

Run 18 in the Injectors

K. Zeno

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Run 18 in the Injectors

Keith Zeno
9-24-2018

The RHIC Run 18 consisted of 2 parts: The first was an approximately two-and-a-half-month-long period of Zirconium (Zr) and Ruthenium (Ru) running (Early March to May 9) and the second was a shorter period of Au running (May 9 to June 18). For the first part, rare isotopes of Zr and Ru were used alternately to fill RHIC. These isotopes, ^{96}Zr and ^{96}Ru , have essentially the same mass but different numbers of protons and neutrons. In the AGS they were fully stripped ($^{96}\text{Zr}^{40+}$ and $^{96}\text{Ru}^{44+}$) and in the Booster the charge states $^{96}\text{Zr}^{16+}$ and $^{96}\text{Ru}^{12+}$ were used.¹ From May 31 to June 4 an AGS flattop energy of 3.85 GeV was used, instead of the nominal 9.8 GeV, for a fixed target Au experiment in RHIC. Injector setup with beam began on February 20th and all 3 beams were available for RHIC by early March.

EBIS was used as the preinjector for Zr and Au, and Tandem was used for Ru. EBIS was also used concurrently for NSRL from March 19 until the end of the run. Since these isotopes of Zr and Ru were in short supply, unnecessary use of the injectors with those beams was discouraged (particularly in the case of Zr). The use of Zr and Au beams sometimes also interfered with stable NSRL running, and conversely, NSRL sometimes interfered with stable injector running, the stability of which was for the most part related to the stability of EBIS. This interdependence was, at least in part, more of an issue this year than previously because of the NSRL GCR configuration that was used extensively this run. And for that reason as well, the use of beams in the injectors was more limited than usual. Alternating between 3 species in the injectors also makes it difficult to keep each of those setups optimized. On the other hand, at least for Zr and Ru, RHIC's requirements were well below what the injectors (and preinjectors) could provide, so the fact that their operation was often less than optimal did impact RHIC much.

Overview of the Three Injector Setups

For Zr (EU5/BU5/AU5) and Ru (TU1/BU1/AU1) the basic Booster setup is like the one used for Au (EU3/BU3/AU3). Figure 1 shows the 3 Booster main magnet functions overlaid. For all three species, injection occurs 10.5 ms after Bt0 on a 200 ms long magnet cycle, which has a porch during which an 4-2-1 bunch merge is performed at a $B\rho$ of 7.67 T-m. Extraction occurs around 130 ms after Bt0 at a $B\rho$ of about 9.46 T-m. The magnet cycle is the same for all three species except early in the cycle where it differs to accommodate different injection fields. The injection fields for Zr, Ru, and Au, as measured by the hall probe are 830 g, 1068 g, and 858g, respectively. Since the Zr and Au injection fields are quite similar and the Ru injection field is higher, it was possible to make the Zr and Ru cycles by making only small modifications to the existing Au cycle.

The Zr and Ru setups in the AGS were also derived from previous Au setups. The initial Zr setup began on Feb 27 and employed a 12-6-2 AGS merge using 12 Booster cycles with one

¹ Detailed information about these isotopes, the injection and extraction energies in the Booster and AGS, etc. can be found in "[Gardner, C., Notes on the setup of Ruthenium and Zirconium ions in the Booster and AGS for RHIC Run 18](#)".

bunch per cycle transferred to the AGS. But beginning on Mar 29, a supercycle with only 8 Booster cycles with beam and an 8-4-2 merge in the AGS was used for RHIC Zr fills. This was initially set up on AU7, but on Apr 4th was moved to AU5, the normal AGS Zr user, so that the user number in all 3 machines (EBIS, Booster, and AGS) would be the same. Since the RHIC Zr intensity requirement was low enough that it could be satisfied with only 8 EBIS pulses, this setup was preferred because there were stability issues with EBIS which could be mitigated by using a less demanding duty cycle. The Ru setup also used an 8-4-2 merge in the AGS, with 8 Tandem pulses associated with 8 Booster cycles. As with Zr (and Au) there is one bunch per Booster cycle transferred to the AGS.

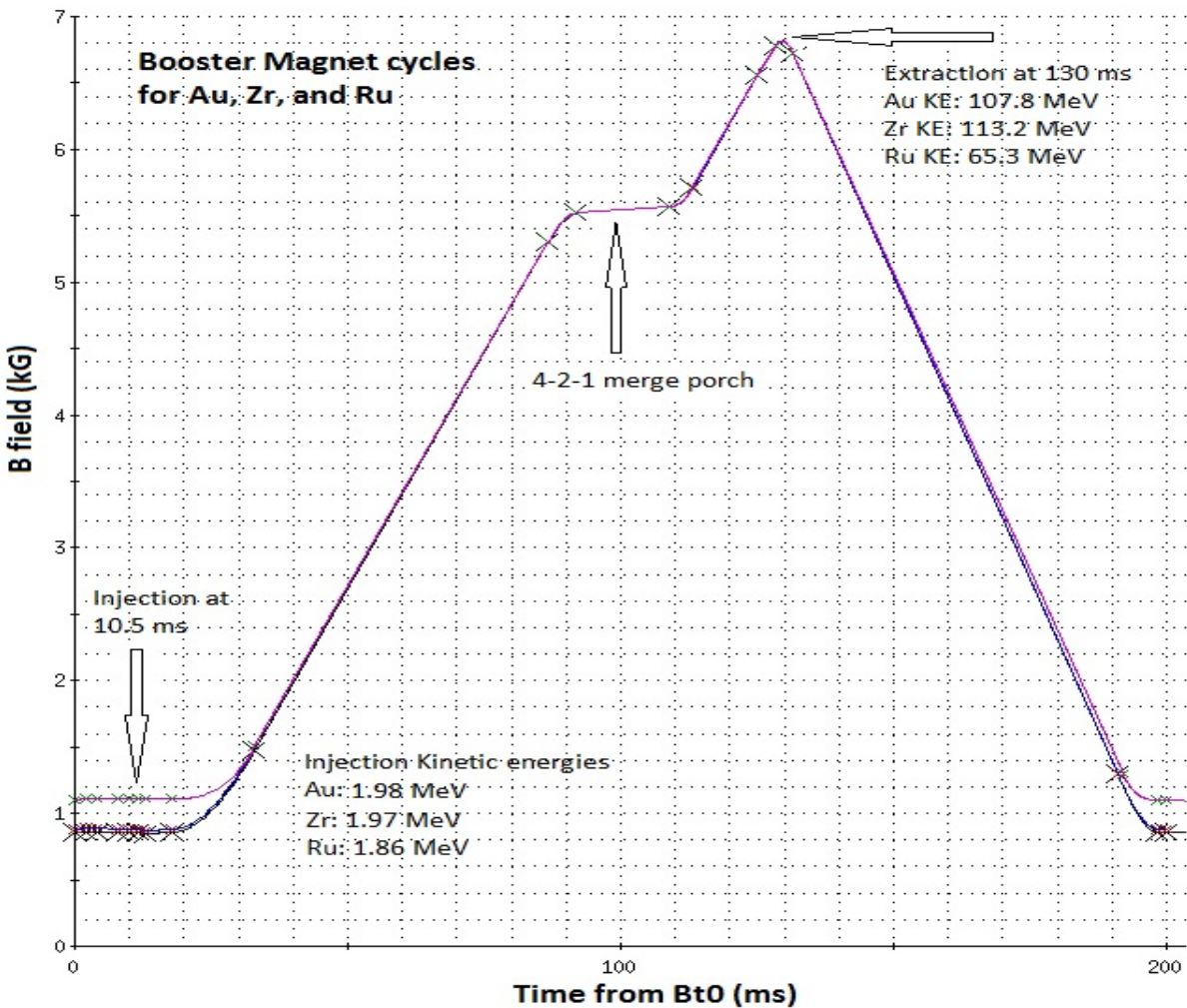


Figure 1: An overlay of the Booster magnet functions for $^{197}\text{Au}^{32+}$, $^{96}\text{Zr}^{16+}$, and $^{96}\text{Ru}^{12+}$ (pink). The kinetic energies (KE) are per nucleon.² The Rf harmonic is 4 up to the merge porch and 1 after it.

² Kinetic energies per nucleon (W/A) are taken from "[Gardner, C., Notes on the setup of Ruthenium and Zirconium ions in the Booster and AGS for RHIC Run 18](#)".

Figure 2 is a schematic of the 8-4-2 Zr and Ru setups together with the 12-6-2 Au setup early in the AGS cycle. Note that although the Booster injection B_p for Ru is the highest and for Zr and Au it is similar, in the AGS Ru has a significantly lower injection field and the Zr and Au injection fields are similar.

The AGS extraction field for both Zr and Ru is 9470 g, which is about 3% lower than the Au extraction field (9720 g). The kinetic energies per nucleon at AGS extraction for Zr, Ru, and Au are about 9.2, 10.3, and 8.9 GeV, respectively.³

Even though the supercycle has been as short as 6.0 sec for the 12-6-2 Au cycle it was kept at 6.6 sec for 12-6-2 cycles so the EBIS duty cycle would be lower. For the 8-4-2 cases it could be as short as 5.4 sec but was also kept at 6.6 sec to simplify operations while running with NSRL.

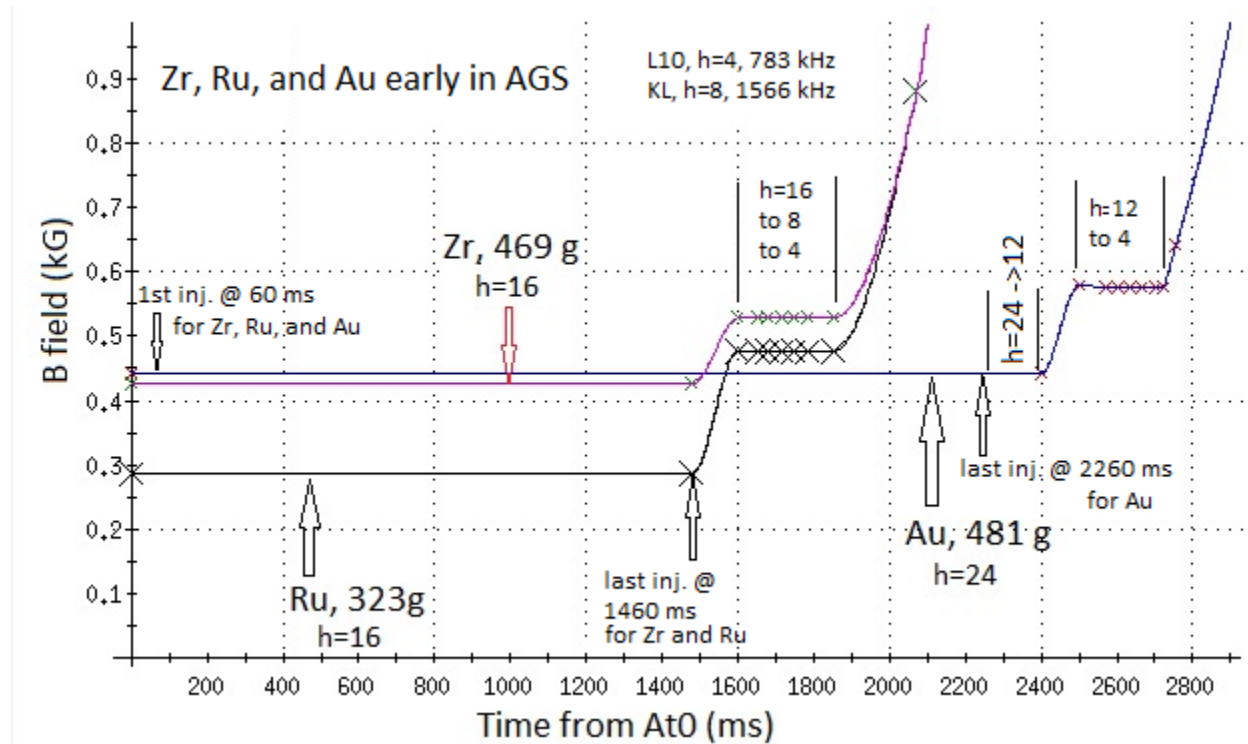


Figure 2: A schematic comparing the $96\text{Zr}40+$ (magenta), $96\text{Ru}44+$ (black), and $197\text{Au}77+$ (blue) AGS main magnet functions and setups early in the AGS. In each case the injection porch, merge porch, and the early ramp are shown. For Zr, only the 8-4-2 setup is shown. The 12-6-2 Zr setup has the same timing and merges as the Au setup. Note that the injection fields indicated were measured using the hall probe and are different than the function's values.

For the 8-4-2 setups, the bunches are injected into h=16 buckets and only 2 sets of 4 buckets are filled. Those 2 sets of bunches are diametrically opposed to each other. Similarly, for

³ Extraction fields and kinetic energies are from "Gardner, C., ["Notes on the setup of Ruthenium and Zirconium ions in the Booster and AGS for RHIC Run 18"](#)".

the 12-6-2 setups two sets of 6 bunches are injected into $h=24$ buckets that are diametrically opposed to each other. The $h=4$ (L10) and $h=8$ (KL) cavities are fixed frequency, so the field at which the merges occur depends on the species.⁴

The Au 12-6-2 setup used this run is the same as the one used in Runs 16 and 17 and has been described in detail elsewhere and the Zr 12-6-2 setup is very similar to it. The 8-4-2 Zr and Ru setups are also very similar to the 8-4-2 Au setup described in detail elsewhere.⁵ So, much of the rest of this note will concern itself with beam related measurements made with Zr and Ru in the injectors, and after that the Gold performance this run will be compared with Run 16. A possible change in the AGS γ_t during the past few years will also be investigated.

Zirconium Measurements

How much of the Beam in the Booster is $^{96}\text{Zr}16+$?

The enriched EBIS target material contains several isotopes of Zr (90, 91, 92, 94, and 96).⁶ Particularly noteworthy is charge state $15+$ of ^{90}Zr as it has essentially the same $B\rho$ at Booster injection and charge to mass ratio as $^{96}\text{Zr}16+$ ($16/96=15/90$). So, one expects that it will be accelerated by the EBIS Rf, transported through EtB, pass through the inflector, and be injected and accelerated in the Booster just as well as $^{96}\text{Zr}16+$ is. Analysis of the target indicates that 19.3% of it is ^{90}Zr and $59.6\pm 1.4\%$ of it is ^{96}Zr . Consequently, it is not a simple task to measure the various ^{96}Zr intensities and efficiencies through the injectors. Perhaps naively, one would expect the EBIS to produce $^{90}\text{Zr}15+$ from the ^{90}Zr in the target with nearly the same efficiency that it produces $^{96}\text{Zr}16+$ from the ^{96}Zr there since the charge states of both these species are nearly the same.

Assuming only these 2 species are injected and accelerated in the Booster an estimate for the $^{96}\text{Zr}16+$ intensity in the Booster can be obtained from measurements of their relative abundance using the MW060 multiwire in BtA.⁷ MW060 sits just downstream of the large bend in BtA created by the DH2&3 magnets and these magnets are just downstream of the stripping foil.

It's assumed that the stripping foil fully strips $^{90}\text{Zr}15+$ and $^{96}\text{Zr}16+$ with the same efficiency, and that when DH2&3 is adjusted to roughly center the respective beam on MW060 that the transport efficiency for each species from the stripping foil to the multiwire is the same. Under normal running conditions $^{96}\text{Zr}40+$ is visible on MW060, and by lowering the current in

⁴ K. Zeno, "[Overview and analysis of the 2016 Gold Run in the Booster and AGS](#)" C-A/AP/571, September 2016, gives a more detailed description of both the 8-4-2 and 12-6-2 AGS merges.

⁵ See the link in footnote 3 and K. Zeno, "[Longitudinal Emittance Measurement in the Booster and AGS during the 2014 RHIC Gold Run](#)", C-A/AP/523, August 2014.

⁶ [Certificate of Analysis No. 141-1](#), Trace Sciences International, October 23, 2017 indicates 19.27% ^{90}Zr , 5.1% ^{91}Zr , 7.86% ^{92}Zr , 8.17% ^{94}Zr , and $59.6 \pm 1.4\%$.

⁷ Any difference in the response of the multiwire to ions with a differing number of neutrons is ignored.

DH2&3 by a factor of $(90/96)=0.9375$ the horizontal profile for 90Zr40+ should have the same position on the multiwire that 96Zr40+ did with the higher current.

