RHIC LONGITUDINAL PARAMETER REVISION

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Abstract

Recent experience showed that bunch rotations are needed in the AGS for gold as well as proton operations before the beams are injected into RHIC. The longitudinal bunch area is increased for gold operation from 0.3 up to 0.5 eV·s/u at design intensity. This paper reviews the revised longitudinal parameters in RHIC during injection, acceleration, transition crossing, rebucketing, and storage for gold and proton beams, accommodating for the change in injection conditions at the AGS.

1 INTRODUCTION

The physics experiments in the Relativistic Heavy Ion Collider (RHIC) require[1] the rms bunch length (σ_s) of the ion beams to be less than 25 cm during collision. This requirement will be met by operating the storage radio-frequency (rf) system at a frequency of 197 MHz. At nominal intensity, the beam size grows due to intra-beam scattering (IBS),[2] and the bunch length is ultimately confined by the width of the rf bucket. On the other hand, matching the longitudinal bunch shape between AGS and RHIC requires a 28 MHz rf system to be used for injection, acceleration, and transition crossing. Several improvements have been made to the design of both the RHIC and AGS rf systems since the 1989 Conceptual Design Report.[3] The rf harmonics have been changed in the AGS (from 12 to 8) and in RHIC (acceleration system from 342 to 360, storage system from 2508 to 2520).[1] A first-order matched transition (γ_T) jump system has been designed,[4] reducing the chromatic nonlinearity and lattice perturbation. The first-order nonlinear momentum compaction factor α_1 was changed from $+0.6$ to -0.6.[5]

The nominal 95% bunch area was baselined[1] in the 1997 Design Manual to be 0.3 eV·s/u for gold beams and 0.3 eV·s for proton beams, in order to cross transition

Table 1: Nominal RHIC Parameters.

Circumference [m]	3833.845
Ion species	proton to ^{197}Au^{79+}
Number of bunches/ring	60
Number of crossing points	6
β^* at collision [m]	2
Betatron tunes, H/V	28.19/29.18
Transition energy, γ_T	22.89
Bending radius, arc dipole [m]	242.781
Acceleration system:	
rf harmonic number	360
maximum voltage [kV]	600
Storage system:	
rf harmonic number	$2520 (= 7 \times 360)$
maximum voltage [MV]	6

Table 2: Updated parameters for RHIC gold operation with 10-hour store.

Quantity	Injection	Store (begin)	Store (end)
Kinetic energy [GeV/u]	10.4	100	100
Ions per bunch, N_b	10^9	10^9	6×10^8
95% bunch area [eV·s/u]	0.2–0.5	0.3–0.7	1.1
95% emittance [πmm·mr]	10	15	43
rms bunch length, σ_s [m]	0.55–0.88	0.11–0.17	0.22
$\mathcal{L}$ [10^{26} cm^{-2}s^{-1}]		8	0.9

efficiently[5] and to transfer the bunches from the acceleration to the storage buckets with a minimum beam loss. In recent years, experience with gold beams in the AGS-RHIC injector complex[6, 7] indicated the difficulty to achieve the previously specified small bunch area of 0.3 eV·s/u at design intensity. Therefore, the primary purpose of this report is to investigate the impact of a larger bunch area at injection. Furthermore, we take this opportunity to review under these new conditions the complete ramping process including matching at injection, efficiency of transition crossing, efficiency of rebucketing from RHIC acceleration system to storage system, and IBS growth during storage.

Tables 1, 2 and 3 list relevant machine and beam parameters. The change of beam parameters from the beginning to the end of storage is mainly due to intra-beam scattering.

2 GOLD OPERATION

Except for protons, beams of all ion species are injected below transition energy. Intra-beam scattering is most severe for fully stripped gold ions (^{197}Au^{79+}) at the design intensity of 10^9 per bunch. In this section we discuss operational scenarios for gold ions. The results are applicable to all other ion species except for protons.

2.1 Injection

Matching between the rf systems of RHIC and AGS is essential in preserving the longitudinal bunch area at injection. The rf system in the AGS operates at harmonic 8 during gold operation with a voltage of about 300 kV. In

Table 3: Updated parameters for RHIC proton operation with 10-hour store.

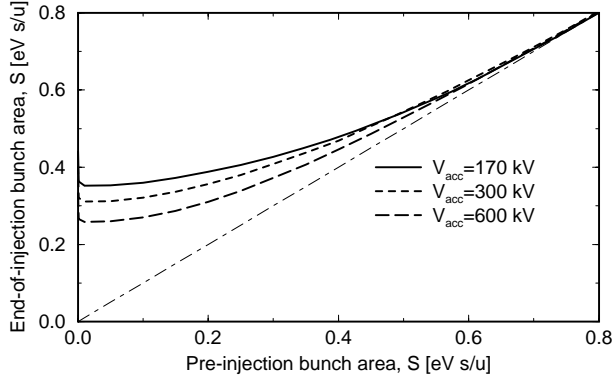| Quantity	Injection	Store (begin)	Store (end)
Kinetic energy [GeV]	28.3	250.7	250.7
Ions per bunch, N_b	10^{11}	10^{11}	10^{11}
95% bunch area [eV·s]	0.5	0.5	1.2
95% emittance [πmm·mr]	20	20	29
rms bunch length, σ_s [m]	0.51	0.09	0.14
$\mathcal{L}$ [10^{31} cm^{-2}s^{-1}]		1.5	1.1

