

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

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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 ( $^{96}\text{Ru}$ ) and Zirconium-96 ( $^{96}\text{Zr}$ ) 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 ( $^{96}\text{Ru}12+$ ) come from the MP7 Tandem van de Graaff; Zirconium ions ( $^{96}\text{Zr}16+$ ) 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  $^{96}\text{Ru}$  and  $^{96}\text{Zr}$  ions. In AGS an 8-4-2 merge is used for  $^{96}\text{Ru}$  ions. For  $^{96}\text{Zr}$  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  $^{96}\text{Ru}$  and  $^{96}\text{Zr}$  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  $^{96}\text{Ru}^{12+}$  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 transferred 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  $5.3\text{e}9/8 = \underline{0.663\text{e}9}$   $^{96}\text{Ru}^{12+}$  ions per Booster load.

This number comes from **Figure 2**.

2. With 8 Tandem pulses per AGS cycle, the intensity at Booster Output was  $4.256\text{e}9/8 = \underline{0.532\text{e}9}$   $^{96}\text{Ru}^{12+}$  ions per Booster load.

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

3. Booster Output/Input is therefore  $0.532/0.663 = \underline{0.802}$ .

4. The intensity at AGS Extraction was  $2.141\text{e}9/8 = \underline{0.2676\text{e}9}$   $^{96}\text{Ru}^{44+}$  ions per Booster load.

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

5. The intensity at AGS extraction is then  $\underline{1.07\text{e}9}$   $^{96}\text{Ru}^{44+}$  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  $^{96}\text{Ru}^{12+}$  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  $1.07 \times 10^9$   $^{96}\text{Ru}^{44+}$  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  $^{96}\text{Ru}$  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  $^{96}\text{Ru}$  and  $^{27}\text{Al}$  powders, respectively, is pressed into the cathode cavity.

The number ratio of  $^{96}\text{Ru}$  to  $^{27}\text{Al}$  atoms in the mixture is then

$$R = \frac{W_R/96}{W_A/27} = \frac{27 W_R}{96 W_A} \quad (1)$$

which amounts to an effective abundance

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

of  $^{96}\text{Ru}$  atoms. To achieve a particular value of  $A$ , the required  $R$  is

$$R = \frac{A}{1 - A}. \quad (3)$$

The value of  $A$  chosen for the 2018 run is

$$A = 25\% \quad (4)$$

which gives

$$R = 1/3 \quad (5)$$

and

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

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 1e9 ions per bunch. This is well below what can be delivered.

## 4 Zirconium intensity estimate for Run 18

In March 2017, EBIS provided  $90\text{Zr}^{15+}$  and  $96\text{Zr}^{16+}$  ions for injection into Booster. These were obtained using a source target composed of naturally occurring Zirconium. The abundances of  $90\text{Zr}$  and the desired isotope  $96\text{Zr}$  are 51.5% and 2.80% respectively.

Because the charge-to-mass ratios of  $90\text{Zr}^{15+}$  and  $96\text{Zr}^{16+}$  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  $90\text{Zr}^{40+}$  and  $96\text{Zr}^{40+}$ . The magnets of the R-line was first tuned to transport the  $90\text{Zr}^{40+}$  ions to the NSRL target room. The extraction septum magnet and R-line magnets were then scaled to transport the  $96\text{Zr}^{40+}$  ions. This produced a small but easily discernible signal in the target room.

A calibrated measurement of  $90\text{Zr}^{15+}$  and  $96\text{Zr}^{16+}$  circulating beam current in Booster was not done prior to this estimate. Here I obtain an estimate based on the well known numbers for  $\text{Au}^{32+}$  and  $\text{Au}^{77+}$  ions in Booster and AGS respectively. As reported in [6], EBIS delivers 12 pulses of  $\text{Au}^{32+}$  ions to Booster each AGS cycle at an intensity of  $1.25\text{e}9$  ions per pulse. This produces two bunches with an intensity of  $3.0\text{e}9$   $\text{Au}^{77+}$  ions per bunch at AGS extraction. The overall efficiency of the process is therefore

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

Since  $\text{Zr}^{16+}$  has half the charge of  $\text{Au}^{32+}$ , one expects roughly twice as many  $96\text{Zr}^{16+}$  ions per pulse from EBIS. This assumes, of course, that the source target consists of 100%  $96\text{Zr}$ . One would then have 12 pulses of  $96\text{Zr}^{16+}$  ions delivered to Booster each AGS cycle at an intensity of  $2.5\text{e}9$  ions per pulse. Assuming the same efficiency as above then gives two bunches with an intensity of  $6.0\text{e}9$   $96\text{Zr}^{40+}$  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%  $96\text{Zr}$ , then the number of  $96\text{Zr}^{40+}$  ions per bunch would be reduced from  $6.0\text{e}9$  to  $4.8\text{e}9$ .

