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Introduction

The purpose of RF system in RHIC is 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 28.15MHz. 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 storage RF system with a superconducting 56 MHz cavity was proposed [2]. This upgrade will provide significant increase in the acceptance of 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 197MHz bucket of 5 nsec is too short to accommodate long bunches otherwise. However, due to bucket non-linearity and hardware complications some increase in the longitudinal emittance occurs during re-bucketing. The 56MHz cavity will produce sufficiently short bunches which would allow one to operate without re-bucketing procedure.

This Note summarizes simulation of beam evolution due to Intra-beam scattering (IBS) for beam parameters expected with the 56 MHz SRF cavity upgrade. Expected luminosity improvement is shown both for Au ions at 100 GeV/nucleon and for protons at 250 GeV.

Performance of Au ions beams at top energy of 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]. Stochastic cooling in the longitudinal direction was already successfully implemented in RHIC, suppressing longitudinal emittance growth due to IBS in one of RHIC rings. Implementation of stochastic cooling in the transverse plane is presently under development [3].

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

At injection energy 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 nsec with 28MHz RF. Such bunch length is too long to fit into 5.1 nsec bucket length of 197MHz RF. The short bunch length for collisions is thus obtained via RF gymnastics with bunch rotation (called "re-bucketing"). However, some increase in the longitudinal emittance occurs during this procedure. Longitudinal emittance after re-bucketing is about 1.5eV-s/nucleon. Also, as a result of re-bucketing, significant intensity spill into the neighbouring buckets occurs as well. Typically, about 30% of bunch intensity is spilled into the neighbouring buckets. This would correspond to a two-fold reduction in useful luminosity if these satellite buckets would not contribute to the collisions within the detector vertex. Of course, bunches in the satellite buckets still collide within the vertex, making luminosity reduction caused by the spill slightly less severe.

The RF upgrade with 56MHz cavity will produce sufficiently short bunches which would allow one to operate without 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. Comparison of RF parameters for present 28 and 197 MHz RF and planned 56 MHz RF is given in Table 1. Also note that for longitudinal emittance of 0.8eV-s/nucleon the full bunch length with 56MHz RF is only 4.8nsec, which is smaller than the length of 197MHz RF bucket. This suggests that further shortening of bunch length may be possible by adiabatic capture from 56MHz RF into the 197MHz RF, which would maximize luminosity within vertex even further.

Au@100 GeV/nucleon	28MHz	56MHz	197MHz
RF voltage, kV	300	2500	3000
Bucket acceptance, eV-s/nucleon	4.9	5	0.84
Bucket length, nsec	36	18	5.1
initial RMS bunch length, m ($S_{95\%}$=1.5eV-s/n)			0.28
Initial full length, 5*RMS, nsec ($S_{95\%}$=1.5eV-s/n)			4.6
Initial RMS bunch length, m ($S_{95\%}$=0.8eV-s/n)	0.58	0.29	0.2
Initial full length, 5*RMS, nsec ($S_{95\%}$=0.8eV-s/n)	9.7	4.8	3.4

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

For a stationary RF bucket, the bucket acceptance is give by:

$$A_s = 8\frac{R}{hc}\sqrt{\frac{2ZeV_{rf}E_s}{\pi h\eta}},$$

where R is the machine radius, h is the RF harmonic number, η is the slippage factor, V_{rf} is the total RF gap voltage per turn, Z is the ion charge number and E_s is the energy of synchronous particles. The choice of 56MHz cavity with 2.5 MV voltage results in RF bucket acceptance 6 times larger than the one of 197MHz RF.

IBS simulations were performed with 56MHz 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 Martini's model of IBS in BETACOOL code [6, 7]. Presently, typical bunch intensity of Au ion beam used in RHIC operation is about $1.1{\bullet}10^9$. 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 the transition energy which limits average beam current to about 130 mA. This corresponds to bunch intensity of N=1.3•10^9 for 103 bunches. Work in presently underway to elevate this instability threshold. Thus, operation with 1.5•10^9 (corresponds to 165 mA current with 112 bunches) might be possible few years from now. In Figs. 1-3 results of simulations are shown for bunch intensity of N=1.5•10^9 and 1•10^9 and longitudinal emittance of $S_{95\%}$=0.8 eV-sec/nucleon (expected with 56MHz RF).

