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Notes on the setup of Ruthenium and Zirconium ions in Booster and AGS for RHIC Run 18

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Following are notes accumulated prior to and during the setup of Ruthenium-96 (96Ru) and Zirconium-96 (96Zr) ions in Booster and AGS for Ru-Ru and Zr-Zr collisions in RHIC. These document the parameters used and provide an informal history of what was done. A formal summary of the setup and its performance during Run 18 is given in [1].

Ruthenium ions (96Ru12+) come from the MP7 Tandem van de Graaff; Zirconium ions (96Zr16+) come from the Electron Beam Ion Source (EBIS). This is shown schematically in **Figure 1**.

In Booster a 4-2-1 merge is used for both 96Ru and 96Zu ions. In AGS an 8-4-2 merge is used for 96Ru ions. For 96Zr ions in AGS, either a 12-6-2 or an 8-4-2 merge is used. The 12-6-2 merge is used if bunches of the highest possible intensity are needed. These merges were developed for the operation of RHIC with Gold ions, and are documented in [2] and [3].

Section 1 gives a summary of what was achieved with Ruthenium in 2016.

Sections 2 through 6 give estimated and achieved intensities of 96Ru and 96Zr for Run 18.

Sections 7 through 11, and 28 give the various ion masses.

Sections 12 through 15 give the ion parameters in Booster.

Sections 16 through 24 give the ion parameters in AGS.

Sections 25 through 27 give the ion parameters in RHIC.

1 Summary of 2016 Ruthenium setup [4]

In March 2016, Tandem provided 96Ru12+ ions for injection into Booster. These were obtained using a source target composed of naturally occurring Ruthenium. The desired isotope has 96 nucleons and an abundance of just 5.54%. Eight single-bunch Booster loads were transfered to AGS per AGS cycle. The 8 bunches were merged into 2 on the AGS injection porch, and these 2 were accelerated to AGS extraction energy. Each accelerated bunch therefore contains 4 Booster loads.

1. With 8 Tandem pulses per AGS cycle, the intensity at Booster Input was 5.3e9/8 = 0.663e9 96Ru12+ ions per Booster load.

This number comes from **Figure 2**.

2. With 8 Tandem pulses per AGS cycle, the intensity at <u>Booster Output</u> was 4.256e9/8 = 0.532e9 96Ru12+ ions per Booster load.

This number comes from **Figures 3** and **4**.

- 3. Booster Output/Input is therefore 0.532/0.663 = 0.802.
- 4. The intensity at <u>AGS Extraction</u> was 2.141e9/8 = 0.2676e9 96Ru44+ ions per Booster load.

This number also comes from **Figures 3** and **4**.

- 5. The intensity at AGS extraction is then 1.07e9 96Ru44+ ions per bunch.
- 6. Additional setup documentation is given in Figures 5, 6, and 7.
- 7. Isotopic abundances of Ruthenium are listed in **Figure 8**. A sample is shown in **Figure 9**.

2 Ruthenium intensity estimate for Run 18

In March 2016, Tandem provided 8 pulses of 96Ru12+ions (per AGS cycle) for injection into Booster. These were obtained using a source target composed of naturally occurring Ruthenium. The desired isotope has 96 nucleons and an abundance of just 5.54%. This produced two bunches with an intensity of <u>1.07e9</u> 96Ru44+ ions per bunch at AGS extraction.

If the abundance is increased to X% by enrichment then the intensity per bunch would (presumably) increase by a factor of X/5.54. Figure 10 shows the separation of ruthenium isotopes at the Enriched Stable Isotope Prototype Plant (ESIPP) at ORNL. The result is a powder of virtually 100% Ruthenium-96. At BNL this is diluted with a powder of Aluminum-27 in order to provide any desired effective abundance. The mixture is pressed into a cavity in the cathode of a sputter source. A schematic of a generic source of negative ions by cesium sputtering is shown in Figure 11. A schematic of the pulsed negative ion cesium sputter source system used to produce negative 96Ru ions for injection into the MP7 Tandem van de Graaff is shown in Figure 12. Here a mixture consisting of weights W_R and W_A of 96Ru and 27Al powders, respectively, is pressed into the cathode cavity.

The number ratio of 96Ru to 27Al atoms in the mixture is then

$$R = \frac{W_R/96}{W_A/27} = \frac{27\,W_R}{96\,W_A} \tag{1}$$

which amounts to an effective abundance

$$A = \frac{W_R/96}{(W_A/27) + (W_R/96)} = \frac{R}{1+R}$$
(2)

of 96Ru atoms. To achieve a particular value of A, the required R is

$$R = \frac{A}{1 - A}.\tag{3}$$

The value of A chosen for the 2018 run is

$$A = 25\% \tag{4}$$

which gives

$$R = 1/3 \tag{5}$$

and

$$\frac{W_R}{W_A} = \frac{96}{27} R = \frac{32}{27}.$$
(6)

With an effective abundance of 25% the intensities achieved in 2016 could be increased by a factor of 25/5.54, which would give 4.83e9 96Ru44+ ions per bunch at AGS extraction. The intensity at Booster injection would be 3.0e9 96Ru12+ ions per Tandem pulse. The intensity at AGS extraction needed to provide the desired Ru-Ru collision luminosity in RHIC is just 1e9 96Ru44+ ions per bunch. This is well below the estimate of what can be delivered with an effective abundance of 25%.

3 Ruthenium intensities achieved in Run 18

As measured and recorded in [5], the number of 96Ru ions achieved in Booster and AGS with 8 Booster loads per AGS cycle is

Booster input 10.4e9 Booster early 9.4e9 Booster late 8.9e9 AGS late 4.6e9.

This gave 2.2e9 96Ru44+ ions in each bunch to be extracted to RHIC.

The intensity needed at AGS extraction to provide the desired Ru-Ru collision luminosity in RHIC is just <u>1e9</u> ions per bunch. This is well below what can be delivered.

4 Zirconium intensity estimate for Run 18

In March 2017, EBIS provided 90Zr15+ and 96Zr16+ ions for injection into Booster. These were obtained using a source target composed of naturally occurring Zirconium. The abundances of 90Zr and the desired isotope 96Zr are 51.5% and 2.80% respectively.