The sintered target for the laser ion source (LION) is composed of  $\text{ZrO}_2$  obtained from Trace Sciences International. Some 60% of the zirconium in this compound is  $96\text{Zr}$  [7]. We therefore expect at most  $1.5\text{e}9$   $96\text{Zr}^{16+}$  ions per EBIS pulse at Booster injection and  $3.6\text{e}9$   $96\text{Zr}^{40+}$  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

$$\mathcal{R}_T = \frac{0.60}{0.19} = 3.1579 \quad (8)$$

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

$$\mathcal{R}_B = \frac{N_{96}}{N_{90}} \quad (9)$$

where  $N_{96}$  and  $N_{90}$  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

$$\mathcal{R}_C = \frac{16 \times N_{96}}{15 \times N_{90}} = \frac{16}{15} \mathcal{R}_B. \quad (10)$$

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

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

As an **estimate** we take

$$\mathcal{R}_B = \mathcal{R}_T. \quad (12)$$

This gives

$$\mathcal{R}_C = \frac{16}{15} \mathcal{R}_T = 3.3684 \quad (13)$$

and

$$\mathcal{F} = \frac{\mathcal{R}_C}{1 + \mathcal{R}_C} = 0.7711. \quad (14)$$

**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]

$$\mathcal{R}_B = \frac{0.702}{0.298} = 2.3557. \quad (15)$$

This gives

$$\mathcal{R}_C = \frac{16}{15} \mathcal{R}_B = 2.5128 \quad (16)$$

and

$$\mathcal{F} = \frac{\mathcal{R}_C}{1 + \mathcal{R}_C} = 0.7153. \quad (17)$$

The measurements also give an efficiency of 87% for the stripping of the zirconium ions to  $96\text{Zr}40+$  and  $90\text{Zr}40+$ .

## 6 Zirconium intensities achieved in Run 18

As measured and recorded in [9], the number of  $96\text{Zr}$  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  $96\text{Zr}40+$  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 1e9 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

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

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

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

where [10, 11]

$$a = 95.907\,590\,25(49) \quad (20)$$

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

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

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

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

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  $96\text{Ru}12+$ ,  $96\text{Ru}16+$ , and  $96\text{Ru}44+$  ions are

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

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

and

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

## 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

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

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

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

where [10, 11]

$$a = 95.908\,2714(21) \quad (28)$$

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

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

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

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

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  $96\text{Zr}12+$ ,  $96\text{Zr}16+$ , and  $96\text{Zr}40+$  ions are

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

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

and

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

## 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

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

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

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

where [10, 11]

$$a = 89.904\,6977(20) \quad (36)$$

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

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

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

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

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  $90\text{Zr}12+, 90\text{Zr}15+, 90\text{Zr}16+,$  and  $90\text{Zr}40+$  ions are

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

$$mc^2(90\text{Zr}15+) = 83.738\,032\,7521 \text{ GeV} \quad (40)$$

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

and

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

## 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

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

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

$$mc^2 = am_u c^2 - Qm_e c^2 + E_Q \quad (44)$$

where [10, 11]

$$a = 196.966\,568\,79(71) \quad (45)$$

is the relative atomic mass of the neutral gold atom,

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

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

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

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

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

$$mc^2(\text{Au}77+) = 183.434\,181\,300 \text{ GeV} \quad (49)$$

and

$$mc^2(\text{Au}79+) = 183.433\,343\,902 \text{ GeV}. \quad (50)$$

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:

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

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

### Zirconium-96:

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

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

### Zirconium-90:

$$\frac{mc^2}{Q} (90\text{Zr}15+) = 5.58253551681 \text{ GeV} \quad (55)$$

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

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

### Gold:

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

$$\frac{mc^2}{Q} (\text{Au}77+) = 2.38226209481 \text{ GeV} \quad (59)$$

$$\frac{mc^2}{Q} (\text{Au}79+) = 2.32194106205 \text{ GeV} \quad (60)$$

The mass-to-charge ratios of  $96\text{Zr}16+$  and  $90\text{Zr}15+$  are nearly identical. This means that  $90\text{Zr}15+$  can be substituted for  $96\text{Zr}16+$  during the setup of Booster if need be.

The mass-to-charge ratio of  $96\text{Zr}16+$  is smaller than that of  $\text{Au}32+$ . This makes the bending and accelerating fields in Booster more effective for the Zirconium ion. Similarly, the mass-to-charge ratios of  $96\text{Ru}44+$  and  $96\text{Zu}40+$  are smaller than those of  $\text{Au}77+$  and  $\text{Au}79+$ . This makes the bending and accelerating fields in AGS and RHIC more effective for the Ruthenium and Zirconium ions.

## 12 Tandem $^{96}\text{Ru}^{12+}$ 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.  $B\rho = 9.46$  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 comparison)

**At injection:**

1.  $W/A = 1.97627401907$  MeV per nucleon
2.  $B\rho = 1.24651719998$  Tm
3.  $B = 898.999826895$  Gauss
4. Inflector  $V = 58.3955914656$  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.  $B\rho = 7.66880062604$  Tm
3.  $B = 5.53081051382$  kG
4.  $W/A = 72.0897525649$  MeV per nucleon

**At extraction:**

1.  $B\rho = 9.46202808578$  Tm
2.  $B = 6.82973355563$  kG
3.  $W/A = 107.758798130$  MeV per nucleon
4.  $f = 658.910$  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  $V = 56.8686008773$  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.  $B\rho = 7.67323949959$  Tm
3.  $B = 5.53401187081$  kG
4.  $W/A = 75.8897344594$  MeV per nucleon

### At extraction:

1.  $B\rho = 9.46$  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.  $W/A = 1.97451155573$  MeV per nucleon
2.  $B\rho = 1.21379626424$  Tm
3.  $B = 875.401182958$  Gauss
4. Inflector  $V = 56.8627137839$  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.  $B\rho = 7.67244515831$  Tm
3.  $B = 5.53343898447$  kG
4.  $W/A = 75.8818782797$  MeV per nucleon

### At extraction:

1.  $B\rho = 9.46$  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 $^{96}\text{Ru}44+$ energy loss in the BTA stripper