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

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

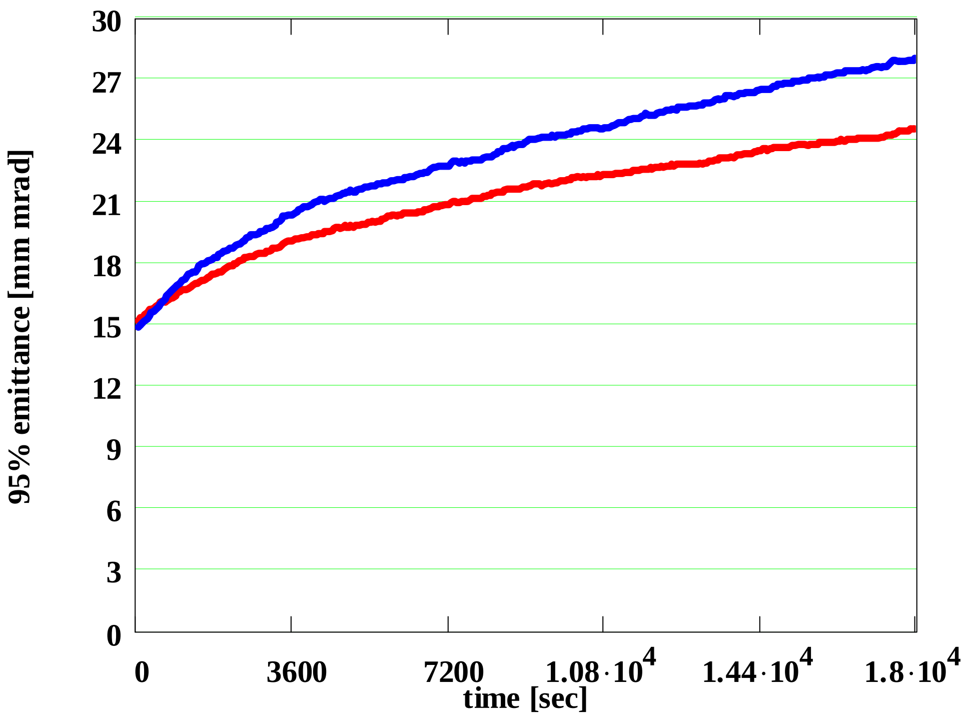

Figure 1: Evolution of 95% normalized transverse emittance for Au ions with beam parameters in Table 2. Red lower curve – for bunch intensity 1×10^9; blue upper curve – for bunch intensity 1.5×10^9 (using IBS-lattice “dAu82” from 2008 RHIC physics run in Yellow ring).

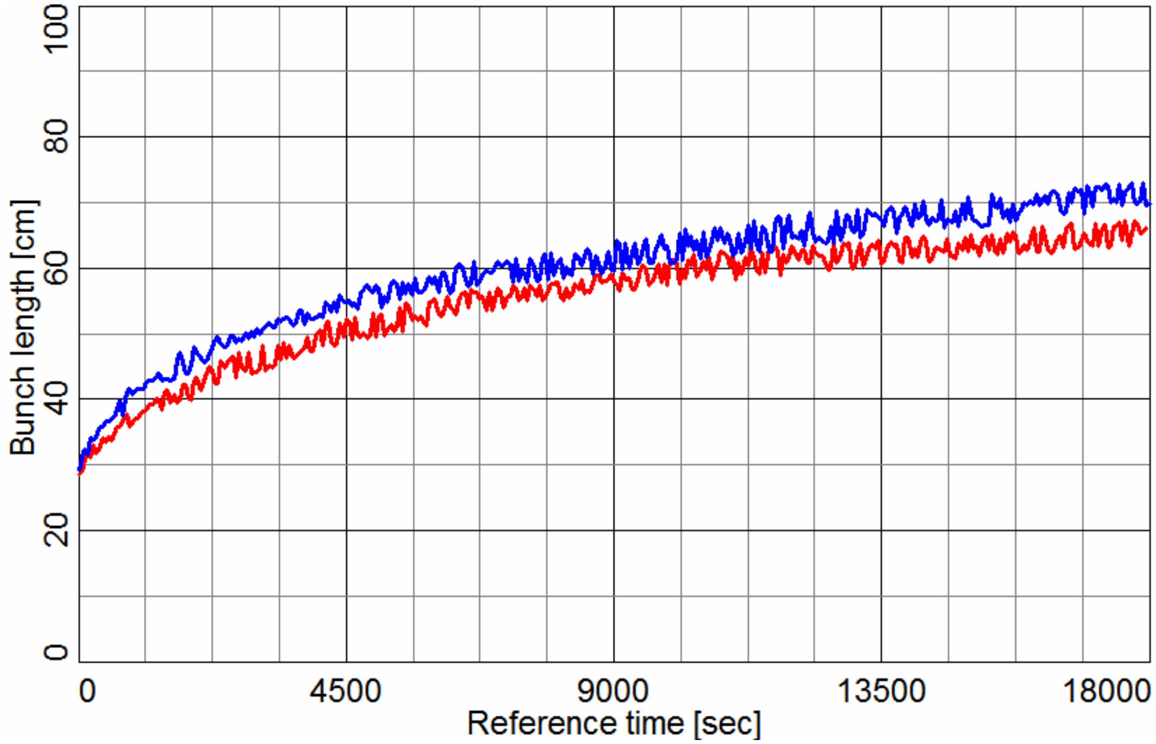

Figure 2: Evolution of RMS bunch length for Au ion bunch with beam parameters in Table 2. Red lower curve – for bunch intensity 1×10^9; blue upper curve – for bunch intensity 1.5×10^9.

