The Collider Scenario

An important choice in the RHIC design was the utilization of short bunches colliding head-on to enhance the luminosity while keeping the average current and stored beam energy low. Formation of thebunches occurs prior to injection. The injector chain for ions consists of the Tandem Van de Graaff accelerators, the Booster synchrotron, and the Alternating Gradient Synchrotron (AGS). The sequence of steps in the chain of accelerators is shown in Fig. 2 for the prototypical example of gold ions. The injector chain for polarized protons consists of the optically pumped polarized proton source, the 200 MeV proton linac, the Booster, and the AGS.

Two Tandem Van de Graaff accelerators are available. They can be used for two different ion species, or one as a backup for the other. A two-stage operation is employed with the negative ion source at ground potential. The negative ions, with charge -1, are accelerated from ground to +15 MV potential. They pass through a stripping foil in the high voltage terminal yielding partially stripped ions, with a positive charge, Q_T, which is a function of the element being accelerated. The partially stripped ions are accelerated back to ground potential, increasing their energy by $15\times Q_T$ MeV. For the prototypical example of gold beams, the ions exit the Tandem at the kinetic energy of 1 MeV/n and with Q = +12 charge state.

Exiting from the Van de Graaff, the ions are further stripped to charge state +32. They then traverse a long (~ 550 m) heavy ion transfer line to the AGS (HITL), continue in a new, shorter section by-passing the AGS (HTB) and proceed to be injected into the Booster synchrotron. The beam from the Tandem will be stacked in both horizontal and vertical betatron space by adding linear coupling to the Booster lattice. The 700 μsec Tandem pulse yields 45 Booster turns for gold. The stacking/capture efficiency is about 50%, so for gold, the 4.5×10^9 ions from Tandem yield 2.2×10^9 ions accelerating in the Booster.

The Booster can accelerate this beam to 0.65 T in less than 100 ms. A single rf system (two cavities) operating on the 6th harmonic of the revolution frequency provides the accelerating voltage over this range. The kinetic energy of the six bunches at extraction is 100 MeV/n. In the Booster-to-AGS (BtA) transfer line, the ions are stripped once again by a foil to charge state +77 (only K-shell electrons remaining) and then enter the AGS.

Four such Tandem/Booster cycles, occurring at a 5 Hz repetition rate, fill the circumference of the AGS using 600 ms of the AGS repetition period. The bunches are injected into matching AGS rf buckets (h = 12). After the fourth transfer, the beam is debunched and rebunched into 4 bunches.

With 75% acceleration efficiency (Booster and AGS together), this bunch would contain 1×10^9 ions [(75% acc eff)×(60% BtA foil stripping)×(2.2×10^9)].