The stripper consists of a  $6.45 \text{ mg/cm}^2$  aluminum foil followed by a  $8.39 \text{ mg/cm}^2$  “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  $\text{Ru}44+$  ion just upstream of the aluminum foil is

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

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

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

The rate of energy loss of the  $\text{Ru}44+$  ion is obtained by scaling the Bethe-Bloch result for protons [15]. Thus

$$-\frac{dE}{dx} = -Z^2 \frac{dE_p}{dx} \text{ cm}^2/\text{g} \quad (63)$$

where  $Z = 44$ . Multiplying this by the surface density of the aluminum foil ( $6.45 \text{ mg/cm}^2$ ) gives

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

This is the energy lost by the  $\text{Ru}44+$  ion upon passing through the aluminium foil. The kinetic energy of a proton that has the same velocity as the  $\text{Ru}44+$  ion just downstream of the aluminum foil is then

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

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

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

Using this result in (63) with  $Z = 44$ , and multiplying by the surface density of the carbon foil ( $8.39 \text{ mg/cm}^2$ ) gives

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

The total energy lost upon passing through both foils is then

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

## 17 $^{96}\text{Ru}44+$ 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

### At extraction:

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.  $12f = 1.9575$  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

### At extraction:

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 $^{96}\text{Zr}40+$ energy loss in the BTA stripper

The stripper consists of a  $6.45 \text{ mg/cm}^2$  aluminum foil followed by a  $8.39 \text{ mg/cm}^2$  “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  $\text{Zr}40+$  ion just upstream of the aluminum foil is

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

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

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

The rate of energy loss of the  $\text{Zr}40+$  ion is obtained by scaling the Bethe-Bloch result for protons [15]. Thus

$$-\frac{dE}{dx} = -Z^2 \frac{dE_p}{dx} \text{ cm}^2/\text{g} \quad (71)$$

where  $Z = 40$ . Multiplying this by the surface density of the aluminum foil ( $6.45 \text{ mg/cm}^2$ ) gives

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

This is the energy lost by the  $\text{Zr}40+$  ion upon passing through the aluminium foil. The kinetic energy of a proton that has the same velocity as the  $\text{Zr}40+$  ion just downstream of the aluminum foil is then

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

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

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

Using this result in (71) with  $Z = 40$ , and multiplying by the surface density of the carbon foil ( $8.39 \text{ mg/cm}^2$ ) gives

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

The total energy lost upon passing through both foils is then

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

## 20 $^{96}\text{Zr}^{40+}$ 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

### At extraction:

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.  $12f = 1.9575$  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

### At extraction:

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 $^{96}\text{Zr}40+$ 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.  $B\rho = 3.75894398778$  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

### At extraction:

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<sup>2</sup> aluminum foil followed by a 8.39 mg/cm<sup>2</sup> “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

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

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

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

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

$$-\frac{dE}{dx} = -Z^2 \frac{dE_p}{dx} \text{ cm}^2/\text{g} \quad (79)$$

where  $Z = 40$ . Multiplying this by the surface density of the aluminum foil (6.45 mg/cm<sup>2</sup>) gives

$$\Delta E_a = 0.5918 \text{ MeV per nucleon.} \quad (80)$$

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

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

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

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

Using this result in (79) with  $Z = 40$ , and multiplying by the surface density of the carbon foil (8.39 mg/cm<sup>2</sup>) gives

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

The total energy lost upon passing through both foils is then

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

## 24 $^{90}\text{Zr}40+$ 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  $^{90}\text{Zr}40+$  ions
9.  $B = 412.573677390$  Gauss
10.  $B\rho = 3.75894392907$  Tm for  $^{96}\text{Zr}40+$  ions

Here we see that values of  $B\rho$  for  $^{90}\text{Zr}40+$  and  $^{96}\text{Zr}40+$  ions are sufficiently far apart to keep  $^{90}\text{Zr}40+$  ions out of AGS as long as the BTA line and AGS are tuned for injection of  $^{96}\text{Zr}40+$  ions.

## 25 $^{96}\text{Ru}44+$ in RHIC

**At injection:**

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

**At extraction with energy 100 GeV per nucleon:**

1.  $B\rho = 727.744709665$  Tm
2.  $f = 78192.9026543$  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.  $E/A = 9.79596126523$  GeV per nucleon
5.  $\gamma = 10.5204666076$

### At extraction:

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

## 27 $^{96}\text{Zr}40+$ in RHIC

**At injection:**

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

**At extraction with same revolution frequency as  $^{96}\text{Ru}44+$ :**

1.  $B\rho = 800.542946750$  Tm
2.  $f = 78192.9026542$  Hz
3.  $360f = 28.1494449555$  MHz
4.  $E/A = 100.002968838$  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

$$E_Q = E_Z - \mathcal{E}_{Z-Q} \quad (85)$$

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

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

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

Table 1: Zirconium ion binding energies  $E_Q$

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

### 28.2 Ruthenium

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

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

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

Table 2: Ruthenium ion binding energies  $E_Q$

$Q$	$Z - Q$	$\mathcal{E}_{Z-Q}$ (eV)	$E_Q$ (eV)
12	32	121851	1271
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

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

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

Table 3: Gold Ion Binding Energies  $E_Q$

$Q$	$Z - Q$	$\mathcal{E}_{Z-Q}$ (eV)	$E_Q$ (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