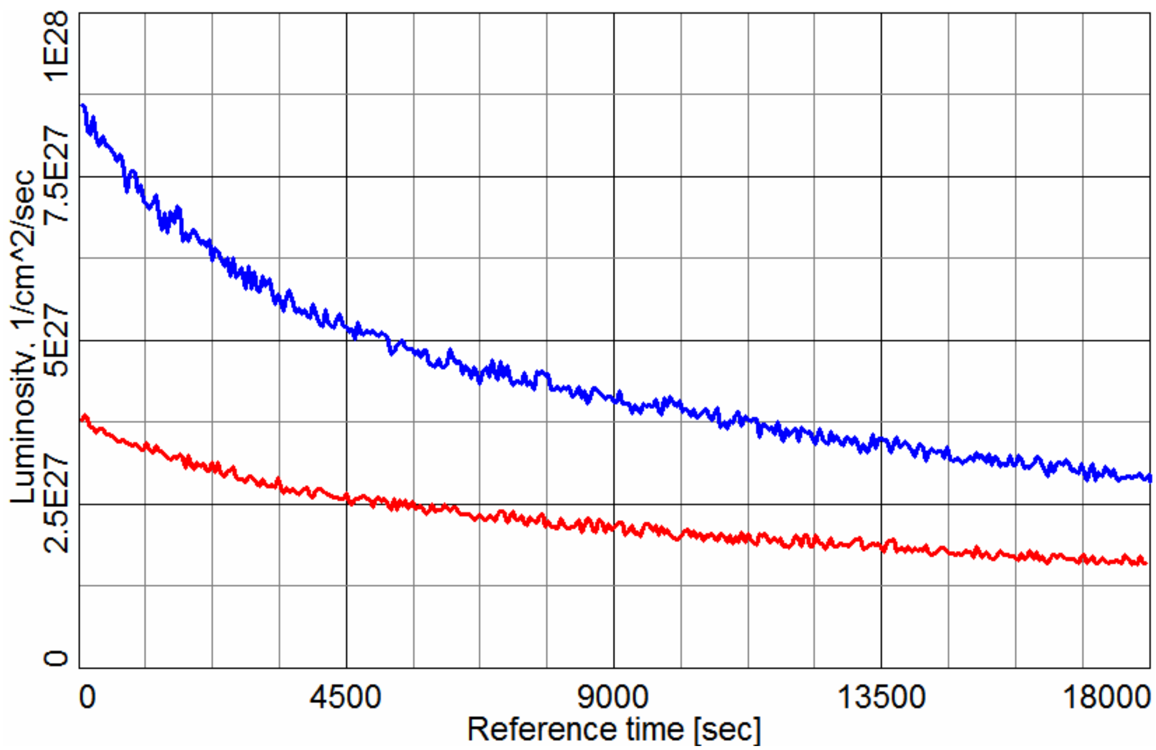

Figure 3: Resulting luminosity for 112 Au ions bunches, β*=0.8 m for beam parameters in Table 2. Red lower curve – for bunch intensity 1×10^9; blue upper curve – for bunch intensity 1.5×10^9.

Au@100 GeV/nucleon	197 MHz	56MHz
Run-7, $N=1.1\times10^9$, $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$	1.2×10^{27}	
$N=1\times10^9$, $\beta^*=0.8m$, $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$		2.4×10^{27}
$N=1\times10^9$, $\beta^*=0.8m$, $\langle L\rangle_{\pm30cm}$, $cm^{-2}s^{-1}$		1×10^{27}
$N=1.5\times10^9$, $\beta^*=0.8m$, $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$		4.8×10^{27}
$N=1.5\times10^9$, $\beta^*=0.8m$, $\langle L\rangle_{\pm30cm}$, $cm^{-2}s^{-1}$		1.9×10^{27}
$N=1\times10^9$, $\beta^*=0.5m$, with 3D stochastic cooling Ref.[8], $\langle L\rangle_{full}$, $cm^{-2}s^{-1}$	4.3×10^{27}	5.5×10^{27}
$N=1\times10^9$, $\beta^*=0.5m$, with 3D stoch. cooling, Ref. [8], $\langle L\rangle_{\pm30cm}$, $cm^{-2}s^{-1}$	3×10^{27}	4×10^{27}

Table 3. Expected luminosity performance with future 56MHz RF upgrade. Subscript "full" indicates full luminosity without the vertex cut, while subscript "±30cm" corresponds to luminosity within the vertex cut of ±30cm. Luminosity values for the last two rows which show performance with addition of a full 3D stochastic cooling upgrade were taken from simulations done by M. Blaskiewicz [8, 9].

To summarize, the 56 MHz SRF cavity upgrade offers 6 times larger bucket acceptance compared to the 197MHz RF and shorter bunch lengths compared to the 28MHz RF. It also eliminates intensity spill in the neighbouring buckets and avoids longitudinal emittance increase, which happens during re-bucketing. Comparison of different RF systems is summarized in Table 1. Note that for small longitudinal emittances of 0.5-0.8eV-s/nucleon (which is expected at top energy without re-bucketing), the 56MHz RF provides bunches less than 5 nsec long which allows further reduction of bunch length with adiabatic capture into 197MHz RF without the need of re-bucketing.

Expected improvement in average beam luminosity is summarized for different bunch intensities in Table 3. For bunch intensity $N=1.5\bullet10^9$, without stochastic cooling, one gets full luminosity without vertex cut $\langle L\rangle_{full}=4.8\bullet10^{27}$ cm^{-2} s^{-1} in a 4-hour store (for 112 bunches and $\beta^*=0.8$ meters), and $\langle L\rangle_{full}=2.4\bullet10^{27}$ cm^{-2} s^{-1} for $N=1.0\bullet10^9$. The best luminosity performance is expected with both 56MHz RF cavity and all-plane (3D) stochastic cooling upgrades which should provide around $\langle L\rangle_{full}=5.5\bullet10^{27}$ cm^{-2} s^{-1} (with $\beta^*=0.5$ meters) for bunch intensity of $N=1.0\bullet10^9$ [8] and up to $\langle L\rangle_{full}=7\bullet10^{27}$ cm^{-2} s^{-1} for bunch intensity of $N=1.5\bullet10^9$ [9].

Performance of proton beams at top energy of 250 GeV

This section summarises expected performance for protons beams with 59MHz cavity upgrade. Comparison of RF parameters for present 28 MHz and 197 MHz RF and planned 56 MHz RF is given in Table 4. The choice of 56MHz cavity with 2.5 MV voltage results in RF bucket acceptance 6 times larger than the one of 197MHz.

