BNL-225440-2024-TECH

C-A/AP/706

The 2023 Gold Run in the Injectors

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March 2024

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U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP)

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3-25-2024

RHIC Run 23 used Gold beam from Tandem with an AGS extraction energy of 9.8 GeV. The same basic setup, 8 single bunch transfers from the Booster and a 12-6 merge in the AGS to provide 4 bunches at extraction, had been used before to deliver Tandem Au to RHIC. But in those cases, it was used for low energy runs (3.85 GeV in 2021 and 5.75 GeV in 2020) where extraction was below transition energy (7.9 GeV).[1]

Tandem beam was used for this run because the intensity and stability of EBIS Au did not meet the requirements for RHIC. Physics was first declared in RHIC on May 22nd and on August 1st the run was cut short by about 2 months due to a major failure in RHIC.

Prior to the advent of EBIS as the preinjector in 2012, 9.8 GeV Tandem Au was regularly delivered to RHIC but the setup in the Booster and AGS was quite different: Four Booster transfers of 6 bunches each were merged into 4 bunches using a 24-12-4 merge scheme.[2]

The supercycle length was 6.0 sec before June 29th when it was extended to 6.6 sec to accommodate EBIS commissioning. The Tandem, Booster, and AGS were on user 1 for the 9.8 GeV setup. Some work with EBIS Au^{32+} took place on EBIS, Booster, and AGS user 5 using the standard 9.8 GeV injector setup with a 4 to 1 merge in Booster and a 6-3-1 type merge in AGS. The Siemens motor generator was used for the entire run.

An intensity limit of 8.0e9 Au^{77+} ions in the AGS was in effect during the run to protect the J7 plunging stripping foil and the Copper absorber of the AGS beam dump. This corresponds to a merged bunch intensity limit of 2.0e9 Au^{77+} ions for 4 equal intensity bunches. The per bunch intensity limit can be increased to 2.67e9 by reducing the number of BtA transfers from 8 to 6. There was also a Booster Late intensity limit of 16e9 Au ions in effect to protect the BtA stripping foil from damage due to overheating.[3] Lowering the number of transfers also makes this limit less of a constraint. BtA foil 5, which was installed in 2020 and had not been used regularly prior to this run was used all run and showed no obvious signs of deterioration.[4]

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[1] In 2019, 9.8 GeV Tandem Au^{31+} was set up in the AGS with the 12-6 merge but there were only 4 Booster transfers to provide 2 final bunches and the injection porch was shorter. The Westinghouse motor generator was used that year and this beam was not transferred to RHIC. See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, November 2019.

[2] L. Ahrens, et al, "Setup and Performance of the RHIC Injector Accelerators for the 2007 Run with Gold Ions". Proceedings of PAC07, Albuquerque, New Mexico, USA , pg. 1862. This contains a description of the pre-EBIS Tandem Au setup in the injectors.

[3] Kiel Hock, Haixin Huang, Keith Zeno, "Au Intensity Limits in the Injectors, Run 23" memo dated June 27, 2023. See Dec 20, 2023 Booster-AGS-EBIS elog entry at 15:21. Note also that the BtA foil heating also depends on the supercycle length. Experience in previous runs suggests that damage does not occur at or below 16e9 ions and given the AGS intensity limit more than 16e9 would normally not be needed. In runs 20 and 21, when damage did occur, the limit was 20e9 Au ions even with shorter supercycles (5.4 and 6.0 sec) because the AGS limit was higher (9.6e9) and the RHIC requirements were more demanding. See K, Zeno, Run 21 in the injectors, C-A/AP/653, pgs, 4-6.

[4] Fractional changes to the setting were made several times during the run but no difference in transfer efficiency was observed so the foil drive position was left at 5.0. Foil 5 is one of the 3 Al+C foils used for Au (5, 6, and 7). So, foils 5 and 7 are still in good condition. Foil 6 was damaged during run 21.

In May, a Tandem Au 3.85 GeV setup from 2021 was also re-established on AGS user 2. It was used for APEX on May 24 and July 26. Initial work with 3.85 GeV beam was on May 19. Proton beam was also set up during the run and extracted to W dump on July 10. It was used for APEX on July 12. Although the OPPIS source was used the AGS setup was without snakes.

The AGS Magnet Cycle

The AGS magnet cycles for the Tandem and EBIS 9.8 GeV setups are shown in Figure 1. The Tandem cycle differs from the EBIS one in that the early part of the ramp after the 12-6 merge porch is much faster and the F to P transfer happens at a lower field (0.98 vs. 1.65 kG). In 2019, when a Tandem 9.8 GeV cycle was run the F to P transfer was at the same field as for EBIS Au. The 2019 cycle used the Westinghouse motor generator and so dB/dt at transition was lower than this year (11 vs. 17 G/ms).

The EBIS Au early ramp after the merge porch is relatively slow so that the F to P transfer will occur at a higher field. There is a transient in the dB/dt at the F to P transfer which will cause beam loss at lower fields because the bucket is nearly full. Since the longitudinal emittance (ε_L) of the Tandem beam after only a 12-6 merge is much smaller, and that merge happens at a higher energy, the early ramp after the porch can be faster and the F to P transfer can happen at a lower field without beam loss.

The Tandem Au 3.85 GeV magnet cycle in 2021 only used the F bank, the Tandem Au 5.75 GeV setup from 2020 used the P bank and the F to P transfer occurred at the same field as for the EBIS Au 9.8 GeV setup.

As mentioned, the AGS merge porch for Tandem Au is higher than the one for EBIS Au (911 vs, 576 G). The L10 cavity is not used for the AGS merge, so the energy at the merge porch is not constrained by its frequency range, but it is constrained by the frequency range of the h=6 cavity (KL) and that is one reason why it is as high as it is. One might also expect that having it that high would mitigate any potential space charge effects just after the merge and squeeze into h=12 buckets.

The magnet reference for both this cycle and the standard EBIS Au cycle have a discontinuity in dB/dt at the end of the merge porch. In both cases the dB/dt is the reference abruptly changes from 0 to 3G/ms at that time. This has been shown to help reduce intensity dependent beam loss there related to space charge.[5]

The flattop is longer than it is for EBIS Au 9.8 GeV. It needs to be to accommodate the extraction of 4 bunches instead of 2. However, given the spacing between extractions (250 ms)

[5] K. Zeno, "Overview and Analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, September 2016, See pg. 8 in particular.

the flattop could have been about 500 ms shorter than it was, which would have allowed for a 5.4 or 5.6 sec supercycle.

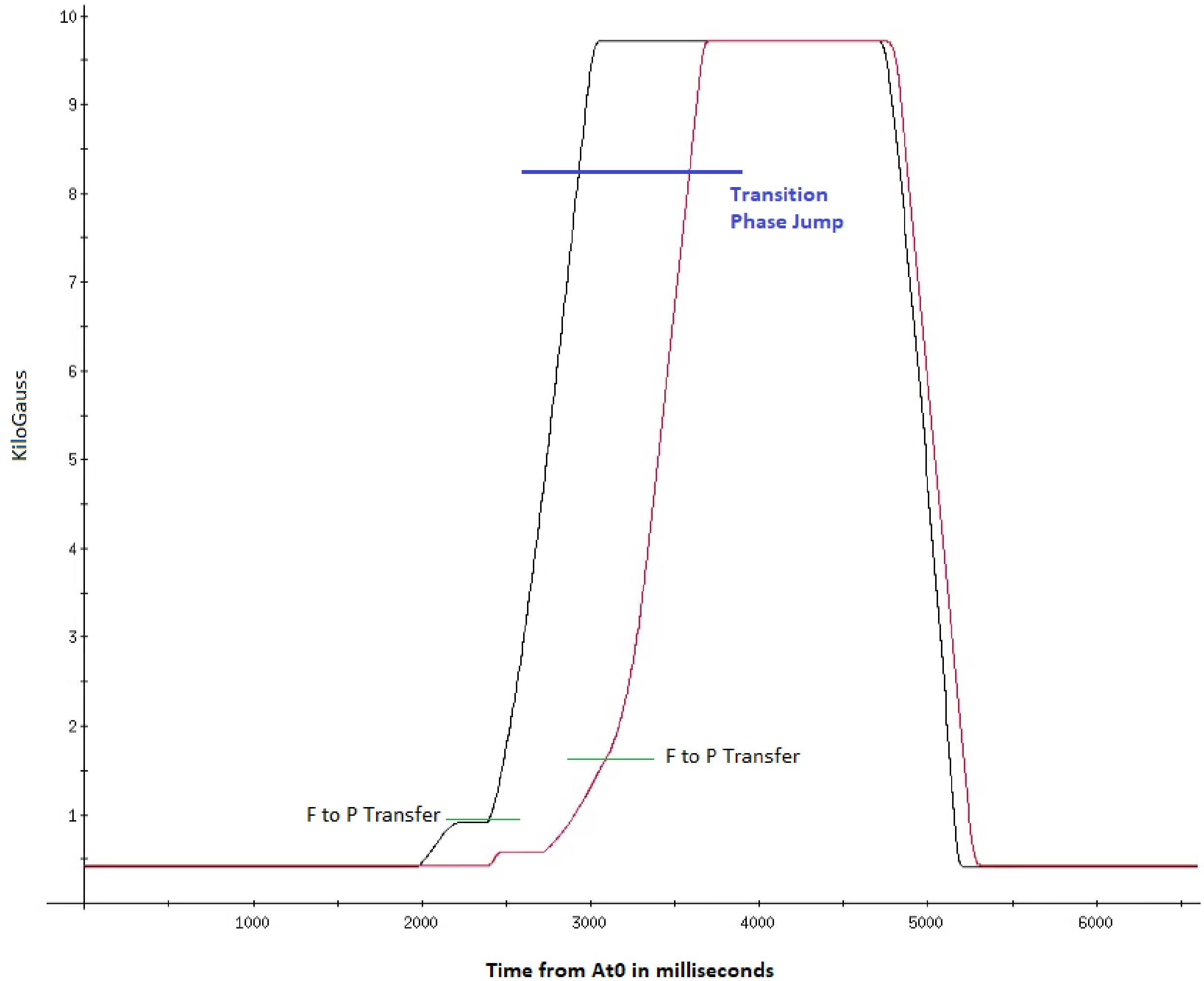

Figure 1: Comparison of Tandem (black) and EBIS Au 9.8 GeV AGS magnet cycles. Also shown are the fields where the F to P transfers occur as well as where transition occurs.

