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# RHIC Performance With 56 MHz RF and Gold Ion Beams Pre-cooled at Lower Energy

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# RHIC PERFOMANCE WITH 56 MHZ RF AND GOLD ION BEAMS PRE-COOLED AT LOWER ENERGY

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## Introduction

Presently there is an R&D ERL under construction at Collider-Accelerator Department (C-AD) at BNL with its commissioning scheduled for FY09-10 [1]. The use of this full energy 21 MeV ERL in RHIC tunnel was recently proposed for a Proof-of-Principle demonstration of Coherent Electron Cooling of gold ions at 40 GeV/nucleon [2].

The purpose of this Note is to summarize numerical studies aimed at understanding the potential improvement of RHIC luminosity by using this R&D ERL for pre-cooling of Au ion beams with conventional electron cooling system at 40 GeV/nucleon. The constraints were such that electron beam parameters should be close to those expected from R&D ERL. Additionally, the cooling section in RHIC should not require major RHIC modification.

As a result of these studies it was found that pre-cooling of gold ion at about 40 GeV/nucleon approximately doubles the average store luminosity of RHIC at top energy of 100 GeV/nucleon compared to the expected luminosity improvement with 56MHz RF upgrade [3, 4]. Significant luminosity improvement may be also gained on top of future expected luminosity performance with combined upgrades of 56MHz RF and all-plane stochastic cooling system with present beam parameters [5]. The electron beam parameters needed for such pre-cooling (see Table 1) are close to those expected from the R&D ERL which is presently under construction at BNL. With electron beam parameters from Table 1 it takes about 20 minutes to cool the transverse emittance of gold ions by a factor of two at 40 GeV/nucleon.

Similar studies were done for protons as well. However, it was found that the electron beam parameters needed for pre-cooling of protons would require a significant upgrade of the present injector of the R&D ERL. Thus, discussion about protons is omitted from the present Note.

## Performance of Au ions at top energy of 100 GeV/nucleon

Both transverse and longitudinal emittance of gold ions can be pre-cooled at 40 GeV/nucleon using conventional electron cooling technique. Then the pre-cooled gold beams will be accelerated to the top energy of 100 GeV/nucleon for collisions. We note that pre-cooling of the longitudinal emittance of gold ions results in a stronger IBS growth rate and do not show significant luminosity improvement unless such an enhanced IBS is counteracted at the top energy as well. In addition, longitudinal cooling would require small momentum spread of the electron beam, placing strict requirements on the R&D ERL. On the other hand, pre-cooling of only the transverse emittance offers a potential luminosity improvement at top energy and, at the same time, does not impose strict requirements on the R&D ERL electron beam parameters. Consequently only this latter option is presented here for simplicity.

Figure 1 shows results of simulations using BETACOOL code [6] for gold ions at 100 GeV/nucleon. Simulations were done assuming planned upgrade of RHIC RF with 56MHz SRF storage cavity with 2.5MV [3]. The four curves shown correspond to two intensities of ion bunch

$1\times10^9$ and $1.5\times10^9$ for the case of a typical initial transverse emittance of 15μm and initial transverse emittance of 7.5 μm (95%, normalized) with initial 95% longitudinal emittance of 0.8 eV-sec/nucleon. The small emittance of 7.5 μm was obtained by pre-cooling at 40 GeV/nucleon (see next section). Also, for the case of initially pre-cooled emittance of 7.5 μm we choose β*=0.5m (since we should not be limited by losses in triplets in this case), while for large initial emittance of 15 μm we use present β*=0.8m. The luminosity values are given for 112 bunches.

