UPGRADING RHIC FOR HIGHER LUMINOSITY*

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Abstract

While RHIC has only just started running for its heavy ion physics program, in the first run last summer, we achieved 10% of the design luminosity. In this paper we discuss plans for increasing the luminosity by a factor of 35 beyond the nominal design. A factor of 4 should be straightforward by doubling the number of bunches per ring and squeezing the β^* from 2 to 1 m at selected interaction points. An additional factor of 8 to 10 could be possible by using electron cooling to counteract intrabeam scattering and reduce emittances of the beams.

1 GOLD-GOLD LUMINOSITY UPGRADE

The RHIC lattice allows for simultaneous operation at six different interaction regions, each with a design luminosity of 2×10^{26} cm^{-2} s^{-1} for gold beams. It is expected that this design luminosity will be reached during the FY2001 heavy ion run. The machine parameters are shown in Table 1 in column "RDM" (RHIC Design Manual).

Scheme	Units	RDM	RDM+	RHIC II
ε initial	$\pi\mu$m	15	15	15
ε final	$\pi\mu$m	40	40	<6
β^*	m	2	1	1
N_B		60	120	120
N	10^9	1	1	1
ξ		0.0016	0.0016	0.004
σ'^*	μrad	108	153	95
σ^*	μm	216	150	95
L_0	$10^{27}\text{cm}^{-2}\text{s}^{-1}$	0.8	3.2	8.3
<L>	$10^{27}\text{cm}^{-2}\text{s}^{-1}$	0.2	0.8	7

Table 1: The luminosity performance of RHIC in scenarios of Au+Au collisions at 100 GeV/nucleon. The luminosity averages given for "RDM" and "RDM+" are averaged over a 10 hour store. For the "RHIC II" scenario luminosity is averaged over 5 hours due to the beam-beam burn-off from actual collisions.

In table 1 (and in the following), ε is the normalized 95% emittance, β^* is the IP beta function, ξ is the beam-beam parameter per IP, N_B the number of stored bunches, N the number of ions per bunch, σ'^* angular beam size at IP, σ^* rms beam size at the IP, L_0 the initial luminosity and <L> the average luminosity. A first upgrade of the luminosity by about a factor of four consists of increasing the number of bunches from about 60 to about 120 and decreasing β^* from 2 m to 1 m. This will not require any substantial new hardware. However, due to the larger beam size in the interaction triplets the non-linear local correction elements will have to be carefully optimized. It is expected that this level of performance can be reached during the FY2003 running period. The machine parameters for this enhanced luminosity are shown in column "RDM+".

A further increase of the number of bunches or decrease of β^* is possible and has been studied. However, it would require substantial upgrades or modifications of the collider detectors. The former will reduce the time interval between collisions to less than 100 ns and the latter would require additional triplets close to the collision point. Alternatively the luminosity can be enhanced by increasing the number of ions per bunch or by de-creasing the transverse emittance of the beam. However, already at the present bunch intensity and beam emittance the luminosity is expected to decrease very rapidly during a store due to intrabeam scattering (IBS). This is the reason for the large difference between peak and average luminosity in Table 1. To overcome this limitation we are proposing to counteract intrabeam scattering by electron cooling the gold beams at storage energy.

Cooling the gold beams at 100 GeV/nucleon requires electron beam energy of about 50 MeV and an average beam current of about 10 mA. A detailed discussion of the electron cooling of RHIC can be found in a companion paper [1]. With electron cooling the beam emittance can be reduced and maintained throughout the store and the luminosity increased until non-linear effects of the two colliding beams on each other limit any further increase (beam-beam limit). With the parameters shown in Table 1 in column "RHIC II", a luminosity increase by 35-fold over RHIC design luminosity could eventually be achieved. The RHIC electron cooler could be completed by FY2006.

Upgrading the heavy ion beam from gold to uranium ions at similar bunch intensities will require the Electron Beam Ion Source (EBIS), which is presently in development [2].

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2 LUMINOSITY UPGRADES FOR POLARIZED PROTON OPERATION

The RHIC spin physics program uses the unique capability of RHIC to accelerate and collide polarized proton beams at a center-of-mass energy of up to 500 GeV and a luminosity of up to 2×10^{32} $\text{cm}^{-2}\text{s}^{-1}$.

Although the physics potential of this capability still needs to be exploited there are upgrades to RHIC that can significantly extend the physics reach of this program.