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



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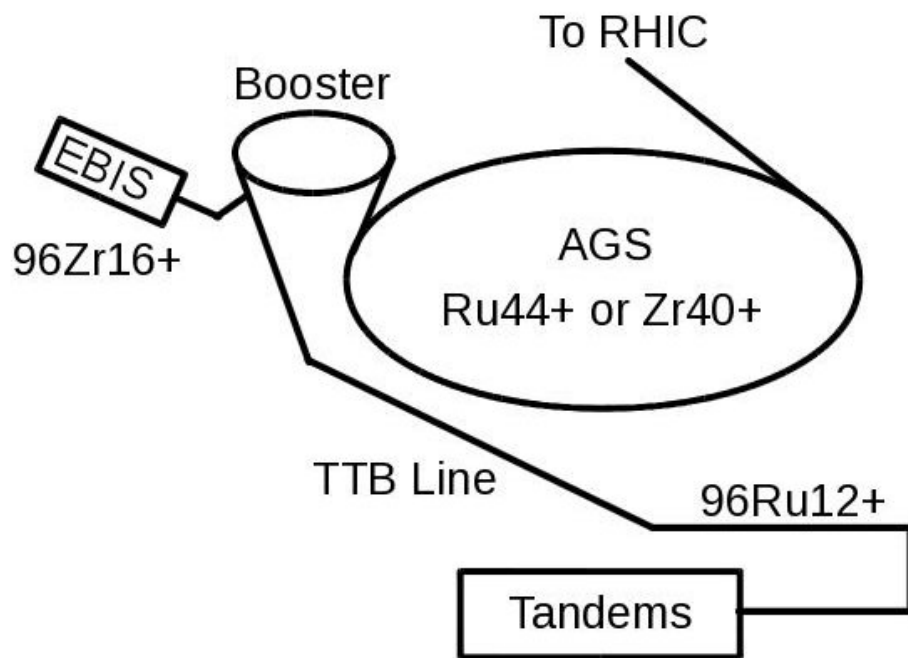


Figure 1: Delivery of  $^{96}\text{Ru}^{44+}$  and  $^{96}\text{Zr}^{40+}$  ions to RHIC.

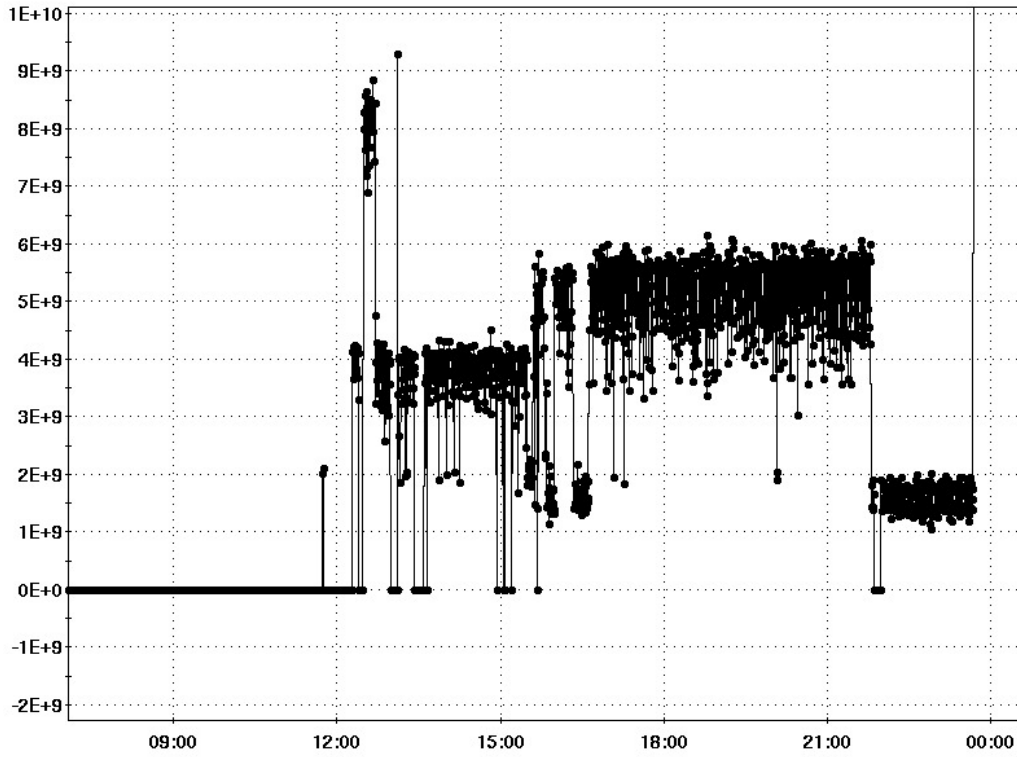


Figure 2: Tandem Ruthenium-96 at end of TTB line. Here the total number of  $^{96}\text{Ru}^{12+}$  ions in 8 Tandem pulses at Booster Input is  $5.3e9$ .  
K.L. Zeno, 29 March 2016.