Because the charge-to-mass ratios of 90Zr15+ and 96Zr16+ are very close to one another, both ions can be accelerated simultaneously in Booster. This was done on 29 March 2017 and is documented in the NSRL-2017 elog. The ions were stripped of all electrons just upstream of the D6 extraction septum magnet, thereby becoming 90Zr40+ and 96Zr40+. The magnets of the R-line was first tuned to transport the 90Zr40+ ions to the NSRL target room. The extraction septum magnet and R-line magnets were then scaled to transport the 96Zr40+ ions. This produced a small but easily discernible signal in the target room.

A calibrated measurement of 90Zr15+ and 96Zr16+ circulating beam current in Booster was not done prior to this estimate. Here I obtain an estimate based on the well known numbers for Au32+ and Au77+ ions in Booster and AGS respectively. As reported in [6], EBIS delivers <u>12 pulses</u> of Au32+ ions to Booster each AGS cycle at an intensity of <u>1.25e9</u> ions per pulse. This produces two bunches with an intensity of <u>3.0e9</u> Au77+ ions per bunch at AGS extraction. The overall efficiency of the process is therefore

$$\mathcal{E} = \frac{2 \times 3 \times 10^9}{12 \times 1.25 \times 10^9} = 40\%.$$
 (7)

Since Zr16+ has half the charge of Au32+, one expects roughly twice as many 96Zr16+ ions per pulse from EBIS. This assumes, of course, that the source target consists of 100% 96Zr. One would then have 12 pulses of 96Zr16+ ions delivered to Booster each AGS cycle at an intensity of <u>2.5e9</u> ions per pulse. Assuming the same efficiency as above then gives two bunches with an intensity of <u>6.0e9</u> 96Zr40+ ions per bunch at AGS extraction. This is the most one can expect. If, for example, the source target consists of 80% instead of 100% 96Zr, then the number of 96Zr40+ ions per bunch would be reduced from 6.0e9 to 4.8e9.

The sintered target for the laser ion source (LION) is composed of ZrO_2 obtained from Trace Sciences International. Some 60% of the zirconium in this compound is 96Zr [7]. We therefore expect at most <u>1.5e9</u> 96Zr16+ ions per EBIS pulse at Booster injection and <u>3.6e9</u> 96Zr40+ ions per bunch at AGS extraction.

5 96Zr16+ and 90Zr15+ beam current ratio

Some 19% of the zirconium in the source target is 90Zr [7]. This gives

$$\mathcal{R}_T = \frac{0.60}{0.19} = 3.1579 \tag{8}$$

for the number ratio of 96Zr to 90Zr atoms in the target. As already mentioned, the charge-to-mass ratios of the 96Zr16+ and 90Zr15+ ions are very close to one another. This means that both ions circulate simultaneously in Booster and their currents need to be sorted out.

Let

$$\mathcal{R}_B = \frac{N96}{N90} \tag{9}$$

where N96 and N90 are the number of 96Zr16+ to 90Zr15+ ions injected into booster per EBIS pulse. The ratio of 96Zr16+ and 90Zr15+ beam currents in Booster is then

$$\mathcal{R}_C = \frac{16 \times N96}{15 \times N90} = \frac{16}{15} \mathcal{R}_B.$$
 (10)

If 96Zr16+ and 90Zr15+ are the only beam currents, then the fraction of the total current that is due to 96Zr16+ ions would be

$$\mathcal{F} = \frac{\mathcal{R}_C}{1 + \mathcal{R}_C}.$$
(11)

As an **estimate** we take

$$\mathcal{R}_B = \mathcal{R}_T. \tag{12}$$

This gives

$$\mathcal{R}_C = \frac{16}{15} \,\mathcal{R}_T = 3.3684 \tag{13}$$

and

$$\mathcal{F} = \frac{\mathcal{R}_C}{1 + \mathcal{R}_C} = 0.7711. \tag{14}$$

Measurements made by K. Zeno [8] in the Booster-To-AGS (BTA) transfer line allow for a determination of the ratio \mathcal{R}_B . In the BTA line the 96Zr16+ and 90Zr15+ ions pass through a stripping foil where most of them are fully stripped to 96Zr40+ and 90Zr40+ ions. The ions then pass through a bending magnet and can be seen as well separated beams on a profile monitor that sits downstream of the bend. By appropriately

integrating the voltages registered on the wires of the profile monitor, the ratio \mathcal{R}_B is found to be [8]

$$\mathcal{R}_B = \frac{0.702}{0.298} = 2.3557. \tag{15}$$

This gives

$$\mathcal{R}_C = \frac{16}{15} \,\mathcal{R}_B = 2.5128 \tag{16}$$

and

$$\mathcal{F} = \frac{\mathcal{R}_C}{1 + \mathcal{R}_C} = 0.7153. \tag{17}$$

The measurements also give an efficiency of 87% for the stripping of the zirconium ions to 96Zr40+ and 90Zr40+.

6 Zirconium intensities achieved in Run 18

As measured and recorded in [9], the number of 96Zr ions achieved in Booster and AGS with 8 Booster loads per AGS cycle is

Booster input 8.94e9 Booster early 8.56e9 Booster late 7.06e9 AGS early 5.3e9 AGS late 5.0e9.

This gave close to 2.5e9 96Zr40+ ions in each bunch to be extracted to RHIC.

The corresponding efficiencies are

Bearly/Binput=0.96 B late/B early=0.82 AGS early/B late=0.75 AGS late/AGS early=0.95 AGS late/B input=0.56.

The intensity needed at AGS extraction to provide the desired Zr-Zr collision luminosity in RHIC is just <u>1e9</u> ions per bunch. This is well below what can be delivered.

7 Ruthenium-96 ion masses

A Ruthenium-96 ion with charge eQ has N = 52 neutrons, Z = 44 protons, and (Z - Q) electrons. Here Q is an integer and e is the charge of a single proton. The mass number is

$$A = N + Z = 96. (18)$$

This is also called the number of nucleons. The natural abundance of this isotope is 0.0554(14). The mass energy equivalent of the ion is

$$mc^2 = am_u c^2 - Qm_e c^2 + E_Q (19)$$

where [10, 11]

$$a = 95.907\,590\,25(49) \tag{20}$$

is the relative atomic mass of the neutral Ruthenium-96 atom,

$$m_u c^2 = 931.494\,0954(57) \,\,\mathrm{MeV}$$
 (21)

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

$$m_e c^2 = 0.510\,998\,9461(31)\,\mathrm{MeV}$$
 (22)

is the electron mass energy equivalent. The binding energy E_Q is the energy required to remove Q electrons from the neutral atom. As shown in Section 28 this amounts to 1.271 and 2.561 KeV for Q = 12 and 16, respectively.

