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The 2020 Low Energy Gold Run in the Injectors

K. Zeno

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The 2020 Low Energy Gold Run in the Injectors

Keith Zeno
12-31-2020

During Run 20 the injectors provided Gold to RHIC at four different energies (3.85, 4.59, 5.75, and 7.3 GeV).[1] The majority of the run was spent providing 4.59 and 5.75 GeV beams. The RHIC physics program using 5.75 GeV beam took place from Dec. 10, 2019 to Feb. 24, 2020, although there was a period of about 2 weeks (Jan. 27th to Feb. 10th) where 7.3 and 4.59 GeV were used. The 4.59 GeV program took place from Feb. 24. 2020 to Sept.1 2020. Data taking for the 4.59 GeV program was interrupted by the COVID-19 shutdown which lasted about 3 months, from Mar. 20 to June 21. So, the 5.75 GeV program was about 2 months long and the 4.59 GeV program was about 3 months long. There were also other short periods where 7.3 GeV beam was provided to RHIC for CeC development and fixed target data taking. 3.85 GeV beam was also provided near the end of the run in preparation for next year (Sept. 2-11).

Injector setup began on Nov. 11th, injection into RHIC first occurred on Dec. 5th, and physics data taking began in RHIC on Dec. 10th. Tables I and II are chronologies of the injector setups that were used during the run together with some details. Setups 6 and 10, which are highlighted in yellow, were used for the 5.75 and 4.59 GeV RHIC programs, respectively. 7.3 GeV running used setup 5, and 3.85 GeV running used setups 11 and 13.

This year, in addition to EBIS, the Tandem was used as the pre-injector for a substantial part of the run. It was used for the entire 5.75 GeV program, a good portion of the 3.85 GeV running (setup 13), and also for some setup activities when EBIS was down.

When EBIS was used as the pre-injector, Booster user 5 (BU5) was used, and Booster user 1 (BU1) was used for Tandem beam. During normal running when EBIS was used there were 12 beam requests and for Tandem there were 8. In both cases there was one bunch transferred to the AGS per Booster cycle.

The Booster setup for EBIS was essentially unchanged from what it has been for the past few years. The 7.3 GeV program used the 6-3-1 type merge in the AGS that has been used since Run 16. The AGS setup used for much of 4.59 GeV LEReC commissioning, which also used EBIS beam, employed a 4 to 1 type merge that had not been used before (setup 7). The Booster and AGS setups for the 5.75 GeV program, which used Tandem beam, were developed for the most part during Run 19.[2] In this case there was a 6-3-1 merge in the Booster, and a 2 to 1 type merge in the AGS.

Previous to this run, the highest Au intensity in the AGS was about 7.4e9 ions and the highest Booster Late intensity was about 13.5e9. Both these intensities were with Tandem Au before the switch to EBIS as the pre-injector in Run 12. The AGS intensity during the 5.75 GeV program was limited to protect equipment (vacuum chambers, J10 dump, G10 kicker, etc.).

The BtA stripping foils also began to deteriorate a week or two into the 5.75 GeV program and consequently the Booster Late intensity was also limited. These limits were eventually set to 9.6e9 and 20.0e9, respectively. The foils lasted long enough to complete the run

[1] These are total energies (γmc^2) not kinetic energies.

[2] These setups are described in detail in K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/624, Nov. 2019, pgs. 29-36.

and there were no equipment failures in the AGS related to the higher intensity. The Westinghouse motor generator was used for the AGS main magnet before the COVID shutdown, and Siemens was used after it.

Set-up	Initial Setup	Pre-Injector	AGS user	AGS Merge Harmonics	# of bunches merged	Flattop energy (GeV)	Final # of Bunches	Nominal bunch Intensity[3]	Typical Long. Emit (eVs/n) and measurement date	
1	11/18	EBIS	5	24-12	2	4.59	6	1e9	0.28	11/19
2	11/19	EBIS	5	**12-4**	**3**	4.59	**3**	1.5e9	0.41	11/19
3	11/20	Tandem	1	12-6	2	5.75	3	1.5e9	0.26	11/22
4	11/27	**Tandem**	5	12-4	**2**	4.59	3	1.6e9	0.32	11/27
5	12/2	EBIS	6	24-12-4	6	7.30	2	2.8e9	0.74	7/14
6	12/3	Tandem	1	12-6	2	5.75	**4**	2.3e9[1]	0.28	2/18
7	12/5	EBIS	5	**24-16-8**	**3**	4.59	**4**	1.5e9	0.40	2/3
8	12/5	**Tandem**	5	24-16-8	**2**	4.59	4	1.25e9	0.30	12/18
9[4]	12/26	Tandem	8	12-6	2	5.75	3	N/A	N/A	N/A
10	2/7	EBIS	3	24-12-6	4	4.59	3	2.0e9	0.50	6/18
11	7/21	EBIS	2	24-16-8	3	3.85	4	1.5e9	0.35	9/1
12	8/19	**EBIS**	8	**24-12-6**	**4**	**2.50**	3	2.0e9	N/A	N/A
13	8/31	Tandem	1	12-6	2	**3.85**	4	2.2e9[2]	0.24	9/10

1- The bunch intensity was limited because the total AGS intensity was limited for equipment protection. Initially this limit was 8.0e9. It was raised to 8.8e9 on Jan 21 and 9.6e9 on Jan 24. With 4 final bunches/cycle the latter corresponds to 2.4e9/bunch.

2- Total AGS intensity was limited to 9.6e9 (2.4e9/bunch) for equipment protection.

3- The definition of Nominal bunch intensity is a little vague. In some cases (setups 3, 4, 8, 9, 12) the intensity required for RHIC setup, was lower than what was available and in other cases the EBIS intensity was lower than it could have been. In the latter cases, where a date is not given, the nominal intensity shown is what would be obtained if EBIS were performing nominally. The latter is taken as 0.5e9 times the number of bunches merged in AGS.

4- Setup 9 was made so that the per bunch intensity would not be limited as much by the total AGS intensity limit (which at that time was 8.0e9). Instead of 8 transfers and 4 bunches on AGS flattop (setup 6) there were 6 and 3, respectively. The supercycle was shortened from the 5.6 sec used for setup 6 to 4.6 sec, but this setup was not used for RHIC.

Table I: Chronology of injector setups during Run 20. Setups 6 and 10, highlighted in yellow, were the setups used for the 5.75 and 4.59 GeV programs, respectively. Setup 5 was used for CeC development and the 7.3 GeV fixed target program. Setups 11 and 13 were both used in RHIC in preparation for the 3.85 GeV program next year. Setup 7 was used for 4.59 GeV LEReC commissioning. The dates shown in the "initial setup" column are when beam was first introduced into the AGS for that setup. The "# of bunches merged" column shows the number of bunches merged in the AGS, in all cases there was 1 bunch in the Booster at extraction. The "Final # of bunches column" indicates the number of bunches available per AGS cycle for transfer to RHIC. Items in bold indicate the first time the indicated configuration was used for an AGS user already shown in the table. For example, in setup 4 the pre-injector for AU5 was changed from EBIS to Tandem for the first time. In this particular case the pre-injector for AU5, which was designed for EBIS, was switched back and forth between EBIS and Tandem depending on the availability of EBIS.

	Pre-Injector	# of bunches merged	Flattop energy (GeV)	# of Bunches	Initial SC length	Final SC length and when use of that length began	Date extracted from AGS	Date injected into RHIC
1	EBIS	2	4.59	6	6.6 s	-	-	-
2	EBIS	**3**	4.59	**3**	6.6 s	-	-	-
3	Tandem	2	5.75	3	6.6 s	-	11/26	-
4	**Tandem**	**2**	4.59	3	6.6 s	-	11/27	-
5	EBIS	6	7.30	2	6.6 s	6.0 s on 7/2	12/3	1/28
6	Tandem	2	5.75	**4**	6.6 s	5.6 s on 12/13	12/3	12/5
7	EBIS	**3**	4.59	**4**	6.6 s	6.0 s on 1/22	12/5	12/5
8	**Tandem**	**2**	4.59	4	6.6 s	-	12/5	12/5
9	Tandem	2	5.75	3	4.6 s	-	-	-
10	EBIS	4	4.59	3	6.0 s	5.6 s w/o NSRL on 3/5 5.4 s w/o NSRL on 7/16	2/8	2/8
11	EBIS	3	3.85	4	6.0 s	-	8/26	9/2
12	**EBIS**	4	**2.50**	3	6.6 s	-	-	-
13	Tandem	**2**	**3.85**	4	6.0 s	-	9/1	9/2

Table II: Chronology of injector setups during Run 20. Included in this table, but not in Table I, is a history of Supercycle (SC) lengths, as well as when beam using each setup was first extracted from the AGS and first injected into RHIC. As in Table I, the setups used for the 5.75 and 4.59 GeV programs are highlighted in yellow.