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

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

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 9MHz cavity upgrade operation with smaller longitudinal emittance (0.5-1 eV-s) may become possible. The goal of 9MHz cavity is to get long bunches with low longitudinal emittance on the ramp to prevent transverse emittance growth suspected to be driven by electron cloud [10]. At the top energy of 250 GeV such small longitudinal emittance would result in smaller bunch length with 28 MHz RF. The 56MHz RF cavity offers even smaller bunch length thus improving vertex luminosity compared to operation with the 28MHz RF, for any value of the longitudinal emittance. In addition, for small longitudinal emittances the 56MHz RF will allow even further shortening of the length of proton bunch with an adiabatic capture in 197MHz RF without a need of re-bucketing. Tables 5-7 shows expected bunch lengths for different longitudinal beam emittances.

p @ 250 GeV, S=2 eV-s	28 MHz	56 MHz	197 MHz
RF voltage, kV	300	2500	3000
RMS bunch length, meters	0.6	0.3	0.2
RMS bunch length, nsec	2	1	0.7
Full bunch length (5•RMS), nsec	10	5	3.5

Table 5. Expected initial bunch length for present longitudinal emittance of 2 eV-s.

p @ 250 GeV, S=1 eV-s	28 MHz	56 MHz	197 MHz
RF voltage, kV	300	2500	3000
RMS bunch length, meters	0.42	0.21	0.15
RMS bunch length, nsec	1.4	0.7	0.5
Full bunch length (5•RMS), nsec	7	3.5	2.5

Table 6. Expected initial bunch length for longitudinal emittance of 1 eV-s.

p @ 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, nsec	1	0.5	0.3
Full bunch length (5•RMS), nsec	5	2.5	1.5

Table 7. Expected initial bunch length for longitudinal emittance of 0.5 eV-s.

Below we show BETACOOL simulation of beam evolution due to IBS first with present longitudinal emittance of 2 eV-s and then with smaller emittance of 1 eV-s (assuming operation with smaller emittance will be possible in the future). Simulations assumed separate operation either with 56MHz or 197MHz RF.

Protons @ 250 GeV	56 MHz cavity	197 MHz cavity
RF bucket acceptance, eV-s	14.2	2.4
Bunch intensity	2×10^{11}	2×10^{11}
RF voltage, MV	2.5	3.0
RMS bunch length, cm	32	22
RMS momentum spread	0.00041	0.00058
Longitudinal emittance, 95%, eV-s	2.0	2.0
Transverse normalized emittance, 95%, μm	15	15

Table 8. Initial parameters of proton beam with 2 eV-s longitudinal emittance used in simulations.

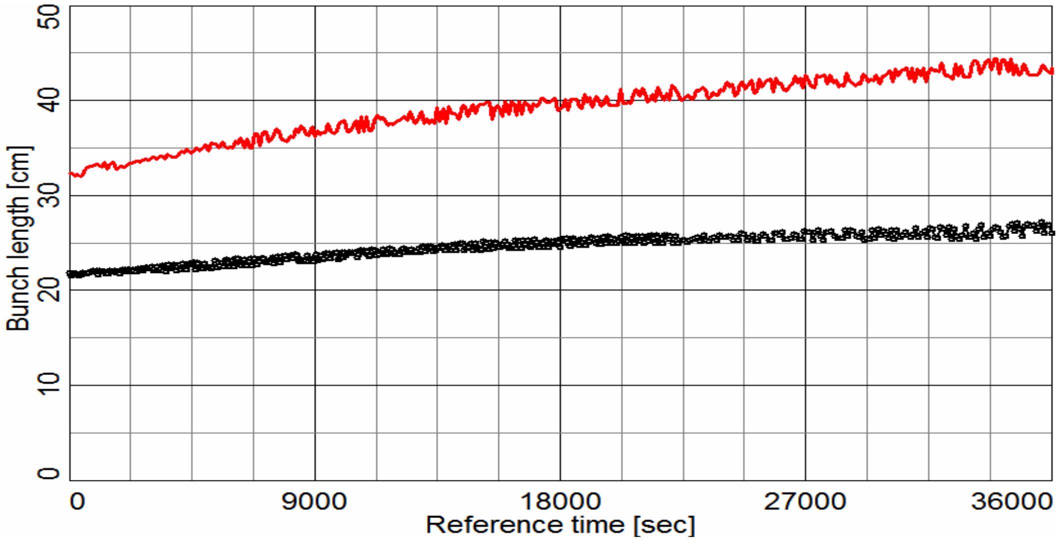

Figure 7: Evolution of RMS bunch length due to IBS for beam parameters in Table 8. Top red curve: for 56MHz RF; lower black curve for 197MHz RF.

