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Ultimate RHIC Performance Estimates

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The RHIC performance estimates for pp operation given in the Conceptual Design Report are intentionally conservative as to energy and luminosity. The ultimate RHIC performance was estimated by an ad-hoc committee with F. Dell, H. Foelsche, H. Hahn, S. Y. Lee, G. Parzen, E. Raka, S. Tepikian, and P. Thompson as members. The present note summarizes the committee's conclusions.

I. Proton Operation

The proton energy of 250 GeV requires a magnetic field in the arc dipoles of 3.45 T with a dipole current of 4.56 kA. The quench field in the dipoles is 4.6 T (I_q = 6.5 kA) corresponding to a quench energy of 330 GeV. However, operation above 300 GeV may be difficult in view of radiation quenching and the current lead design. It must also be pointed out that the correction coil system is designed for 250 GeV, and performance degradation at higher energy was considered acceptable. Achieving highest luminosity at or above 300 GeV will require a more elaborate magnet correction system to compensate magnet saturation effects.

The pp design luminosity of 0.84×10^{31} cm^{-2} sec^{-1} is achieved with 10^{11} protons per RHIC bunch (column 1 in Table I). This is obtained by acceleration of 12 bunches in the AGS and transfer of 5 AGS pulses to RHIC. Nominally there will be 57 bunches in RHIC thereby filling 1 out of every 6 buckets. (In practice, fast AGS ejection will provide 11 bunches and thus 5×11=55 bunches in RHIC). The present AGS can deliver about 10^{11} protons/bunch with a 1 eV•sec phase space which fits into the RHIC bucket. At higher intensities, the phase space is blown up at transition and transfer into RHIC is impossible. In the future, after addition of the gamma-transition jump and the higher harmonic rf cavity in the AGS, one can expect AGS bunches with 2 - 3×10^{12} protons with 2 eV•sec, which is the limit for transfer into RHIC. Further improvements in the gamma-transition system may put the ultimate AGS limit at 5×10^{12} protons/bunch in 2 eV•sec. Injection above the AGS transition energy (γ_{tr} = 8.5) is clearly advantageous but is not available in the present scenario. The booster would have to operate above 19.2 T in the dipoles. Increasing the booster circumference to 1/3 C_{AGS} would allow injection above the transition energy. A second booster would avoid transition energy in AGS and Booster as well.

Ignoring intensity limitations in the AGS, the maximum pp luminosity achievable in RHIC is given by the beam-beam limit. Experience with the SPS suggests a maximum $\Delta\nu$ = 0.004 per beam crossing. The maximum luminosity at the beam-beam limit is given by

$$\frac{L}{\Delta\nu_{B_B}} = \frac{1}{2} \frac{f_{rev}}{r_o} \frac{A}{Q^2} \frac{(\beta\gamma)}{\beta*} B\, N_B$$

whereby it is assumed that the crossing angle is increased with N_B to maintain the maximum tolerable beam-beam tune shift. In RHIC the crossing angle is limited (6 mrad) by the aperture of the first dipole BC1 thereby setting the limit on the number of protons/bunch $N_B = 1.4 \times 10^{12}$, which is well within the AGS capability after installation of the gamma-transition jump. The simple beam transfer scheme described above results in nominally $B \doteq 57$ bunches and a pp luminosity of 1×10^{32} cm^{-2} sec^{-1}.

Achieving this luminosity will require addition of power supplies to allow low beta ($\beta^* = 3$ m) insertions, external beam dump and thus extraction equipment, and more powerful rf tubes to handle the higher stored currents. The incremental cost estimate is 10M$ (6M$ extraction, 3M$ power supplies, 1M$ rf, etc.)

Achieving a pp luminosity above 1×10^{32} cm^{-2} sec^{-1} becomes more speculative. Given the limit of $N_B = 1.4 \times 10^{12}$ protons/bunch, the luminosity can be increased only by filling more buckets:

(1) Faster injection kickers in RHIC would allow a gain of 2 (or 3?). Injection of complete AGS pulses (11 bunches) is no longer possible and transfer of individual bunches becomes necessary.

(2) Acceleration in the AGS of 5×10^{12} protons/bunch with 2 eV•sec and transfer of 11 bunches in one pulse. Debunching and rebunching in RHIC results in 8×10^{11} protons/RHIC bunch and $L = 3.3 \times 10^{32}$ cm^{-2} sec^{-1}. (Second column in Table I)

(3) Injection above the AGS transition energy and acceleration in the AGS on the 72th harmonic would allow to reach the ultimate RHIC limit of 6×10^{32} cm^{-2} sec^{-1}. (Third column in Table I)

II. Polarized Proton Operation

Operation of RHIC with polarized protons will be possible. The performance is source limited: The AGS intensity after addition of the booster is estimated at about 3×10^{11} protons/bunch yielding a luminosity of about 4×10^{31} cm^{-2} sec^{-1} at 300 GeV. A preliminary evaluation of the implications for polarized proton operation in RHIC has been carried out. It was found that RHIC will need two Siberian snakes per ring to maintain polarization during acceleration and two spin rotators per beam per experimental crossing point if longitudinal polarization is desired. There are several possible designs for the snakes available. These snakes required a total $\int Bdl$ of 14×1.37 T•m with some spaces. If conventional magnets with magnet aperture of 15 cm are used, the space needed is about 22 m long. If superconducting magnets with good field aperture of 8 cm are used the space needed may be shortened by about a factor of 2. The present lattice provides adequate space for either solution.