On April 3rd, the area of a Gaussian fit of the horizontal profile for beam from one Booster cycle was 2.75 for the profile visible when DH2&3 was set to 1795A (a typical setting) and 1.17 for the profile visible when it was set to 1688A (Figure 3).⁸ For 1795A the center of the profile is -4.66 mm and for 1688A it is -4.41 mm, which is the same to within measurement error. One would expect the DH2&3 current required to move the 90Zr40+ beam to the same position on the multiwire to be $1795A \cdot (90/96)=1683A$ so the profile with DH2&3 set to 1688A is the likely candidate for it.⁹

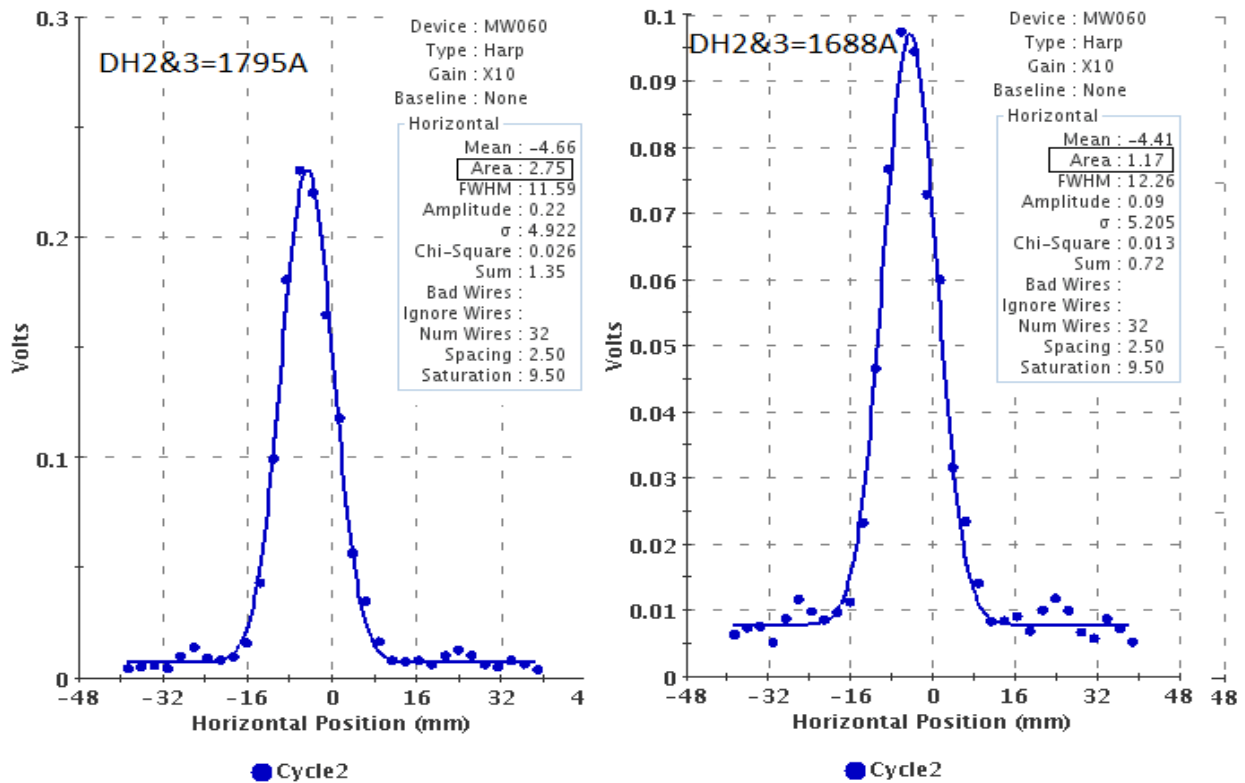


Figure 3: BtA MW060 horizontal profiles with Gaussian fits identified as 96Zr40+ (left) and 90Zr40+ (right) for DH2&3 currents of 1795 and 1688A, respectively. The area of the left profile is 2.75 and the area of the right profile is 1.17, From this the fraction of the beam extracted from the Booster that is 96Zr40+ is $2.75/(2.75+1.17)=0.702$.

⁸ See [Booster-AGS-EBIS_2018 elog](#) 1720 and 1723 entries. Since neutrons do not have a charge the difference in the number of neutrons for the two species is not expected to affect the multiwire's response to them.

⁹ By itself a difference of +5A (1688A instead of 1683A) in the DH2&3 current should result in the 90Zr40+ profile being about 7.5 mm to the right of the 96Zr40+ position at 1795A. The difference between the predicted value of 1683A and the actual one (1688A) could be attributable to the fact that the quadrupoles between the stripping foil and the multiwire were not scaled for 90Zr40+. There are 3 of them (QH4, QV5, and QH6) that run at approximately 300A.

There are other beams present besides the fully stripped 90Zr and 96Zr, but they all would require a significantly higher current than 1688A to put them in the same position. For example, the 96Zr39+ beam would require a DH2&3 current of $(40/39)*1795A$ and the closest beam to 90Zr40+ would be 90Zr39+ which would require a current of $1795A*(40/39)*(90/96)=1726A$.¹⁰ So, it seems very likely that the profile for a current of 1688A is 90Zr40+ and the fraction of the beam at Booster extraction that is 96Zr16+ is then $2.75/(1.17+2.75)=0.702$. These measurements were taken with the same Booster late intensity (a reading of 1100 on the scaler). From the analysis of the target mentioned above, and assuming that the relative amount of 90Zr15+ and 96Zr16+ coming from EBIS is the same as the relative amount of 90Zr and 96Zr in the target, one would expect the fraction of beam in the Booster that's 96Zr16+ to be $59.6/(59.6+19.27)=0.756$ (see footnote 5), somewhat higher than the value obtained here.

Assuming the fraction of the beam in Booster that is 96Zr16+ is 0.702 and that the other beam present is solely 90Zr15+, the fraction of the total current in the Booster that is from 96Zr16+ can be determined. Since the charge states are different the fraction is not just 0.702, but 0.715.¹¹ Another BtA MW060 measurement of the same kind was performed on Apr 20th which indicated that the fraction of 96Zr40+ was 0.733.¹² The fraction of the Booster current that would be 96Zr16+ would then be 0.745. If the xf108 beam current transformer at the end of EtB is only measuring current from these two species that fraction should also be the same there.

The Booster Scaler Calibrations for 96Zr

The Zr Booster input intensity scaler derived from xf108 was set so that it would have been correct if all the beam were 96Zr16+ for the entire run. Therefore, to get the best estimate for the 96Zr16+ input intensity its value should be multiplied by about 0.715.

To obtain the best estimate for the Booster late 96Zr16+ intensity throughout the run from the scaler is more complicated. From what I can discern from the elogs and Logview, it looks like the gain setting was set to a value consistent with 75% of the current coming from 96Zr16+ on Feb 27th (160). On Apr 3rd, the gain was lowered from 160 to 145, which after the change, made the Booster Late scaler correct if it were all 96Zr16+. It is puzzling that, if I set the gain for a fraction of 0.75 on Feb 27th, why is it that with the same gain setting on Apr 3rd it

¹⁰ By raising the DH2&3 current from 1688A to 1715A a smaller profile is present at -23 mm while the profile identified as 90Zr40+ is still present on the far right of the display. Owing to the low intensity of this beam the fit of this profile is not good. The area of it is about 1/10th that of the profile identified with 90Zr40+. This is in rough agreement with the ratio of the profile areas identified with 96Zr39+ and 96Zr40+, $0.41/2.75=0.15$. See [April 3rd Booster-AGS-EBIS 2018 elog](#) 1710, 1720, and 1726 entries.

¹¹ See pgs. 6 and 7 of C. Gardner, "[Notes on the setup of Ruthenium and Zirconium ions in the Booster and AGS for RHIC Run 18](#)".

¹² See [April 20 Booster-AGS-EBIS 2018 elog](#) 1757 and 1800 entries

had to be lowered from 160 to 145 to reflect the intensity if it were pure $^{96}\text{Zr}16+$? The setting should have had to be raised to something like $160/0.75=213$ for that.

Just after Apr 3rd, I incorrectly thought that I should multiply the pure $^{96}\text{Zr}16+$ setting by 0.66, not 0.715, to reflect the actual amount of it in the Booster. So, on Apr 4th, after checking the calibration I lowered the gain to 88. On Apr 12th I finally used an appropriate value for the fraction, 0.715, and set the gain to 100. There were other, smaller changes after that, but It seems that something changed in the scalers response to the gain setting between Feb 27th and Apr 3rd.

BtA Foil Stripping Efficiency for Zr

Fully stripped ^{96}Zr , which has a charge state of $40+$ is used for injection into the AGS. The BtA stripping foil used is composed of a layer of Carbon followed by a layer of Aluminum and is also used for Au and Ru. There are 2 of these foils installed in BtA and their performance is not discernably different. For the following stripping efficiency measurement one of those foils, foil 5, was used (the other is foil 6).

Once again, the MW060 multiwire and DH2&3 are used, but this time to determine the stripping efficiency. DH2&3 is adjusted so that the different ^{96}Zr charge states appear on the horizontal display. If there is a profile visible the area of its Gaussian fit is used as a relative measure of the amount of beam present in that charge state. The proportion of beam that is stripped to $^{96}\text{Zr}40+$ can then be determined. As with the previous BtA measurements these were performed on Apr 3rd using one Booster cycle and were taken at the same Booster late scaler value.

A candidate for the $^{96}\text{Zr}39+$ beam was found and to center it on the multiwire a DH2&3 setting of 1846A was required. Raising DH2&3 by one Amp shifts the profile to the right by about 1.5 mm. With a setting of 1795A the center of the $^{96}\text{Zr}40+$ profile was at -4.66 mm (see Figure 3) and one would expect the $^{96}\text{Zr}39+$ profile to be at that position if DH2&3 were set to $1795A * 40/39 = 1841A$, and to center it should require an additional 3A, or a setting of 1844A, close to the required value for the candidate profile.

The area for the Gaussian fit of that profile was 0.41. DH2&3 was adjusted to look for $^{96}\text{Zr}38+$ and $^{96}\text{Zr}37+$ using the DH2&3 settings 1895 and 1946A, respectively, but no profiles were found around those settings. It's inferred from this that the only 2 charge states with enough beam to see on the multiwire downstream of the foil are $39+$ and $40+$ and the amount of beam present for the other charge states is negligible. Since the area of the $^{96}\text{Zr}40+$ profile was 2.75, the stripping efficiency to $40+$ is therefore $2.75/(2.75+0.41)=0.87$.¹³ Figure 4 shows the $^{96}\text{Zr}39+$ candidate profile and the $^{96}\text{Zr}40+$ profile is shown in Figure 3.

¹³ See the [Booster-AGS-EBIS 2018 Apr 3rd elog](#) 1710 and 1720 entries.

The same technique was used to look for the $^{90}\text{Zr}39+$ peak and a candidate was found. For the ^{90}Zr beam the stripping efficiency to $40+$ was $1.17/(1.17+0.09)=0.93$. This is quite a bit higher than the value obtained for ^{96}Zr , but the ^{90}Zr intensity is lower so the signal to noise ratio is smaller.¹⁴ An even smaller profile was found where one would expect to see $^{90}\text{Zr}38+$. If it were $^{90}\text{Zr}38+$ than one would expect a $^{96}\text{Zr}38+$ profile to be larger and yet there was nothing visible with the appropriate DH2&3 current.¹⁵

Another stripping efficiency measurement was performed on Apr 12th using the same technique with ^{96}Zr except the average of 5 profile area measurements for both $39+$ and $40+$ were used and these were weighted using the Booster late intensity for each measurement. A value for the stripping efficiency to $40+$ of 87.8% was obtained (in this case foil 6 was used).¹⁶

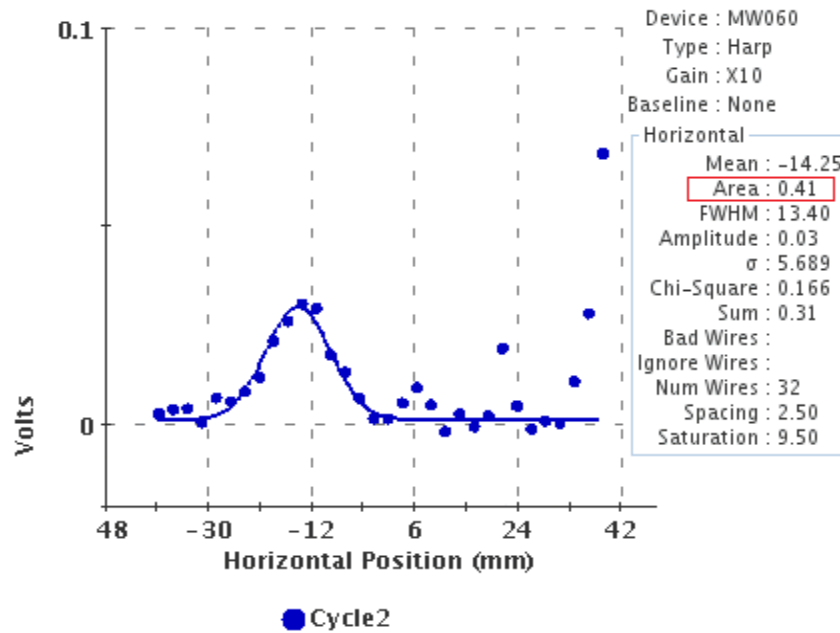


Figure 4: Candidate horizontal profile for $^{96}\text{Zr}39+$ with a DH2&3 setting of 1833A. Note the left side of the $^{96}\text{Zr}40+$ profile is visible on the far right of the display. Note that this is the same beam that required a setting of 1846A to center, it was moved to the left here by setting DH2&3 to 1833A to obtain a better profile and fit.

96Zr Efficiencies under Optimal Conditions

Measurements on a scope of intensities at different times in the Booster and AGS cycles on the same supercycle and using calibrated signals for the Booster and AGS current

¹⁴ See the [Booster-AGS-EBIS 2018 Apr 3rd elog](#) 1723 and 1726 entries.

¹⁵ See the [Booster-AGS-EBIS 2018 Apr 3rd elog](#) 1730 and 1732 entries.

¹⁶ See the [Booster-AGS-EBIS 2018 Apr 3rd elog](#) entries 1852 through 1906. The effect on the multiwire response due to the electron present in the $^{96}\text{Zr}39+$ case is ignored. On April 5th the default foil used for Zr was switched from 5 to 6 so that the foil would not have to be changed during mode switching (both Ru and Au use foil 6). It is not expected that this would have any discernable effect on performance.

transformers were made on Apr 3rd.¹⁷ EtB xf108 (a.k.a. Booster Input) data is taken from Logview for that time to give an overall picture of 96Zr performance under optimal conditions.¹⁸ The 8-4-2 AGS merge was in use at the time. The xf108 and Booster measurements are scaled by 0.715 for the reason discussed above. Table I shows the results.

In the table, ‘Booster Early’ is the peak intensity as measured on the normalized circulating transformer and ‘Booster Late’ is the intensity right at extraction. ‘AGS Early’ was measured with the unnormalized AGS transformer on the same AGS cycle as the Booster measurements. ‘AGS Late’ was determined by measuring the fraction of the beam just after the last transfer remaining at 3380 ms (the time the first bunch would be extracted). This fraction was obtained from a Logview plot of the normalized AGS transformer around the time when the other measurements were taken, although not on the same exact AGS cycle, and multiplying the AGS Early intensity by that factor.¹⁹ Figure 4 shows the Booster cycles and the injection porch for the AGS 8-4-2 cycle.

Time in Cycle	Intensity
Booster Input	9.39e9
Booster Early	8.56e9
Booster Late	7.06e9
AGS Early	5.3e9
AGS Late	5.0e9

Booster Early/Booster Input	0.91
Booster Late/Booster Early	0.82
AGS Early/Booster Late	0.75
AGS Late/AGS Early	0.95
AGS Late/Booster Input	0.53

Table 1: 96Zr intensities and efficiencies on April 3rd for 8 Booster cycles with beam and an 8-4-2 merge in the AGS.

Given a stripping efficiency in BtA of 87.8%, only $0.878 \times 7.06e9 = 6.20e9$ of the $7.06e9$ 96Zr ions at Booster extraction are available for injection into the AGS as 96Zr40+, so the transfer efficiency (Booster Late/AGS Early) of what’s available as 96Zr40+ is $5.3e9/6.20e9$ or 85%.

¹⁷ See the [Booster-AGS-EBIS 2018](#) elog Apr 3 1915 (for Booster Late) and 1916 (for AGS Early) entries and also the [Apr 10](#) 1454 entry (for Booster early).

¹⁸ See the [Booster-AGS-EBIS 2018](#) elog Apr 10 1430 entry. Also, I checked the Booster input (xf108) scaler on Apr 10 (see [here](#), 1649 entry) and it was about 5% lower than the scope measurement. Both these measurements were taken within a couple of hours of each other, so I multiplied the $8.94e9$ obtained at 1430 by 1.05 to get a better estimate of the xf108 intensity ($9.39e9$).

¹⁹ See the [Booster-AGS-EBIS 2018](#) elog Apr 10 1430 entry.

Measurements on Apr 6th with the 8-4-2 merge and the full bunch squeeze indicate that the amount of beam in the satellite (baby) bunches was negligible.²⁰ So, since there are 2 bunches on the AGS flattop and the full bunch squeeze was on during the Apr 3rd measurements, the bunch intensity would be $2.5e9$.²¹ On April 6th and without the KL portion of the bunch squeeze, the fraction of the beam in the baby bunches was 16.4%.²² On Mar 22nd, using the 12-6-2 merge, a bunch intensity of $2.57e9$ ions was also measured.²³

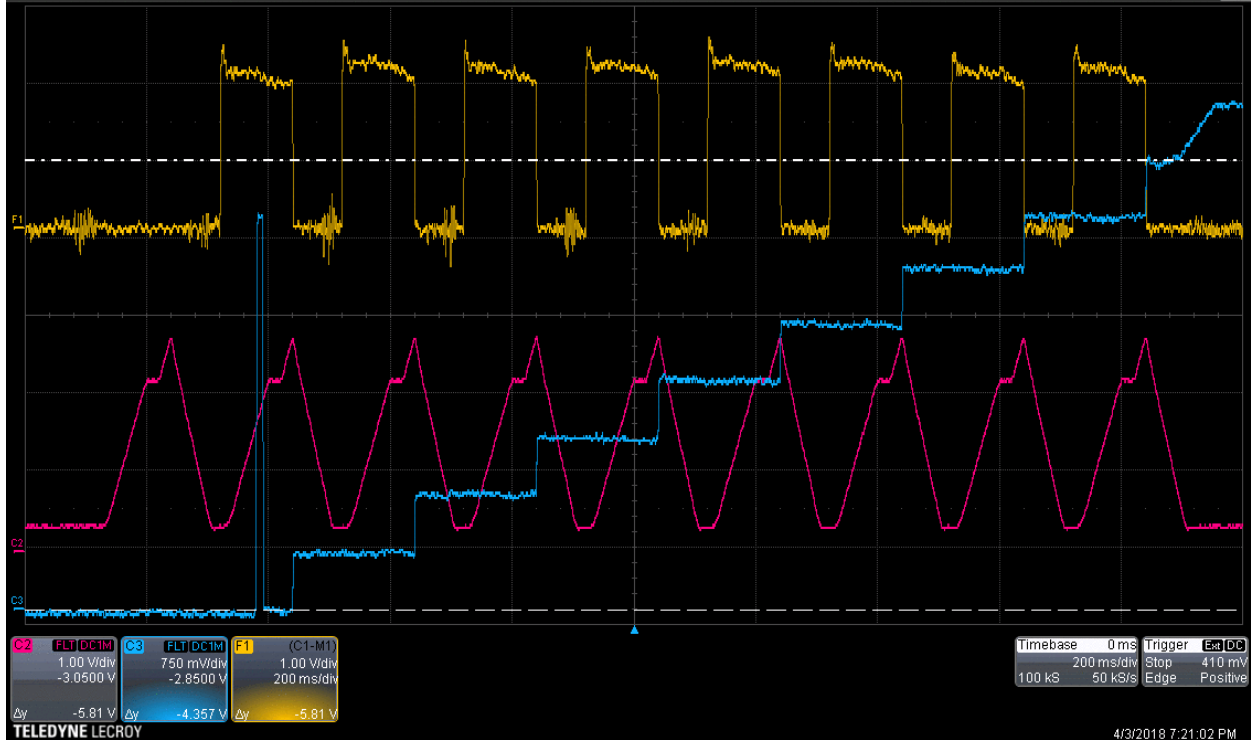


Figure 5: The Zr 8-4-2 Booster and AGS cycle. The orange trace is the Booster normalized transformer, the blue trace is the AGS unnormalized transformer, and the red trace is the Booster main magnet current. 200 ms/div.