The 5.75 GeV Part of the Run

The 6-3-1 Merge in the Booster

Although there was not much time given to optimizing it, the 6-3-1 merge in the Booster was tested last year with Gold from Tandem. The cycle that was used last year only allowed for 6 transfers before the PPMR limit would have been exceeded. It was found that extending the merge porch by 2 jiffies (and accordingly the cycle length by the same amount) would allow for 8 transfers before the PPMR limit would be exceeded. So, although work began with the cycle from last year (setup 3), it was soon changed to the longer cycle (setup 6). This change makes the Booster cycle 267 ms long. Figure 1 shows a mountain range display of the 6-3-1 merge with the longer porch and Figure 2 shows the Rf cavities used and their harmonics together with the main magnet current and the current transformer. Figures 1 and 2 can be compared to see what voltages and harmonics are used during different parts of the merge.

Figure 3 is a mountain range display of the bunch at AGS injection using both the shorter and longer merge porch. Although the full bunch length in both cases is similar, the core of bunch using the longer porch is narrower. Note that the Booster WCM signal (Figure 1) has a much slower time response than the AGS WCM (Figure 3) so there is structure on the AGS WCM that is not visible on the Booster signal.

An ε_{long} measurement at Booster extraction was made on Feb. 21st. Ten bunch length measurements were made on the 1st turn in the AGS using the WCM, the average of which was 268.4ns (σ=19.0ns). A synchrotron frequency (f_{synch}) near Booster extraction of 925±25 kHz was

measured using the Booster WCM. For the average bunch length of 268.4 ns this gives an ε_{long} of 0.0820±0.022 eVs, where the uncertainty reflects the uncertainty in the synchrotron frequency.[3] Similar measurements have been made with EBIS Au, and the results have varied, but most recently in Run 19 an ε_{long} of 0.0864 to 0.0878 eVs was obtained.[4] In 2007, a value of 0.046 eVs was found for the total ε_{long} of the 6 bunches at Booster extraction using Tandem beam without a merge.[5] This amounts to 0.0820/0.046 or 78% emittance growth due to the merge. In 2017, a value of 0.068±0.005 eVs was obtained for the total ε_{long} of the 4 unmerged bunches at Booster extraction suggesting about 30% growth from the 4-2-1 merge used with EBIS beam.[6]

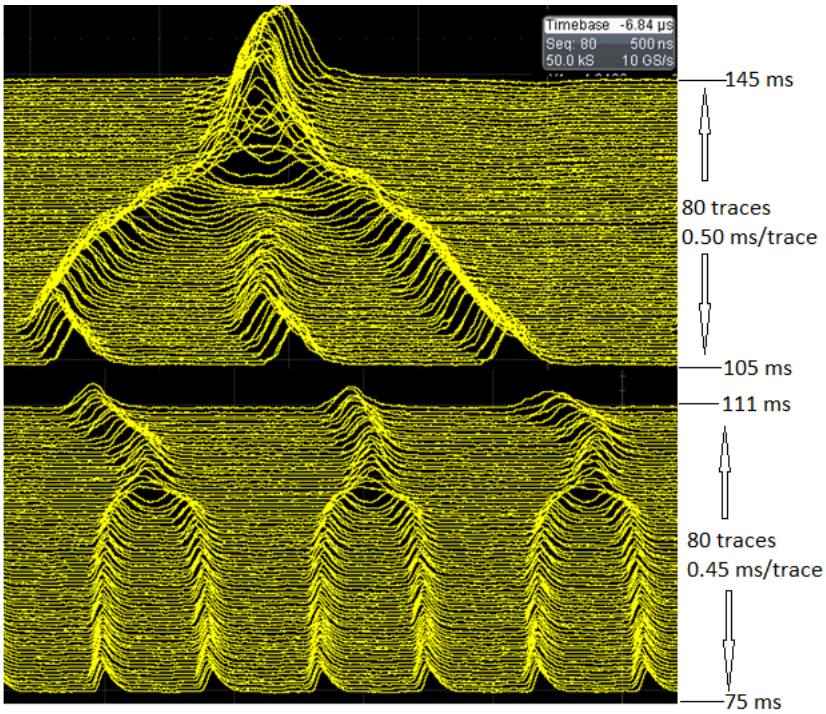

Figure 1: Mountain range displays of the Booster wall current monitor (WCM) during the 6-3-1 merge using the longer merge porch. The bottom section shows the 6-3 portion and the top shows the 3-1 portion. The times from Bt0 that the 2 displays were taken and the spacing between traces is shown on the right.[7]

[3] See entries from 1339 to 1402 in the Feb 21, 2020 Booster-AGS-EBIS 2020 elog.
[4] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pgs. 7 and 8.
[5] See K. Zeno, "Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Bunch Merge", C-A/AP/596, pg. 2
[6] Ibid. pgs. 3 and 4.
[7] See Nov. 26, 2019 Booster-AGS-EBIS 2020 elog entries at 1831 and 1940. Compare the 6-3-1 merge on mountain range display from last year in Figure 22 on pg. 36 of K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/624, Nov. 2019 and the 1427 entry in the Nov. 26, 2019 Booster-AGS-EBIS 2020 elog which both use the shorter merge porch.

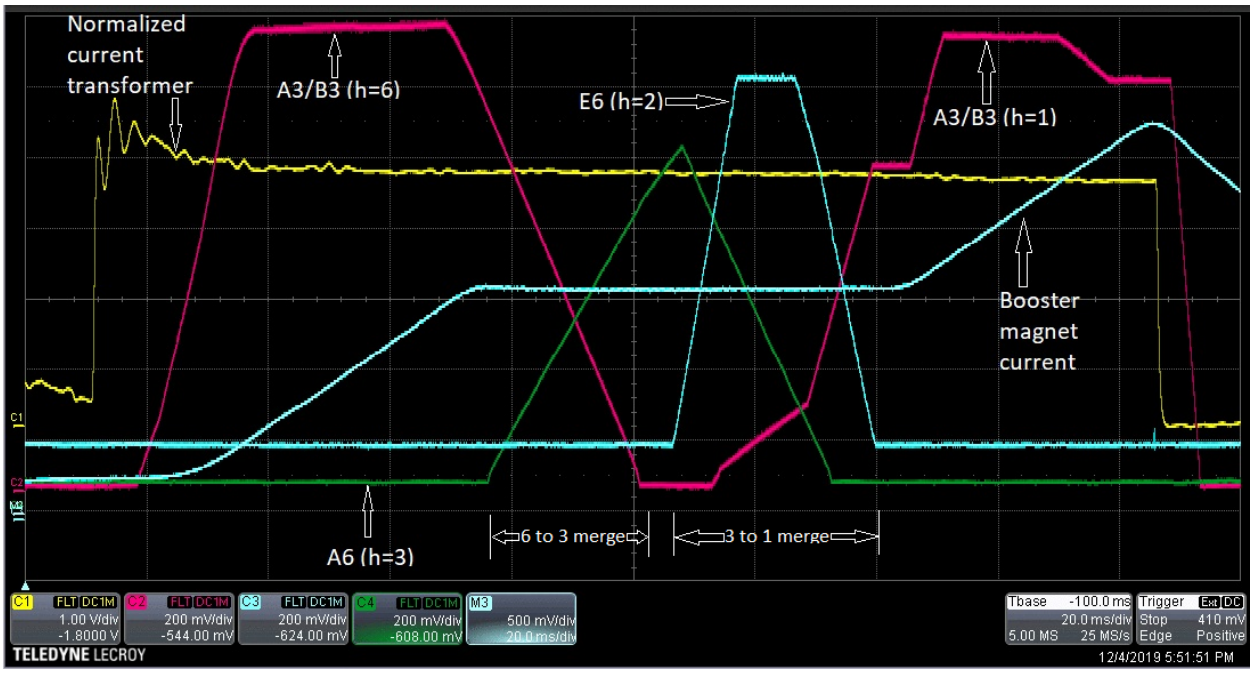

Figure 2: The Booster 6-3-1 merge used with Tandem Au for the 5.75 GeV program. Shown are the Rf cavities used and their harmonics together with the Booster main magnet current and normalized current transformer. The times where the 6-3 and 3-1 portions of the merge take place are also shown. The signal shown for A3/B3 is just A3, but B3 has the same function. The sweep speed is 20 ms/div. and the trigger is Bt0 (so the time at the center is at Bt0+100 ms).[8]

