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PROJECTIONS OF POTENTIAL LUMINOSITY IMPROVEMENT FOR LOW-ENERGY RHIC OPERATION WITH ELECTRON COOLING

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Introduction

Electron cooling was proposed to increase luminosity of the RHIC collider for heavy ion beams at low energies [1-2]. Luminosity decreases as the square of bunch intensity due to the beam loss from the RF bucket as a result of the longitudinal intra beam scattering (IBS), as well as due to the transverse emittance growth because of the transverse IBS. Both transverse and longitudinal IBS can be counteracted with electron cooling. If IBS were the only limitation, this would allow one to keep the initial peak luminosity close to constant throughout the store essentially without the beam loss (provided that loss of ions due to recombination is counteracted, and acceptance of the RF bucket is sufficient). In addition, the phase-space density of the hadron beams can be further increased by providing stronger electron cooling. Unfortunately, the defining limitation for low energies in RHIC is expected to be the space charge [3], which prohibits strong cooling at lowest energies of interest. Experimental studies of the space-charge effects and beam lifetime in RHIC were reported in Refs. [4-5]. Additional limitations at low energies and their possible mitigations were discussed in Refs. [6-7].

Recently, new low-frequency RF systems were suggested which may help to mitigate limitations of beam lifetime observed at low energies, including the space-charge effects, and thus could offer better path towards luminosity improvement with cooling at low energies [8-9]. The corresponding studies of IBS for RHIC operation with various RF systems were reported in [10].

This Note clarifies what assumptions were used for various scenarios and thus what luminosity improvement one may expect from cooling with an existing 28 MHz RHIC RF system and with the new low-frequency RF systems proposed.

Luminosity limits at low energies in RHIC

In a collider, maximum achievable luminosity is typically limited by the beam-beam effects. However, at low-energy RHIC operation with heavy ions the dominant beam intensity limitation is expected from the direct space-charge effects of the beam [3]. A particle within the beam can experience amplitude growth and be lost if its tunes get inside the stopband of the imperfection resonance. In general, since the growth rate associated with the resonance depends on the tune spread within the beam, the strength of the resonance and its order, one can accommodate smaller tune spread when interested in longer beam lifetime. A beam lifetime in excess of several minutes have been achieved with the tune spread of about 0.1 [11]. In LEAR, it was possible to accommodate the space-charge tune shifts of about 0.1 with a proper choice of the working point and with the help of electron cooling [12].

The initial space-charge tune spread values during RHIC operation at γ=4.1 were close to 0.1. The short beam lifetime was attributed to a combination of several effects [4-7]. For a slightly higher energy of γ=6.2, significantly better beam lifetime was measured for a comparable space-charge tune spread values. In addition, significant effects on the beam lifetime were observed when beams were put into collisions. For the space-charge tune spread larger than 0.05 it appeared difficult to find sufficient space free from the dangerous resonances on the tune diagram to avoid effects of beam-beam on the lifetime. When the space-charge tune spread is modest (0.03-0.05) and beam-beam parameter is much smaller than the space-charge tune spread, one may expect to find the working point where effects of beam-beam are minimized, which was successfully tested experimentally in RHIC in 2011 as part of the Accelerator Physics Experiments (APEX).

Performance expected with cooling

The role of electron cooling for the lowest energy points is to counteract IBS: this prevents transverse emittance growth and intensity loss from the RF bucket due to the longitudinal IBS. As the energy is increased, the space-charge effect on the hadron beam becomes smaller which permits cooling of the transverse or longitudinal emittances of the hadron beams as well, allowing in turn to reduce the β^*. During RHIC operation at γ=4.1 and γ=6.2, measured fast time component of the beam lifetime decay was much shorter than expected from the IBS and was attributed to other effects [4-7]. As a result, beam lifetime at the lowest energy points has to be significantly improved first in order to expect substantial luminosity gains from electron cooling.