Zr Emittance Measurements

Zr Transverse Emittance

The 95% normalized transverse emittances at the BtA multiwire MW006, located 6 feet downstream of the exit of the Booster and upstream of any of the magnetic elements in BtA, can be estimated from the transverse profiles there using values for the β functions of $\beta_x=3.0$ m and

²⁰ See the [Booster-AGS-EBIS 2018](#) elog Apr 6 1617 entry. Note that on Mar 12 with the 12-6-2 merge and the full bunch squeeze the baby bunches contained 7.1% of the total intensity ([Booster-AGS-EBIS 2018](#)) and other measurements from Mar 22 gave 5.6% and 9% (see [Booster-AGS-EBIS 2018](#) Apr 9 1533 and 1542 entries).

²¹ See the [Booster-AGS-EBIS 2018](#) elog Apr 6 1617 and 1630 entries.

²² See the [Booster-AGS-EBIS 2018](#) elog Apr 6 1639 and 1653 entries.

²³ See [Booster-AGS-EBIS 2018](#) elog Apr 9 1542 entry.

$\beta_y=16.0$ m obtained from MAD model predictions for polarized protons.²⁴ On March 30th the FWHM values for both planes were obtained from the Gaussian fits of the profiles to yield values of $\epsilon_x=1.68 \pi$ mm mrad and $\epsilon_y=5.36 \pi$ mm mrad for the horizontal and vertical emittances, respectively.²⁵

Normally, because the Booster injection bump is in the horizontal plane, one would expect ϵ_x to be larger than ϵ_y , but in the nominal setup Q_x and Q_y appear to cross late in the Booster cycle. This can have the effect of switching the values of ϵ_x and ϵ_y . On Apr 12 this effect was investigated, and with the normal tunes ϵ_x was 1.84π mm mrad and ϵ_y was 5.78π mm mrad, whereas when the setting for Q_y was lowered significantly ϵ_x became 5.23 and ϵ_y became 1.47π mm mrad, which confirmed this suspicion.²⁶ The emittances measured with the eIPM were measured on the AGS flattop for both cases and the result was about the same: $\epsilon_x=3.9$ and $\epsilon_y=9.3 \pi$ mm mrad with the Booster emittances flipped and $\epsilon_x=3.9$ and $\epsilon_y=9.6$ without them flipped. The BtA efficiency was about 10% lower without them flipped.²⁷

Zr Longitudinal Emittance in the AGS

Measurements of the Zr longitudinal emittance (ϵ_l) of the bunch first injected into the AGS at the time of the last transfer (1400 ms later) for the 8-4-2 setup were performed on March 30th.²⁸ After 1400 ms the bunch has had time to filament so it is fairly well matched to the bucket. The average length of 6 of these bunches was 237.3 ± 3.5 ns²⁹, with a measured $h=16$ synchrotron frequency of 1.530 kHz and Rf frequency of 2.67408 MHz this gives an ϵ_l of 0.0916 ± 0.002 eV-s/n corresponding to a 4 bunch ϵ_l of 0.366 ± 0.008 eV-s/n.

The ϵ_l of a merged AGS bunch just after the beginning of the AGS ramp was also measured.³⁰ The measurement was made just after the squeeze voltage reaches zero. The KL squeeze voltage used was less than the maximum (4.5 vs. 7 kV) and a small amount of beam was present in the baby bunches. The average length of 6 of these bunches was 273.8 ± 4.4 ns, with a measured $h=12$ synchrotron frequency of 3.369 kHz and Rf frequency of 2.36196 MHz this gives an ϵ_l of 0.432 ± 0.01 eV-s/n. So, there seems to be about a factor of $0.432/0.366=1.18$ in ϵ_l

²⁴ See K. Zeno, "[Booster and AGS Transverse Emittances During the 2006 and 2009 Polarized Proton Runs](#)" C-A/AP/404, September 2010, footnote 3 and page 3. Using the same logic, but with the value of $\beta\gamma$ at Booster extraction for Zr of 0.51 instead of the polarized proton value of 2.3 the 95% normalized horizontal emittance (ϵ_x) is found from the FWHM by the formula $\epsilon_x=0.183x^2$ and the vertical by $\epsilon_y=0.034y^2$ where x and y are the FWHM in the horizontal and vertical planes, respectively. Note that the horizontal width is not corrected for dispersion.

²⁵ See [Booster-AGS-EBIS 2018 elog Mar 30](#) 1847 entry

²⁶ See [Booster-AGS-EBIS 2018 elog Apr 12](#) 1713 and 1714 entries

²⁷ See [Booster-AGS-EBIS 2018 elog Apr 12](#) 1812 and 1814 entries

²⁸ See [Booster-AGS-EBIS 2018 elog Mar 30](#) 1919 through 1926 entries.

²⁹ The uncertainty shown is plus or minus the standard deviation of the measurements.

³⁰ See [Booster-AGS-EBIS 2018 elog Mar 30](#) 1930 to 1938 entries

growth between the 2 times in the cycle. Aside from the merge itself, there is also a small ramp to the merge porch between these two times (see Figure 2).

The preceding day (Mar 29) an ϵ_l measurement was made on the flattop with the same KL squeeze voltage as for the measurement above (4.5 kV).³¹ The average of 6 bunch length measurements was 24.5 ± 0.9 ns and with a synchrotron frequency of 103.8 Hz this corresponds to an ϵ_l of 0.56 ± 0.04 eV-s/n. So, the growth from the beginning of the ramp to the flattop for Zr was about $0.56/0.432=1.30$.

Ruthenium Measurements

Ru Efficiencies under Optimal Conditions

Measuring the Ru efficiencies (and intensity) is more straightforward than it is for Zr because the Ru beam coming from Tandem is pure 96Ru^{12+} . However, the pulse length of the beam from Tandem is an easily adjustable parameter and the efficiencies will vary depending on what it is. The setup was optimized for an approximately 400 μs long pulse, which provided more bunch intensity than was necessary to satisfy the RHIC intensity requirements. A pulse length of about 150 μs was more typical when filling RHIC.

On Apr 11th the injection efficiency was measured for a 400 μs long pulse. The TtB section 29 current transformer is used to measure the intensity of the beam just before it is injected into the Booster. It is located at 104 ft and the entrance to the inflector is at about 143 ft. Using the nominal calibration of 100 $\mu\text{A}/\text{V}$ with a 1 M Ω termination an injected intensity, for one Tandem pulse, was $1.79\text{e}9$ 96Ru^{12+} ions and the intensity measured on the injection current transformer at its peak (with baseline subtracted) was $1.62\text{e}9$ ions for the same pulse which gives an injection efficiency of 90.5%.³²

The injected intensity as measured on the injection transformer and the intensity at Booster extraction as measured on the normalized circulating beam transformer were measured on a scope for the same Booster cycle (i.e.-simultaneously) using a 400 μs pulse. The injected intensity was $1.50\text{e}9$ and the Booster extraction intensity was $1.41\text{e}9$ 96Ru^{12+} ions, so the efficiency here was 94% (both signals had their baselines subtracted).³³ The efficiency from section 29 to Booster extraction is then $0.905*0.94$ or 85.1%.

On Mar 30th a transfer efficiency measurement was performed using a 400 μs pulse. The measurements were taken on the same supercycle. The total Booster intensity at extraction time was $8.88\text{e}9$ 96Ru^{12+} ions and Ru^{44+} intensity in the AGS at the time of the last transfer was

³¹ See [Booster-AGS-EBIS 2018 elog](#) Mar 30 1941 and 1953-1959 entries

³² See [Booster-AGS-EBIS 2018 elog](#) Apr 11 1545 to 1608 entries

³³ See [Booster-AGS-EBIS 2018 elog](#) Apr 11 1612 to 1617 entries

4.93e9 ions (55.5%).³⁴ This measurement was taken at a different time and intensity than the previous measurements but the same pulse width. Although the efficiencies do depend on the pulse length, there is no apparent intensity dependence in the Booster or on the AGS injection porch (at least up to this time in the AGS cycle). So, I think it is fair to combine these two sets of results.

On the same day, but a different cycle, when measured on the baseline subtracted normalized AGS current transformer signal, the intensity at AGS extraction was the same as the intensity at the time of the last transfer but the normalized signal was not flat between these times. This probably has to do with the baseline not being flat when it's fed into the normalizer. So, on the same cycle, I measured the intensity on the unnormalized signal at the last transfer and the AGS flattop intensity using the appropriate respective calibrations and found that the flattop intensity was 94.3% of the intensity at the last transfer.³⁵ From these measurements I can compile a representative list of intensities and efficiencies when the pulse length is 400 μ s with an AGS flattop intensity of 4.65e9 (see Table 2).

Time in cycle	Intensity	Method
Section 29 (Booster Input)	10.4e9	Booster Early/0.905
Booster peak (Booster Early)	9.45e9	Booster Late/0.94
Booster @ extraction (Booster Late)	8.88e9	Direct measurement
AGS @ last transfer (CBM)	4.93e9	Direct measurement
AGS flattop (Late)	4.65e9	AGS CBM*0.943

Efficiency	Value
(Booster Early)/(Booster Input)	90.5%
(Booster Late)/(Booster Early)	94.0%
(AGS CBM)/(Booster Late)	55.5%
(AGS Late)/(AGS CBM)	94.3%

Table 2: 96Ru intensities and efficiencies through the cycle for 400 μ s Tandem pulses, 8 Booster cycles with beam, and 2 bunches on the AGS flattop.

On May 7th another transfer efficiency measurement was made with a 400 μ s pulse. The intensity at Booster extraction was 8.16e9 and at the last transfer to the AGS it was 4.34e9 for a transfer efficiency of 53.2%.³⁶ In practice the transfer efficiency was normally lower than this in part because certain BtA supplies, the L20 septum in particular, were not stable for most of the run. The intensities and efficiencies quoted here are for optimal running conditions.

On Apr 17th, with a moderate KL squeeze voltage of 3.5 kV (out of 7 kV) a 15 cycle average of the percentage of the beam in the baby bunches was 2.4%, but on Mar 2nd and Mar

³⁴ See [Booster-AGS-EBIS 2018 elog](#) Mar 30 1510 and 1511 entries

³⁵ See [Booster-AGS-EBIS 2018 elog](#) Mar 30 1535 and 1537 entries

³⁶ See [Booster-AGS-EBIS 2018 elog](#) May 7 1737 to 1749 entries.

14th with the same KL voltage they were negligible (<1%).³⁷ On Apr 11th the intensity of a bunch on the flattop was measured to be 2.82e9 ions.³⁸

BtA Foil Stripping Efficiency for Ru

As with Zr, fully stripped Ru is injected into the AGS and stripped by an Al and C foil. Unlike Zr, which used foil 5 initially and then was switched to 6, foil 6 seems to have been used exclusively for Ru, although this is not expected to make any difference. Two stripping efficiency measurements were made, one on Mar 30th and the other on Apr 23rd.

Using a method analogous to the one described above for Zr, the Mar 30th measurement found 3 different charge states identified with 42+, 43+, and 44+, where charge state 44+ is fully stripped.³⁹ With DH2&3 set to 1212.45A the center of the profile is located at +1.64 mm. A setting of 1212.45A*44/43=1240.65A should put 96Ru43+ at a similar position and a setting of 1240.54A placed a profile at +4.18 mm so this was identified with that charge state. Similarly, a setting of 1212.45A*44/42=1270.19A should put 96Ru42+ at a similar position to where 96Ru44+ was with a setting of 1212.45A. With that setting, a profile was clearly visible with its center located at +6.85 mm. This profile was identified with 96Ru42+. No profile was visible with DH2&3 set to 1212.45A*44/41=1301.17A so there was no 96Ru41+ visible.

The area of each of the 3 horizontal profiles was measured and the Booster late intensity, as measured on the Booster Late scaler, was the same in each case. The fits were not as good as they were for Zr. The areas of those fits were 3.64, 1.86, and 0.25 for charge states 44+, 43+, and 42+, respectively. So, the stripping efficiency to 44+ would be $3.64/(3.64+1.86+0.25)=63.3\%$. Figure 6 shows the 3 profiles.

The other set of measurements are from Apr 23rd.⁴⁰ They are also with beam from one Booster cycle. In this case the areas were also weighted with the Booster Late intensity, as it was slightly different for the 3 cases. The profile fits in this case are better than they were on Mar 30th. Table 3 summarizes the data and Figure 7 shows the profiles and fits. This measurement gave a stripping efficiency to 96Ru44+ of 62.3%. It is probably a more accurate measurement than the one on Mar 30th, which gave 63.3%, because the fits are considerably better. An estimate for the stripping efficiency to 44+ was made by P. Thieberger for a kinetic energy of 55 MeV and the result was 55%. However, the kinetic energy at extraction is 65 MeV so one would expect a higher stripping efficiency than that.⁴¹ Given a stripping efficiency of 62.3%, the transfer efficiency of the 96Ru available as 44+, for a 400 μ s pulse, is $55.5/62.3=89.1\%$.

³⁷ See [Booster-AGS-EBIS_2018_eolog](#) Mar 2 1704 entry and See [Booster-AGS-EBIS_2018_eolog](#) Mar 14th 1439 entry

³⁸ See [Booster-AGS-EBIS_2018_Apr_11_eolog](#) 1500 entry.

³⁹ See [Booster-AGS-EBIS_2018_Mar_30_eolog](#) 1620 to 1632 entries

⁴⁰ See [Booster-AGS-EBIS_2018_Apr_23_eolog](#) 1331 to 1345 entries

⁴¹ See C. Gardner, [Booster-AGS-EBIS_2018_April_23rd_eolog](#) 1206 entry

Ruthenium Emittance Measurements

Ru Transverse Emittance

Since Ru comes from Tandem, the length of the injected pulse may be varied. A longer pulse will fill more of the available aperture and so the transverse ϵ is expected to be larger. This is likely true for both planes since the multi-turn injection is intentionally coupled. Extraction from the Booster occurs at a $\beta\gamma$ of 0.38 which is significantly lower than it is for Zr. The conversions from profile widths at MW006 to 95% normalized transverse ϵ , using the same method used to determine those for Zr, are $\epsilon_x=0.137x^2$ and $\epsilon_y=0.0257y^2$ where x and y are the full widths at half maximum obtained from the Gaussian fits. Note that as with Zr, no correction to ϵ_x is made for the part of the horizontal width due to dispersion.

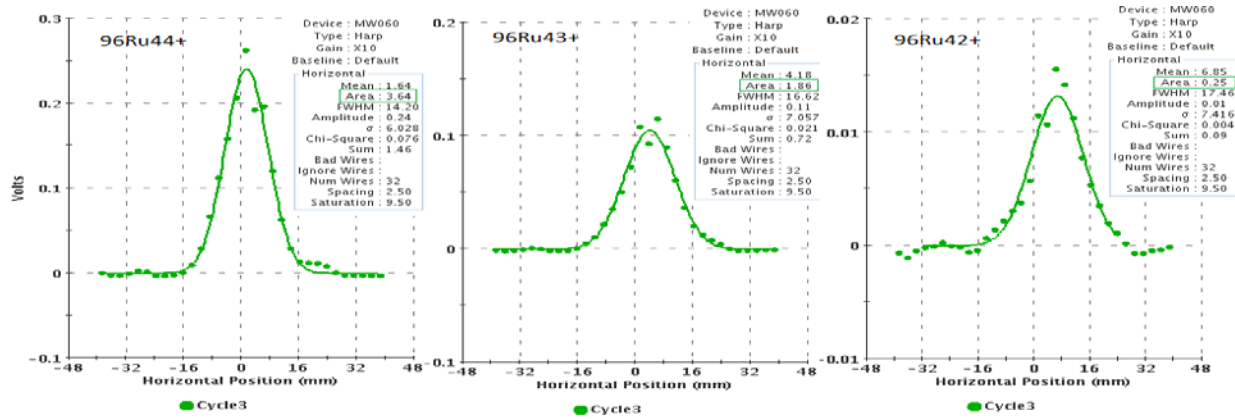


Figure 6: MW060 horizontal profiles with Gaussian fits of the 3 charge states of 96Ru visible downstream of the BtA stripping foil from Mar 30th. DH2&3 is set to 1212A for 44+ (left), 1241A for 43+ (center), and 1270A for 42+ (right).

Charge State	Area	Booster Late (volts)	Weighted Area	Center (mm)	Expected DH2&3 setting (A)	Actual DH2&3 setting (A)	Fraction of total beam
44+	2.60	1.755	2.60	-11.92	1205.13	1205.13	0.623
43+	1.28	1.715	1.371	-6.76	1233.16	1234.43	0.328
42+	0.18	1.715	0.202	-9.32	1262.52	1260.07	0.048
41+	0	-	0	-	1293.31	1293.04	0

Table 3: Results of BtA MW060 96Ru horizontal profile stripping efficiency measurements from Apr 23rd. ‘Charge State’ is the charge state identified with the profile, ‘Area’ is the area of the Gaussian fit of the profile, ‘Booster Late’ is the intensity of the Booster circulating transformer at extraction, ‘Weighted Area’ is (Area)*1.755/(Booster Late), ‘Center’ is location of the center of the Gaussian fit, ‘Expected DH2&3 setting’ is 1205.13*44/(Charge State), ‘Fraction of total beam’ is (Weighted Area)/(2.60+1.371+0.202).