Since the spin physics program relies on high precision measurements a luminosity upgrade is most useful. The proton beam intensity can be increased, or the beam emittance be decreased until the beam-beam limit is reached which corresponds to a luminosity of about 4×10^{32} cm^{-2} s^{-1}. The RHIC electron cooler proposed for heavy ion operation could be used at injection energy to achieve this reduction of the proton beam emittance. The machine parameters for the expected luminosity during FY2001 (column “RDM”), the enhanced luminosity as discussed above for gold beams (column “RDM+”), and the luminosity at the beam-beam limit (column “RHIC II”) are listed in Table 2.

Scheme	Units	RDM	RDM+	RHIC II
ε	$\pi\mu$m	20	20	12
β^*	m	2	1	1
N_B		60	120	120
N	10^{11}	1	2	2
ξ		0.0037	0.0073	0.012
σ'^*	μrad	79	112	86
σ^*	μm	158	112	86
L_0	$10^{31}\text{cm}^{-2}\text{s}^{-1}$	1.5	24	40

Table 2: The luminosity performance of RHIC in scenarios of p+p collisions at 250 GeV per beam. Note that for the RHIC II and RDM+ scenarios, we have assumed that beams are colliding at only two or three IP’s respectively, so the total tune shift limit is still 0.024.

It seems also possible to install in one or two interaction regions an additional pair of high-field focusing triplets that would reduce β^* to about 30 cm, increasing the luminosity by an additional factor of 3. Finally, the number of bunches in each ring could be increased from 120 to 360, increasing the luminosity by another factor of 3. These two last upgrade options would also require an upgrade to the detectors.

Taken together these upgrades would allow for polarized proton luminosity at 500 GeV of up to 4×10^{33} $\text{cm}^{-2}\text{s}^{-1}$, a 20-fold increase over the present luminosity goal for pp.

It may also be interesting to increase the center-of-mass energy of the polarized proton collisions. The arc dipoles and quadrupoles in RHIC have a margin of about 30% beyond the operating field for 250 GeV beam energy. Exploiting this margin would allow for operation at a center-of-mass energy of about 650 GeV. One or two interaction regions would have to be refitted with higher field magnets to produce collisions whereas the remaining interaction regions could be retuned for simply transporting the higher energy beam without producing collisions.

3 SINGLE BUNCH INTENSITY LIMIT

The beam-beam parameter ξ, which is proportional to N/ε, places a fundamental limit on the single bunch phase space density N/ε, since $\xi=1.5rN/\varepsilon$ where r is the classical ion radius. ξ has a critical maximum value which cannot be surpassed, due to nonlinear dynamics. Note that neither the beta function β^* nor the energy γ enter the expression for ξ, thus the single bunch intensity limit cannot be enhanced or reduced by optics or energy upgrades. Also note that ξ is a “beam-beam” parameter, not a “tune shift” parameter – if there are N_{IP} head-on collisions per turn, a small amplitude particle suffers a total tune shift of

$$\Delta Q=N_{IP}\cdot\xi$$

The exact critical maximum value ξ_c depends on many details such as the number of head-on collisions per turn, the presence of long range beam-beam interactions, the betatron and synchrotron tunes, the chromaticity, the possible presence of external sources of tune modulation, damping, etc. Even without a detailed model of an upgraded RHIC, it is reasonable to assume that

$$\xi_c \approx 0.024/N_{IP}$$

an approximate value which is justified not only by general calculations and simulations, but also by direct experience at the SPS[3], and the Tevatron[4, 5]. It is unclear how electron cooling may affect this limit.

The single bunch intensity limit due to the beam-beam interaction is directly proportional to the emittance, which is nominally expected to increase from about 15 μm to about 40 μm in the course of a 10-hour store, due to intrabeam scattering (IBS). Using nominal numerical values for ξ_c and ε, the maximum single bunch gold intensity is found to be

$$N_c=2.6\cdot10^9(\varepsilon/15\mu\text{m})(\xi_c/0.004)$$

This is to be compared with the nominal single bunch intensity of 10^9 ions per bunch quoted in the RHIC Design Manual [6]. The beam-beam limit is not far away.

4 LUMINOSITY AT THE BEAM-BEAM AND ANGULAR APERTURE LIMITS

The luminosity per interaction point is given by

$$L=N_B\xi^2\sigma'^{*2}(4\pi f_{rev}\gamma^2/r^2)$$

Where f_{rev} is the revolution frequency. The term in parentheses is constant at fixed energy. This parameterization is appropriate when the maximum luminosity is simultaneously limited – or nearly limited – by beam-beam effects and by interaction region optics, since then the values of ξ and σ'^* are well known.

