BEAM LIFETIME AND LIMITATIONS DURING LOW-ENERGY RHIC OPERATION *

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Abstract

The low-energy physics program at the Relativistic Heavy Ion Collider (RHIC), motivated by a search for the QCD phase transition critical point, requires operation at low energies. At these energies, large nonlinear magnetic field errors and large beam sizes produce low beam lifetimes. A variety of beam dynamics effects such as Intrabeam Scattering (IBS), space charge and beam-beam forces also contribute. All these effects are important to understand beam lifetime limitations in RHIC at low energies. During the low-energy RHIC physics run in May-June 2010 at beam γ=6.1 and γ=4.1, gold beam lifetimes were measured for various values of space-charge tune shifts, transverse acceptance limitation by collimators, synchrotron tunes and RF voltage. This paper summarizes our observations and initial findings.

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 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 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, the direct space-charge force from the beam itself is expected to become the dominant limitation [5]. Also, the interplay of both beam-beam and space-charge effects may impose an additional limitation on the achievable luminosity lifetime [6].

Operation of RHIC for Low-Energy physics program started in 2010 which allowed us to have a look at interplay of various effects experimentally.

* Work supported by Brookhaven Science Associates, LLC under contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

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RHIC EXPERIENCE

Low-energy RHIC operation in 2010 at γ=6.1 and γ=4.1 provided measurements of beam lifetime with the space-charge tune shifts up to 0.1, different transverse acceptance limitation by collimators, different synchrotron tunes and different values of the RF voltage. In addition, several dedicated sessions of Accelerator Physics Experiments (APEX) were used to explore the beam lifetime.

Beam Lifetime without Collisions

Table 1 shows typical beam lifetimes measured in different experiments without collisions. Incoherent space-charge tune shift values ΔQ_{sc} were calculated using measured beam parameters at the start of the measurement. Other effects which were different for the experiments at different energies are indicated under comments (in Tables 1-2 minimum transverse acceptance indicates number of the rms beam sizes σ_x in the half-aperture, and Q_s is the synchrotron tune).

Beam lifetime values reported in the Tables are the result of fitting the intensity decay for individual bunches. Quoted time constant τ corresponds to a $(1+t/\tau)^{-1/2}$ fit rather than standard exponential fit since it resulted in much better fitting of the data compared to an exponential fit. In some cases, especially for beams under collisions, the intensity is better fitted with two time constants: fast and slow. In such a case, only the fast component of the time decay constant is reported.

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_x acceptance, Q_s=0.002
0.05, 0.04	1600	6.1	3σ_x acceptance, Q_s=0.006
0.09, 0.07	700	6.1	3σ_x acceptance, Q_s=0.006
0.1	70	4.1	2.2σ_x acceptance, Q_s=0.013

For the experiment at γ=10 there was no attempt to find better working point for beams without collisions. It is expected that for such a modest space-charge tune shift value (ΔQ_{sc} =0.03) it should be possible to find working point with beam lifetime better than reported in Table 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 few 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 minutes have been measured with the tune shifts in access of 0.1 in other machines [7].

At γ=6.1 the lifetime of high-intensity bunches shown in Figure 1 and Table 1 was about 700s for the space-charge tune shifts close to 0.1 ($\Delta Q_{sc,x}$=0.086, $\Delta Q_{sc,y}$=0.065). Also, measured emittance growth (both longitudinal and transverse) was in agreement with the IBS. Thus, one cannot conclude that beam lifetime was already limited by the space-charge tune shifts values and associated imperfection machine resonances.

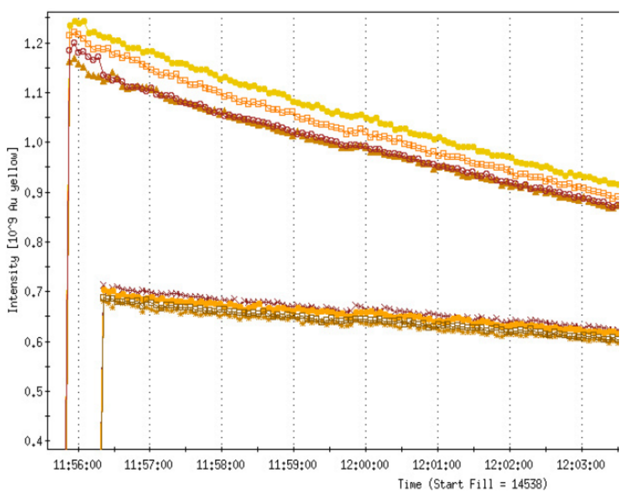

Figure 1: Intensity (x10[9]) evolution of several bunches at γ=6.1 without collisions.