On Mar 20th, the transverse emittances were measured at MW006 for different Tandem pulse lengths.⁴² For a 400 μs long pulse, the measured FWHMs at MW006 were $x=5.73$ and $y=12.15$ mm corresponding to $\epsilon_x=4.50$ and $\epsilon_y=3.79$ π mm mrad. The Tandem current varied considerably through the run, but, at least on this day, the pulse length needed to deliver the desired bunch intensity to RHIC ($\sim 1e9$ ions) was about 117 μs . In general, it was probably 150 μs or less and rarely, if ever, less than 100 μs . On that day the FWHMs for a 117 μs long pulse were $x=4.50$ and $y=9.66$ mm, corresponding to $\epsilon_x=2.8$ and $\epsilon_y=2.4$ π mm mr, significantly less than what they are with the longer pulse. With a 50 μs pulse, which corresponds to a bunch intensity much lower than that, the FWHMs were $x=4.05$ and $y=8.22$ mm, corresponding to $\epsilon_x=2.25$ and $\epsilon_y=1.7$ π mm mr. Figure 8 shows the profile data and fits for these three cases.

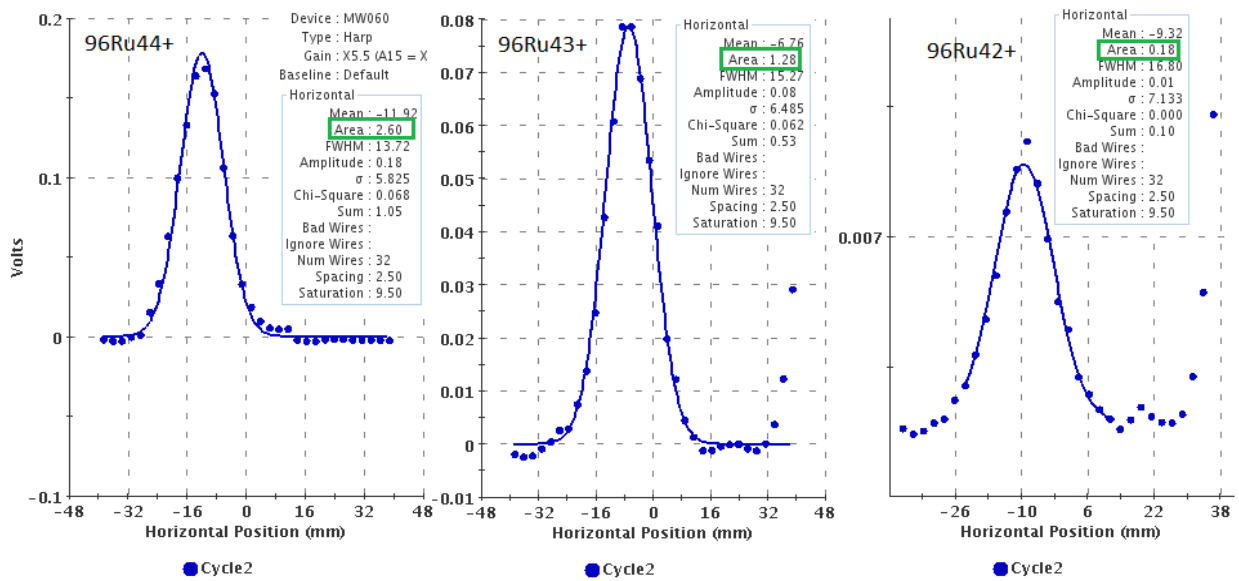


Figure 7: MW060 horizontal profiles with Gaussian fits of the 3 charge states of 96Ru visible downstream of the BtA stripping foil from Apr 23rd.

The emittance increase between the 2 pulse lengths, 400 and 117 μs , is just the ratio of the squares of the widths for each case. In the x-plane it is $(x_{400\mu\text{s}}/x_{117\mu\text{s}})^2 = (5.73/4.50)^2 = 1.62$ and in the y-plane it is $(y_{400\mu\text{s}}/y_{117\mu\text{s}})^2 = (12.15/9.66)^2 = 1.58$. These ratios are quite different for profiles taken at MW060 with the 2 pulse lengths: $(x_{400\mu\text{s}}/x_{117\mu\text{s}})^2 = (15.80/14.17)^2 = 1.24$ and $(y_{400\mu\text{s}}/y_{117\mu\text{s}})^2 = (16.22/14.34)^2 = 1.28$.⁴³ MW060 is downstream of the stripping foil so the ratios there do not measure this emittance increase unless the contribution from the foil is negligible, in which case the ratios should be the same as at MW006. But the fact that they are smaller than at MW006 indicates that, in both planes, the foil is causing more ϵ growth for the shorter pulse than for the longer one.

⁴² See [Booster-AGS-EBIS Mar 20 elog](#) 1638 through 1710 entries and 1808 entry. With the 400 μs long pulse the intensity of the bunches injected into RHIC was about 2.4e9.

⁴³ See [Booster-AGS-EBIS Mar 20 2018 elog](#) 1810 entries

eIPM measurements are also available for the 2 cases. For the 117 μs pulse (ϵ_x, ϵ_y) were (5.4, 5.4) π mm mr at 2000 ms (early in the main acceleration ramp) and (7.5, 7.2) π mm mr from 3100-3300 ms (on the flattop).⁴⁴ For the 400 μs pulse, the values were (8.7, 7.8) π mm mr at 2000 ms and about (9.9, 10.2) π mm mr from 3100 to 3300 ms.⁴⁵ The flattop intensity in the 400 μs case was about $4.4\text{e}9$ ions (2 bunches) and in the 117 μs case it was about $2.25\text{e}9$ (2 bunches).

For the 117 μs pulse the ϵ ratios between MW006 and 2000 ms are a factor of (5.4/2.8) = 1.9 in the horizontal and (5.4/2.4) = 2.3 in the vertical. For the 400 μs pulse they are (8.7/4.50) = 1.9 in the horizontal and (7.8/3.79) = 2.1 in the vertical. The ϵ growth attributable to the foil, defined as ϵ after the foil over ϵ before the foil, is not known, but according to the MW060 data it should be significantly less in the 400 μs case than in the 117 μs case. Yet the ratios for MW006 and 2000 ms look about the same and if this were so they should be smaller for 400 μs . Maybe there is a mechanism besides the foil that causes additional growth in the 400 μs case (ex.-space charge).

The growth up the ramp for the 117 μs case is a factor of (7.5/5.4) = 1.4 in the horizontal and (7.2/5.4) = 1.3 in the vertical. In the 400 μs case it is (9.9/8.7) = 1.1 in the horizontal and (10.2/7.8) = 1.3 in the vertical. So, the amount of horizontal growth is greater for the shorter pulse and the vertical growth is about the same for the 2 cases.

Ru Longitudinal Emittance

As with Zr, on Mar 30th, longitudinal emittance measurements in the AGS were made of the bunch first injected at the time of the last transfer using the bunch length and synchrotron frequency. Seven bunch length measurements were made, and the result was 276.6 ± 8.6 ns. That result, together with the measured synchrotron frequency (1.798 kHz), gives an ϵ_l before the merge of 0.080 ± 0.04 eV-s/n for a 4 bunch ϵ_l of 0.32 ± 0.02 eV-s/n.⁴⁶

The emittance of a merged bunch near the beginning of the ramp was also found. Four bunch length measurements at At0+1876 ms were made and the average bunch length was 244.5 ± 6.4 ns with a synchrotron frequency of 3.518 kHz. This corresponds to a merged bunch ϵ_l of 0.37 ± 0.15 eV-s/n, which gives about a factor of $0.37/0.32 = 1.16$ in emittance growth between the time of the last transfer and the beginning of the ramp.⁴⁷ Both these measurements were made with a 400 μs Tandem pulse.

⁴⁴ See [Booster-AGS-EBIS Mar 20 elog](#) 1712 entry (C. Liu and I. Zhang). Note the values there are rms. I've multiplied them by 6 to get the 95% vales.

⁴⁵ See [Booster-AGS-EBIS Mar 20 elog](#) 1524 entry (C. Liu). Note the values there are rms. I've multiplied them by 6 to get the 95% values. Also, the values here are the average of the 2 measurements shown in the elog.

⁴⁶ See [Booster-AGS-EBIS Mar 30 2018 elog](#) entries 1707 to 1719.

⁴⁷ See [Booster-AGS-EBIS Mar 30 2018 elog](#) entries 1639 to 1650.

An emittance measurement on the flattop was made the same day, although a 200 μs long Tandem pulse was used. The average of 7 bunch length measurements was 22.6 ± 1.4 ns and the synchrotron frequency was 115.2 Hz. This gives an ϵ_1 of 0.46 ± 0.06 eV-s/n.⁴⁸ So, the growth from the beginning of the ramp to the flattop would be $0.46/0.37=1.25$.

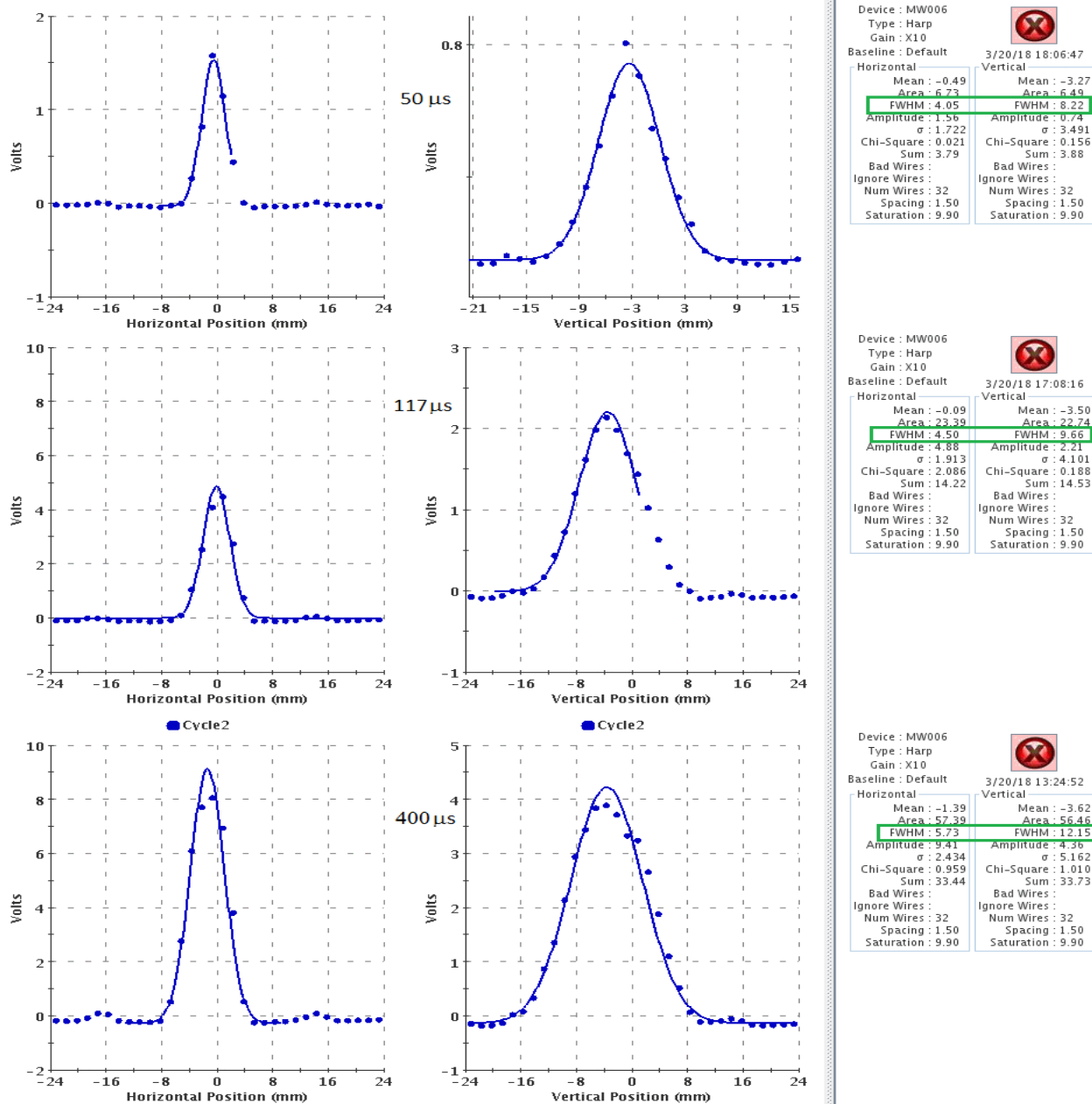


Figure 8: Ruthenium BtA MW006 profile data and Gaussian fits for Tandem pulse lengths of 50 μs (top), 117 μs (middle), and 400 μs (bottom) from Mar 20th. At the time 117 μs was a typical pulse length used for filling RHIC.

⁴⁸ See [Booster-AGS-EBIS Mar 30 2018 elog](#) entries 1302 to 1310.

Another flattop ϵ_1 measurement was made on Apr 13th using a pulse length of about 170 μs . The average of 4 bunch length measurements was 24.0 ± 0.4 eV-s/n, and with a synchrotron frequency of 117 Hz this corresponds to an ϵ_1 of 0.529 ± 0.017 eV-s/n.⁴⁹ Using the ϵ_1 value at the beginning of the ramp from Mar 30th this would give a more typical factor of $0.529/0.372=1.42$ in ϵ_1 growth. A KL squeeze voltage of 3.5 kV out of a possible 7 kV was used for all these measurements. The amount of beam in the baby bunches was 2.4% on Apr 17th and 3.9% on Apr 23rd (both with KL set to 3.5 kV). On Mar 2nd, again with 3.5 kV the baby bunches were quite small, probably less than 1%.⁵⁰

Ru is notable because it is the first time the 4-2-1 merge in the Booster has been used for a Tandem species. Although the bunches have more structure than either Zr or Au from EBIS on the first turn in the AGS, the ϵ_1 after filamentation appears to be somewhat smaller: 0.32 vs 0.366 eV-s/n for Zr and about 0.44 eV-s/n for Au (when $h=16$ is the injection harmonic).⁵¹ Figure 9 shows both Ru and Zr as seen on the AGS wall current monitor on the first turn.⁵²

Figure 10 shows the entire 4-2-1 Ru bunch merge using the D1 PUE sum signal (which has a much slower time response than the wall current monitor in the AGS).⁵³ Each 4 ms section was taken on a different Booster cycle but it looks like the oscillations are quite reproducible. The merge appears to be substantially worse than it is for Zr or Au.⁵⁴ This is probably because the ϵ_1 of the Booster beam from Tandem is less than it is for beam from EBIS and because it is harder to preserve the emittance of smaller bunches when they are merged than larger ones. The bunches coming into the merge also look like they might be undergoing coupled bunch oscillations. Despite all this the Ru ϵ_1 on the AGS flattop (and on the injection porch) is no larger, and perhaps even smaller than the Zr (or Au) ϵ_1 when using an 8-4-2 merge setup.⁵⁵ The average of the 2 Ru flattop measurements described above is 0.49 eV-s/n, the Zr ϵ_1 was 0.56 eV-s/n, and Au when run with an 8-4-2 merge was about 0.69 eV-s/n.

Dependence of Transfer Efficiency on Tandem Pulse Length

The BtA transfer efficiency (AGS CBM/Booster Late) is worse for a 400 μs pulse than for a much shorter pulse. This is not surprising because the transverse emittance is smaller for a

⁴⁹ See [Booster-AGS-EBIS Apr 13 2018 elog](#) entries 1556 to 1604.

⁵⁰ See [Booster-AGS-EBIS Mar 2 2018 elog](#) 1704 entry

⁵¹ See K. Zeno, "[Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Bunch Merge](#)", C-A/AP/59, December 2017, Table II on page 12 for Au data.

⁵² [Booster-AGS-EBIS 2018 elog](#) Mar 30 1916 entry.

⁵³ From [Booster-AGS-EBIS 2018 Apr 11 elog](#) 1636 to 1642 entries

⁵⁴ See [Booster-AGS-EBIS 2017 elog Apr 11](#) 1957 entry for what the Au merge looks like (albeit with less resolution).

⁵⁵ Although it's likely that there has been some improvement to the Booster merge since 2014, the Au flattop ϵ_1 was about 0.69 eV-s/n then, which is when the 8-4-2 merge was used. See K. Zeno, "[Longitudinal Emittance Measurements in the Booster and AGS during the 2014 RHIC Gold Run](#)", C-A/AP/523, August 2014, pg. 26, Table V.

shorter pulse. The Ru rigidity in BtA and on the AGS injection porch is also quite low (see Figure 2).

On Apr 11th the pulse length was lowered from 400 μs to 125 μs and Booster Late, as measured by the intensity scaler, dropped by about a factor of $3.3\text{e}9/12.2\text{e}9=0.27$. But AGS CBM, as measured on a scope, dropped by only a factor of $176/500=0.34$. So, whatever the transfer efficiency was for a 400 μs pulse, for a 125 μs pulse it would be about a factor of $0.34/0.27=1.26$ higher.⁵⁶ Unfortunately, reliable transfer efficiency measurements for both lengths made using scope signals are not available for this time. The Booster Late and AGSCBM (a.k.a. AGS Early) scaler values from LogView indicate that the transfer efficiency increased by a factor of 1.23, going from $5.7\text{e}9/1.22\text{e}9=46.7\%$ to $1.9\text{e}9/3.3\text{e}9=57.6\%$.