Tandem 9.8 GeV Au Transverse Emittance

In BtA

On May 8th the RMS normalized transverse emittances measured using the BtA multiwire MW006 horizontal and vertical profiles with a bunch intensity at Booster extraction of 0.7e9 was $(\varepsilon_x,\varepsilon_y)$=(0.197, 0.202) mm mr with a 400 μs Tandem pulse. A similar measurement on July 26th was (ε_x, ε_y)=(0.329, 0.553) mm mr with a 450 μs Tandem pulse. In this case, the bunch intensity at Booster extraction was about 1.5e9.[6]

On the AGS Flattop

The AGS (ion) IPM was plagued with noise throughout the run that could not be subtracted out. However, comparison of the fits and data for individual profiles shows that some of the data is usable. The RF was on during the flattop for the available measurements, but an estimate of the effect of the RF being on during the measurements has been made using previous data for similar running conditions. Using that correction a transverse RMS emittance of 1.8 mm mr in both planes was obtained with a bunch intensity of 2.0e9.[7] Note that, since the beam passes through a stripping foil in BtA, some growth between MW006 and the AGS flattop is to be expected even in the ideal case.

Tandem Au Longitudinal Emittance in the AGS

Although there are not many longitudinal emittance (ε_L) measurements this run, there are some. Table I is a summary of those. The bunch intensities for these measurements are on the low side. For 1.35e9, the highest bunch intensity shown, ε_L is about 0.23 eVs. ε_L for the EBIS Au 9.8 GeV setup is about 3.4 times larger than that (~0.78 eVs). 6 bunches are merged into 1 in that setup instead of 2, so if the ε_L of the bunches at AGS injection were the same for the 2 setups one would expect the bunches using EBIS to be 3 times larger.

Before the advent of EBIS, the 6 bunches per Booster cycle transferred to AGS were merged into 1 and the flattop ε_L was 0.23 eVs.[8] This is about the same ε_L as with this setup yet in this case the final bunch comes from the beam in 2 Booster cycles. If a larger ε_L was desired for RHIC it could be increased to 0.40 eVs by mismatching the BtA phase without any obvious degradation in the AGS transfer and acceleration efficiency. This corresponds to the May 15

[6] The May 8th profiles can be found in the Booster-AGS-EBIS elog 13:57 entry from that date, and the July 26th profiles can be found in the 16:02 entry of that elog from that date. The RMS normalized emittances at MW006 are found from the profile FWHMs (x,y) using the formulas ε_x=(0.178x^2)/6 and ε_y=(0.033y^2)/6. The FWHM (x,y) for the May 8th case was (2.57mm, 6.05mm) and it was (3.33mm, 10.03mm) for the July 26th case(cycle 3).
[7] The measurement at 3500 ms for the Jul 31, 2023 21:05:17 cycle is used. For this with RF on, the RMS emittances (ε_x,ε_y) are (2.5, 2.2) mm mr. On the Apr 20, 2018 14:51:19 cycle the AGS Late was 2.4e9 and when the RF shut off the RMS εx dropped by 0.7 mm mr and the RMS εy dropped by 0.4 mm mr. The estimated RMS emittances with RF off for the Jul 31 data then becomes 1.8 mm mr in both planes (10.8 mm mr 95%). The Refit option was used in both cases. For the Jul 31 data AGS late was 7.95e9 for 4 bunches for 1.99e9/bunch. The 2018 data was also with 9.8 GeV Au but the beam was from EBIS.
[8] L. Ahrens, et al, "Setup and Performance of the RHIC Injector Accelerators for the 2007 Run with Gold Ions". Proceedings of PAC07, Albuquerque, New Mexico, USA , pg. 1862.

12:32 case in Table I. Mismatching more than that did not lead to a larger bunch and caused some acceleration loss.[9]

Time	WCM	f_{synch} (Hz)	Bunch Length (ns)	# of length measurements	Vector Sum (kV)	f_{synch}_V /Vsum	ε_L (eVs)	Bunch Intensity
May 11 15:21	G5	100.24	14.07	6	251.7	0.79	0.20	1.1e9
May 15 12:14	F20		13	1	251.7		0.19	0.8e9
May15 12:32*	F20		20.3	3	251.7		0.41	0.7e9
May 15 12:35	G5		14.72	5	251.7		0.22	0.75e9
May 30 19:28	F20		13.2	2	251.7		0.17	0.7e9
June 26 1744	F20		15.13	3	249.7		0.23	1.35e9

*-This measurement was taken with the BtA phase detuned to make the ε_L larger. The matched setting was 80° and this is 85°.

Table I: Longitudinal Emittance measurements on the AGS flattop for 9.8 GeV Tandem Au. The measurements were taken with the G5 and F20 WCMs as noted. The synchrotron frequency (f_{synch}) was only measured for the first measurement. Since the vector sum voltage is practically the same for all the cases this f_{synch} is used for them as well. Length measurements made with the G5 WCM are the length of the first half of the bunch x 2, and for those made with F20 the full length is measured.

Tandem Au was used during Run 19 for 9.8 GeV. ε_L was larger then, about 0.40 eVs although for a bunch intensity of 2.1e9.[10] As mentioned, the AGS magnet cycle was different and the Westinghouse was used. The Booster merge porch was also shorter then, 34 vs 67 ms.

In Run 20, during the Tandem Au 5.75 GeV run, the flattop ε_L ranged from 0.23 to 0.31 eVs. ε_L seemed to have a bunch intensity dependence, 0.23 eVs was at the lowest intensity, 0.8e9, and 0.31 was at the highest, 2.4e9.[11] The 67 ms long Booster merge porch was used during that Run.

On May 18 the full bunch lengths of filamented bunches on the injection porch were measured using the G5 WCM.[12] The lengths of the first transfer bunch were measured at the 2nd transfer 267 ms later. The result was 297.1 ns and the σ of the 6 measurements was 4.9 ns. f_{synch} was 882 Hz which corresponds to 9.68 kV. This gives an ε_L of 0.0753 eVs with a σ of 0.0020 eVs. Ideally the ε_L of a merged bunch would be twice that, 0.15 eVs. The intensity of a merged bunch at AGS Late was only 0.73e9. In run 20, the measured ε_L of Tandem Au bunches on the injection porch that had filamented out was much larger, 0.125 eVs.[13] In Run 21, an ε_L of 0.10

[9] See Booster-AGS-EBIS elog from May 15 2023 entries from 12:14 to 12:39. The BtA phase is in h=1 degrees, so 5° corresponds to 60 h=12 degrees.
[10] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, November 2019, Table 4 on pg. 4.
[11] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors" C-A/AP/638, December 2020. See Table V on pg. 22.
[12] See Booster-AGS-EBIS elog from May 18 2023 entries from 17:06 to 17:39.
[13] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors" C-A/AP/638, December 2020, pg. 21.

eVs was obtained for a filamented bunch on the porch.[14] The Booster merge porch was 67 ms long in all these cases. Each of these 3 yearly measurements were taken with a different foil and the one used this run had not been used regularly before.

Au Intensity in the Injectors for 9.8 GeV

Figure 2 shows the average bunch intensity on the AGS flattop (AGS Late) during RHIC fills this Run. The intensity ramps up from 8-9e8 near the beginning to about 1.8-1.9e9 just before the Run ended. If the run had continued the plan was to increase the bunch intensity further by reducing the number of Booster transfers to 6 from 8 and thereby producing 3 instead of 4 final bunches. This approach would have been needed to stay below the Booster Late and AGS intensity limits. Some work with 6 transfers in preparation for this had been done but, for some reason, progress in increasing the final bunch intensity was rather slow.

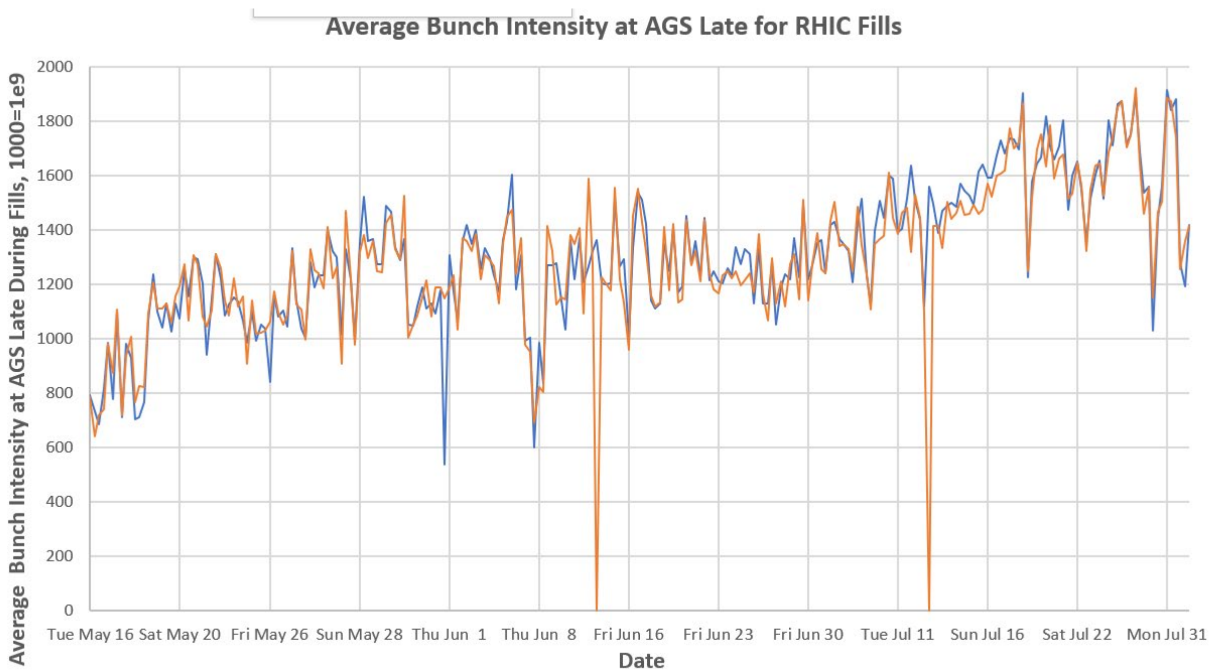

Figure 2: The AGS flattop average bunch intensity for RHIC fills in the blue and yellow rings. On June 1st the number of bunches on the flattop was increased from 2 to 4. The data is from the FDAView program. The intensity data from the program, "blueAgsXcbmAvg" and "yellowAgsXcbmAvg", is divided by 2 before June 1 and by 4 afterwards to obtain the average bunch intensity and the x-axis is "injStartTime".

In addition to the desire for more bunch intensity, work with EBIS Au was a priority because the Tandem had made a commitment which required Au beam to be off for an extended

[14] See K. Zeno, "Run 21 in the Injectors", C-A/AP/653, September 2021. See Table VI on pg. 14 and the related discussion.

period starting August 4th and so EBIS Au would have to be used but the intensity and stability of the EBIS Au beam was not sufficient.

