BNL-98927-2012-TECH

C-A/AP/473;BNL-98927-2012-IR

Parameters for the injection, acceleration, and extraction of gold and copper ions in Booster, AGS, and RHIC

C. J. Gardner

November 2012

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

BNL-98927-2012-IR

C-A/AP/#473
November 2012

Parameters for the injection, acceleration, and extraction of gold and copper ions in Booster, AGS, and RHIC

C.J. Gardner

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

Parameters for the Injection, Acceleration, and Extraction of Gold and Copper Ions in Booster, AGS, and RHIC

C.J. Gardner

November 27, 2012

During the 2012 RHIC run, uranium, gold, and copper ions from EBIS were accelerated in Booster and AGS and delivered to RHIC for the physics program. In this note the nominal parameters for gold and copper are given. The parameters for uranium are given in a separate note.

In order to achieve the desired number of ions per bunch in RHIC, it was necessary to merge bunches in both Booster and AGS. This is described in Sections 11 and 12 of Reference [1].

1 Mass

A gold ion with charge eQ has $N = 118$ neutrons, $Z = 79$ protons, and $(Z - Q)$ electrons. Here Q is an integer and e is the positive elementary charge. The mass number is

$$A = N + Z = 197. \tag{1}$$

This is also called the number of nucleons. The mass energy equivalent of the ion is

$$mc^2 = am_uc^2 - Qm_ec^2 + E_Q \tag{2}$$

where [2, 3]

$$a = 196.9665687(6) \tag{3}$$

is the relative atomic mass of the neutral gold atom,

$$m_uc^2 = 931.494061(21)\ \text{MeV} \tag{4}$$

is the mass energy equivalent of the atomic mass constant, and

$$m_e c^2 = 0.510998928(11) \text{ MeV} \tag{5}$$

is the electron mass energy equivalent. The binding energy E_Q is the energy required to remove Q electrons from the neutral gold atom. This amounts to [4, 5] 0.332 MeV for the helium-like gold ion ($Q = 77$) and 0.517 MeV for the fully stripped ion. For $Q = 32$ we have $E_Q = 14.5$ KeV.

Similarly, a copper ion with charge eQ has $N = 34$ neutrons, $Z = 29$ protons, and $(Z - Q)$ electrons. The mass number is

$$A = N + Z = 63 \tag{6}$$

and the relative atomic mass is [2]

$$a = 62.9295975(6). \tag{7}$$

For $Q = 11$ the binding energy is $E_Q = 1.29$ KeV; for the fully stripped ion ($Q = 29$) we have $E_Q = 45.0$ KeV [4, 5].

2 Kinetic Parameters

In a circular accelerator the ion moves along an orbit of circumference C with revolution frequency f. The radius of the orbit is defined to be $R = C/(2\pi)$. The velocity of the ion is then

$$v = 2\pi R f. \tag{8}$$

This gives momentum, energy, and kinetic energy

$$p = mc\beta\gamma, \quad E = mc^2\gamma, \quad W = mc^2(\gamma - 1) \tag{9}$$

where

$$\beta = v/c, \quad \gamma = 1/\sqrt{1-\beta^2}. \tag{10}$$

The magnetic rigidity of the ion in units of Tm is

$$B\rho = kp/Q \tag{11}$$

where $k = 10^9/299792458$ and p is the momentum in units of GeV/c. The angular frequency is

$$\omega = 2\pi f. \tag{12}$$

We also define the phase-slip factor

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \tag{13}$$

where γ_t is the transition gamma.

3 RF Parameters

1. The stationary bucket area is

$$A_S = 8\,\frac{R_s}{hc}\left\{\frac{2eQV_gE_s}{\pi h|\eta_s|}\right\}^{1/2} \tag{14}$$

   where h is the RF harmonic number, V_g is the total RF gap voltage per turn, and the subscript "s" denotes parameter values for the synchronous particle.

2. The half-height of a bucket is

$$\Delta E = \left(\frac{h\omega_s}{8\sqrt{2}}\right) A_S\,|(\pi - 2\phi_s)\sin\phi_s - 2\cos\phi_s|^{1/2} \tag{15}$$

   where ϕ_s is the synchronous phase.

3. The synchronous phase is given by

$$V_g \sin\phi_s = 2\pi R_s \rho_s \dot{B}/c \tag{16}$$

   where ρ_s is the radius of curvature, B is the magnetic field and $\dot{B} = dB/dt$. Employing Gaussian units (R_s and ρ_s in cm, $c = 2.99792458 \times 10^{10}$ cm/s, and $\dot{B}$ in G/s) gives $V_g \sin\phi_s$ in Statvolts. Multiplying by 299.792458 then gives $V_g \sin\phi_s$ in Volts.