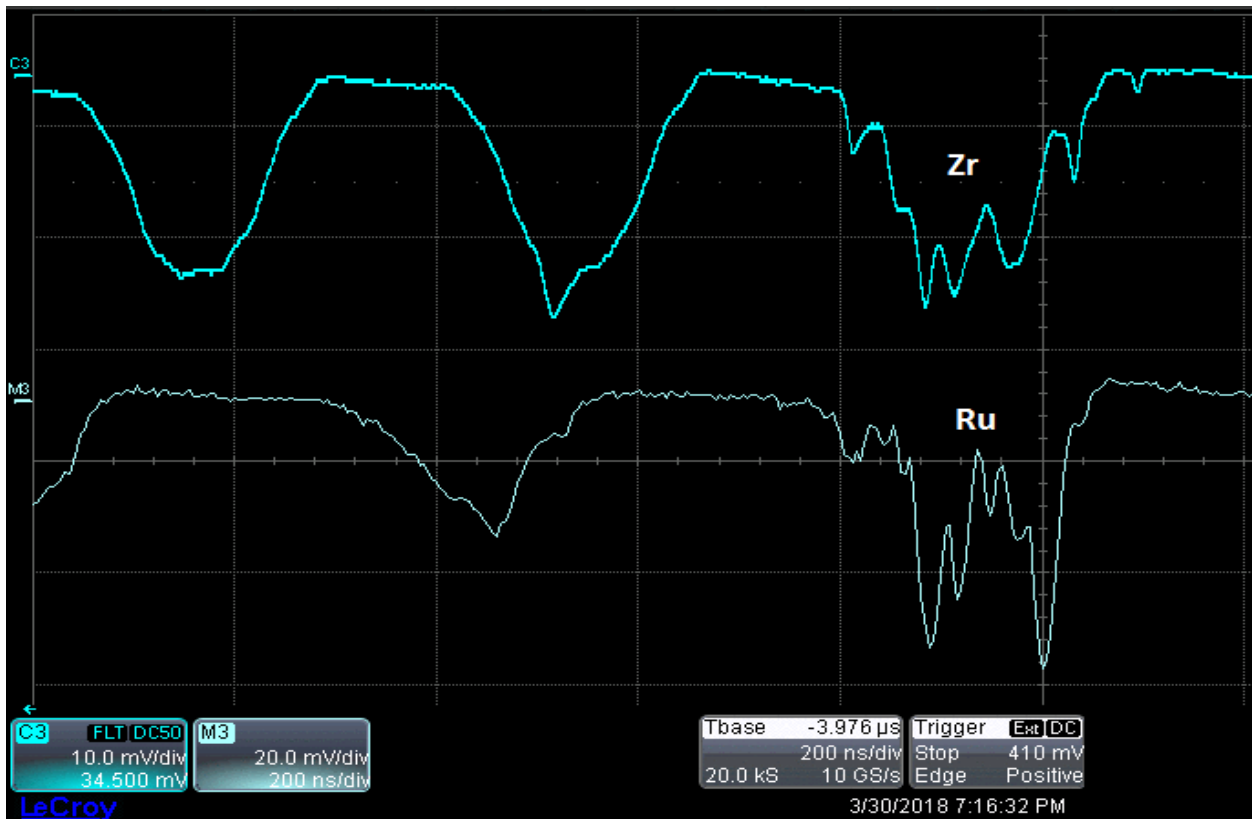


Figure 9: Typical Zr (top) and Ru bunches on the 1st turn in the AGS as seen on the wall current monitor. In both cases the bunch on the first turn is the one on the right. The other bunches are from previous transfers. The sweep speed is 200 ns/div. Note that the gain of the Zr trace is twice that of the Ru trace and that the revolution frequency for Ru is significantly lower than for Zr (129 vs 167 kHz). In both cases injection is into h=16 buckets.

⁵⁶ See [Booster-AGS-EBIS 2018 Apr 11 elog](#) entries from 1519 to 1523. Only the pulse length was changed.

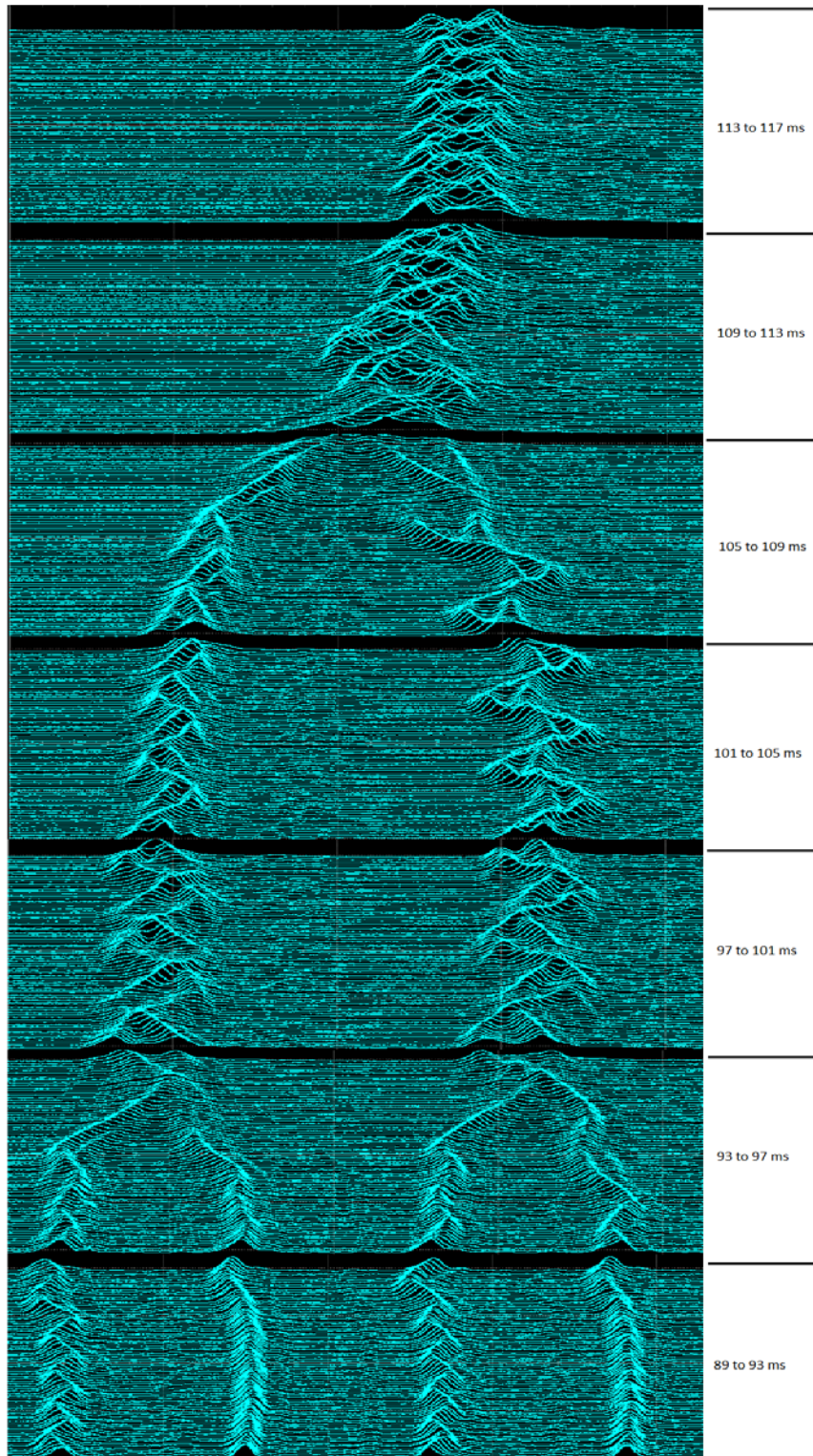


Figure 10: A composite of mountain range displays of the D1 PUE sum signal showing the Ru 4-2-1 bunch merge in the Booster. Each of the seven 4 ms long sections was taken on a different cycle and contains 80 traces with $50 \mu\text{s}$ between each trace. Times are from Bt0. Note that there is no $h=2$ voltage until 92 ms.

Another loss is evident when using a 400 μs pulse but is not there when a short pulse is used. It occurs after the last transfer at the beginning of the ramp to the merge porch. The Ru loss rate on the injection porch deteriorates quickly when the Rf voltage is raised, so it is kept low there but it needs to be raised for the ramp to the merge porch. Whether or not this loss is space charge related is not clear, it could be due to the increased beam size associated with the higher momentum spread when the voltage is raised. Figure 11 shows the AGS normalized transformer for a 125 μs and a 400 μs pulse.⁵⁷

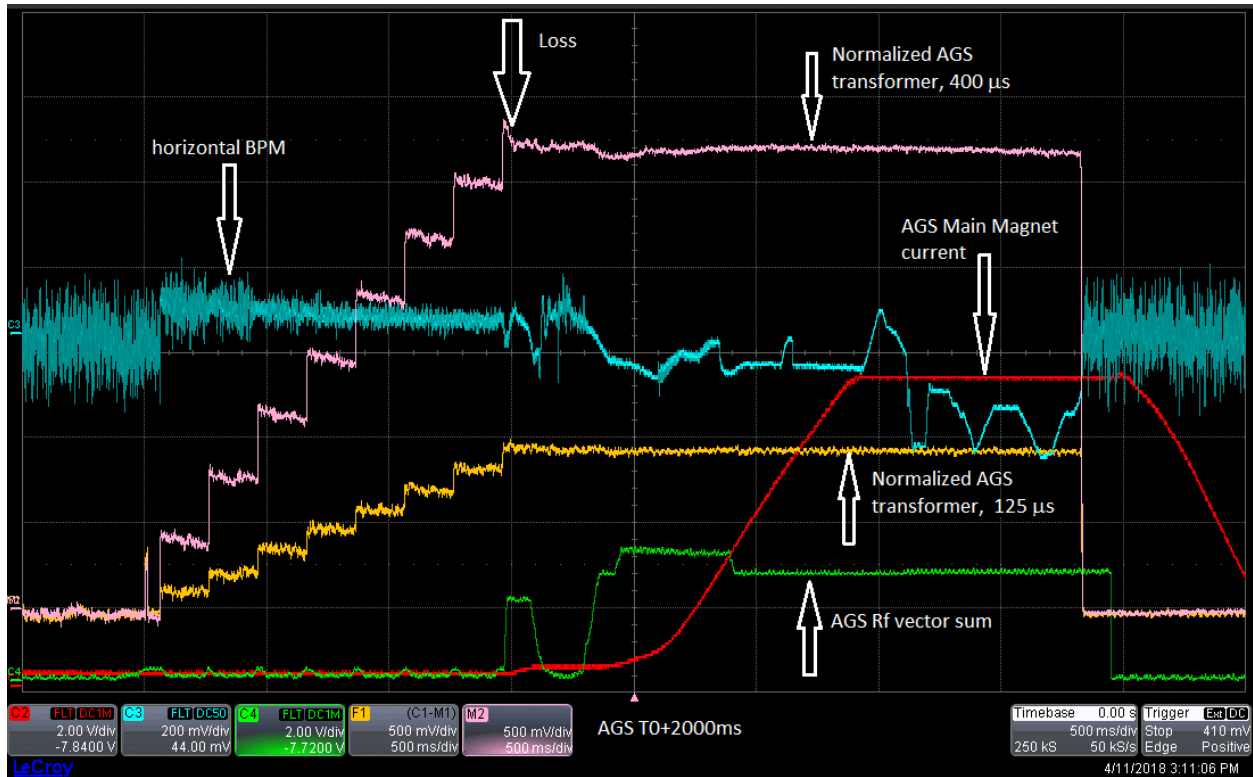


Figure 11: Comparison of Ru beam in the AGS for 125 and 400 μs long Tandem pulses as viewed on the normalized transformer. Note the loss in the 400 μs case at the beginning of the ramp to the merge porch that is not present for the 125 μs pulse case. Sweep speed is 500 ms/div.

Gold Performance

For the Au part of the run the 12-6-2 merge was used in the AGS and the same 4-2-1 merge was used in the Booster. This setup was also used in the relatively long Au run in 2016 and the shorter Au run in 2017.

During this run the highest bunch intensities seem to have been on Jun 13th where, for a 4 minute interval, the AGS late intensity averaged $5.77\text{e}9$ ions ($\sigma=0.07\text{e}9$), Booster Late intensity

⁵⁷ See [Booster-AGS-EBIS 2018 Apr 11 elog](#) 1522 and 1523 entries.

averaged 12.13×10^9 ($\sigma=0.17 \times 10^9$) and Booster input averaged 14.13×10^9 ($\sigma=0.34 \times 10^9$).⁵⁸ So, the efficiency (Booster Late)/(Booster input) was $12.13/14.13=85.8\%$. The percentage of beam in the baby bunches was measured around that time as 4.72% ($\sigma =0.21\%$), which means that $5.77 \pm 0.07 \times 10^9$ ions on the flattop would correspond to 2.75 ± 0.04 ions/bunch (where the uncertainty shown in the bunch intensity is for 1σ in both the baby bunch and flattop intensity measurements).⁵⁹

The best performance bunch intensity-wise in Run 16 was on Apr 21. The data for 11 cycles near the time when a peak bunch intensity with the WCM of 3.15×10^9 ions was measured were: Booster Input = $15.13 \pm 0.19 \times 10^9$, Booster Late = $12.61 \pm 0.05 \times 10^9$, and AGS "Late" = $6.56 \pm 0.03 \times 10^9$ (where the uncertainties are the standard deviations of the measurements).⁶⁰ So the efficiency (Booster Late)/(Booster input) was $12.61/15.13=83.3\%$. The amount of beam in the baby bunches appears to have been about 4.1% which means that for an AGS "Late" of 6.56×10^9 the bunch intensity would be $(0.959 * 6.56 \times 10^9)/2$ or 3.15×10^9 , the same as that found using the WCM.⁶¹ The flattop bunch intensity over Booster Late was therefore $(0.959 * 6.56)/12.61=50.0\%$ and on June 13th of this year it was just $(0.955 * 5.77)/12.13=45.3\%$.⁶²

The overall efficiency (flattop bunch intensity)/(Booster input) in the optimal running state from this run was $(0.955 * 5.77)/14.13=38.9\%$ and in the Run 16 case it was $(0.959 * 6.56)/15.13=41.6\%$.

Finding Accurate Values for the Booster Input Intensity

To compare Run 16 and 18 performance properly accurate measurements of the Booster input intensity are essential. So, I think it's worthwhile to investigate the sources of error in those

⁵⁸ This is the average of 39 cycles worth of data for Booster Input, Booster Late, and AGS_AftTrans from 1028:05 to 1032:15. The data can be found in MCR/InjectorPerformance.logreq. AGS_AftTrans is used for AGS late as AGS Late is corrupted and any loss between the 2 times is typically negligible.

⁵⁹ I obtained this value for the baby bunch percentage from the AGS normalized transformer during a fill that occurred from 0948 to 0951 that day, 40 minutes earlier. The data is recorded in the LogView file: AGS/Instrumentation/currentXfmr/ags.beamCurrent_Snap.logreq. I took 10 cycles and for each cycle averaged over 60 data (60 ms) just before the first extraction (N1), after the last extraction (N2), and after the beam was dumped to get the baseline (N3). For each cycle then the fraction of beam in the baby bunches is $(N2-N3)/(N1-N3)$.

⁶⁰ The data is from the LogView file MCR/Personal/Kelz/xf108Strip.logreq from 1704:23 to 1705:27 on Apr 21st. The AGS_before_transition scaler is used in place of AGS Late because the AGS Late (and AGS_after_transition) scaler data was corrupted. The loss between those 2 times in the cycle is typically negligible. It was noted in the elog that at the time Helium was running for NSRL. The WCM bunch intensity measurement is shown in the 1707 entry in [Booster-AGS-EBIS 2016 elog Apr 21](#).

⁶¹ Bunch intensity measurements were made for 25 cycles and the average was 3.054×10^9 ions (see 1628 entry in [Booster-AGS-EBIS 2016 elog Apr 21](#)) and AGS before transition averaged 6.367×10^9 during this interval. So, the baby bunch fraction was $1-(3.054/(0.5 * 6.367))=0.041$.

⁶² Another measurement of this on Jun 6th gives 46.2%, see [Booster-AGS-EBIS 2018 Jun 6th elog](#) 1701 entry. It also indicates an efficiency (flattop bunch intensity)/(Booster input) of 39.1%. These are with the collimator in and H-foil out.

measurements in detail and perhaps find more accurate values for what the input intensity was in the two cases considered above.

More than One Beam Profile Visible on EtB MW096

When running Au there is typically a smaller profile visible to the right of the main profile on the second to last multiwire in EtB. This multiwire, MW096, is between the 2 dipole magnets that make up the arc146 bend and is 12 feet upstream of xf108. The contribution to the xf108 current from the beam associated with the smaller profile, about 12 mm to the right of the main profile, was investigated on May 29th using a collimator just upstream of the multiwire.⁶³

This collimator, etb-ch96-r.mot:go, was set to 575000 for the run but was changed briefly for these measurements. By observing the MW096 profile display as the collimator is moving it's not hard to see where the edge of the collimator is. One can move the edge of this collimator past the profile on the right and that profile will get smaller. The xf108 current will usually go down during this but the Booster intensity will stay the same.

On May 29th this was done, the profile got smaller and the xf108 current went down by about 10%, while the Booster intensity was unaffected. However, on Apr 3rd moving the collimator did not have an appreciable effect on the xf108 current. On Apr 3rd the main peak was about 3 mm further to the right than on May 29th, so maybe the smaller peak was further to the right as well and so was being collimated out with the nominal setting of 575000. Figure 12 shows the profile display with and without the smaller profile collimated out.

On Jun 23rd of Run 16 injection efficiency measurements were also made with and without the collimator moved in past that peak (also shown in Figure 12). With it inserted the injection efficiency was about 9% higher (93 vs. 85%) and the injected intensity was not noticeably different.⁶⁴ So, at that time about 9% of the xf108 current with the collimator retracted was from the smaller peak.

Note also that the May 29th main profile does not look as narrow as it did in the 2016 data. The profiles from Apr 3rd are more like those from 2016.⁶⁵ The effect of the collimator was

⁶³ Increasing arc146 moves the beam to the left on MW096. If the smaller profile were Au31+ with the same energy as Au32+, a +3.2% change in arc146 would be required to move it to the same position as the Au32+ profile. But a change of only +0.92% is needed to move a profile +12mm. So, the smaller peak is not Au31+ with the same energy as Au32+. See [NSRL 2018 Sep 20 elog](#) 1355 entries.

⁶⁴ See [Booster-AGS-EBIS 2016 elog](#) Jun 23rd 1619 to 1642 entries.