Figure 3 shows the intensites at different stages in the injectors for a RHIC fill near the end of the run where AGS Late was near the administrative limit of 8.0e9 ions with 4 final bunches per AGS cycle. AGS Early, which samples the intensity just after the last transfer, is also shown and nearly overlays AGS Late. In fact, AGS Late is slightly higher, because the normalized current transformer baseline is not flat (The AGS scaler gain is set so that the AGS Late intensity is the most accurate). Booster Late, which is the sum of the intensities in the Booster before extraction for the 8 transfers, averages slightly below the administrative limit of 1.6e10 ions per AGS cycle. Booster Input is the sum of the intensities of the 8 Tandem Au^{31+} pulses measured about 40 feet from the end of the TTB line. It averages about 2.5e10 ions during this fill.

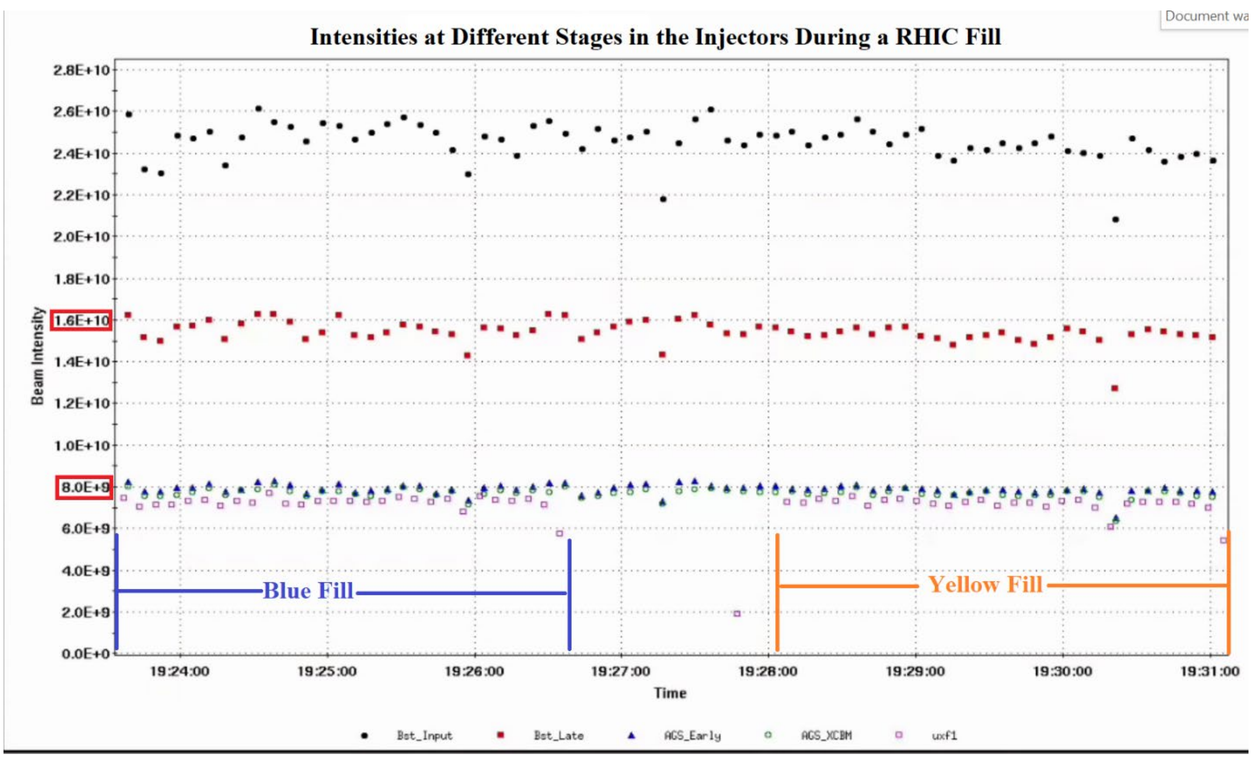

Figure 3: Intensities at different stages in the injectors during a RHIC fill. Booster Input (black circles), Booster Late (red squares), AGS Early (hollow green circles), AGS Late (blue triangles), and uxf1 (hollow purple squares) are shown. The Booster Late and AGS administrative limits are highlighted in red. This was for fill 34072 which occurred on July 31.

Figure 4 shows the history of the Booster Late scaler over the run. Before June 1st there are only 4 Booster transfers (or less). The data highlighted in blue is for Au from EBIS. For that data, the number of Booster cycles with beam is generally less than the standard 12, but the data where the intensity is close to 4e9 is with 12 pulses.

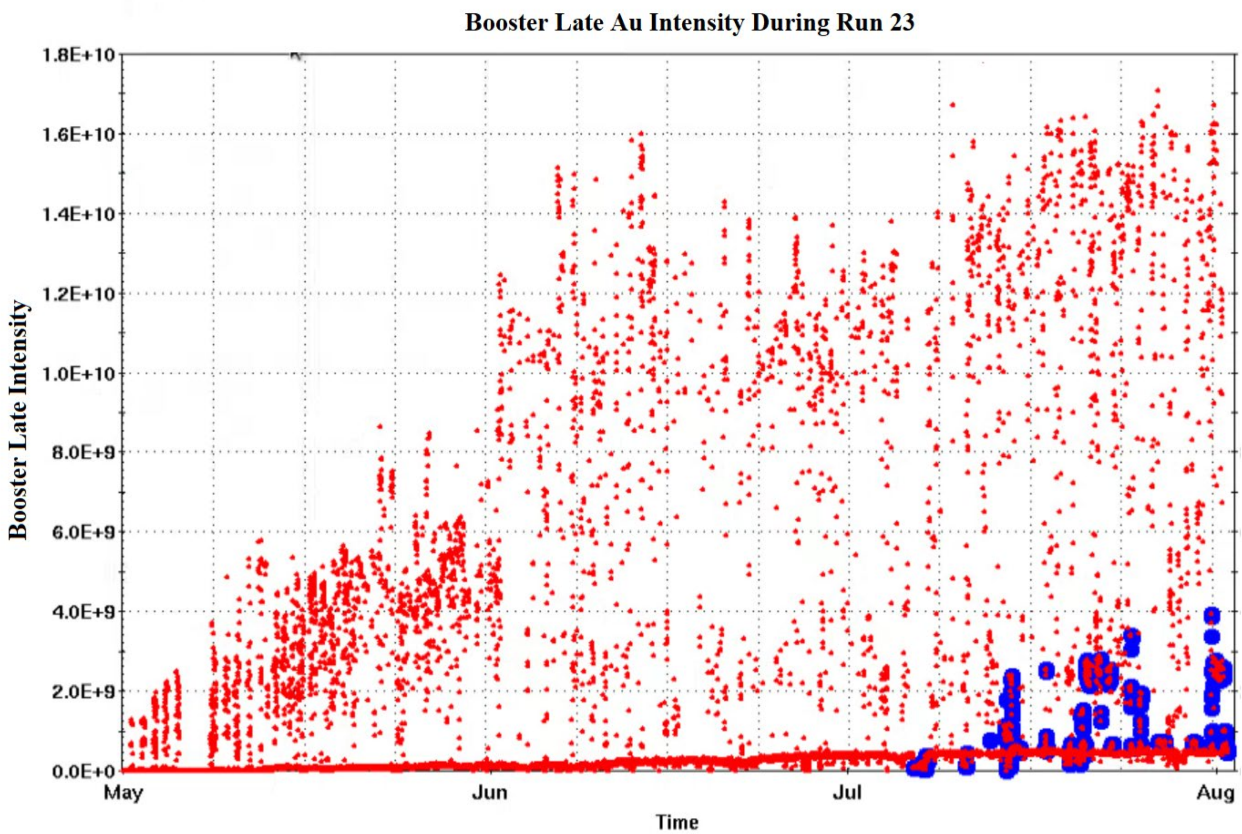

Figure 4: The Booster Late Au intensity during the run. The data highlighted in blue is Au from EBIS.

BtA Cogging

There were 2 BtA cogging patterns used this run. A simple pattern was used from the beginning of the run until June 6th. With this pattern, transfers 1 and 2 go into the first extracted bunch, transfers 3 and 4 go into the 2nd bunch extracted, 5 and 6 go into the 3rd extracted bunch, and 7 and 8 go into the 4th extracted bunch.

On June 6th the pattern was changed. The 1st bunch extracted was made up of the 1st and 8th transfers and the 4th bunch extracted was made up of the 2nd and 7th transfers. The transfers comprising the 2nd and 3rd bunch extracted were not changed. This change was made so that the bunch intensity of the 4 bunches would be more uniform. Even if each of the transfers were the same intensity, a merged bunch comprised of the first 2 transfers injected will have less intensity than those transferred later because there is a slow loss across the injection porch. Merging early transfers with late transfers will tend to even out the intensity of the final bunches. It is also true that the intensity on the first Booster cycle was sometimes lower than the others. This was because the EtB partner on the Supercycle had not been set early enough and because sometimes the intensity on the first pulse from Tandem was lower than the others.[15]

On July 24th this was reverted to the initial setup because it was realized that the A5 kicker pulse was too wide. The A5 was in the narrow or so-called proton mode, where it is about 1 μs wide. With the cogging pattern from June 6th to July 24th, during the 6th and 8th transfers the kicker pulse is too wide. During the 6th transfer the bunch in the 7th position (2nd transfer) will get an unwanted kick and on the 8th transfer the bunch in the 3rd position will.

Figure 5 concerns the June 6th to July 24th pattern, it's a mountain range of the WCM just after the 7th transfer, which is how it would look just before the 8th transfer. The 8th transfer is cogged to go into position 2 and the A5 kicker pulse has been overlayed to look as it may have looked for the 8th transfer. Although the actual timing may have been slightly different, it's clear that the kicker pulse is not narrow enough to entirely miss both bunches in positions 1 and 3.[16]

There are 8 transfers and 12 RF buckets in the AGS. When the simple cogging pattern is used, unlike in the case considered above, the transfers are injected into consecutive buckets. After the last transfer is injected, there are still 4 empty buckets that must pass through the kicker before the first bunch injected passes through it. With the other cogging pattern, as shown in Figure 5, there are no (extra) empty buckets for 2 of the transfers (the 6th and 8th). Before the cogging pattern was reverted to the initial pattern (Booster Late)/(AGS Late) was 51% and afterwards it was 53-54%.[17]

The Booster F4 Extraction Bump Problem

As in Run 20, the F4 extraction bump (A.K.A. F4_BLW) had problems this run.[18] Although F4 is one of the 2 principal bumps that make up the extraction bump, as in run 20, it was not hard to restore nominal BtA efficiency without it. Since there was no discernable negative effect from running without it we did so for a substantial part of the run (June 27 to Aug. 1). There seems to be a ground fault problem with it, which may still remain.[19] The power supply did work on some level but would sometimes trip and remain off for some time. Optimizing BtA for these 2 states was not worth the trouble since the BtA efficiency was just as high with it off, so it was generally left off. Although many BtA related devices have different setpoints for the 2 states, adjusting the F6 septum current to center the beam on the MW006

[15] See Booster-AGS-EBIS July 14 2023 elog entries from 12:04 to 13:14.

