BNL-104864-2014-TECH

AGS/AD/Tech Note No. 448;BNL-104864-2014-IR

Heavy Ion Parameters for 1996

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October 1996

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U.S. Department of Energy

USDOE Office of Science (SC)

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Technical Note

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This is the 1996 version of the note on heavy ion parameters put out last year [1]. Ions of Iron and Gold will again be accelerated in the Tandem, Booster, and AGS for the 1996 HIP (Heavy Ion Physics) run. For the first part of the run, NASA again requires Iron ions at 1 GeV kinetic energy per nucleon to bombard various biological samples. They have also expressed interest in acquiring some data with ions at 600 MeV per nucleon. The iron ions will be extracted by slow extraction from the AGS and transported to experimental area A3. For the remainder of the run, Gold ions will be delivered to the experimental areas and to the ATR (AGS To RHIC) line. The experiments require Slow Extracted Beam while the ATR line requires a single bunch kicked out of the AGS with the Fast Extracted Beam setup commissioned last year. All experiments except two require Gold ions at the same momentum delivered for the past two years, namely 11.7 GeV/c per nucleon. (This momentum has been verified by measurements of frequency and radius in the AGS at extraction [2].) The other two experiments require Gold ions with kinetic energies of 6 and 8 GeV per nucleon. The ATR line and RHIC require gold ions with momentum 11.2 GeV/c per nucleon. Following is a summary of the various ion parameters during injection, acceleration, and extraction in the Tandem, Booster and AGS.

1 Charge State and Acceleration Overview

Negative ions enter the Tandem with charge minus one and are accelerated from ground potential to the center terminal where they are stripped of $1 + Q_t$ electrons thereby becoming positive ions (with charge Q_t) which are then accelerated back to ground potential. A foil located downstream of the Tandem and upstream of the first 90° bend in the TTB (Tandem To Booster) line may be inserted to allow additional stripping of the ions before they enter the Booster. The charge state after this stripping is Q_b. Ions with this charge are transported down the TTB line and injected into the Booster where they are captured and undergo further acceleration. The harmonic of the accelerating voltage is $h = 8$, and, for the case in which the ions are to be slowly extracted from the AGS, the bunches are simply kicked out of the Booster after acceleration at this harmonic. (The F3 kicker in the Booster and the A5 kicker in the AGS cannot stay on long enough for all 8 bunches to be extracted from the Booster and injected into the AGS; typically only 5 of the 8 bunches are cleanly transfered to the AGS. This situation eventually will be remedied with modified power supplies for the kicker magnets.) For the case in which a single bunch is to be delivered to RHIC, an accelerating voltage with harmonic $h = 4$ is turned on in the Booster just before extraction and the bunches are allowed to rotate 90° in the $h = 4$ buckets—a process we call a pseudo-merge—after which they are kicked out of the Booster.

After extraction from the Booster, the ions pass through a foil in the BTA (Booster To AGS) line and emerge with charge Q_a. Ions with this charge are transported down the BTA line and injected into the AGS where they are again accelerated. If the bunches have undergone a pseudo-merge before extraction from the Booster, they are transfered into Rf buckets at harmonic $h_a = 16$ in the AGS and accelerated at this harmonic; otherwise they are first allowed to debunch and are then captured and accelerated to full energy at harmonic $h_a = 12$. At harmonic $h_a = 16$ the bunches cannot be accelerated to full energy; after acceleration at $h_a = 16$ they must be merged and then accelerated to full energy at harmonic $h_a = 8$. (This year we will do an additional merge before extraction with an accelerating voltage at harmonic $h_a = 4$.)

After extraction from the AGS, the ions are either transported to fixed-target experiments in the experimental hall or they are sent down the ATR line where they pass through a final foil which strips away the remaining electrons. The charge of the fully stripped ion is Q_r. The nominal charge states for the ions of the 1996 HIP run are summarized in the following table. (Note that the subscripts t, b, a, and r are used to denote the charge states in the tandem, booster, ags, and rhic respectively.) The number of nucleons, n, and atomic mass, a, are also included.