**/Booster/ComfortDisplays/GoldTab** \_ □ ×

File PPM Setup Logging Diagnostics

ON The Planetarium U1 Mar 29 20:18:44 Cycle 60220

xf108_1	X
xf108_2	X
xf108_3	X
xf108_4	X
xf108_5	X
xf108_6	X
xf108_7	X
xf108_8	X
xf108Sum	X
-	-
Early_1	0.0
Early_2	0.0
Early_3	0.0
Early_4	0.0
Early_5	0.0
Early_6	0.0
Early_7	0.0
Early_8	0.0
Booster_Early	-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

Stop

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

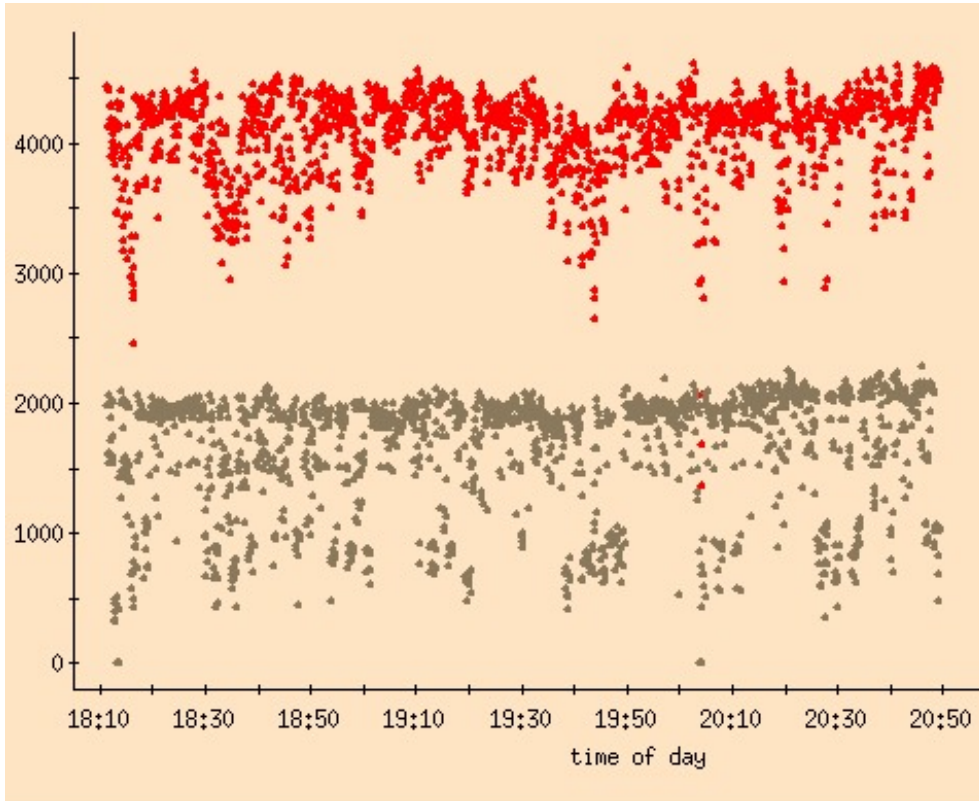


Figure 4: Tandem Ruthenium-96 in Booster and AGS.  
On the vertical axis, 1000 corresponds to  $1.0 \times 10^9$  Ruthenium ions.  
K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 20:49, 29 March 2016.

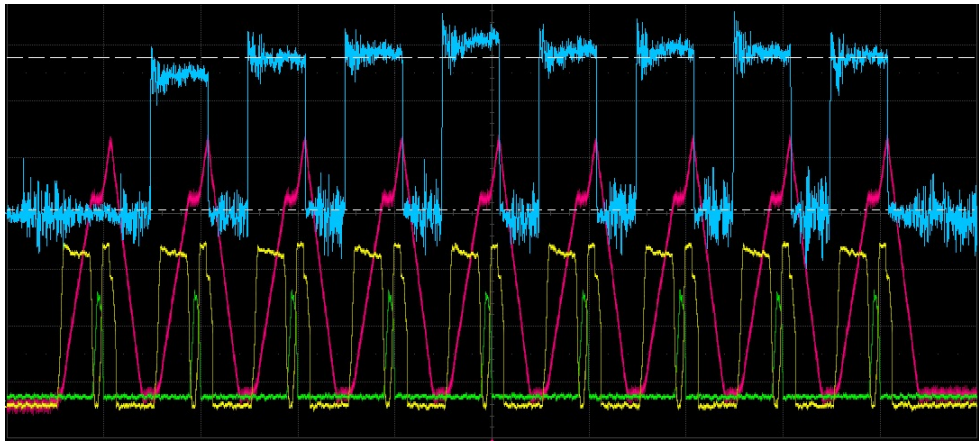


Figure 5: Eight pulses of Tandem 96Ru12+ in Booster.  
K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 16:24, 29 March 2016.

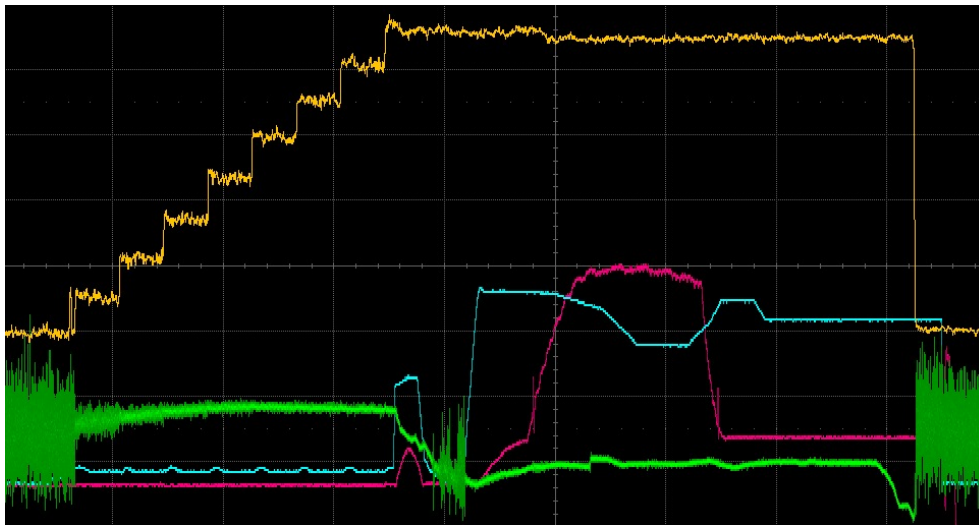


Figure 6: Eight loads 96Ru44+ in Ags.  
K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 17:11, 29 March 2016.