[16] The mountain range display is taken from Booster-AGS-EBIS July 24 2023 elog entry at 14:33 and the A5 kicker trace is taken from the Booster-AGS-EBIS Apr 2, 2021 elog 19:26 entry by W. Jackson. Note that, in the elog entry, the kicker trace's time axis is in ns. And the trace shown in Figure 5 has been scaled to match the time/div of the mountain range display.

[17] See Booster-AGS-EBIS July 24, 2023 elog entires from 14:33 to 15:09.

[18] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec. 2020, pgs. 36-38 for information and analysis about the problem in Run 20.

[19] For example see the June 29, 2023 OC log 08:03 entry by I. Blackler,

multiwire seems most critical. With F4 on the optimal current is 12791A and with it off it is 13048A, about 250A higher.[20]

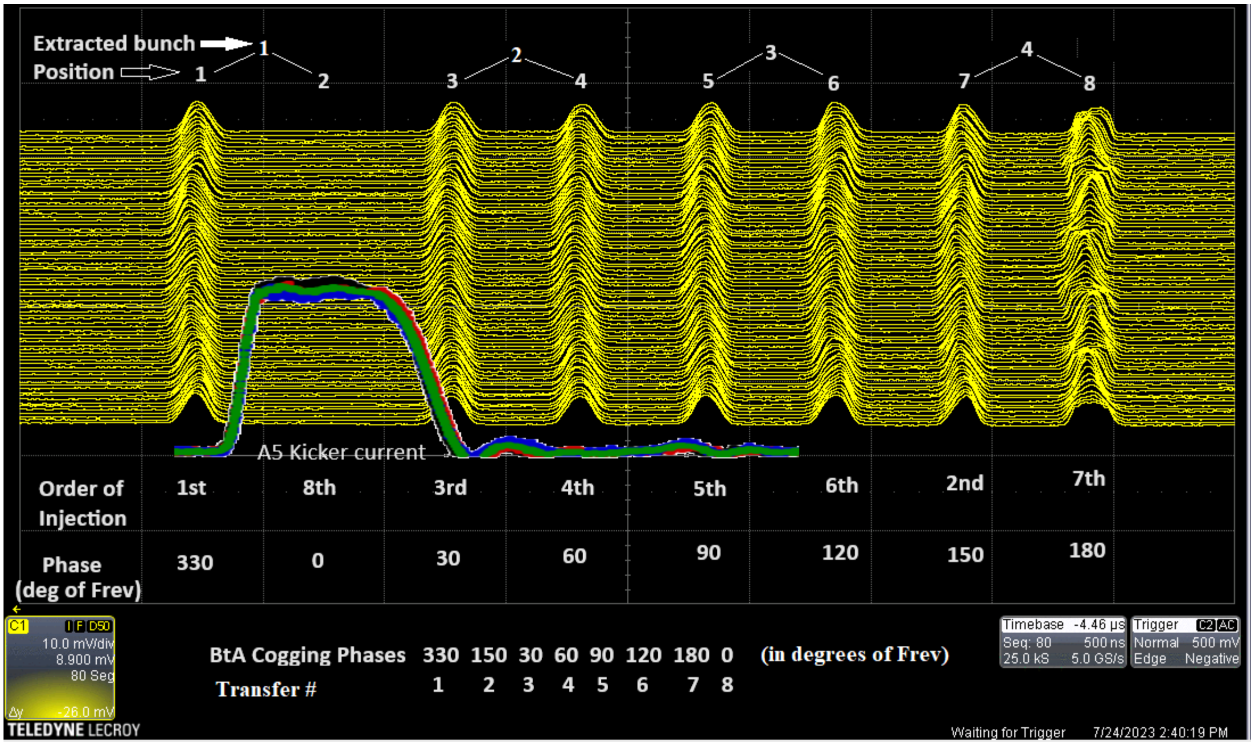

Figure 5: G5 WCM mountain range display looking after the 7th and before the 8th transfer. It shows the cogging pattern used during the period from June 6th to July 24th. Superimposed on the display is the A5 kicker current timed for the 8th transfer. Other information related to cogging, order of injection, and the order extracted from the AGS, is also shown. The BtA cogging phases, as they appeared on the AGS/Rf/cfe-929-rfll1/dsp_4 pet page are also shown associated with the transfer #. The AtR cogging pattern, which determines which bunches will be kicked out and in what order, was (0, 60, 120, 180). It is also found on that pet page.

Some Notable Losses on the Tandem 9.8 GeV Cycle

Intensity Dependent Loss at the Beginning of the Ramp to the Merge Porch

Sometimes there is a loss at the end of the AGS injection porch when the Rf voltage starts to ramp for acceleration to the merge porch. This loss is intensity dependent, and typically is not apparent at AGS early intensities below 7e9 ions or so.[21] It is also more pronounced sometimes more than others at a similar intensity. Figure 6 shows an example of this. The AGS Early intensity here is about 7.5e9. Although it is where one would expect a capture loss to occur it

[20] See Booster-AGS-EBIS elog on June 27 2023 entries at 19:19 and 19:20.

[21] A similar intensity dependent loss has been seen in previous Tandem Au runs. In 2021 the intensity threshold seemed to be higher (8.5-9e9). See the 2nd image in the Booster-AGS-EBIS March 13, 2021 elog entry at 16:24 and the 14:40 entry.

does not seem to be primarily a capture loss. Space charge seems the likely mechanism and the bunch from the last transfer has the least time to filament out and so may be denser and so more susceptible to space charge. Although some time was spent trying to reduce this loss by adjusting tunes, stopband correctors (octupole and sextupole), and so on, I think it was still an issue when the run ended.

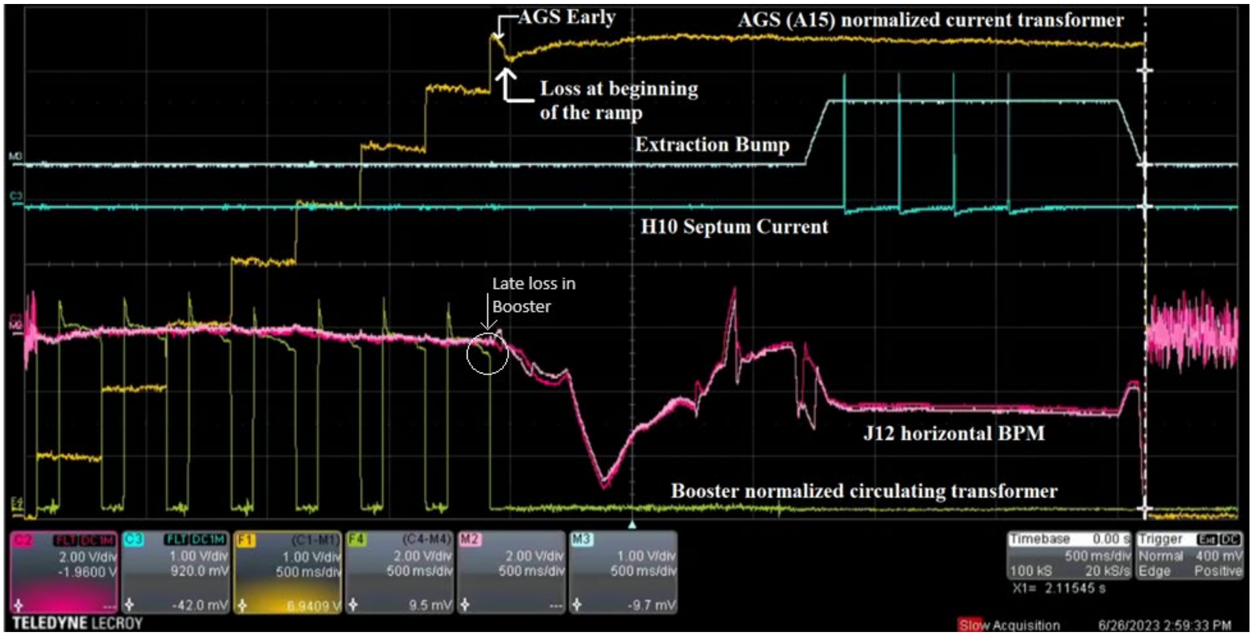

Figure 6: Tandem Au 9.8 GeV in the injectors. The intensity dependent loss at the beginning of the ramp to the merge porch is pointed out on the AGS transformer. The AGS Early sample time is also indicated. Also note the losses near the end of each Booster cycle (discussed below). The baselines are subtracted for the current transformers. The trigger is At0+2500 ms and there are 500 ms/div.[22]

Post Merge Loss on the Booster Tandem Au Cycle

The A3 and B3 cavities are used for h=1 after the merge and the RF frequency is near the lower limit of their frequency range there (~400 kHz). Running at higher voltages near this limit can damage the cavities. The RF group had more concern about damaging A3 than B3. The A3 voltage was limited to 10 kV during this part of the cycle whereas B3 ran around 15 kV. The total available voltage used to accelerate the beam without losses was enough, but if the merge was not optimized well there would be a loss. This loss, particularly since it occurs at relatively high energy could lead to some vacuum deterioration, which in turn will lead to more beam loss, and so on. The loss is evident on the Booster transformer trace in Figure 6.[23]

[22] Taken from Booster-AGS-EBIS June 26 2023 entry at 14:56.
[23] The Booster-AGS-EBIS elog entry on June 26 at 18:12 shows a case where there was no loss.

Transition Crossing

The AGS Tandem Au setups used prior to this run but using the 6-3-1 merge in the Booster and 12-6 merge in the AGS were mainly for low energy RHIC runs so the AGS extraction energy was typically below transition and so there was little experience with transition crossing. With the 9.8 GeV setup there were some intensity dependent losses and curious behavior associated with it.

Figure 7 shows a case where there were only 3 final bunches each of about 2.0e9 ions.[24] Note that the peak current after the jump drops by about a third. There is also a loss sometimes, as shown in the figure about 15 ms after the jump, though it is only a few percent of the total intensity. The response of the transformer is slow but not slow enough that this loss would actually be occurring right at the jump. Even if it did occur there the loss would not be enough to account for a 30% or so drop in the peak current. Logged data from that time of the RF vector sum and bunch-to-bucket phase do not indicate any problems that could account for this behavior.