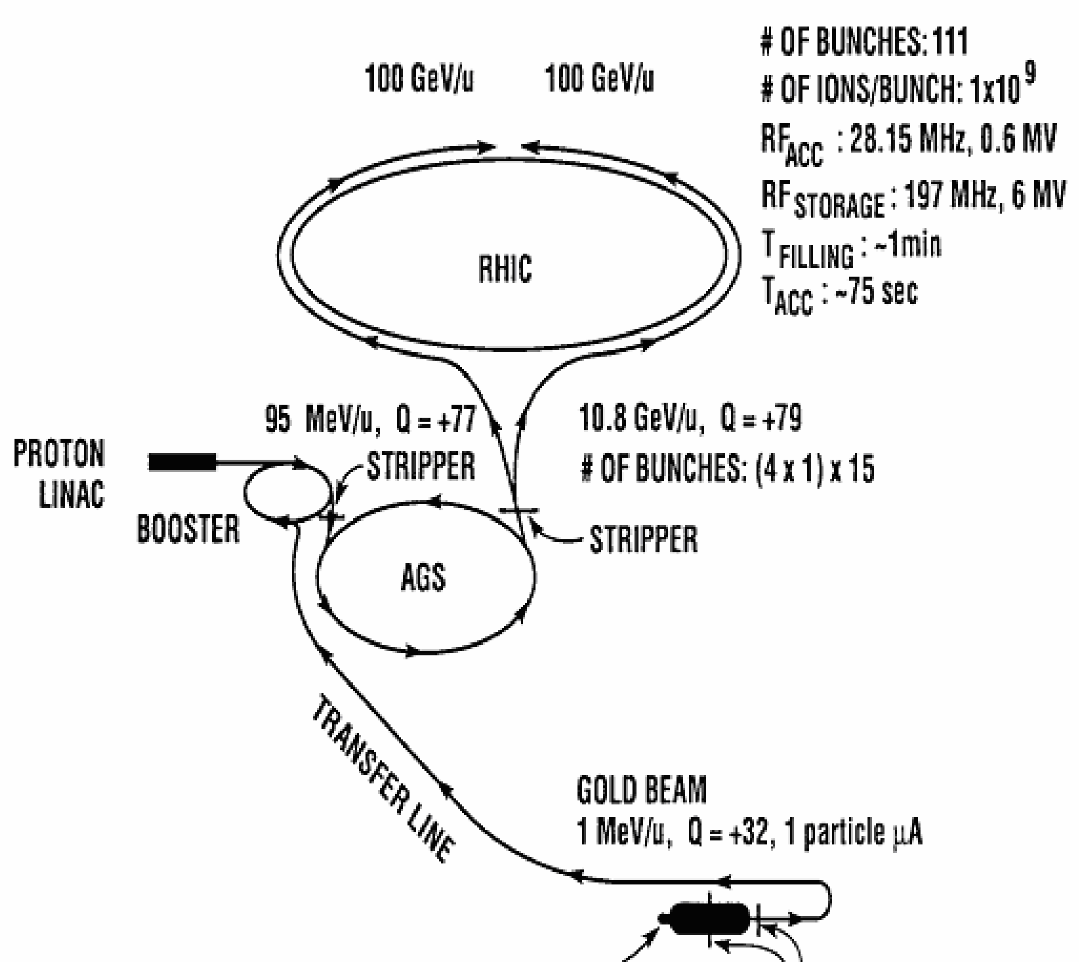

Fig. 2. RHIC Acceleration Scenario for gold.

Finally, the beam is fast extracted into the existing AGS to RHIC (AtR) transfer line tunnel. A final stripping from +77 to +79 takes place at the start of this line. For protons the acceleration strategy is simplified, the merges are unnecessary, since intensity is not a problem. For heavy ion and proton cycles, the final kinetic energies (8.9 GeV/n and 22.9 GeV respectively) correspond to a peak AGS $B\rho$ of 80 Tm.

The AGS to RHIC (AtR) transfer line uses conventional room temperature magnets, some of which exist from procurements for the former CBA project, and employs a magnetic septum magnet and fast kicker system to deposit the beam vertically onto the injection closed orbit.

A total of up to 111 bunches are injected into each collider ring in bunch-to-bucket fashion. The AGS extraction system will allow single-bunch transfer of the four AGS bunches into one of the two collider rings. Filling both rings with ions requires about 1 minute, currently only 1 polarized proton bunch is accelerated per AGS cycle and filling both rings with polarized protons takes about 10 min. Minimizing the filling time is important in order to prevent bunch area dilution due to intrabeam scattering. For the lightest ions, protons and deuterium, approximately 2×10^{11} ions/bunch can be stored in the collider. The nominal number of ions per bunch transferred to the collider is given in Table 2. The intensity is estimated from Tandem currents after allowing for some losses in the Booster and the AGS.

Beam parameters, i.e. bunch area S and normalized transverse emittance ε_N, at RHIC injection are given in Table 2. The beam parameters for ions from the Tandem are taken to be the same for all species, i.e. 0.5 eV·s/n and 10 mm ·mrad. Those for protons are different, with a larger emittance, i.e. 20 mm.mrad, since they come from a different source. The bunch area containing 95% of the beam population, S, is defined by $S = 6\pi\, \sigma_\tau\, \sigma_E$ where σ_τ is the rms bunch length in units of time and σ_E the rms energy spread. Correspondingly, the normalized emittance, is defined by $\varepsilon_N = (\beta\ \gamma)\ \varepsilon = (\beta\ \gamma)\ 6\ \sigma_{H,V}^2\ /\ \beta_{H,V}$ where $\sigma_{H,V}$ is the rms beam width or height and $\beta_{H,V}$ the horizontal or vertical amplitude lattice function. By local convention, the energy spread is quoted as $\pm\sqrt{6}\ \sigma$ and the (total) bunch length as $2\sqrt{6}\ \sigma$.