Figure 1: Growth in bunch area of a gold beam due to intra-beam scattering during the initial 2-minute injection period.
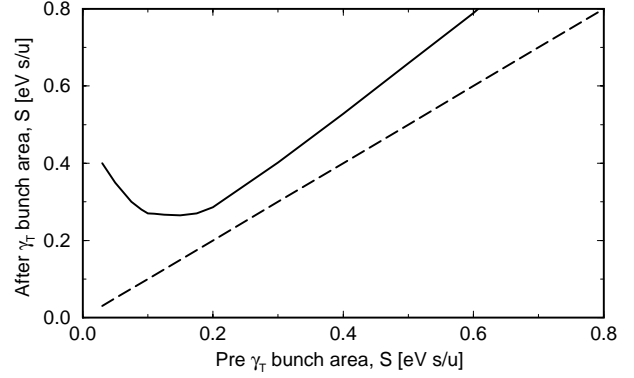

Figure 2: Growth in bunch area of a gold beam at transition in the presence of a γ_T jump of ± 0.4 units in 60 ms. The rf voltage is chosen to be 300 kV, minimizing both chromatic nonlinear effects and beam loading.

order to preserve the longitudinal bunch area, the rf system in RHIC would need to operate at a voltage of 113 kV. The resulting bucket area would be 0.66 eV·s/u, too small for a bunch with a 95% area of $S = 0.5$ eV·s/u. Therefore, a bunch rotation in AGS is necessary to change the aspect ratio of the bunch by a factor of about 1.6, matching the bunch into a RHIC bucket of 1.5 eV·s/u created by a voltage of 600 kV. Since 4 bunches are accelerated during every AGS cycle, but only one bunch is extracted at a time into RHIC, the bunch rotation process is required to be reversible in order to avoid bunch filamentation.[8]

Due to fast IBS growth, RHIC injection needs to be completed in about 2 minutes. At injection,[9] the transverse temperature of the beam is much higher than the longitudinal temperature, i.e.

$$\langle \frac{\sigma_x}{\beta_x} \rangle \approx \langle \frac{\sigma_y}{\beta_y} \rangle \gg \left(\frac{1}{\gamma} - \frac{1}{\gamma_T} \right) \sigma_p$$

where $\langle \ \rangle$ indicates an average over the circumference, σ_x and σ_y are the rms transverse beam sizes, and σ_p is the rms momentum deviation ($\Delta p/p$). The growth in longitudinal bunch area will be significant during the initial two minutes[9] of injection. Fig. 1 shows the bunch area at the end of injection as a function of the pre-injection bunch area. The maximum rf voltage of 600 kV is chosen to raise the longitudinal temperature in order to minimize this growth. Fortunately, the growth in transverse emittance due to IBS is negligible ($< 1\%$).

2.2 Transition Crossing

Both chromatic nonlinear effects and beam self-field effects are significant at transition due to the slow ramp of superconducting magnets. Transition crossing in RHIC requires a γ_T jump to effectively increase the crossing rate. The quadrupole correctors are excited to lower the γ_T of the lattice by 0.8 units in 60 ms. Even with the γ_T jump, growth in longitudinal bunch area is expected during crossing. Fig. 2 shows the bunch area after transition as a function of that before transition. At small bunch area S below about 0.1 eV·s/u, single-bunch instability starts[5] to occur. On the other hand, at large bunch area above about 0.6 eV·s/u the nominal γ_T jump becomes inadequate.[10]

Effects of chromatic nonlinearity depend strongly on the machine lattice. The growth in bunch area is approximately proportional to the factor $(\alpha_1 + 1.5)$.[5] During the entire period of the γ_T jump, α_1 varies between -0.5 and -0.7.

With an initial area of 0.5 eV·s/u at injection, the bunch area is expected to be about 0.52 eV·s/u before transition (Fig. 1), and is near 0.7 eV·s/u after transition (Fig. 2). In the presence of the γ_T jump, no beam loss is expected at transition.

2.3 Rebucketing

After being accelerated to the top energy with the acceleration system, the beam must be transferred and "rebucketed" by the storage system for collision.[11] The objectives of the rebucketing are to reduce the bunch length to meet the experimental and luminosity requirements ($\sigma_s \ll \beta^*$), and to minimize the particle loss and energy deposition in the superconducting magnets.

