BEAM DYNAMICS AND EXPECTED RHIC PERFORMANCE WITH 56 MHZ RF UPGRADE *

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Abstract

An upgrade of the RHIC storage RF system with a superconducting 56 MHz cavity was recently proposed. This upgrade will provide a significant increase in the acceptance of the RHIC 197 MHz storage RF bucket. This paper summarizes simulations of beam evolution due to intra-beam scattering (IBS) for beam parameters expected with the 56 MHz SRF cavity upgrade. Expected luminosity improvements are shown for Au ions at 100 GeV/nucleon and protons at 250 GeV.

INTRODUCTION

The purposes of RF system in RHIC are to capture injected bunches, accelerate them to the top energy, and store bunches at the top energy for many hours. The accelerating RF system operates at harmonic number h=360 of the particle revolution frequency f=78.196 kHz, which corresponds to 28.15 MHz. The storage RF system accepts the shortened bunches at top energy and provides longitudinal focusing to keep these bunches short during the store time (collision mode). The storage system operates at harmonic number h=7x360=2520, which corresponds to an RF frequency of 197.05 MHz [1].

Recently, an upgrade of the storage RF system with a superconducting 56 MHz cavity was proposed [2]. This upgrade will provide significant increase in the acceptance of the storage RF bucket. Presently, the short bunch length for collisions is obtained via RF gymnastics with bunch rotation (called "re-bucketing"), because the length of the 197 MHz bucket of 5.1 ns is too short to otherwise accommodate long bunches. However, due to bucket non-linearity and hardware complications some increase in the longitudinal emittance occurs during re-bucketing. The 56 MHz cavity will produce sufficiently short bunches that will allow RHIC to operate without re-bucketing procedure. Here expected performance is summarized both for Au ions at 100 GeV/nucleon and for protons at 250 GeV.

PERFORMANCE FOR AU ION BEAMS AT 100 GEV/NUCLEON

IBS limits the present performance of the RHIC collider with heavy ions. To achieve required luminosities for a future upgrade of the RHIC complex, the Collider-Accelerator department at BNL has been developing several approaches to counteract IBS such as electron and stochastic cooling [2, 3].

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In addition, work is being done on the reduction of the transverse IBS growth rate with a modification of the RHIC lattice. As a first step in this direction, a new RHIC lattice was developed over several dedicated Accelerator Physics Experiments (APEX) [4, 5]. In this paper, IBS for RHIC beams was simulated with the new "dAu82" lattice, used in 2008 RHIC physics run in the Yellow ring. This newly implemented lattice has 95° horizontal phase advance per arc cell and a transition gamma of γ_t=26.6.

At RHIC injection energy, the typical 95% longitudinal emittance of Au ions is $S_{95\%}$=0.3-0.5 eV-s/nucleon. The emittance is growing during the ramp reaching the values of about 0.8 eV-s/nucleon at the top energy, which corresponds to a full bunch length of 9.7 ns with the 28 MHz RF. This bunch length is too long to fit into 5.1 ns bucket length of the 197 MHz RF. A short bunch length for collisions is thus obtained via RF gymnastics with bunch rotation. However, some increase in the longitudinal emittance occurs during this procedure. Longitudinal emittance after re-bucketing is about 1.5 eV-s/nucleon. In addition, as a result of re-bucketing, significant intensity spill into the neighbouring buckets also occurs. Typically, about 30% of the bunch intensity is spilled into the neighbouring buckets, as shown in Fig. 1. This would correspond to a two-fold reduction in useful luminosity if these satellite buckets do not contribute to the collisions within the detector vertex.

Table 1: Comparison of RF parameters for present and planned RF cavities.

Au ions, 100 GeV/n	28MHz	56MHz	197MHz
RF voltage, kV	300	2500	3000
Bucket acceptance, eV-s/nucleon	4.9	5	0.84
Bucket length, ns	36	18	5.1
Initial RMS bunch length, meters (for $S_{95\%}$=0.8eV-s/n)	0.58	0.29	0.2
Initial full length, 5*RMS, ns (for $S_{95\%}$=0.8eV-s/n)	9.7	4.8	3.4

The RF upgrade with the 56 MHz cavity will produce sufficiently short bunches which will allow one to operate without a re-bucketing procedure. This would prevent longitudinal emittance increase as a result of re-bucketing and eliminate intensity spill in the neighbouring buckets thus maximizing useful luminosity. A comparison of RF parameters for present 28 and 197 MHz RF and planned 56 MHz RF is given in Table 1.

