BNL-222206-2021-TECH

C-A/AP/653

Run 21 in the Injectors

K. Zeno

September 2021

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

DISCLAIMER

Run 21 in the Injectors

Keith Zeno
9-30-2021

During Run 21 the injectors provided Gold for RHIC at four different energies (3.85, 7.30, 8.65, and 9.80 GeV). They also provided Oxygen and deuterons. Some aspects of the setups are summarized in Tables I and II. Setup for the run began in late January 2021 and the run ended in early July. The first 3 months were mostly spent providing Au from Tandem to RHIC at 3.85 GeV for collisions using LEReC (setup 1).

Setup	**Ion**	**Flattop Energy (GeV)**	**AGS user**	**AGS RF merge harmonics**	**# of bunches merged**	**AGS RF ramp harmonic**	**Final # of bunches**	**Nominal bunch intensity**	**Typical longitudinal emittance**	
									eVs/n	**date**
1	Au	3.85	1	12-6	2	12	4	2.3e9	0.21	3/25
2	Au	3.85	2	24-16-8	3	12	4	1.2e9	0.39	1/30
3	Au	7.30	6	24-12-4	6	10	2	2.3e9	0.71	3/11
4	Au	8.65	7	24-12-4	6	10	2	2.3e9	0.90	5/28
5	Au	9.80	5	24-12-4	6	10	2	2.3e9	0.76	6/25
6	O	12.21	3	18-9-3	6	9	2	1.1e10	1.10	5/13
7	Au	3.85	8	24-12-4	6	10	2	2.3e9	0.71	6/2
8	d	9.86	3	12-6-3	4	9	2	1.3e11	0.58	6/27

Table I: The setups used during Run 21 and some of their properties. In all cases there is 1 bunch per transfer from the Booster to AGS. The AGS RF ramp harmonic is what is used on the ramp after the merge(s). For each setup, the AGS RF injection harmonic used is the same as the first of the AGS RF merge harmonics.

Setup	**Ion & Energy (GeV)**	**Pre-injector**	**Booster user**	**Setup starts**	**Date extracted from AGS**	**Date injected into RHIC**	**Date used in RHIC**	**Date finished in RHIC**
1	Au 3.85	Tandem	1	1/21	1/28	1/29	2/4	5/1
2	Au 3.85	EBIS	5	1/26	1/30	1/30	1/31	5/5
3	Au 7.30	EBIS	5	1/27	1/27	2/1	3/11	6/17
4	Au 8.65	EBIS	5	4/8	4/8	5/24	5/25	6/7
5	Au 9.80	EBIS	5	5/4	6/25	6/28	7/3	7/7
6	O 12.21	EBIS	3	5/5	5/9	5/9	5/11	5/24
7	Au 3.85	EBIS	5	6/2	6/7	6/7	6/7	6/28
8	d 9.86	Tandem	3	6/22	6/28	6/28	7/3	7/7

Table II: More properties of the setups used in Run 21. "Date used in RHIC" means when the beam was first used for physics, CeC development, or the like. "Date finished in RHIC" is when use of the beam in RHIC for that setup finished. The Supercycle length was 6.0 sec for all setups except the 1st, which was 6.0 sec until 3/9 when it was changed to 5.4 sec.

There were 3 other modes employing collisions during the run: Au at 8.65 GeV (setup 4), Oxygen at 12.21 GeV (setup 6, same rigidity as Au 9.8 GeV), and deuteron-Gold both at about 9.8 GeV (setups 8 and 5).[1] There were 2 other 3.85 GeV setups that were used for fixed target runs.[2] 7.3 GeV (setup 3) and 9.8 GeV (setup 5) were used for CeC development. Setups 1 and 8

[1] Setup 5 was also used for CeC development during the d-Au part of the run.

[2] Setup 2 was also used instead of setup 1 for 3.85 GeV collisions from 1/31 to 2/4 because Tandem was unavailable due to TtB Access controls work.

used Tandem as the pre-injector and all others used EBIS. Setups that used EBIS nominally had 12 Booster transfers and those that used Tandem had 8. As usual, the Booster setup was the same for all EBIS Au setups (BU5).

Most of these setups have been used in previous years. However, Oxygen (setup 6) had not been, and neither had Au at 8.65 GeV (setup 4) and setup 7, which uses a 6-3-1 type merge with 3.85 GeV. Although 8.65 GeV was new, it is essentially the same as 7.3 GeV except the flattop is slightly above transition instead of slightly below it.[3] Deuterons were last used in 2016 and the deuteron setup (8) used this year was essentially the same as that one. Setup 5 (Au 9.8 GeV) was used for d-Au as well as fixed target and CeC development.

The EBIS Au intensity was typically about 20% lower than it has been in previous years. This did not have a major impact since the RHIC requirements for those setups were not as demanding as in previous runs. Using lower EBIS intensity reduced the risk of an EBIS failure. A significant EBIS failure would impact not only RHIC but also NSRL, which ran during most of the run. The lower EBIS intensity is reflected in the nominal bunch intensities indicated in Table I.

The required deuteron bunch intensity was also a lot lower than it had been in 2016. It turned out that an AGS bunch intensity of about 0.7e11 was used for d-Au although the bunch intensity available was typically around 1.3e11. In 2016 an AGS bunch intensity as high as about 1.8e11 was sometimes used.

Last run the BtA stripping foils used for Au were damaged by the beam while in 5.75 GeV mode. This mode used Tandem as the pre-injector, and had intensities per AGS cycle that the foils had not been exposed to before.[4] The same kind of damage was anticipated for this run during 3.85 GeV (setup 1) since the setup upstream of the foil is the same and it was expected to be in operation for several months. Preceding this run the foil drive was opened, the 2 damaged foils that had been used for Au were removed, and new foils of the same kind were installed at positions 5, 6, and 7. Foils for Oxygen were also installed at positions 3 and 4.

Stripping Efficiencies of the 3 New Au BtA Foils

On Feb. 11th the stripping efficiency of the Au BtA foils from Au^{31+} to Au^{77+} was measured using BU1 and BtA multiwire MW060. The data and results are shown in Table III. The measurements were taken with beam only on Booster cycle 2 so the intensity, as measured on the Booster Late scaler, for each set of multiwire profiles would be known. The stripping efficiencies of foils 5, 6, and 7 were found to be 60.6%, 60.7%, and 61.2%, respectively.

The stripping efficiencies of the 2 Au foils that were replaced were measured in 2019 using EBIS beam and they were 63.7 and 63.9%.[5] These values are a little higher than they are

---

[3] For 7.3 GeV γ was 7.85 and η was -2.40e-3 and for 8.65 GeV γ was 9.29 and η was 2.24e-3 (using γ_t=8.50). The energy, 8.65 GeV, was specifically selected because $|\eta|$ is (nearly) the same as it is for 7.3 GeV.

[4] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, pgs. 6-15 for more about the foil damage. See also C. Gardner, "Change of BtA foils 2020" for detailed information about the new foils.

[5] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pgs. 12-14.

for the new foils. The extraction energy is a little higher for EBIS than it is for Tandem beam since the rigidity is the same but the EBIS charge state is +32 not +31. Measurements from 2011 with Tandem Au^{31+} beam, at a slightly lower energy than used this run for Tandem found 59-61%.[6] The BtA efficiency was not obviously different this year than it was last year with the old foils. Although a stripping efficiency measurement from when this type of foil was first used was 65%.[7]

Foil 5

Charge State	**Au^{75+}**	**Au^{76+}**	**Au^{77+}**	**Au^{78+}**	**Au^{79+}**	**Total Area**
Area	1.19	7.15	15.46	1.61	0.11	25.52
Intensity	1.92e9	1.92e9	1.92e9	1.92e9	1.93e9	-
1.92e9/Intensity	1	1	1	1	0.995	-
Area*(1.92e9/Intensity)	1.19	7.15	15.46	1.61	0.11	25.52
Stripping efficiency	0.047	0.280	**0.606**	0.063	0.004	-

Foil 6

Charge state	**Au^{75+}**	**Au^{76+}**	**Au^{77+}**	**Au^{78+}**	**Au^{79+}**	**Total Area**
Area	1.05	6.88	14.66	1.52	0.06	24.17
Intensity	1.83e9	1.83e9	1.83e9	1.83e9	1.81e9	-
1.83e9/Intensity	1	1	1	1	1.006	-
Area*(1.83e9/Intensity)	1.05	6.88	14.66	1.52	0.06	24.17
Stripping efficiency	0.043	0.285	**0.607**	0.063	0.003	-

Foil 7

Charge state	**Au^{75+}**	**Au^{76+}**	**Au^{77+}**	**Au^{78+}**	**Au^{79+}**	**Total Area**
Area	1.29	6.78	15.58	1.63	0.09	25.37
Intensity	1.81e9	1.92e9	1.92e9	1.92e9	-	-
1.92e9/Intensity	1.061	1	1	1	1	-
Area*(1.92e9/Intensity)	1.37	6.78	15.58	1.63	0.09	25.45
Stripping efficiency	0.054	0.266	**0.612**	0.064	0.004	-

Table III: Stripping efficiency measurements for the new BtA foils used for stripping to Au^{77+} (foils 5, 6, and 7). The stripping efficiency for each charge state is in the last row of the table for the foil in question. It is calculated by dividing the value for that charge state in the 5th row by the total area indicated for that row. These measurements were taken at the center foil position with BtA DH1 set to 352A. The data is from Feb. 11th and was taken with Tandem Au^{31+} (BU1).[8]

Another stripping efficiency measurement was made with Tandem Au on April 14th using foil 6. The results are shown in Table IV. The efficiency was slightly higher than the previous measurement (62.1 vs. 60.7%). The foil can be moved vertically with respect to the beam and the beam can be moved horizontally on the foil using the BtA DH1 dipole . This measurement was taken with the beam at a different position on the foil than on Feb. 11th.

[6] See Booster-AGS-Au_2011 elog Jun 22 1627 entry
[7] P. Thieberger et al, "Improved gold ion stripping at 0.1 and 10 GeV/nucleon for the Relativistic Heavy Ion Collider" Phys. Rev. Spec Topics, 2008, pg. 011001-8. The energy for these measurements was the same as in 2011.
[8] See Booster-AGS-EBIS_2021 elog Feb. 11 entries from 1357 to 1423.

Charge state	Au^{75+}	Au^{76+}	Au^{77+}	Au^{78+}	Au^{79+}	Total Area
Area	0.7	4.11	10.06	1.18	0.11	16.16
Intensity	1.11e9	1.19e9	1.19e9	1.19e9	1.20e9	
1.193e9/Intensity	1.071	1	1	1	0.995	
Area*(1.193e9/Intensity)	0.75	4.11	10.06	1.18	0.11	16.21
Stripping efficiency	0.043	0.254	**0.621**	0.073	0.007	

Table IV: Stripping efficiency measurements for foil 6, position 5.90 with BtA DH1 set to 400 A. The stripping efficiency is calculated the same way as in Table III. Data is from April 14th.[9]

The History of BtA Stripping Foil Deterioration During Tandem 3.85 GeV Running

The injectors ran with 3.85 GeV for about 3 months. The intensity was similar to 5.75 GeV last year. This year the current in the BtA quad QV3, which is just upstream of the foil, was reduced from 800 to 600A in hopes that this might increase the beam size at the foil and thereby reduce the foil heating which is thought to damage the foils. This is a vertically focusing quad. This change did not noticeably affect the transfer efficiency.

Foil 6 was used exclusively for 3.85 GeV. During last run damage started to occur only about a week after the intensity (per supercycle) was increased into the range where it seems to occur (Booster late >1.6e10).[10] This year, foil degradation was not noticed until about 2 months after the first injection into RHIC on Feb. 4th, but the Booster Late was generally lower than the 1.6e10 threshold for about the first month (see Figure 1). That was mainly because putting more bunch intensity into RHIC did not improve the collision rate. As that situation improved the intensity was increased to near the administrative limit of 0.96e10 per AGS cycle. Booster Late is also limited to 2.0e10 administratively.

It is hard to say definitively, but it may be that the reduced current in QV3 increased the intensity threshold where deterioration starts to occur. Nevertheless, it did start to happen. Figure 2 is a timeline of the changes in foil position required to maintain BtA efficiency. Foil 5 was used for all the other Au setups, which used EBIS beam, and showed no sign of deterioration.

As noted last run, the injected bunch viewed on the mountain range develops a low momentum tail when the foil starts to deteriorate (see Figure 3).[11] Looking for this is perhaps the most straightforward way to determine that the foil is starting to deteriorate since other factors may cause the BtA efficiency to decrease and this tail often develops before any obvious decrease in BtA efficiency. For example, in the damaged foil case shown in Figure 3 the BtA efficiency was 52-53%, at least as indicated by the scalers, which is fairly typical. As it

[9] See Booster-AGS-EBIS_2021 elog Apr. 14 entries from 1314 to 1341..
[10] See the Booster-AGS-EBIS_2021 1225 to 1230 entries on Nov. 30th
[11] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, pgs. 7 to 11.

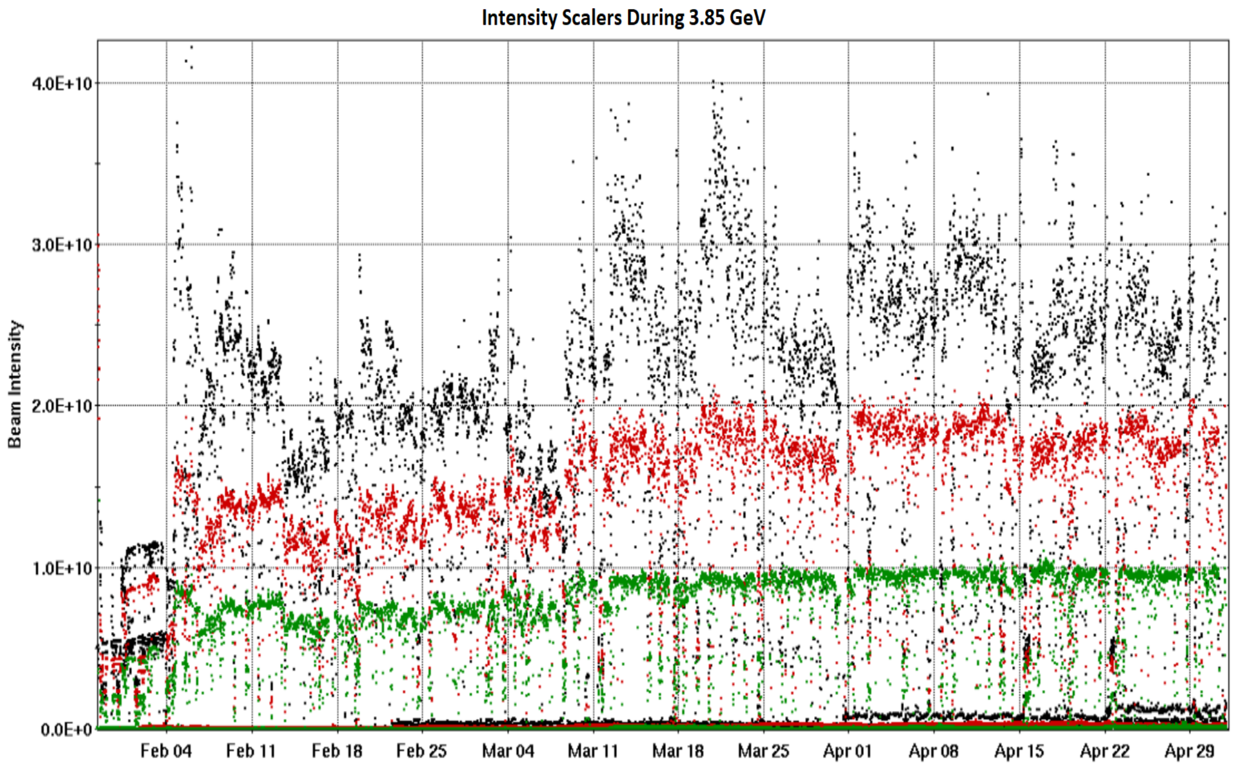

Figure 1: Booster input (black), Booster Late (red), and AGS Late (green) during 3.85 GeV (1/21 to 5/1)

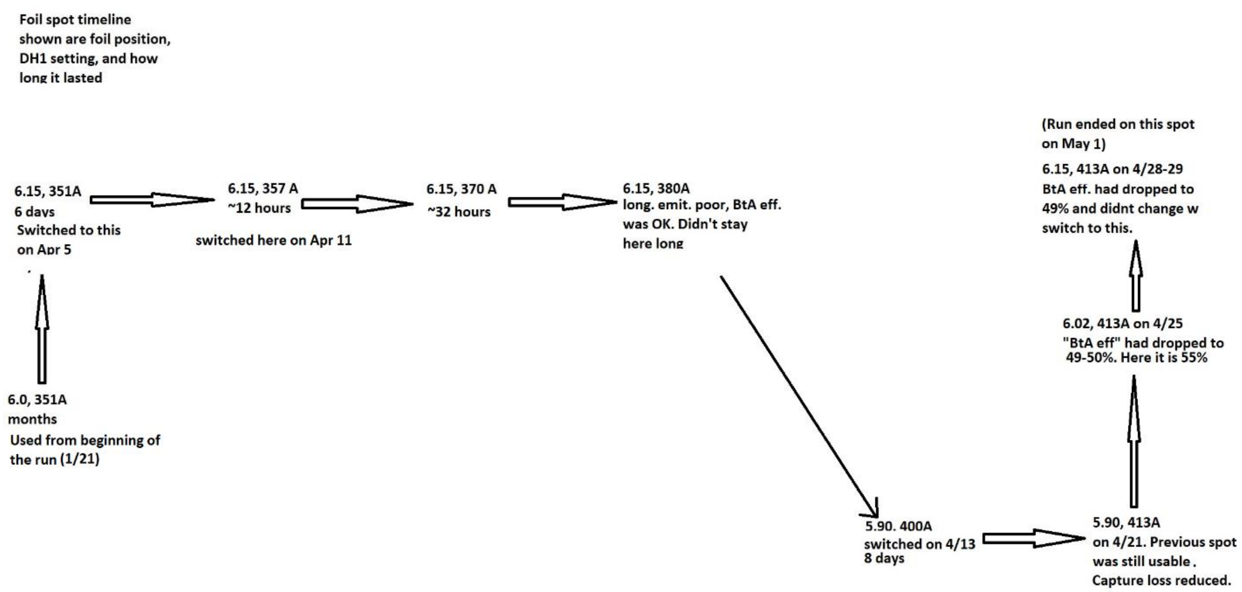

Figure 2: Timeline of foil position changes required to maintain nominal BtA efficiency during 3.85 GeV. When DH1 is changed the beam spot on the foil moves horizontally and when the foil position is changed the foil moves vertically.