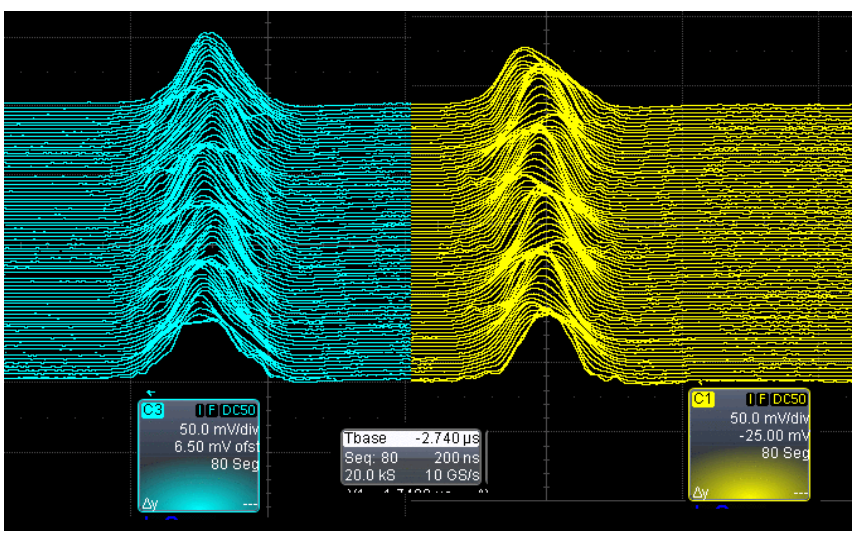

Figure 3: Bunches at AGS injection on the WCM mountain range using the shorter (34 ms, left) and longer (67 ms, right) Booster 6-3-1 merge. The voltages at Booster extraction and AGS injection are quite similar in both cases. In both cases there is 20 μs between each trace and 80 traces (a total of 1.6 ms). The sweep speed (200 ns/div) and scope gain (50 mV/div) are the same for both.[9]

[8] Adapted from the Booster-AGS-EBIS 2020 elog Dec. 4, 2019 1750 entry.

[9] The shorter merge (left) is from the Nov. 26, 2019 1409 entry in the Booster-AGS-EBIS 2020 elog and the longer one is from the Dec.3, 2019 1709 entry in the Booster-AGS-EBIS 2020 elog.

Figure 4 shows one of the bunch length measurements used above. Note that the length of this bunch if the tails are neglected is about 222 instead of 268 ns. The ε_{long} corresponding to 222ns is 0.0564±0.0015 eVs (for f_{synch}=925±25 kHz), which is significantly closer to the unmerged case (0.046 eVs). Figure 5 shows the 10 bunches whose lengths were measured. Note that, at least for this set of bunches, the shape varies quite a bit and the average length and σ are not adequate to characterize this. Injection occurs into h=12 buckets so, unlike the standard setup with EBIS beam that uses h=24, there is no need to 'quad pump'.

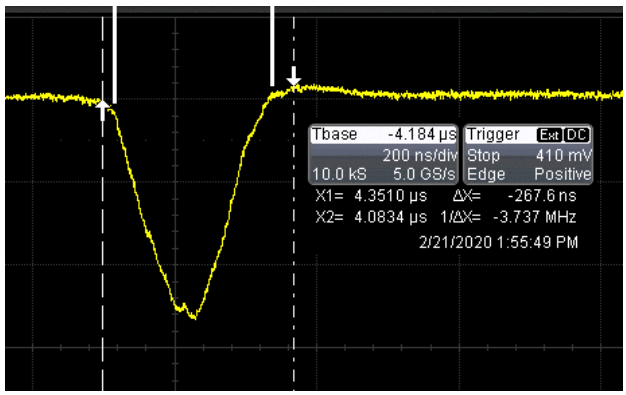

Figure 4: This is one of the 10 bunch length measurements used to calculate the Booster extraction ε_{long} discussed above. The full length is 268 ns long (dashed vertical lines), but the length excluding the tails is about 222 ns (solid vertical lines).

BtA Foil Deterioration During the 5.75 GeV Part of the Run

The BtA foils used this year had been used for Au operation since 2008 without any major problems. Prior to 2012 and the advent of EBIS, the Booster Late intensity per Booster cycle was as high as about 3.4e9 using Tandem, which is 40% higher than during this year's 5.75 GeV running. However, there were 8 Booster transfers this year instead of the 4 there were then, so the total amount of beam transferred per AGS cycle was significantly higher.[10] Calculations using 8 transfers at about the maximum Booster Late this run (20e9) indicate that the Aluminum in the foils will reach a temperature close to its melting point.[11]

There are 2 BtA stripping foils used for Au, foils 5 and 6, and deterioration of the transfer efficiency was first noticed while using foil 6 on Dec. 17th. Prior to that Booster Late was typically about 16e9, although there was a brief period where it reached 20e9 on Dec. 12th and

[10] Prior to Run 12, h=6 was used in the Booster without a merge, and such a setup allows for no more than 4 Booster transfers. See K. Zeno, "Overview and analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, Sept. 2016, pgs. 1 to 4, for an explanation of this.

[11] C. J. Gardner, "FY2020 parameters for Gold ions in Booster, AGS, and RHIC", sections 27-29, Sept. 25, 2020 (forthcoming C-A/AP note). With 8 transfers of 2.5e9 every 5.6 sec and a beam size on foil of 1 cm^3 calculations indicate that the temperature of the foil would reach 900°K and the melting point of Al is 933°K.

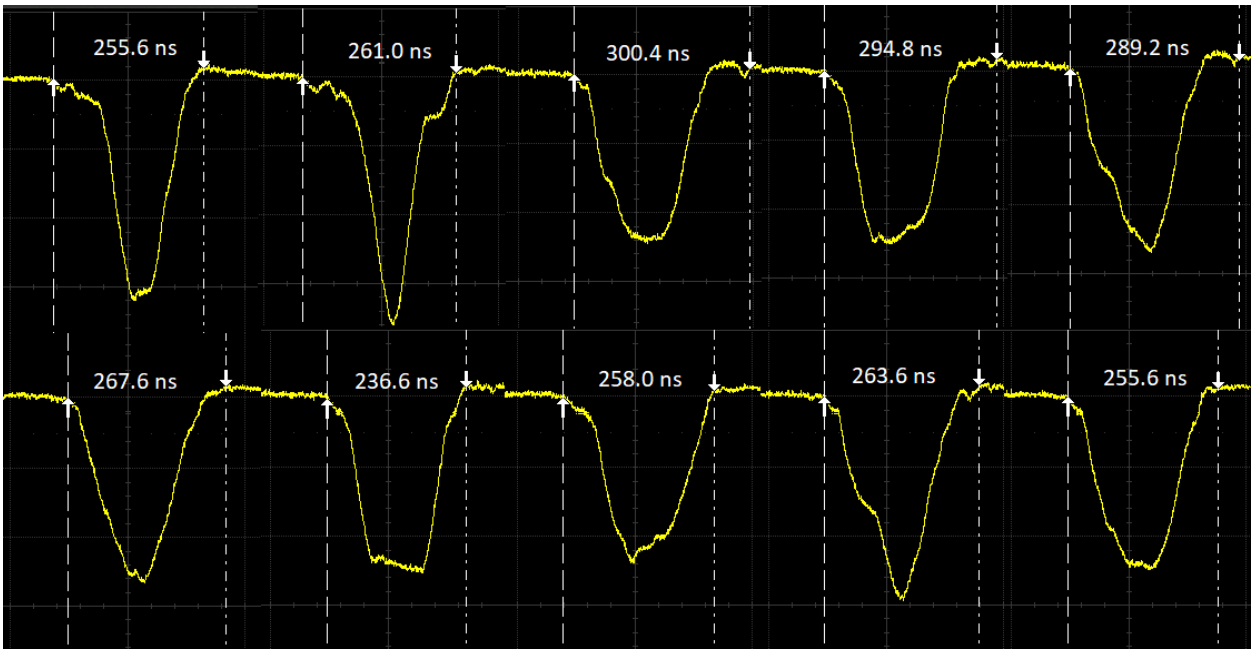

Figure 5: The AGS WCM traces for the 10 bunches on the first turn used to measure the bunch length at Booster extraction. The vertical lines indicate the length of each bunch and that length is also displayed.

another where, just before the deterioration was noticed on Dec. 17th, it reached 18 to 19e9.[12] When the deterioration was noticed, the foil was changed from 6 to 5 and foil 5 was used for as long as possible, which turned out to be the rest of the 5.75 GeV part of the run.

The ability to move to different (vertical) positions on a foil,[13] and move the beam horizontally on it as well (using BtA DH1), were essential for prolonging the foil's lifetime, but there were problems with the F3 kicker throughout the run which complicated matters.

After the 5.75 GeV part of the run, the 4.59 GeV part began in which EBIS was used and the foil was switched to 6. There was no further deterioration of foil 6 noticed for the remainder of the run. With EBIS Au the Booster Late intensity is substantially lower.