III. Gold Operation

The ultimate performance of RHIC in the case of gold-on-gold is limited by other constraints connected to the beam growth due to intrabeam scattering. At 30 GeV/nucleon the beam intensity is limited by the dynamic aperture of the magnets. The luminosity of 6×10^{25} cm^{-2} sec^{-1} averaged over 10 hours is obtained with 1.1×10^{9} ions/bunch, zero crossing angle and standard insertion with β^{*} = 6 m. The only possible gain by a factor of 2 comes from faster injector kickers. The desire to avoid multiple collision points prevents beam transfer solutions which further reduce the distance between bunches.

At 100 GeV/nucleon, the gold beam intensity is limited by the rf bucket size to the design value of 1.1×10^{9} ions/bunch yielding a 10 hour luminosity of 4.4×10^{26} cm^{-2} sec^{-1} with an insertion having zero crossing angle and a low-beta of β^{*} = 3m. Doubling the rf voltage by adding 6 cavities with power amplifiers (at a cost of 3 to 4 M$) allows increase of the beam intensity by a factor of 5 to 5.5×10^{9} ions/bunch which is now limited by the dynamic magnet aperture. Even at this intensity the beam-beam limit is not reached after the initial fast beam growth due to intrabeam scattering. Thus operation with zero crossing angle is still possible and the luminosity which depends on the number of ions per bunch, the number of bunches and the normalized emittance as

$$L \propto \frac{B\ N_B^{2}}{\varepsilon_N}$$

is estimated at about 7×10^{27} cm^{-2} sec^{-1} averaged over 10 hours (Table II). Increasing the kicker-speed yields the ultimate gold-on-gold luminosity in RHIC of 1.4×10^{28} cm^{-2} sec^{-1}. It should, however, be pointed out that it may be difficult or impossible to accelerate 5.5×10^{9} gold ions/bunch in RHIC due to the known microwave instability when passing the transition energy (γ_T = 25). Avoiding this limitation may require another stage of acceleration between the AGS and RHIC implying a project twice the scope of the Stretcher Ring which is presently being considered. A Stretcher Ring capable of doubling the AGS energy would open the road to the ultimate RHIC performance.

References

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Table I. pp Operation @ 10h

N_B	10^{11}	8×10^{11}*	1.4×10^{12}†	
B	57	6×57	n×57	
E_{kin}	250	300	300	GeV
γ	266	320	320	
ε_N/π	23.5	33.7	43.4	$\times10^{-6}$ m
σ_H (β=50m)	0.88	0.94	1.06	mm
$A_{SL}=6\,\sigma_H$	5.3	5.6	6.4	mm
σ_H^* (β^*=3m)	0.22	0.23	0.26	mm
Δ_B (V=1.2MV)	±2.6	±2.3	±2.3	$\times10^{-3}$
$\Delta E/E$	±0.80	±1.3	±1.5	$\times10^{-3}$
σ_ℓ	0.50	0.88	1.0	m
α	0	3.7	6	mrad
$q=\frac{1}{2}\alpha\sigma_\ell/\sigma_H^*$	0	7.1	11.5	
$\Delta\nu_{BB}$	3.1	4	4	$\times10^{-3}$
$\Delta\nu_{LR}$	0	2.5	2	$\times10^{-5}$
L	0.84	33	n×10	$\times10^{31}$ $cm^{-2}sec^{-1}$
σ_I	35	8.7	6.1	cm
B in B_{arc}	3.45	4.15	4.15	T
B in BC1	4.63	4.28	3.48	T
B in BC2	2.73	2.74	2.41	T
Beam energy	0.23	13.5	n×3.8	MJ

*Rebunching in RHIC requiring 5×10^{12} p/AGS bunch in 2 eV·sec
†RHIC limit. n = 2 or 3 with faster kickers, n = 6 with rebunching in AGS

Table II. Au-Au Operation

N_b	1.1	5.5	$\times 10^9$
B	n × 57*	n × 57	
γ	100	100	
ε_N/π	31	49	$\times 10^{-6}$ m
σ_H	1.61	2.03	mm
$A_{SL} = 6\sigma_H$	9.6	12.2	mm
$\Delta_B(V = 1.2$ MV)	2.68		$\times 10^{-3}$
$\Delta_B(V = 2.4$ MV)		3.67	$\times 10^{-3}$
δ_E	1.07	1.43	$\times 10^{-3}$
$\Delta E/E = 2.5\delta_E$	2.62	3.6	$\times 10^{-3}$
σ_H^*	0.39	0.50	mm
σ_ℓ	1.42	1.90	m
α	0	0	
$\Delta\nu_{BB}$	0.9	2.8	$\times 10^{-3}$
L	n×4.4	n×69	$\times 10^{26}$ cm^{-2} sec^{-1}

* n=2 with fast injection kickers