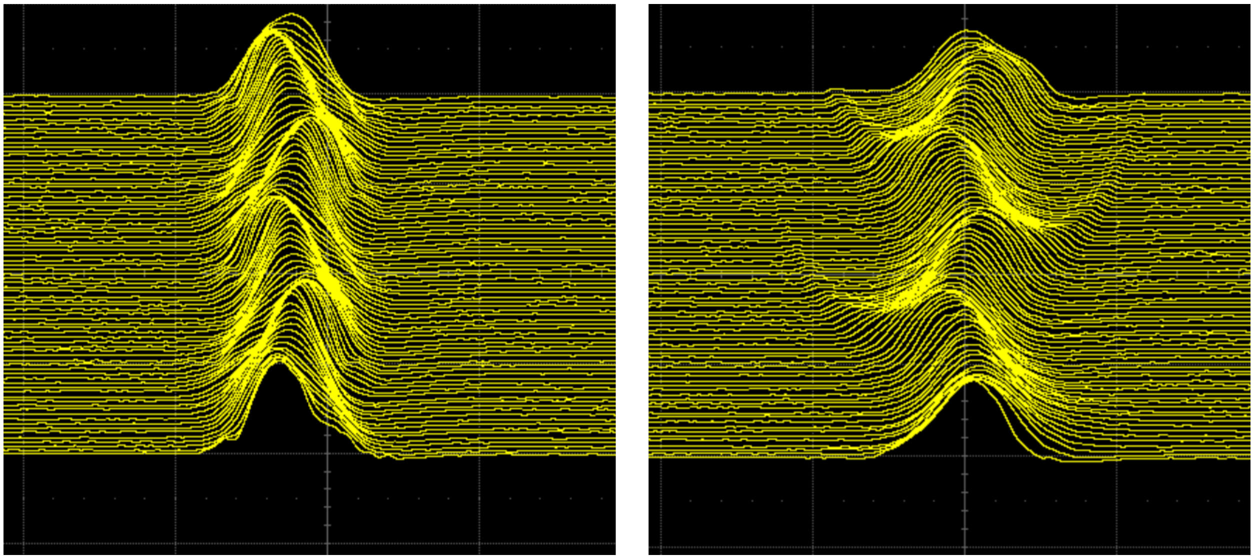

Figure 3: Comparison of wall current monitor mountain range display at AGS injection when beam is passing through an undamaged part of the BtA foil (left, April 15 at 2208) and when it is passing through a damaged spot (right, April 13 at 1331). There are 80 traces, the spacing between traces is 50 μs, the sweep speed is 200 ns/box, and the gain is 100 mV/div. 50Ω termination. The RF voltage is the same in both cases (40 kV on the logged vector sum).

deteriorates, the capture loss at the beginning of the ramp to the merge porch increases and the flattop longitudinal emittance (ε_{long}) also increases.[12]

When this is observed and the BtA efficiency is decreasing it is not obvious that the stripping efficiency decreases.[13] So perhaps, at least in cases where the foil deterioration is not severe, the BtA efficiency may decrease because of the increased momentum spread associated with the low momentum tail. As was shown last year though, the BtA efficiency can drop sharply, and in those cases the foil may develop a hole or the like (at least in the Aluminum layer), so comparing the amount of beam in nearby charge states will not tell the whole story.[14]

The transverse emittance, as indicated with the AGS ion IPM, gets smaller when the foil deteriorates. It seems that this is because of blowup that occurs right at injection and is not as bad when the bunch gets larger longitudinally. In fact, during the latter part of the 3.85 GeV running, the injected bunch was made wider using quad pumping at Booster extraction. This seemed to reduce the blowup.

[12] Compare capture loss in 1515 and 1655 entries in Booster-AGS-EBIS Apr 13 2021 elog. The foil spot is bad for the 1515 case and good for the 1615 case. ε_{long} was also measured for both cases (see entries from 1625 to 1634 for the bad foil spot and entries from 1657 to 1706 for the good spot). ε_{long} was 0.287 eVs and 0.218 eVs for the bad and good spots, respectively.

[13] See Booster-AGS-EBIS Apr 26 2021 elog entries from 1259 to 1316. The areas of profiles for charge states 76, 77 and 78 were measured on MW060. The fraction of beam in Au^{77+} over that in these 3 states was 0.663 with 52-53% BtA efficiency (foil 5.90, DH1 at 413A) and 0.659 with a "better" foil spot (foil 6.02, DH1 413A) that had 56% efficiency. The stripping efficiency seems about the same in both cases, but the BtA efficiency is not.

[14] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, pgs. 7 to 15.

Transverse and Longitudinal Emittances on the Tandem 3.85 GeV Cycle

Table V is a compilation of ε_{long} measurements made on the Tandem 3.85 GeV flattop. For normal operating conditions ε_{long} is typically about 0.21 eVs and there is no obvious intensity dependence over the bunch intensity range from 1.5 to 2.2e9. A larger ε_{long} was used during the last 2 weeks or so of the run, but that was done intentionally to reduce transverse emittance growth at AGS injection. Note also that when the BtA foil is deteriorating, ε_{long} is larger (compare rows 12 and 13).

On April 14th the A6 RF cavity in the Booster tripped off and RHIC was filled without it.[15] The STAR event rate in RHIC was comparable to what it was with A6 on even though ε_{long} was about 60% larger (0.341 eVs, row 14 in Table V) than what is typical (0.21 eVs).[16] The AGS late intensity during that fill was also about 7% lower than it would have been if A6 was on.

	Date	**f_{synch} (Hz)**	**Bunch length (ns)**	**ε_{long} (eVs)**	**Bunch Intensity**	**Notes**
1	Feb. 4	302	42.65	0.215	1.7e9	
2	Feb. 6	295.2	43.5	0.219	1.75e9	
3	Feb. 6	295.2	40.52	0.190	1.7e9	Booster merge needed tuning
4	Feb. 8	162	58.9	0.217	1.7e9	Flattop voltage lowered
5	Feb. 8	162	73.3	0.330	1.3e9	A6 RF mostly off
6	Feb. 10	160.72	59.7	0.215	1.8e9	Foil 7
7	Feb. 10	160.72	59.5	0.219	1.9e9	Back to foil 6
8	Feb. 10	160.72	57.4	0.205	1.8e9	Booster merge tuning
9	Feb. 17	161.7	58.25	0.212	1.7e9	
10	Mar. 3	163.24	55.48	0.195	1.5e9	
11	Mar. 25	161.7	57.24	0.205	2.15e9	
12	Apr. 13	163.8	67.8	0.287	2.3e9	Bad foil position
13	Apr. 13	163.8	58.71	0.218	2.2e9	Good foil position
14	Apr. 14	163.8	74.2	0.341	2.0e9	A6 off
15	Apr. 23	162.61	65.66	0.268	2.2e9	QP on since Apr. 16
16	Apr. 25	160.08	66.8	0.273	2.3e9	QP on

Table V: ε_{long} measurements taken on the Tandem 3.85 GeV flattop (setup 1). Quad Pumping (QP) at Booster extraction was used from April 16 to the end (May 1).

[15] With A6 off the 6-3-1 merge in Booster becomes a debunch-rebunch from 6 to 2 followed by a 2-1 merge. In the Booster-AGS-EBIS 2021 elog the Apr14 1734 entry shows how the injected bunch looks on an AGS WCM mountain range display when A6 is on and off.

[16] See 1734 entry in Booster-AGS-EBIS April 14 2021 elog. The baby bunches during the fill with A6 off were quite small (about 0.5%). The integrated starEventTrigger3:rate signal for the fill without A6 (31330) was 49960 and for the following 2 fills with A6 on it was 49440 and 49725.

It was found that the (normalized RMS) transverse emittances, (ε_x, ε_y), in the AGS when A6 was off were significantly smaller. For an AGS late of 8.8e9 (ε_x, ε_y) on the flattop at 3500 ms was (1.51, 1.69) mm mr with A6 on and (1.22, 1.25) mm mr with it off (see Figure 4). Note that both the emittances with A6 off are smaller from the start and the emittances in the 2 cases more or less just track each other through the cycle but are offset from each other. So, it seems reasonable to suspect that the growth associated with the smaller ε_{long} when A6 is on occurs immediately after a bunch is injected.

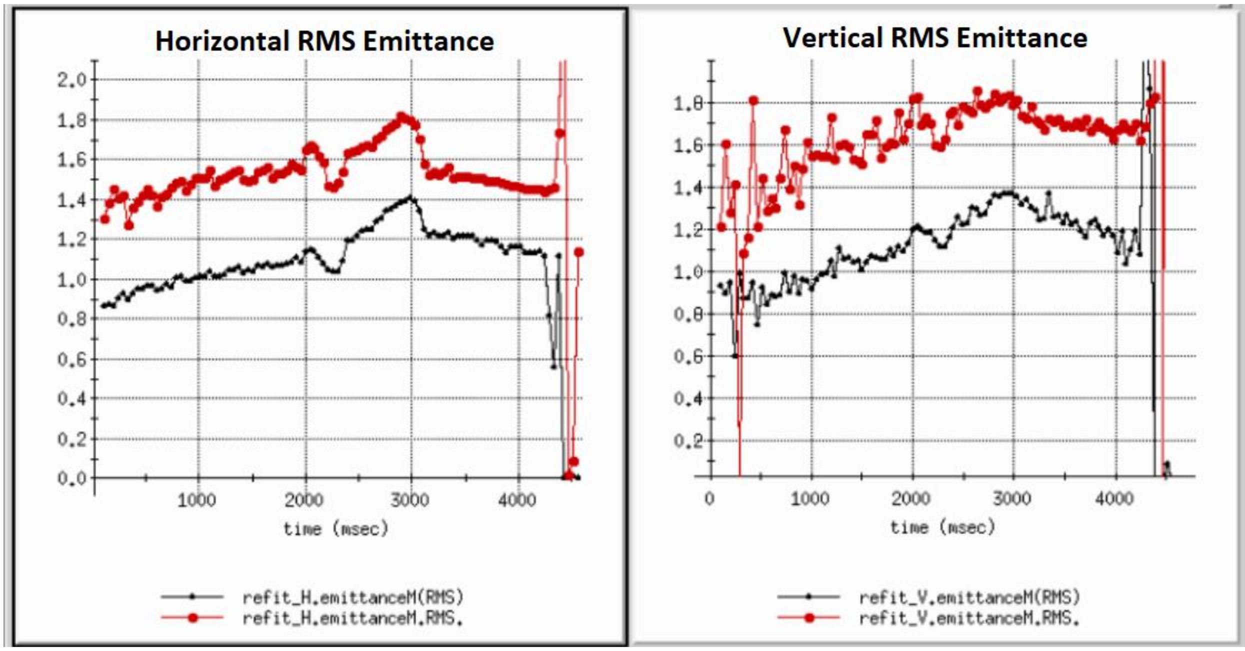

Figure 4: Comparison of AGS ion IPM RMS normalized transverse emittances with A6 on (red) and off (black) with an AGS late of 8.8e9. A6 off data from April 14 at 17:25:44 2021 and on data from April 14 at 19:00:53 2021. Both sets of data use Refit and the RF is on during flattop.

Figure 5 shows the effect on transverse emittance due to the increased ε_{long} associated with a damaged spot on the BtA foil.[17] In this case the flattop ε_{long} is about 32% larger than when the beam hits a good spot. Both cases have an AGS Late of 9.3e9, and (ε_x, ε_y) for the undamaged spot at 3500 ms was (1.56, 1.74) mm mr and (1.42, 1.52) mm mr for the damaged one. The behavior here is similar to that in Figure 4 but the effect is not as large.

Starting on April 16th quad pumping (QP) was setup at Booster extraction to make the bunches wider when injected into the AGS to decrease the peak charge density to reduce the transverse blowup.[18] Figure 6 compares with and without QP cases at an AGS Late of 9.3e9. The without QP case is the same data as in Figure 5 for the undamaged case. From the figure it

[17] In the Booster-AGS-EBIS 2021 elog the Apr. 13 1331 entry shows what the injected bunch looks like on the AGS WCM mountain range display with the damaged foil spot and the 1655 entry shows what it looks like with an undamaged spot.
[18] No reduction in the blowup was evident from scanning the tunes, chromaticities, octupole and sextupole stopband correctors away from where they had already been optimized for normal size bunches.

appears that QP can be quite effective in reducing the blowup. Rows 15 and 16 in Table V indicate that ε_{long} on the flattop with QP on was about 0.27 eVs.

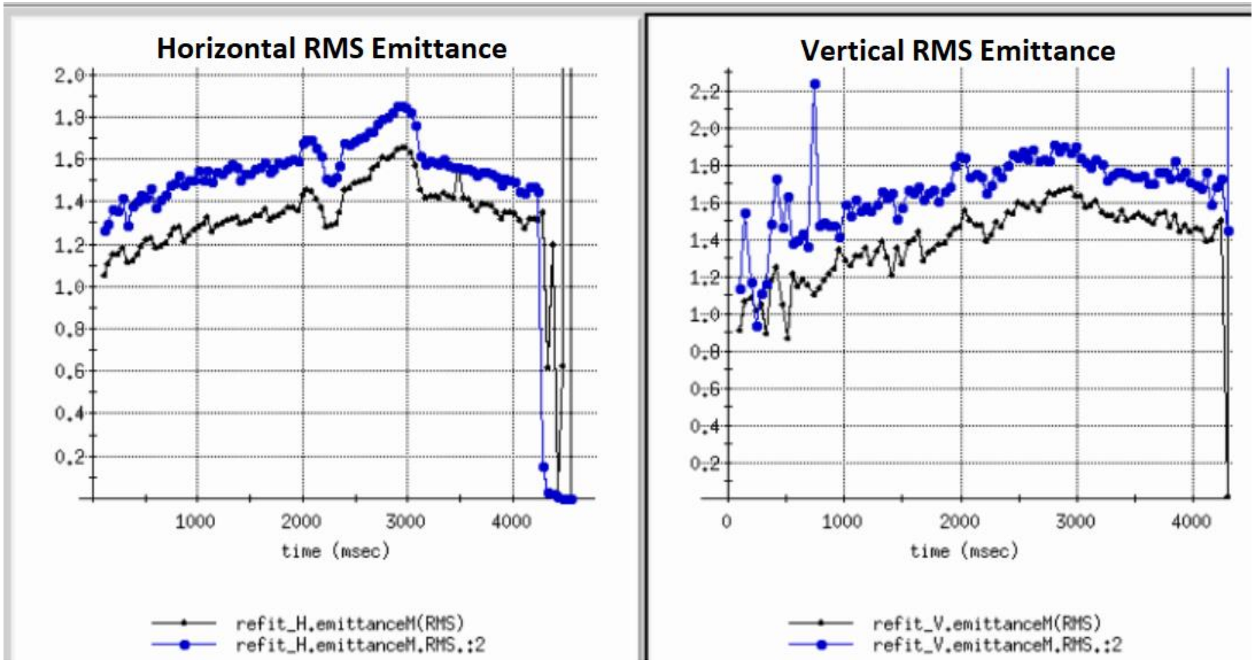

Figure 5: AGS ion IPM RMS normalized transverse emittances with the beam hitting a damaged spot on the BtA foil and a correspondingly large flattop ε_{long} (black, 0.287 eVs, row 12 in Table V) and hitting an undamaged spot and smaller flattop ε_{long} (blue, 0.218 eVs, row 13 in Table V). AGS late is 9.3e9 in both cases. Data in black is from April 13 16:25:13 and data in blue is from April 13 at 19:20:10. Both sets of data use Refit and the RF is on during flattop.