4. The width of a bucket is

$$\Delta t = \frac{|\pi - \phi_s - \phi_e|}{h\omega_s} \tag{17}$$

   where the phase ϕ_e satisfies

$$\cos(\pi - \phi_s) - \cos\phi_e = -(\pi - \phi_s - \phi_e)\sin\phi_s. \tag{18}$$

5. The area of a bucket is

$$A_{\mathrm{bk}} = \alpha(\phi_s) A_S \tag{19}$$

   where

$$\alpha(\phi_s) = \frac{\sqrt{2}}{8}\int_{\phi_L}^{\phi_R} |(\pi - \phi_s - \phi)\sin\phi_s - \cos\phi_s - \cos\phi|^{1/2}\,d\phi. \tag{20}$$

Below transition we have $\phi_e < \pi - \phi_s$ and the limits of integration are $\phi_L = \phi_e$ and $\phi_R = \pi - \phi_s$. Above transition we have $\pi - \phi_s < \phi_e$ and the limits of integration are $\phi_L = \pi - \phi_s$ and $\phi_R = \phi_e$. The integral $\alpha(\phi_s)$ must be evaluated numerically. An approximate expression is [6]

$$\alpha(\phi_s) \approx \frac{1 - \sin\phi_s}{1 + \sin\phi_s}. \tag{21}$$

6. The synchrotron frequency for small-amplitude oscillations about ϕ_s is

$$F_s = \frac{c}{2\pi R_s} \left\{ \frac{-h\eta_s e Q V_g \cos\phi_s}{2\pi E_s} \right\}^{1/2} \tag{22}$$

and the corresponding synchrotron tune is $Q_s = 2\pi F_s/\omega_s$. Note that measurement of F_s gives a value for $V_g \cos\phi_s$, while measurement of dB/dt gives a value for $V_g \sin\phi_s$. These two can be used to obtain V_g and ϕ_s.

7. Let ϕ_l and ϕ_r be the phases at the left and right boundries of a bunch matched to a bucket. We have

$$\phi_l < \phi_s < \phi_r \tag{23}$$

and the width of the bunch is

$$\Delta t = \frac{\Delta\phi}{h\omega_s}, \quad \Delta\phi = \phi_r - \phi_l. \tag{24}$$

In terms of $\Delta\phi$ and ϕ_s we have

$$\phi_r = \frac{\Delta\phi}{2} + \arcsin\left\{ \frac{\Delta\phi \sin\phi_s}{2\sin(\Delta\phi/2)} \right\} \tag{25}$$

and

$$\phi_l = -\frac{\Delta\phi}{2} + \arcsin\left\{ \frac{\Delta\phi \sin\phi_s}{2\sin(\Delta\phi/2)} \right\}. \tag{26}$$

If $\Delta\phi$ is small we have

$$\sin(\Delta\phi/2) \approx \frac{\Delta\phi}{2}, \quad \frac{\Delta\phi \sin\phi_s}{2\sin(\Delta\phi/2)} \approx \sin\phi_s \tag{27}$$

and

$$\phi_l \approx \phi_s - \frac{\Delta\phi}{2}, \quad \phi_r \approx \phi_s + \frac{\Delta\phi}{2}. \tag{28}$$

8. The half-height of a bunch matched to a bucket is

$$\Delta E = \left(\frac{h\omega_s}{8\sqrt{2}}\right) A_S \, |\cos\phi_r - \cos\phi_s + (\phi_r - \phi_s)\sin\phi_s|^{1/2} \, . \tag{29}$$

9. The area of a bunch matched to a bucket is

$$A_{\mathrm{b}} = F(\phi_s, \Delta\phi)\, A_S \tag{30}$$

where

$$F(\phi_s, \Delta\phi) = \frac{\sqrt{2}}{8} \int_{\phi_l}^{\phi_r} |\cos\phi_l - \cos\phi + (\phi_l - \phi)\sin\phi_s|^{1/2} \, d\phi. \tag{31}$$

The integral $F(\phi_s, \Delta\phi)$ must be evaluated numerically. If $\Delta\phi$ is small we have

$$F(\phi_s, \Delta\phi) \approx \frac{\pi}{64} (\Delta\phi)^2 \, |\cos\phi_s|^{1/2} \, . \tag{32}$$

4 Ring Parameters

Parameter	Booster	AGS	RHIC	Unit
C_I	C_b	C_a	$C_r + \delta C$	m
C_E	$C_a/4$	$4(C_r + \delta C)/19$	$C_r + \delta C$	m
ρ	13.8656	85.378351	242.7806	m
γ_{tr}	4.832	8.5	22.89	

Here C_I and C_E are the circumferences of the closed orbits in the machines at injection and extraction (or store) respectively. C_b, C_a, and C_r are the circumferences of the "design" orbits in Booster, AGS, and RHIC respectively. These are

$$C_b = 201.780, \quad C_a = 2\pi(128.4526), \quad C_r = 3833.845181 \tag{33}$$

meters. δC is the shift (if any) of the RHIC orbit circumference from the design value C_r. Note that $4(C_r/19) = 2\pi(128.4580)$ m which gives an AGS radius at extraction approximately 5 mm larger than the "design" AGS radius (128.4526 m) reported by Bleser [7, 8]. The radius of curvature ρ in the Booster and AGS main dipoles is given in Refs. [7, 8, 9]. The RHIC ring parameters are taken from Ref. [10] and from MAD runs by Steve Tepikian.