Indications in the Longitudinal

There were a couple debunching measurements made at AGS injection with Tandem beam during the run. The first measurement was also made on Feb. 21 using foil 5 just after ε_{long} at Booster extraction was measured. This was near the end of the 5.75 GeV program when having to find a new spot on the BtA stripping foil was a common. The momentum spread in that

[12] See the 1225 to 1230 entries on Nov.30th in the Booster-AGS-EBIS 2021 elog

[13] The foils are in a rotary drive and a foil can be moved by rotating the foil wheel by small amounts. For example, when using foil 5, the foil is centered when it is set to 5. If it is set to 5.1 it will stay on foil 5 but rotate slightly. This rotation amounts to moving the foil vertically with respect to the beam. Care must be taken when doing this since by rotating it it is possible to hit the foil holder with beam, which could damage it. See BtA Foil Stripper Motion in the Instrumentation wiki for more details.

measurement was asymmetric, with the Δp/p of the trailing edge of the bunch being about 3 times that of the leading edge.

However, that was not the case for the measurement made on Sept 3, where the Δp/p of the edges was more or less symmetric. This measurement used foil 6 and was made during the 3.85 GeV program (setup 13). Figure 6 shows the mountain range display that was used for that measurement. The debunching time was found to be 3.45 ms, which using a bunch length of 268 ns, corresponds to a Δp/p half width of 1.10e-3.[14]

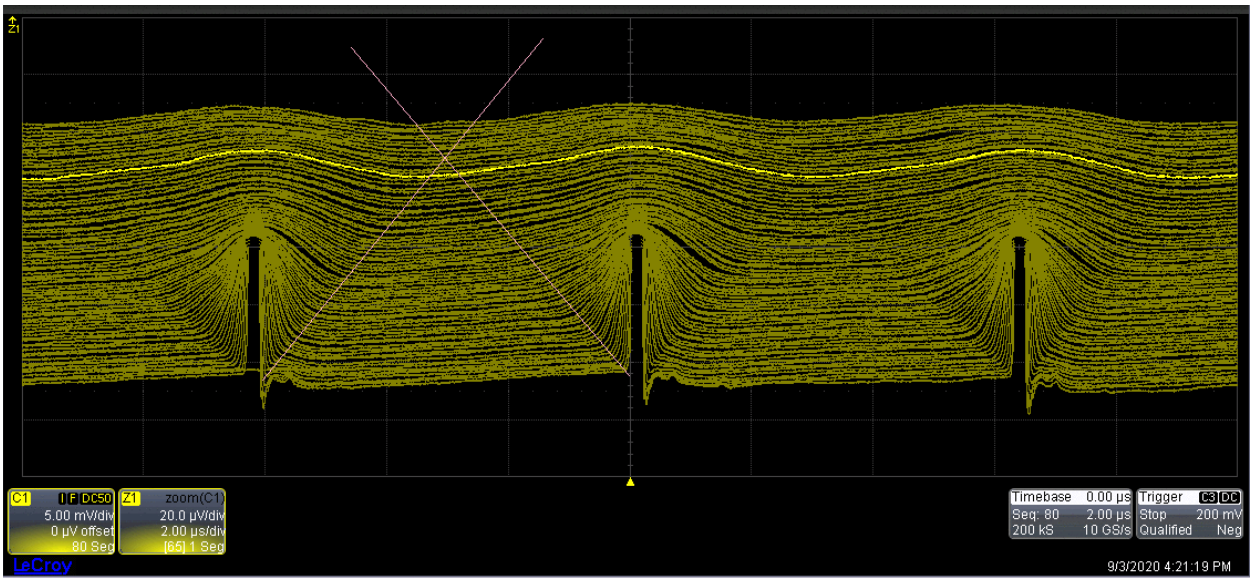

Figure 6: Debunching measurement at AGS injection using a mountain range display of the WCM from Sept. 3rd. The pink lines are where the leading and trailing edges of the spreading bunch are judged to be. There are 80 traces and the highlighted trace is the 65th trace from the bottom. The leading and trailing edges appear to cross around the 70th trace. There is 50 µs between traces, so that takes about 50µs*(70-1)=3.45 ms. Foil 6 was used.[15]

Figure 7 shows the mountain range display for the debunching measurement from Feb. 21st.[16] The red lines are where the leading and trailing edges of the bunch are judged to be. It takes the leading edge about 73 traces to spread halfway around the ring. With 50 µs between traces that corresponds to 3.60 ms (Δp/p=1.05e-3), which is similar to the Sept. 3rd result. On the other hand, the trailing edge only takes about 25 turns, or 1.2 ms (Δp/p=3.14e-3), to spread halfway around the ring. Although the mechanism is unclear, it seems plausible that this asymmetry may be due to foil deterioration. Lower momentum particles are responsible for the trailing edge spreading out. So, perhaps the deterioration is related to the development of a low

[14] See K. Zeno, "Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Bunch Merge", C-A/AP/596, Dec. 2017, pg. 7-8 for a explanation of how Δp/p is found from the debunching time.
[15] See entries at 1620 and 1621 in the Sept 3 Booster-AGS-EBIS elog.
[16] See Booster-AGS-EBIS Feb 21 elog entries from 1353 to 1513. Figure 7 is from the 1450 entry, where the 30th trace is highlighted.

momentum tail from passing through the foil. However, the transfer efficiency was only somewhat lower than optimal for this case (maybe 51-52% vs. 54%).

Note that, as shown in Figure 8 for the Feb 21st measurement, that the rate at which the trailing edge spreads out appears to be greater just after injection than it is later on. This could be because of the AGS's momentum aperture, which may prevent the lowest momentum particles from surviving. Obviously, if this is beam loss it could be linked with the reduced transfer efficiency that has been observed and attributed to foil deterioration.[17] One could argue that it is due to some artifact of the WCM signal, but this behavior is not apparent in the Sept. 3rd mountain range display (Figure 6). There could also be a reduction in transfer efficiency due to the BtA momentum aperture.

Figure 9 is also a mountain range at injection but with the Rf on and using foil 5. It was taken on Feb.18th when the transfer efficiency was very poor (~30%).[18] The foil position was set near the central position so it is very unlikely that any of beam was hitting the foil holder. The Rf frequency is well matched to the center of the bunch, but there is a large tail that first develops on the right side of the bunch but not on the left reminiscent of the asymmetry in the Feb 21st debunching display. Its shape evolves like one might expect a bunch with a low energy tail might evolve. Also, if the low energy tail is caused by the foil, it would not immediately affect the bunch shape, since it would presumably take quite a few turns to become apparent. This is consistent with what's observed here since the bunch right at injection looks reasonably symmetric.

Measurements using EBIS Au at AGS injection have been made many times in previous years. In 2019 there were 4 measurements with foil 6 for which the values for $\Delta p/p$ were 1.04, 1.13, 1.17 and 1.233e-3. For foil 5, there were 2 measurements, 1.30 sand 1.38e-3, which were both unusually high. Historically, up until then at least, a significant difference in the $\Delta p/p$ between the 2 foils had not been noticed. These measurements were made with no quad pumping and similar Rf voltage references at Booster extraction to this year (13.0 kV for A3 and B3 then and 12.5 kV for both this year).[19] So, the $\Delta p/p$ of the Tandem Au, at least in the symmetric case, is similar to what it is for EBIS Au.

Indications in the Transverse

In extreme cases like the one on Feb. 18th there can be obvious signs of a problem on the BtA multiwires. Especially MW060, which is the first one downstream of the foil and is at a location of high dispersion. Figure 10 shows MW060 profiles for 2 cases, In case 1 the transfer is about 52% and in case 2 it is 18%.[20] In case 1 the foil is set to 5.20 and in case 2 it is set to 5.00.

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[17] The transfer efficiency when the Feb 21st measurement was taken was not horrible, but was likely several percent lower than optimal, maybe 51 vs. 54%.

[18] Taken from 1532 entry in the Booster-AGS-EBIS Feb. 18, 2020 elog.

[19] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pgs. 8 and 9.