Since space-charge driven beam lifetime prohibits strong cooling of beam emittance or bunch length at lowest energies, an approach of operation with longer bunch length was recently suggested [8]. As an example, the bunch length was increased by using the 9 MHz RF system instead of the 28 MHz RF, which would allow us to cool transverse emittance by the same amount the bunch length was increased (keeping the space-charge tune shift constant), allowing to reduce the β^* by having smaller beam size in the triplets. In simulations (ideal: with only IBS-driven beam lifetime), it was shown that an additional factor in luminosity improvement may be possible. Since transverse cooling will increase available transverse acceptance at low energies, beam lifetime is expected to be improved as well, similar to the beam lifetime improvement with larger transverse acceptance for the same space-charge tune spread in the measurements [5]. Therefore, a new low-frequency RF, 9 or 4.5 MHz [9], offers a better path forward towards luminosity improvement with electron cooling and beam lifetime improvement at low energies. Additional advantages of the new RF system is a possibility to provide a wide range of energies available for physics as described in [9].

With an existing 28 MHz RF system we do not have the same flexibility as with the low-frequency RF because of the shorter bunches and thus large space-charge tune spread. However, because of significant beam losses from the RF bucket (due to limited longitudinal acceptance), one should be able to provide some modest transverse cooling without increasing the space-charge tune spread substantially. As a result, one might expect some improvement in beam lifetime, although it will not be as good as with the low-frequency RF system and longer bunches.

Below we present simulations [13] of electron cooling for the present 28 MHz RHIC RF and discuss what luminosity improvement could be expected. For the purpose of this Note, details of an electron cooler being used and electron beam parameters are not essential, since electron cooler should provide beam parameters and net cooling power adequate for each cooling scenario being considered. For completeness, for the two scenarios which are shown below parameters of electron cooler are provided.

Luminosity with present 28 MHz RHIC RF system

Figure 1 shows simulation of electron cooling at γ=4.1 (c.m. energy of ion beams 7.7 GeV). Since initial space-charge tune spread is already 0.05, we cannot cool transversely significantly. In simulations shown, only modest transverse cooling was applied so that maximum space-charge tune spread increases only to about 0.1. Thus we make a speculative assumption that a reasonable beam lifetime may be achievable for such a significant tune spread because transverse acceptance is increased due to cooling and becomes comparable to the acceptance which we had in experiments at slightly higher energy of γ=6.2, at which much better beam lifetime was measured [4-5].

For simulations shown in Fig.1, we assumed electron cooler with the cooling section length of 10 m, and bunched electron beam produced by the SRF gun. The total electron charge of 2 nC was put on each ion bunch. For an approach based on the 112 MHz gun, this could be accomplished by splitting this total charge over several electron bunches and providing longitudinal painting along the ion bunch (details of cooler parameters can be found in [14] and in the White Paper on low-energy electron cooler for RHIC in preparation).

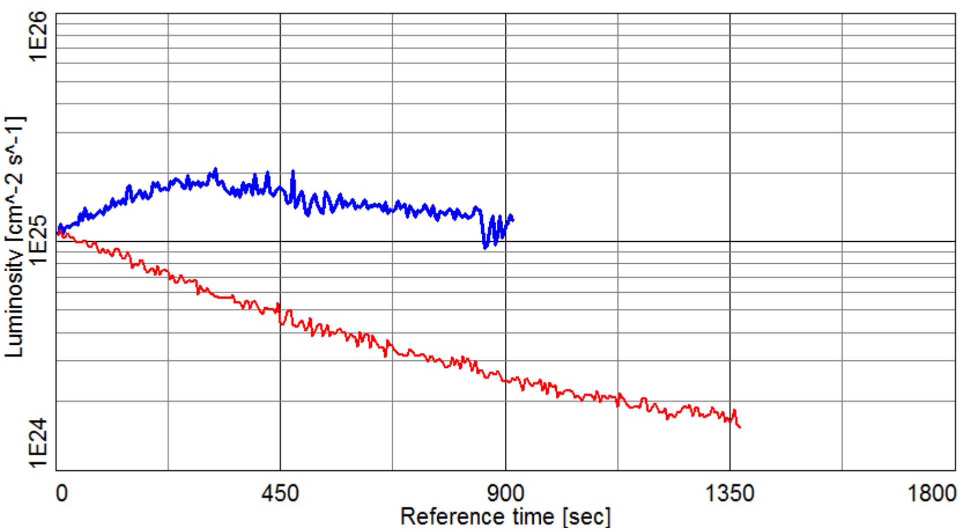

Figure 1. Luminosity at γ=4.1 and 28 MHz RF (450 kV) for β*=3m, 111 bunches with $5\cdot10^8$ bunch intensity and transverse 95% normalized emittance of 15 mm mrad. Bottom red curve: IBS and losses from RF bucket only; top blue curve: IBS, electron cooling and ion losses from the RF bucket (no other losses like possible loss of ions on recombination with electrons if not compensated, which is small for present parameters, etc.).