At least when using the normal ε_{long} the transverse emittance is quite intensity dependent. There was much speculation as to the mechanism for this. For example, due to the nature of multiturn injection, when the Tandem pulse width is increased, as it often is to provide more intensity, the transverse emittance will tend to grow. To address this possibility, the 3 available BtA multiwires were inserted at the same time to reduce the intensity injected into AGS. For Au, which is not fully stripped, inserting a multiwire reduces the intensity but probably doesn't affect the transverse emittance much, and if it does affect it, it seems unlikely that it would decrease it.

Figure 7 shows the emittance with and without the multiwires inserted with 2 different Booster Late intensities, 5e9 and 10e9. Only 4 transfers are used here but most intensity dependent effects should depend on the bunch intensity not the total intensity. The lower Booster Late used a 300 μs Tandem pulse and the higher a 600 μs one. The 5e9 case corresponds to a bunch intensity on the flattop of 1.25e9 without them inserted and 0.9e9 with them inserted. The 10e9 case corresponds to a bunch intensity on the flattop of 2.1e9 without them inserted and 1.7e9 with them inserted.

The emittances indicated by the IPM are larger with the multiwires out. At face value this suggests that at least a component of the intensity dependence occurs in the AGS, but the IPM's response to bunched beam is intensity dependent. The dip in the emittances, especially the horizontal, around 2200 to 2400 ms is associated with the merge. During some of this time only 1 cavity is on and it is h=6 not 12 so the bunches are much wider, albeit with twice the intensity. If the bunch intensity dependence of the IPM was dominating the increase in the measurement

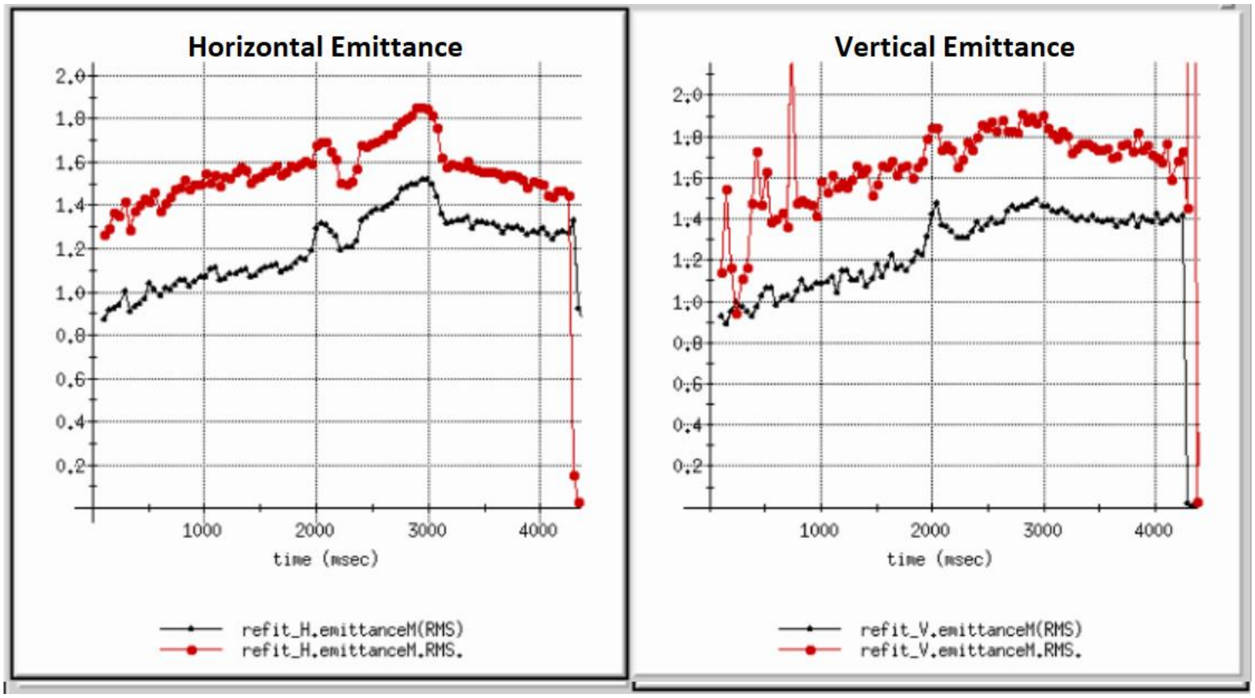

Figure 6: Comparison of AGS ion IPM RMS normalized transverse emittances with (black) and without (red) Quad pumping that makes the bunches wider at AGS injection. AGS Late in both cases was 9.3e9. The x-axis is time from At0. Data in black is from April 19 at 17:58:18 and data in red is from April 13 19:20:10. Both sets of data use Refit and the RF is on during flattop.

with intensity then one would expect the dependence to be less during the merge than in other places where the charge density is higher, like on the ramp, but there is not much difference.

The 4 transfers are also visible in the horizontal data. When the beam is injected ε_x goes down and then rises again until the next transfer. The emittance also appears to increase from the 4th transfer until the end of the injection porch, near 2000 ms.

The transverse emittance was also measured on BtA MW006 for 300 and 600 μs pulses when these measurements were made at these 2 Booster late intensities.[19] For the 300 μs pulse the RMS normalized (ε_x,ε_y) was (0.28, 0.23) and for 600 μs it was (0.48,0.45) mm mr. So, the beam was about twice as large at that time for a 600 μs pulse. The IPM, for the multiwire out cases, indicates that ε_x is about 1.3 mm mr for the first data point for 600 μs and roughly half of that (0.7 mm mr) for a 300 μs pulse. It also shows that ε_y for 600 μs is about 1.7 mm mr and is

[19] See Booster-AGS-EBIS March 24 2021 elog entries at 1356 and 1357. To calculate the RMS normalized emittances at MW006 from the FWHMs (x,y) the formulas $\varepsilon_x=(0.178x^2)/6$ and $\varepsilon_y=(0.033y^2)/6$ are used. For Tandem Au βγ is 0.492 and β_x=3.0 m and β_y=16.0 m, Injection bump timing (bdl.bij.fast_time) was set to 630 μs for both pulse widths.

once again about half of that for 300 μs, 0.9 mm mr. The beam also passes through the stripping foil downstream of MW006 and some transverse blowup is likely to occur from that.

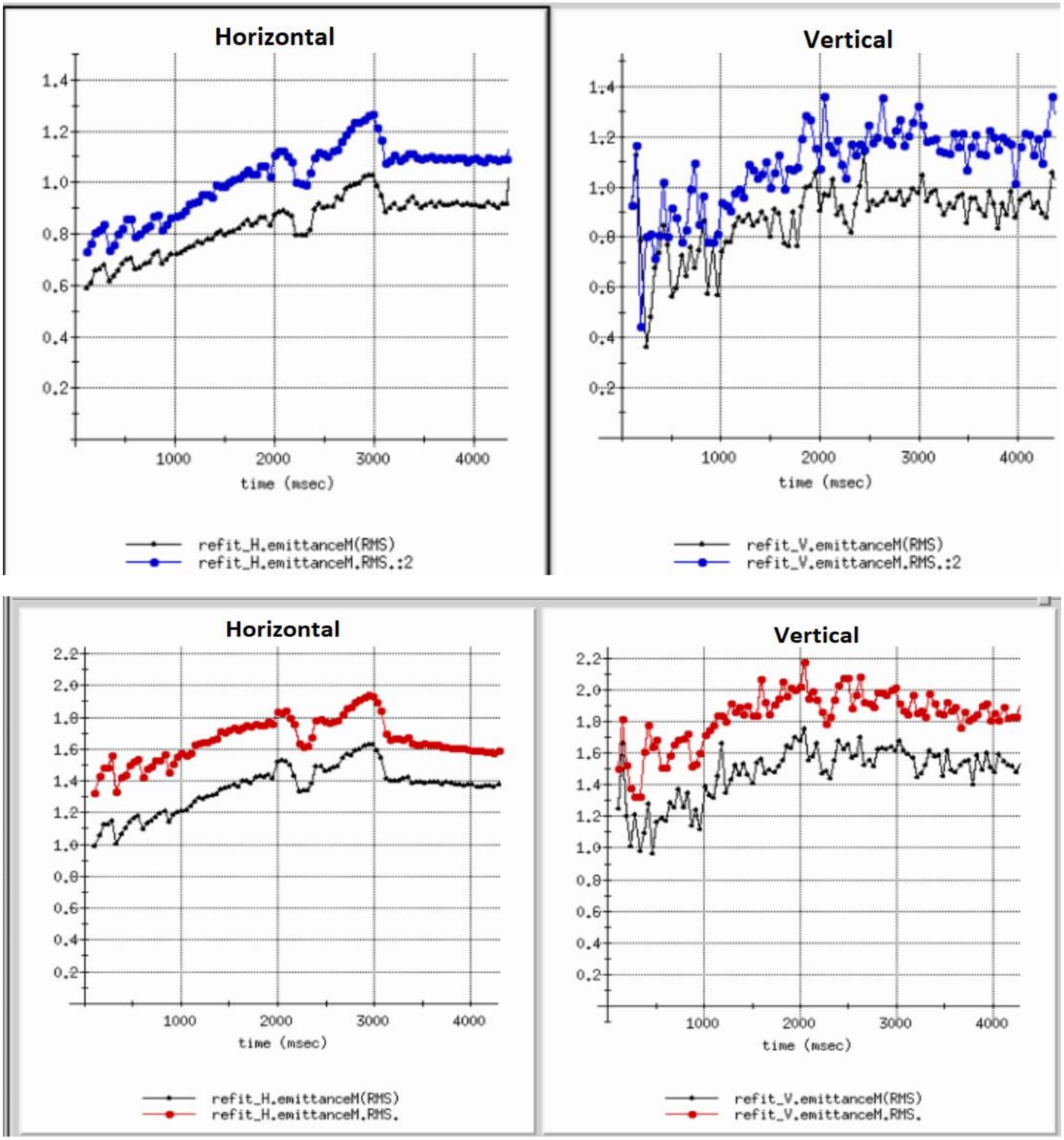

Figure 7: Comparison of AGS ion IPM RMS normalized transverse emittances with and without (blue and red) BtA multiwires inserted. There are only 4 transfers. In the top plots (300 μs pulse width) the bunch intensity on the flattop without multiwires inserted is 1.25e9 and 0.9e9 with them inserted and in the bottom plots (600 μs pulse width) they are 2.1e9 and 1.7e9, respectively. Data in blue is from March 24 15:04:59 and data in red is from 15:02:44. The black trace in the top plot is from 15:06:41 and in bottom plot it is from 15:01:17. All data uses Refit and the RF is on during flattop.

Another transverse emittance measurement at MW006 with 2 different pulse widths was made on Feb. 9th.[20] But this time, in addition to changing the pulse width, the injection bump timing was also optimized for both pulse widths. The Booster late intensity was increased from 6.6 to 8.6e9 (for 4 Tandem pulses) and the transverse emittances at MW006 remained about the same: (0.34,0.43) mm mr for 450 μs and (0.36, 0.39) mm mr for 750 μs pulse.

IPM data from March 25th with the RF off on the injection porch and 8.8e9 at Booster late (500 μs pulse), which would typically correspond to a flattop bunch intensity of about 2.1e9, gave an (ε_x,ε_y) of (0.76, 0.74) mm mr.[21] This is significantly smaller than the emittance on the injection porch for the 2.1e9 case in Figure 7 even with the multiwires inserted.

Some IPM data was also taken with the Rf off on the flattop. This was done with only 4 transfers to keep the total intensity low so that if the dump doesn't happen properly with the Rf off it would still be rather safe. It was not known beforehand, but the dump was OK in this state. Figure 8 is a comparison of the Rf off and on cases with a bunch intensity of about 2.2e9.[22]

Figure 9 shows (ε_x,ε_y) at 2 different intensities with the Rf turning off on the flattop. It is important to look at this because the IPM reads artificially high with bunched beam and the higher the intensity the greater the effect. Also, it is clear from the figure that the emittances when the RF is off do indeed go up as the intensity increases. Also, in the higher intensity case ε_x reads higher during the merge porch than it does on the flattop with RF off but it reads the same in the lower intensity case. This may be because there is still some effect during the merge due to the beam being bunched and at the lower intensity that effect is minimal. It looks like there is little growth during the ramp in either case although there appears to be slow growth on the injection porch in both cases.

In summary, at least in some cases, higher intensity in the Booster can result in larger transverse emittance in BtA which translates to larger emittance in the AGS. A significant amount of intensity dependent growth also occurs right at injection into the AGS. The transfer efficiency is also intensity dependent, especially near the AGS intensity limit (9.6e9), and is likely related to the intensity dependence of the transverse emittance on the porch. An intensity dependent slow loss is evident across the injection porch, this effect is easier to see when using only 4 transfers. There is also slow but significant growth on the injection porch that does not seem to be intensity dependent, but there does not seem to be much growth after the injection porch. At typical filling intensity ε_x and ε_y read about 0.2 mm mr too high on the flattop with the RF on.

ε_{long} at Different Times in the 3.85 GeV Tandem Cycle

Measurements of ε_{long} at Booster extraction and on the AGS injection porch were made on Feb 5th and are detailed in Table VI.[23] The porch measurement is made after the bunch has

[20] See Booster-AGS-EBIS Feb. 9 2021 elog 1342 and 1347 entries.
[21] Logged IPM data from March 25 at 14:43:59. The profiles at 600 ms are used for the measurement.
[22] See Booster-AGS-EBIS March 25 2021 elog entries from 1300 to 1435.
[23] See the Booster-AGS-EBIS Feb 5 2021 elog entries from 1712 to 1842.

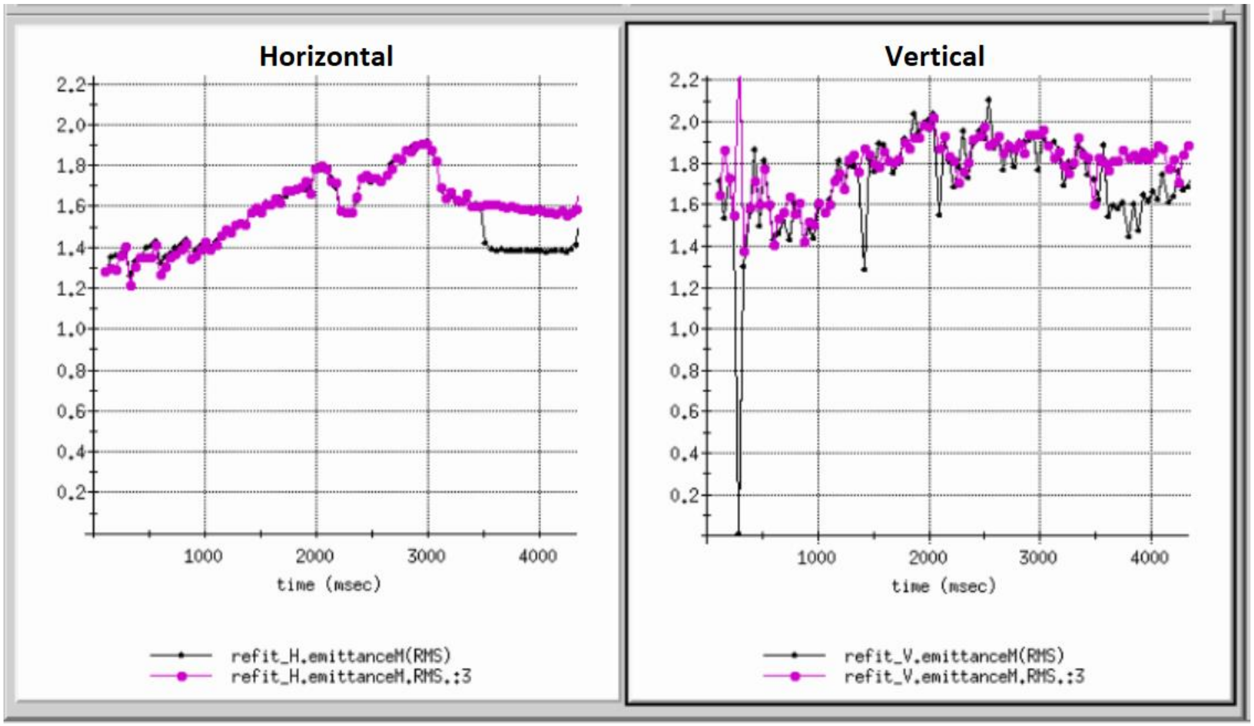

Figure 8: Comparison of AGS ion IPM RMS transverse emittances with the RF turning off at 3500 ms (black) and with it staying on (magenta) for a bunch intensity of 2.2e9. RF off data is from March 25 at 12:59:35 and RF on data is from 13:05:58.