Table I: Charge States and Atomic Parameters						
Atom	n	a	Q_t	Q_b	Q_a	Q_r
Iron	56	55.93434	+10	+10	+26	+26
Gold	197	196.966541	+12	+32	+77	+79

2 Acceleration in Tandem

Negative ions of iron oxide (FeO^-) or gold (Au^-) enter the Tandem with charge minus one and mass m_s, having been accelerated through a potential difference of

$$V_s = 130\,\text{keV} \tag{1}$$

in the ion source. Neglecting the atomic binding energy, the mass of the iron oxide ion is

$$m_s = au + bu + m_e \tag{2}$$

where $a = 55.93493$ is the atomic mass of iron (Fe^{56}), $b = 15.99491$ is the atomic mass of oxygen (O^{16}), $u = 931.49432$ MeV$/c^2$ is the unified atomic mass unit, and $m_e c^2 = .5110034$ MeV is the electron mass. The mass of the gold ions (Au^-) is

$$m_s = au + m_e \tag{3}$$

where $a = 196.966541$. The part of the negative ion consisting of a neutral atom of iron or gold, minus Q_t electrons, has mass

$$m_t = au - Q_t m_e \tag{4}$$

and gains energy

$$W_s = V_s m_t / m_s \tag{5}$$

in the ion source. Upon acceleration from the "tank" potential to the center terminal of the Tandem, this part of the negative ion gains energy

$$W_f = V_t m_t / m_s \tag{6}$$

where V_t is the terminal voltage. In the center terminal the ions pass through a thin foil and emerge as individual atoms with various charge states. Upon acceleration back to "tank" potential, the iron or gold ions with charge Q_t gain additional energy $Q_t V_t$ so that the total energy gained by each of these ions due to the accelerating voltage in the Tandem is

$$W_t = W_f + Q_t V_t = (m_t/m_s + Q_t)V_t. \tag{7}$$

Assuming each ion loses energy δW as it passes through the foil in the center terminal, the total kinetic energy of the ion emerging from the Tandem will be $W_s + W_t - \delta W$. For the 2 microgram foils typically used in the terminal, δW is approximately 180 keV (as per Peter Thieberger).

3 Booster Injection

The momentum of ions transported down the TTB line and injected into the Booster is determined by the setting of the magnetic field (as measured by NMR probes) in the 90° bends of the TTB line. The Tandem voltage required to give the desired momentem is then obtained by adjusting the voltage so that the ion beam is centered in slits located downstream of the bends. If we let p be the momentum of the ions injected into the booster, then their energy is

$$E = \sqrt{p^2c^2 + m^2c^4} \tag{8}$$

where the mass is

$$m = au - Q_b m_e. \tag{9}$$

(Putting in numbers we find that the masses of the iron and gold ions injected into the booster are 52.0979596 and 183.4568621 GeV/c^2.) The kinetic energy is then

$$W = E - mc^2, \tag{10}$$

and

$$W_s + W_t - \delta W = W \tag{11}$$

where W_s and W_t are given by (5) and (7). The Tandem voltage is therefore

$$V_t = W_t/(m_t/m_s + Q_t) = (W - W_s + \delta W)/(m_t/m_s + Q_t). \tag{12}$$

It is convenient to parameterize the momentum and energy in terms of the kinetic energy defined by (10). Thus using (8) and (10) we have

$$cp = \sqrt{W^2 + 2mc^2W}, \quad E = mc^2 + W. \tag{13}$$

We can then derive all other injection parameters from cp and E. Thus the rigidity of the ion beam in units of Tm is

$$B\rho = kp/Q \tag{14}$$

where $k = 3.33564095 \times 10^{-3}$, p is the momentum in units of MeV/c, and Q is the ion charge. The inflector voltage, V_I, required to bring the beam into the acceptance region of the Booster is [3]

$$eV_I = \frac{D}{R} c^2 p^2 / (QE) \tag{15}$$

where $D = 0.017$ m and $R = 8.74123$ m. The velocity and revolution frequency of the ion as it enters the Booster are

$$v = c\beta = c^2 p/E, \quad f = v/C, \quad C = 2\pi R_a/4 = \pi R_a/2 \tag{16}$$

where C is the Booster circumference and $R_a = 128.454$ meters is the radius of the AGS. The frequency of the accelerating voltage in the Booster is hf, where $h = 8$ for the 1996 run. The following table summarizes the various Tandem and Booster injection parameters. The nominal injection parameters for iron and gold are those corresponding to kinetic energies $W = 126.8$ and 182.13 MeV respectively.

