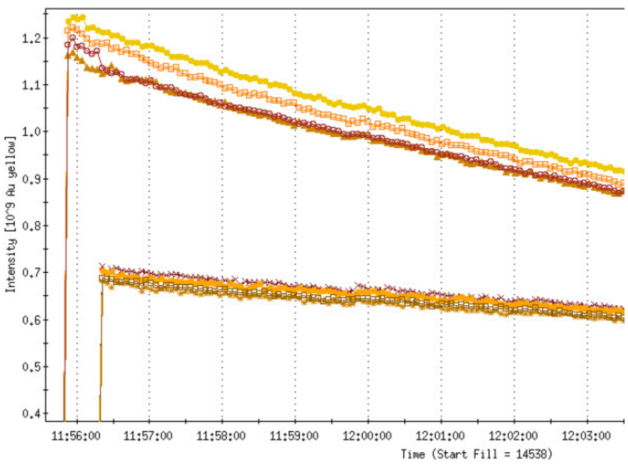

Figure 4: Lifetime of individual bunches with different intensities at γ=6.1 without collisions.

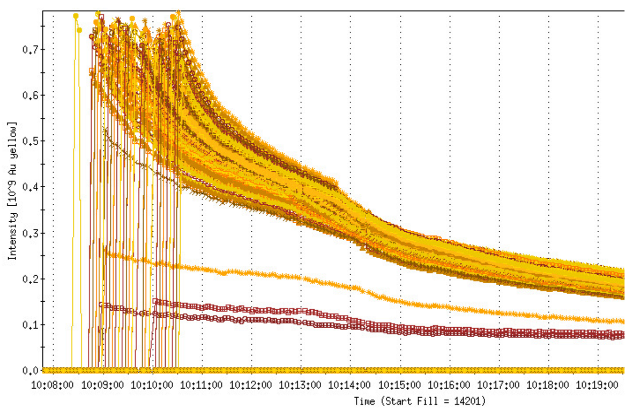

Figure 5: Lifetime of individual bunches in Yellow ring with different intensity before and after collisions at γ=4.1 (bunches were injected in Blue ring and put into collisions at about 10:14).

For energies with γ=4.1 and 6.1 additional experiments were done with different values of RF voltage. Smaller values of RF voltage result in smaller value of synchrotron tune and smaller momentum spread within the beam. Figure 6 shows the measured lifetime of unbunched beam at γ=4.1 in Blue ring (bunches were injected first in Yellow ring), with measured values given in Table 3.

Table 3: Measured beam lifetime of unbunched beam of Au ions in RHIC for different RF voltages at γ=4.1.

V_{rf} [kV]	τ [s]	Q_s
450	80	0.013
300	200	0.011
200	300	0.0086

100	500	0.006

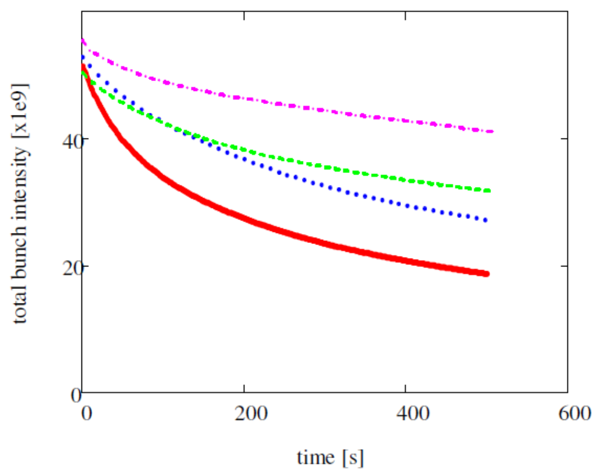

Figure 6: Lifetime of unbunched beam in Blue ring after beams were put into collisions for total RF voltages in RHIC of 450 (bottom red curve), 300, 200 and 100kV (top pink curve) at γ=4.1.

For large values of the synchrotron tune the beam lifetime was poor. When the synchrotron tune was reduced to a smaller value by decreasing the RF voltage, good beam lifetime was recovered. This is summarized in Table 3 and Fig. 6.

For higher energy, corresponding to γ=6.1, the synchrotron tune was already small even for large RF voltage of 450 kV (total per ring), which resulted in better beam lifetime. Corresponding dependence is given in Table 4.

Table 4: Measured beam lifetime of unbunched beam of Au ions in RHIC for different RF voltages for γ=6.1.

V_{rf} [kV]	τ [s]	Q_s
450	400	0.0064
300	500	0.0055
200	600	0.0045
100	800	0.0032

SUMMARY

For several present and future accelerator projects it is important to understand space-charge limitations when beams are colliding. Available theoretical and experimental knowledge about independent limitation due to the space-charge or beam-beam effects is extensive and provides useful guidelines, but the interplay of both effects is largely unexplored.

Motivated by the Low-Energy RHIC program and the proposal to use electron cooling for low energy RHIC operation, a series of measurements were performed in RHIC in order to understand what beam lifetime can be expected for different values of the space-charge tune shift with and without beam-beam effects. Our observations and initial analysis are summarized in this paper.

ACKNOWLEDGMENTS

We would like to thank M. Bai, R. Calaga, R. Connolly, V. Litvinenko, D. Kayran, K. Zeno, A. Zelenski and other members of Collider-Accelerator department at BNL for useful discussions and help during various stages of these studies.

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