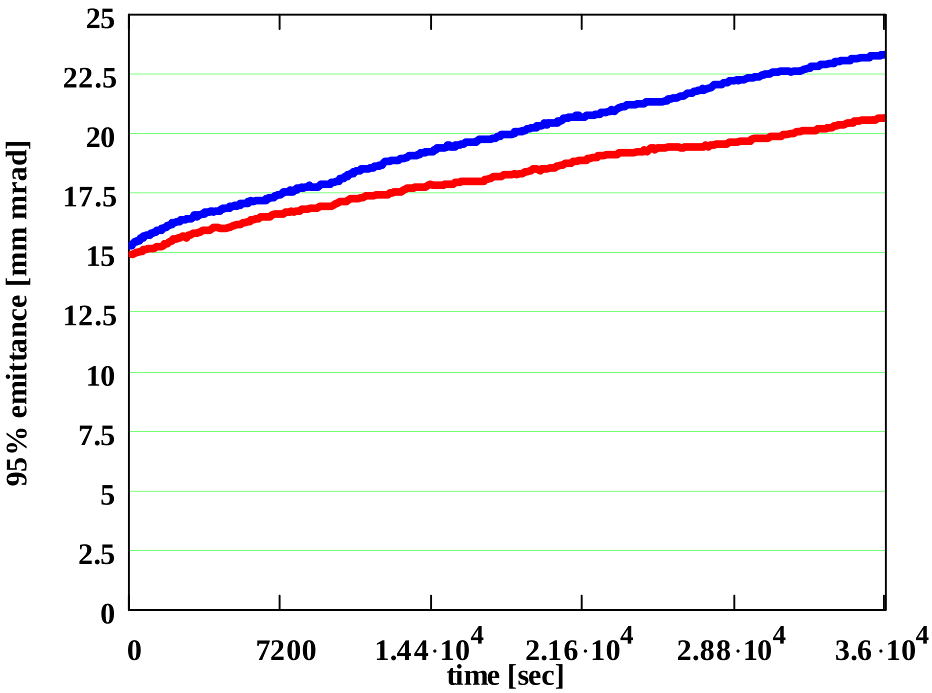

Figure 8. Evolution of 95% normalized transverse beam emittance due to IBS for beam parameters in Table 8. Lower red curve: for 56MHz RF; upper blue curve for 197MHz RF.

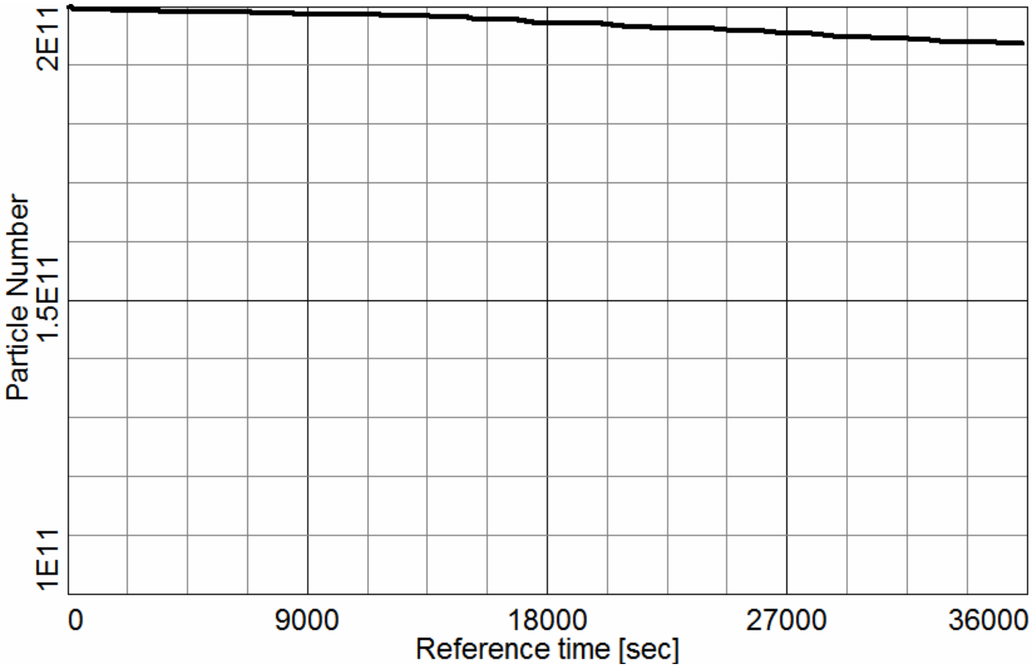

Figure 9. Intensity loss due to smaller bucket acceptance for 197MHz RF cavity.

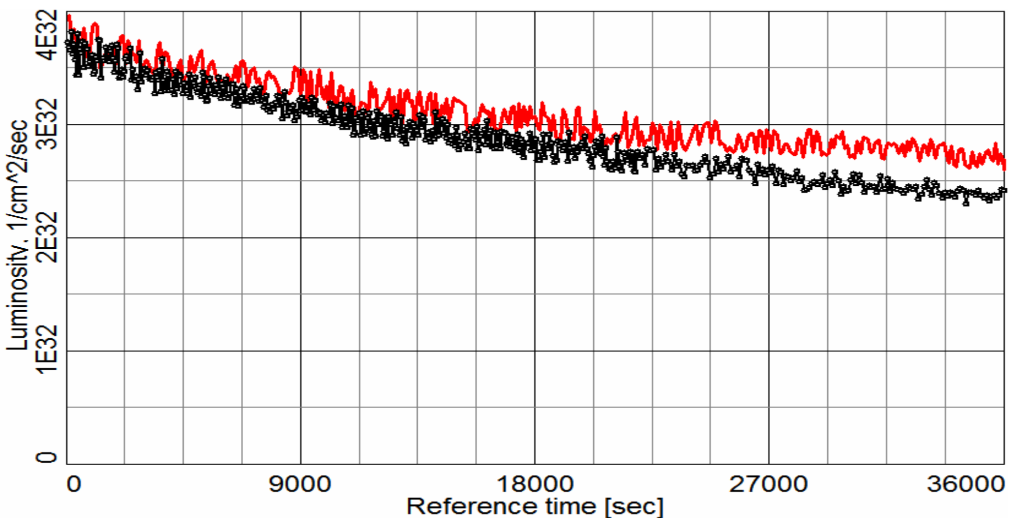

Figure 10. Full luminosity (without vertex cut) with 112 bunches, β*=0.8m for 56MHz (red curve) and 197MHz RF (black curve).