The beam parameters are quoted for a typical set of ion species in order to illustrate the variation of the collider performance over the entire mass range. The Tandem Van de Graaff source is capable of delivering many other elements, most of them in adequate intensity. In fact, the choice of ^{16}O and ^{28}Si may entail operational difficulties due to the mass-to-charge ratio being $A/Z = 2$, potentially leading to beam contamination with lighter fragments of equal rigidity. Since this problem could be circumvented by the use of isotopes or different elements such as ^{11}B and ^{35}Cl, the discussion is limited here to the few illustrative examples of Table 2.

The bunch separation in the collider ring is 108 ns, and this corresponds to a rise time of 95 nsec. The injection kicker allows the transfer of single bunches from the AGS. The adoption of beam transfer from the AGS to RHIC in the single-bunch mode allows considerable freedom in the choice of the harmonic number and bunch pattern. The bunches are captured in stationary buckets of the so-called acceleration rf system operating at 28.15 MHz, corresponding to a harmonic h = 360. The acceleration rf system has 2 cavities per ring capable of providing a total of 300 kV peak voltage. In order to avoid bunch area dilution, it is essential to match the shape of the bunches from the AGS to the shape of the buckets of the collider rf. The harmonic chosen together with the rf voltage available provide adequate bucket area in the collider but require for protons bunch rotation in the AGS prior to the bunch transfer. The beams are injected into RHIC at 300 kV for gold and heavy ions, but 150 kV for protons. The nominal bunch parameters at injection into the collider are quoted in Table 2.

After injection of the beam, the rf voltage can be adjusted adiabatically to optimum values for acceleration and the crossing of the transition energy (nominally 300 kV for the prototypical gold beam). In order to avoid bunch area dilution at transition, a γ-transition jump is executed, limiting the bunch area growth. Proton beams are injected above but close to transition.

After having reached the operating kinetic energy corresponding to a $B\rho = 839.5$ T·m, ion bunches are transferred from the acceleration (28.15 MHz) to the storage rf system at 197 MHz. The harmonic number of the storage rf is $h = 360\times7 = 2520$, resulting in a bucket length of 1.52 m. This frequency was chosen in order to limit the growth of the bunch due to intrabeam scattering to an rms bunch length of <25 cm. The resulting rms diamond length is less than ~18 cm.

With a bunch area after transition of 0.7 eV·s/n, the length of a gold bunch is before rebucketing longer than the storage bucket length. Shortening of the bunch is necessary for all ion species and is accomplished by a non-adiabatic bunch rotation in the acceleration system. Each of the RHIC rings has 3 storage system cavities and shares additional 4 common cavities with the other ring for a total voltage of 6 MV. The 3 cavities provide the marginal voltage required to accept the shortened bunches. After transfer, the storage rf voltage is adiabatically raised to its maximum value available and kept constant during the storage cycle.

The stored ion beam energy is 350 kJ per ring for ions, and 900 kJ for polarized protons, small enough to be aborted onto an internal beam dump at the end of the storage period or in case of equipment malfunction. The beam will be dumped in a single turn (13 μsec) by activating the abort kicker, which deflects the beam horizontally onto a dump block. In order to facilitate the beam abort design, a gap of ~ 1 μsec is provided.

Operation of the collider and achievement of full performance requires continuous monitoring of many beam characteristics, and appropriate beam instrumentation is provided. A central control system allows the control of, and communication among, the various collider systems.

The major parameters of the collider are listed in Table 3. The accelerator systems are described in greater detail in the subsequent sections of this Configuration Manual.