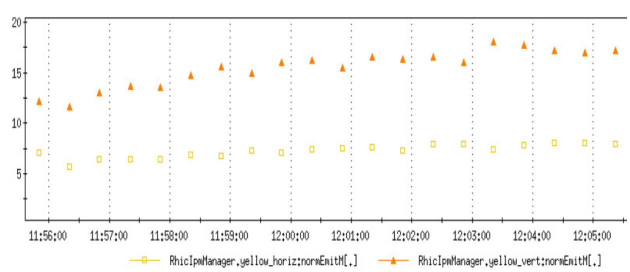

Figure 2: Vertical axis: horizontal and vertical emittance (95% normalized [mm mrad]) for beam in Yellow ring without collisions at γ=6.1; horizontal axis: clock time.

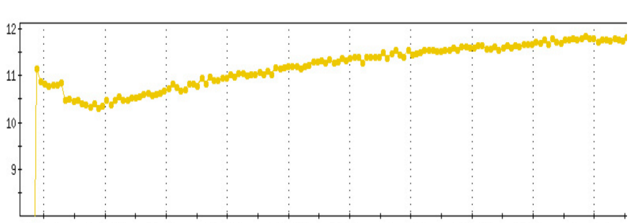

Figure 3: Vertical axis: bunch length (WFHM [ns]) growth at γ=6.1 without collisions; horizontal axis: clock time.

During operation at lower energy with γ=4.1, the initial beam lifetime without collisions was much worse compared to γ=6.1, as shown in Fig. 4. For high-intensity bunches with N=7.3×10^{8} particles per bunch, the peak current was 0.74A and initially ΔQ_{sc}=0.1 with a fast component of beam lifetime before collision of about 70s. For the same beam parameters calculated IBS growth times for transverse and longitudinal emittance were 370s and 660s, respectively. For low-intensity bunches with N=2.6×10^{8}, the peak current was 0.26A and ΔQ_{sc}=0.04 with a beam lifetime before collision of about 300s.

Significant limitation of dynamic aperture at γ=4.1 was expected due to large measured sextupole component in RHIC dipole magnets when they operate at low currents needed for this energy [8]. 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 lead to better beam lifetime as well. However, measured values of sextupole errors in the dipoles at γ=6.1 were approximately the same, and thus similar limitation in the dynamic aperture could be expected. The synchrotron tune Q_s was significantly different at these low energies, which leads to tune modulation with nonzero chromaticity, and can contribute to the resonance trapping mechanism and beam loss.

Studies were also done to explore various working points for γ=4.1. Beam lifetime below fractional tunes of 0.1 was limited due to large space-charge tune values. Without collisions it was possible to find working points with better beam lifetime and large space charge. However, with collisions there was significant degradation of beam lifetime for such working points.

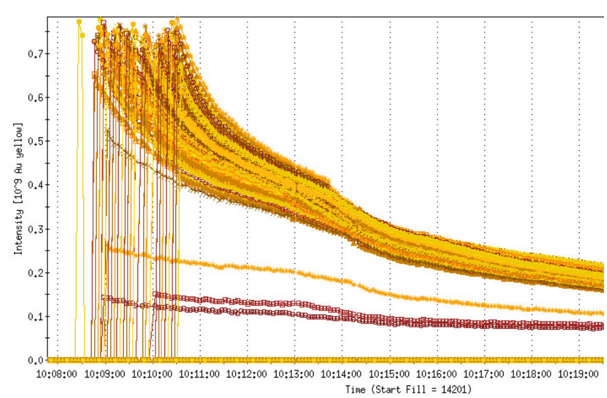

Figure 4: Intensity (x10[9]) of individual bunches in Yellow ring before and after collisions at γ=4.1 (bunches were injected in the Blue ring and put into collisions at about 10:14 clock time on horizontal axis).

Beam Lifetime with Collisions

In the presence of collisions, IBS was not sufficient to explain measured intensity loss. Also instead of the growth of transverse emittance, as in Fig. 2 without collisions, characteristic behavior of transverse emittances with beams in collision is shown in Fig. 5. Such behavior was observed both at γ=6.1 and γ=4.1.