For the fully stripped ion (Q = 44) we have $E_Q = 0.123122$ MeV.

Thus the mass energy equivalents for the 96Ru12+, 96Ru16+, and 96Ru44+ ions are

$$mc^2(96\text{Ru}12+) = 89.331\,223\,3056\,\text{GeV}$$
 (23)

$$mc^2(96\text{Ru}16+) = 89.329\,180\,5998\,\text{GeV}$$
 (24)

and

$$mc^2(96\text{Ru}44+) = 89.314\,993\,1903\,\text{GeV}.$$
 (25)

8 Zirconium-96 ion masses

A Zirconium-96 ion with charge eQ has N = 56 neutrons, Z = 40 protons, and (Z - Q) electrons. Here Q is an integer and e is the charge of a single proton. The mass number is

$$A = N + Z = 96. (26)$$

This is also called the number of nucleons. The natural abundance of this isotope is 0.0280(9). The mass energy equivalent of the ion is

$$mc^2 = am_u c^2 - Qm_e c^2 + E_Q (27)$$

where [10, 11]

$$a = 95.908\,2714(21) \tag{28}$$

is the relative atomic mass of the neutral Zirconium-96 atom,

$$m_u c^2 = 931.494\,0954(57) \,\,\mathrm{MeV} \tag{29}$$

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

$$m_e c^2 = 0.510\,998\,9461(31)\,\mathrm{MeV}$$
 (30)

is the electron mass energy equivalent. The binding energy E_Q is the energy required to remove Q electrons from the neutral atom. As shown in Section 28 this amounts to 1.534 and 3.253 KeV for Q = 12 and 16, respectively. For the fully stripped ion (Q = 40) we have $E_Q = 0.097790$ MeV.

Thus the mass energy equivalents for the 96Zr12+, 96Zr16+, and 96Zr40+ ions are

$$mc^2(96\text{Zr}12+) = 89.331\,858\,0558\,\text{GeV}$$
 (31)

$$mc^2(96\text{Zr}16+) = 89.329\,815\,7790\,\text{GeV}$$
 (32)

and

$$mc^2(96\text{Zr}40+) = 89.317\,646\,3413\,\text{GeV}.$$
 (33)

9 Zirconium-90 ion masses

A Zirconium-90 ion with charge eQ has N = 50 neutrons, Z = 40 protons, and (Z - Q) electrons. Here Q is an integer and e is the charge of a single proton. The mass number is

$$A = N + Z = 90. (34)$$

This is also called the number of nucleons. The natural abundance of this isotope is 0.5145(40). The mass energy equivalent of the ion is

$$mc^2 = am_u c^2 - Qm_e c^2 + E_Q (35)$$

where [10, 11]

$$a = 89.904\,6977(20) \tag{36}$$

is the relative atomic mass of the neutral Zirconium-90 atom,

$$m_u c^2 = 931.494\,0954(57) \,\,\mathrm{MeV}$$
(37)

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

$$m_e c^2 = 0.510\,998\,9461(31)\,\mathrm{MeV}$$
 (38)

is the electron mass energy equivalent. The binding energy E_Q is the energy required to remove Q electrons from the neutral atom. As shown in Section 28 this amounts to 1.534, 2.680, and 3.253 KeV for Q = 12, 15, and 16, respectively. For the fully stripped ion (Q = 40) we have $E_Q = 0.097790$ MeV.

Thus the mass energy equivalents for the $90\mathrm{Zr}12+,\,90\mathrm{Zr}15+,\,90\mathrm{Zr}16+,$ and $90\mathrm{Zr}40+$ ions are

$$mc^2(90\text{Zr}12+) = 83.739\,564\,6029\,\text{GeV}$$
 (39)

$$mc^{2}(90\text{Zr15+}) = 83.738\,032\,7521\,\text{GeV}$$
 (40)

$$mc^2(90\text{Zr}16+) = 83.737\,522\,3261\,\text{GeV}$$
 (41)

and

$$mc^2(90\text{Zr}40+) = 83.725\,352\,8884\,\text{GeV}.$$
 (42)

10 Gold ion masses

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 charge of a single proton. The mass number is

$$A = N + Z = 197. (43)$$

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

$$mc^2 = am_u c^2 - Qm_e c^2 + E_Q \tag{44}$$

where [10, 11]

$$a = 196.966\,568\,79(71) \tag{45}$$

is the relative atomic mass of the neutral gold atom,

$$m_u c^2 = 931.494\,0954(57) \,\,\mathrm{MeV}$$
(46)

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

$$m_e c^2 = 0.510\,998\,9461(31)\,\mathrm{MeV}$$
(47)

is the electron mass energy equivalent. The binding energy E_Q is the energy required to remove Q electrons from the neutral atom. As shown in Section 28 this amounts to 0.3324 MeV for the helium-like gold ion (Q = 77) and 0.5170 MeV for the fully stripped ion. For Q = 32 we have $E_Q = 14.5$ KeV.

Thus the mass energy equivalents for the Au32+, Au77+, and Au79+ ions are

$$mc^{2}(\text{Au}32+) = 183.456\,858\,353\,\text{GeV}$$
 (48)

$$mc^{2}(\text{Au77+}) = 183.434\,181\,300\,\text{GeV}$$
 (49)

and

$$mc^{2}(\text{Au79+}) = 183.433\,343\,902 \text{ GeV}.$$
 (50)

The setup of Booster and AGS with gold ions is well established and well documented [2, 3]. It provides a point of reference for the setups with ruthenium and zirconium.