⁶⁵ See [Booster-AGS-EBIS 2018 elog](#) Apr 3rd 1317 entry

also checked on Jun 6, 2018. At that time Booster input was about 6% lower with it inserted and the main profile was more like the one from Apr 3rd as well.⁶⁶

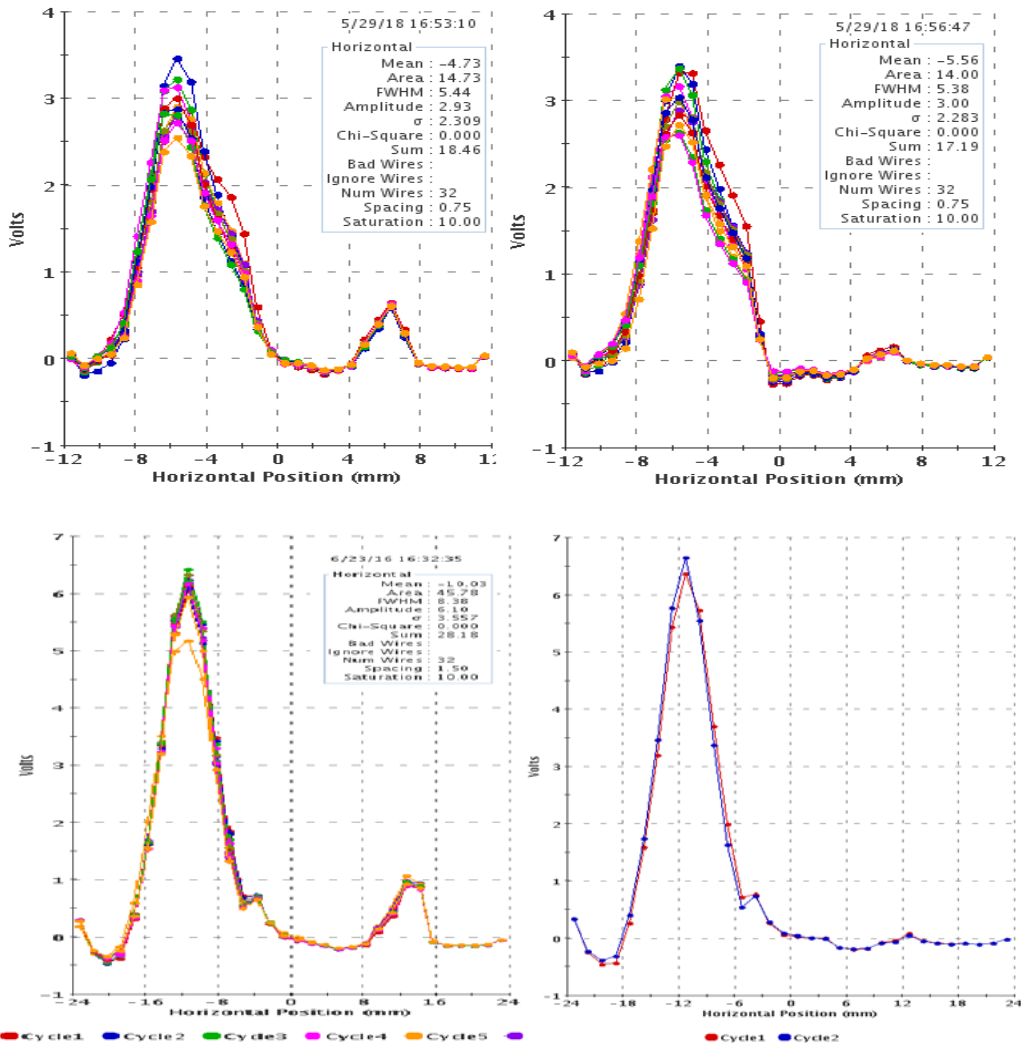


Figure 12: The EtB MW096 horizontal profile displays from May 29th, 2018 with (top, right) and without (top, left) the collimator inserted and Jun 23, 2016 with (bottom, right) and without (bottom, left) it inserted. Note that the wire spacing the program uses seems to have changed from 1.5 to 0.75 mm since 2016 but that actual spacing has not changed.

The EtB xf108 Calibration

The xf108 calibration used for the Run 16 and 18 data was 2.083 mA/V.⁶⁷ But it was noticed that if one measures the height of the calibrate pulse at different current settings one

⁶⁶ See [Booster-AGS-EBIS_2018 elog](#) Jun 6th 1643 entry. In Figure 12, at least from the profile shown, one could argue that the collimator was intercepting some of the main profile in the May 29 case. The main profile from June 6th in the collimator inserted case looks OK.

⁶⁷ This corresponds to a ETB xf108 calibration constant of 5.257e9 which is set on the pet page EBIS/Instrumentation/Transformers/EtBGpmConstants.

arrives at different calibrations. There was a trend however, the smaller the size of the calibrate pulse the more current per volt. So, the setpoint of the calibrate pulse was varied and for several different settings the xf089 and xf108 voltages were measured (xf089 is another EtB transformer located at 89 feet in the EtB line).⁶⁸

Linear fits of the setpoint vs. voltage as measured on a scope were made for both xf089 and xf108 in low gain, which is the gain typically used (see Figure 13). The fits for the 2 transformers are nearly identical, and for xf108 the slope is 2.102 mA/V and the y-intercept is 84 μ A. Of course, a fit to the data will never give a y-intercept of exactly zero, but this non-zero y-intercept is not a noise or signal strength issue. On both xf089 and xf108, setpoints below 80-90 μ A give no voltage on the transformer signal. The non-zero y-intercept causes the (apparent) calibration to be a function of the calibrate pulse setpoint.

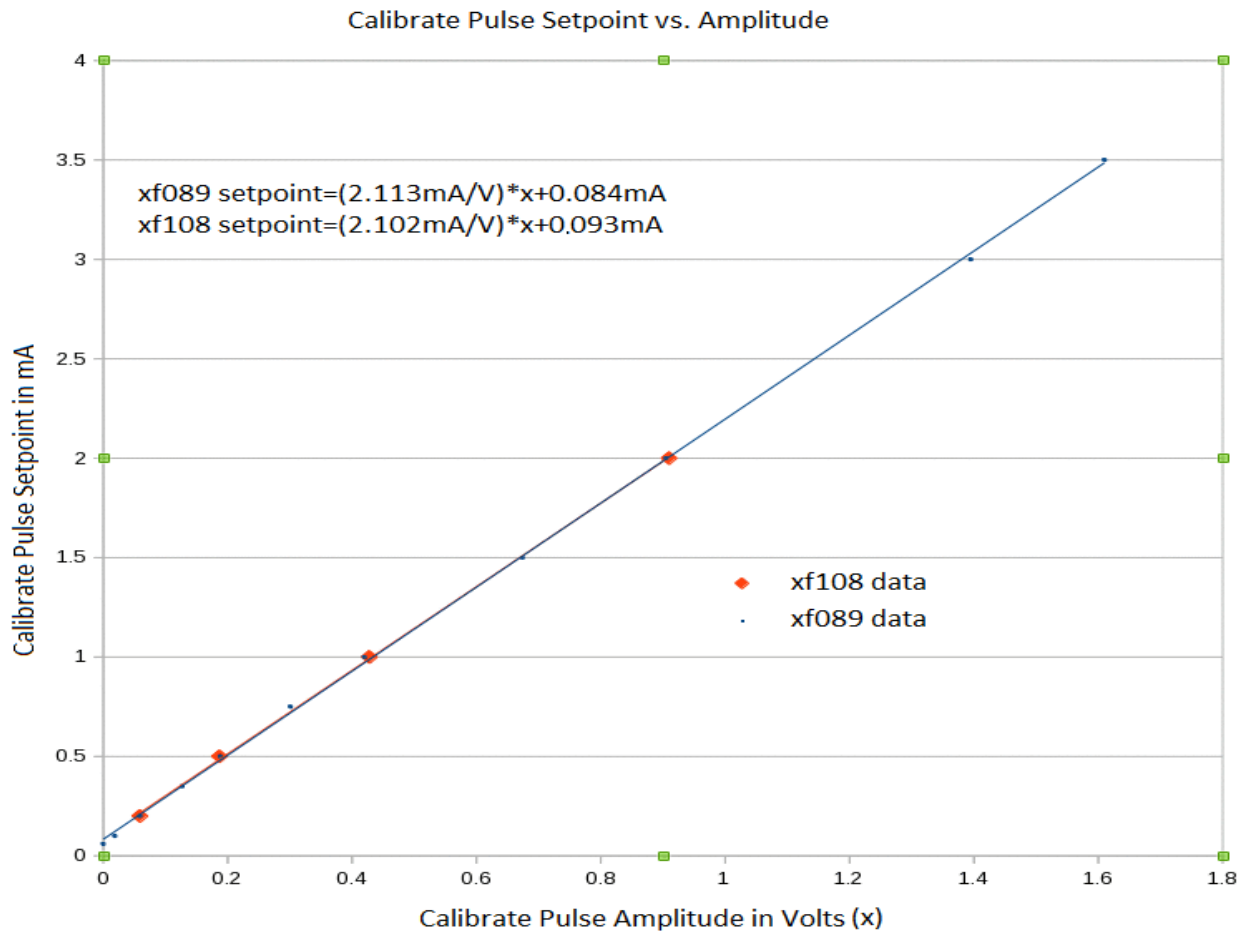


Figure 13: Calibrate pulse setpoint vs. amplitude measured on a scope for xf089 and xf108 in low gain.

⁶⁸ See [Booster-AGS-EBIS 2018 elog](#) Mar 29 1850 entry

One question is whether the non-zero y-intercept is caused by a problem with the calibrate pulse or the transformer(s). The fact that the linear fits to the data are good indicates that the output of the calibrate pulse is linear. If the current in the calibrate pulse is always 84 μA less than requested, the slope of the linear fit will give the correct calibration. An offset is not unprecedented, in Run 12 there was a 0.33 mA offset in the output of the calibrate pulse so that, for example, a 1 mA setting produced a 0.67 mA calibrate pulse.⁶⁹

On the other hand, although it seems quite unlikely, if the transformer had a 84 μA offset so that the actual current was 84 μA greater than what's measured, the actual intensity, assuming a 40 μs long pulse would be $(84\mu\text{A} * 40\mu\text{s} * 6.24e18 \text{ charges/coul}) / 32 = 6.6e8 \text{ Au}^{32+}$ ions higher than if it did not. So, considering that a typical EBIS pulse is about $1e9 \text{ Au}^{32+}$ ions, the actual xf108 intensity would be about 70% higher than what's measured.

It seems most likely that an offset in the calibrate pulse current is responsible for this behavior. The calibration arrived at using the slope is only slightly different than what was used to find Booster Input in the measurements above, 2.102 vs 2.083 mA/V. All the other beam current transformers in the preinjectors and injectors have at most 2 or 3 possible calibrate pulse settings, whereas the setpoints of the calibrate pulse for EtB transformers can be set arbitrarily over a large range.

The Noise on the xf108 Signal

The noise level on the integrated xf108 signal available through the controls system is significant. For one Au pulse the noise causes the integrated value to vary by about $\pm 15\text{-}20\%$. When there are 12 EBIS pulses per supercycle the noise level on the sum of the integrated values for those pulses is probably less than $\pm 5\%$ and a 10 cycle running average can be used to bring it down to a level comparable to that on the Booster Late scaler.⁷⁰ Still though, the correct value for Booster input on any one supercycle has a plus or minus several percent uncertainty if the scaler is used. A much less noisy measurement can be made using a scope by taking the average of the integral of the xf108 signal for the 12 pulses within a supercycle and multiplying it by 12.

Booster Efficiency and the H- Foil

The H- stripping foil is often left inserted so that NSRL can run protons from LINAC. While this has nothing to do with xf108, the Booster Late intensity is typically about 5% higher when it's retracted.⁷¹ An orbit bump is put in to keep the Au beam away from it, but even when a lot of effort is put into accounting for it, there is usually still some effect. This is nothing new and so was also true in Run 16, but in neither the optimal case this year or the one in 2016 was it inserted.

⁶⁹ See M. Wilinski, [Booster-AGS-EBIS 2012 elog](#) Feb 15 1203 entry

⁷⁰ See [Booster-AGS-EBIS 2018 elog Aug 13](#) 1323 and 1327 entries

⁷¹ See [Booster-AGS-EBIS 2018 elog](#) May 29 1712 entry

The xf108 Baseline

It is not unusual for the xf108 baseline to vary on the time scale of days by an amount corresponding to as much as $\pm 1e9$ ions. To determine the actual input from the scaler reading that reading must be adjusted to reflect these changes in baseline. Inspection of the LogView scaler data can give an idea of what the baseline offset was during these optimal cases because if there are 12 beam requests but EBIS is off or an EtB faraday cup is inserted the scaler will still read and that value reflects the baseline counts (which unlike the other scalers can be either negative or positive).

There doesn't appear to be a reasonable set of data logged in this state near the times in 2016 and 2018 in question. The closest data of this kind (about a day away for the 2018 measurements and 2 days away in for those in 2016) indicate for both cases that the baseline was about $+5e8$ ions, but if the input is adjusted for this then (Booster Late)/(Booster input) becomes unrealistically high ($>90\%$), at least if it has also been adjusted to compensate for the extra profile.

There is some data from Jun 6th this run with the collimator in, the foil out and baseline offset recently zeroed, albeit not at the highest intensity.⁷² However, the Booster has not given any indication of intensity dependence with EBIS Au so I would expect this data to reflect efficiencies at higher intensities as well. There are 42 supercycles worth of beam data: the average Booster input⁷³ was $11.32e9$ ($\sigma=0.36e9$) and the average Booster Late was $9.50e9$ ($\sigma=0.22e9$). Using these values, the efficiency (Booster Late)/(Booster Input) is 83.9% .⁷⁴

Note that the σ for Booster Late is smaller than it is for Booster input even when 'normalized' for intensity, 0.31 vs. $0.22e9$. This is likely due to the noise in the input measurement. There is Booster input baseline data in LogView from just before the baseline was zeroed and which is about 10 minutes before the data with beam. There are 17 data points and each is the sum of 12 EBIS requests (without beam). Their average value is $+4.76e8$ with a σ of $2.4e8$, note that this σ is three quarters of what it was when there was beam.

Since the baseline drifts, one wonders if its average value could have even changed between when the baseline was zeroed and when the measurements with beam were taken. To see if it might have, the 17 baseline data points were divided into 2 groups, the first 8 and last 8. The average value of the first 8 was $3.95e8$ and that of the last 8 was $5.50e8$, a difference of $1.55e8$. On the other hand, if I take every other data point, put those into one group and put the

⁷² The baseline data is from the MCR/InjectorPerformance.logreq Logview file for Jun 6 1648:45 to 1650:38 (see [here](#)). The etb-fc96 faraday cup was inserted at the time. The beam data is from the same Logview file for Jun 6, from 1657:03 to 1701:44 (see [here](#)). The baseline was zeroed at 16:54 and the foil was commanded out at 16:56:57.

⁷³ The average Booster input from the scaler was $11.22e9$, I multiplied that by $2.102/2.083$ to get $11.32e9$.

⁷⁴ A Booster efficiency measurement made using a scope on Jun 23 2016 with the collimator in and foil out was 83.2% (xf108:1.129e9 and Booster Late:0.939e9). See [Booster-AGS-EBIS Jun 23 2016 elog](#) 1820 and 1821 entries.

remainder into another group and then calculate the average of each group I get $4.83e8$ and $4.68e8$, respectively. The difference, $0.15e8$, is only a tenth of what it was using the other method, which strongly suggests that a drift is occurring even over this short interval. So, although perhaps conservative, let's say the average baseline during the beam measurements could have been as much as $1.55e8$ or $\pm 0.77e8$ different from what it was when the baseline was zeroed 5 minutes earlier.⁷⁵ This would correspond to an uncertainty in the efficiency of $\pm 0.77e8/11.32e9$ or about $\pm 0.7\%$.

Uncertainty in Booster Late

There are also sources of error for Booster Late. Even if it is calibrated as well as it can be (which it usually is), there is still a granularity issue. That is, the scaler gain was set to 72, so if the correct gain setting was 71.5 or 72.5 (which it can't be set to), the uncertainty in Booster Late would be $\pm 0.7\%$. Adding both the xf108 baseline and Booster Late uncertainties together gives an efficiency of $83.9 \pm 1.4\%$. It should also be noted that there is sometimes a small loss between where the current transformer is sampled for Booster Late (Bt0+125 ms) and when extraction occurs 5 ms later (the sample time was the same in both Run 16 and 18). A Booster efficiency measurement made on May 29th using a scope with the collimator in and foil out for one Booster cycle was $7.36e8/8.81e8=83.5\%$.⁷⁶

Inferring Booster Input from Booster Efficiency Measurements

If one assumes that the Booster efficiency was $83.9 \pm 1.4\%$ for both the Run 16 and 18 highest bunch intensity cases one can work backwards and estimate Booster Input.⁷⁷ For the Run 16 case it would be $12.61/(0.839 \pm 0.014) = 15.03 \pm 0.25e9$ and in Run 18 it would be $12.13/(0.839 \pm 0.014) = 14.46 \pm 0.24e9$ and so the Booster input would be $3.9 \pm 3.5\%$ higher for the Run 16 data. The values that were initially used for Booster Input for Runs 16 and 18 were 15.13 and $14.13e9$, respectively, which would indicate the input was 7.1% higher in Run 16. However, I tend to think the ratio of the inputs inferred from the Booster efficiency and Booster Late have a smaller uncertainty given the uncertainties in the baseline offsets ($\pm 1e9$ or $\pm 6.6\%$) and in the contributions from the smaller profile.⁷⁸

⁷⁵ What it means to zero the baseline is not so clear if the baseline offset is drifting while one is trying to zero it, but I'll neglect this here.

⁷⁶ See Booster-AGS-EBIS May 29 2018 elog [2001 entry](#). I adjusted the input value slightly by using a calibration of 2.102mA/V instead of 2.11mA/V .

⁷⁷ Note that I've resorted to this before to determine the Booster Input intensity, see K. Zeno, "[Overview and analysis of the 2016 Gold Run in the Booster and AGS](#)" C-A/AP/571, September 2016 bottom of page 11 and footnote 32.