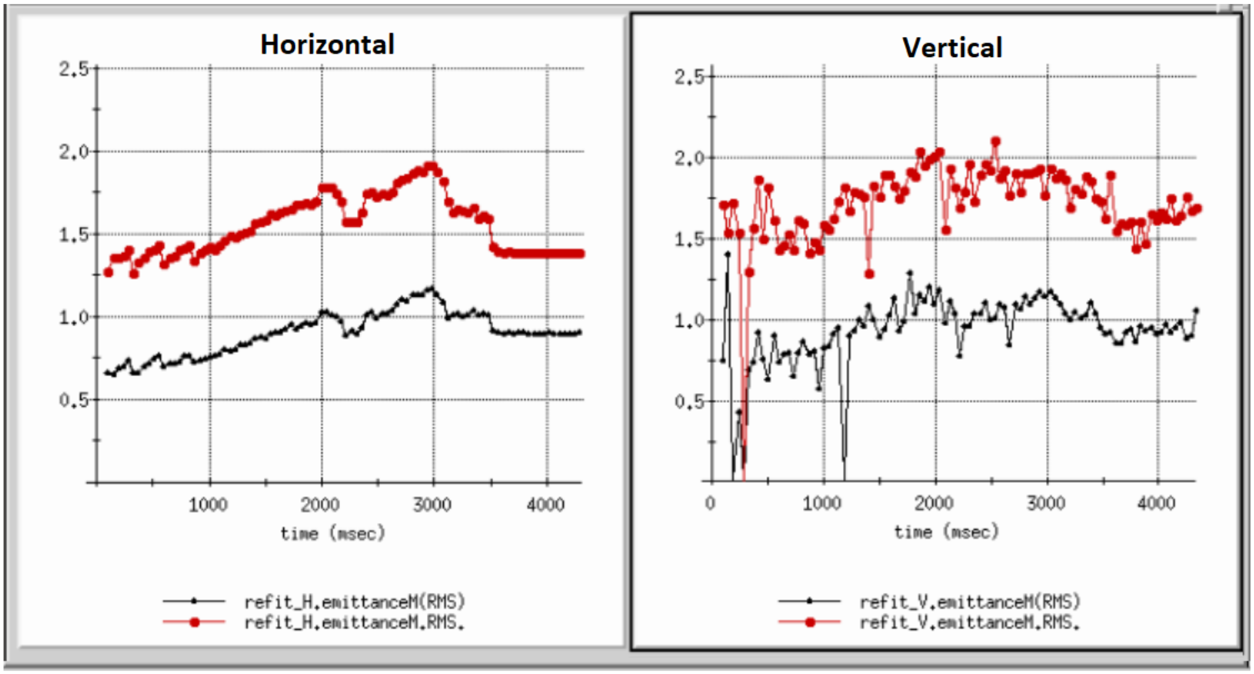

Figure 9: Comparison of AGS ion IPM RMS transverse emittances with the RF turning off on flattop at 3500 ms at 2 different bunch intensities: 2.2e9 (red, March 25 at 12:59:35, 550 μs pulse) and 1.1e9 (black, March 25 at 12:55:59, 250 μs pulse).

had about 1 second to filament out. In EBIS setups the bunch is generally injected into h=24 buckets, but this setup uses h=12 buckets which allows for wider bunches so that potential space charge effects can be reduced. Using a larger bucket also allows for more filamentation and therefore more longitudinal emittance growth to occur. Last run ε_{long} of a similarly 'equilibrated bunch' on the injection porch was larger, 0.125 vs. 0.099 eVs this year.[24] That measurement was taken on a 5.75 GeV cycle which is basically the same setup up to this point in the cycle.

If there were no growth from the 12-6 merge, or after the time of the injection porch measurement until the merge, then ε_{long} of a bunch just after the merge would be 0.198 eVs. This value is nearly the same as what was typically measured on the flattop around this time in the run (see Table V), indicating only a minimal amount of growth up the ramp, which is unusual. Since ε_{long} is particularly small, could it be that the growth up the ramp, at least when the P-bank is not used, is minimal when ε_{long} is small?[25]

Time in Cycle	**f_{synch} (Hz)**	**Bunch length (ns)**	**ε_{long} (eVs)**
Booster extraction	907	253.6	0.069
1st bunch injected at 5th transfer	1601	245.2	0.099

Table VI: ε_{long} at Booster extraction and of the first injected bunch after sitting on the AGS injection porch until the 5th transfer 1067 ms later. The bunch intensity on the AGS flattop for both measurements was about 1.8e9.

BtA and AGS Acceleration Efficiencies for Tandem 3.85 GeV

Scope measurements were made using the normalized Booster circulating transformer and AGS (A15) unnormalized circulating transformer signals on April 14.[26] Booster Late was 17.62e9 when AGS Late was 9.6e9 on the same cycle. The (acceleration) efficiency from just after the last transfer (AGS Early) to At0+3500 ms (AGS Late) was 96.0% on this cycle. At0+3500 ms is less than 100 ms before the 1st extraction. AGS Early was 10.00e9, which makes the BtA efficiency, 10.00e9/17.62e9, equal to 56.8%. The BtA foil stripping efficiency, measured just before this measurement, was 62.1% (see Table IV).

Last year, on the Tandem 5.75 GeV cycle at a similar AGS Late (9.70e9) the BtA efficiency was 57.3% and the AGS acceleration efficiency was 94.7%.[27] These efficiencies are similar to those measured this year even though the BtA foils are new.

On Feb 22 these efficiencies were also measured on a scope with an AGS Late of 7.74e9.[28] Booster Late was 14.46e9 and AGS Early was 7.93e9. In this case the BtA efficiency

[24] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, pgs. 15-16.

[25] ε_{long} on flattop was a bit larger last year for 3.85 GeV (0.240±0.022 eVs). See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, page 34. There was no evidence of foil deterioration at the time.

[26] See Booster-AGS-EBIS 2021 elog entries on April 14 from 1404 to 1417. The logged BtA and AGS acceleration efficiencies that use the intensity scalers are not nearly as accurate as measurements using these signals. This is because the baseline of the AGS normalized transformer has an offset that varies and is not flat. It also is not normalized properly. These measurements were taken before ε_{long} was intentionally increased.

[27] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, Table VI on pg 22.

[28] See Booster-AGS-EBIS 2021 elog entries on Feb 22 from 1357 to 1442.

was 7.93e9/14.46e9=54.8% and the AGS acceleration efficiency was 7.74e9/7.93e9= 97.6%. The efficiency from Booster Late to AGS Late was 7.74e9/14.46e9=53.5% compared to 54.5% in the April 14th case above.

Flattop Longitudinal Emittances for EBIS Au Setups

The 7.30 and 8.65 GeV setups are both close to transition and so finding their longitudinal emittances depends strongly on the exact value of γ_t. Normally the Rf voltage used in the calculation is found from f_{synch}, but this doesn't work well in these cases. Instead, the RF voltage found from f_{synch} measurements at energies far away from γ_t are plotted against the RF vector sum on the flattop and a linear fit of the data is performed. That linear fit is then used to estimate the RF voltage and γ_t is adjusted in the calculation until f_{synch} matches the measured f_{synch}. Table VII shows the data that was used, which is also plotted in Figure 10.

Setup	Flattop Energy	Date	RF Vector Sum (kV)	RF voltage from f_{synch} (kV)
1	3.85 GeV	Feb 4	107.5	76.1
1	3.85 GeV	Feb 6	99.4	72.7
1	3.85 GeV	Feb 8	32.0	21.97
2	3.85 GeV	Jan. 30	44.8	33.4
6	12.21 GeV	May 11	248	175.5
7	9.86 GeV	Jun 8	102.55	75.9

Table VII: RF vector sum and RF voltage derived from f_{synch} for different energy flattops far from γ_t. See Tables I and II for setup information.

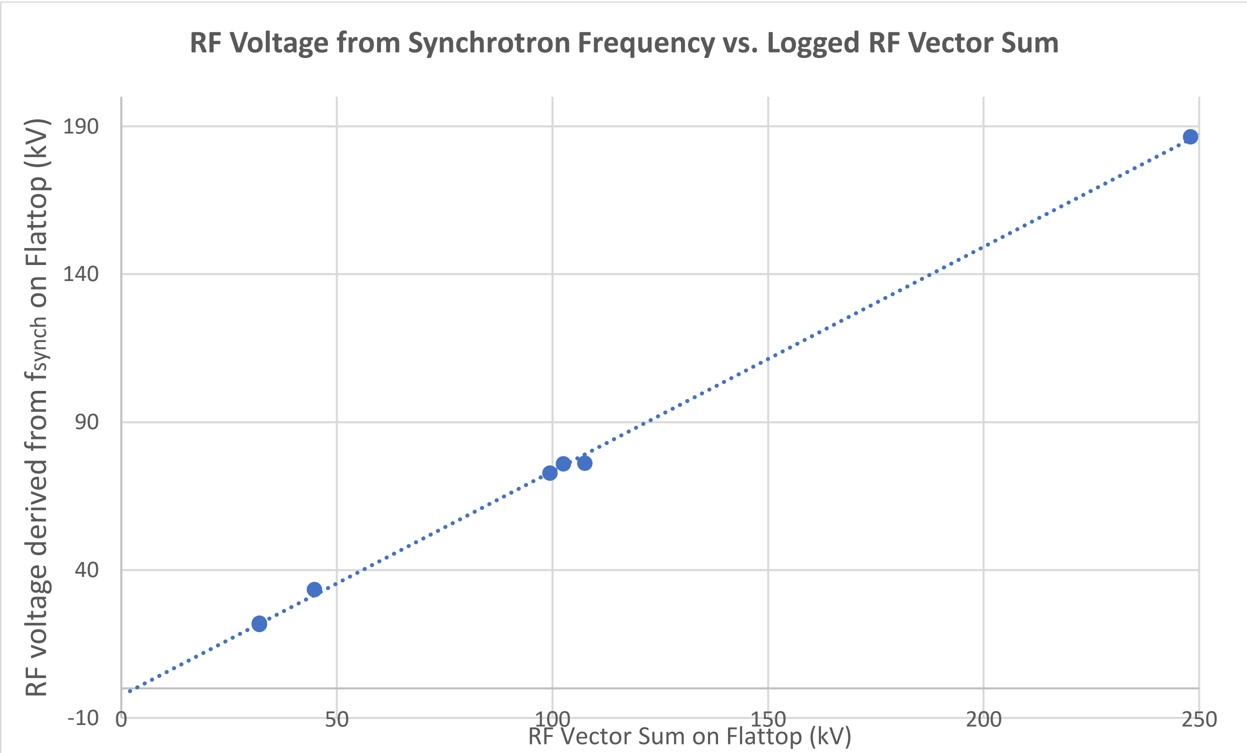

Figure 10: Plot of data in Table VII. The linear fit of the data is y=0.7587x-2.4726.

Table VIII is a compilation of ε_{long} measurements for the 3.85, 7.3, 8.65, and 9.80 GeV setups with a standard 6-3-1 merge (setups 7, 3, 4, and 5 in Table I respectively). The pulsed main magnet voltage bank (P bank) is used for all but the 3.85 GeV case. All use h=10 on the ramp and flattop.

The values found for ε_{long} on the 8.65 GeV flattop are larger than for 7.30 GeV. They are also larger than typical values for 9.80 GeV, which are usually about 0.80 eVs. Unfortunately, there was not a proper ε_{long} measurement taken this run for 9.80 GeV, but there was 1 bunch length measurement taken, and if that length is used together with the RF voltage estimated from the RF vector sum a value of 0.759 eVs is obtained. Note that the RF voltage is relatively low for all the measurements except the 9.80 GeV one. For 3.85 GeV, although the RF voltage was relatively low like the 7.30 and 8.65 GeV cases, the bunches are much longer.

Setup	**Date**	**f_{synch} (Hz)**	**Estimated RF voltage**	**Average Bunch length**	**# of length measurements**	**γ_t**	**ε_{long} (eVs)**
3.85 GeV	6/2	240.8	58.06 kV	88.52±1.9 ns	10	8.500	0.714±0.028
7.30 GeV	3/11	38.46	57.24 kV	35.76±1.3 ns	5	8.439	0.785±0.055
7.30 GeV	5/4	35.78	48.36 kV	35.76±1.7 ns	5	8.455	0.714±0.066
8.65 GeV	5/25	35.90	57.24 kV	36.50±1.4 ns	10	8.491	0.881±0.066
8.65 GeV	5/28	34.06	49.74 kV	38.60±1.6 ns	11	8.467	0.902±0.073
9.80 GeV	6/25	N/A	176.7 kV	29.80 ns	1	8.500	0.759

Table VIII: ε_{long} calculations for 3.85, 7.30, 8.65, and 9.80 GeV 6-3-1 merge setups. For all but the 3.85 GeV setup the estimated RF voltage is calculated from the linear fit described above. For 7.3 and 8.65 GeV, γ_t is then adjusted until f_{synch} matches what was measured. For 9.80 GeV, which is farther from transition energy, an f_{synch} measurement is not available, and the estimated RF voltage is used for the calculation with γ_t set to 8.500. Also, for 9.80 GeV only 1 bunch length measurement was made.[29] For 3.85 GeV, ε_{long} is calculated in the usual way. The uncertainties reflect the standard deviations of the bunch length measurements.

An ε_{long} measurement of an equilibrated bunch on the injection porch was also made using the 6-3-1 3.85 GeV setup and a value of 0.0974 eVs was found, corresponding to a 6-bunch ε_{long} of 0.584 eVs.[30] All 4 of the 6-3-1 type merge setups are basically the same until after the 3-1 merge so it is likely that a similar value would be obtained for the others as well. This value, 0.0974 eVs, is similar to what was found last year for an equilibrated EBIS Au bunch, 0.096 eVs.[31] Although in 2016 it was somewhat smaller, about 0.088 eVs.[32] It is also similar to ε_{long} measured this year for an equilibrated Tandem Au bunch on the porch injected into h=12 buckets (0.099 eVs, Table VI).

[29] Most of the data can be found in the Booster-AGS-EBIS elogs from those dates. If the 8.65 GeV measurements were done in the usual way (i.e.- with γ_t=8.50 and RF voltage from f_{synch}), the values obtained for ε_{long} would be even larger, 0.889 and 0.945 eVs respectively.

[30] See Booster-AGS-EBIS 2021 elog entries on June 10 from 1256 to 1303 and 1416 entry

[31] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, Table VI on pg. 30.

[32] See K. Zeno, "Overview and Analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, September 2016, Table III on page 29.

Although it wasn't measured this year, there is typically not a lot of growth from the last transfer until after the 3-1 merge (maybe 10%).[33] In any case, the growth from the equilibrated bunch to the flattop for these different energies can be calculated and is shown in Table IX. There is not much (obvious) dependence this time of flattop ε_{long} on flattop energy.

Although the 8.65 GeV case seems anomalous, I can't find a reason why. One thing about this setup is that transition happens close to the flattop. With the γ_t jump on, it happens about 10 ms before the start of the rollover, but the amount of quad oscillations after the jump looked typical.[34] It might have been informative to measurement the flattop ε_{long} without using the γ_t jump since it occurs a few ms earlier when configured that way and it is easy to do. It could also be that the method I'm using for finding ε_{long} near transition is flawed.