[20] See 1427 and 1528 entries in the Booster-AGS-EBIS Feb. 18, 2020 elog. Note that the intensity and profiles on the multiwire upstream of it (MW006) are nearly identical and the magnet settings between them are as well. The only difference is that DH2-3 is 1.2A lower in the latter case (1780.4 vs 1779.2A), but despite this difference the

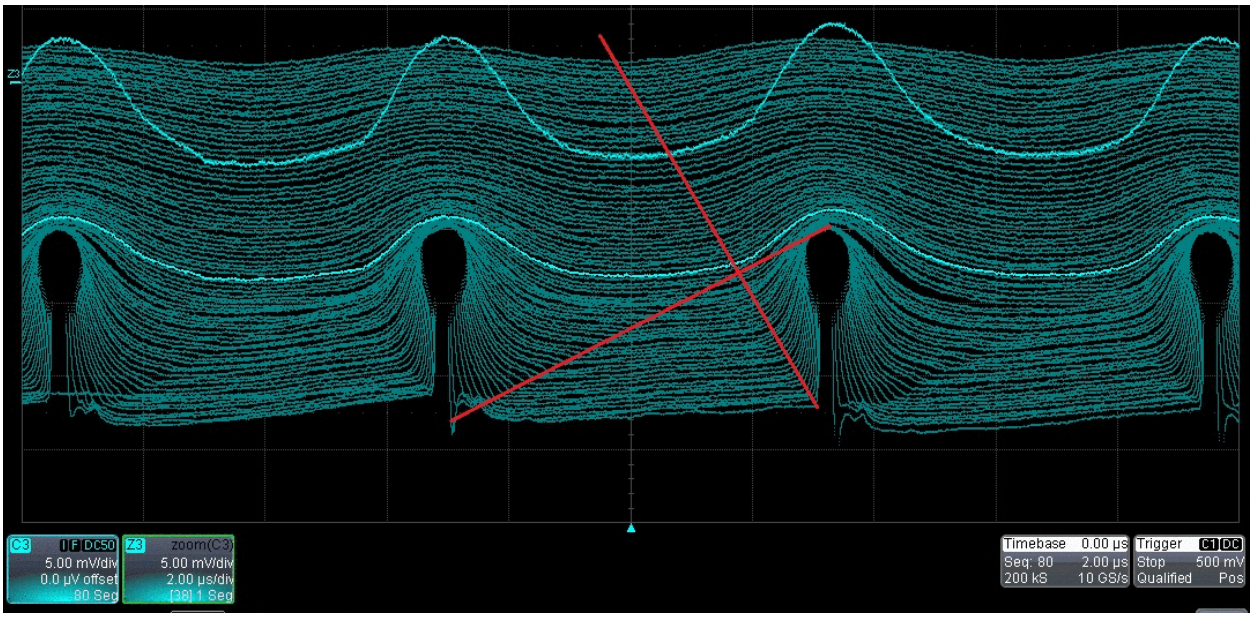


Figure 7: Debunching measurement at AGS injection using a mountain range display of the WCM from Feb. 21st. The red lines are where the leading and trailing edges of the spreading bunch are judged to be. There are 80 traces and the highlighted trace is the 38th trace from the bottom. There is 50 µs between traces. The leading edge appears to spread halfway around the ring in about 3.6 ms, but it only takes the trailing edge about 1.20 ms to do so. This is foil 5.

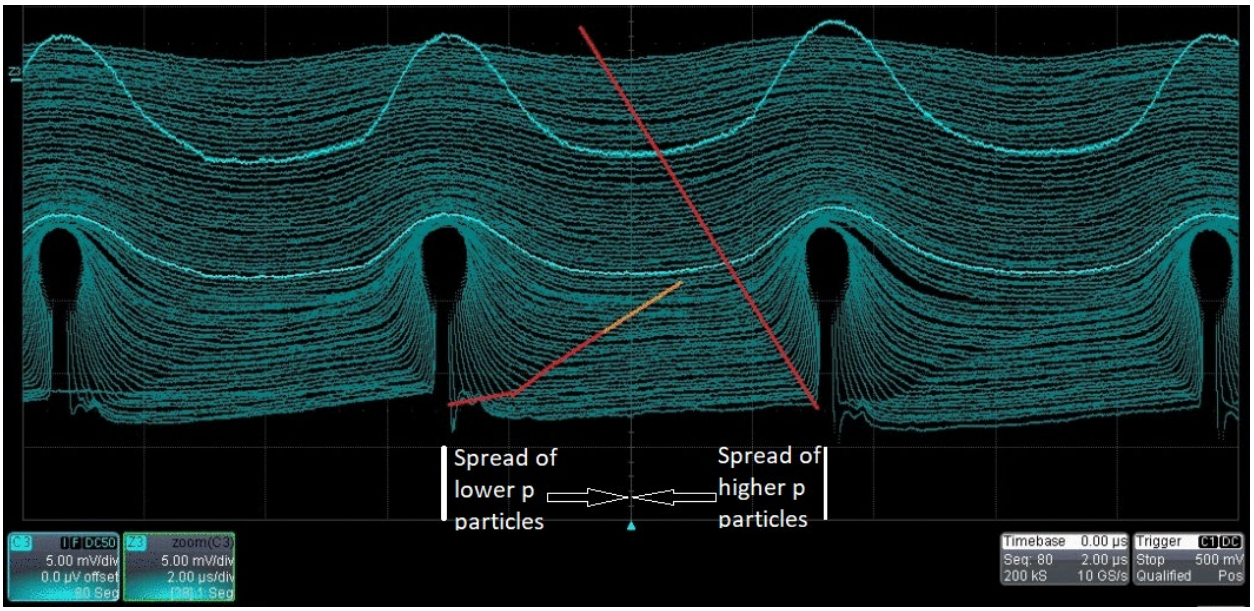


Figure 8: Same display as Figure 7 except that instead of 'fitting' a single straight line to the trailing edge, two straight lines are 'fit'. One for just after injection and one for the rest. Note that the slope of the line closer to injection has a steeper slope and this behavior is not evident in the symmetric case (Figure 6).

position of Au77+ on MW060 is only 0.11 mm different in the 2 cases. The area of the vertical profiles, a good measure of the relative intensities is 13.36 for case 1 and 13.39 for case 2 on MW006.

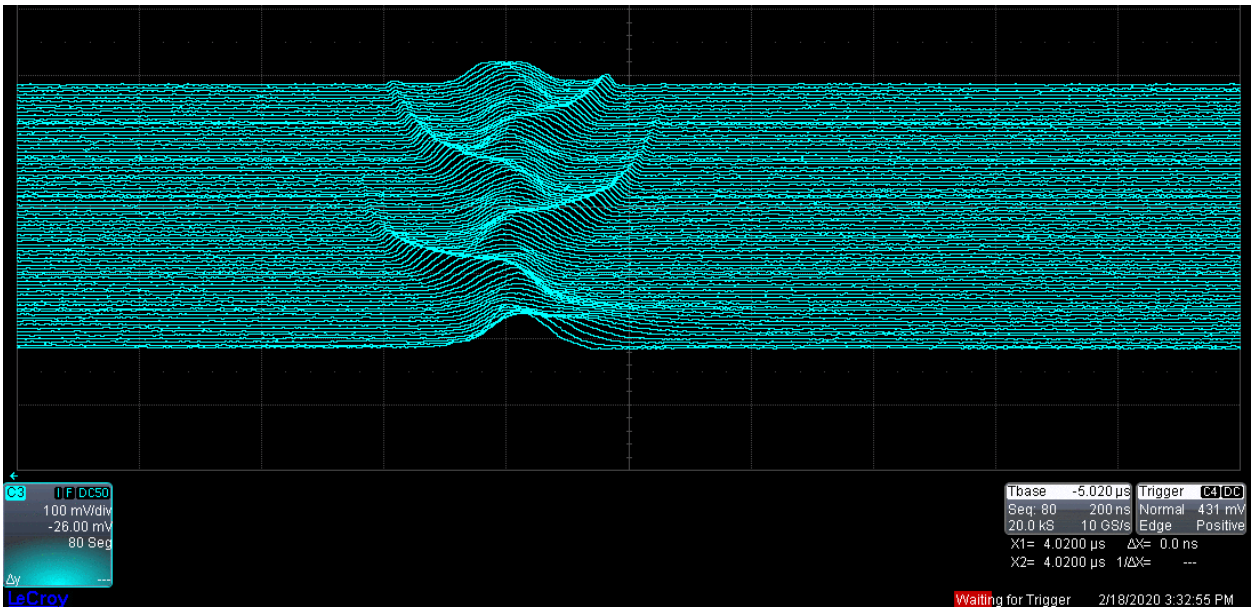


Figure 9: Mountain range display of the WCM at AGS injection with the Rf on at a time when the transfer efficiency was very poor (~30%). This is using foil 5.