Copper and gold ions respectively are accelerated in the blue and yellow rings of RHIC. Because the ions have different magnetic rigidities and must pass through the same DX magnets, the orbit circumferences in the blue and yellow rings are not the same. Steve Tepikian has calculated the circumference shifts δC in each ring at injection and at store. These are given in items 7 and 8 of the next section.

5 Initial Conditions and Assumptions

1. The revolution frequency of the Au32+ and Cu11+ ions (from EBIS) at Booster injection is 96.100 kHz.
2. The revolution frequency of the Au32+ ion at Booster extraction is $f = 658.91$ KHz [11]. The corresponding magnetic rigidity is $B\rho = 9.4620277$ Tm. The rigidity that can be extracted from Booster into the BTA line is limited by the F3 extraction kicker. The advertised limit is $B\rho = 9.5$ Tm [12]. We have successfully extracted Au31+ ions (originating from Tandem) at $B\rho = 9.43$ Tm for several years.
3. The revolution frequency of the Cu11+ ion at Booster extraction is $f = 660.15$ KHz [13]. The corresponding magnetic rigidity is $B\rho = 8.8149099$ Tm.
4. The set revolution frequency of the Au77+ ion at AGS injection is $f = 163.125$ KHz. This gives an energy loss of 2.453 MeV per nucleon in the BTA stripper.
5. The set revolution frequency of the Cu29+ ion at AGS injection is $f = 164.938$ KHz. This gives an energy loss of 0.1539 MeV per nucleon in the BTA stripper.
6. The magnetic rigidity of the Au79+ ion at RHIC injection is taken to be $B\rho = 81.1137824$ Tm. The revolution frequency of the Cu29+ ion at RHIC injection is the same as that of the Au79+ ion.
7. The orbit circumference for copper ions in the blue ring **at injection** is 0.611 mm **greater than** C_r. The orbit circumference for gold ions in the yellow ring **at injection** is 1.961 mm **less than** C_r.
8. The energy of the gold ion at RHIC Store is 100 GeV per nucleon. The revolution frequency of the copper ion is the same as that of the

gold ion. The orbit circumference for copper ions in the blue ring **at store** is 0.539 mm **greater than** C_r. The orbit circumference for gold ions in the yellow ring **at store** is 1.898 mm **less than** C_r.

The parameter values given in the following sections are calculated with these initial conditions and assumptions. For many of the parameters more digits are given than would be warranted by the precision with which the parameter could be measured; this is done for computational convenience.

6 Inflector Voltage

At Booster injection, the voltage V_I required for particles with mass m, velocity $c\beta$, and charge Q to follow the nominal trajectory through the inflector is given by

$$eV_I = \frac{G}{R_I}\left(\frac{mc^2}{Q}\right)\beta^2\gamma. \tag{34}$$

Here $G = 0.021$ m is the gap between the cathode and septum of the inflector and $R_I = 8.74123$ m is the radius of curvature along the nominal trajectory. Using the calculated values of β and γ at Booster injection, we obtain $V_I = 57.743$ and 53.669 kV respectively for the Au32+ and Cu11+ ions from EBIS.

Because of an unresolved calibration error, the actual setpoint for the inflector voltage needs to be

$$V_I(\text{setpoint}) = 1.034\, V_I \tag{35}$$

which gives

$$V_I(\text{setpoint}) = 59.707\,\text{kV} \tag{36}$$

for Au32+ ions and

$$V_I(\text{setpoint}) = 55.493\,\text{kV} \tag{37}$$

for Cu11+ ions.

7 Booster Injection Field

The nominal magnetic field in the Booster dipoles at injection is

$$B = (B\rho)/\rho \tag{38}$$

where $B\rho$ is given by (11) and ρ is the nominal radius of curvature. Using the calculated values of $B\rho$ we obtain $B = 893.96$ and 830.87 Gauss respectively for the Au32+ and Cu11+ ions from EBIS.

The magnetic field is measured with a Hall probe and the Booster Gauss Clock. The Hall probe sits in the reference dipole and gives the value of the field at BT0. The Gauss Clock gives the change in field between BT0 and the time of measurement. The measured field is defined to be the field at BT0 plus the field change given by the Gauss Clock. For Au32+ ions from EBIS the measured field at injection is 891.6 Gauss.

8 AGS Injection Field

Similarly, the nominal magnetic field in the AGS dipoles at injection is $B = 454.96$ and 391.26 Gauss for the Au77+ and Cu29+ ions respectively.