Setup	**Date**	**Flattop ε_{long} (eVs)**	**(flattop ε_{long})/(porch ε_{long})**
3.85 GeV	6/2	0.714±0.028	1.22±0.05
7.30 GeV	3/11	0.785±0.055	1.34±0.09
7.30 GeV	5/4	0.714±0.066	1.22±0.11
8.65 GeV	5/25	0.881±0.066	1.51±0.11
8.65 GeV	5/28	0.902±0.073	1.54±0.13
9.80 GeV	6/25	0.759	1.30

Table IX: ε_{long} growth from the 6-bunch value on the injection porch to flattop for the different EBIS Au setups (see Table VIII). Uncertainties reflect the standard deviations of the measured flattop bunch lengths as in Table VIII. Note that all energies use the P-bank except for 3.85 GeV.

The only other EBIS Au setup used the 24-16-8 3-1 type merge that occurs on the injection porch (setup 2 in Table I), does not use the P-bank, and uses h=12 on the ramp. ε_{long} was measured on Jan 30th and then again on Feb. 18th. The details are in Table X. Using the equilibrated bunch ε_{long} found above, 0.0974 eVs, the growth factor to flattop for these 2 cases are 1.35 and 1.41, respectively. This setup was also used last year and 2 ε_{long} measurements were made then which were a little smaller than what was measured this year: 0.352±0.025 and 0.388±0.029 eVs.[35]

Date	**f_{synch} (Hz)**	**RF V from f_{synch}**	**Average bunch length**	**# of length measurements**	**ε_{long} (eVs)**
Jan 30	199.9 Hz	33.35 kV	72.11±1.3 ns	11	0.394±0.013
Feb 18	199.9 Hz	33.35 kV	73.72±2.3 ns	10	0.411±0.024

Table X: 3.85 GeV 24-16-8 merge setup (#2 in Table I) flattop ε_{long} measurements. f_{synch} was not measured on Feb. 18th but the RF vector sum was the same as for the Jan 30th measurement so that f_{synch} was used. The uncertainties reflect the standard deviations of the bunch length measurements.

[33] See for example K. Zeno, "Overview and Analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, September 2016, In that case the equilibrated 6-bunch ε_{long} was 0.528 eVs (Table III) and after 3-1 merge it was 0.576 eVs (Table IV).

[34] See Booster-AGS-EBIS 2021 elog entries from April15th from 1556 to 1607.

[35] See K. Zeno, "The 2020 Low Energy Gold Run in the Injectors", C-A/AP/638, Dec 2020, pg 34.

Oxygen

The O^{6+} beam was provided by EBIS on EU3 and set up in the Booster on BU3. As is typical for EBIS beams, a 4-2-1 merge was used in the Booster to provide the AGS (AU3) with 1 bunch per Booster cycle. The Booster cycle was 200 ms long and the merge porch field (as measured by the hall probe) was about 3130 g.[36] Either the A6 and/or E6 RF cavity can be used for h=2 and the required frequency is not far below their maximum limit (1.42 vs. 1.45 MHz).[37] This field was chosen so that the standard merge timing (used for EBIS Au^{32+}) could be used while still allowing for a ramp rate after the merge that is not too high (71g/ms) and a down ramp rate that did not exceed the voltage limit for the main magnet P.S.

Extraction occurs at the peak field which was set so that f_{rev} would be 960 kHz ($B\rho$=7.011 Tm). This f_{rev} allows for injection into h=18 buckets and that allows for an 18-9-3 merge in the AGS.[38] The standard 24-12-4 merge could also have been used but the rigidities upstream and downstream of the foil would have only been 47% of what they are with this setup, which it was feared would substantially reduce the transfer efficiency. Even with this setup the Booster extraction field is considerably lower than it is for EBIS Au (4830 vs. 6675 g on the hall probe).[39]

Figure 11 shows both the O^{6+} and Au^{32+} magnet cycles. f_{rev} at Booster injection is the same for all EBIS beams (96.65 kHz), so O^{6+} requires an injection field about 500 g lower than for Au^{32+} (358 vs. 850 g on the hall probe).[40] Extraction occurs about 10 ms later than it does on the Au^{32+}cycle (Bt0+129 vs. 139 ms). The PPMR was satisfied for 13 of these cycles per supercycle.

The newly installed foil 4 was used to strip the O^{6+} to O^{8+} in BtA. The rigidity downstream of the foil was just high enough that the L20 septum had to operate in proton mode ($B\rho$=5.258 Tm).[41] The AGS injection field, as measured with the hall probe, was 649 g. With the standard 24-12-4 merge 2 sets of 6 bunches are injected into 2 diametrically opposed sets of buckets. This can't be done with the 18-9-3 merge because the 9-3 merge would not work. However, consecutively filling 12 of the 18 buckets does work. As with the 24-12-4 merge, the

[36] See logged data for bmm.control:bFieldAvgM[*] (hall probe) in Booster/PowerSupplies/MainMagnet/BMMcurrent_U3.logreq from 5/5/21 at 1944

[37] E6 was used.

[38] This scheme was suggested by C. Gardner, private communication.

[39] For O^{6+} see logged data for bmm.control:bFieldAvgM[*] (hall probe) in Booster/PowerSupplies/MainMagnet/BMMcurrent_U3.logreq from 5/5/21 at 1944. For Au^{32+} see logged data for MCR/Personal/Kelz/BField_13cycles.logreq from 6/30/21 at 1721.

[40] For O^{6+} see Booster-AGS-EBIS 2021 elog May 8 1256 entry. For AU^{32+} see logged data for MCR/Personal/Kelz/BField_13cycles.logreq from 6/30/21 at 1721.

[41] The amplitude of the L20 current signal and its current readback on the pet page required to inject Au beam (BU5) into the AGS are different depending on whether L20 is in ion or proton mode. In proton mode the signal was 8.0% higher and the required readback was 6.8% higher than in ion mode. See Booster-AGS-EBIS 2021 elog entry on May 6 at 2020. The signal amplitude (in proton mode) required to inject O8+ was 4.15 V with 1 MΩ termination (see May 7 1913 entry).

18-9 merge occurs at the end of the injection porch and the 9-3 merge happens on a porch (753 g, hall probe).[42] The 2 final bunches were put into h=9 buckets for acceleration.

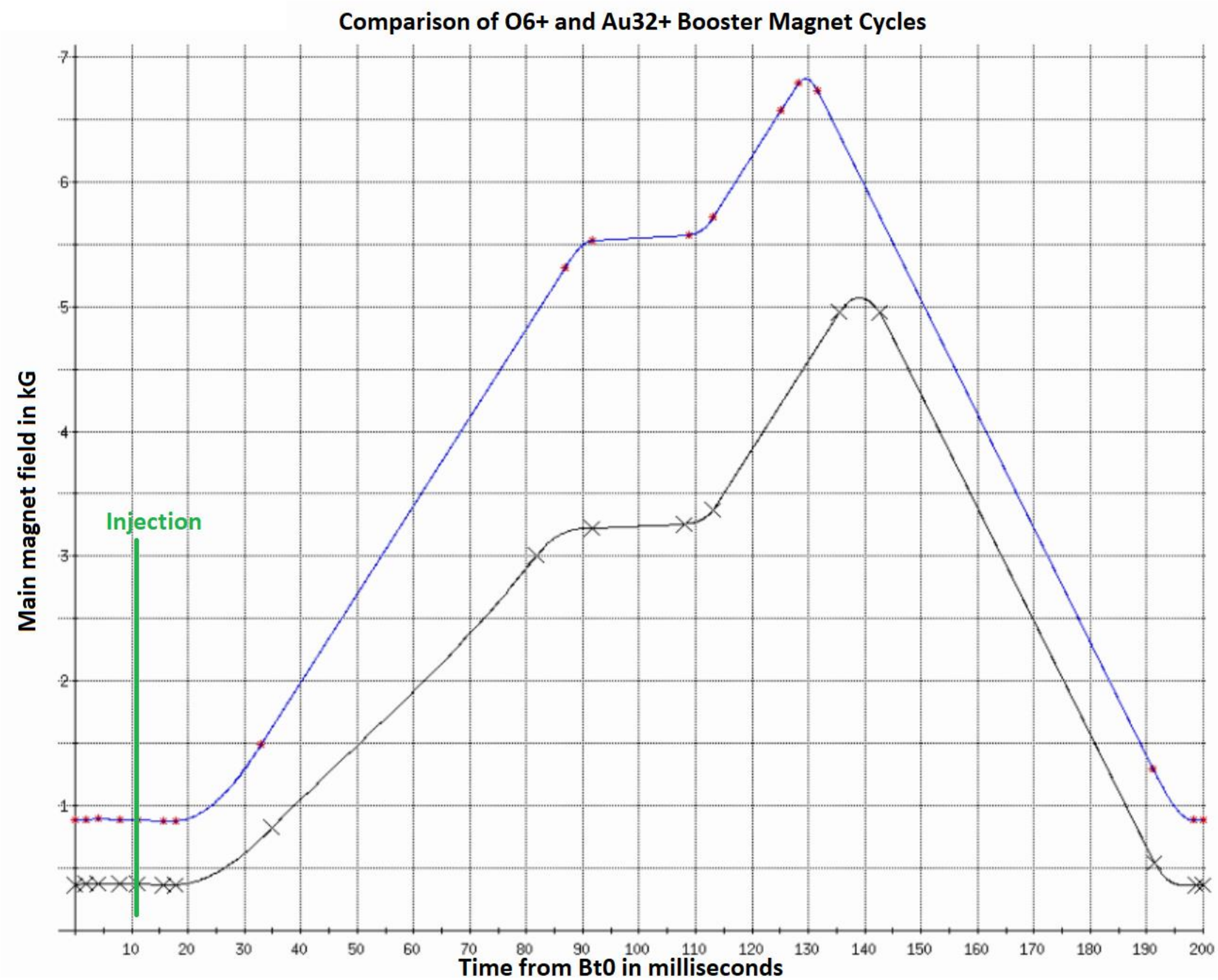

Figure 11: Comparison of O^{6+} (black) and Au^{32+} (blue) Booster magnet cycles references.

Measuring Oxygen Intensity in the AGS

How to go about calibrating the AGS intensity scalers for Oxygen did not prove to be a simple matter. On May 8, when setup with beam began in the AGS, a transformer gain of x10 was used and the scalers were calibrated such that 1000 counts equaled 1e9 O^{8+} ions. It turns out however that the AGS scalers saturate at 20000 counts (20e9 ions) and the O^{8+} intensity eventually exceeded that. Additionally, the beam current as measured on the A15 unnormalized transformer signal saturates at intensities above about 22e9 on the flattop in x10 gain and the intensity eventually exceeded that too. But with typical O^{8+} current that signal is poor when in x1 gain and it is used to measure the intensity on a scope and to calibrate the scalers.[43]

[42] See the logged data for amm.control:bFieldAvg[,] (hall probe) in AGS/PowerSupplies/MainMagnet1KHzSignals.logreq for 05/11/2021 at 18:40 for injection and porch field.
[43] See unnormalized transformer signal in x1 gain in Booster-AGS-EBIS 2021 elog entry on May 11 at 1403.

Also, in x10 gain the 5 mA calibrate pulse gives a calibration that is 5.8% higher than the 500 μA pulse does.[44] It was eventually decided that, since the amplitude of the 5 mA pulse is closer to the amplitude of the unnormalized transformer on the flattop at typical running intensity and the 5 mA pulse is typically used, to use the 5 mA calibration.[45]

Since the scalers saturate at 20000 counts, the calibration was changed such that 100 counts=1e9 ions. Initially, the scaler gain was reduced by about a factor 10 to accomplish this. But the amplitude of the normalized signal is proportional to the scaler gain and so that change results in a lower quality normalized signal. It also reduces the precision with which the scalers can be calibrated. A way to compensate for switching to 100 counts=1e9 is to lower the number of counts per volt that the scalers produce. With a lower number of counts per volt the scaler gain can be raised and so the precision of the scaler calibration and quality of the normalized signal improve. Regardless, the fact that the unnormalized signal (in x10) saturates at 22e9 on flattop required a change to x1 gain.

There are more details, but on May 19, settings were arrived at that gave a consistent and usable calibration: x1 transformer gain (amx.circxf_ctrl), CV2 (500 counts/V), a scaler gain of 146 (aix.xf_ags.gain), 5 mA pulse used for calibration, and 100 scaler counts=1e9 O^{8+} ions.

Oxygen Intensities and Efficiencies

The intensities and efficiencies at their best are shown in Table XI. This data is from the scalers after the calibration problems were largely resolved but are not as accurate as scope measurements typically are. Figure 12 shows the intensity scalers for the last 3 days or so of Oxygen running. This is also after the calibration problems. Figure 13 shows the current transformers in the Booster and AGS for Oxygen.[46] Note that the size of the baby bunches was typically less than 1%.

Intensity Scaler	Intensity
Booster Input	3.30e10
Booster Late	2.65e10
AGS Early	2.45e10
AGS Late	2.35e10

Efficiency	Value
(Booster Late)/(Booster Input)	80%
(AGS Early)/(Booster Late)	92%
(AGS Late)/(AGS Early)	96%

Table XI: Oxygen intensities and efficiencies measured with the scalers during the best running conditions obtained and with 2 final bunches. Booster input is the intensity from EBIS using the EtB xf108 transformer, Booster Late is the intensity just before extraction, AGS Early is the intensity immediately after the last transfer and AGS Late is the intensity at 4000 ms, The 1st extraction occurs near 4080 ms.[47]

[44] In x1 gain the 500 μA pulse would be on the order of 30 mV which is too small to measure accurately.
[45] See Booster-AGS-EBIS 2021 elog entries from 1725 to 1935 on May 17.
[46] Taken from the Booster-AGS-EBIS 2021 elog entry on May 19 at 1432.
[47] The intensity data was taken from the period between 1922 and 1927 on May 20. It can be found in the MCR/InjectorPerformance.logreq LogView file.

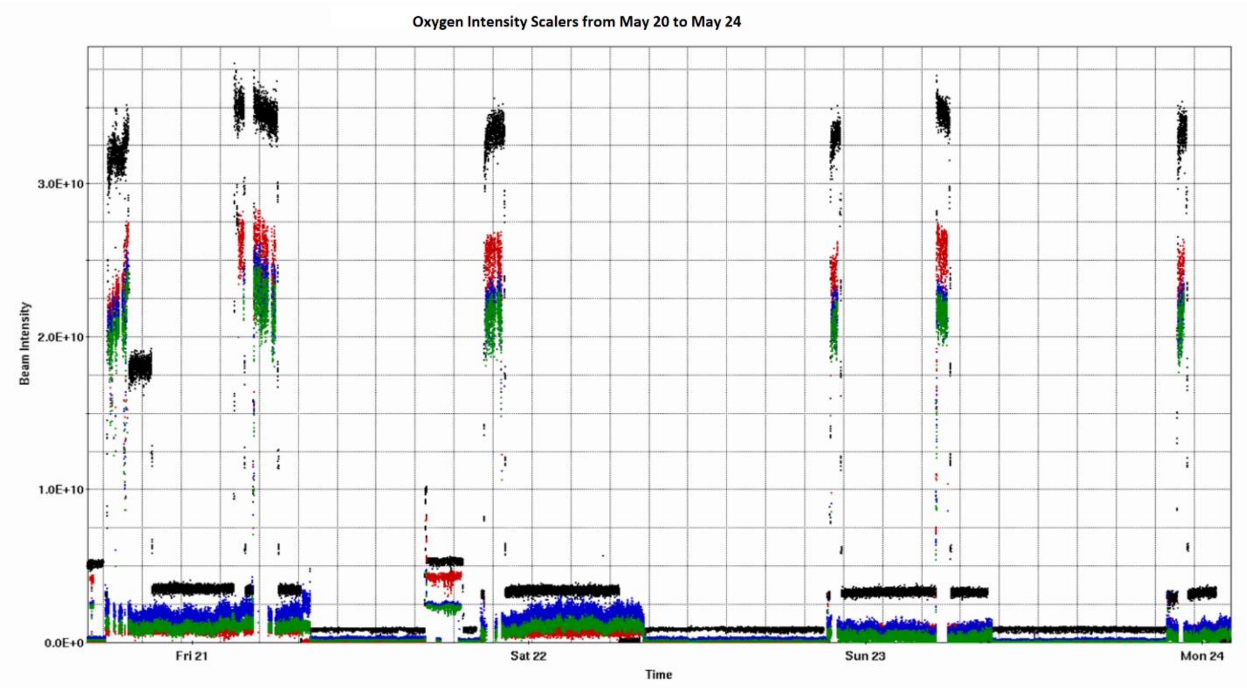

Figure 12: Oxygen Intensity scalers for the 3 day period just before the end of Oxygen running. Black is Booster Input, red is Booster Late, blue is AGS Early, and green is AGS Late.