11 Mass-to-charge ratios

Ruthenium-96:

$$\frac{mc^2}{Q} (96\text{Ru}12+) = 7.44426860880 \text{ GeV}$$
(51)

$$\frac{mc^2}{Q} (96\text{Ru}44+) = 2.02988620887 \text{ GeV}$$
(52)

Zirconium-96:

$$\frac{mc^2}{Q} (96\text{Zr}16+) = 5.58311348619 \text{ GeV}$$
(53)

$$\frac{mc^2}{Q}96\text{Zr}40+) = 2.23294115853 \text{ GeV}$$
(54)

Zirconium-90:

$$\frac{mc^2}{Q} \left(9rZr15+\right) = 5.58253551681 \text{ GeV}$$
(55)

$$\frac{mc^2}{Q}(90\text{Zr}16+) = 5.23359514538 \text{ GeV}$$
(56)

$$\frac{mc^2}{Q} (90\text{Zr}40+) = 2.09313382221 \text{ GeV}$$
(57)

 \underline{Gold} :

$$\frac{mc^2}{Q} (\text{Au}32+) = 5.73302682353 \text{ GeV}$$
(58)

$$\frac{mc^2}{Q} (\text{Au77+}) = 2.38226209481 \text{ GeV}$$
(59)

$$\frac{mc^2}{Q} (\text{Au79+}) = 2.32194106205 \text{ GeV}$$
(60)

The mass-to-charge ratios of 96Zr16+ and 90Zr15+ are nearly identical. This means that 90Zr15+ can be substituted for 96Zr16+ during the setup of Booster if need be.

The mass-to-charge ratio of 96Zr16+ is smaller than that of Au32+. This makes the bending and accelerating fields in Booster more effective for the Zirconium ion. Similarly, the mass-to-charge ratios of 96Ru44+ and 96Zu40+ are smaller than those of Au77+ and Au79+. This makes the bending and accelerating fields in AGS and RHIC more effective for the Ruthenium and Zirconium ions.

12 Tandem 96Ru12+ in Booster (2016 setup)

At injection:

- 1. Kinetic energy W = 178.632965152 MeV
- 2. W/A = 1.86076005366 MeV per nucleon
- 3. $B\rho = 1.57113135548$ Tm
- 4. B = 1.13311458248 kG
- 5. Inflector V = 71.4535040658 kV (setpoint = 72.210 kV)
- 6. Revolution frequency f = 93.818 kHz
- 7. 4f = 375.272 kHz

On merge porch:

- 1. f = 439.100 kHz
- 2. $B\rho = 7.68190691524$ Tm
- 3. B = 5.54026289179 kG
- 4. W/A = 43.5111615928 MeV per nucleon

At extraction:

- 1. $B\rho = 9.46 \text{ Tm}$
- 2. B = 6.82826967438 kG
- 3. W/A = 65.2406124660 MeV per nucleon
- 4. f = 528.955228455 kHz

Isotopic abundances are listed in Figure 8. A Ruthenium sample is shown in Figure 9.

13 EBIS Au32+ in Booster (for comparision)

At injection:

- 1. W/A = 1.97627401907 MeV per nucleon
- 2. $B\rho = 1.24651719998~{\rm Tm}$
- 3. B = 898.999826895 Gauss
- 4. Inflector $V=58.3955914656~\mathrm{kV}$
- 5. Revolution frequency f = 96.640 kHz
- 6. 4f = 386.560 kHz

On merge porch (for 12 transfers to AGS):

- 1. f = 553.000 kHz
- 2. $B\rho = 7.66880062604~{\rm Tm}$
- 3. B = 5.53081051382 kG
- 4. $W/A=72.0897525649~{\rm MeV}$ per nucleon

- 1. $B\rho = 9.46202808578~{\rm Tm}$
- 2. B = 6.82973355563 kG
- 3. W/A = 107.758798130 MeV per nucleon
- 4. $f=658.910~\mathrm{kHz}$

14 EBIS 96Zr16+ in Booster (nominal)

At injection:

- 1. W/A = 1.97471598027 MeV per nucleon
- 2. $B\rho = 1.21392193063$ Tm
- 3. B = 875.491814729 Gauss
- 4. Inflector $V=56.8686008773~{\rm kV}$
- 5. Revolution frequency f = 96.640 kHz
- 6. 4f = 386.560 kHz

On merge porch (for 12 transfers to AGS):

- 1. f = 566.000 kHz
- 2. $B\rho = 7.67323949959~{\rm Tm}$
- 3. B = 5.53401187081 kG
- 4. W/A = 75.8897344594 MeV per nucleon

At extraction:

- 1. $B\rho = 9.46 \text{ Tm}$
- 2. B = 6.82826967438 kG
- 3. W/A = 113.169258721 MeV per nucleon
- 4. f = 672.895700696 kHz

Isotopic abundances are listed in Figure 8. A Zirconium sample is shown in Figure 13.

15 EBIS 90Zr15+ in Booster (contaminant)

At injection:

- 1. $W/A = 1.97451155573~{\rm MeV}$ per nucleon
- 2. $B\rho = 1.21379626424$ Tm
- 3. B = 875.401182958 Gauss
- 4. Inflector $V=56.8627137839~{\rm kV}$
- 5. Revolution frequency f = 96.640 kHz
- 6. 4f = 386.560 kHz

On merge porch (for 12 transfers to AGS):

- 1. f = 566.000 kHz
- 2. $B\rho = 7.67244515831~{\rm Tm}$
- 3. B = 5.53343898447 kG
- 4. W/A = 75.8818782797 MeV per nucleon

At extraction:

- 1. $B\rho = 9.46 \text{ Tm}$
- 2. B = 6.82826967438 kG
- 3. W/A = 113.179704701 MeV per nucleon
- 4. f = 672.951076002 kHz

Isotopic abundances are listed in Figure 8. A Zirconium sample is shown in Figure 13.