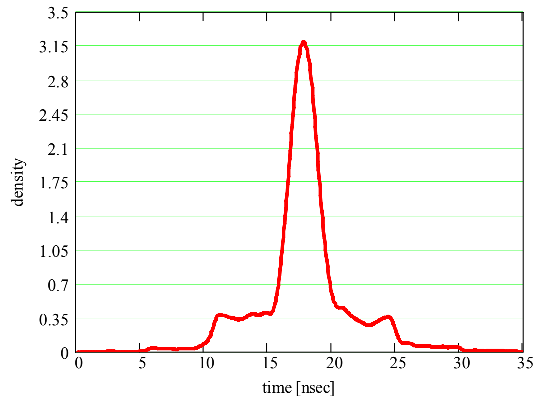

Figure 1: Example of a typical measured longitudinal density distribution just after re-bucketing from 28 MHz into the 197MHz RF [10].

Note that for a longitudinal emittance of 0.8 eV-s/nucleon, the full bunch length with the 56 MHz RF is only 4.8 ns, which is smaller than the length of the 197 MHz RF bucket. This suggests that further shortening of the bunch length should be possible by adiabatic capture from the 56 MHz RF into the 197 MHz RF, which would raise luminosity within the vertex. Such an application of a combined operation of the 56 MHz and 197 MHz RF systems becomes especially important in light of a proposed detector upgrade which will result in a vertex length even shorter than presently used.

IBS simulations were performed with the 56 MHz RF for ion beam parameters in Table 2 with bunch intensities of $1{\bullet}10^9$ and $1.5{\bullet}10^9$ per bunch. Simulations were performed using the BETACOOL code [6-7]. Recent implementation of non-linear arbitrary RF in BETACOOL allows us to simulate losses from RF bucket more accurately, including for distributions similar to those produced with re-bucketing (see Fig.1), as well as luminosity calculation for such distributions [8].

Table 2: Initial parameters of Au ions beam used in simulations.

Energy of Au ions, GeV/nucleon	100
RF harmonic	720
RF voltage, MV	2.5
RMS bunch length, cm	29
RMS momentum spread	0.00044
Transverse normalized emittance, 95%, μm	15
Longitudinal emittance, 95%, eV-s/nucleon	0.8

Presently, the typical bunch intensity of Au ion beam used in RHIC operation is about $1.1{\bullet}10^9$. A bunch intensity of $1.5{\bullet}10^9$ was already used in accelerator experiments but is not yet operational due to a beam instability at transition energy which limits average beam current to about 130 mA. This corresponds to bunch intensity of $N=1.3{\bullet}10^9$ for 103 bunches. Work in presently underway to elevate this instability threshold. Thus, operation with $1.5{\bullet}10^9$ (corresponds to 165 mA current with 112 bunches) might be possible few years from now. In Fig. 2 results of simulations are shown for simulations using only the 56 MHz RF system for bunch intensity of $N=1.5{\bullet}10^9$ and $1{\bullet}10^9$ and longitudinal emittance of $S_{95\%}$=0.8 eV-sec/nucleon. More details of simulations can be found in Ref. [9].

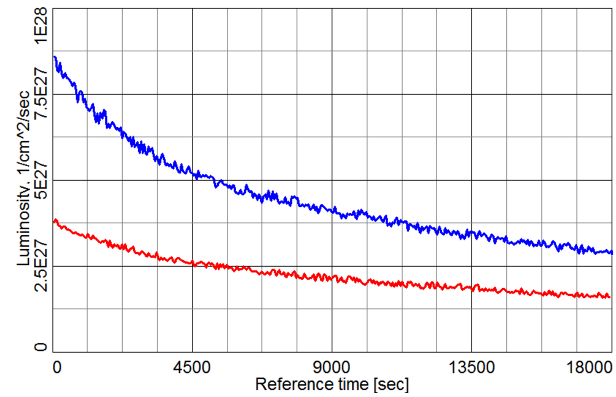

Figure 2: Luminosity (only 56 MHz RF, no cooling) for 112 Au ions bunches, β*=0.8 m for beam parameters in Table 2. Red lower curve – for bunch intensity 1×10^9; blue upper curve – for bunch intensity 1.5×10^9.

Table 3: Simulated luminosity performance with future 56 MHz RF upgrade. Subscript "full" indicates luminosity without the vertex cut, while subscript "±30cm" corresponds to luminosity within the vertex cut of ±30cm.