9 BTA Stripper

The stripper used to strip gold ions in the BTA (Booster-To-AGS) transfer line consists of a 6.45 mg/cm^2 aluminum foil followed by a 8.39 mg/cm^2 carbon foil. In Section 20 we use these surface densities to calculate the energy loss of Au77+ ions in the foils.

The stripper used to strip copper ions consists of a 4.38 mg/cm^2 nickel foil followed by a 6.4 mg/cm^2 aluminum foil.

10 AGS Injection Septum Magnet Current

The field required in the L20 septum magnet is

$$B = (B\rho)/\rho \tag{39}$$

where $B\rho$ is the magnetic rigidity of the beam and $\rho = 18.625$ m [15] is the radius of curvature of the nominal trajectory through the magnet. The required current is given by

$$NI = gB/\mu_0 \tag{40}$$

where $N = 1$ is the number of conductor turns; $g = 0.0467$ m [15] is the magnet gap; and $\mu_0 = 4\pi \times 10^{-7}$ Tm/A.

For Au77+ ions at injection, the magnetic rigidity is $B\rho = 3.88434088$ Tm. This gives $B = 0.208555$ T and $I = 7750$ A.

For Cu29+ ions at injection, the magnetic rigidity is $B\rho = 3.3405536$ Tm. This gives $B = 0.179359$ T and $I = 6665$ A.

For comparison, the magnetic rigidity of polarized protons at AGS injection is $B\rho = 7.205178$ Tm. This gives $B = 0.3869$ T and $I = 14380$ A.

11 AGS Injection Kicker Current

The current required in the A5 kicker is [14, 15]

$$I = \frac{B\rho}{K} \sin\phi \tag{41}$$

where

$$K = 1.8718 \times 10^{-5} \text{ Tm/A} \tag{42}$$

and

$$\phi = 3.35 \text{ milliradians} \tag{43}$$

is the desired kick angle. Using the calculated values of $B\rho$ at AGS injection we obtain currents of 695.2 and 597.9 A respectively for Au77+ and Cu29+ ions. The maximum available current is 1100 A.

12 AGS Injection Kicker Short Pulse Waveforms

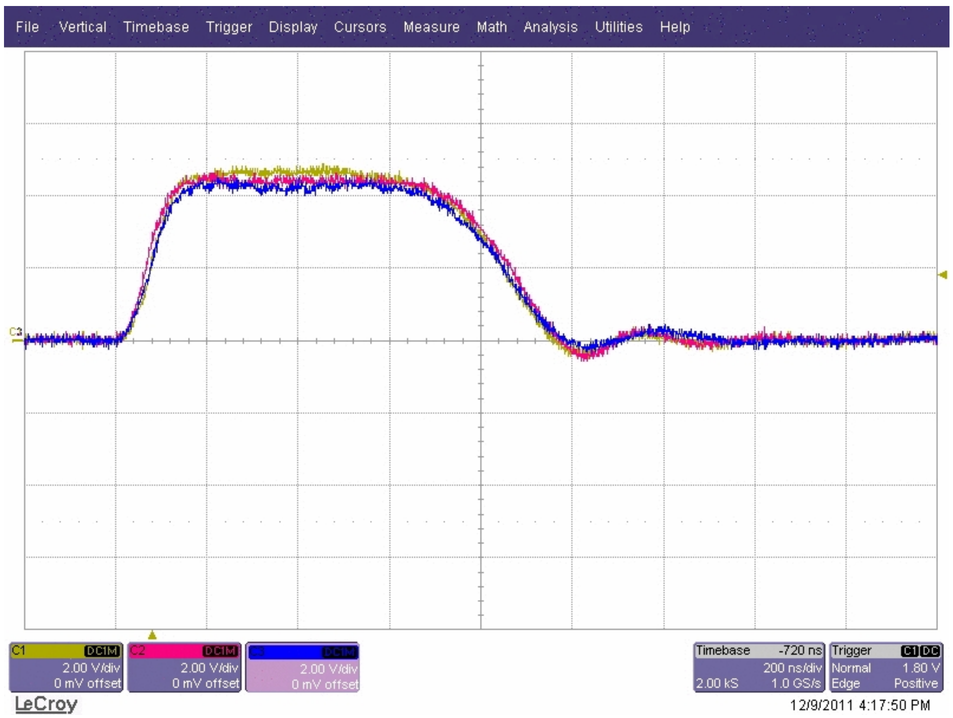

Figure 1: AGS injection kicker waveforms in the short pulse mode. The three traces are from the three modules of the kicker. They were taken by Yugang Tan on 9 Dec 2011. The time per division is 200 ns. The RF bucket width on the AGS injection porch is 383 ns for Au77+ ions and 379 ns for Cu29+ ions. In order to put beam into adjacent buckets, the rise time of the kicker must be less than or equal to the bucket width minus the bunch width. The rise time is approximately 100 ns, which implies that the bunch width must be less than or equal to 283 and 279 ns for Au77+ and Cu29+ bunches respectively. A single bunch with these widths easily fits on the flattop portion of the pulse which is some 600 ns long. The total width of the pulse is some 1200 ns. With this kicker pulse one could in principle fill 14 of the 16 RF buckets on the AGS injection porch. The pulse is too wide to fill the remaining buckets without interfering with beam in the adjacent buckets. This was not an issue during the run as only 8 of the buckets needed to be filled. The filling pattern was four adjacent filled buckets followed by four adjacent empty buckets.