Figures 11-14 show beam evolution due to IBS for the case of smaller initial longitudinal emittance of 1 eV-sec and beam parameters shown in Table 9.

Protons @ 250 GeV	56 MHz cavity	197 MHz cavity
RF bucket acceptance. eV-s	14.2	2.4
Bunch intensity	2×10^{11}	2×10^{11}
RF voltage, MV	2.5	3.0
RMS bunch length, cm	22	16
RMS momentum spread	0.00029	0.00042
Longitudinal emittance, 95%, eV-s	1.0	1.0
Transverse normalized emittance, 95%, µm	15	15

Table 9. Initial parameters of proton beam with 1 eV-s longitudinal emittance used in simulations.

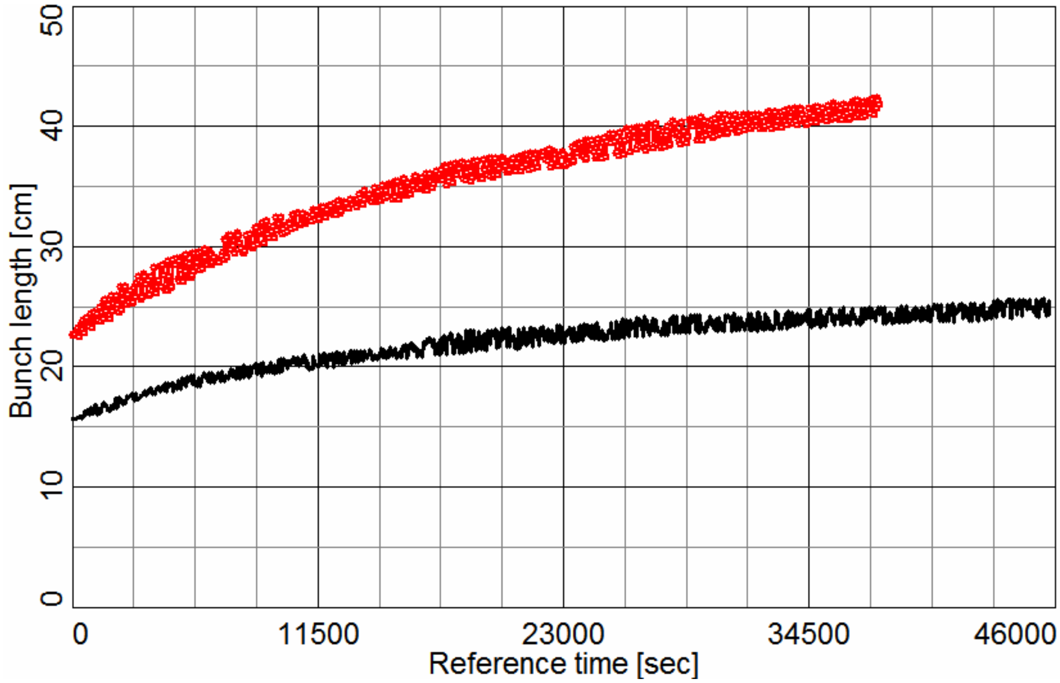

Figure 11. Evolution of RMS bunch length due to IBS for beam parameters in Table 9. Top red curve: for 56MHz RF; lower black curve for 197MHz RF.

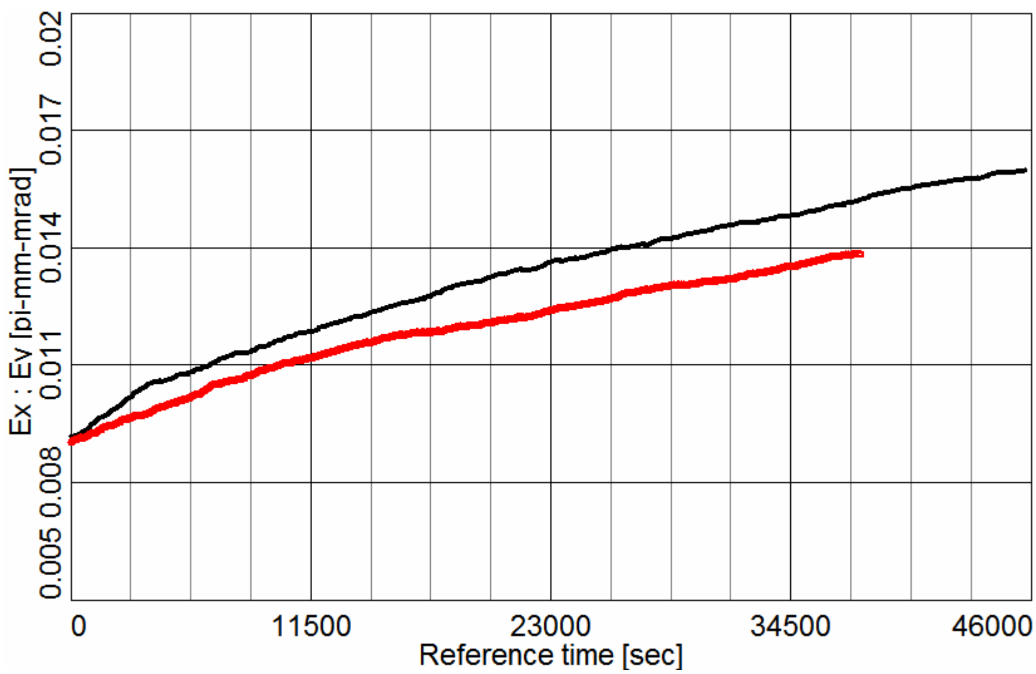

Figure 12: Evolution of RMS un-normalized transverse beam emittance due to IBS for beam parameters in Table 9. Lower red curve: for 56MHz RF; upper black curve for 197MHz RF.