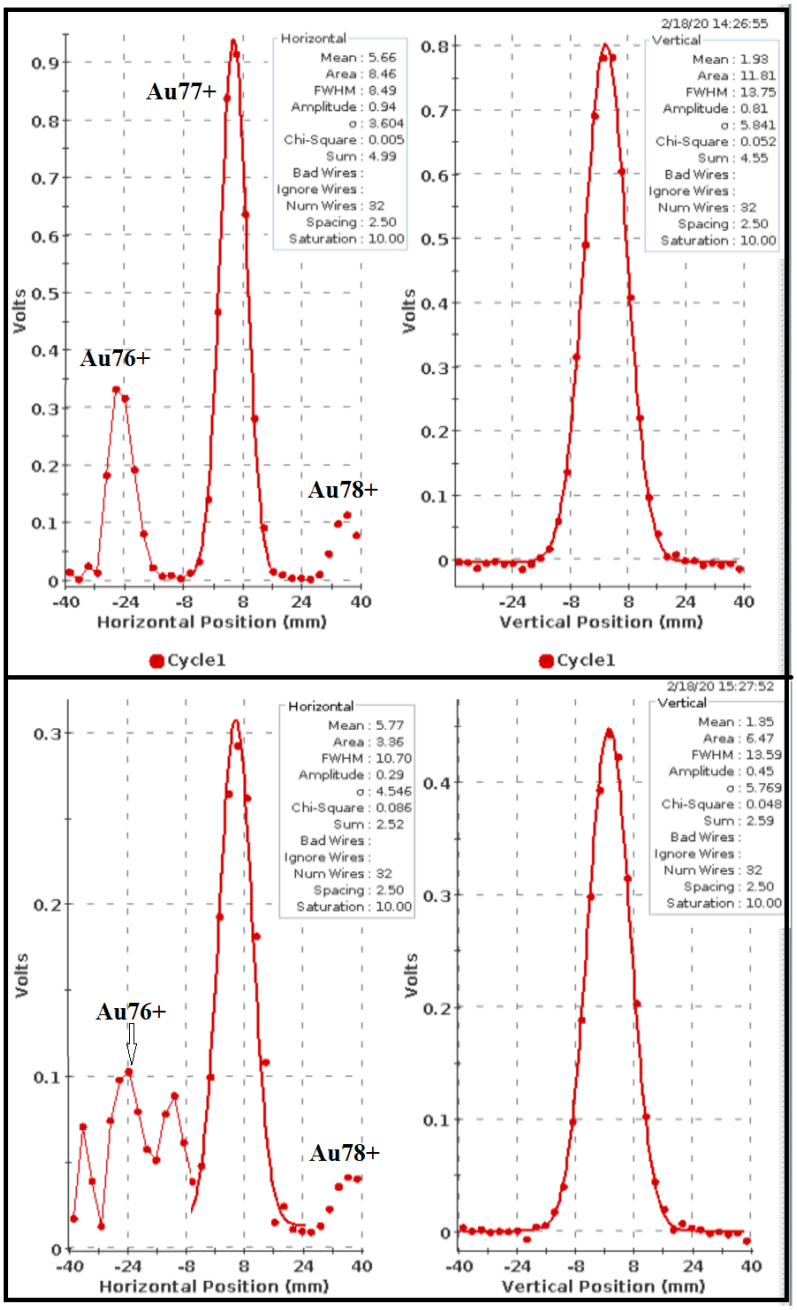
Note that the ratio of the vertical areas in case 2 and 1 is 6.47/11.81 which indicates that only about 55% of the beam in case 1 still gets to MW060 in case 2.[21] From this one might expect the BtA efficiency to be 0.55*52%=29%, which is still somewhat higher than 18%.

However, the ratio of the areas of the Au77+ profiles in the 2 cases is only about 40% (3.36/8.46) from which one might expect the BtA efficiency to be 21%, which is pretty close to what's observed.

From the figure it is evident that, in case 2, there is not just Au76+ visible to the left of the main Au77+ profile but apparently a couple other profiles as well. The presence of these profiles could explain why the ratio of the Au77+ profiles is lower than the ratio of the vertical profiles, 40 vs. 55%, since the area of the vertical profile in case 2 includes the beam associated with these. Also, those profiles have lower rigidities than the main Au77+ profile, which, if they too were Au77+ would imply they have a lower momentum as well. This would be consistent with the pronounced low momentum tail observed in the longitudinal when the beam is hitting a bad spot on the foil (see Figure 9).

Although it is more difficult to fit well in case 2, the FWHM of the Au77+ profile is somewhat larger in that case than in case 1 as well, 10.70 vs. 8.49 mm, which might be indicative of increased momentum spread. The widths of the vertical profiles in the 2 cases are the same, so the increased width is likely not due to increased scattering.

[21] In both cases MW006 was inserted. Note that this analysis and that which follows assumes that the multiwire's response to all the different beams is nearly the same, which may or may not be true, depending on what beams they are. Also, I'm assuming that the vertical profile includes the beam from whatever signal is visible on the horizontal wires and doesn't include whatever is not.



Case 1, foil position is 5.20

Case 2, foil position is 5.00

Figure 10: BtA MW060 profiles with Tandem Au. In case 1 (top) the BtA efficiency is 52% and in case 2 (bottom) it is 18%. Virtually the only thing that is different is the position of the stripping foil (5.20 for case 1 and 5.00 for case 2). Gaussian fits are shown for the Au77+ peaks and the vertical profiles.

It is difficult to measure the area of the Au76+ profile in case 2, but the ratio of the peak wire voltage for Au76+ and Au77+ in each case is about the same, 0.33/0.91=0.36 in case 1 and 0.10/0.29=0.34 in case 2. The ratios of Au78+ and Au77+ peak wire voltages are also similar, 0.11/0.91=0.12 for case 1 and 0.045/0.34=0.13 for case 2. So, perhaps surprisingly, it doesn't

seem like the relative proportions of the different charge states near Au77+ change much when the foil deteriorates. Unfortunately, I did not look for lower charge states than Au76+, which I could've done by raising DH2-3. Normally about 5% of the beam at MW060 is Au75+ and no profile is visible for charge states below that.[22]

In less extreme cases of foil deterioration the horizontal profiles on MW060 will still look more or less normal (i.e.-like case 1 in Figure 10), but their total area, which is proportional to the intensity, drops and the vertical profile area also drops, but not by as much. For example, on Dec 18th the foil was changed from 5 to 6 and the area of the Au77+ profile, when normalized to the area on MW006, dropped by a factor of 0.62.[23] The transfer efficiency also dropped by a large amount, from about 47 to 35%, but the MW060 vertical profile area, when adjusted for intensity at MW006, only dropped by a factor of 0.91. In this case then, since there are no other profiles visible in the horizontal, one can infer that part of the signal for the vertical profile comes from beam that is not visible on the horizontal wires.

Foil Position Scans

A few scans of foil position vs. BtA efficiency were taken during the run. Figure 11 contains 2 scans for foil 5, which was used for the majority of 5.75 GeV running. Note that the deterioration is much worse for the Aug. 21st data because that data was taken after the entire 5.75 GeV program.[24] Once that was completed only foil 6 was used. The highest BtA efficiency for the Aug. 21st data is higher than it is for the Dec. 27th data. That is because the Aug. 21st data was taken with EBIS beam and other details unrelated to the foil condition.

Figure 12 contains 3 scans of the Foil 6 position vs. BtA efficiency. Again, the Aug. 21st scan was taken with EBIS beam. The other 2 scans, from Jan. 3, were taken with 2 different settings of BtA DH1.[25] The working hypothesis is that changing DH1 allows one to move the beam horizontally on the foil (recall that changing the foil position moves the foil vertically). By using both DH1 and the foil position one can move where the beam hits the foil in both x and y, allowing more of the foil to be used. Note that there is a bad spot centered around 6.05 on the Jan. 3rd data that is not evident in the Aug. 21st data. This is likely because the horizontal position is different in the Aug. 21st data. In the Jan. 3rd data the dip in the efficiency at 6.05 is less with DH1 set to 363A than it is at 373A, probably for the same reason.

The foils were replaced after the Run. Figure 13 is a photo of foils 5 and 6 after removal from the BtA line. Foil 6 is black because it has a Carbon coating on top of the Aluminum which foil 5 does not. Foil 5 appears to have a lot more damage than foil 6, which is expected since, as noted, foil 6 was not used much during the 5.75 GeV part of the run so it would be usable for the

[22] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, Table 6 on pg. 13 (which is for EBIS beam).
[23] See 1531 entries in the Booster-AGS-EBIS Dec. 18, 2020 elog
[24] See entries from 1344 to 1729 in the Booster-AGS-EBIS Aug. 21 2020 elog. The horizontal position on the foil is also likely different in the 2 cases in Figure 11. That could also affect the efficiency, but this foil was scanned extensively in both x and y, and there were not many good spots left on it by the end of the 5.75 GeV running.
[25] See entries from 1952 to 2011 in the Booster-AGS-EBIS Jan. 2 2020 elog.

remainder of it.[26] Note that although it's black and so it's harder to see damage on foil 6 there does appear to be a bad spot which, judging from Figure 12, would correspond to position 6.05.