16 96Ru44+ energy loss in the BTA stripper

The stripper consists of a 6.45 mg/cm^2 aluminum foil followed by a 8.39 mg/cm^2 "glassy" carbon foil [12, 13]. We can estimate the energy loss in the foils as follows:

The kinetic energy of a proton that has the same velocity as the Ru44+ ion just upstream of the aluminum foil is

$$W_p = 65.8 \text{ MeV.}$$
 (61)

The rate of energy loss of a proton passing through the foil with kinetic energy W_p is [14]

$$-\frac{dE_p}{dx} = 7.765 \text{ MeV cm}^2/\text{g.}$$
 (62)

The rate of energy loss of the Ru44+ ion is obtained by scaling the Bethe-Bloch result for protons [15]. Thus

$$-\frac{dE}{dx} = -Z^2 \frac{dE_p}{dx} \,\mathrm{cm}^2/\mathrm{g} \tag{63}$$

where Z = 44. Multiplying this by the surface density of the aluminum foil (6.45 mg/cm²) gives

$$\Delta E_a = 1.010 \text{ MeV per nucleon.}$$
(64)

This is the energy lost by the Ru44+ ion upon passing through the aluminium foil. The kinetic energy of a proton that has the same velocity as the Ru44+ ion just downstream of the aluminum foil is then

$$W_p = 64.8 \text{ MeV.}$$
 (65)

The rate of energy loss of a proton passing through the carbon foil with this kinetic energy is [14]

$$-\frac{dE_p}{dx} = 9.082 \text{ MeV cm}^2/\text{g.}$$
 (66)

Using this result in (63) with Z = 44, and multiplying by the surface density of the carbon foil (8.39 mg/cm²) gives

$$\Delta E_c = 1.537 \text{ MeV per nucleon.}$$
(67)

The total energy lost upon passing through both foils is then

$$\Delta E = \Delta E_a + \Delta E_c = 2.547 \text{ MeV per nucleon.}$$
(68)

17 96Ru44+ in AGS with 8 to 4 to 2 merge (2016 setup)

At injection:

- 1. Revolution frequency f = 129.878125 kHz
- 2. 16f = 2.078050 MHz (Standard RF cavities)
- 3. T = 1/f
- 4. T/16 = 481.220374871 ns
- 5. 6T/16 = 2887 ns (see Figures 14 and 15)
- 6. W/A = 62.6820612547 MeV per nucleon
- 7. $B\rho = 2.52700176824$ Tm
- 8. B = 295.976876883 Gauss

On 8 to 4 to 2 merge porch:

- 1. 16f = 3.132 MHz (Standard RF cavities)
- 2. 12f = 2.349 MHz (Standard RF cavities)
- 3. 8f = 1.566 MHz (KL cavity)
- 4. 4f = 0.783 MHz (L10 cavity)
- 5. W/A = 164.348903766 MeV per nucleon
- 6. $B\rho = 4.19857706977$ Tm
- 7. B = 491.761321295 Gauss

- 1. $B\rho = 81.11378003$ Tm
- 2. B = 9471.79665265 Gauss
- 3. 12f = 4.44174003759 MHz
- 4. W/A = 10.2538280939 GeV per nucleon
- 5. $\gamma = 12.0213018201$

18 Au77+ in AGS (for comparison)

At injection with 12 to 6 merge:

- 1. Revolution frequency f = 163.125 kHz
- 2. 24f = 3.915 MHz (Standard RF cavities)
- 3. $12f=1.9575~\mathrm{MHz}$ (Standard RF cavities)
- 4. T = 1/f
- 5. T/24 = 255.427841635 ns
- 6. 8T/24 = 2043 ns (see Figures 14 and 16)
- 7. W/A = 105.291998331 MeV per nucleon
- 8. $B\rho = 3.88434102815$ Tm
- 9. B = 454.956201737 Gauss

On 6 to 2 merge porch:

- 1. 12f = 2.349 MHz (Standard RF cavities)
- 2. 8f = 1.566 MHz (KL cavity)
- 3. 4f = 0.783 MHz (L10 cavity)
- 4. W/A = 164.485536147 MeV per nucleon
- 5. $B\rho = 4.92742448406$ Tm
- 6. B = 577.128092350 Gauss

- 1. 12f = 4.43700723632 MHz
- 2. $B\rho = 83.2210113689$ Tm
- 3. B = 9717.86170763 Gauss
- 4. W/A = 8.86486800852 GeV per nucleon
- 5. $\gamma = 10.5204666071$

19 96Zr40+ energy loss in the BTA stripper

The stripper consists of a 6.45 mg/cm^2 aluminum foil followed by a 8.39 mg/cm^2 "glassy" carbon foil [12, 13]. We can estimate the energy loss in the foils as follows:

The kinetic energy of a proton that has the same velocity as the Zr40+ ion just upstream of the aluminum foil is

$$W_p = 114.1 \text{ MeV.}$$
 (69)

The rate of energy loss of a proton passing through the foil with kinetic energy W_p is [14]

$$-\frac{dE_p}{dx} = 5.161 \text{ MeV cm}^2/\text{g.}$$
 (70)

The rate of energy loss of the Zr40+ ion is obtained by scaling the Bethe-Bloch result for protons [15]. Thus

$$-\frac{dE}{dx} = -Z^2 \frac{dE_p}{dx} \,\mathrm{cm}^2/\mathrm{g} \tag{71}$$

where Z = 40. Multiplying this by the surface density of the aluminum foil (6.45 mg/cm²) gives

$$\Delta E_a = 0.5548 \text{ MeV per nucleon.}$$
(72)

This is the energy lost by the Zr40+ ion upon passing through the aluminium foil. The kinetic energy of a proton that has the same velocity as the Zr40+ ion just downstream of the aluminum foil is then

$$W_p = 113.6 \text{ MeV.}$$
 (73)

The rate of energy loss of a proton passing through the carbon foil with this kinetic energy is [14]

$$-\frac{dE_p}{dx} = 5.935 \text{ MeV cm}^2/\text{g.}$$
 (74)

Using this result in (71) with Z = 40, and multiplying by the surface density of the carbon foil (8.39 mg/cm²) gives

$$\Delta E_c = 0.8299 \text{ MeV per nucleon.}$$
(75)

The total energy lost upon passing through both foils is then

$$\Delta E = \Delta E_a + \Delta E_c = 1.385 \text{ MeV per nucleon.}$$
(76)

20 96Zr40+ in AGS with 12 to 6 to 2 merge

At injection with 12 to 6 merge:

- 1. 24f = 4.0165165 MHz (Standard RF cavities)
- 2. 12f = 2.00825825 MHz (Standard RF cavities)
- 3. T = 1/f
- 4. T/24 = 248.971963641 ns
- 5. 8T/24 = 1992 ns (see Figures 14 and 16)
- 6. W/A = 111.769123102 MeV per nucleon
- 7. $B\rho = 3.75894392907$ Tm
- 8. B = 440.268977445 Gauss

On 6 to 2 merge porch:

- 1. 12f = 2.349 MHz (Standard RF cavities)
- 2. 8f = 1.566 MHz (KL cavity)
- 3. 4f = 0.783 MHz (L10 cavity)
- 4. W/A = 164.353785841 MeV per nucleon
- 5. $B\rho = 4.61857196989$ Tm
- 6. B = 540.953522269 Gauss

- 1. $B\rho = 81.11378003$ Tm
- 2. B = 9471.79665265 Gauss
- 3. 12f = 4.43851514760 MHz
- 4. W/A = 9.24444303256 GeV per nucleon
- 5. $\gamma = 10.9360716217$

21 Au77+ in AGS (for comparison)

At injection with 12 to 6 merge:

- 1. Revolution frequency f = 163.125 kHz
- 2. 24f = 3.915 MHz (Standard RF cavities)
- 3. $12f=1.9575~\mathrm{MHz}$ (Standard RF cavities)
- 4. T = 1/f
- 5. T/24 = 255.427841635 ns
- 6. 8T/24 = 2043 ns (see Figures 14 and 16)
- 7. W/A = 105.291998331 MeV per nucleon
- 8. $B\rho = 3.88434102815$ Tm
- 9. B = 454.956201737 Gauss

On 6 to 2 merge porch:

- 1. 12f = 2.349 MHz (Standard RF cavities)
- 2. 8f = 1.566 MHz (KL cavity)
- 3. 4f = 0.783 MHz (L10 cavity)
- 4. W/A = 164.485536147 MeV per nucleon
- 5. $B\rho = 4.92742448406 \text{ Tm}$
- 6. B = 577.128092350 Gauss

- 1. 12f = 4.43700723632 MHz
- 2. $B\rho = 83.2210113689$ Tm
- 3. B = 9717.86170763 Gauss
- 4. W/A = 8.86486800852 GeV per nucleon
- 5. $\gamma = 10.5204666071$

22 96Zr40+ in AGS with 8 to 4 to 2 merge

At injection:

- 1. 16f = 2.6776777 MHz (Standard RF cavities)
- 2. T = 1/f
- 3. T/16 = 373.457940812 ns
- 4. 6T/16 = 2240.747644872 ns (see Figures 14 and 15)
- 5. W/A = 111.769126406 MeV per nucleon
- 6. $B\rho = 3.75894398778~{\rm Tm}$
- 7. B = 440.268984322 Gauss

On 8 to 4 to 2 merge porch:

- 1. 16f = 3.132 MHz (Standard RF cavities)
- 2. 12f = 2.349 MHz (Standard RF cavities)
- 3. 8f = 1.566 MHz (KL cavity)
- 4. 4f = 0.783 MHz (L10 cavity)
- 5. W/A = 164.353785841 MeV per nucleon
- 6. $B\rho = 4.61857196989$ Tm
- 7. B = 540.953522269 Gauss

- 1. $B\rho = 81.11378003$ Tm
- 2. B = 9471.79665265 Gauss
- 3. 12f = 4.43851514760 MHz
- 4. W/A = 9.24444303256 GeV per nucleon
- 5. $\gamma = 10.9360716217$

23 90Zr40+ energy loss in the BTA stripper

The stripper consists of a 6.45 mg/cm^2 aluminum foil followed by a 8.39 mg/cm^2 "glassy" carbon foil [12, 13]. We can estimate the energy loss in the foils as follows:

The kinetic energy of a proton that has the same velocity as the 90Zr40+ ion just upstream of the aluminum foil is

$$W_p = 114.1 \text{ MeV.}$$
 (77)

The rate of energy loss of a proton passing through the foil with kinetic energy W_p is [14]

$$-\frac{dE_p}{dx} = 5.161 \text{ MeV cm}^2/\text{g.}$$
 (78)

The rate of energy loss of the Zr40+ ion is obtained by scaling the Bethe-Bloch result for protons [15]. Thus

$$-\frac{dE}{dx} = -Z^2 \frac{dE_p}{dx} \,\mathrm{cm}^2/\mathrm{g} \tag{79}$$

where Z = 40. Multiplying this by the surface density of the aluminum foil (6.45 mg/cm²) gives

$$\Delta E_a = 0.5918 \text{ MeV per nucleon.} \tag{80}$$

This is the energy lost by the Zr40+ ion upon passing through the aluminium foil. The kinetic energy of a proton that has the same velocity as the Zr40+ ion just downstream of the aluminum foil is then

$$W_p = 113.5 \text{ MeV.}$$
 (81)

The rate of energy loss of a proton passing through the carbon foil with this kinetic energy is [14]

$$-\frac{dE_p}{dx} = 5.910 \text{ MeV cm}^2/\text{g.}$$
 (82)

Using this result in (79) with Z = 40, and multiplying by the surface density of the carbon foil (8.39 mg/cm²) gives

$$\Delta E_c = 0.8815 \text{ MeV per nucleon.}$$
(83)

The total energy lost upon passing through both foils is then

$$\Delta E = \Delta E_a + \Delta E_c = 1.4733 \text{ MeV per nucleon.}$$
(84)

24 90Zr40+ in AGS

At injection:

- 1. Revolution frequency f = 167.313 kHz
- 2. 24f = 4.015512 MHz (Standard RF cavities)
- 3. 12f = 2.007756 MHz (Standard RF cavities)
- 4. T = 1/f
- 5. T/24 = 249.034245197 ns
- 6. 8T/24 = 1992 ns (see Figures 14 and 16)
- 7. W/A = 111.689494517 MeV per nucleon
- 8. $B\rho = 3.52248602416$ Tm for <u>90Zr40+</u> ions
- 9. B = 412.573677390 Gauss
- 10. $B\rho = 3.75894392907$ Tm for <u>96Zr40+</u> ions

Here we see that values of $B\rho$ for 90Zr40+ and 96Zr40+ ions are sufficiently far apart to keep 90Zr40+ ions out of AGS as long as the BTA line and AGS are tuned for injection of 96Zr40+ ions.