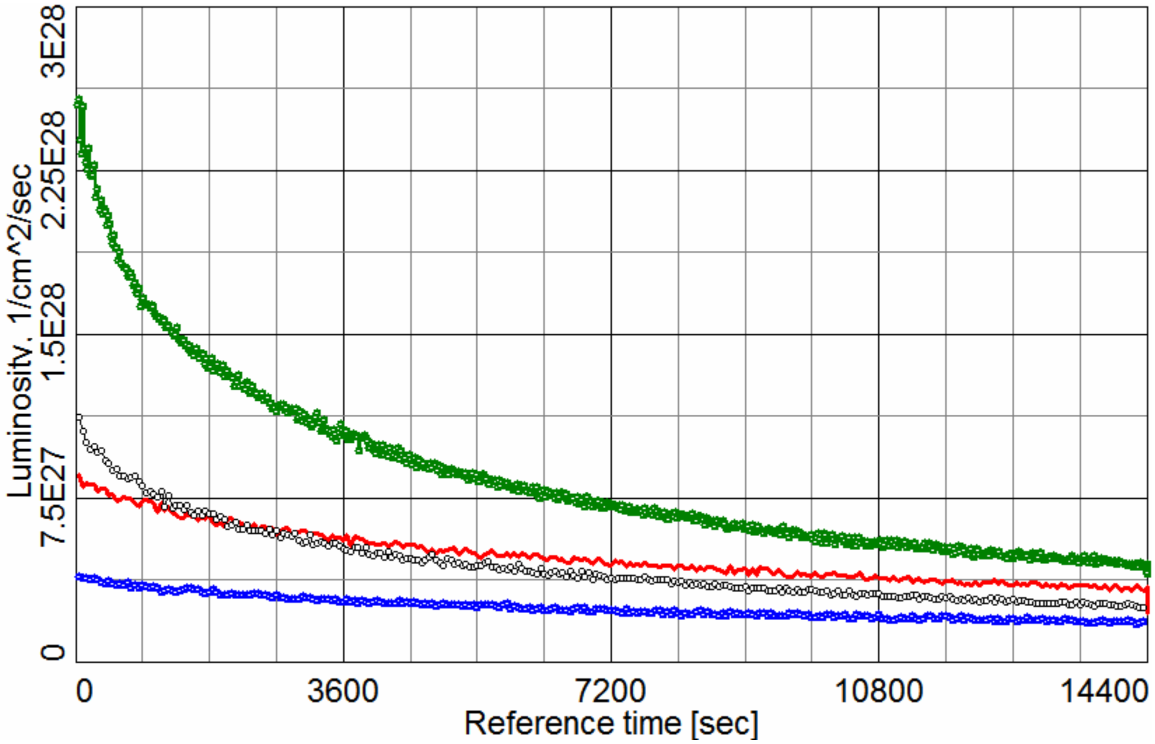


Figure 1. Luminosity of gold ions at 100 GeV/nucleon : 1) green – gold ions bunch intensity $N=1.5\times10^9$, initial emittance $\varepsilon_x=7.5$ μm (95%, normalized), β*=0.5m; 2) gray – $N=1.0\times10^9$, initial pre-cooled $\varepsilon_x=7.5$ μm (95%, normalized), β*=0.5m; 3) red – $N=1.5\times10^9$, $\varepsilon_x=15$ μm (95%, normalized), β*=0.8m; 4) blue – $N=1\times10^9$, $\varepsilon_x=15$ μm (95%, normalized), β*=0.8m.

For the green curve (pre-cooled, $1.5\times10^9$) in Fig. 1 the average luminosity (without the vertex cut) is $1\times10^{28}$ $cm^{-2}s^{-1}$ while for the red (base emittance, $1.5\times10^9$) and grey (pre-cooled, $1.0\times10^9$) curves it is about $5\times10^{27}cm^{-2}s^{-1}$. The blue curve is for the initial base emittance of $\varepsilon_x=15$ μm and $1\times10^9$ ions per bunch. As a result, without stochastic cooling, one may expect to get about factor of 2 improvement in average luminosity by pre-cooling at low-energy with R&D ERL.

Note, that without pre-cooling at lower energy and the same intensity per bunch ($1.5\times10^9$), one may expect average luminosity of about $5\times10^{27}$ $cm^{-2}s^{-1}$ (full luminosity without the vertex cut) without stochastic cooling but with the planned 56MHz RF upgrade [4] and up to $7\text{-}8\times10^{27}$ $cm^{-2}s^{-1}$ with an addition of all-plane stochastic cooling system [5]. In other words, stochastic cooling offers at least 60% improvement (possibly more due to the control of bunch length) on top of luminosity with just 56 MHz cavity upgrade along. For the case of pre-cooled gold ion beam emittance by a factor of two to 7.5 μm initial, stochastic cooling may provide further luminosity improvement. If one assumes, for example, 60% luminosity improvement with stochastic cooling for such pre-cooled beams it would bring an average luminosity per store to the level of about $1.6\times10^{28}cm^{-2}s^{-1}$. In such a case, there is a potential two-fold improvement in luminosity compared to the expected luminosity of about 6-8×$10^{27}$ $cm^{-2}s^{-1}$ for nominal initial emittance of 15μm with the 56 MHz RF and full 3D stochastic cooling upgrades [5]. Note that for such high luminosities shorter stores of about 3-4 hours compared to present 5-6-hour stores would be more optimal due to significant beam intensity loss on burn-off process in collisions.