In simulation shown in Fig. 1, an improvement factor of about 3 in integrated luminosity could be expected with cooling. In addition, during 2010 RHIC run we had transverse emittance growth and were not yet able to operate with β* of 3 m as shown in Fig. 1. If without cooling operation at this energy would be possible only with β*=6 m as in 2010, than up to a factor of 6 improvement with cooling might be possible. However, simulations in Fig. 1 include only IBS and losses from the RF bucket and do not account for an additional beam lifetime limitation observed experimentally. It is thus only speculated that the space-charge driven beam lifetime should improve with the help of the transverse cooling. Without an actual improvement of beam lifetime at this energy it could result in about factor of 2 luminosity increase only. As a result, with an existing 28 MHz RF system and experimentally observed beam lifetime limitations at γ=4.1, one may expect anywhere from only a factor of 2 to about factor of 6 improvement from cooling.

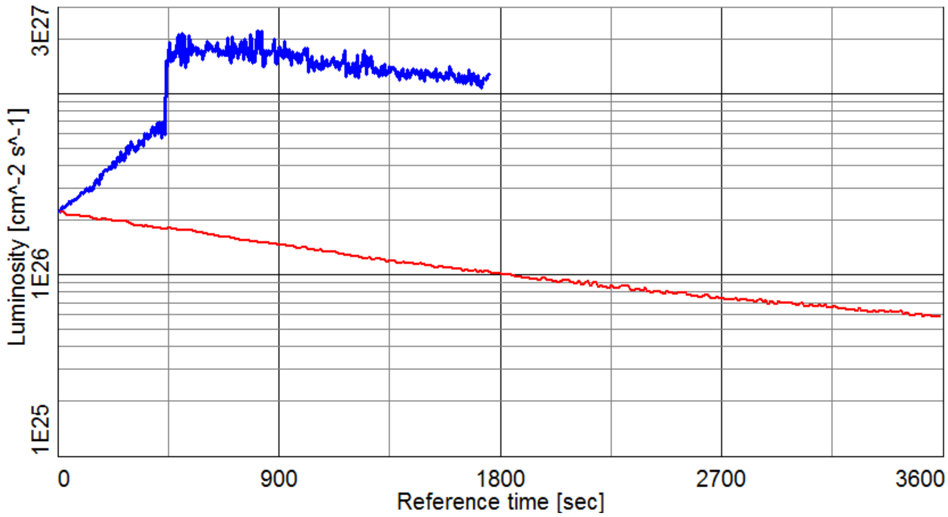

Figure 2. Luminosity at γ=10.7 and 28 MHz RF (450 kV) for initial β^*=3m, 111 bunches with $1.5 \cdot 10^9$ bunch intensity and transverse 95% normalized emittance of 15 mm mrad. Bottom red curve: IBS and losses from the RF bucket only; top blue curve: IBS, electron cooling and ion losses from the RF bucket (no other effects included).

As the energy is increased, the space-charge effect on the hadron beam becomes smaller which permits cooling of the transverse emittance, allowing in turn to reduce the β^*. In addition, better beam lifetime may be expected due to larger transverse acceptance available at higher energies. Figure 2 shows example of luminosity simulation for the highest energy of γ=10.7 (c.m. energy of 20 GeV) for which electron cooling is being considered. Here we used 10 m electron cooling section and total electron charge of 5 nC with an angular spread of electron beam in the cooling section comparable to the one of an ion beam [14].

At γ=10.7 for bunch intensity of $1.5 \cdot 10^9$, the space-charge tune spread is only about 0.03 for the 28 MHz RF (450 kV) which allows to cool transverse emittance and decrease β^* as shown in Fig. 2. Since more transverse acceptance is available due to smaller beam size at this energy one might be able to achieve good beam lifetime even with the space-charge tune spread close to 0.1 (although effects of beam-beam on beam lifetime, which are not accounted for in present simulations, could be still a problem). Note that during low-energy run at γ=10.5 in 2011 we were not able to inject high bunch intensity in the lattice with small β^* so that luminosity improvement from cooling would be even larger than indicated in Fig. 2 if compared to the luminosity already achieved experimentally at this energy (see Figs. 3-4).