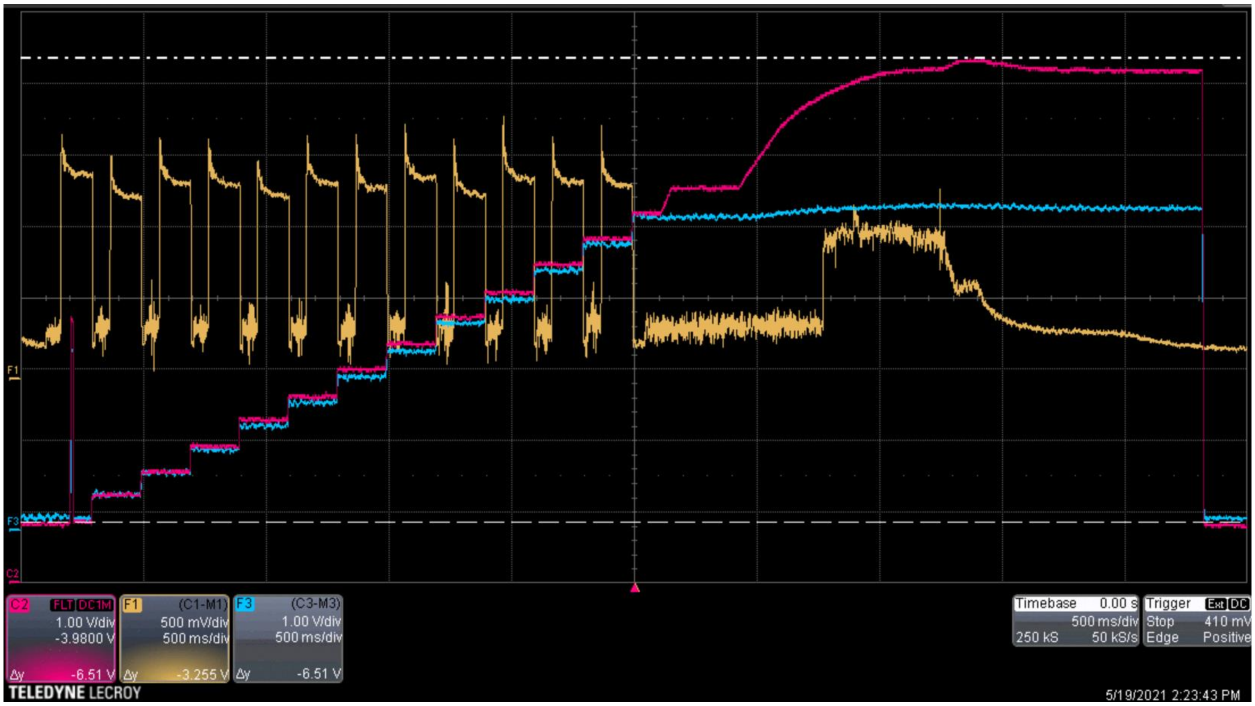

Figure 13: Booster normalized current transformer with baseline subtracted (F1, yellow), AGS A15 normalized current transformer with baseline subtracted (F3, blue), and AGS A15 unnormalized transformer (C2, red) signals during Oxygen running. The trigger is At0+2300 ms and the sweep speed is 500 ms/division. The AGS transformer is in x10 gain.

The Booster Injection Field on Cycle 2

NSRL was generally running during this period. The NSRL magnet cycles have the EBIS Au dwell field which is practically the same as the EBIS Au injection field. In this state there is a discontinuity in the reference at the beginning of the dummy cycle. This discontinuity is large enough that the injection field on cycle 2 (the first cycle with beam) is about 2 g higher than it is on the other cycles.[48] When beam was optimized for all but cycle 2, the Booster intensity on cycle 2 was about half of what it was on the other cycles.[49]

Eventually another Booster user (BU7) was added to the end of the supercycle with a magnet cycle that started at the NSRL dwell field and ended at the Oxygen dwell field (practically the same as the Oxygen injection field). With the magnet on this user pulsing the cycle 2 injection field and efficiency was the same as on the other cycles.[50] The brf.xtrcn_strt.gt gauss event was not occurring on the dummy cycle either before this change. This had ramifications with how BtA multiwire data was acquired and baselines subtracted.[51] The addition of this user also resolved that problem.

Oxygen Emittances

Table XII contains the flattop ε_{long} measurements made with Oxygen. The flattop rigidity is practically the same as it is for 9.8 GeV Au although the energy is higher (12.2 GeV). The values obtained for O are considerably larger than they are for 9.8 GeV Au. Naively one might have expected them to be similar. Also, although they are larger, they did seem to drop over the few days these measurements were taken. Although some improvement may have been due to tuning in the Booster and AGS, it does not look like that can account for the majority of it. At the beginning of Oxygen running the EBIS intensity was very unstable and generally lower. EBIS stability improved greatly as the run progressed and the intensity also improved. It may be that the momentum spread of the EBIS beam decreased as well.

On May 13th ε_{long} measurements were made of the bunch first injected on the 2nd transfer 200 ms later.[52] The first measurement was 0.153±0.008 eVs (167.8±6.47 ns bunch), corresponding to a 6-bunch emittance of 0.91±0.048 eVs. This is much larger than what was measured for an equilibrated EBIS Au bunch (0.0974 eVs). Subsequently, Booster capture was improved and another measurement gave 0.136±0.011 eVs (159.6±9.2 ns bunch). The intensity for these measurements was quite low, perhaps corresponding to a merged bunch intensity of around 4e9. Another measurement made after that with an equivalent merged bunch intensity of about 6e9 was 0.125±0.006 eVs (150.5±4.8 ns bunch). Unfortunately, the flattop ε_{long} was not measured after this change to capture, but 0.125 eVs is still substantially larger than what's measured for EBIS Au.

---

[48] See Booster-AGS-EBIS 2021 May 11 elog entries from 1647 to 1815.
[49] See Booster-AGS-EBIS 2021 May 8 elog entry at 2331.
[50] See Booster-AGS-EBIS 2021 May12 elog entries from 1633 to 1913.
[51] See Booster-AGS-EBIS 2021 May 7 elog entries from 1434 to 1705.
[52] See Booster-AGS-EBIS 2021 May 13 elog entries from 1657 to 1910.

It is not necessary to quad pump Oxygen bunches at Booster extraction because they are already narrower than the buckets they are injected into. They are less than 200 ns long when injected and an h=18 bucket there is 231 ns long. So, there is more filamentation possible than for Au and the growth from that may contribute to the larger ε_{long} measured on the porch.

Date and Time	**f_{synch} (Hz)**	**Rf voltage (kV)**	**Bunch Length (ns)**	**# of length measurements**	**ε_{long} (eVs)**	**Bunch Intensity**	**Notes**
5/10 1300	102.6	162.3	42.96±1.06	5	1.40±0.07	5e9	No γ_t jump
5/10 1640	110.5	188.4	43.04±1.19	5	1.51±0.08	6e9	γ_t jump on
5/10 1847	110.5	188.4	41.76±0.91	5	1.43±0.06	7e9	After work on Booster merge
5/10 1852	110.5	188.4	41.07±2.23	6	1.38±0.15	8e9	Lowered RF V. at injection
5/11 1455	110.0	186.5	39.62±1.60	10	1.28±0.10	8e9	
5/13 1302	105.0	170	37.90±2.19	10	1.12±0.13	7e9	KL has been on after merge
5/13 1257	105.0	170	37.08±1.12	10	1.07±0.06	7e9	With proper KL function

Table XII: Flattop ε_{long} measurements with Oxygen. Uncertainties in bunch lengths are their standard deviations which are reflected in uncertainties in ε_{long}.[53] The RF voltage shown is that required to obtain the measured f_{synch}. Station KL (h=6) is used for the 9-3 merge. Normally, after that is complete, its voltage is set to zero, its phasing is changed by 180^o, and its voltage is brought back up to help squeeze the bunches into the h=9 buckets for acceleration. For all measurements shown here except the last the voltage was inadvertently left on during this rephasing. However, the effect on the flattop ε_{long} appears to have been minimal.[54]

The horizontal and vertical normalized RMS emittances (ε_x, ε_y) in BtA upstream of the foil measured with the MW006 multiwire were 0.68 and 0.34 mm mr, respectively (Figure 14).[55] The AGS Late intensity was about 1.1e10 at the time. An AGS ion IPM measurement on the flattop when AGS Late was 2.3e10 (as in Table XI) gave (ε_x,ε_y) of (1.69, 1.40) mm mr.[56]

Deuterons

The Deuteron setup in the Booster and AGS, which uses Tandem beam, was the same as it was in Run 16. However, it was not described in the injector note from 2016 so it is probably worth describing here. The Booster magnet cycle is unusual because it maintains the EBIS Au^{32+} dwell field to accommodate NSRL. For multiple cycles, EBIS constrains the Booster cycle length to be a multiple of 200 ms. Also, making the cycle longer than that, with the usual 13 cycles, will generally cause the PPMR limit to be exceeded. But with Deuterons only 9 cycles are required and the extraction field is quite low so the cycle length can be increased without exceeding the PPMR limit. This allows for time to ramp the magnet down from the EBIS Au

[53] See Booster-AGS-EBIS 2021 elog from those dates and times for the data.
[54] See Booster-AGS-EBIS 2021 May 13 elog entries from 1236 to 1246.
[55] Values of β_x=3.0 m and β_y=16.0 m are used. The relativistic β is 0.646 and γ is 1.31 at Booster extraction. The formulas used to calculate ε_x and ε_y are $\varepsilon_x=(\beta\gamma/3.0m)\ \sigma_x^2 = 0.282\ \sigma_x^2$ and $\varepsilon_y=(\beta\gamma/16.0m)\ \sigma_y^2 = 0.0528\ \sigma_y^2$ where σ_x and σ_y are the RMS widths of the horizontal and vertical profile Gaussian fits, respectively.
[56] Logged data from May 20, 2021 at 19:23:31. The signals are not strong, especially the vertical, but the profiles and their fits at 3845 ms look reasonable. The emittance values at that time, which is on the flattop, are quoted here. This is with the RF on.

dwell field to the deuteron injection field on every Booster cycle. It also allowed for an increase in the length of the injection/capture porch, from about 7 to 14 ms, and merge porch, from about 18 to 24 ms. Injection occurs at 31 ms, extraction occurs at the peak of the magnet cycle, near 163 ms, and the cycle length is 233 ms (see Figure 15).

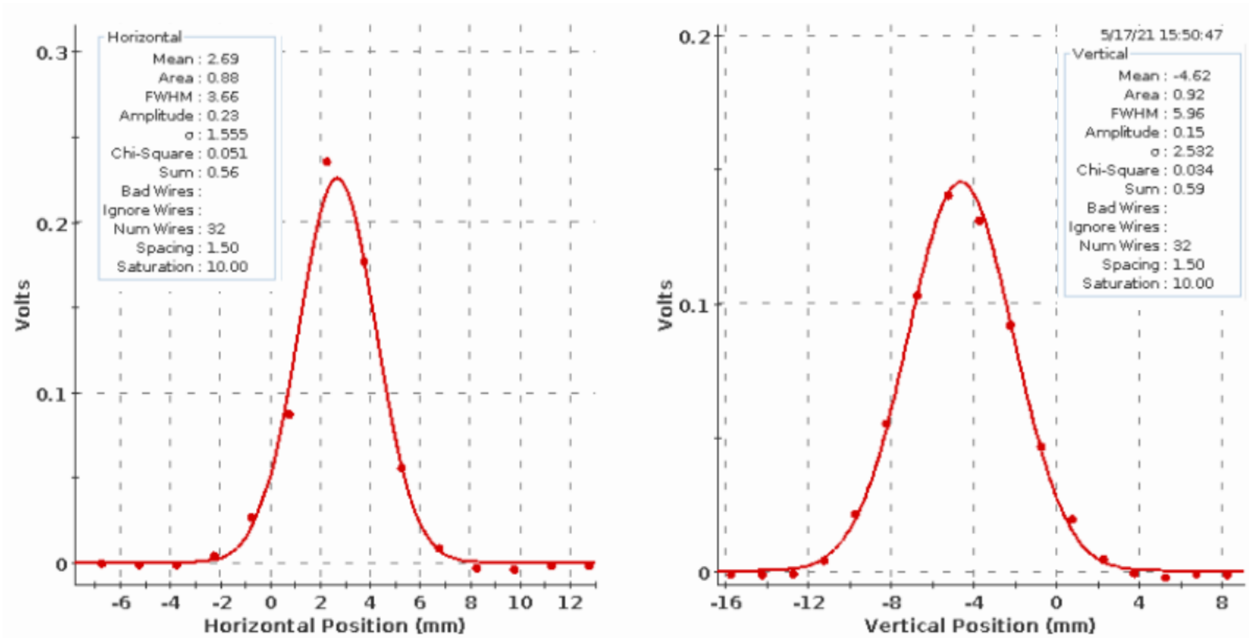

Figure 14: BtA MW006 multiwire O^{6+} profiles from May 17. The RMS widths of the Gaussian fits for the profiles, σ_x and σ_y, are 1.555 mm and 2.532 mm, respectively, corresponding to normalized RMS transverse emittances ε_x=0.68 and ε_y=0.34 mm mr.

The f_{rev} at Booster injection is high enough for deuterons (186.12 kHz) that they can be captured in an RF harmonic as low as 2. So, h=2 was used so that only a 2-1 merge was needed to provide 1 bunch at Booster extraction. There were 8 transfers and the bunches were injected into h=12 buckets (f_{rev} in AGS was 261450 Hz). The AGS injection field on the hall probe was 758g (Bρ=6.18 Tm).[57] Proton mode was used for the L20 septum and the scope signal (AXI.L20_SEPTUM_I) amplitude was 5.81 V terminated into 1 MΩ.[58] A 12-6-3 merge was used at the end of the injection porch, and the 2 merged bunches were accelerated in h=12 buckets to the flattop.

[57] Note that this Bρ, which is calculated from the momentum, results in a B of 724 g when the nominal ρ in AGS of 85.378351 m is used. So, the calculated Bρ is only 95.5% of the hall probe reading. In the Booster at extraction the hall probe reads lower than the calculated Bρ, 4315 vs. 4457 g, using ρ=13.8656 m. See C.J. Gardner, FY2016 Parameters for Deuterons and Gold Ions in Booster, Ags, and RHIC, June 10, 2016 for calculated Bρ and logged data for the hall probe from 6/28/21 1330 in Booster/PowerSupplies/MainMagnet/BMMcurrent_U3.logreq bmm.control:bFieldAvgM[.] and Ags/PowerSupllies/MainMagnet1kHzSignals.logreq amm.control:bFieldAvgM[.], for example.

[58] See Booster-AGS-EBIS_2016 elog entry from Mar 11 at 1553.