Figures 2-3 show evolution of beam emittance and bunch length for the case of highest bunch intensity of $N_i$=1.5×$10^9$ and longitudinal 95% bunch emittance of 0.8 eV-sec/nucleon. The emittances plotted in Fig. 2 are RMS un-normalized, so that to get a conventional 95% normalized emittance the values in Fig. 2 should be multiplied by βγ•6=642, for this case. Note that final values of emittances at the end of 5-hour store are relatively small, which is a consequence of the fact that bunch length with 56MHz RF is relatively long as well as the fact that we used IBS-lattice from Run-8 with 95° phase advance per FODO cell which reduces transverse IBS growth rate [7, 8]. Also note that for such high luminosities significant portion of bunch intensity is lost on burn-off process in collisions which also slows down IBS growth rates.

It is expected that bunch length growth due to IBS will be controlled by stochastic cooling, which was not included in present simulations. Without control of bunch length with cooling, significant part of the luminosity will be outside of the vertex with ±30cm, as well as substantial part of luminosity will be lost on the "hour-glass" effect when RMS bunch length becomes comparable to the β* value. In Fig. 1 luminosities were quoted without reduction on the hour-glass effect assuming that some control of bunch length will be possible. Otherwise, without control of bunch length growth, for the case of small β*=0.5m and bunch length growth shown in Fig. 3, the reduction factor in luminosity will be 0.76, and the highest quoted average over store luminosity value in Fig. 1 would be 0.76•1×$10^{28}$ $cm^{-2}s^{-1}$.

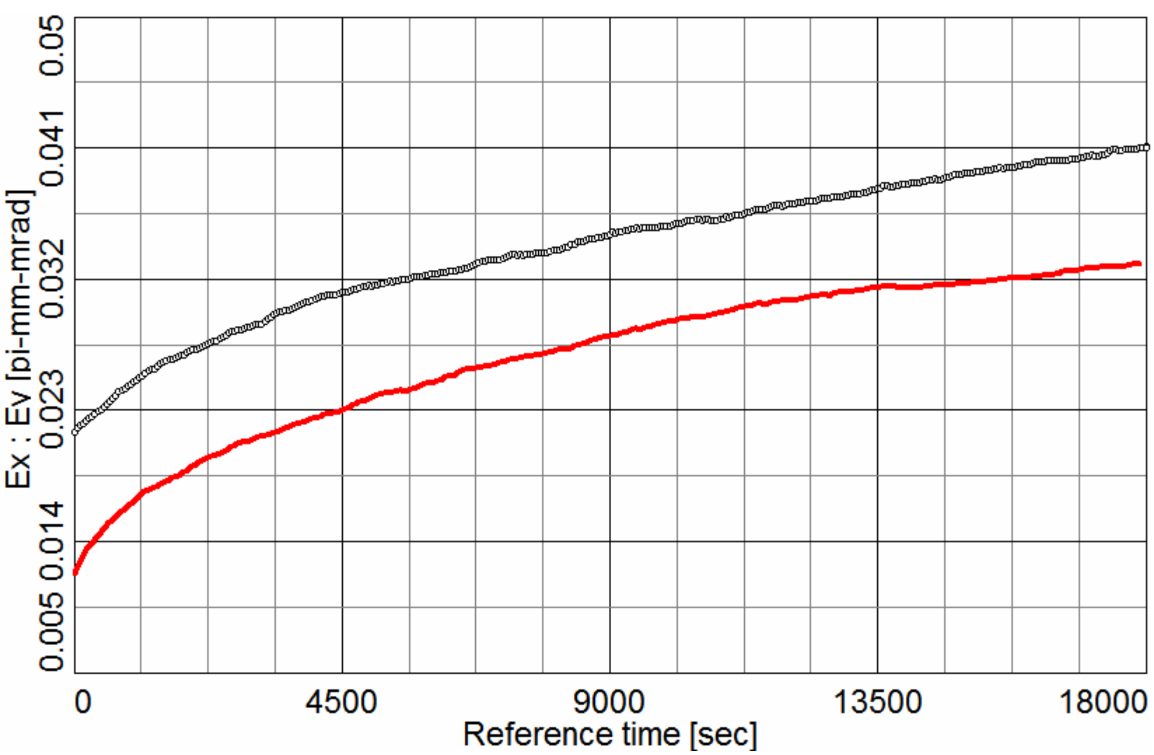


Figure 2. Evolution of RMS un-normalized emittance of Au ions at 100 GeV/nucleon for bunch intensity N=1.5×$10^9$, longitudinal emittance of 0.8eV-sec/nucleon, 56 MHz RF with 2.5MV: 1) red curve – pre-cooled beam with initial 95% normalized emittance of 7.5 μm, final emittance 21 μm; 2) black upper curve – nominal initial emittance of 15 μm, final emittance 26.3 μm.