With a bunch area after transition from 0.3 to 0.7 eV·s/u, a bunch rotation (achieved by temporarily switching the acceleration rf phase to the unstable fixed point) is necessary to shorten the bunch length. Beam loss may occur due to
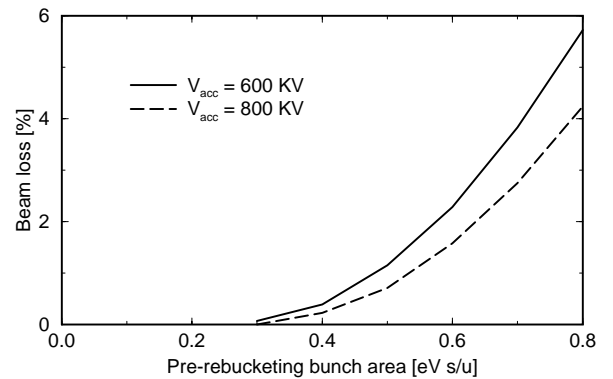

Figure 3: Beam loss as a function of pre-rebucketing bunch area at acceleration system voltages of 600 kV (nominal) and 800 kV, respectively.
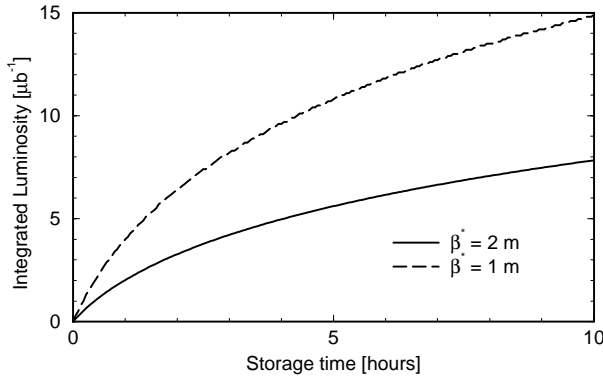
Figure 4: Luminosity variation during storage of a gold beam of $S = 0.5$ eV·s/u initial longitudinal bunch area.

the nonlinearity of the bunch rotation process, as shown in Fig. 3. With an initial bunch area of 0.5 eV·s/u at injection at the nominal intensity, the pre-rebucketing area is about 0.7 eV·s/u. For a nominal acceleration rf voltage of 600 kV, and a storage voltage of 6 MV, the beam loss is estimated to be about 3.5%.

Each of the two intersecting rings in RHIC has 3 "dedicated" storage rf cavities and shares another 4 common cavities with the other ring. If only 3 independent cavities (total 3 MV) are used in a simplified rebucketing scheme, the beam loss would increase to about 5.3%.

2.4 Collision

The gold beam fills the entire rf bucket within the first hour of storage at the top energy due to intra-beam scattering. Subsequently, particles diffuse across the separatrix[2] becoming coasting beam background. We assume a full coupling in the transverse plane so that the growth of the horizontal emittance is significantly reduced.[9] It is seen that an increase of the longitudinal bunch area from 0.3 to 0.7 eV·s/u does not significantly change the IBS behaviour of the beam during the 10-hour storage: transversely the emittance grows by a factor of 3 to 43 πmm·mr, and longitudinally particles fill up the bucket within the first hour.

At β^* of 2 m, the intensity loss of the gold beam is expected to be about 45% in 10 hours, mostly due to IBS diffusion with particles escaping outside the rf bucket.[2] Reducing the value of β^* to 1 m leads to an increase of particle losses due to Coulomb induced processes upon collisions[12], but this effect is small (about 10%) compared with intra-beam scattering. Assuming that beam loss due to transverse dynamic aperture limitations is negligible, Fig. 4 shows the increase of integrated luminosity (a factor of 1.9) with 1 m β^* operation. The luminosity performance is insensitive to the initial bunch area.

3 PROTON OPERATION

Proton beams are injected into RHIC above transition at $\gamma = 31.2$. The operation is expected to be less complicated compared with gold beams.

The proton beam is injected from the AGS and captured with the 28 MHz RHIC acceleration system. Since injection occurs near transition energy, the matching voltage of the RHIC acceleration system is only 19 kV when the AGS operates with harmonic 8 at 300 kV. The effect of beam loading is expected to be strong at this low voltage. In order to avoid complications, a reversible bunch rotation is again needed in AGS before the beam is extracted for RHIC injection. Intra-beam scattering does not cause noticeable emittance increase for protons at injection.

Rebucketing will be performed at top energy after the acceleration is completed. The bucket area at top energy is about 2 1/2 times larger than that (per nucleon) of the gold. No beam loss is expected during proton rebucketing.

The effects of intra-beam scattering for proton beams are much less compared with gold beams. Again, we assume a full transverse coupling. During 10-hour storage the transverse emittances grow by about 40% to 29 πmm·mr. The longitudinal bunch area grows by a factor of 2.2 to 1.2 eV·s/u, still considerably less than the bucket area. Particle loss due to IBS is negligible. Again, performance at storage is insensitive to the initial bunch area.

At a higher intensity of 2×10^{11} per bunch, proton beam loss due to intra-beam scattering is still negligible. During 10-hour storage the transverse emittances grow to about 33 πmm·mr, and the longitudinal bunch area grows to about 1.6 eV·s/u.

4 REFERENCES

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[11] The complication of transition crossing requires rebucketing to be performed above transition. Rebucketing just after transition during acceleration is attractive, but technically difficult. Although the energy deposited by the lost particles is smaller and spread out over a certain period, any loss will hit the machine aperture during the subsequent acceleration, as contrast to drifting as a coasting beam background without hitting the aperture when the rebucketing is performed at top energy.

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