It seems like the bunch behaves as if it has a higher restoring force below transition and a lower one after it even though the RF voltage is constant. Similar behavior has been observed with Deuterons from Tandem which have relatively small and intense bunches like these.[25] This behavior does not seem to occur at lower intensities for either Tandem Au or Deuterons. It does not seem to occur with EBIS Au bunches either which often have a higher intensity but have an ε_L that is about 3 times larger. It is my understanding that a longitudinal space charge effect around transition would cause a higher restoring force before transition and a lower one after it so that the behavior of the peak current would be the opposite of what is observed.[26] It is also reminiscent of experience with high intensity protons where the gap voltage was lowered during the jump, reaching a minimum right at the jump and then raised abruptly, within a few ms, to minimize beam loss.

Instabilities on the Injection Porch

As in previous Tandem runs, the beam can become unstable on the injection porch when there are RF cavities off.[27] In this case, as shown in Figure 8, there was beam loss associated with oscillations on a horizontal BPM during the latter part of the injection porch. During this time, the stability in the AGS was very sensitive to the BtA horizontal steering as well. Figure 9

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[24] Taken from Booster-AGS-EBIS July 21, 2023 elog entry at 12:53.
[25] See K. Zeno, "Run 21 in the Injectors", C-A/AP/653, September. 2021, Figure 18 on page 27 and related discussion.
[26] See L.A. Ahrens, "A γt-Jump Scheme for the Brookhaven AGS", AGS/AD/Tech Note No. 265, September 1986. See the plot on pg.3 and related discussion.
[27] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, December 2020, section called Beam Loading on the Injection Porch on the 3.85 GeV Tandem Cycle" pg. 35-37. Note that the cogging pattern then was the simple pattern described earlier.

shows a more extreme case with the Bunch-to-Bucket phase and Radial Average signals also shown. The cogging pattern was as described in Figure 5, where the 2nd transfer, 5th transfer or both may receive an unwanted kick at the 6th transfer, although it is evident from the Bunch-to-Bucket phase that the instability starts before the 6th transfer.

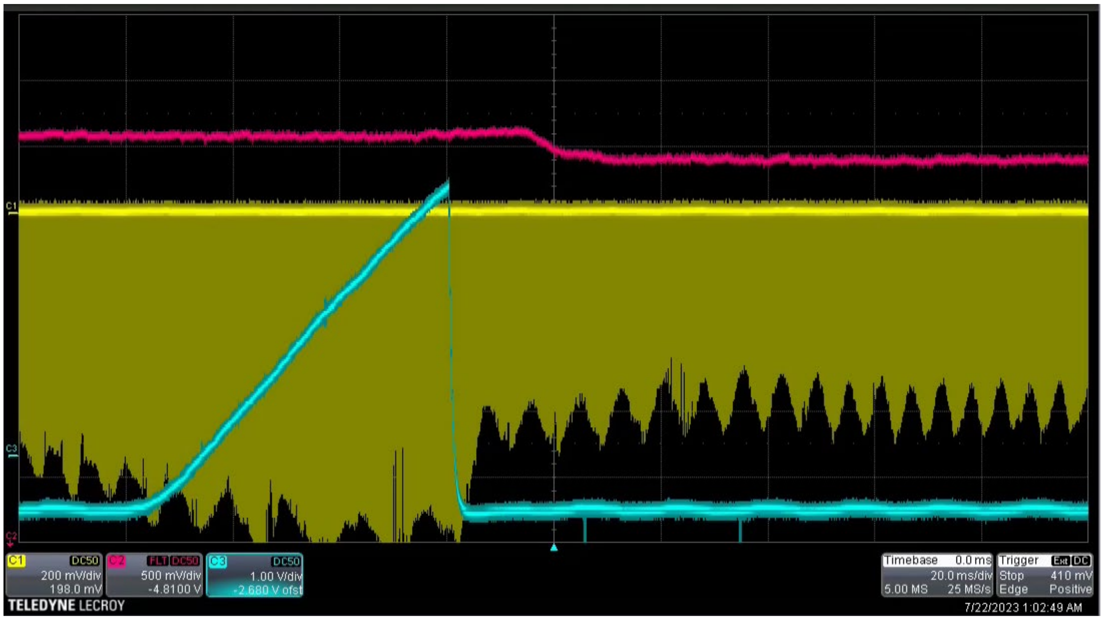

Figure 7: Transition crossing with 2.0e9/bunch. The yellow trace is the G5 WCM (200 mV/div.), the blue trace is the A17 γ_T-jump quad current (1V/div.), and the red trace is the A15 normalized current transformer (500 mV/div.). All signals with 50 Ω term. The sweep speed is 20 ms/div.

There were 2 RF cavities (BC and C) that were off at the time, and both had beam induced voltage.[28] The RF group reconfigured station BC, which had the most induced voltage, about 400 V per gap toward the end of the porch, so that there no longer was any.[29] The instability disappeared once this was done.

EBIS Au in the Injectors

As noted, Tandem Au was used for the run instead of EBIS Au because it did not meet the requirements for RHIC. In this section, I will try to document the experience with EBIS Au in the injectors.

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[28] See Booster-AGS-EBIS July 21, 2023 elog entries from 19:16 to 20:26. Also shown here is the induced voltage on the cavities and what the BPM and the transformer look like with and without the beam loading. There is some logged intensity scaler data from that time as well as logged transformer traces. The Booster Late was 14 to 16e9 during this time and the AGS Early was sometimes as high as 8e9 and sometimes as low as 2e9 because of the instability.

[29] See the AGS_RF_stay elog on July 21, 2023 entries.

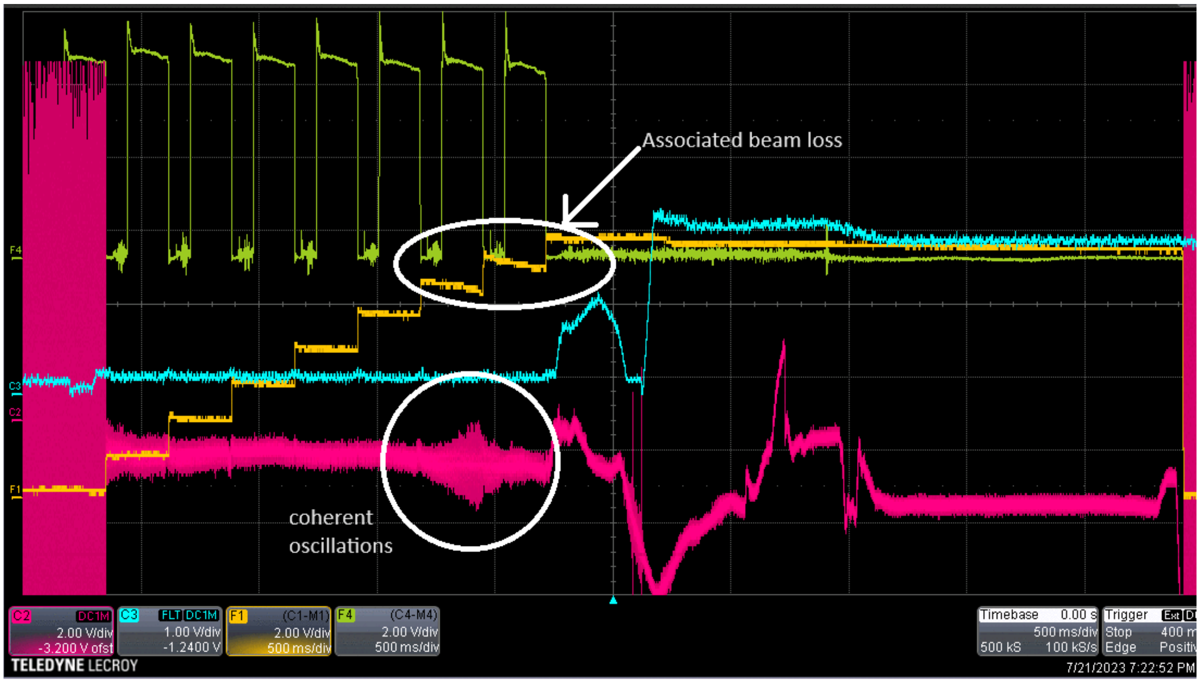

Figure 8: Beam loss and coherent horizontal oscillations after the 6th transfer to the AGS. F1 is the normalized AGS current transformer with baseline subtracted (orange), F4 is the normalized Booster current transformer with baseline subtracted (green), C3 is the AGS detected vector sum (blue), and C2 is the horizontal BPM at J12 (red). 500 ms/div with trigger at At0+2200 ms.

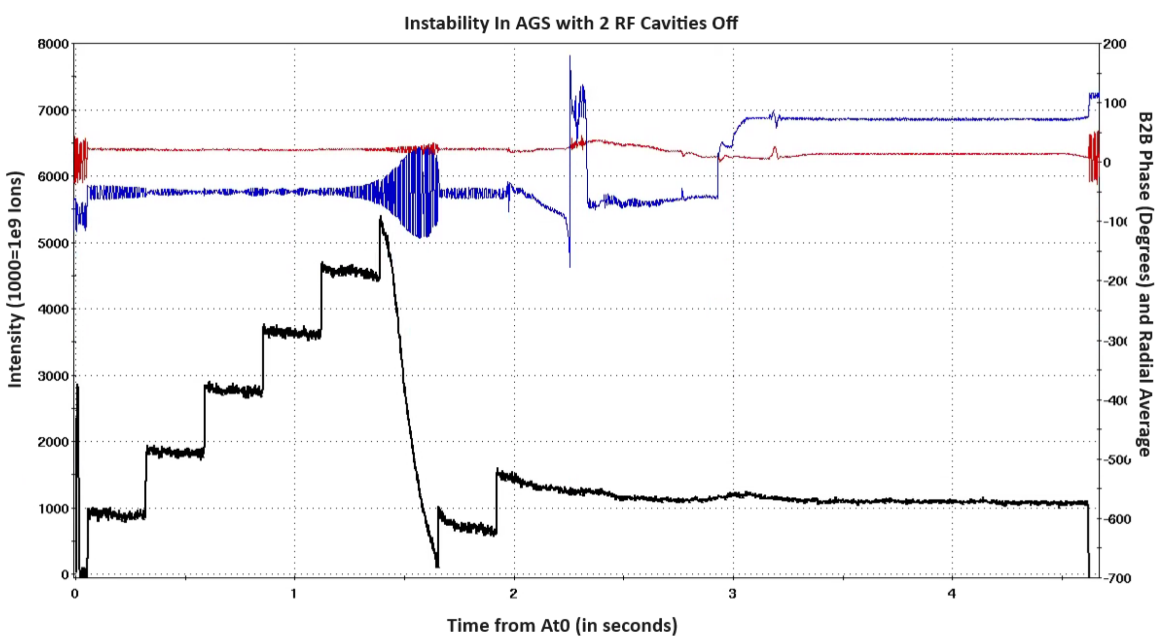

Figure 9: The normalized AGS current transformer (black) on a cycle where the beam loss due to the instability is extreme. The steering in BtA was being changed at the time. The baseline is not subtracted well. Bunch-to Bucket phase (blue) and Radial Average (red) signals are also shown. The logged data is from AGS/Instrumentation/currentXfmr/ags.beamCurrent_Snap.logreq and AGS/RF/LLRF/agsDSPAll.logreq on July 21, 2023 at 18:49:27.