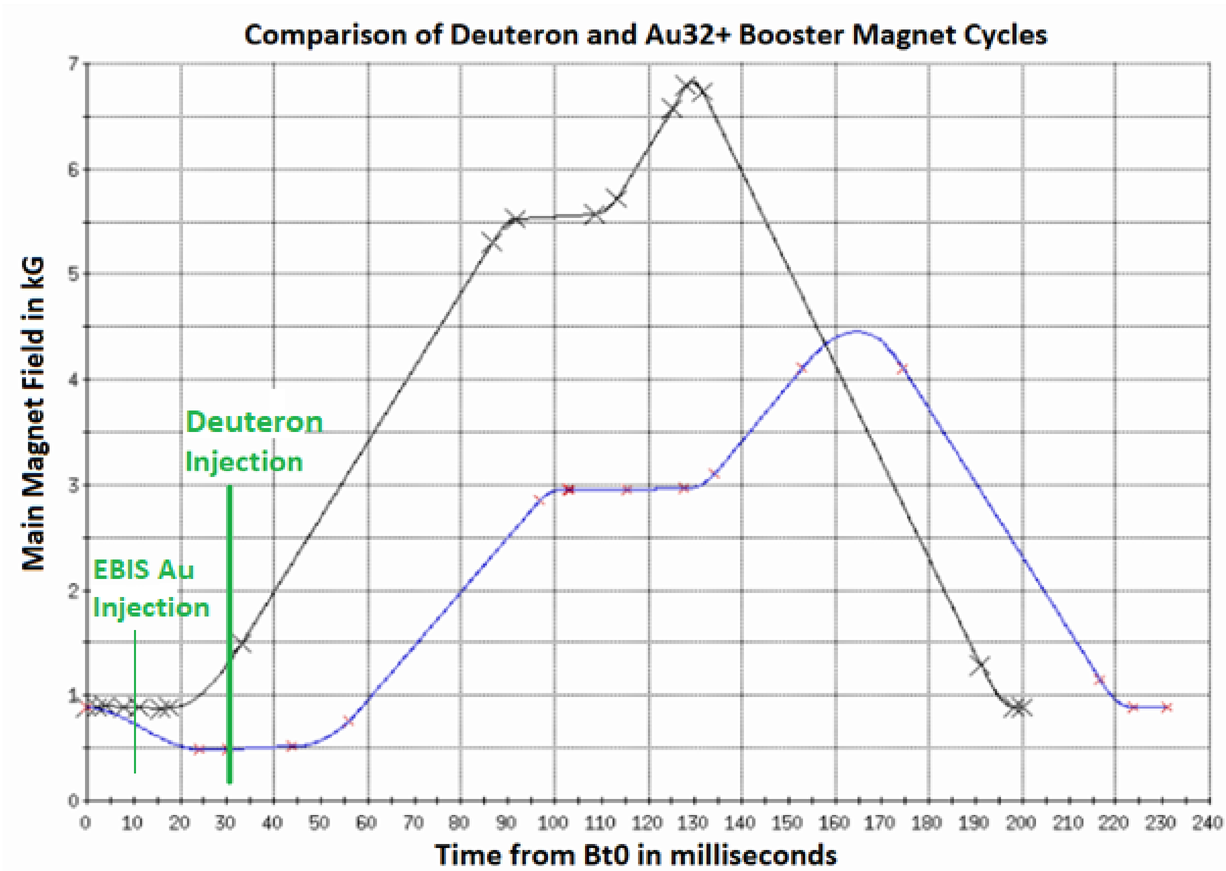

Figure 15: Comparison of Deuteron (BU3, blue) and EBIS Au^{32+} (BU5, black) magnet cycles. Also shown are the EBIS Au^{32+} and deuteron injection times, Bt0+10.5 and 31 ms respectively.

Initially, the flattop ε_{long} was about 0.58 eVs.[59] However, as in 2016, it was intentionally increased for RHIC by injecting in the Booster into a relatively high RF voltage, about 15 vs. 1.4 V, then lowering the voltage back to around 2V and capturing. Figure 16 shows how the envelope of the wall current monitor signal appeared in both states.[60] Figure 17 shows a bunch on the AGS flattop in both states.[61] During d-Au running in RHIC the wider bunches were used. The ε_{long} of the wider bunch was perhaps 40% larger.

Figure 18 shows how Deuterons look around transition, at least when ε_{long} is in the small state. The behavior is unusual because the peak current drops abruptly after the γ_t jump. The RF voltage is constant from 80 ms before the jump until 50 ms after it. The same behavior was observed during Run 16.[62] If this was due to a longitudinal space charge effect which switches sign at transition one might expect substantial quadrupole oscillations but they are no more

[59] Only one bunch length was measured (25.0 ns) and f_{synch} was 91.8 ns. See Booster-AGS-EBIS 2021 elog entries on June 27 at 1616 and 1618 and on June 30 at 1241 and 1301.
[60] See Booster-AGS-EBIS 2021 elog entry on June 30 at 1553 and 1554.
[61] See Booster-AGS-EBIS 2021 elog entry on June 30 at 1643.
[62] See Booster-AGS-EBIS_2016 elog entry on June 10 at 1747. Note also that in Run 16 when using wider bunches transition looked normal (see 1702 entry on May 20 2016).

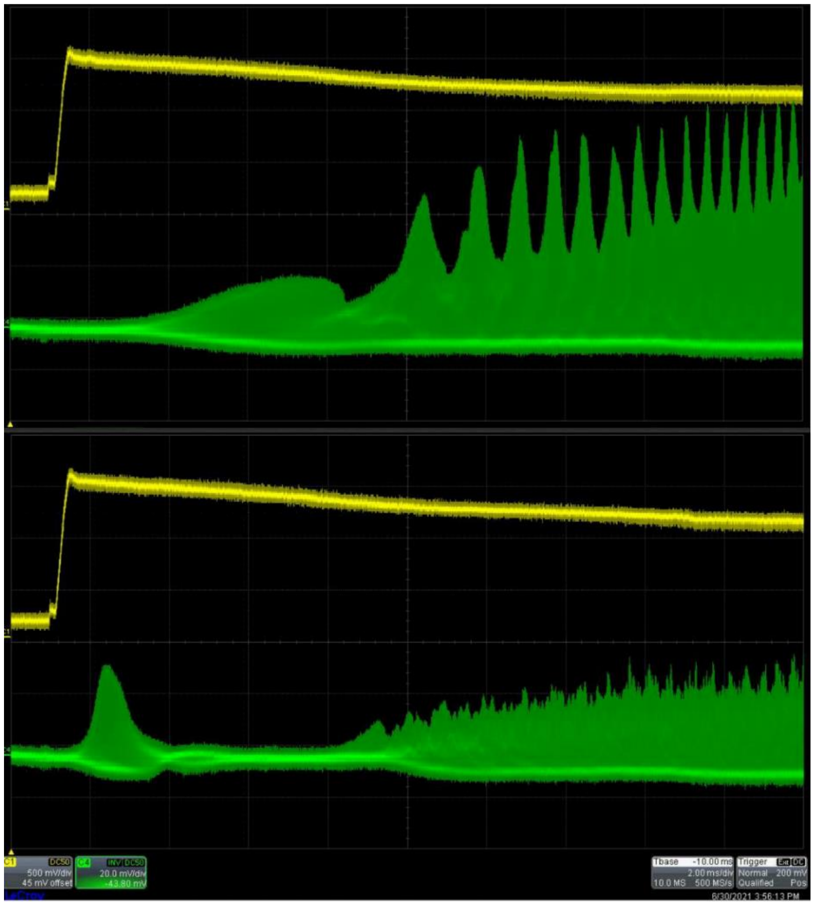

Figure 16: Deuteron capture in the Booster without (top) and with (bottom) the RF voltage detuned. The yellow traces are the injection transformer and the green are the wall current monitor. The trigger is Bt0+30 ms. The sweep speed is 2ms/box.

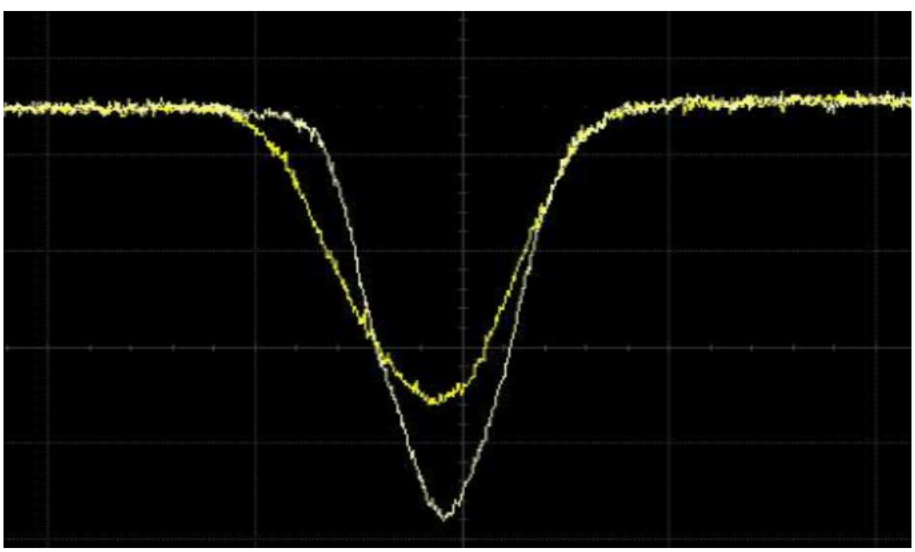

Figure 17: Deuteron bunches as seen on the AGS flattop on the WCM with and without the RF voltage at Booster injection detuned. 20 ns/box, 500 mV/div, trigger at At0+3500 ms.

evident than they typically are. At the time, there was no beam loss associated with transition and the bunch intensity was about 1.5e11. I don't recall having seen this behavior with any other species, although it is not obviously inconsistent with high intensity proton behavior. In that case, the RF voltage was lowered as the γ_t jump quad current increases and then raised abruptly right after the jump to improve beam survival.

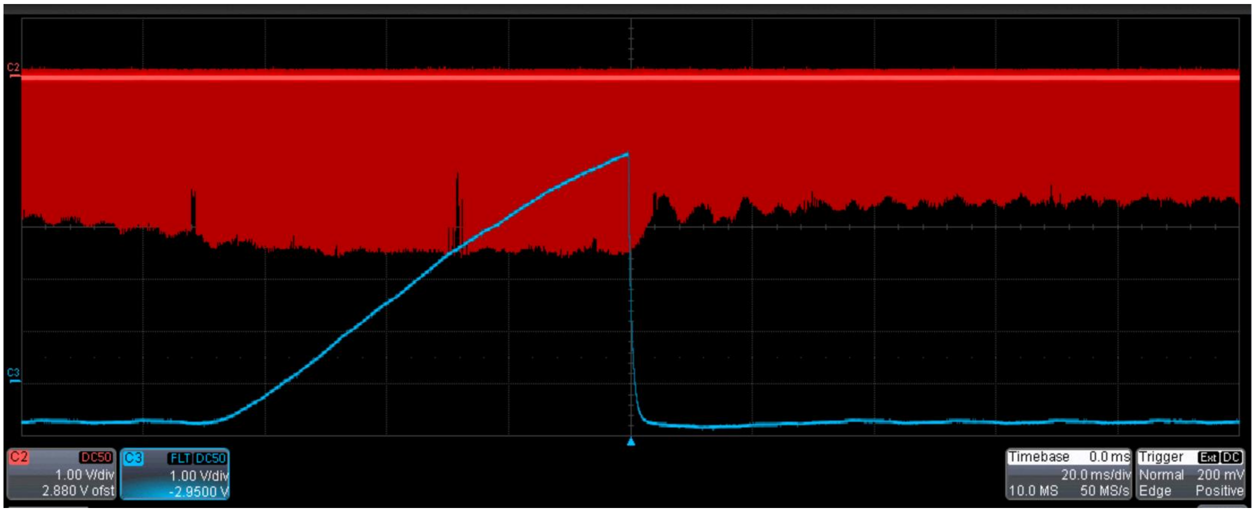

Figure 18: The wall current monitor envelope for low ε_{long} deuterons around transition. The A17 γ_t jump quad current is also shown.[63] The jump occurs near At0+2950 ms and the vector sum is constant from 2870 to 3000 ms. The sweep speed is 20 ms/div.

It is possible to piece together an ε_{long} measurement at AGS injection. The measured bunch length, when ε_{long} was in the small state, was about 130 ns.[64] An f_{synch} measurement is not available but the matched voltage estimated from the logged vector sum using the relation shown in Figure 10 is 32.96 kV. This gives an ε_{long} of 0.129 eVs corresponding to a 4-bunch ε_{long} of 0.518 eVs. Using the flattop ε_{long} value above (0.58 eVs) gives only 12% growth from injection to flattop. So, whatever is going on at transition does not seem to cause much longitudinal growth.

In the case where ε_{long} was intentionally blown up in the Booster, a bunch at AGS injection was about 180 ns long.[65] This corresponds to a 4-bunch ε_{long} of 0.908 eVs. As noted, the flattop ε_{long} in this case was about 40% larger, or 0.81 eVs. This indicates a reduction, although given the coarseness of some of these measurements that is not surprising.

Although the AGS Late bunch intensity was as high as about 1.75e11, an intensity of about 0.7e11/bunch was used to obtain 0.5e9/bunch in RHIC. The Au bunch intensity was also lowered to provide about 0.8e9/bunch in RHIC. It was lowered by relaxing the bunch squeeze

[63] Booster-AGS-EBIS_2021 elog June 27 entry at 15:42
[64] Booster-AGS-EBIS_2021 elog June 27 entry at 1530 for small ε_{long} case.. Note also that there is little in the way of quad. oscillations so the voltage is close to matched.
[65] Booster-AGS-EBIS_2021 elog July 6 entry at 11:02 for large ε_{long} case. Note voltage appears to be close to matched here as well.

which reduced ε_{long} significantly, perhaps from about 0.80 to about 0.57 eVs. In hindsight though, I would have expected it to be reduced more than that.

Figure 19 shows BtA MW006 profiles and Gaussian fits with an equivalent AGS Late intensity of about 3.2e11 (1.6e11/bunch). The Tandem pulse width was 350 μs. The horizontal and vertical normalized RMS emittances (ε_x, ε_y) found from these fits are (1.34, 0.75) mm mr.[66]

The AGS (ion) IPM was not operational during Deuterons. The AGS eIPM profiles at 3500 ms on the flattop with an AGS Late of 2.3e11 indicated normalized RMS emittances of 5.08 and 1.32 mm mr in the horizontal and vertical, respectively.[67]

While ε_x in BtA was rather large, the eIPM indicates it was almost 4 times as large as that at 3500 ms for this case. The eIPM vertical data resembles a Gaussian more so than the horizontal does and has smaller error bars (see Figure 20). In this case, which seems representative at least for that day, ε_x was about 2.0 mm mr at the start of the ramp, about 3.5 mm mr halfway up it (~2500 ms), and about 5.0 mm mr at the start of the flattop (3000 ms).[68] Both the BtA and eIPM measurements were taken on the same day but several hours apart. This was during RHIC running so ε_{long} was intentionally large.

Finding the AGS Injection Field

During Oxygen setup it was difficult finding the correct AGS injection field. Initially, the AGS main magnet reference was set to the value of B found from Bρ that is associated with the AGS injection momentum, the charge state, and bending radius (p=qBρ). While this may very well be the correct value for B, simply setting the main magnet reference to that value did not produce a B field close enough to the one required to establish spiraling beam. The beam spiraled when the reference was lowered from that value, 616g, to about 600g. The hall probe is used to measure the main magnet field, but simply changing the magnet reference until the hall probe reads the calculated value for B does not get the beam to spiral either. In fact, the magnet reference was closer to the calculated field than the hall probe reading was.

---

[66] βγ for deuterons is 0.9896 (relativistic β=0.703 and γ=1.407). The formulas used to calculate ε_x and ε_y are $\varepsilon_x=(\beta\gamma/3.0\text{m})\ \sigma_x^2 = 0.330\ \sigma_x^2$ and $\varepsilon_y=(\beta\gamma/16.0\text{m})\ \sigma_y^2 = 0.0618\ \sigma_y^2$ where σ_x and σ_y are the RMS widths of the horizontal and vertical profile Gaussian fits, respectively.

[67] The eIPM data is from June 30 at 21:59:42.

[68] The eIPM appears to be configured to mainly acquire data automatically only when filling or extracting. When filling cogging and synchro occur and so the radius changes by a different amount on every cycle. However, inspection of the radius at 3500 ms in logged data indicates that the cogging/synchro is over by then, which is about 30 ms before the first extraction. So, it seems to be a good time for a measurement. There are oscillations in the radius at 3000 ms which might affect the measurement there, although the fact that the measurements at both times are similar leads me to think it's OK. The extraction bumps are also up by 3500 ms.

There is other logged data (i.e.- 6/29 at 18:41:57, AGS Late ~3.2e11) where the 3500 ms profile looks much worse (See Test_Keith elog Sept 2, 2021 1334 entry) and the reported ε_x is about 8 mm mr. The 3000 ms profile looks no worse though and ε_x is still about 5 mm mr there. At lower intensity (AGS Late 1.2e11) ε_x at 3500 ms was about 2.9 mm mr but 4.2 mm mr at 3000 ms. The profile at 3500 ms (See Test_Keith elog Sept 2, 2021 1346 entry) does not look obviously worse than the 2.3e11 case.