13 AGS Injection Kicker Long Pulse Waveforms

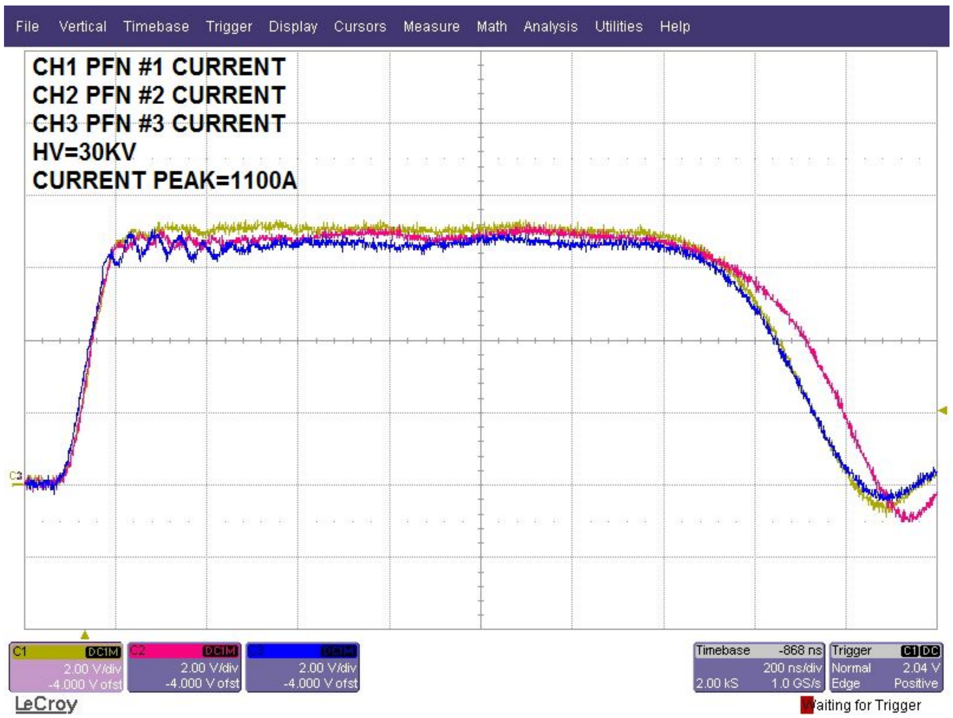

Figure 2: AGS injection kicker waveforms in the long pulse mode. The three traces are from the three modules of the kicker. They were taken by Yugang Tan in Oct 2010. The time per division is 200 ns. The RF bucket width on the AGS injection porch is 383 ns for Au77+ ions and 379 ns for Cu29+ ions. Here the flattop portion of the pulse is some 1300 ns long. The total pulse width is some 2000 ns. In principle this kicker pulse could be used to fill 8 buckets wtih a filling pattern of four adjacent filled buckets followed by four adjacent empty buckets.

14 Gold Parameters in Booster

Parameter	Injection	Merge porch	Extraction	Unit
Q	32	32	32	
mc^2	183.456851	183.456851	183.456851	GeV
W/A	1.95418043	49.259795	107.75879	MeV
cp/A	60.3613437	306.87652	460.77475	MeV
E/A	0.933207234	0.98051285	1.0390118	GeV
$B\rho$	1.23952258	6.3017214	9.4620277	Tm
β	0.0646816072	0.31297552	0.44347401	
$\gamma - 1$	0.00209844191	0.052896251	0.11571376	
η	-0.953	-0.859	-0.7605	
ϵ_H (95%)	12.0π	12.0π	12.0π	mm mrad
ϵ_V (95%)	5.64π	5.64π	5.64π	mm mrad
h	4	1	1	
hf	384.400	465.000	658.910	KHz
R	$201.780/(2\pi)$	$201.780/(2\pi)$	128.4526/4	m

Here ϵ_H and ϵ_V are the normalized horizontal and vertical transverse emittances. These follow from the assumption that during injection the horizontal and vertical acceptances in Booster are completely filled. The horizontal and vertical acceptances are 185π and 87π mm mrad (un-normalized) respectively.