Table II: Tandem and Booster Injection Parameters

Ion	W (MeV)	V_t (MV)	cp (MeV/n)	$B\rho$ (Tm)	V_I (kV)	hf (kHz)
	125.8	11.680	64.69037	1.20839	48.872	824.523
Fe^{10+}	126.8	11.773	64.94729	1.21319	49.260	827.782
	127.8	11.865	65.20320	1.21797	49.648	831.027
	181.13	13.937	41.39216	.849990	22.006	527.795
Au^{32+}	182.13	14.014	41.50632	.852334	22.127	529.247
	183.13	14.091	41.62017	.854672	22.248	530.696

Note that the values of W, V_t, V_I, and hf listed for iron differ slightly from those calculated in Ref. [1]. This is because that calculation used the weighted atomic mass of iron rather than the atomic mass of the most abundant isotope, Fe^{56}, which is what is actually delivered by the Tandem. The calculation of the terminal voltage was also incorrect for both iron and gold. These errors have been corrected and the parameters listed in Table II have been adjusted so that the momentum cp and magnetic rigidity $B\rho$ are the same as they were last year.

4 Booster Extraction

The iron and gold ions are accelerated at harmonic $h = 8$ to $hf = 5.0$ MHz before being kicked out of the Booster into the BTA line. Since the maximum energy to which a given ion can be accelerated is ultimately limited by the maximum field of the Booster magnets, it is convenient to parameterize the Booster extraction parameters in terms of the magnetic rigidity $B\rho$. Thus we have

$$p = Q_b B\rho/k, \quad E = \sqrt{p^2c^2 + m^2c^4}, \quad W = E - mc^2, \quad f = c^2p/(EC) \tag{17}$$

where m is given by (9) and k is defined by (14). We also define P to be the momentum of a proton which has the same rigidity as the ion under consideration. Thus

$$P = B\rho/k = p/Q_b. \tag{18}$$

The following table summarizes the various Booster extraction parameters.

Table III: Booster Extraction Parameters					
Ion	$B\rho$ (Tm)	cP (GeV)	cp (MeV/n)	W (MeV/n)	hf (MHz)
	7.6578	2.296	409.9555	86.3209	4.793051
Fe^{10+}	8.0578	2.416	431.3692	95.1431	5.000023
	8.4578	2.536	452.7830	104.3334	5.201614
	8.4670	2.538	412.3196	87.1966	4.812133
Au^{32+}	8.8670	2.658	431.7985	95.2372	4.999994
	9.2670	2.778	451.2774	103.5820	5.183411

5 Stripping in BTA

After extraction from the Booster and before passing through the stripping foil in the BTA line, the ions have charge Q_b, mass $m_b = au - Q_b m_e$, and energy $E_b = \sqrt{p_b^2c^2 + m_b^2c^4}$, where cp_b is given by cp in Table III. The part of each of these ions consisting of a neutral atom of iron or gold, minus Q_a electrons, has mass and energy

$$m_a = au - Q_a m_e, \quad E_a = E_b m_a/m_b. \tag{19}$$

Upon passing through the foil, the ions lose energy δE and those emerging with charge Q_a then have energy and momentum

$$E = E_a - \delta E, \quad cp = \sqrt{E^2 - m_a^2c^4}. \tag{20}$$

The energy loss and stripping efficiencies in the BTA foil have been calculated and measured by Roser [4–6] for the case of Au^{33+} ions passing through various foils (Carbon, Aluminum, Copper) with momenta ranging from 330 to 760 MeV/c per nucleon. For the 1996 HIP run, a 0.010 inch thick Carbon foil will be used to strip the Fe^{10+} ions to charge state $Q_a = 26$ (fully stripped), and a 0.004 inch thick Carbon foil will be used to strip the Au^{32+} ions to charge state $Q_a = 77$ (two remaining electrons). (The same foils were used in 1995.) The 0.004 and 0.010 inch thick foils occupy positions 3 and 6 respectively in the BTA foil holder.