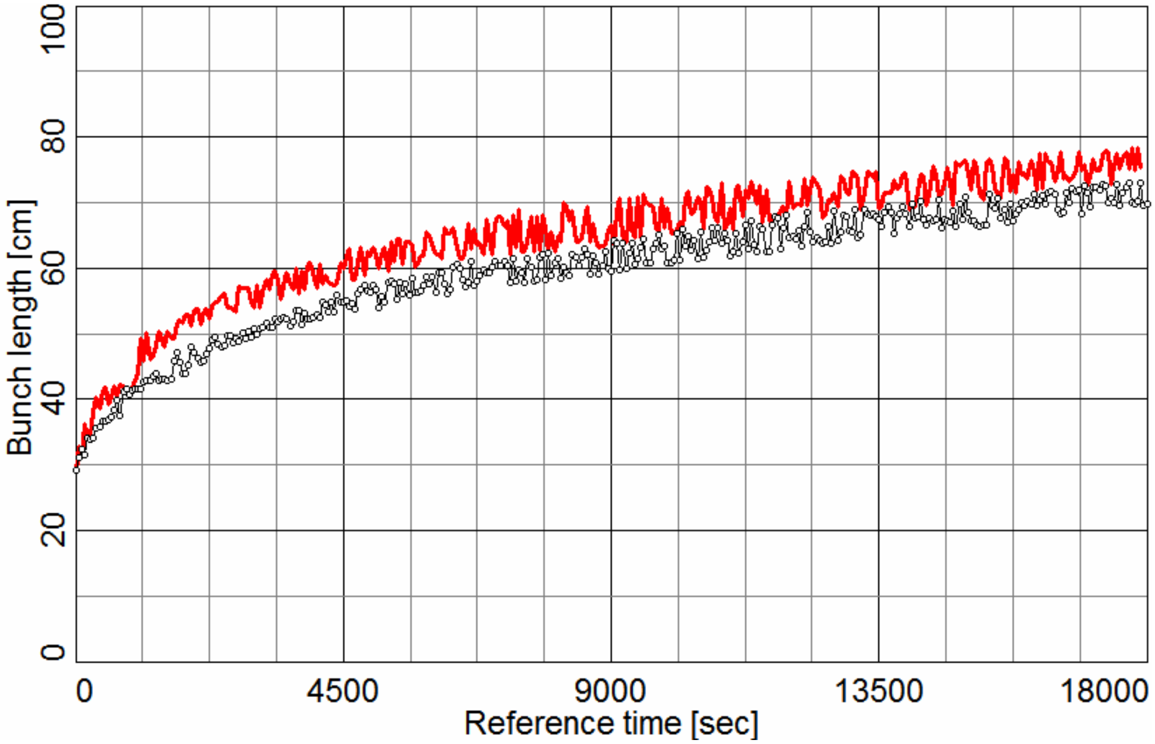


Figure 3. Evolution of RMS bunch length of Au ions at 100 GeV/nucleon for bunch intensity $N=1.5\times10^9$, longitudinal emittance of 0.8 eV-sec/nucleon, 56 MHz RF with 2.5MV: 1) red curve – pre-cooled beam with initial 95% normalized emittance of 7.5 μm, 2) black upper curve – nominal initial emittance of 15 μm.

To summarise, it appears that pre-cooling of the transverse emittance of gold ions with R&D ERL at lower energies can further improve Au-ion luminosity of RHIC at top energy of 100 GeV/nucleon compared to the expected future RHIC performance with nominal transverse emittances.

## Parameters of electron cooler for pre-cooling

This section briefly summarizes the parameters of the electron cooler used in simulations for pre-cooling of gold ions at 40 GeV/nucleon. The cooler design is based on the high-energy non-magnetized cooling approach developed at BNL for cooling ions at 100 GeV/nucleon [3]. Due to a strong dependence of electron cooling rates on relativistic $\gamma$, pre-cooling at 40 GeV/nucleon allowed us to simplify parameters of the cooler significantly, compared to the high-energy cooler for ions at 100 GeV/nucleon. The main goal of these studies was to check whether pre-cooling can be done with parameters of electron beam close to those expected from R&D ERL which can directly benefit to the RHIC program in the nearest future.