⁷⁸ The presence of the smaller profile can only increase the measured input. However, although unlikely, the ratio of the measured inputs in runs 16 and 18 could differ by as much as $\pm 10\%$. Yet, it's likely that the contributions are not zero but are similar in both sets of data in which case the ratio would not be affected much.

Booster Late to AGS Bunch Intensity Efficiency

So, working backwards from Booster Late it appears that the Booster Input was perhaps 4% higher during optimal running in 2016 than during that in this run. If the input were the same this run as in the Run 16 case one would expect the highest AGS bunch intensity to be 2.86e9 instead of 2.75e9. This is still lower than what was observed in Run 16 (3.15e9) and for the lower input to account for all the difference it would need to have been 14.5% higher than it was.

The ratio (AGS flattop bunch intensity)/(Booster Late) was about 3% higher during the best running conditions of Run 16 than it was this run. In fact, though during much of Run 16 this efficiency was more like it was this run (46%), on Apr 12th it increased to about 49-50%.⁷⁹ Comparing this ratio in the Run 16 case to the case this run is more reliable than comparing the Booster input intensities. This improvement caused the average flattop bunch intensity to increase from about 2.70 to 2.83e9 and was attributed, at least in part, to a decrease in the size of the baby bunches.⁸⁰ Note that if the Booster input was 4% higher this year and this ratio was 0.49 instead of 0.46 then the flattop bunch intensity would have been quite close to what was measured in 2016.

The improvement on Apr 12th, 2016 is noted in the elog after a change was made earlier that day to the Booster main magnet power supply parameters in the Booster main magnet application.⁸¹ Before that change the power supply had developed a problem and the current was not stable. However, that change was still in place during run 18. The problem that prompted the change was not noticed this run, and in Run 16 it was hard not to notice. However, the Booster main magnet could have been more stable this run (as it always could be with setups that involve a merge), and perhaps further adjustment of these parameters would help, but this is just speculation.

The most obvious symptom of the variation in the main magnet current this run, which may have occurred on a time scale of something less than an hour to many hours, was a recurring synchro loss which could temporarily be fixed by making small changes to the time when Rf track goes to hold at the beginning of the merge porch or by redoing the synchro table.⁸² Note however, that having to make these kinds of changes is not unusual, although it became more common after, at the power supply groups request, the points inserted on the main magnet

⁷⁹ See Figure 14 and discussion on pgs. 20-22 in K. Zeno, [“Overview and analysis of the 2016 Gold Run in the Booster and AGS”](#) C-A/AP/571, September 2016.

⁸⁰ See top of pg. 21 in K. Zeno, [“Overview and analysis of the 2016 Gold Run in the Booster and AGS”](#) C-A/AP/571, September 2016.

⁸¹ See [Booster-AGS-EBIS 2016 elog, Apr 12](#) 1405 and 2015 entries. The parameter MaxIIABNeg was changed from -950 to -900 V and MaxIABNeg was changed from -800 to -850 V.

⁸² The parameter that was changed is on the [Booster/Rf/914-rfll1/Timing/delayV202Dsp](#) pet page and is called “Hold RF Track”.

function to flatten the merge porch were removed. They were removed on Mar 15th, 2016 after a major main magnet power supply failure.⁸³

During the 2018 run there were many problems with the L20 septum, and the A5 kicker had stability problems as well, but these issues probably did not contribute to the lower efficiency in the Jun 13th measurements.⁸⁴ The baby bunch percentage seems to have been about the same in both the 2016 and 2018 optimized cases.

Au Emittance

Au Transverse Emittance

The 95% normalized transverse emittances at BtA MW006, which is before the stripping foil, can be obtained in the same way they were for Ru and Zr, again using $\beta_x=3.0$ m and $\beta_y=16.0$ m at the multiwire and a Booster extraction $\beta\gamma$ of 0.495. The equation relating ϵ_x to x , where x is the FWHM of the Gaussian fit is then $\epsilon_x=0.179x^2$ and similarly $\epsilon_y=0.0333y^2$. Profiles from May 14th are shown in Figure 14. The horizontal FWHM is 3.50 mm which corresponds to 2.19π mm mrad and the vertical FWHM is 12.22 mm which corresponds to 4.97π mm mrad.

Similar measurements from Run 16 give $(x, y) = (3.24, 11.47)$ mm and $(\epsilon_x, \epsilon_y) = (1.87, 4.38) \pi$ mm mrad. The quantity $(\epsilon_x^2 + \epsilon_y^2)^{1/2}$, which is indicative of the total transverse ϵ , was 14% larger this year, and that difference could also be a factor in why the (AGS bunch intensity)/(Booster Late) was higher in Run 16.⁸⁵ It's not clear why it was larger, perhaps the tune paths through the Booster were not optimized as well as in Run 16.

The EBIS Au Booster injection setup is like that for Zr, it uses multi-turn injection in the horizontal plane without (intentional) coupling between planes. Therefore, as in that case one expects that ϵ_x would be larger than ϵ_y after the injection process, and like Zr the opposite is observed at MW006. The reason for this is the same as in the Zr case, the tunes cross just before extraction time which has the effect of flipping the ϵ_x and ϵ_y so that at extraction ϵ_y is larger than ϵ_x . This was done intentionally to reduce ϵ_x at extraction in the 12-6-2 setup since quad pumping is used at extraction. As with Ru and Zr, the Au beam passes through a stripping foil so one expects the emittances in the AGS to be larger than what's observed here.

The transverse emittances in the AGS were measured with the IPM.⁸⁶ ϵ_x and ϵ_y on the injection porch (~2400 ms) were about 7.8 and 7.2 π mm mrad, respectively. On the flattop, with the Rf off, ϵ_x and ϵ_y were both about 8.4 π mm mrad. These measurements were taken with

⁸³ See [Booster-AGS-EBIS 2016 elog Mar 15th](#) 1432 entry.

⁸⁴ The A5 kicker had been fixed by then and the L20 septum was in 'the good state'.

⁸⁵ See [Booster-AGS-EBIS 2016 elog](#) May 19th 1328 entry.

⁸⁶ See [Booster-AGS-EBIS 2018 elog](#) Apr 20 1450 and 1452 entries. These are the emittances when the Refit option is used.

an AGS late of about $2.5e9$ with 6 transfers so the bunch intensity was probably in the $2.3-2.4e9$ range. In Run 16 the IPM injection porch and flattop emittances were about $(\epsilon_x, \epsilon_y) = (6.5, 6.5)$ and $(9.5, 9.5) \pi \text{ mm mrad}$, respectively (the bunch intensity at that time was about $2.8e9$).⁸⁷

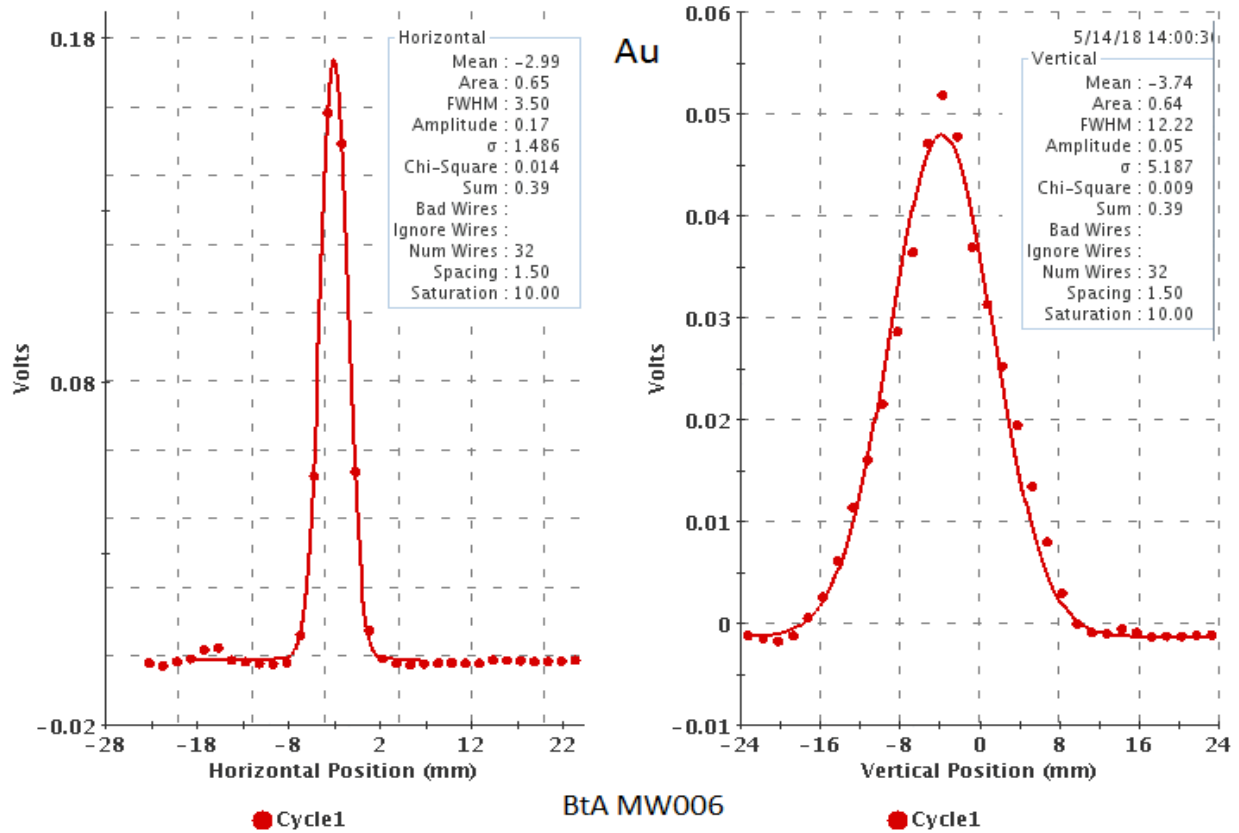


Figure 14: BtA MW006 profiles for EBIS Au together with Gaussian fits from May 14th 2018.

Au Longitudinal Emittance

Four measurements of ϵ_l on the flattop were done from mid-April until the end of the run with the full squeeze on. The average of those was 0.802 eV-s/n and they had a σ of 0.018 eV-s/n .⁸⁸ The average of 6 flattop measurements taken during Run 16 was $0.75 \pm 0.037 \text{ eV-s/n}$.⁸⁹ On May 15th the flattop ϵ_l was measured with the full squeeze and with no KL squeeze. With the full squeeze it was 0.83 eV-s/n and without the KL squeeze it was 0.68 eV-s/n .

The AGS longitudinal emittances are calculated using the Bbat program. On June 13th, I turned off the γ_τ jump and timed in the transition phase jump to minimize beam loss and

⁸⁷ See [Booster-AGS-EBIS 2016 elog April 7th](#) 1552 entry

⁸⁸ See [Booster-AGS-EBIS 2018 elog](#) Apr 19th, May 15th, Jun 6th and Jun 15th.

⁸⁹ See pg. 35 in K. Zeno, ["Overview and analysis of the 2016 Gold Run in the Booster and AGS"](#) C-A/AP/571, September 2016.

quadrupole oscillations when it occurs.⁹⁰ At the time, the revolution frequency (f_{rev}) at 3558.13 ms, when the phase jump occurs, was 368811 Hz (“*Frev_System*” reported from the Rf system). The frequency of the WCM signal was also measured on a scope. The average of 4 AGS cycles was 368808.665 with a σ of 5.268 Hz.⁹¹

According to Bbat, f_{rev} from *Frev_System* corresponds to $\gamma=8.428$. By trying to calculate the emittance at different values of γ using Bbat it’s easy to see that the program uses a value of 8.500 for γ_t . If I calculate γ using $v=2\pi r f_{rev}$, I need to set r to 128.45714 m to get γ to equal 8.428 for $f_{rev}=368811$ Hz. Note that this value of γ equals γ_t only if $r=R_o$ where R_o is the design or central radius.⁹² Regardless, this is the AGS radius Bbat uses, and it corresponds to a circumference (C) of 807.12 m

Emittance calculations can also be performed using bbrat, and this program allows C and γ_t to be changed. If I use $C=807.12$ and $\gamma_t=8.500$ I get the same emittance values that I do using Bbat. C. Gardner’s notes on RHIC Run parameters use $R_o=128.4526$ m ($C=807.092$ m), and if I use that value of R_o for r and $f_{rev}=368811$ Hz in $v=2\pi r f_{rev}$ I get that γ_t is 8.407.⁹³ If I use f_{rev} measured on a scope from the WCM I get that $\gamma_t=8.404\pm 0.01$, in good agreement. Using Bbat, the flattop emittance calculated with a synchrotron frequency of 97.2 Hz and bunch length of 28.5 ns results in an ϵ_l of 0.782 eV-s/n, whereas if $\gamma_t=8.407$ and a radius of 128.4526 m are used in bbrat the result is 0.742 eV-s/n, which is 5.1% less.⁹⁴

This difference in the value for γ_t has a significant effect on the calculated flattop emittance because of Au77+’s relatively low charge to mass ratio, which causes transition to happen at a γ not that far from the extraction γ , which is about 10.5. As a further complication, the extraction radius is about 5 mm to the outside, and it turns out that this C (807.125m) is very close to what Bbat uses. However, calculating ϵ_l at extraction energy using bbrat with this C changes ϵ_l slightly but not enough to change the quoted result at all.

When I set the phase jump (again with no γ_t jump) to happen at the Rf frequency that $\gamma=8.500$ corresponds to using Bbat then it occurs at 3564.8 ms and there was considerable beam loss and very large quadruple oscillations after the phase jump. With that setting the peak in the

⁹⁰ See [Booster-AGS-EBIS 2018](#) elog June 13th 1706 to 1717 entries.

⁹¹ See [Booster-AGS-EBIS 2018](#) elog June 13th 1823 entry.

⁹² Note that according to AGSOrbitDisplay the radius around transition was about +5 mm (at least on Jun 5th with the γ_t jump on), but at transition f_{rev} is not a function of changes in γ so even if the beam’s radius was to the outside, f_{rev} would be the same as if it were at R_o and γ_t must be the value of γ at R_o at some fixed B field or else γ_t would not be well-defined.

⁹³ See C.J. Gardner, “[FY2016-17 Parameters for Gold Ions in Booster, AGS, and RHIC](#)”, May 23, 2017, Equation (34) on pg. 5.

⁹⁴ See [Booster-AGS-EBIS 2018](#) elog Jun 15th 1615 entry. Note however in the elog I’m using a γ_t of 8.428 and $C=807.12$ m which gives 0.745 eV-s/n. When $C=807.092$ m is used together with $\gamma_t=8.407$ then the calculated ϵ_l is 0.742 eV-s/n.

WCM envelope occurs about 6 ms before the phase jump.⁹⁵ Note that the correct time for minimizing quadrupole oscillations was 6.7 ms earlier, quite close to the 6 ms earlier observed for the peak in the envelope, which I would expect to happen near γ_t .

So, the average flattop ϵ_1 of 0.802 eV-s/n mentioned above becomes 0.761 eV-s/n when $\gamma_t=8.407$ is used. One implication of this is that the ϵ_1 growth during the ramp is about 5% less than thought (previously the growth calculated from bunch length and synchrotron frequency was around 45%). Also, the calculated ϵ_1 up the ramp will be somewhat different especially near transition. For example, the calculated ϵ_1 after transition but before the flattop has often been significantly higher than on the flattop. In one case 0.91 eV-s/n was measured at 3620 ms and 0.80 eV-s/n was measured on the flattop, which starts around 3715 ms.⁹⁶

Has γ_t Changed over the Past Few Years?

γ_t does not generally remain constant through the cycle, for example, it depends on the quadrupole and sextupole strengths which vary and probably also whether the extraction bumps are on or off. It is however possible to check what the AGS model calculates near transition (say 3500 ms, just before the γ_t jump comes on) and where the flattop emittance is measured (3900 ms). AGSModelViewer was used with setpoint data from the Jun 13th 1711 snapramp to calculate this. At 3500 ms the model indicates that γ_t was 8.496 and at 3900 ms it indicates $\gamma_t=8.485$. These values differ substantially from what was measured, 8.407, but do not differ much from each other. So, there is little indication from the model that γ_t differs by much between transition time and when the flattop measurements are taken. Why the model differs so much from the measured value is another question.

One wonders if this discrepancy is in any way related to the different behavior of the vertical chromaticity during the last polarized proton run, and if it were related I would expect transition timing to have changed.⁹⁷ Logged Rf data from polarized proton Runs 15 and 17 in cases where the γ_t jump is off and optimized for that state could possibly be used to determine what γ_t was then.

As far as logged data goes, the time that the phase jump occurs can be seen on the *b2bphaseIn* signal which has 10 kHz sampling. However, the logged data (from June 13th) shows that the time that it occurs varies by as much as ± 1 ms from cycle to cycle. The time it occurs at can also be seen on the *Frev_system* logged data, at least when the γ_t jump is on, because there is a spike at the time of the phase jump, and it varies by as much as ± 1.5 ms. The B field reported

⁹⁵ See [Booster-AGS-EBIS June 15th 2018 elog](#) 1704 to 1715 entries

⁹⁶ See Table V on pg. 32 of K. Zeno, "[Overview and analysis of the 2016 Gold Run in the Booster and AGS](#)" C-A/AP/571, September 2016.

⁹⁷ See pgs. 4 to 13 in K. Zeno, "[An overview of the Booster and AGS polarized proton operations during Run 17](#)", C-A/AP/694, October 2017.

in the logged data varies by as much as ± 25 g at the time of the phase jump. These variations are too large to reflect what is actually happening, so the logged data does not appear to be very useful for finding statistics or to see if there has been any significant variation in γ_t over the past runs. Although the jitter on *Frev_system* was not looked at in a lot of detail when the measurements were taken in June using a GPM monitor nothing near this amount of variation was apparent. So, especially since f_{rev} was also measured using the WCM on a scope and it agreed well with it, those measurements are probably valid.

On Jun 13th the AC phase loop was set to turn on at 2402 ms. Looking at the *b2bphaseIn* logged data, the time of the initial response to the phase loop coming on varies from 2401.3 to 2403.6 ms over 15 consecutive cycles, or about ± 1 ms (roughly the same amount that the transition phase jump appears to vary). This is another indication of a problem with how the logged data is aligned to At0 because the actual variation in the time it comes on is probably considerably less than the rate at which this signal is sampled (0.1 ms) as it is a real time event.