Au, 100 GeV/nucleon	197 MHz	56 MHz
Run-7, $N=1.1\times10^9$, $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$	1.2×10^{27}	
$N=1\times10^9$, β*=0.8m, $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$		2.4×10^{27}
$N=1\times10^9$, β*=0.8m, $\langle L\rangle_{\pm30cm}$, $cm^{-2}s^{-1}$		1×10^{27}
$N=1.5\times10^9$, β*=0.8m, $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$		4.8×10^{27}
$N=1.5\times10^9$, β*=0.8m, $\langle L\rangle_{\pm30cm}$, $cm^{-2}s^{-1}$		1.9×10^{27}
$N=1\times10^9$, β*=0.5m, with 3D stochastic cooling Ref.[10], $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$	4.3×10^{27}	5.5×10^{27}
$N=1\times10^9$, β*=0.5m, with 3D stoch. cooling, Ref. [10], $\langle L\rangle_{\pm30cm}$, $cm^{-2}s^{-1}$	3×10^{27}	4×10^{27}

Expected improvement in average beam luminosity is summarized for different bunch intensities in Table 3. For bunch intensity $N=1.5{\bullet}10^9$, without stochastic cooling, one gets full luminosity without vertex cut $\langle L\rangle_{full}=4.8{\bullet}10^{27}$ $cm^{-2}s^{-1}$ in a 4-hour store (for 112 bunches and β*=0.8 meters), and $\langle L\rangle_{full}=2.4{\bullet}10^{27}$ $cm^{-2}s^{-1}$ for $N=1.0{\bullet}10^9$. To maximize luminosity gain within the vertex cut one should use 56 and 197 MHz RF systems together. This will allow us to reduce bunch length at the beginning of the store to about 20 cm rms for the longitudinal emittance of 0.8 eV-s/nucleon, for example. In fact, with such an approach an even shorter bunch length might be possible if one can preserve smaller longitudinal emittances (0.3-0.5 eV-s/nucleon) during acceleration to the store energy.

The best luminosity performance is expected with both 56 MHz RF cavity and all-plane (3D) stochastic cooling upgrades which should provide around $\langle L \rangle_{full}=5.5 \cdot 10^{27}$ cm^{-2} s^{-1} (with $\beta^*=0.5$ meters) for bunch intensity of $N=1.0 \cdot 10^9$ [10] and up to $\langle L \rangle_{full}=7 \cdot 10^{27}$ cm^{-2} s^{-1} for bunch intensity of $N=1.5 \cdot 10^9$ [11].

PERFORMANCE FOR PROTON BEAMS AT 250 GEV

Comparison of RF parameters for present 28 MHz and 197 MHz RF with planned 56 MHz RF is given in Table 4. The choice of the 56 MHz cavity with 2.5 MV voltage results in RF bucket acceptance 6 times larger than the one of the 197 MHz.

Table 4: Comparison of RF parameters for present and planned RF cavities.

protons, 250 GeV	28 MHz	56 MHz	197MHz
Harmonic number	360	720	2520
RF voltage, kV	300	2500	3000
Bucket length, ns	35.5	17.8	5.1
Bucket acceptance, eV-s	13.9	14.2	2.4

Up to now, operation with protons was limited by large longitudinal emittance at the top energy of 100 GeV. The emittance was intentionally increased by mismatch at injection to avoid transverse emittance growth. With the ongoing 9 MHz cavity upgrade, operation with smaller longitudinal emittance (0.5-1 eV-s, 95%) may be possible. The goal of the 9 MHz cavity is to get long bunches with low longitudinal emittance on the ramp to prevent transverse emittance growth suspected to be driven by electron clouds [12]. At the top energy of 250 GeV such small longitudinal emittance would result in smaller bunch length with the 28 MHz RF.

The 56 MHz RF cavity offers even smaller bunch length thus improving vertex luminosity compared to operation with the 28 MHz RF, for any value of the longitudinal emittance. As an example, Tables 5 shows expected bunch lengths for small longitudinal beam emittance of 0.5 eV-s (95%)

BETACOOL simulations of beam evolution due to IBS for various values of longitudinal emittance and resulting luminosity can be found in Ref. [9].

Table 5: Expected initial bunch length for longitudinal emittance of 0.5 eV-s (95%).

protons, 250 GeV, S=0.5 eV-s	28 MHz	56 MHz	197 MHz
RF voltage, kV	300	2500	3000
RMS bunch length, meters	0.3	0.15	0.1
RMS bunch length, ns	1	0.5	0.3
Full bunch length (5•RMS), ns	5	2.5	1.5

To summarize, for protons at 250 GeV, planned 56 MHz SRF cavity upgrade offers significantly better vertex luminosity compared to present 28 MHz RF due to shorter bunch length for any value of the longitudinal emittance. Luminosity performance with the 56 MHz RF seems to be also slightly better than with the 197 MHz cavity operated alone [9]. Compared to the 197 MHz no intensity loss due to longitudinal IBS is expected because of a significantly larger bucket acceptance for the 56 MHz SRF cavity.

The best performance is expected with combined operation of 56 and 197 MHz RF systems since 56 MHz RF offers possibility of further shortening of proton bunches with adiabatic capture (no re-bucketing) into the 197 MHz RF. As a result, the rms bunch length could be shortened to about 10 cm (for 0.5 eV-s longitudinal emittance). Such short bunch length is strongly desired due to a future upgrade of the detectors to a shorter vertex.

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