Figure 10 is a plot of intensities at different stages in the injectors on July 31st. During this time the number of EBIS pulses varied. When there were 12 pulses, the Booster input intensity dropped by about one third over the course of half an hour, this was due to EBIS vacuum degradation and required the EBIS Au beam to be shut off for 20-30 min for the vacuum to recover.[30]. With 6 pulses it only dropped by about 10% over 25 minutes or so.

At 15:30 NSRL switched from Ag^{29+} to Bi^{43+} and the plot suggests that the 12 pulse input intensity started dropping then. The Booster efficiency (Booster Late/Booster Input) may also have been worse when NSRL was taking Bi^{43+}. Figure 11 shows this efficiency while there were 12 pulses. Initially, the efficiency is about 61%, and it starts dropping around when NSRL switched from Ag^{29+} to Bi^{43+} and has dropped to 52% 20 minutes later.[31]

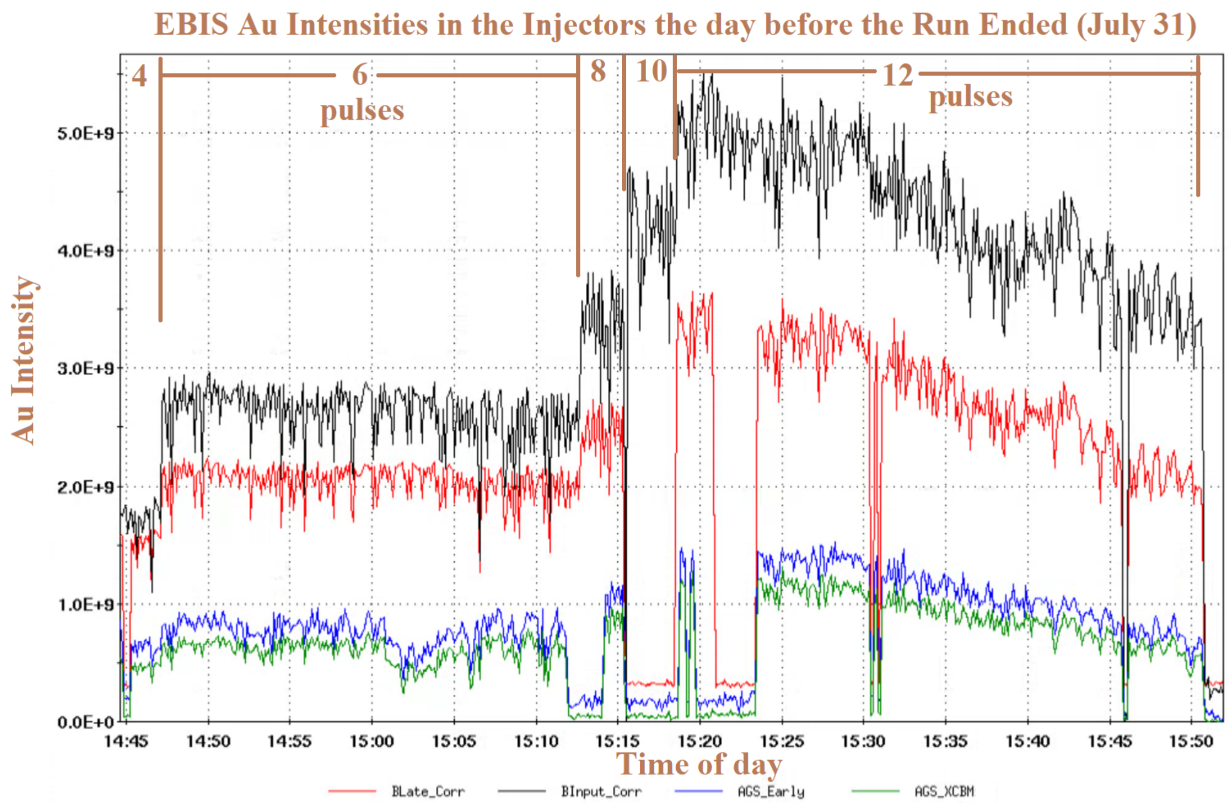

Figure 10: EBIS Au intensity in the injectors on July 31 showing the intensities at different points in the cycle for different numbers of EBIS pulses as noted at the top of the plot. Booster input is in black, Booster Late is in red, AGS Early (right after last transfer) is in blue, and AGS Late is in green.

The BtA efficiency (AGS Early/Booster Late) for EBIS Au this year was also less than it normally is, 41 vs. about 50%, though this probably just needs more time tuning with more

[30] See rhicEBIS elog entry on July 31, 2023 at 16:33.
[31] See Booster-AGS-EBIS elog July 31 2023 17:02 entry

stable beam and more intensity. Also, the problem with the F4 extraction bump added some complication. From Figure 10, the highest AGS Late intensity with 12 pulses and 2 final bunches was 1.1-1.2e9.[32] There was beam in the baby bunches, and a careful measurement of the amount was not done, but judging from visual inspection of a scope trace of the WCM on the flattop the fraction of beam in them was likely less than 10%.[33] So, the intensity of a final bunch was probably near 5e8 ions. If the injector efficiencies were nominal, one would expect the bunch intensity to be more like 1.0e9.[34]

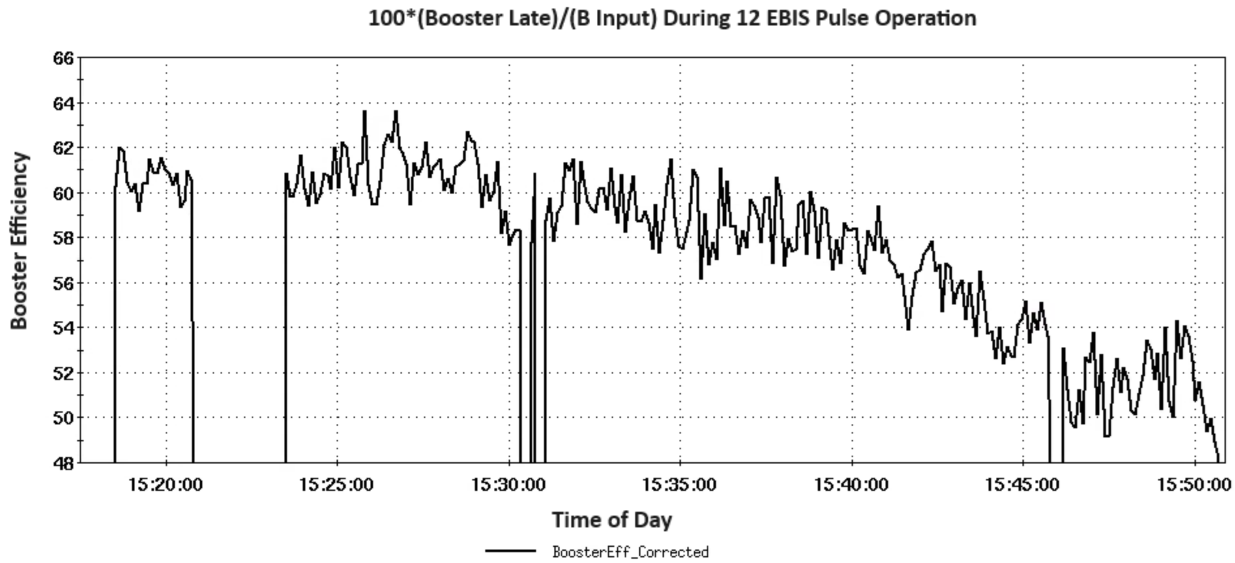

Figure 11: Booster Efficiency during 12 pulse EBIS Au operation. When in 12 pulse mode Booster Input had a baseline offset of 4e8 and Booster Late had an offset of 6e8. To correct for this the Booster efficiency shown is 100*(Booster Late-6e8)/(Booster Input-4e8).

Figure 12 shows the Booster and AGS setup for 12 pulse EBIS running.[35] This was taken shortly after NSRL switched to Bi^{43+}. Note the cycle-to-cycle variation in the Booster intensity due to fluctuations in the EBIS intensity.

After the run ended on August 1st work on the BtA efficiency and the AGS setup was no longer possible because the AGS was off, but some work in the Booster, particularly with 1 EBIS pulse was possible. Table II contains intensity and Booster efficiency measurements from before Aug. 1st with a variable number of EBIS pulses. Note that the Booster efficiency is quite low, somewhere around 60%. Normally it is about 85% and does not show dependence on how many EBIS pulses there are.

[32] See also Booster-AGS-EBIS elog July 31 2023 15:50 entry
[33] See Booster-AGS-EBIS elog July 31 2023 14:52 entry.
[34] For a Booster input of 5e9, a (Booster Late)/(Booster input) of 0.85, an (AGS Late)/(Booster Late) of 0.50, and 5% of beam in baby bunches, one gets 0.95*(5e9*0.85*0.5)/2=1.0e9 ions/bunch.
[35] See Booster-AGS-EBIS elog July 31 2023 15:31 entry

Table III contains Booster efficiency measurements made after the end of the run. These were taken with a scope and only involve single EBIS pulses. The EBIS intensity was usually very unstable during this period and the measurements were taken on cycles where the EBIS (xf108) intensity was at or near its maximum.[36] The peak value in the Table is the highest intensity on the injection transformer, which is the value right at the end of injection. There is often a spike there resulting from beam that is injected but does not survive and a slower but still relatively fast loss after the spike. The spike and slower loss are not visible on the circulating transformer due to its slower time response.