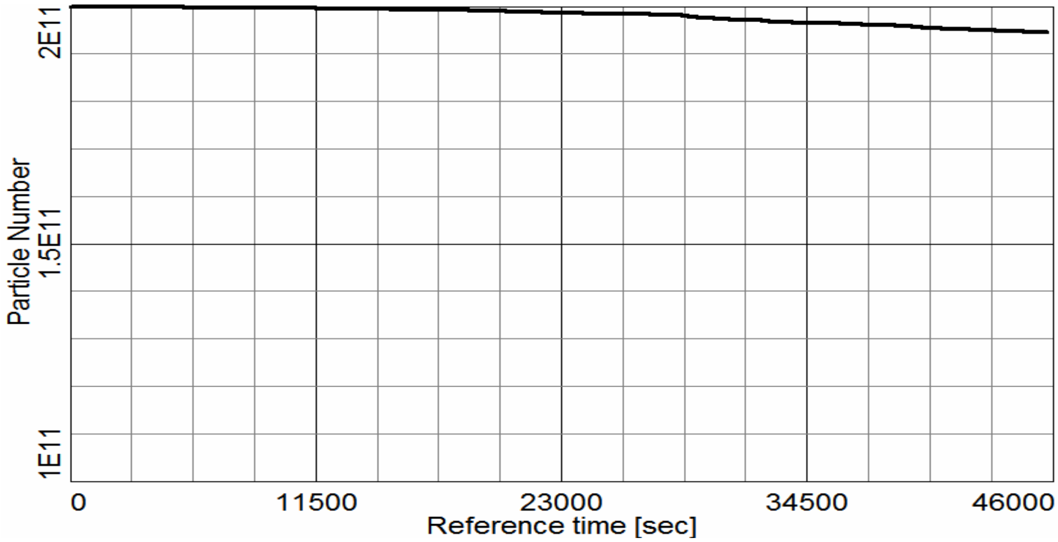

Figure 13: Intensity loss due to smaller bucket acceptance for 197MHz RF cavity.

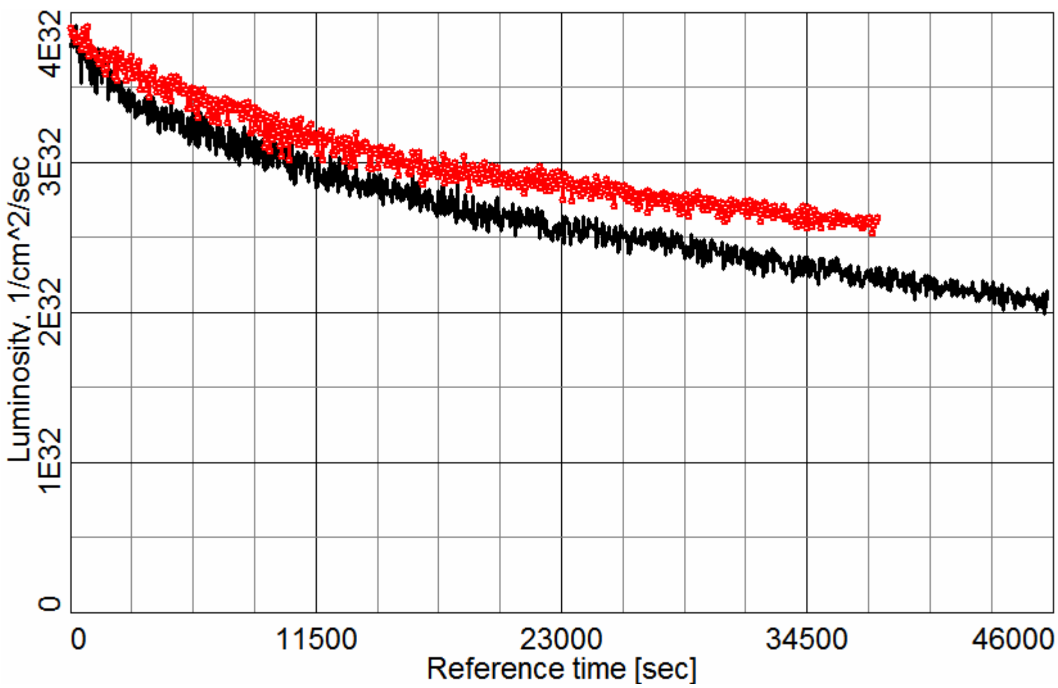

Figure 14. Full luminosity (without vertex cut) with 112 bunches, β*=0.8m for 56MHz (red curve) and 197MHz RF (black curve).

To summarize, for protons at 250 GeV, planned 56MHz SRF cavity upgrade offers significantly better vertex luminosity compared to present 28MHz RF due to shorter bunch length for any value of the longitudinal emittance (see Tables 5-7). Luminosity performance with 56 MHz RF seems to be slightly better than with 197MHz cavity for beam parameters shown in Tables 8-9. Compared to 197MHz no intensity loss due to longitudinal IBS is expected because of significantly larger bucket acceptance for 56MHz SRF cavity. In addition, the 56 MHz RF offers possibility of further shortening of proton bunches with adiabatic capture into 197MHz RF.