25 96Ru44+ in RHIC

At injection:

- 1. $B\rho = 81.11378003$ Tm
- 2. Revolution frequency f = 77925.2638173 Hz
- 3. 360f = 28.0530949742 MHz
- 4. $E/A=11.1841926063~{\rm GeV}$ per nucleon
- 5. $\gamma = 12.0213018201$

At extraction with energy 100 GeV per nucleon:

- 1. $B\rho = 727.744709665 \text{ Tm}$
- 2. $f=78192.9026543~{\rm Hz}$
- 3. 360f = 28.1494449555 MHz
- 4. E/A = 100 GeV per nucleon
- 5. $\gamma = 107.484753199$

26 Au79+ in RHIC (for comparison)

At injection:

- 1. $B\rho = 81.11378003$ Tm
- 2. Revolution frequency f = 77842.2322162 Hz
- 3. 360f = 28.0232035978 MHz
- 4. $E/A=9.79596126523~{\rm GeV}$ per nucleon
- 5. $\gamma = 10.5204666076$

- 1. $B\rho = 831.763013148$ Tm
- 2. $f=78192.8970556~{\rm Hz}$
- 3. 360f = 28.1494429400 MHz
- 4. E/A = 100 GeV per nucleon
- 5. $\gamma = 107.395959649$

27 96Zr40+ in RHIC

At injection:

- 1. $B\rho = 81.11378003$ Tm
- 2. Revolution frequency f = 77868.6867999 Hz
- 3. 360f = 28.0327272480 MHz
- 4. $E/A=10.1748351819~{\rm GeV}$ per nucleon
- 5. $\gamma = 10.9360716217$

At extraction with same revolution frequency as 96Ru44+:

- 1. $B\rho = 800.542946750 \text{ Tm}$
- 2. $f=78192.9026542~{\rm Hz}$
- 3. 360f = 28.1494449555 MHz
- 4. $E/A=100.002968838~{\rm GeV}$ per nucleon
- 5. $\gamma = 107.484751353$

28 Atomic binding energies

To obtain the energy required to remove a certain number of electrons from a given atom we follow Brown and Thieberger [16] and use the tables given in Ref. [17]. Here the table numbered N gives the energy required to remove all electrons from atoms consisting of N electrons and Z protons, with Z running from N to 118. Tables are given for N = 3 (Lithium-like atoms) through N = 105 (Dubnium-like atoms).

Let E_Q be the energy required to remove the outer Q electrons from a neutral atom containing Z protons, and let \mathcal{E}_{Z-Q} be the energy required to remove the remaining Z - Q electrons. Then we have

$$E_Q = E_Z - \mathcal{E}_{Z-Q} \tag{85}$$

where E_Z is the energy required to remove all Z electrons. Here E_Z is obtained from the first entry of Table Z and \mathcal{E}_{Z-Q} is obtained from entry Z of Table Z - Q.

28.1 Zirconium

For the case of the fully stripped zirconium ion we have Q = Z = 40 and

$$E_Z = 97790 \text{ eV}.$$
 (86)

The ion binding energy E_Q is given in **Table 1** for various charge states Q.

Q	Z-Q	$\mathcal{E}_{Z-Q}\left(\mathrm{eV}\right)$	$E_Q (\mathrm{eV})$
12	28	96256	1534
15	25	95110	2680
16	24	94537	3253
40	0	0	97790

Table 1: Zirconium ion binding energies E_Q

28.2 Ruthenium

For the case of the fully stripped ruthenium ion we have Q = Z = 44 and

$$E_Z = 123122 \text{ eV}.$$
 (87)

The ion binding energy E_Q is given in **Table 2** for various charge states Q.

Table 2: Ruthenium ion binding energies E_Q

ſ	Q	Z-Q	$\mathcal{E}_{Z-Q}\left(\mathrm{eV}\right)$	$E_Q (\mathrm{eV})$
ſ	12	32	121851	1271
ĺ	16	28	120561	2561
	44	0	0	123122

28.3 Gold

For the case of the fully stripped gold ion we have Q=Z=79 and

$$E_Z = 517015 \text{ eV}.$$
 (88)

The ion binding energy E_Q is given in **Table 3** for various charge states Q.

Q	Z-Q	$\mathcal{E}_{Z-Q}\left(\mathrm{eV}\right)$	$E_Q (\mathrm{eV})$
31	48	503474	13541
32	47	502529	14486
33	46	501550	15465
74	5	252058	264957
75	4	230133	286882
76	3	207635	309380
77	2	184624	332391

Table 3: Gold Ion Binding Energies E_Q

Here E_{77} has been obtained from E_{74} , E_{75} , and E_{76} by extrapolation.

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Figure 1: Delivery of 96Ru44+ and 96Zr40+ ions to RHIC.



Figure 2: Tandem Ruthenium-96 at end of TTB line. Here the total number of 96Ru12+ ions in 8 Tandem pulses at Booster Input is 5.3e9. K.L. Zeno, 29 March 2016.

Booster/ComfortDispla	ays/GoldTal: 🗕 🗖 🗙
File PPM Setup Logging I	Diagnostics
ON The Planetarium U1 Mar 29	20:18:44 Cycle 60220
×£108_1	
v£108_2	÷ ÷
xf108 3	÷ ÷
×F108 4	÷
v£108 5	÷
xF100_0	
v£108 7	÷
xF100_1	÷ 1
xf100_0	
	î
Farlu 1	-
Farlu 2	0.0
Farlu 3	0.0
Farlu 4	0.0
Farlu 5	0.0
Farlu 6	0.0
Farlu 7	0.0
Farlu 8	0.0
Booster Farlu	-800.0
Late 1	342.0
Late 2	595.0
Late 3	584.0
Late 4	627.0
Late_5	529.0
Late_6	563.0
Late_7	498.0
Late_8	518.0
Booster_Late	4256.0
ags_1st_xfer	2120
ags_last_transfer	2022
ags_before_transition	2091
ags_after_transition	2168
ags_late	2141
(AGS_CBM)/(B_Late)	475.094
(AGS_Late)/(B_Late)	503.055
PercentBabies	1005.2
	V
	X
	Stop

Figure 3: Tandem Ruthenium-96 in Booster and AGS. K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 20:18, 29 March 2016.