To provide fast pre-cooling with relatively short cooling section (20 meters per ring) we used electron bunch trains (similar to the low-energy cooling approach based on 703MHz gun [9] or pre-cooling for eRHIC). In this approach, there are 9 bunches in each electron bunch train (separated by 42 cm, corresponding to 703 MHz RF in ERL). The repetition frequency of these bunch trains is 9.4MHz so that every ion bunch in RHIC is cooled by means of such electron bunch train. For the present simulation we used 1.56nC charge in each electron bunch, similar to the charge expected in R&D ERL. Parameters of electron cooling system can be further optimized in the future, after the

R&D ERL is commissioned and electron beam parameters are established experimentally. Commissioning of the R&D ERL is presently scheduled for FY09-10.

| | |
|---|---|
| Kinetic energy, MeV | 21 |
| Length of cooling section, m | 20 |
| Charge per bunch, nC | 1.56 |
| Total charge in bunch train (9 bunches), nC | 14 |
| RMS momentum spread | 0.0008 |
| RMS normalized emittance, μm | 3 |
| RMS beam radius in cooling section, mm | 2.2 |

Table 1. Parameters of electron beam used in simulations for pre-cooling of gold ions at 40 GeV/nucleon.

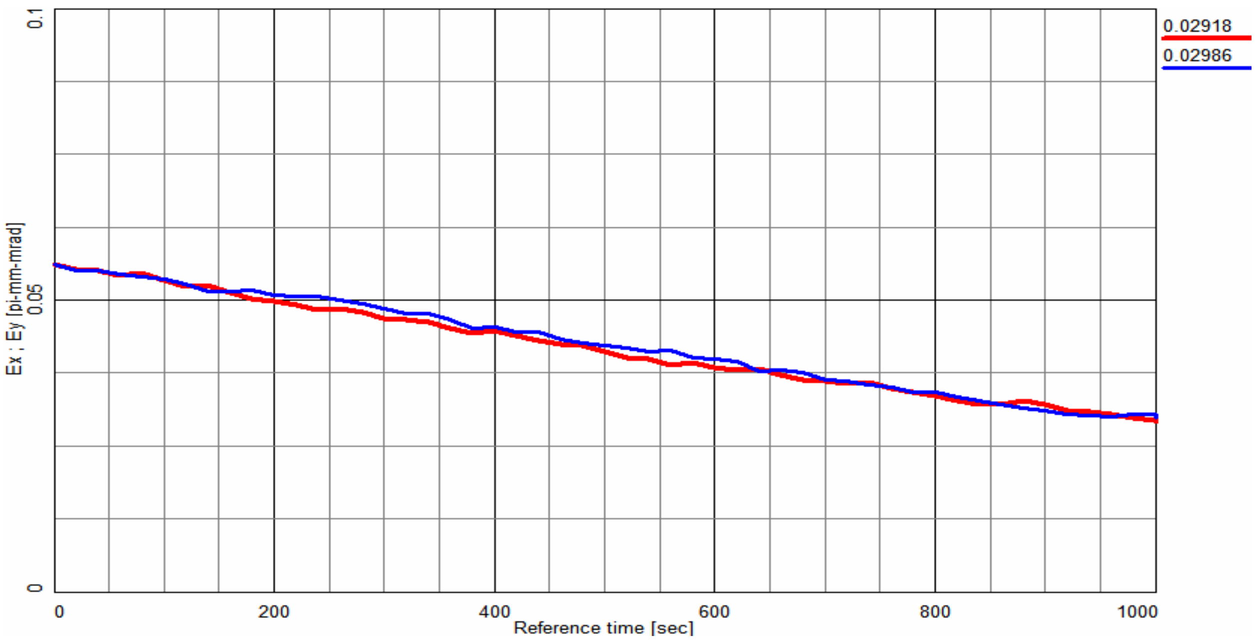


Figure 4. Cooling of the horizontal and vertical emittance (rms, un-normalized) of Au ion beams at 40 GeV/nucleon with electron beam parameters given in Table 1.

Using the parameters of the electron cooler given in Table 1, as shown in Fig. 4, one can cool transverse emittance by a factor of 2 in about 20 minutes. Note, that a 3rd harmonic cavity may be needed to get the required energy spread of the electron beam. The parameters of the cooler can be further optimized as required. This would call a for comprehensive electron cooling and electron beam dynamics studies for the design of electron cooling section at this energy.

## Acknowledgement

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