Table 2. General Beam Parameters for the Collider

Element	Proton	Deuterium	Oxygen	Silicon	Copper	Iodine	Gold
Atomic Number Z	1	1	8	14	29	53	79
Mass Number A	1	2	16	28	63	127	197
Rest Energy (GeV/u)	0.93827	0.93781	0.93093	0.93046	0.92022	0.93058	0.93113
Injection:†							
Kinetic Energy (GeV/u)	28.3	13.7	13.7	13.7	12.6	11.3	10.8
Energy, γ	31.2	15.6	15.7	15.7	14.5	13.1	12.6
Norm. Emittance (mm·mrad)	20	10	10	10	10	10	10
Bunch Area (eV·s/n)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Bunch Length (m)	2.58	4.1	4.1	4.1	4.6	5.32	5.62
Energy Spread ($\times 10^{-3}$)	±1.26	±1.63	±1.63	±1.63	±1.59	±1.52	±1.49
No. ions/Bunch ($\times 10^{9}$)	100	100	8.3	5.6	2.7	1.5	1.0
*Top Energy, @ transfer:**							
Kinetic Energy (GeV/u)	250.7	124.9	124.9	124.9	114.9	104.1	100.0
Energy, γ	268.2	134.2	135.2	135.3	124.5	112.9	108.4
rms Bunch Length (m)	0.10	0.17	0.17	0.17	0.18	0.19	0.19
Energy Spread ($\times 10^{-3}$)	±0.83	±1.35	±1.35	±1.35	±1.41	±1.46	±1.49

†Acceleration rf System $h = 360$, $V_{rf} = 300$ kV, except 170 kV @ p; *Storage rf System $h = 2520$, $V_{rf} = 6$ MV

Table 3. Major Parameters for the Collider

Kinetic Energy, Injection-Top (each beam), Au	8.9-100	GeV/u
p↑	22.9-250	GeV
Luminosity, Au-Au @ 100 GeV/n, store average, Enhanced Design	8×10^{26}	cm^{-2} s^{-1}
p↑-p↑ @ 250 GeV, store average, Enhanced Design	150×10^{30}	cm^{-2} s^{-1}
Proton polarization, store average, Enhanced Design	70	%
No. of bunches/ring, max	111	
No. of ions/bunch, Au	1×10^{9}	
p↑	2×10^{11}	
Luminosity lifetime Au @ $\gamma > 30$	2.5	h
p↑	>10	h
Diamond length	18	cm rms
Circumference, 4-3/4 C_{AGS}	3833.845	m
Beam separation in arcs	90	cm
Number of crossing points	6	
Free space at crossing point	±9	m
Beta @ crossing, horizontal/vertical	10	m
low-beta insertion	1	m
Crossing angle, nominal (maximum)	0 (< 1.7)	mrad
Betatron tune, horizontal/vertical, Au	28.22/29.23	
p↑	28.685/29.695	
Transition Energy, γ_T	22.89	
Magnetic Rigidity, $B\rho$: @ injection / @ top energy	81.1 / 839.5	T·m
Bending radius, arc dipole	242.781	m
No. of dipoles (192/ring + 12 common)	396	
No. of quadrupoles (276 arc + 216 insertion)	492	
Dipole field @ 100 GeV/u, Au	3.458	T
Arc dipole length, effective	9.45	m
Arc Dipole length, physical	9.728	m
Dipole current	5.093	kA
Arc quadrupole gradient	~71	T/m
Arc quadrupole length, effective	1.11	m
Coil i.d. arc magnets	8	cm
Beam tube i.d.	6.9	cm
Operating temperature, Helium refrigerant	< 4.6	K
Refrigeration capacity at 4 K	24.8	kW
Cooldown time, entire system, 80K to 4K	10	d
Vacuum, warm beam tube sections	$\sim10^{-11}$	Torr
Filling mode	Bunch-to-bucket	
Injection kicker strength (95 nsec)	~0.18	T·m
Beam stored energy Au / p↑	350/900	kJ
rf voltage, h=360	600	kV
rf voltage, h=2520	6	MV