Although the logged data is hard to decipher, I can compare the stop fields for the γ_t jump power supplies over past runs.⁹⁸ Although γ_t without the jump cannot be found from these settings, one would expect this field to change if γ_t without the jump changed. Table 4 shows typical γ_t stop times for Runs 14 through 18.⁹⁹ In runs 14 and 15 the γ_t jump stop field is higher by 100 g (2000 gauss clock counts, gcc) than it is in the following years. Near transition energy, this change in field corresponds to a reduction in γ of about 0.11. Considering protons, the γ_t stop field is 27.5 g (550 gcc) higher in runs 14 to 16 than it is in the later runs. This corresponds to a reduction in γ of about 0.075.

Run	γ_t jump stop for Au	γ_t jump stop for PP
14	168356	64200
15	168356	64200
16	166356	64200
17	166356	63650
18	166356	N/A

Table 4: Typical Au and polarized proton settings for γ_t stop (*ags.gam_tr_stop.gt*) in gauss clock counts for runs 14 through 18.

During both polarized proton Run 15 and 17 there was a case where the γ_t jump was off and transition was optimized for that state.¹⁰⁰ As is normally the case, the transition phase jump

⁹⁸ This gauss timeline event, *ags.gam_tr_stop.gt*, is used to trigger the discharge of the γ_t jump quads which happens immediately after this event occurs. A possible issue with this data is that the snakes were not on in 2017.

⁹⁹ For Au I'm using the values in archives from April 18th 2014 (user 1), Jun 15 2015 (user 3), May 15 2016 (user 5), Jun 15 2017 (user 1), and Jun 1st 2018 (user 3). and for protons I'm using the values in archives from May 21, 2014 (user 4), May 30 2015 (user 4), Apr 28 2016 (user 4), and May 8 2017 (user 4).

¹⁰⁰ See [Booster AGS PP 2015 elog](#) Apr 20th 1847 entry and also Apr 7th 1615 entry for the 2015 data. Note that in the Apr 7th entry *transition.gt* has been adjusted to 48260 with the jump off and this value is used on Apr 20th (Logview data from Apr 7th is not available). See [Booster-AGS-PP 2017](#) elog Feb 15 1918 entry for the Run 17 data.

occurs 28.1 ms after the transition.gt gauss event. In Run 15 that event was set to 48260 gcc and in the Run 17 case it was set to 47710 gcc. The difference is 27.5 g, the same difference found from the data with the γ_t jump on. Now, dB/dt is not constant during this part of the cycle, but it is nearly constant, and so the change in field at the phase jump should be about the same. That change, 27.5g, corresponds to a change in γ_t of about 0.075, the same as the amount of change in γ associated with the change in γ_t jump stop between Runs 16 and 17.

Despite the problems with the logged Rf data, I think I can find a somewhat believable value for f_{rev} in the 2017 case using the “*frevFBHzArrayMvalue*” data logged in *agsDspAll.logreq* and from that γ_t . From the *b2bphaseIn* data (also in that log), which has 10 kHz sampling, the time (in the logged data) that the phase jump begins varies from 311.4 to 312.9 ms (see Figure 15). In the f_{rev} data, there is a spike which must have to do with the phase jump. Looking at 18 sets of data the spikes are clustered around 2 times about 1 ms apart, 312.6 ± 0.2 and 313.8 ± 0.15 ms (1 kHz sampling).

The data clustered around 313.8 ms has an $f_{rev}(t)$ which is about 50 Hz lower for any given time during this part of the cycle. As can be seen from the figure, if that data is shifted 1 ms earlier it will overlay with the other data set reasonably well, so it looks like the data may have some kind of 1 ms jitter and perhaps one of those data sets is closer to correct. The *b2bphaseIn* data, which seems to jitter by about the same amount but is not clustered around 2 times, suggests that the data set with the spikes around 312.6 ms is more valid since those spikes are more consistent with a phase shift around 312.15 ms (the middle of the time range that the shifts in *b2bphaseIn* occur). I can interpolate that f_{rev} data using the points before and after the spike to get f_{rev} at 312.15 ms from which I can find γ_t . Doing this I find $f_{rev} = 368807 \pm 10$ Hz and from that $\gamma_t = 8.401 \pm 0.016$ which is close to the value found with Au in Run 18.¹⁰¹

The spikes in the data from 2015 are not so obvious and so I can't get an f_{rev} from that data, but I already know that the change in field between Run 15 and 17 is about 27.5 g, which corresponds to a $\Delta\gamma$ of about 0.075 and if I add that to 8.401 I get 8.476 for γ_t in 2015.¹⁰²

¹⁰¹ The uncertainty only reflects the spread in frequency at 312.15 ms, not the variation in the phase jump time that *b2bphaseIn* indicates. Note that if I used the other set of f_{rev} data (and the same jump time) I would get a value for γ_t that's even lower.

¹⁰² When I looked more closely I found that the time that the phase jump occurs on the *b2bphaseIn* data is gradually decreasing over these 18 cycles from 312.43 ms on the first to 311.51 ms on the last. From experience at looking at variations in the B(t) using the gauss time line this amount of variation is probably not real (if it were not only would getting through transition not work well, but the polarized proton tune jumps probably would not be effective either). Actual variations on the scale of 100 μ s or so are perhaps typical. So, the situation is more complicated than just a 1 ms jitter on the f_{rev} data as there is also some kind of drift. Regardless, for each of the 18 cycles I measured f_{rev} at 50 μ s after the data point before the phase shift occurs (half the sampling rate). However, in the cases where that time was greater than 312.16 ms I found that the f_{rev} data was part of the set with the later spike and if it was earlier than that it was part of the set with the earlier spike. So, I added an additional 1 ms to the time I measured f_{rev} when the measured time of the phase jump was greater than 312.16 ms. I got an average value for f_{rev} of 368804 Hz with a σ of 18 Hz. This is quite close to the value obtained above (368807 Hz).

Considering all this, there seem to be some indications, for both Au and protons, that γ_t is lower now than it was in the past. One thing that doesn't make much sense though is that it seems to have changed for Au in Run 16 and didn't change for protons until Run 17.

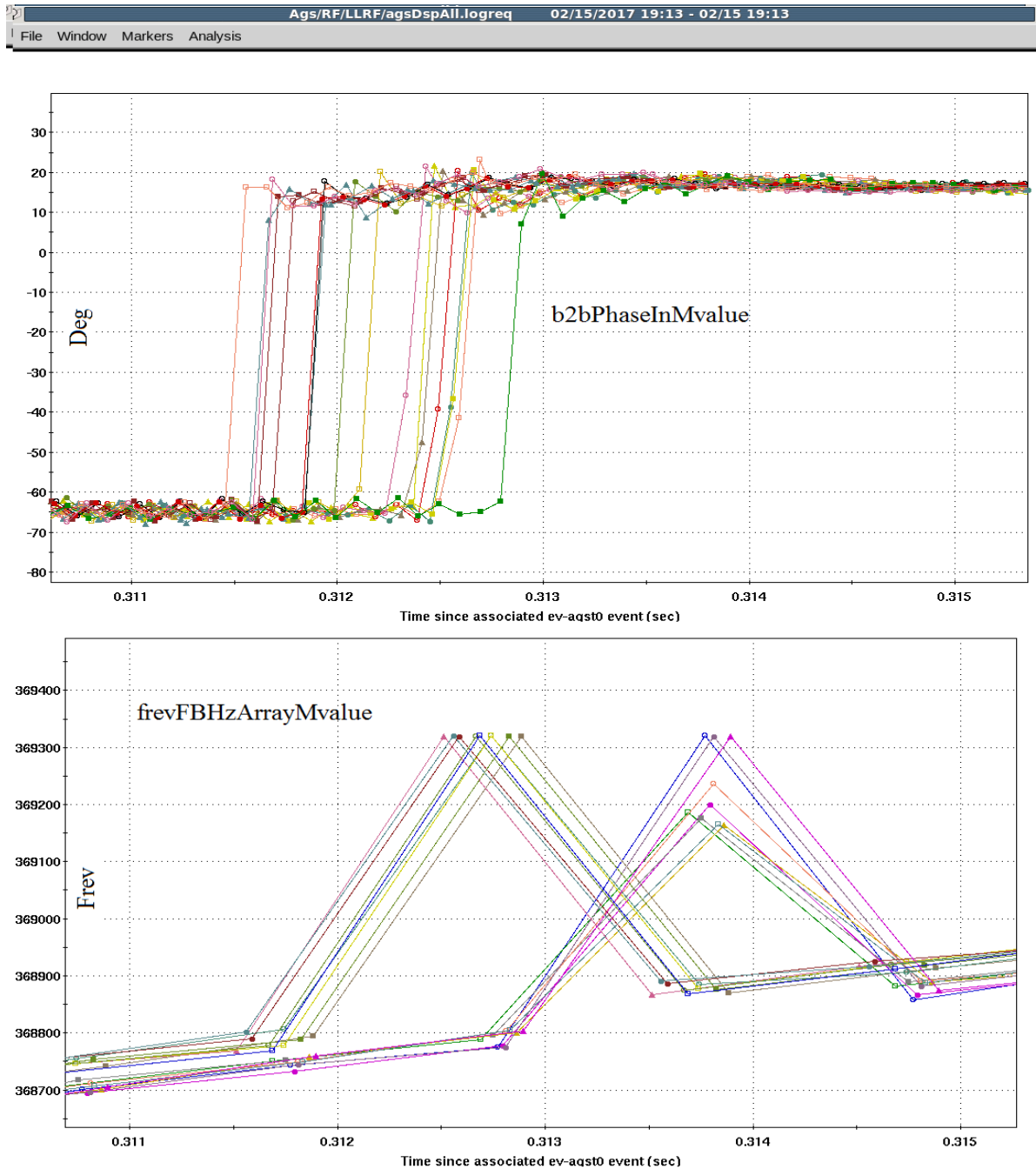


Figure 15: 18 cycles of data from the Ags/RF/LLRF/agsDspAll.logreq log for *b2bphaseInMvalue* (in deg) and *frevFBHzArrayMvalue* (in Hz) for Feb. 15, 2017 between 1917 and 1921 when the γ_t jump was off and arf.transition.gt was set to 47710.

Summary

This note is divided into 3 sections which cover Zr, Ru, and Au performance in the injectors independently of each other even though they ran concurrently. Much of it attempts to document and elaborate on various measurements in the elog and it provides links to the relevant elog entries.

Zirconium

^{96}Zr is notable in that the target material used as its source is composed of several isotopes of Zr, and one of them ($^{90}\text{Zr}^{15+}$) has the same magnetic rigidity at Booster injection and charge to mass ratio as $^{96}\text{Zr}^{16+}$ (the desired species). As a result, the beam in the Booster is a combination of both and they are not resolved from each other until they pass through the stripping foil in BtA. Two measurements of the relative amounts of each beam were made using the MW060 multiwire just downstream of the foil. In one case 70.2% was $^{96}\text{Zr}^{16+}$ and in the other case 73.3% was. The measurements of the composition of the EBIS target by its manufacturer indicate that 75.6% of the beam in Booster should be $^{96}\text{Zr}^{16+}$ assuming $^{90}\text{Zr}^{15+}$ and $^{96}\text{Zr}^{16+}$ perform identically from the target to Booster extraction.

The beam injected into the AGS is fully stripped, $^{96}\text{Zr}^{40+}$, and the efficiency with which the $^{96}\text{Zr}^{16+}$ was fully stripped to $^{96}\text{Zr}^{40+}$ was also measured twice using MW060. This stripping efficiency is quite good: the first result was 87% and the second was 87.8%.

Zr was initially set up with a 12-6-2 merge in the AGS, but the desired RHIC bunch intensity (about 1.0×10^9 ions) did not require the intensity provided by merging 6 bunches into 1, so in late March it was changed to 8-4-2. The peak bunch intensity measured (with the 12-6-2 merge) was 2.57×10^9 ions. Table 1 on pg.9 shows the efficiencies and intensities at different times in the injectors under optimal conditions using the 8-4-2 merge. With the 8-4-2 setup, the 95% transverse normalized emittances in BtA upstream of the stripping foil were $\epsilon_x = 1.68 \pi$ mm mrad and $\epsilon_y = 5.36 \pi$ mm mrad, the AGS flattop emittances, using the eIPM, were $\epsilon_x = 3.9$ and $\epsilon_y = 9.3 \pi$ mm mrad, and the longitudinal emittance on the AGS flattop was 0.56 ± 0.04 eV-s/n. This longitudinal emittance measurement was performed with a moderately strong bunch squeeze typical of what was used to fill RHIC.

Ruthenium

$^{96}\text{Ru}^{12+}$ was delivered to the Booster from Tandem and the setup used an 8-4-2 merge in the AGS. As with Zr, $^{96}\text{Ru}^{12+}$ is fully stripped to $^{96}\text{Ru}^{44+}$ in BtA, but the stripping efficiency was only 62.3%, substantially lower than for Zr. As with Zr, the RHIC bunch intensity requirement of about 1.0×10^9 ions was substantially less than what the injectors could provide.

Since the beam came from Tandem, the Tandem pulse width could be adjusted to change the Booster intensity. Because of the details of multi-turn injection, the transverse emittance in

the Booster gets larger when the pulse width is increased. Booster injection was optimized for high intensity and the pulse width was shortened from there to provide the desired intensity for RHIC.

Table 2 on pg.13 shows the intensities and efficiencies for optimal conditions with a 400 μ s pulse width. The pulse width used for filling RHIC depended on the Tandem current but was generally much less than that, perhaps in the 150 μ s range. The BtA transfer efficiency improves significantly when the pulse width is shortened. In the table, the transfer efficiency is quoted as 55.5%, but in one case, when transfer was not fully optimized, just reducing the pulse width from 400 to 100 μ s increased the transfer efficiency by about 23% (from 46.7 to 57.6%). The highest bunch intensity measured on the AGS flattop was 2.82e9 ions.

Normalized transverse 95% emittance measurements were made in BtA upstream of the foil using MW006 and in the AGS using the eIPM. In BtA, for a 400 μ s pulse ϵ_x was 4.50 and ϵ_y was 3.79 π mm mrad, and for a 117 ms pulse ϵ_x was 2.8 and ϵ_y was 2.4 π mm mrad. On the AGS flattop (ϵ_x, ϵ_y) was (8.7, 7.8) π mm mrad and for a 117 ms pulse (ϵ_x, ϵ_y) was (7.5, 7.2) π mm mrad.

Ru is notable because it is the first time the 4-2-1 Booster merge was used for a Tandem species. Despite the fact that the bunches on the first turn in the AGS have much more structure than the Zr or Au bunches from EBIS (see Figure 9), the total longitudinal emittance of 4 bunches on the injection porch appears to be smaller than it is for Zr or Au when all are injected into h=16 buckets, 0.32 vs. 0.366 and 0.44 eV-s/n for Zr and Au, respectively. The average of two AGS flattop measurements was 0.50 eV-s/n, as compared to 0.56 and 0.69 eV-s/n for Zr and Au respectively, all when using an 8-4-2 merge.

Gold

As in Runs 16 and 17, the 12-6-2 AGS merge setup was used to deliver beam to RHIC. The peak bunch intensity on the flattop averaged 2.75 \pm 0.04e9 (in Run 16 it averaged 3.15e9 ions). The longitudinal emittance on the flattop was 0.802 \pm 0.018 eV-s/n (in run 16 in was 0.75 \pm 0.037 eV-s/n). The normalized 95% transverse emittances as measured in BtA upstream of the foil were (ϵ_x, ϵ_y) = (2.18, 4.98) π mm mrad (in Run 16 they were (ϵ_x, ϵ_y) = (1.87, 4.38) π mm mrad). The emittances, using the IPM, on the injection porch were (ϵ_x, ϵ_y) = (7.8, 7.2) π mm mrad, and on the flattop they were (ϵ_x, ϵ_y) = (8.4, 8.4) π mm mrad.

Sources of error in the Booster input scaler value were discussed in some detail. These sources are: An extra beam in EtB that the xf108 transformer picks up, noise on the integrated xf108 signal, a drift in the xf108 signal baseline, and uncertainties in xf108's calibration. None of these error sources are new.

Three possible contributing factors to the lower bunch intensity this year compared to Run 16 were identified. It appears that during the period with the highest flattop bunch intensity Booster input was 4% lower than it was during a similar period in Run 16. But the bunch intensity in Run 16 was about 14.5% higher, so although a contributing factor, this difference is not enough to entirely account for the lower peak bunch intensity. The efficiency, $(\text{AGS bunch intensity})/(\text{Booster Late})$, was very similar in Run 16 to this run until a change to the Booster main magnet configuration was made that run around which time it increased from about 46 to 49%. Although this change was still in place this run, if that efficiency were the same this year as it was after that change in Run 16 and Booster input was 4% higher, the maximum bunch intensity this run would have been close to what it was in Run 16.

The total BtA transverse emittance measured this year was about 14% larger than that obtained from a measurement in Run 16. Although these emittances were obtained from only one set of MW006 profiles for each run, if they are representative of the each of these runs in general, that difference would also contribute to the lower $(\text{AGS bunch intensity})/(\text{Booster Late})$ efficiency this run.

The program used to calculate the longitudinal emittance, B_{bat} , uses a value for γ_t of 8.50, but a measurement of γ_t at the time of transition with the γ_t jump off was 8.407. When 8.407 is used instead of 8.50 the calculated flattop emittance is about 5% lower. So, using 8.407 for γ_t reduces the calculated emittance this year from 0.80 to 0.76 eV-s/n. As a value of 8.50 for γ_t has been used for years, the question of whether γ_t has changed was investigated. This seemed relevant because of the different vertical chromaticity behavior during the last polarized proton run. Aside from the measurement of γ_t this run, changes in the γ_t jump stop time over the past 5 runs, for Au and protons, and measurements of the B field at transition with the jump off (from proton Runs 15 and 17) were compared and both the stop time data and the transition field measurements suggest that γ_t was higher before 2016.