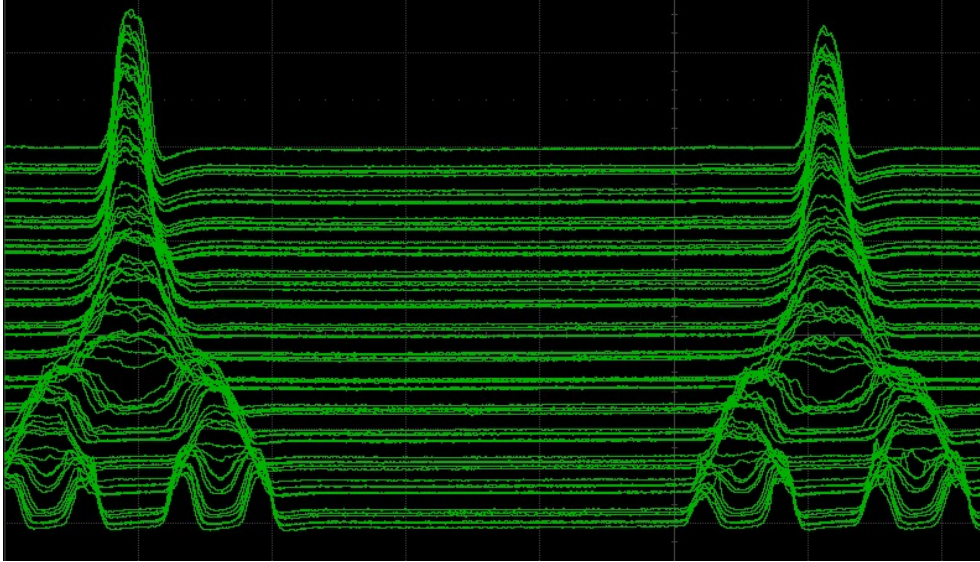


Figure 7: Merge of 4 adjacent  $^{96}\text{Ru}^{44+}$  bunches into 1 on AGS injection porch.  
K.L. Zeno, Booster-AGS-EBIS-2016 Elog, entry 16:09, 29 March 2016.



40 Zr	90	89.904 6977(20)	0.5145(40)	91.224(2)
	91	90.905 6396(20)	0.1122(5)	
	92	91.905 0347(20)	0.1715(8)	
	94	93.906 3108(20)	0.1738(28)	
	96	95.908 2714(21)	0.0280(9)	
41 Nb	93	92.906 3730(20)	1	92.906 37(2)
42 Mo	92	91.906 807 96(84)	0.1453(30)	95.95(1)
	94	93.905 084 90(48)	0.0915(9)	
	95	94.905 838 77(47)	0.1584(11)	
	96	95.904 676 12(47)	0.1667(15)	
	97	96.906 018 12(49)	0.0960(14)	
	98	97.905 404 82(49)	0.2439(37)	
	100	99.907 4718(11)	0.0982(31)	
43 Tc	97	96.906 3667(40)		[98]
	98	97.907 2124(36)		
	99	98.906 2508(10)		
44 Ru	96	95.907 590 25(49)	0.0554(14)	101.07(2)
	98	97.905 2868(69)	0.0187(3)	
	99	98.905 9341(11)	0.1276(14)	
	100	99.904 2143(11)	0.1260(7)	
	101	100.905 5769(12)	0.1706(2)	
	102	101.904 3441(12)	0.3155(14)	
	104	103.905 4275(28)	0.1862(27)	
45 Rh	103	102.905 4980(26)	1	102.905 50(2)
46 Pd	102	101.905 6022(28)	0.0102(1)	106.42(1)
	104	103.904 0305(14)	0.1114(8)	
	105	104.905 0796(12)	0.2233(8)	
	106	105.903 4804(12)	0.2733(3)	
	108	107.903 8916(12)	0.2646(9)	
	110	109.905 172 20(75)	0.1172(9)	
47 Ag	107	106.905 0916(26)	0.518 39(8)	107.8682(2)
	109	108.904 7553(14)	0.481 61(8)	

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



Figure 9: Ruthenium, 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  $^{96}\text{Ru}$  ions. With permission and courtesy of ESIPP at ORNL.