The beta function at a distance d from the IP, still in the drift region before the first quadrupole, is given by

$$\beta(d)=\beta^*+d^2/\beta^*\sim d^2/\beta^*$$

Similarly, the maximum value of $\hat{\beta}$ in the interaction region triplet is inversely proportional to the value of β^*. By analogy with the equation above, this relationship is conveniently described by introducing the nearly constant "effective triplet distance" $\hat{d}$, which is defined by

$$\hat{d} = (\hat{\beta}\,\beta^*)^{0.5}$$

The effective triplet distance also relates the angular beam size at the IP to the maximum beam size $\hat{\sigma}$, since

$$\hat{\sigma} = \hat{d}\,\sigma'^*$$

The upper limit of this maximum beam size is constrained by the requirement of an aperture at least $n \approx 8$ times the rms size of the beam in the triplet quadrupoles. Thus, the angular beam size at the IP must be less than a critical value σ'^*_c which is proportional to the "effective angular aperture" of the triplet, $a/\hat{d}$, through

$$\sigma'^* \leq \sigma'^*_c = a/\hat{d}\,n$$

Note that the critical value σ'^*_c is independent of emittance for non-pathological values of β^*. The effective angular aperture is the principal figure of merit measuring the potency of IP optics schemes. It is improved by using larger bore quadrupoles (increasing a) or by moving the triplet closer to the IP (decreasing $\hat{d}$).

At RHIC, the Effective triplet distance, $\hat{d}$ is 36 m, the triplet bore radius, a, is 65 mm and this leads to a maximum angular beam size σ'^*_c of 226 μrad, a limit which will be slightly violated if a gold beam with an emittance of ε=40 π μm is stored in a lattice with β^*=1 m. With these values, and f_{rev}= 78.3 kHz, we get

$$L=(N_B/120)(\xi/.004)^2(\sigma'^*/226\mu\text{rad})^2 4.6\cdot 10^{28}\,\text{cm}^{-2}\text{s}^{-1}$$

The next natural question to ask is what are the limits on N_B. The image current of the beam which flows in the vacuum chamber walls causes resistive heating. This is not a concern in the sections of beam pipe at room temperature, but has the potential to be a serious problem when the heat is deposited at cryogenic temperatures. A maximum average cryogenic heat load of about 0.5 to 1.0 Watt per meter can be tolerated during continuous running. An analysis [7] lead to the engineering decision to use stainless steel beam pipes without a copper coating. Fig. 1 shows the extension of that analysis to the RHIC upgrades. The linear power load depends strongly on the RMS Gaussian bunch length, and on the number of bunches.

The calculation assumes that all ion bunches have exactly the same charge, and that they are spread uniformly around the circumference. In this case the power spectrum is a series of narrow lines uniformly spaced by $N_B f_{rev}$, under a Gaussian envelope which is the Fourier transform of the bunch shape. The total linear power load is just a sum over all these spectral lines, convoluted with the vacuum chamber resistance at those frequencies – a resistance that is dominated by skin depth effects. As the number of bunches increases, the spacing between spectral lines increases like N_B, but the power in each harmonic increase like N_B^2. Thus when the bunches are longitudinally spaced by very many bunch lengths – for example, when N_B=360 – the linear power load is just proportional to N_B, as is intuitively expected.

Fig. 1 shows that this scaling breaks down when there are 2520 bunches in an ion ring, and the bunch spacing is only 1.52 m, except for very short bunch lengths less than, say, 0.25 m. The suppression of the linear power load which is implied for longer bunch lengths is weakened in more realistic situations – for example, when an abort gap is present and when the bunch populations are not all equal. Nonetheless, it is possible to store as many as 2520 bunches in the ion rings without violating the maximum heat load limit, and without losing much luminosity to the hourglass effect.

Other possible limits, which will not be discussed here, are heating of the Beam Position Monitor signal cables and the electron cloud effect.

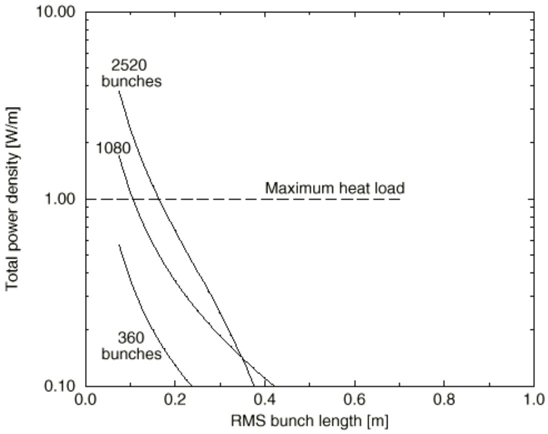

Figure 1. Linear power load deposited at cryogenic temperatures in the stainless steel vacuum chamber, due to beam image currents with 10^9 gold particles per bunch.

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