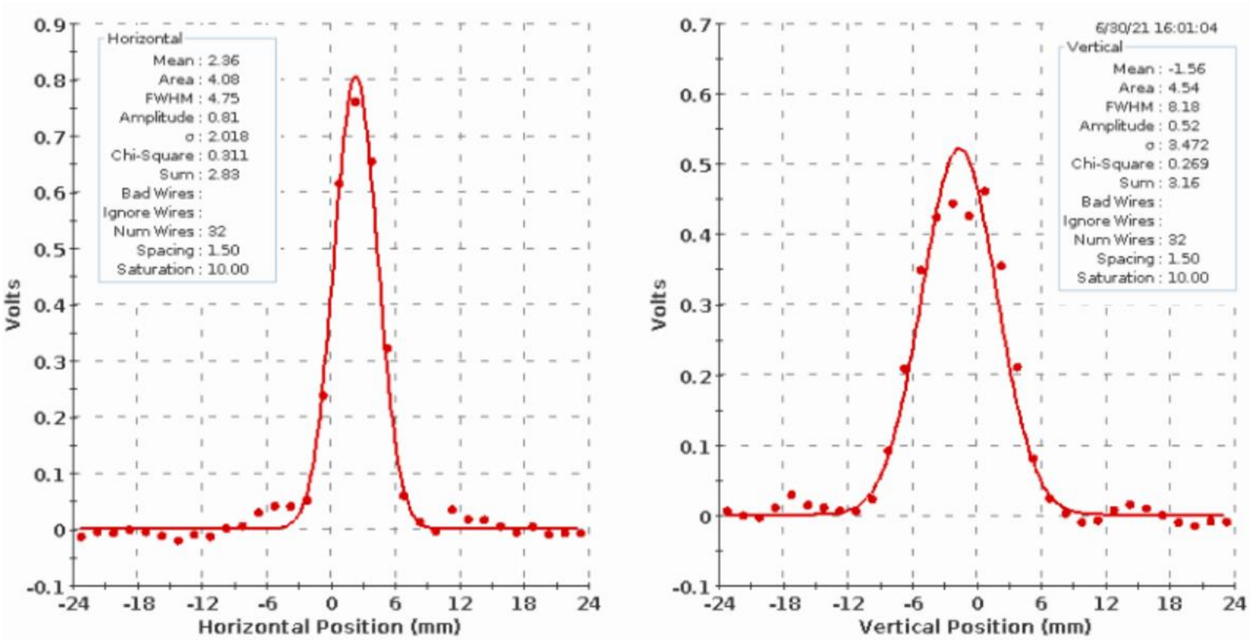

Figure 19: BtA MW006 multiwire deuteron profiles from June 30th. The RMS widths of the Gaussian fits for the profiles, σ_x and σ_y, are 2.018 mm and 3.472 mm, respectively, corresponding to normalized RMS transverse emittances ε_x=1.34 and ε_y=0.75 mm mr.

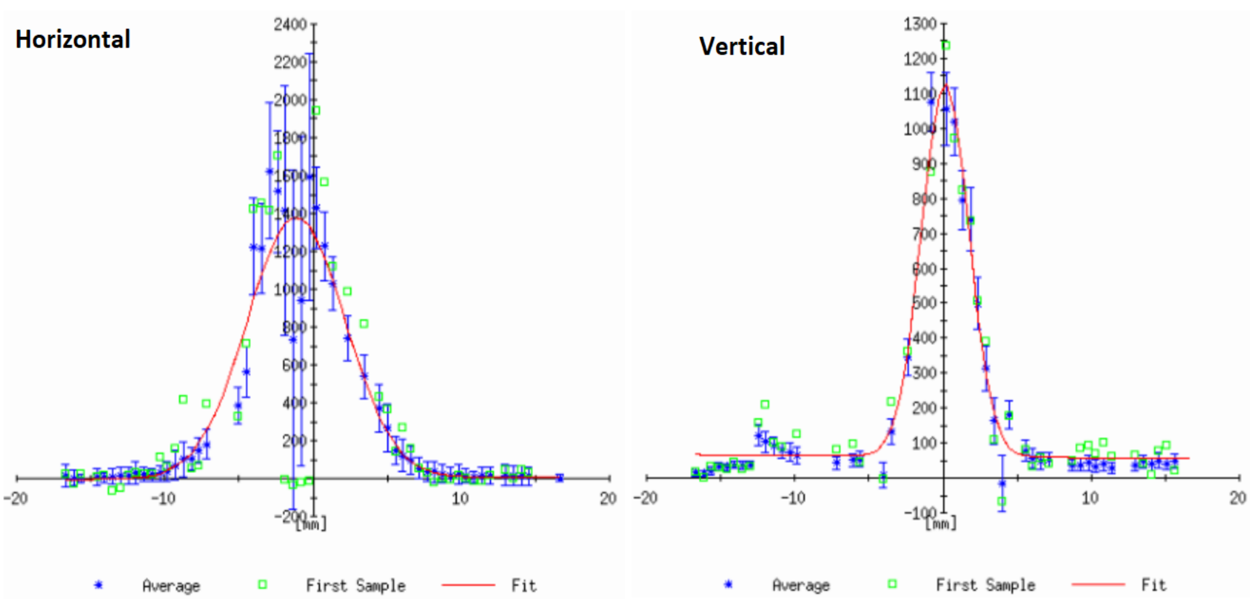

Figure 20: AGS eIPM data with deuterons from June 30 at 21:59:42 at 3500 ms on the flattop. AGS Late is 2.3e11 (2 bunches).

Table XIII is a compilation of this calculated B together with the hall probe readings and the main magnet references required to get different beams to spiral.[69] In addition to what was run this year, typical polarized proton values are also included. The data is plotted together with linear fits in Figure 22.

All the data points fall very close to the linear fits so, for beams that have not been injected before, sufficiently accurate predictions for the hall probe reading and main magnet reference required for beam to spiral can hopefully be found given a calculated B field. To check this, the linear fits were redone without the Oxygen data. Using these fits I obtained 647.6g for the hall probe and 599.8g for the magnet reference.[70] Although 649g was the hall probe reading when the setup was optimized, the beam initially spiraled when the hall probe read 646g, so 647.6g would have been within the range required to establish spiraling beam as well.[71]

Beam	Calculated B	Hall probe	M.M. Reference
Tandem Au77+	440	469.5	427
EBIS Au77+	455	484	443
EBIS O8+	616	649	603
Tandem Deuterons	724	758	704
Polarized Protons	844	878	823

Table XIII: Calculated, Hall probe, and AGS main magnet reference B field, in Gauss, at AGS injection for different beams.

Baby Bunches

The beam that remains in the AGS after the last extraction is in bunches that were not extracted, the so-called satellite or baby bunches. It seems this beam has 2 main sources. First, there are cases where some of the beam injected into the AGS is not captured in the desired bucket yet survives and somehow winds up in the other buckets.[72] It also arises when part of a merged bunch does not fit in the intended bucket when the accelerating RF comes on after a merge.

For the nominal 3.85 GeV Tandem setup the amount of beam remaining in the AGS after the last extraction was too small to see on the current transformer, at least in x1 gain. Once QP was used at Booster extraction to reduce transverse blowup, the amount was small but

[69] The calculated B is found from the Bρ given for the beam in question in "Gardner Notes" together with the bending radius noted there (ρ=85.378351 m). The AGS main magnet references at injection were found from the archived main magnet functions, and the hall probe readings were found from elog entries and logged data.
[70] The fits without the Oxygen data are B(Hall)=1.0132(Bcalc)+23.48 and B(MMRef)=0.9772(Bcalc)-2.4809. The linear fit for the hall probe reading vs. main magnet reference (with Oxygen included) is B(Hall)=1.0367*B(MMRef)+25.658.
[71] See Booster-AGS-EBIS 2021 elog entry on May 7 at 1923 for the hall probe reading when initially injected. The optimized setup data was taken from logged data on May 23 at 0520 for the Hall probe and the reference was taken from the May 23rd 0626 AU3 main magnet archive.
[72] See Booster-AGS-EBIS_2021 elog from June 24th, entries from 13:58 to 14:35, for evidence of this.

measurable, about 0.5%.[73] It is not surprising that the amount is small because the injected bunches are much shorter than the h=12 buckets they are injected into, even in the QP on case, and only 2 bunches are merged into 1.[74]

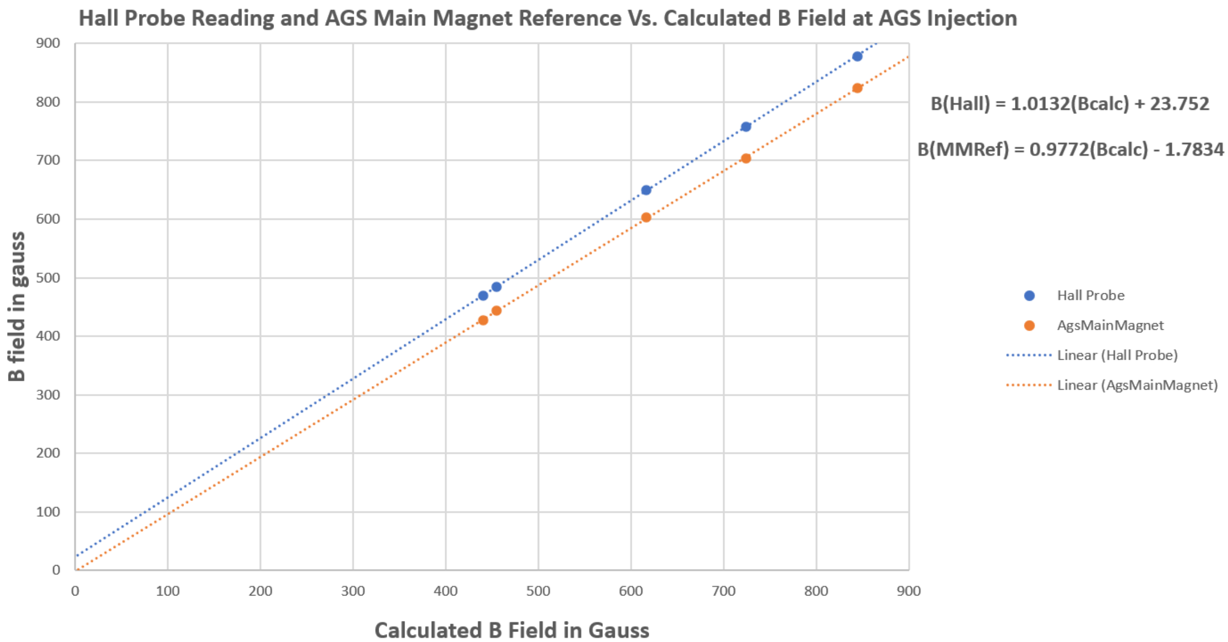

Figure 21: Hall probe readings and Main Magnet references vs. B field calculated from p=qBρ with linear fits. The equations for the linear fits are shown near the upper right corner of the plot where B(calc) is the calculated B field, B(Hall) is the hall probe reading, and B(MMRef) is the AGS main magnet reference, all in Gauss.

Based on a couple of measurements, the fraction of beam in the baby bunches for the Oxygen setup was about 0.8%.[75] The injected bunches were significantly smaller than the h=18 buckets they were injected into, about 150-180 ns vs. 231 ns.[76] For deuterons, when ε_{long} was not intentionally blown up at Booster injection, the amount was too small to see on the transformer. However, with ε_{long} blown up about 1.2% of the beam remained.[77] Without QP the injected bunches were about 130 ns, and when blown up they were about 180 ns long.[78] The h=12 bucket is 319 ns long.

[73] See Booster-AGS-EBIS 2021 April 16th elog 1706 and 1739 entries for QP on case and Ags/Instrumentation/currentXfmr/ags.beamCurrent_Snap.logreq/agsBeamCurrent on 4/7/3032 at 1808 in LogView for QP off case.
[74] The bunch length was 254 ns in the no QP case (see Booster-AGS-EBIS_2021 elog on Feb 5 at 18:24) and about 350 ns with QP on (see April 16th 1704 entry in same). An h=12 bucket is 525 ns long.
[75] See Booster-AGS-EBIS_2021 elog May 11 18:50 entry and May 19 13:27 entry.
[76] See Booster-AGS-EBIS 2021 May 10 elog 1838 entry (~180 ns) as well as May 13 13:16 entry (~150 ns). Recall that the Oxygen ε_{long}, on the flattop at least, got smaller as the run progressed.
[77] See Ags/Instrumentation/currentXfmr/ags.beamCurrent_Snap.logreq/agsBeamCurrent logged data for June 29 at 19:25 for the low ε_{long} case and July 1 at 05:48 for the high ε_{long} case.
[78] See Booster-AGS-EBIS_2021 elog on June 27th at 15:30 for small ε_{long} case and July 6 at 11:02 for the large ε_{long} case.

The 3.85 GeV setup that used EBIS and a 24-16-8 (3-1 type) merge had about 1.5% of the beam in the baby bunches.[79] This merge takes place on the injection porch and acceleration uses h=12.

The remainder of the setups used the 24-12-4 (6-3-1 type) merge and subsequent acceleration in h=10 buckets. The baby bunch measurements for them are compiled in Table XIV. These setups tend to have the largest baby bunches because more bunches are merged into one and injection occurs into h=24 buckets, which are nearly the same length as the injected bunches. Since the merges and the accelerating harmonic are the same for all these setups, there is nothing intrinsic to any of them that would make the size of the baby bunches different from what they are in any other one of these setups. Yet, there is considerable variation.

Not that it is the case here, but a larger fraction of baby bunches does not necessarily mean that the injected bunch is larger. The fraction can be larger if the transfer and survival on the injection porch are particularly good. In that case, more of the beam that doesn't make it into the bucket will survive. The use of h=10 accelerating buckets instead of h=12 reduces the fraction of baby bunches due to the merged bunch not fitting into the accelerating bucket[80], it doesn't affect the part of the baby bunches that come from beam missing the bucket at injection.

For some reason, when the same merge setup was used in 2019 with h=10 accelerating voltage, the baby bunches were generally smaller, about 1-2%.[81] Fortunately, the fact that the baby bunches this run were perhaps larger than they could have been had little or no impact on the run because the required bunch intensities were not demanding.

Date	**Setup**	**AGS user**	**Baby bunch percentage**
Jan 31	2	2	1.7
Feb 18	2	2	1.4
May 25	4	7	2.4
May 28	4	7	2.0
June 6	4	7	2.8
June 9	7	8	4.4
June 10	7	8	3.3
June 14	7	8	4.8
June 14	7	8	3.8
June 16	7	8	2.7

Table XIV: The fraction of beam remaining after the last extraction (a.k.a.- baby bunch percentage) for EBIS Au setups using a 24-12-4 merge. The Setup column refers to Tables I and II.

[79] See Booster-AGS-EBIS_2021 Jan 31st at 13:10 and Feb 18th 17:01 entry.
[80] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pgs. 26-29.
[81] Ibid.

Summary

A synopsis of the various setups used this run can be found in Tables I and II. Stripping efficiencies for the new BtA foils used for Au this run were measured (Tables III and IV). The history of foil deterioration during Tandem Au 3.85 GeV running was also described. Also, for Tandem Au, it was noticed that there is transverse emittance blow up right at AGS injection and that increasing ε_{long} reduces this blowup. This behavior is not evident with EBIS Au. For the last couple weeks of Tandem Au 3.85 GeV quad pumping at Booster extraction was used to reduce the peak current and increase ε_{long} so that there would be less transverse blowup. Table V contains ε_{long} measurements made during Tandem Au 3.85 GeV running.

Measurements of ε_{long} at Booster extraction and on the AGS injection porch for Tandem Au 3.85 GeV were also made (Table VI). An efficiency measurement with an AGS Late of 9.6e9 found 56.8 and 96.0% for BtA and AGS acceleration, respectively.

ε_{long} was measured on the different flattops used this run with EBIS Au and a 6-3-1 type merge (Table VIII). ε_{long} for the 8.65 GeV setup was unexpectedly large. In fact, it was larger than what is typically measured for 9.8 GeV, about 0.90 eVs vs. 0.80 eVs. Partly because of this there was not a simple dependence of ε_{long} on flattop energy (Table IX). ε_{long} was also measured for the 3.85 GeV 3-1 type merge (Table X).

The Oxygen setup in the Booster and AGS was described and the difficulties encountered measuring the intensity were recounted. Efficiencies and intensities are shown in Table XI. ε_{long} on the flattop was measured several times (Table XII) and, although large, decreased significantly during the course of the run. BtA and AGS transverse emittance measurements are also presented.

Given the difficulty finding the Oxygen AGS injection field, a method for determining how to set the AGS injection field for different beams given the B field found from $B\rho$ is described (Table XIII and Figure 21).

The deuteron setup was the same as the one used in run 16, though the required bunch intensity for RHIC was substantially lower. The setup is described in some detail. The unusual behavior of deuterons around transition was also described. Although the AGS ion IPM was not available during deuteron running the horizontal emittance was rather large in BtA (Figure 19) and much larger than that on the AGS flattop using the eIPM. However, it is not clear how accurate those horizontal emittance flattop measurements are (Figure 20).

The amount of baby bunches when using the 24-12-4 merge is summarized in Table XIV.

Acknowledgements: Thanks to Iris Zane for her help.