Because it has been the source of confusion in the past, we note here that the foil holder in the BTA line consists of a rotatable circular array of eight equally spaced positions or slots, seven of which contain foils and one which is left open (or blank) for beams (protons) that do not require stripping. The location and characteristics of each of the seven foils are summarized in Table IV:

Table IV: BTA Foils

Position	Foil	Thickness	Mass
1	Blank	Inches	mg/cm^2
2	Carbon	.003	17
3	Carbon	.004	22
4	Carbon	.005	28
5	Carbon	.007	39
6	Carbon	.010	56
7	Copper	.001	23
8	Copper/Carbon	.001/.003	23/17

The indicated thicknesses are those quoted by the manufacturer. For the Carbon foils they are good to about 0.0001 inches; for the Copper foil they are good to about 10 per cent. The mass per unit area has been calculated assuming densities of 2.2 and 8.9 g/cm^3 for Carbon and Copper.

To estimate the energy loss, δE, we employ the scaling law used in Refs. [4–6]:

$$\left(\frac{dE}{dx}\right)_{^N\mathrm{X}^Z} = \frac{Z^2}{N} \times \left(\frac{dE}{dx}\right)_{\mathrm{Proton}} \left(p = \frac{p_\mathrm{X}}{N}\right). \qquad (21)$$

Here $^N X^Z$ denotes an ion of element X with N nucleons and charge Z, p and p_X are proton and ion momenta, and dE/dx is the energy lost per unit length of the foil material. To apply (21) we need the value of dE/dx in the foil material for protons with momentum $p = p_X/N$. Consulting Table III we see that p_X/N is approximately 430 MeV/c for both iron and gold, and consulting Ref.[7] we find that dE/dx for protons with 430 MeV/c momentum in Carbon is 6.2 MeV per g/cm^2. For iron we have $Z^2/N = 26^2/56$, and for gold $Z^2/N = 77^2/197$. Using these numbers in (21) we then find that $\delta E = 4.2$ MeV per nucleon for Fe^{26+} passing through foil 6 and also for Au^{77+} passing through foil 3.

6 AGS Injection

It is convenient to parameterize the AGS injection parameters in terms of the energy and momentum given by (20). Thus we have

$$\beta = cp/E, \quad f_a = c\beta/(2\pi R_a), \quad W = E - m_a c^2 \tag{22}$$

where f_a is the AGS revolution frequency, $R_a = 128.454$ meters, and m_a is given by (19). We also have

$$B\rho = kp/Q_a, \quad P = B\rho/k = p/Q_a \tag{23}$$

where P is the equivalent proton momentum. (The masses of the iron and gold ions in the AGS are 52.0897835 and 183.4338669 GeV/c^2.)

Let us first assume that the ions lose no energy upon passing through the foil in BTA—i.e. we assume $\delta E = 0$. We then obtain the parameters listed in Table V. The harmonic number at injection is taken to be $h_a = 12$, although it is actually 16 for the case in which the bunches have undergone a pseudo-merge at Booster extraction.

Table V: AGS Injection Parameters ($\delta E = 0$)					
Ion	$h_a f_a$ (MHz)	$B\rho$ (Tm)	cP (GeV)	cp (MeV/n)	W (MeV/n)
Fe^{26+}	1.797394	2.9448	0.883	409.8911	86.3073
	1.875009	3.0987	0.929	431.3015	95.1282
	1.950605	3.2525	0.975	452.7119	104.3170
Au^{77+}	1.804550	3.5183	1.055	412.2680	87.1857
	1.874998	3.6845	1.105	431.7444	95.2252
	1.943779	3.8507	1.154	451.2209	103.5690

Note that the frequencies, $h_a f_a$, listed in Table V correspond to the frequencies, hf, listed in the last column of Table III, and in this case

($\delta E = 0$) we have $f_a = f/4$. The ions do, of course, lose energy as they pass through the stripping foil and so the AGS revolution frequency, f_a, is in fact less than one fourth the Booster revolution frequency f. Using the estimated value of $\delta E = 4.2$ MeV per nucleon obtained above for iron and gold, we obtain the parameters listed in Table VI.

Table VI: AGS Injection Parameters ($\delta E = 4.2$ MeV per nucleon)

Ion	$h_a f_a$ (MHz)	$B\rho$ (Tm)	cP (GeV)	cp (MeV/n)	W (MeV/n)
	1.758489	2.8692	0.860	399.3619	82.1073
Fe^{26+}	1.838712	3.0262	0.907	421.2198	90.9282
	1.916672	3.1829	0.954	443.0305	100.1170
	1.765934	3.4288	1.028	401.7818	82.9857
Au^{77+}	1.838739	3.5985	1.079	421.6627	91.0252
	1.909675	3.7678	1.130	441.5047	99.3690

Comparing these parameters with the corresponding ones in Table V, we see that when the Booster extraction frequency, hf, is 5 MHz, the AGS injection frequency, $h_a f_a$, is reduced from 1.875 to 1.839 MHz (a reduction of 36 kHz) due to the energy loss in the foil.