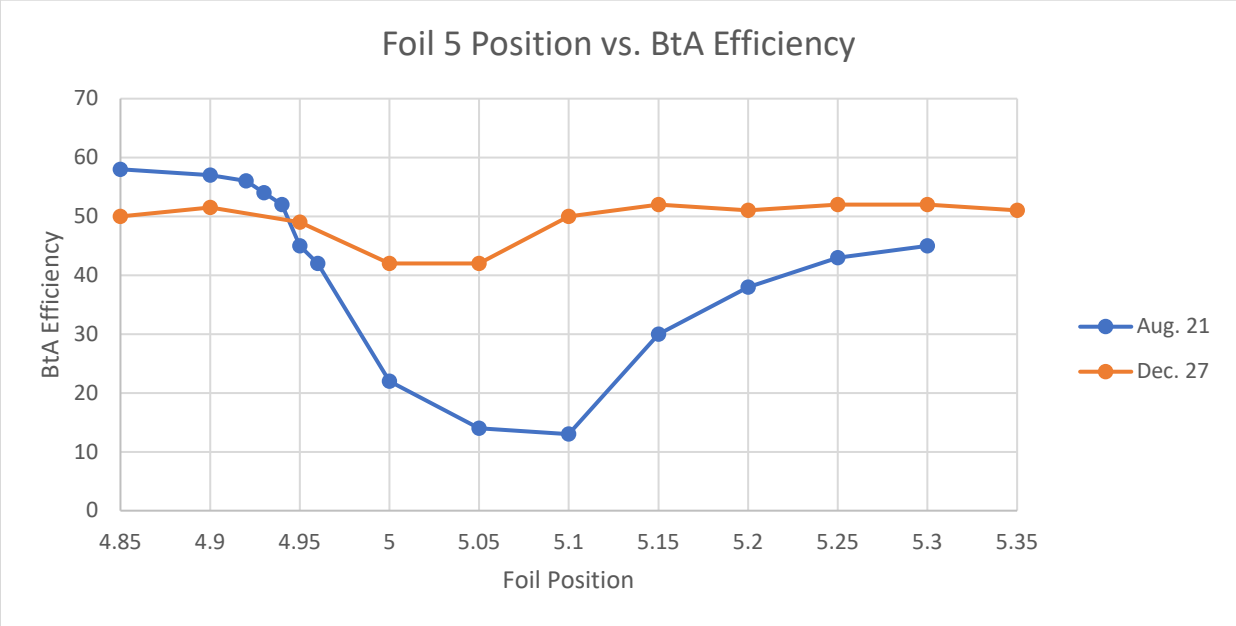


Figure 11: Scans of the BtA foil 5 position vs. BtA efficiency on Dec. 27th and Aug. 21st.

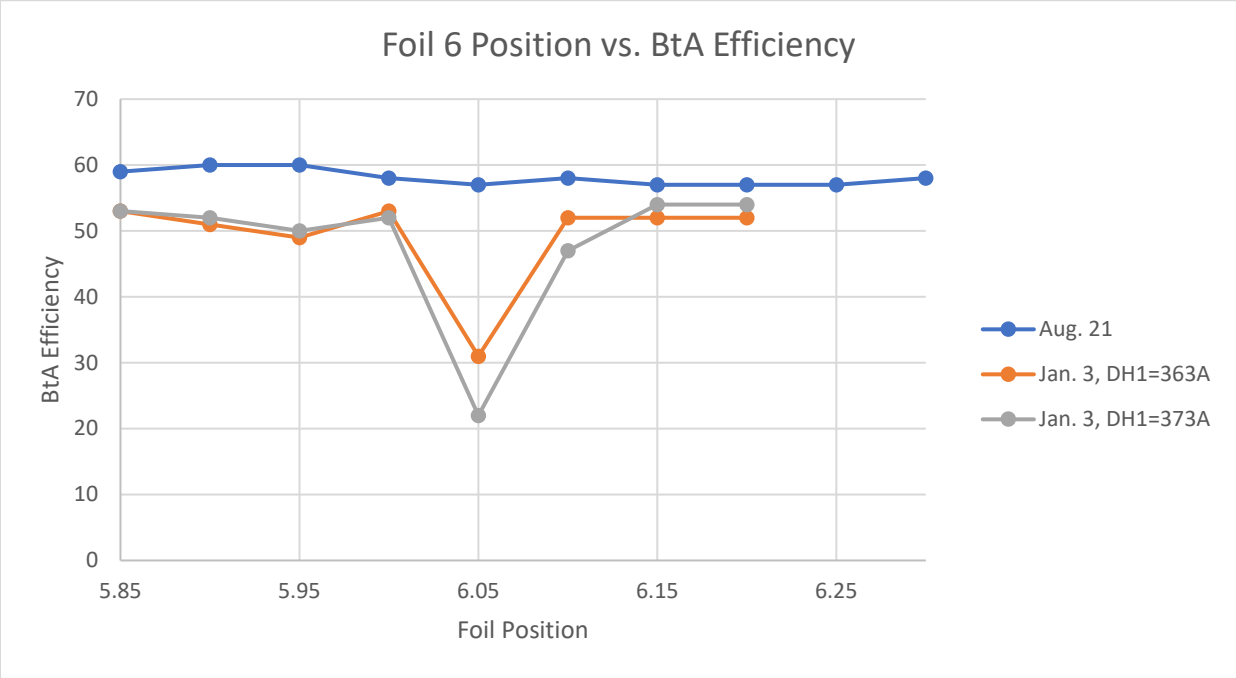


Figure 12: Scans of the BtA foil 6 position vs. BtA efficiency on Jan. 3rd and Aug. 21st. There are 2 scans on Jan. 3rd that have different settings for DH1 which is thought to move the beam horizontally on the foil.

[26] However, the first time it was noticed that the foil was deteriorating was on Dec 17 using foil 6. See the 1715 entries in the Booster-AGS-EBIS Dec 17 2020 elog.

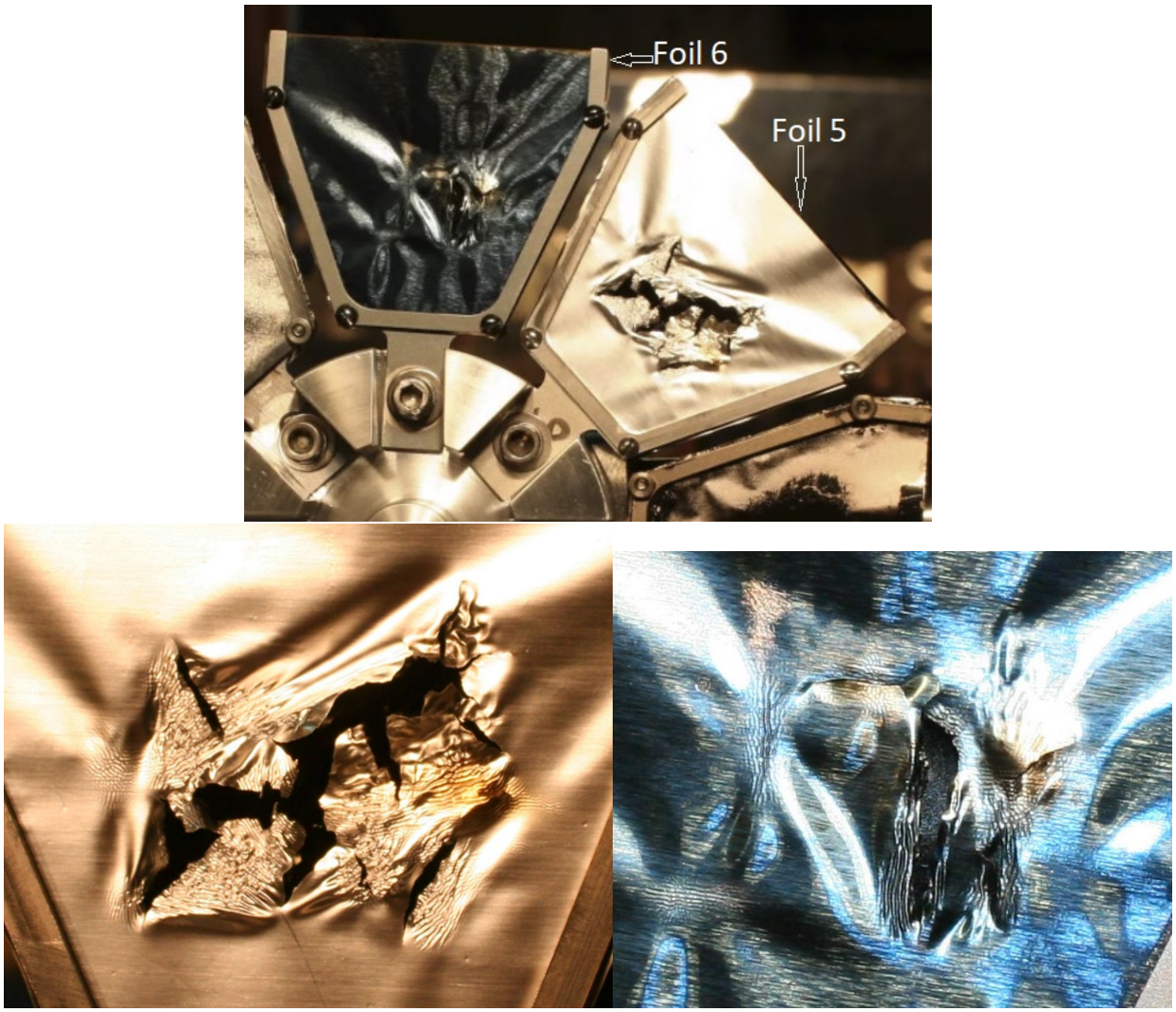


Figure 13: The top photo shows stripping foils 5 and 6 after they were removed from BtA. They are still attached to their holders and still on the foil wheel. Below it are closeups of the damage to foil 5 (left) and 6 (right) where to the right is the beam up direction. Foil 6 has a Carbon coating on top of the Aluminum which makes it black. This is the upstream side .[27]

Both foils have a Carbon coating on the other side. So, in the case of foil 5 at least, it is clear that for some locations on the foil the beam, the direction of which is into the page, would only be passing through Carbon. It would not be surprising if that beam was far from fully stripped, and so would not show up on the MW060.