Table 2 shows space-charge tune shifts and beam lifetime after beams were put into collisions. In these experiments with gold ions total maximum beam-beam parameter was ξ = 0.003 or smaller (see [6] for larger ξ values). 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 stronger beam-beam effect which is consistent with a typical observation for beams colliding with unequal emittances.

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

ΔQ_{sc}	τ [s]	γ	Comments
0.03	600	10	$5\sigma_x$, Q_s=0.002, ξ=0.002 (1 IP)
0.05	400	6.1	$3\sigma_x$, Q_s=0.006, ξ=0.0015 (1 IP)
0.09	260	6.1	$3\sigma_x$, Q_s=0.006, ξ=0.0027 (1 IP)
0.1	70	4.1	$2.2\sigma_x$, Q_s=0.013, ξ=0.003 (2 IP)

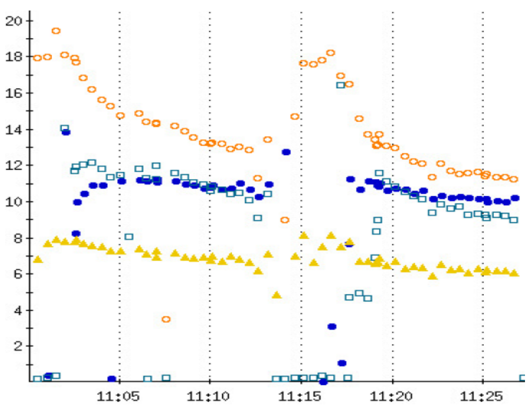

Figure 5: Vertical axis: horizontal and vertical emittance (95% normalized [mm mrad]) in Blue and Yellow ring for two short stores at γ=6.1 with collisions starting at 11:03 and 11:18, respectively.

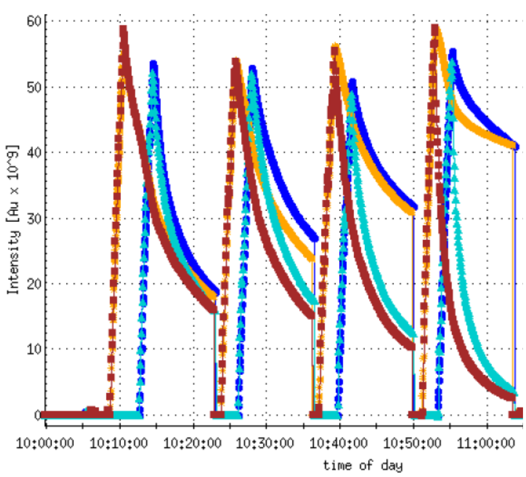

Figure 6: RF voltage scan at γ=4.1. Four stores with 450, 300, 200 and 100kV RF voltage per ring, subsequently. Upper (blue and yellow) curves – total current in the Blue and Yellow rings; lower (light blue and brown) curves - bunched beam current.

For energies with γ=4.1 and γ=6.1 additional experiments were done with different values of the RF voltage. Figure 6 shows such measurement at γ=4.1. The lifetime of de-bunched beam in the Blue ring is summarized in Table 3. For higher energy at γ=6.1, even for large RF voltage of 450 kV (total per ring) better beam lifetime was measured, as shown in Table 4.

Table 3: Measured beam lifetime of de-bunched beam of gold ions in RHIC for different RF voltages at γ=4.1.

τ [s]	V_{rf} [kV]	A_s [eV-s/n]	$\Delta p/p_{max}$ (bucket height)
80	450	0.2	0.0019
200	300	0.165	0.0015
300	200	0.135	0.0013
500	100	0.095	0.0009

Table 4: Measured beam lifetime of de-bunched beam of gold ions in RHIC for different RF voltages at γ=6.1.

τ [s]	V_{rf} [kV]	A_s [eV-s/n]	$\Delta p/p_{max}$ (bucket height)
400	450	0.38	0.0024
500	300	0.31	0.0019
600	200	0.26	0.0016
800	100	0.18	0.0011

SUMMARY

During low-energy RHIC operation at γ=4.1 beam lifetime without collisions was limited due to combination of several effects, including momentum aperture limitation, transverse acceptance and space charge. For operation at γ=6.1 without collisions the limiting effect was mostly IBS. The effect of beam-beam on lifetime was significant for all cases studied (see Tables 1 and 2) and will be investigated further in future experiments.

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