Parameter	Injection	Extraction	Extraction	Extraction	Unit
V_g	0.5	30	30	30	kV
A_S	4.7485	347.55	347.55	347.55	eV s
dB/dt	0	**70**	**35**	**0**	G/ms
ϕ_s	0	40.753	19.050	0	degrees
F_s	0.3414	0.9743	1.0884	1.1195	kHz
A_{bk}	4.7485	70.783	176.91	347.55	eV s
A_b	4.728	23.64	23.64	23.64	eV s
Δt	2533	313.0	291.7	287.0	ns
ΔE	1.432	48.63	51.83	52.64	MeV

Parameter	Injection	Extraction	Unit
No. of Bunches	4	1	
Bucket Width	2601.4568	1517.65795	ns
Ions/Bunch	1.25/4	0.981	10^9 [16]
Bunch Area	0.096/4	0.12	eV s/A

15 Copper Parameters in Booster

Parameter	Injection	Merge Porch	Extraction	Unit
Q	11	11	11	
mc^2	58.6129266	58.6129266	58.6129266	GeV
W/A	1.952314629	49.212763	108.134927	MeV
cp/A	60.3037121	306.58352	461.41395	MeV
E/A	0.9323162295	0.97957668	1.0384988	GeV
$B\rho$	1.15204968	5.8570100	8.8149099	Tm
β	0.06468160717	0.31295772	0.44430858	
$\gamma - 1$	0.00209844191	0.052896251	0.116228634	
η	-0.953	-0.859	-0.760	
ϵ_H (95%)	12.0π	12.0π	12.0π	mm mrad
ϵ_V (95%)	5.64π	5.64π	5.64π	mm mrad
h	4	1	1	
hf	0.384400	465.000	660.15	KHz
R	$201.780/(2\pi)$	$201.780/(2\pi)$	128.4526/4	m

Here ϵ_H and ϵ_V are the normalized horizontal and vertical transverse emittances. These follow from the assumption that during injection the horizontal and vertical acceptances in Booster are completely filled. The horizontal and vertical acceptances are 185π and 87π mm mrad (un-normalized) respectively.

Parameter	Injection	Extraction	Extraction	Extraction	Unit
V_g	0.500	30	30	30	kV
A_S	1.5736	115.26	115.26	115.26	eV s
dB/dt	0	**70**	**35**	**0**	G/ms
ϕ_s	0	40.753	19.050	0	degrees
F_s	0.3541	1.010	1.128	1.160	kHz
A_{bk}	1.5736	23.47	58.67	115.26	eV s
A_b	1.512	7.56	7.56	7.56	eV s
Δt	2364	306.5	285.8	281.2	ns
ΔE	0.4702	15.88	16.92	17.18	MeV

Parameter	Injection	Extraction	Unit
No. of Bunches	4	1	
Bucket Width	2601.4568	1514.8072	ns
Ions/Bunch	4.94/4	4.06	10^9 [17]
Bunch Area	0.096/4	0.12	eV s/A

16 Gold Parameters in AGS

Parameter	Injection	Transition	Extraction	Unit
Q	77	77	77	
mc^2	183.434174	183.434174	183.434174	GeV
W/A	0.10529199	6.98353456	8.86486832	GeV
cp/A	0.45515837	7.85970883	9.75165221	GeV
E/A	1.0364299	7.91467250	9.79600627	GeV
$B\rho$	3.88434088	67.0750887	83.2210138	Tm
β	0.43915981	0.993055472	0.995472231	
γ	1.1130788	8.5000	10.5204673	
η	-0.793	0.0	0.00481	
ϵ_H (95%)	$\leq 12\pi$	$\leq 12\pi$	$\leq 12\pi$	mm mrad
ϵ_V (95%)	$\leq 12\pi$	$\leq 12\pi$	$\leq 12\pi$	mm mrad
h	16	12	12	
hf	2.610000	4.42642072	4.43700951	MHz
R	128.4526	128.4526	128.45798	m

Parameter	Injection	Injection	Extraction	Unit
h	16	4	12	
V_g	33.84	22	161.9	kV
A_S	35.00	225.7	4655	eV s
dB/dt	0	0	0	G/ms
ϕ_s	0	0	180	degrees
F_s	1.886	0.7603	0.0904	kHz
A_{bk}	35.00	225.7	4655	eV s
A_b	27.58	110.3	110.3	eV s
Δt	287.0	833.9	25	ns [18]
ΔE	66.24	87.27	2812	MeV

Parameter	Injection	Injection	Extraction	Unit
h	16	4	12	
Bucket Width	383.142	1532.567	225.377	ns
No. of Bunches	8	2	2	
Ions/Bunch	0.556	2.224	1.62	10^9 [16]
Bunch Area	0.14	0.56	0.56	eV s/A [19, 20]