Figure 4: Tandem Ruthenium-96 in Booster and AGS. On the vertical axis, 1000 corresponds to 1.0e9 Ruthenium ions. K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 20:49, 29 March 2016.



Figure 5: Eight pulses of Tandem 96Ru12+ in Booster. K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 16:24, 29 March 2016.



Figure 6: Eight loads 96Ru44+ in Ags. K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 17:11, 29 March 2016.



Figure 7: Merge of 4 adjacent 96Ru44+ bunches into 1 on AGS injection porch.

K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 16:09, 29 March 2016.

0.5145(40)	01 224(2)
0.1100(10)	91.224(2)
0.1122(3) 0.1715(8)	
0.1713(0)	
0.1730(20)	
0.0200(3)	
1	92.906 37(2)
0.1453(30)	95.95(1)
0.0915(9)	
0.1584(11)	
0.1667(15)	
0.0960(14)	
0.2439(37)	
0.0982(31)	
	[98]
0.0554(14)	101.07(2)
0.0187(3)	
0.1276(14)	
0.1260(7)	
0.1706(2)	
0.3155(14)	
0.1862(27)	
1	102.905 50(2)
0.0102(1)	106.42(1)
0.1114(8)	
0.2233(8)	
0.2733(3)	
0.2646(9)	
0.1172(9)	
0 519 20(9)	107 8682(2)
0.510 59(6)	107.0002(2)
	0.1122(5) 0.1715(8) 0.1738(28) 0.0280(9) 1 0.1453(30) 0.0915(9) 0.1584(11) 0.1667(15) 0.0960(14) 0.2439(37) 0.0982(31) 0.00554(14) 0.1276(14) 0.1260(7) 0.1706(2) 0.3155(14) 0.1862(27) 1 0.0102(1) 0.1114(8) 0.2233(8) 0.2733(3) 0.2646(9) 0.1172(9)

Figure 8: Zirconium and Ruthenium isotope abundances from NIST web site.



Figure 9: <u>Ruthenium</u>, a polyvalent hard white metal, is a member of the platinum group and is in group 8 of the periodic table (Wikipedia).



Figure 10: Ruthenium isotope separation at ORNL. Here the blue glow is due to photoemission as the ion beam interacts with background gas in the vacuum chamber. The glow furthest to the right is due to 96Ru ions. With permission and courtesy of ESIPP at ORNL.



Figure 11: The image above and the following caption are from National Electrostatic Corp. at www.pelletron.com: "Cesium vapor flows from the cesium oven into an enclosed area between the cooled cathode and the heated ionizing surface. Some of the cesium condenses on the front of the cathode and some of the cesium is ionized by the hot surface. The ionized cesium accelerates toward the cathode and is focused on the front face of the cathode. The ionized cesium sputters particles from the cathode through a condensed cesium layer on the cathode face. In this way, negative ions are accelerated from the cathode surface". For the sputter source feeding the BNL MP7 Tandem van de Graaff, a mixture of Aluminum-27 and Ruthenium-96 powders is pressed into the cavity of the cathode to form a target. The effective abundance of 96Ru is set by the relative amounts of the two powders in the mixture.



Figure 12: Schematic of the pulsed negative ion cesium sputter source system used to produce negative 96Ru ions for injection into the MP7 Tandem. A mixture consisting 50 mg of 96Ru and 43 mg of 27Al powders is pressed into the cathode cavity as shown in the enlargement on the lower left. This gives an effective abundance of 25% as discussed in Section 2.



Figure 13: <u>Zirconium</u> is a lustrous, grey-white, strong transition metal that resembles hafnium and, to a lesser extent, titanium (Wikipedia).



Figure 14: 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 481 ns for 96Ru44+ ions in harmonic 16 buckets and 249 ns for 96Zr40+ ions in harmonic 24 buckets. In order to put beam into adjacent buckets, the rise time of the kicker must be less than or equal to B - W, where B is the bucket width and W the bunch width. The rise time is approximately 100 ns, which implies that the bunch width must be less than or equal to 381 and 149 ns for 96Ru44+ and 96Zr40+ bunches respectively. Bunches of these widths easily fit on the flattop portion of the pulse which is some 600 ns long. The total width of the pulse is approximately 1000 ns. For the case in which 8 Booster loads of 96Ru44+ (each consisting of one bunch) are transferred to AGS, one workable filling pattern is four adjacent filled harmonic 16 buckets followed by four adjacent empty buckets, followed by another four adjacent filled buckets. This is illustrated in **Figure 15**. For the case in which 12 Booster loads of 96Zr40+ are transferred to AGS, one workable filling pattern is six adjacent filled harmonic 24 buckets followed by six adjacent empty buckets, followed by another six adjacent filled buckets. This is illustrated in **Figure 16**.



Figure 15: AGS injection kicker timing for 96Ru44+ 4 to 1 merge setup. Here T is the revolution period on the AGS injection porch and T/16 = 481 ns is the harmonic 16 RF bucket width. The kicker rise time is 100 ns. This means that the bunch width, W, must be less than T/16 - 100 = 381 ns. The filling pattern in this case is four adjacent filled harmonic 16 buckets followed by four adjacent empty buckets, followed by another four adjacent filled buckets. This allows each group of four adjacent bunches to be merged into a single bunch. One ends up with a merged bunch sitting in every other harmonic 4 bucket. The total gap available for the kicker pulse is 6T/16 - W = 2887 - W ns.



Figure 16: AGS injection kicker timing for 96Zu40+ 6 to 1 merge setup. Here T is the revolution period on the AGS injection porch and T/24 = 249 ns is the harmonic 24 RF bucket width. The kicker rise time is 100 ns. This means that the bunch width, W, must be less than T/24 - 100 = 149 ns. The filling pattern in this case is six adjacent filled harmonic 24 buckets followed by six adjacent empty buckets, followed by another four adjacent filled buckets. This allows each group of six adjacent bunches to be merged into a single bunch. One ends up with a merged bunch sitting in every other harmonic 4 bucket. The total gap available for the kicker pulse is 8T/24 - W = 1992 - W ns.