Possible improvement of Au ion luminosity with electron cooling at top energy

Electron cooling of Au ions in RHIC at 100 GeV/nucleon was carefully studied for RHIC-II project [2]. The most recent version of the cooler used simplified parameters without a need to move triplets in RHIC [11]. It is expected that RHIC-II average luminosities of $<L>=5\text{-}7 \cdot 10^{27}$ cm^{-2} sec^{-1} can be reached with a full 3D stochastic cooling system and 56 MHz SRF cavity upgrades. Presently there is no plan to have an additional high-energy electron cooling system for Au ions at 100 GeV/nucleon. For completeness, in this section we show potential improvement in luminosity if one would have such high-energy electron cooling system as well.

Kinetic energy, MeV	54
Total length of 2 cooling section, m	50
Charge per bunch, nC	5.0
Total charge in bunch train (3 bunches), nC	15
RMS momentum spread	0.0005
RMS normalized emittance, μm	3
Undulator: period, magnetic field	8 cm, 10G

Table 10. Parameters of electron cooler used for simulations in Fig. 15.

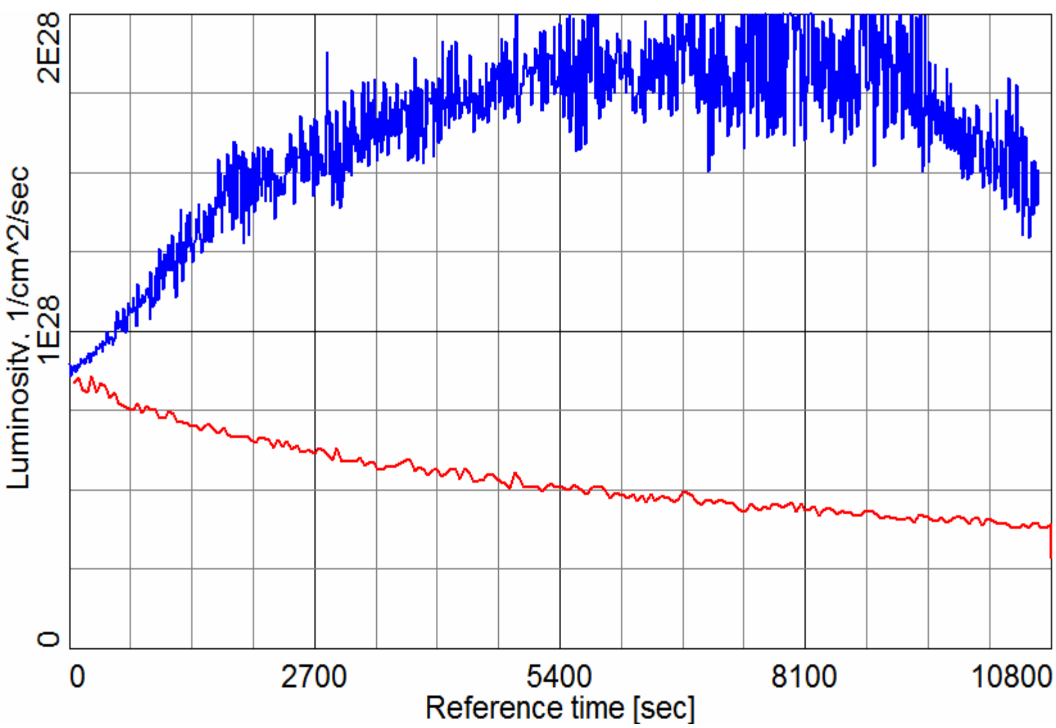

Figure 15. Luminosity of Au ions at 100 GeV/nucleon for ion bunch intensity of $N_i=1.5 \cdot 10^9$, $\beta^*=0.8m$: with electron cooling (blue upper curve) and without cooling (red lower curve).

Without electron cooling average luminosity in 3-hour store is $<L>=5.4 \cdot 10^{27}$ cm^{-2} sec^{-1} without vertex cut and $<L>=2.7 \cdot 10^{27}$ cm^{-2} sec^{-1} with the vertex cut of ±30cm (without stochastic cooling). With electron cooling expected average luminosity in 3-hour store shown in Fig. 15 is $<L>=1.6 \cdot 10^{28}$ cm^{-2} sec^{-1} (with $N_i=1.5 \cdot 10^9$). Since electron cooling also keeps short bunch length within the vertex cut it would provide close to a six-fold improvement in luminosity within the vertex compared to operation with 56MHz SRF cavity along, and about two-fold improvement compared to the expected future performance with full 3D stochastic cooling system and 56 MHz RF upgrades combined [9].

Acknowledgement

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References

[1] RHIC design Manual, 1998.
[2] http://www.bnl.gov/cad/ecooling
[3] M. Blaskiewicz et al., Proc. of PAC07 (Albuquerque, NM, USA), p. 2014.
[4] V. Litvinenko et al., Proc. of EPAC08 (Genoa, Italy), p. 2557 (2008).
[5] A. Fedotov et al., Proc. of HB2008 workshop (Nashville, TN, August 2008).
[6] BETACOOL code, http://lepta.jinr.ru; A. Sidorin et al., NIM A 558, p. 325 (2006).
[7] Physics Guide of BETACOOL code, BNL Tech Note C-A/AP/#262 (2006).
[8] M. Blaskiewicz, private communication (2008).
[9] M. Blaskiewicz, presentation at RHIC MAC08 (BNL, 2008).
[10] S.Y. Zhang and V. Ptitsyn, Phys. Rev. STAB, 11, 051001 (2008).
[11] A. Fedotov (October 2007), unpublished.