Overall possible projection of luminosity improvement as a function of energy is shown in Fig. 3. One can see that close to 10-fold improvement from cooling may be expected only at highest energies if one uses existing 28 MHz RHIC RF system. At lowest energy of γ=4.1 expected luminosity improvement can be anywhere from a factor of 2 only to about factor of 6, as explained above due to significant transverse acceptance limitation and uncertainty how/whether beam lifetime will improve if only very weak transverse cooling is allowed. For the blue dash curve in Figs. 3-4 we used factor of 3 as a possible luminosity improvement factor for the lowest energy of γ=4.1 compared to a measured averaged per store luminosity in 2010-11 (trying to account for observed beam lifetime indirectly).

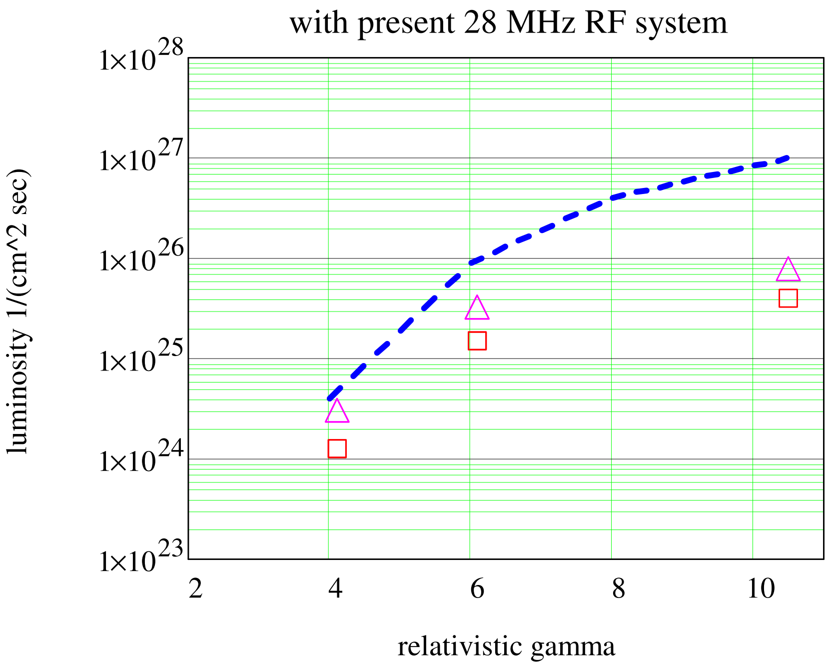

Figure 3. Projection of total average per store luminosity for 111 bunches of Au ions in RHIC for the space-charge tune spread of ΔQ_{sc}=0.05 with electron cooling. Red squares: measured average per store luminosity in Beam Energy Scan I (BES-I); magenta triangles: measured maximum luminosity; blue line: expected luminosity improvement with cooling and existing 28 MHz RF system.