17 Copper Parameters in AGS

Parameter	Injection	Transition	Extraction	Unit
Q	29	29	29	
mc^2	58.60377233	58.60377233	58.60377233	GeV
W/A	0.1079641423	6.97663957	8.85683601	GeV
cp/A	0.4609954061	7.85194877	9.74274763	GeV
E/A	1.0381827506	7.90685818	9.78705462	GeV
$B\rho$	3.340553613	56.8983020	70.5997725	Tm
β	0.44404071036	0.993055472	0.995472899	
γ	1.1160631935	8.5000	10.5212415	
η	-0.789	0.0	0.00481	
ϵ_H (95%)	$\leq 12\pi$	$\leq 12\pi$	$\leq 12\pi$	mm mrad
ϵ_V (95%)	$\leq 12\pi$	$\leq 12\pi$	$\leq 12\pi$	mm mrad
h	16	12	12	
hf	2.639008	4.42642072	4.43700951	MHz
R	128.4526	128.4526	128.45800	m

Parameter	Injection	Injection	Extraction	Unit
h	16	4	12	
V_g	29.22	22	137.7	kV
A_S	11.33	78.62	1489	eV s
dB/dt	0	0	0	G/ms
ϕ_s	0	0	180	degrees
F_s	1.895	0.8222	0.09057	kHz
$A_{\rm bk}$	11.33	78.62	1489	eV s
A_b	8.82	35.28	35.28	eV s
Δt	281.2	783.9	25	ns [21]
ΔE	21.6	29.6	900	MeV

Parameter	Injection	Injection	Extraction	Unit
h	16	4	12	
Bucket Width	378.930	1515.721	225.377	ns
No. of Bunches	8	2	2	
Ions/Bunch	2.8	11.2	6.5	10^9 [17]
Bunch Area	0.14	0.56	0.56	eV s/N [22]

18 Gold Parameters in RHIC

Parameter	Injection	Transition	Store	Unit
Q	79	79	79	
mc^2	183.433337	183.433337	183.433337	GeV
W/A	8.86482786	20.3825165	99.0688663	GeV
cp/A	9.75160770	21.2933012	99.9956649	GeV
E/A	9.79596155	21.3136502	100.000000	GeV
$B\rho$	81.1137824	177.117482	831.763013	Tm
β	0.995472231	0.999045259	999956649	
γ	10.5204673	22.8900	107.395964	
η	-0.00713	0.0	0.00182	
ϵ_H (95%)	$\leq 10\pi$	$\leq 10\pi$	$\leq 10\pi$	mm mrad
ϵ_V (95%)	$\leq 10\pi$	$\leq 10\pi$	$\leq 10\pi$	mm mrad
h	360	360	2520	
hf	28.0232179485	28.1238011	197.046198131	MHz
δC	-1.961	-1.961	-1.898	mm

Parameter	Injection	Store	Unit
h	360	2520	
V_g	302.5	3000	kV
A_S	153.0	164.4	eV s
dB/dt	0	0	G/ms
ϕ_s	0	180	degrees
F_s	0.176	0.232	kHz
A_{bk}	153.0	164.4	eV s
A_b	110.32	110.32	eV s
A_b	0.56	0.56	eV s/A [23]
Δt	25	3.38	ns
ΔE	3002	22022	MeV

19 Copper Parameters in RHIC

Parameter	Injection	Transition	Store	Unit
Q	29	29	29	
mc^2	58.60377233	58.60377233	58.60377233	GeV
W/A	8.85683601	20.3624853	99.7120297	GeV
cp/A	9.74274764	21.2723749	1.006379493	GeV
E/A	9.78705462	21.29270394	100.6422483	GeV
$B\rho$	70.5997725	154.147976	729.262072	Tm
β	0.995472899	0.99904526	0.9999572842	
γ	10.5212415	22.8900	108.1920394	
η	-0.00713	0.0	0.00182	
ϵ_H (95%)	$\leq 10\pi$	$\leq 10\pi$	$\leq 10\pi$	mm mrad
ϵ_V (95%)	$\leq 10\pi$	$\leq 10\pi$	$\leq 10\pi$	mm mrad
h	360	360	2520	
hf	28.0232179485	28.1237822	197.046198131	MHz
δC	0.611	0.611	0.539	mm

Parameter	Injection	Store	Unit
h	360	2520	
V_g	263.7	3000	kV
A_S	48.93	56.49	eV s
dB/dt	0	0	G/ms
ϕ_s	0	180	degrees
F_s	0.176	0.248	kHz
A_{bk}	48.93	56.49	eV s
A_b	35.28	35.28	eV s
A_b	0.56	0.56	eV s/A [23]
Δt	25	3.22	ns
ΔE	960	7342	MeV

20 Au77+ Energy Loss in the BTA Stripper Foils

The stripper used to strip gold ions consists of a 6.45 mg/cm^2 aluminum foil followed by a 8.39 mg/cm^2 "glassy" carbon foil [24, 25]. We can estimate the energy loss in the foils as follows:

The kinetic energy of a proton that has the same velocity as the Au77+ ion just upstream of the aluminum foil is

$$W_p = 108.6 \text{ MeV}. \tag{44}$$

The rate of energy loss of a proton passing through the foil with kinetic energy W_p is [26]

$$-\frac{dE_p}{dx} = 5.348 \text{ MeV cm}^2/\text{g}. \tag{45}$$

The rate of energy loss of the Au77+ ion is obtained by scaling the Bethe-Bloch result for protons [27]. Thus

$$-\frac{dE}{dx} = -Z^2 \frac{dE_p}{dx} \text{ cm}^2/\text{g} \tag{46}$$

where $Z = 77$. Multiplying this by the surface density of the aluminum foil (6.45 mg/cm^2) gives

$$\Delta E_a = 1.038 \text{ MeV per nucleon}. \tag{47}$$

This is the energy lost by the Au77+ ion upon passing through the aluminium foil. The kinetic energy of a proton that has the same velocity as the Au77+ ion just downstream of the aluminum foil is then

$$W_p = 107.5 \text{ MeV}. \tag{48}$$

The rate of energy loss of a proton passing through the carbon foil with this kinetic energy is [26]

$$-\frac{dE_p}{dx} = 6.180 \text{ MeV cm}^2/\text{g}. \tag{49}$$

Using this result in (46) with $Z = 77$, and multiplying by the surface density of the carbon foil (8.39 mg/cm^2) gives

$$\Delta E_c = 1.561 \text{ MeV per nucleon}. \tag{50}$$

The total energy lost upon passing through both foils is then

$$\Delta E = \Delta E_a + \Delta E_c = 2.599 \text{ MeV per nucleon}. \tag{51}$$

This agrees reasonably well with the value 2.453 MeV per nucleon obtained in Section 5.

References

[1] C.J. Gardner, "Simulations of Merging and Squeezing Bunches in Booster and AGS", C-A/AP/Note 460, July 2012.

[2] J.S. Coursey, D.J. Schwab, and R.A. Dragoset, "Atomic Weights and Isotopic Compositions", Nuclear Physics Data, Physical Reference Data, www.nist.gov.

[3] P.J. Mohr and B.N. Taylor, "Values of Fundamental Physical Constants", Physical Constants, Physical Reference Data, www.nist.gov.

[4] K.A. Brown, C. Gardner and P. Thieberger, "Rest Mass of Fully Stripped Ions in RHIC: Updated Values", C-A/AP/Note 293, October 2007.

[5] G.C. Rodrigues, P. Indelicato, J.P. Santos, P. Patte, and F. Parente, "Systematic Calculation of Total Atomic Energies of Ground State Configurations", Atomic Data and Nuclear Data Tables 86 (2004) 117–233.

[6] S.Y. Lee, "Accelerator Physics", World Scientific, 1999, pp. 229–230

[7] E.J. Bleser, "Where are the AGS Magnets", Accelerator Division Technical Note 215, May 20, 1985.

[8] C.J. Gardner, "Notes on Orbit Equations in the AGS", C-A/AP/Note 164, September 2004.

[9] R. Thern, "Booster Dipole Production Measurements", Booster Technical Note 190, March 13, 1991.

[10] W. Fischer and S. Peggs, "RHIC Parameters", Revision of 3/18/97.

[11] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 16 May 2012, entry 15:50.

[12] W. Zhang, R. Sanders, A. Soukas and J. Tuozzolo, "An Overview of the Fast Injection-Extraction Kicker Systems of the Brookhaven AGS-Booster Complex", PAC99, pp. 1264–1266.

[13] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 22 May 2012, entry 16:56.

[14] C.J. Gardner, "Determination of the AGS Injection Kicker Strength from Beam Measurements", C-A/AP/Note 91, December 2002.

[15] C.J. Gardner, "AGS Injection with an Additional Kicker in the A10 Straight Section", C-A/AP/Note 217, September 2005.

[16] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 19 June 2012, entry 14:47.

[17] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 19 June 2012, entry 19:43.

[18] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 19 June 2012, entry 14:49.

[19] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 19 June 2012, entry 15:11.

[20] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 19 June 2012, entry 15:30.

[21] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 6 June 2012, entry 18:21.

[22] K.L. Zeno, Booster-AGS-EBIS-2012 elog, 19 June 2012, entry 12:57.

[23] Here we take the longitudinal emittance to be the same as that at AGS extraction. This gives a lower bound on the longitudinal emittance in RHIC.

[24] C.J. Gardner, et al, "Setup and Performance of the RHIC Injector Accelerators for the 2007 Run with Gold Ions", Proceedings of PAC07, pp. 1862–1864.

[25] P. Thieberger, et al, "Improved Gold Ion Stripping at 0.1 and 10 GeV/nucleon for the Relativistic Heavy Ion Collider", Phys. Rev. ST Accelerators and Beams **11**, 011001 (2008).

[26] M.J. Berger, J.S. Coursey, M.A. Zucker and J. Chang, "Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions", www.nist.gov/physlab/data/star/index.cfm

[27] W.R. Leo, "Techniques for Nuclear and Particle Physics Experiments", Second Revised Edition, Springer-Verlag, 1994, pp. 24–28.