7 AGS Extraction

It is convenient to parameterize the AGS extraction parameters in terms of the magnetic rigidity, $B\rho$, or the corresponding proton momentum $P = B\rho/k$. Thus we have

$$p = Q_a B\rho/k, \quad E = \sqrt{p^2c^2 + m^2c^4}, \quad W = E - mc^2, \tag{24}$$

$$f_a = c^2 p/(2\pi R_a E), \quad \gamma = \frac{E}{mc^2} = 1 + \frac{W}{mc^2} \tag{25}$$

where m is given by (19) and $2\pi R_a$ is the AGS circumference. Table VII summarizes the various parameters for ions of iron and gold. The harmonic number at extraction is taken to be $h_a = 12$.

Note that for Au^{77+} ions with $W = 6$ and 8 GeV per nucleon at extraction, we have $\gamma = 7.44$ and 9.59 which are both somewhat close to the nominal gamma-transition of 8.5. The concern here is that the time required for the beam to debunch becomes infinite as the gamma of the ions approaches gamma-transition (good debunching is required for a uniform SEB spill). The debunch time is proportional to $1/\eta$, where

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \qquad (26)$$

and $\gamma_t \approx 8.5$. For $\gamma = 7.44$ and 9.59 we find $1/\eta = -237$ and 337. These are to be compared with $1/\eta = 133$ for the case of Au^{77+} ions with momentum 11.7 GeV/c per nucleon which have a gamma of 12.6.

Table VII: AGS Extraction Parameters

Ion	$B\rho$ (Tm)	cP (GeV)	cp (GeV/n)	W (GeV/n)	$h_a f_a$ (Mhz)
	8.7290	2.6169	1.21499	0.60000	3.539215
	10.4813	3.1422	1.45888	0.80001	3.758376
Fe^{26+}	12.1507	3.6427	1.69125	1.00000	3.905595
	13.7679	4.1275	1.91634	1.19999	4.009910
	15.3493	4.6016	2.13646	1.39999	4.086785
	23.7187	7.1107	2.77931	2.00000	4.226442
	41.3256	12.3891	4.84244	4.00001	4.377141
Au^{77+}	58.6145	17.5722	6.86832	6.00002	4.416922
	75.8034	22.7253	8.88248	8.00001	4.433036
	92.9480	27.8651	10.89144	10.00003	4.441126
	93.8746	28.1429	11.00002	10.10822	4.441443
Au^{77+}	95.5815	28.6546	11.20002	10.30752	4.442002
	97.2880	29.1662	11.39999	10.50681	4.442532
	98.9948	29.6779	11.59999	10.70617	4.443036
Au^{77+}	99.8484	29.9338	11.70001	10.80587	4.443278
	100.7017	30.1896	11.80000	10.90554	4.443514

8 Beam Intensities

Listed in Table VIII are Beam Intensities recorded during the 1995 HIP run when we were running well with one load transfered from Booster to AGS per AGS cycle. (For part of the Gold run we ran with lower current from Tandem but with two Booster loads transfered to the AGS per AGS cycle instead of just one.)

Table VIII: 1995 Beam Intensities		
	Iron	Gold
End of TTB:		
Current	35 micro-Amps	36 micro-Amps
Pulse Width	700 micro-sec	660 micro-sec
Total Ions	153×10^8	46×10^8
Booster:		
Early	32×10^8 Ions	19×10^8 Ions
Late	25×10^8 Ions	13×10^8 Ions
AGS:		
Early	4.9×10^8 Ions	5.4×10^8 Ions
Late	4.2×10^8 Ions	3.9×10^8 Ions
Extracted	3.4×10^8 Ions	2.8×10^8 Ions
Beam Lines:		
A Line	1.0×10^8 Ions	69×10^6 Ions
B Line		6.2×10^6 Ions
C Line		39×10^6 Ions

9 References

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