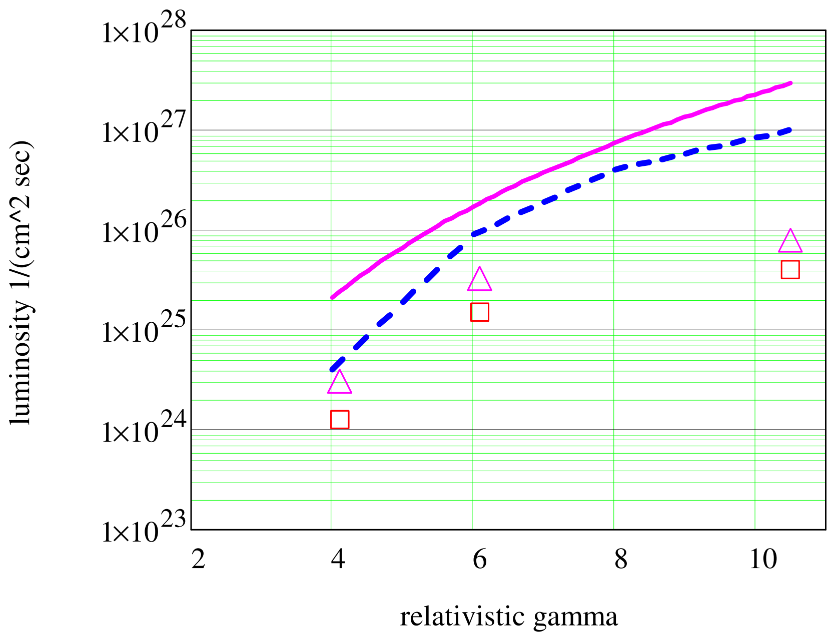

Figure 4. Projection of total average per store luminosity for 111 bunches of Au ions in RHIC for the space-charge tune spread of ΔQ_{sc}=0.05 with electron cooling. Red squares: measured average per store luminosity in BES-I; magenta triangles: measured maximum luminosity; blue line: expected luminosity improvement with cooling and present 28 MHz RF system. Magenta top solid line: with cooling and long ion bunches (proposed new low-frequency RF).

In Figures 3-4, red squares and magenta triangles indicated average per store and maximum luminosities delivered during the low-energy RHIC physics runs in 2010-11, respectively.

As indicated by the blue dash line in Fig. 4, expected luminosity improvement in luminosity becomes very modest at lowest energy points. More than that, improvement factors are uncertain due to the limitations observed at low energies experimentally. The curves stop at lowest energy of γ=4.1 (c.m. energy of 7.7 GeV) since RHIC was not able yet to operate at lower energies with conditions suitable for physics program.

Since operation with longer bunches allows us to apply significant transverse cooling which should improve beam lifetime at lowest energies, it offers better path forward towards luminosity improvement, as indicated by the top magenta line on Fig. 4. Note that projection of luminosity improvement using low-frequency RF system and long ion bunches shown by the magenta line corresponds to an ideal improvement, of course (with beam lifetime driven by IBS only which is assumed to be counteracted successfully by electron cooling). The purpose of such a projection is just to indicate a potential for possible luminosity improvement with longer bunches. Such projection does not include beam lifetime limitations observed at lowest energies for large values of the space-charge tune spread and additional limitations caused by the beam-beam effects [4-5]. In blue dash curve we tried to account for such limited improvement at the lowest energies indirectly. In reality, achievable luminosity will be probably smaller than indicated by the magenta line (blue dash line for the 28 MHz RF) because of the uncertainty how electron cooling can improve the beam lifetime observed and due to a required experimental optimization between various processes, including 3-D electron cooling (this will be the first electron cooling in a collider), ion beam loss on recombination and beam lifetime.

Summary

Low-energy RHIC physics program would greatly benefit from a significant luminosity increase at low energies. It was reported before that using electron cooling to counteract IBS at these energies and providing longer physics stores could increase luminosity significantly, with expected limitation imposed by the space-charge effects. Experimental studies of beam lifetime at low energies in RHIC suggest that luminosity improvement from cooling could be limited to a very modest increase for the lowest energies of interest unless beam lifetime is significantly improved.

Recently, it was suggested that for the lowest energies, where we are limited by the space charge, an improvement in luminosity and beam lifetime may be expected by operating with longer bunches and low-frequency RF system, which would extend benefits of cooling at such low energies [8]. Further advantages of new low-frequency RF system were described in Ref. [9], with corresponding studies of IBS and desired RF voltages reported in [10].

Here, we summarize what luminosity improvement may be expected for existing 28 MHz RHIC RF and new low-frequency RF systems proposed. Luminosity projection lines shown in Figs. 3-4 correspond to an ideal condition (they do not directly include experimentally observed limitations due to the space-charge and beam-beam at lowest energies of RHIC operation). Some optimizations between 3-D electron cooling, loss of ions on recombination with electron beam and ion beam lifetime due to various effects will be needed experimentally which will determine how close one can get to the projected luminosity improvement for the scenarios presented. New low-frequency RF system together with an appropriate electron cooling suggests the best path forward towards realization of better operational conditions in RHIC for physics program at low energies.

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