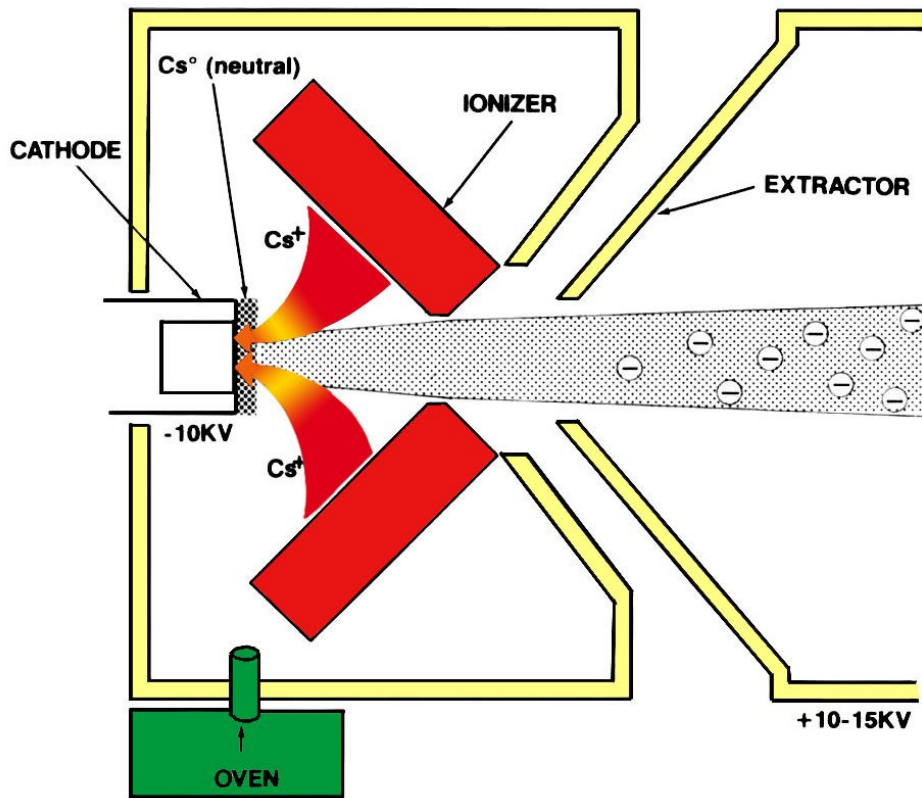


Figure 11: The image above and the following caption are from National Electrostatic Corp. at [www.pelletron.com](http://www.pelletron.com): “Cesium vapor flows from the cesium oven into an enclosed area between the cooled cathode and the heated ionizing surface. Some of the cesium condenses on the front 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  $^{96}\text{Ru}$  is set by the relative amounts of the two powders in the mixture.

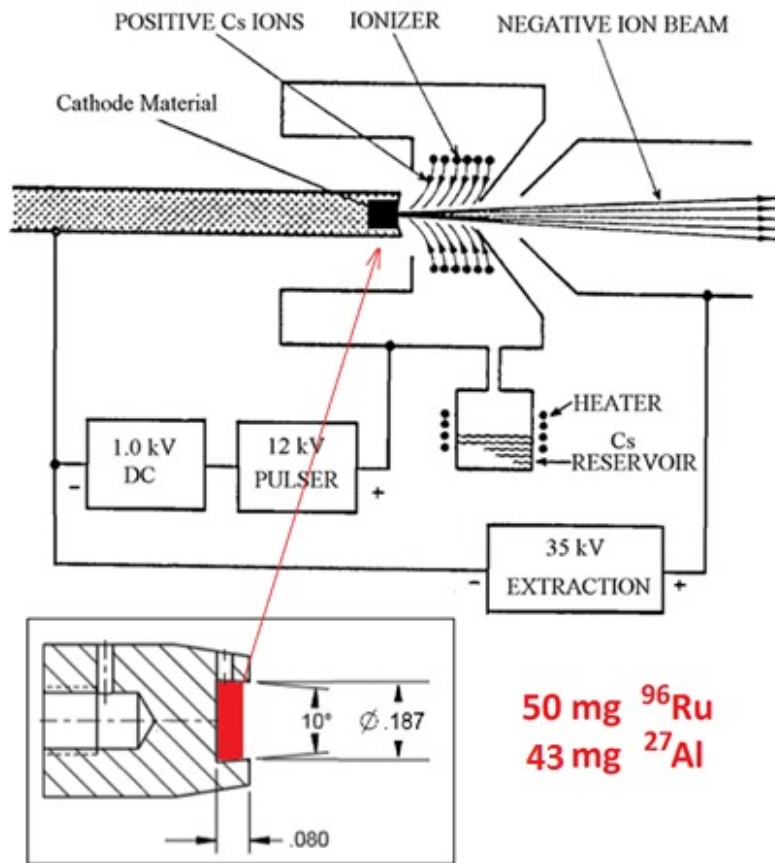


Figure 12: Schematic of the pulsed negative ion cesium sputter source system used to produce negative  $^{96}\text{Ru}$  ions for injection into the MP7 Tandem. A mixture consisting 50 mg of  $^{96}\text{Ru}$  and 43 mg of  $^{27}\text{Al}$  powders is pressed into the cathode cavity as shown in the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