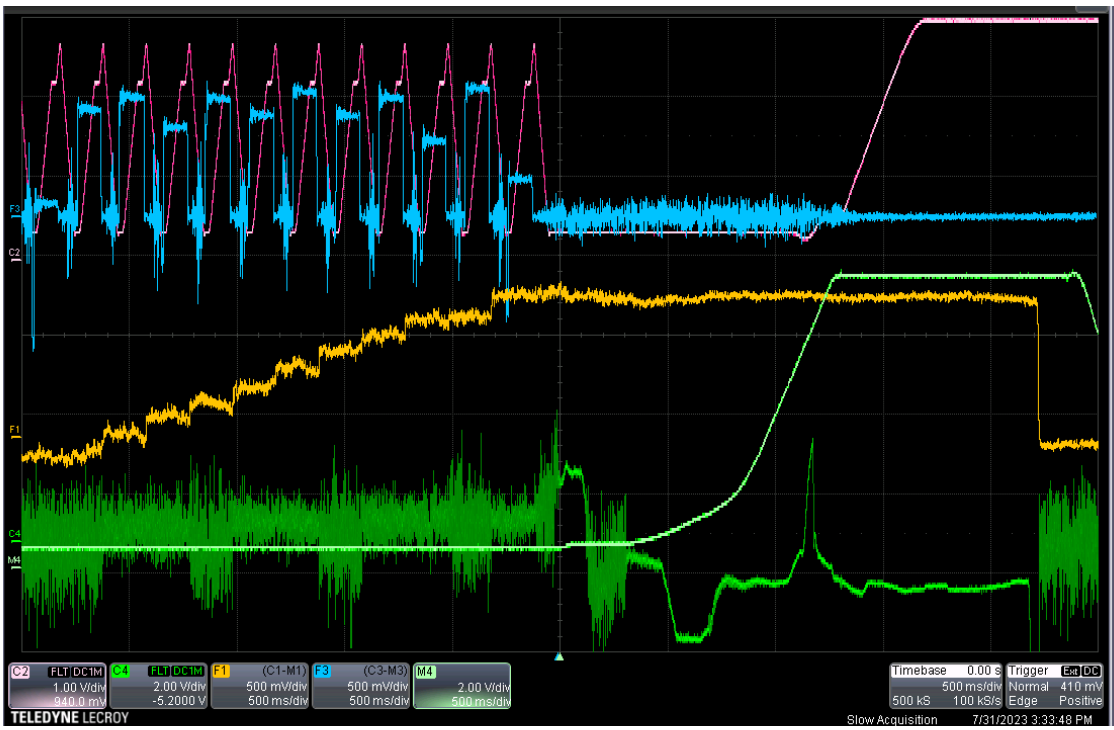

Figure 12: 12 pulse EBIS Au setup. The Booster normalized circulating current transformer with baseline subtracted is in blue (F3), the AGS A15 current transformer with baseline subtracted is in orange (F1). The Booster main magnet current is in red (C2) and the AGS main magnet current is in green (M1). The AGS J12 horizontal BPM is also shown in green (C4). The sweep speed is 500 ms/div and the trigger is At0+2400 ms.

Figure 13 shows how injection looked on July 31, when the injection efficiency was about 61% (see Table II) and the spike was clearly visible. The spike and the slower loss appear to account for the loss of 20% or so of the injected beam. Note also that it is hard to tell how wide the EBIS pulse on xf108 is because there is no clear end to the trailing edge, but it looks to be about 50 μs, which is longer than it typically is (~35 μs). The profile shapes on the last 2 EtB multiwires this year were not noticeably different than in previous years.

[36] For example, see the Booster-AGS-EBIS Aug. 4, 2023 elog entry at 1735.

There were significant changes made in the Booster to the injection setup on Aug. 3rd. The Q_h setting was changed from 4.70 to 4.84 and the injection bump was adjusted to make it fall more slowly. In principle, a Q_h closer to an integer should allow for a more slowly falling bump without reducing the injection efficiency. The motivation for this change was to be able to inject a pulse longer than it had been, say 50 vs. 35 μs. At the time the changes did not result in higher Booster efficiency, though it was no worse.

Time	B Input minus baseline	B Input baseline	B Late minus baseline	B Late baseline	Booster Efficiency	# of EBIS pulses
7/14 15:50	~1e9	1e8	4.36e8	scope	44%	2*
7/14 19:38	2.98e9	3e8	1.6e9	5e8	54%	6*
7/17 18:40	2.7e9	3e8	1.7e9	5e8	60%	6*
7/19 19:25	6.0e8	3e7	3.8e8	2.5e8	63%	1
7/24 19:05	2.0e9	4e8	1.3e9	6e8	65%	6*
7/24 20:41	4.8e9	4e8	2.7e9	6e8	56%	12
7/25 16:08	1.8e9	2e8	1.1e9	6.7e8	61%	6
7/31 15:20	5.1e9	4e8	3.1e9	6e8	61%	12

* Indicates that the spacing between EBIS pulses was 400 ms for these cases instead of the usual 200 ms, at EBIS's request.

Table II: Some Booster intensity and efficiency measurements made prior to Aug. 1st. The Booster Efficiency is 100*(B Late-baseline)/(B Input-baseline). The baseline is not negligible and so has been subtracted from the intensity scaler data. The first Booster Late measurement was made on a scope so there is no baseline to subtract.

Time	xf108	Peak	Booster Late	(B Late)/xf108	Notes
8/1 17:47	5.00e8	4.32e8	3.5e8	70%	
8/1 18:52	4.73e8	4.44e8	3.79e8	80%	
8/2 17:36	5.28e8	4.34e8	3.77e8	71%	
8/3 17:47	5.10e8	4.31e8	3.79e8	74%	Changing injection bump and tunes, out
8/4 14:22	5.39e8	4.14e8	3.68e8	68%	
8/4 18:24	4.86e8		4.08e8	84%	Changed RFQ out
8/9 14:37	4.95e8		4.30e8	87%	More changes to inj. Bump
8/10 14:26	4.59e8		4.27e8	93%	

Table III: Booster efficiency measurements in August using a single EBIS pulse. These were made on a scope (i.e.- the scalers were not used). The Booster Input scaler uses the EtB xf108 transformer.

The low Booster efficiency this run was due to lower-than-normal injection efficiency. The losses through the rest of the cycle were not worse than usual. There are different losses that contribute to lower injection efficiency. First, there is the Au^{32+} beam that passes through xf108 but never reaches the injection transformer at C6. For example, this loss could be due to a beam that is too wide to completely fit through the inflector. Then there is the beam that gets to the injection transformer but does not survive multiturn injection (the spike), and lastly there is the slower loss mentioned above.

The RFQ amplitude and phase were also changed significantly on Aug. 4th. After the change the Booster input dropped about 8% but the Booster Late intensity went up, eventually by about 10%.[37] After further changes to the injection bump the Booster efficiency was within the normal range.[38]

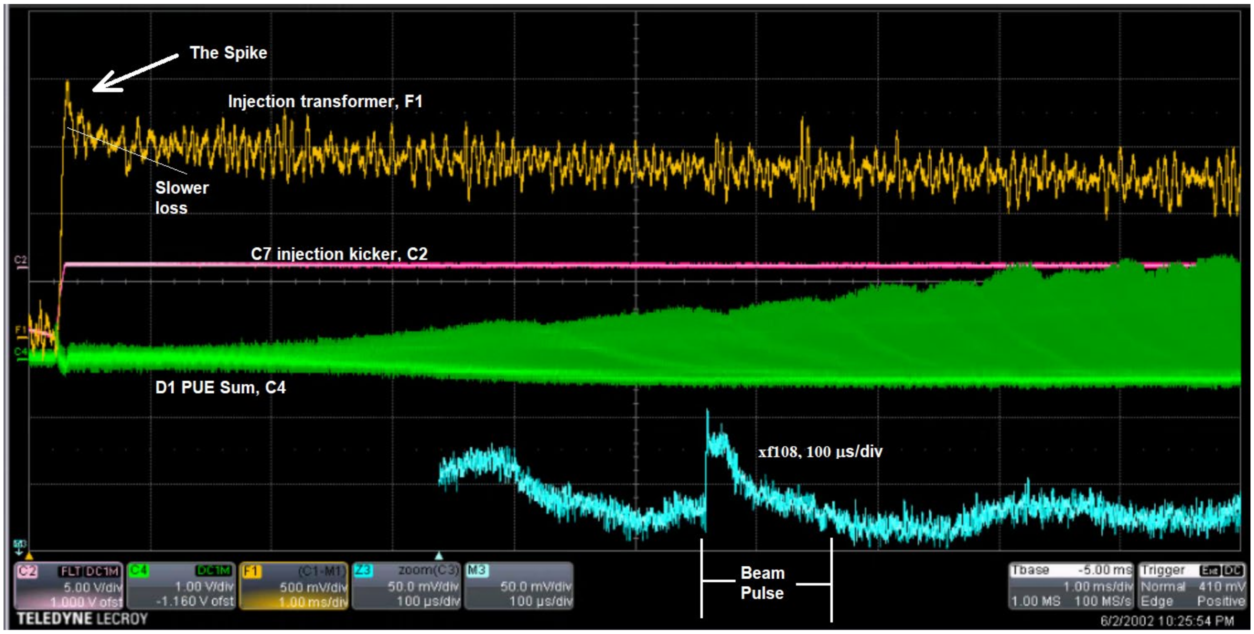

Figure 13: EBIS Au injection into the Booster on July 31. The orange trace is the injection transformer with the baseline subtracted (500 mV/div, F1), the red trace is the C7 injection kicker (5V/div, C2, 1 MΩ), the green trace is the D1 PUE Sum (1V/div, C4, 50 Ω), and the blue trace is EtB xf108 current transformer (50 mV/div, Z3, 50 Ω). The sweep speed is 1 ms/div and the trigger is pseudopeaker + 3300 µs except for the xf108 trace which is 100 µs/div and the trigger is shifted.[39]

It was also noticed on Aug 18th that the C1 injection kicker was collapsing more slowly than C7.[40] They should collapse at the same rate. Work on improving C1's fall time was postponed until after the NSRL run so that the changes would not affect that and on Dec. 7th this work was done. It is not clear if the problem with C1 was at least in some part responsible for the poor injection efficiency and if changing the injection setup was a way of getting around it.

[37] See Booster-AGS-EBIS elog entries from 1735 to 1826 on Aug. 4th 2023.
[38] See Booster-AGS-EBIS elog from Aug. 8 2023 at 19:44.
[39] Taken from the Booster-AGS-EBIS July 31, 2023 elog entry at 14:31.
[40] See Booster-AGS-EBIS elog on Aug. 18 2023 from 15:13 to 16:22.

However, the Booster efficiency was OK when EBIS Au was used in Run 22 and there is some evidence that C1 was in a similar state then.[41]

Figure 14 shows how injection looked on Aug. 10th, after the above changes were made. Note the spike is much less pronounced and the slower loss is not readily apparent. The transformer signal will have a negative slope over the 10 ms interval shown whether there is a slow loss there or not because of the fast time response of the signal. The efficiency, peak/xf108, here is 94%. Note that the EBIS pulse is still perhaps about 50 μs long. The highest Booster Late measured on a scope while using only a single EBIS pulse during this post-run period was 4.64e8 ions (Figure 15).[42] At that time, judging from the scalers, a typical Booster Late averaged about 4.3e8 and Booster input was roughly 10% higher than that.[43]

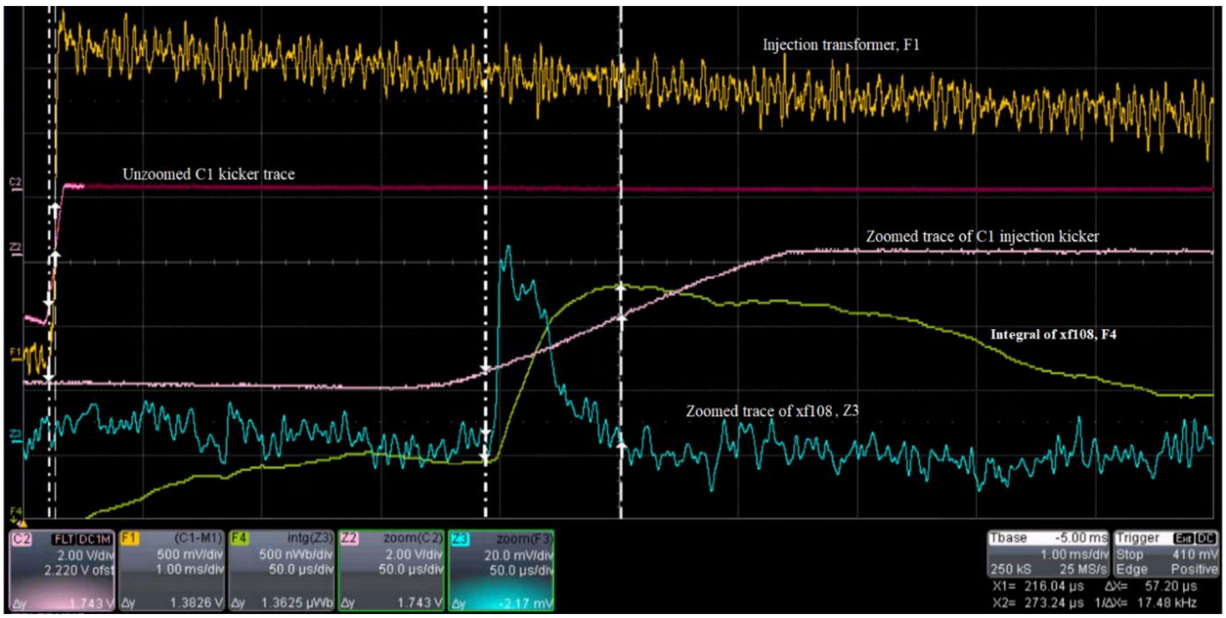

Figure 14: EBIS Au injection into the Booster on August 10th. The orange trace is the injection transformer with the baseline subtracted (500 mV/div, F1), the darker red trace is the C1 injection kicker (2V/div, C2, 1 MΩ), the lighter red trace is a zoomed trace of the C1 kicker (2V/div, Z2, 1 MΩ, 50 μs/div), the blue trace is the zoomed EtB xf108 transformer (20 mV/div, Z3, 50 μs/div, 50 Ω), and the green trace is the integral of the xf108 signal (1.3625 μVs or 5.61e8 Au ions). The peak intensity on the injection transformer is 5.25e8 ions, 94% of the xf108 intensity. The zoomed kicker and xf108 traces show where the injected beam falls on the injection bump. The sweep speed is 1 ms/div and the trigger is pseudopeaker+3300 μs except for the zoomed traces which have 50 μs/div and their trigger is shifted.[44]

[41] On Feb. 3, 2022 the Booster efficiency was about 85% (Booster-AGS-EBIS Feb, 3 2022 17:04 entry) and logged data seem to indicate that C1 was slower than C7 then too, but it is hard to say definitively if it was slow to the same degree (Booster-AGS-EBIS Aug. 21, 2023 entries from 13:18 to 13:31).
[42] See Booster-AGS-EBIS Aug. 18, 2023 elog entry at 17:44.
[43] See Booster-AGS-EBIS Aug. 18, 2023 elog entry at 17:45. The injection Q_h and injection bump were briefly reverted to the setup that was in place prior to August 1st, and the Booster efficiency, which was about 90% dropped to about 75% (see Aug. 18 17:28 entry in the same elog).
[44] From Booster-AGS-EBIS elog 13:58 entry on Aug. 10, 2023.

The H- stripping foil was inserted for all the measurements from July (Table II) and retracted for the ones made in August (Table III). It is more difficult to reach the same Booster efficiency with it inserted so it was removed during the work in August to make things easier. However, on August 11^{th} it was inserted and that setup was optimized. There is a bump used to move the orbit away from the foil. After loading this bump and making some other changes to the 5^{th} harmonic of the horizontal orbit, the Booster efficiency, as measured by the scalers, reached about 90%.[45] It may have been slightly higher with the foil retracted and those orbit changes reverted, but the difference was not nearly enough to account for the difference between the July and August efficiencies. In July, the bump around the foil was in place, as it usually is (for NSRL).

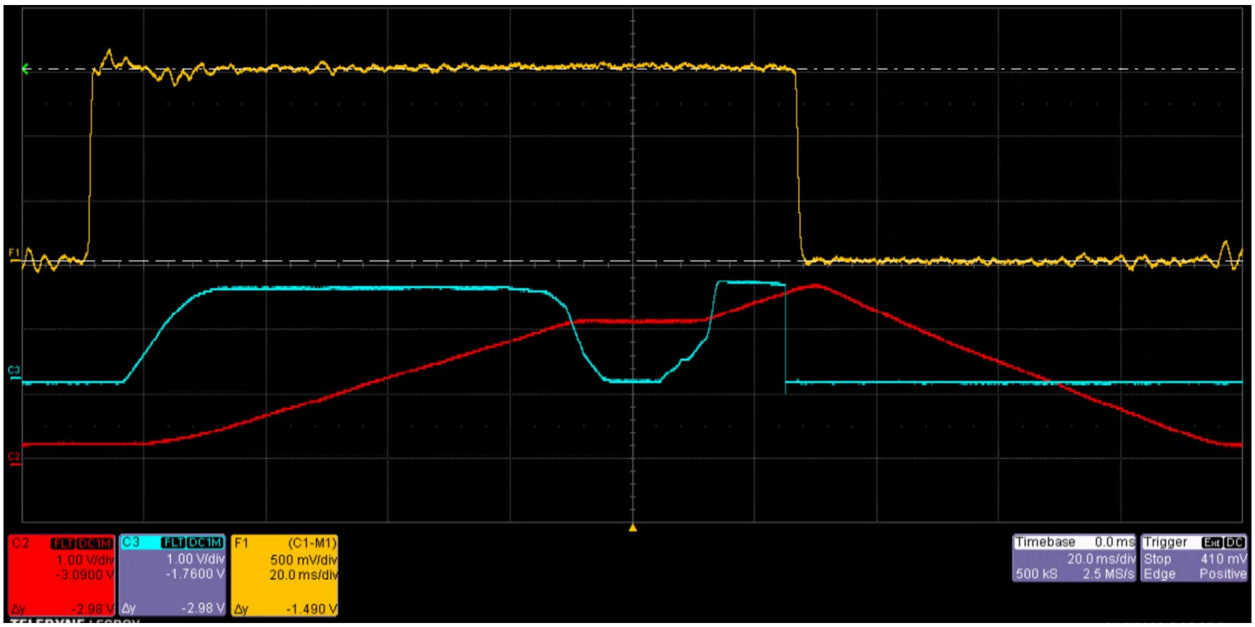

Figure 15: Booster Late intensity measurement using the normalized circulating transformer (F1) for the EBIS Au cycle on Aug. 18^{th}. Also shown are the A3 RF voltage (blue, C3) and the Booster main magnet current (red, C2). Using the calibration 3.12e8 Au^{32+} ions per volt, 1.49V corresponds to 4.64e8 ions.

Summary

Au beam from Tandem with an AGS flattop energy of 9.8 GeV was used for this run. The setup had not been used to provide beam to RHIC before. What was expected to be the challenging part of the run, requiring bunch intensities greater than 3e9 ions, did not come to

[45] See Booster-AGS-EBIS Aug. 11, 2023 elog entries from 15:01 to 15:24.

pass because the run ended prematurely.[46] Average bunch intensities of about 1.9e9 (7.6e9 AGS Late) were provided for a few fills not long before the end of the run (see Figure 2).

Unfortunately, ε_L was not measured at that intensity but was 0.23 eVs for a bunch intensity of 1.35e9 (Table I). This is about the same as for the Tandem Au setup used prior to the advent of EBIS and about a third of what it is using the EBIS Au setup with a 6-3-1 type merge in the AGS. However, whereas ε_L has not shown intensity dependence for that EBIS setup there are some indications that ε_L for this year's setup did.

ε_L measurements on the injection porch were taken after filamentation in runs 20, 21, and 22. Nominally the setup was the same in all 3 cases, but the measured ε_L was 0.125 eVs in run 20, 0.099 eVs in run 21, and 0.0753 eVs this run. The BtA foils were replaced between runs 20 and 21. The foil used in Run 20 (#5), became severely damaged during the course of that run, and the foil used in Run 21 (#6) also became damaged but to a lesser extent. Although, once a spot on the foil started to deteriorate the beam was moved to another spot. The BtA foil used this run, #5, had not been used regularly up until this run and there was no deterioration of the BtA performance observed with it. The Booster late intensity was limited to 16e9, but the limit in Runs 20 and 21 was 2.0e9. Perhaps the different foils and the Booster Late intensity used have something to do with the different ε_L's measured.

An RMS transverse emittance measurement on the flattop using the Ion AGS IPM with an AGS Late of about 8.0e9 was 1.8 mm mr in both planes.

Experience this run with Au from the upgraded EBIS was documented (pgs. 13-21). The higher Booster Late intensity for 1 cycle was about 4.6e9. After some difficulties the Booster efficiency did reach normal levels (85% or higher). Instead of 50% or so, the BtA efficiency with 12 pulses only reached about 41%. The highest bunch intensity on flattop was about 5e8 ions. That occurred when the Booster efficiency was still low.

[46] See Travis Shrey's FY23 Overview presentation at the 2022 RHIC retreat, "RHIC 2023 Operations Plan", pg.3 where he notes a desired bunch intensity of 3.2e9 at RHIC injection.