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

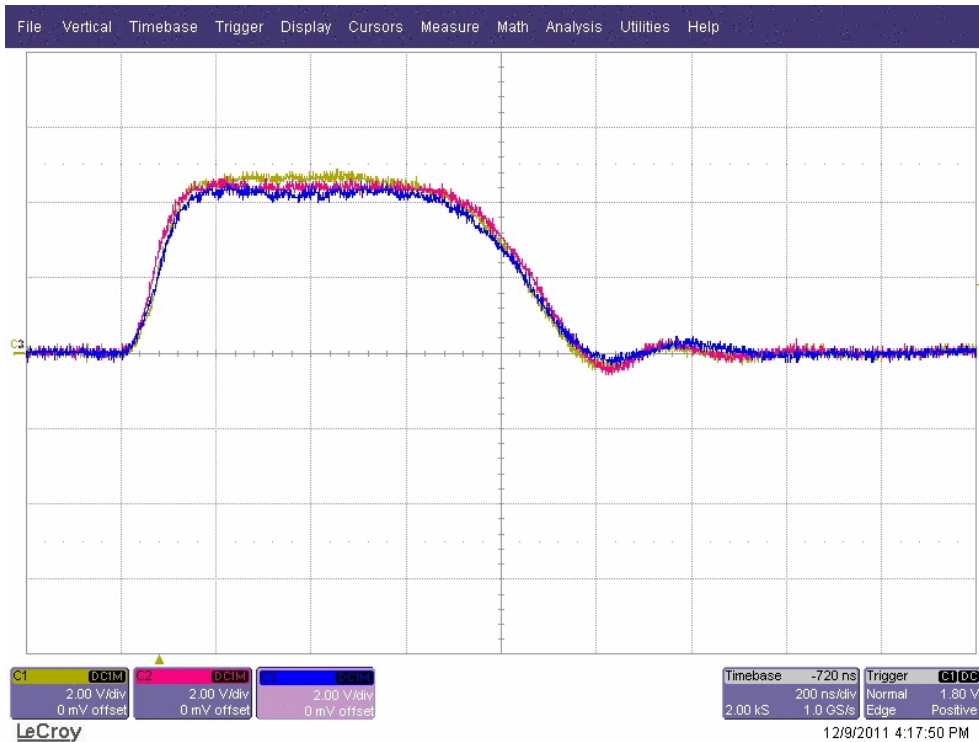


Figure 14: AGS injection kicker waveforms in the short pulse mode. The three traces are from the three modules of the kicker. They were taken by Yugang Tan on 9 Dec 2011. The time per division is 200 ns. The RF bucket width on the AGS injection porch is 481 ns for 96Ru44+ ions in harmonic 16 buckets 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**.

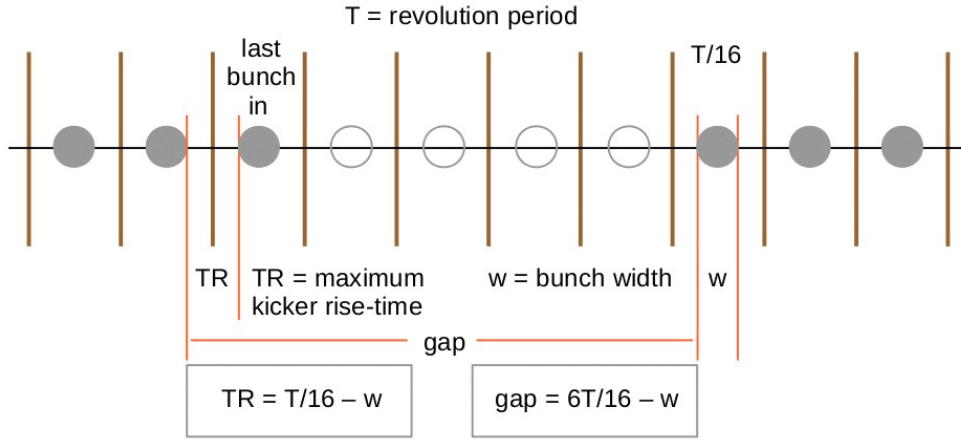


Figure 15: AGS injection kicker timing for 96Ru44+ 4 to 1 merge setup. Here  $T$  is the revolution period on the AGS injection porch and  $T/16 = 481$  ns is the harmonic 16 RF bucket width. The kicker rise time is 100 ns. This means that the bunch width,  $W$ , must be less than  $T/16 - 100 = 381$  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.



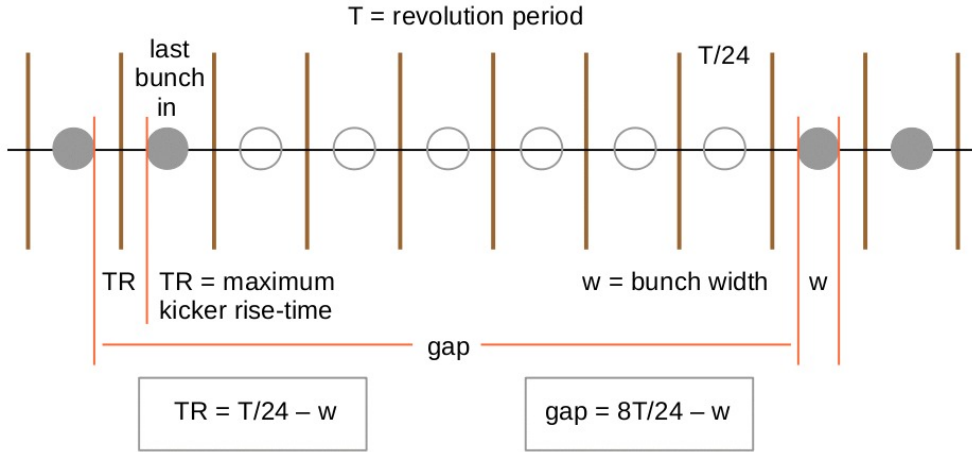


Figure 16: AGS injection kicker timing for 96Zu40+ 6 to 1 merge setup. Here  $T$  is the revolution period on the AGS injection porch and  $T/24 = 249$  ns is the harmonic 24 RF bucket width. The kicker rise time is 100 ns. This means that the bunch width,  $W$ , must be less than  $T/24 - 100 = 149$  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.