BtA Transfer Efficiency for 5.75 GeV

Figure 14 shows the Booster and AGS current transformers on the 5.75 GeV cycle.[28] Because the AGS normalized transformer signal's baseline is not flat and the normalization is less than ideal, using the intensity scalers to determine efficiencies leads to significant error.

[27] L. DeSanto Jr. took the photos. Nov. 2020.
[28] See entries from 1343 to 1433 entries in the Booster-AGS-EBIS Feb. 12 2020 elog.

Also, the Booster Late scaler on the first cycle reads artificially low sometimes so the total Booster Late scaler cannot be calibrated well. The BtA efficiency derived from the scalers, (AGS_Early/Booster_Late)[29], is typically off by several percent from the answer one would get from time consuming scope measurements. In the case considered here the efficiency from the scalers was 53-54%, which was fairly typical when the transfer was optimized.

Measurements from the scope traces in Figure 14 yield a Booster Late intensity of 17.87±0.15e9, and an AGS Early intensity of 10.25±0.18e9. This gives a BtA efficiency of 57.3±1.5%. The AGS Late intensity, measured at At0+3300 ms, was 9.70±0.16e9, so 54.3±1.3% of the beam at Booster extraction winds up in the 4 bunches on the AGS flattop.[30] From the scope the AGS acceleration efficiency, AGS_Late/AGS_Early was 94.7% and from the scalers it was 99-100%. The AGS measurements here use the unnormalized transformer.

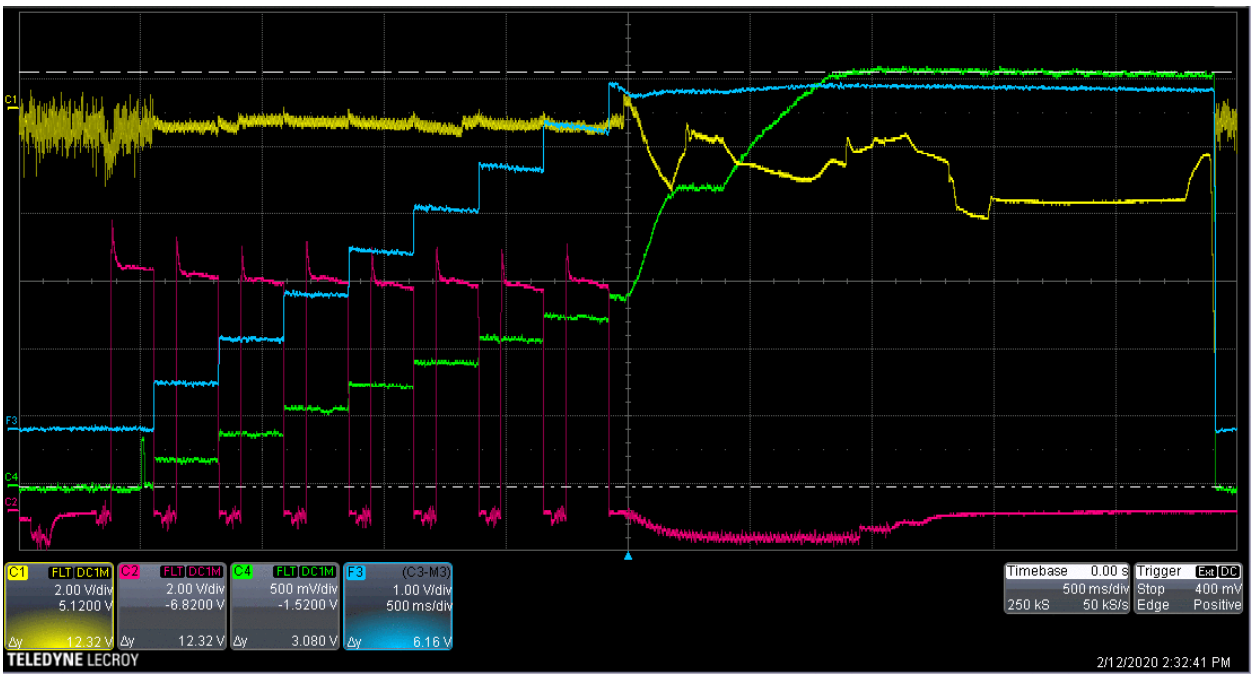


Figure 14: Booster and AGS current transformer signals on the 5.75 GeV cycle. The red trace is the normalized Booster transformer, the blue trace is the normalized AGS transformer, the green trace is the unnormalized AGS transformer, and the yellow trace is the J12 horizontal BPM. The trigger is At0+2000 ms and the sweep speed is 500 ms/div. The Booster transformer calibration was 0.328e9 Au31+ ions/volt and the AGS unnormalized calibration at At0+3300 ms was 3.150e9/V. The cursors show the voltage on the unnormalized transformer at that time, 3.08V or 9.70e9 Au77+ ions. The total voltage for the 8 Booster cycles right at extraction was 54.46V or 17.87e9 Au31+ ions.

[29] The Booster_Late considered here is the sum of Booster_Late for each of the 8 Booster cycles with beam per AGS cycle and AGS_Early is measured just after the last transfer.

[30] The uncertainties shown reflect the uncertainty in the size of the calibrate pulses for each transformer. The AGS pulse is 14.25±0.23 mA/V and the Booster pulse is 108.2±0.9 μA/V. See 1343 and 1353 entries in the Booster-AGS-EBIS Feb. 12 2020 elog.

Booster Efficiency for 5.75 GeV

The Booster acceleration efficiency, (Late intensity/Early peak) is not always as high as indicated in Figure 14. (~85%). As is typical with Tandem beam, it varied a lot.[31] Figure 15 shows the overall Booster efficiency, (Booster Late/Booster Input), and the intensities through the cycle for the last 2 weeks of 5.75 GeV running, Note that a typical overall Booster efficiency is about two-thirds and that this efficiency is more or less inversely proportional to the input, which is often proportional to the pulse width.

AGS late is more or less constant near the 9.6e9 limit until the last day or 2 of 5.75 GeV when the F3 kicker's problems got worse, including the failure of one of its 3 modules. Booster Late also increases over the period from maybe 17 to 20e9 to keep the AGS late near 9.6e9 as the average BtA efficiency decreased due to the deterioration of the foil.

Transverse Emittance for 5.75 GeV

An emittance measurement was made using MW006 in BtA on Dec. 13th. The Tandem pulse width was 540 μs with a Booster input of about 20.1e9, Booster Late of about 14.2e9, and AGS late of about 7.7e9 when 8 Booster transfers are used. Figure 16 shows the profiles and using a gaussian fit of the data this gives an RMS normalized horizontal transverse emittance (ε_{xRMS}) of 0.32 mm mr and an ε_{yRMS} of 0.37 mm mr. A similar calculation using data from 2010 Tandem Au31+ running and a 530 μs pulse yields ε_{xRMS}=0.66 and ε_{yRMS}=0.34 mm mr.[32]

A set of MW006 profiles from Feb 10th, when the pulse width was 700 μs, yielded ε_{xRMS} =0.48 and ε_{yRMS}=0.51 mm mr which is somewhat larger. This is probably, at least in part, because the pulse width is longer.

The pulse width used this year was shorter than it was before the advent of EBIS when Tandem was used as the pre-injector. This is because the required intensity per Booster cycle was less this year, so the pulse width used then, about 1000 μs, was not required. A shorter Tandem pulse will in general produce a smaller transverse emittance because when the first part of the pulse is injected it fills the phase space close to the center and what's injected later in the pulse fills phase space that is successively further from the center.

This is relevant because as the Booster Late intensity is increased by lengthening the pulse width the density of the beam in the center does not increase proportionately. So, even though the per cycle Booster Late was much lower this run than it was back then (roughly two thirds of it), the density at the center of the beam would likely not have been less by that much. Perhaps this was a factor in the BtA foil's deterioration. The pulse length used this year to fill RHIC varied considerably but generally ranged between 500 and 800 μs.

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[31] A similar scope display in the 1833 entry in Booster-AGS-EBIS Feb 11 2020 elog indicates about 65%. A Booster injection efficiency measurement (ibid., 2016-2023 entries) indicated 92.7% for a 610 μs pulse.

[32] See 1448 and 1449 entries in the Booster-AGS-EBIS Jan. 6 2020 elog

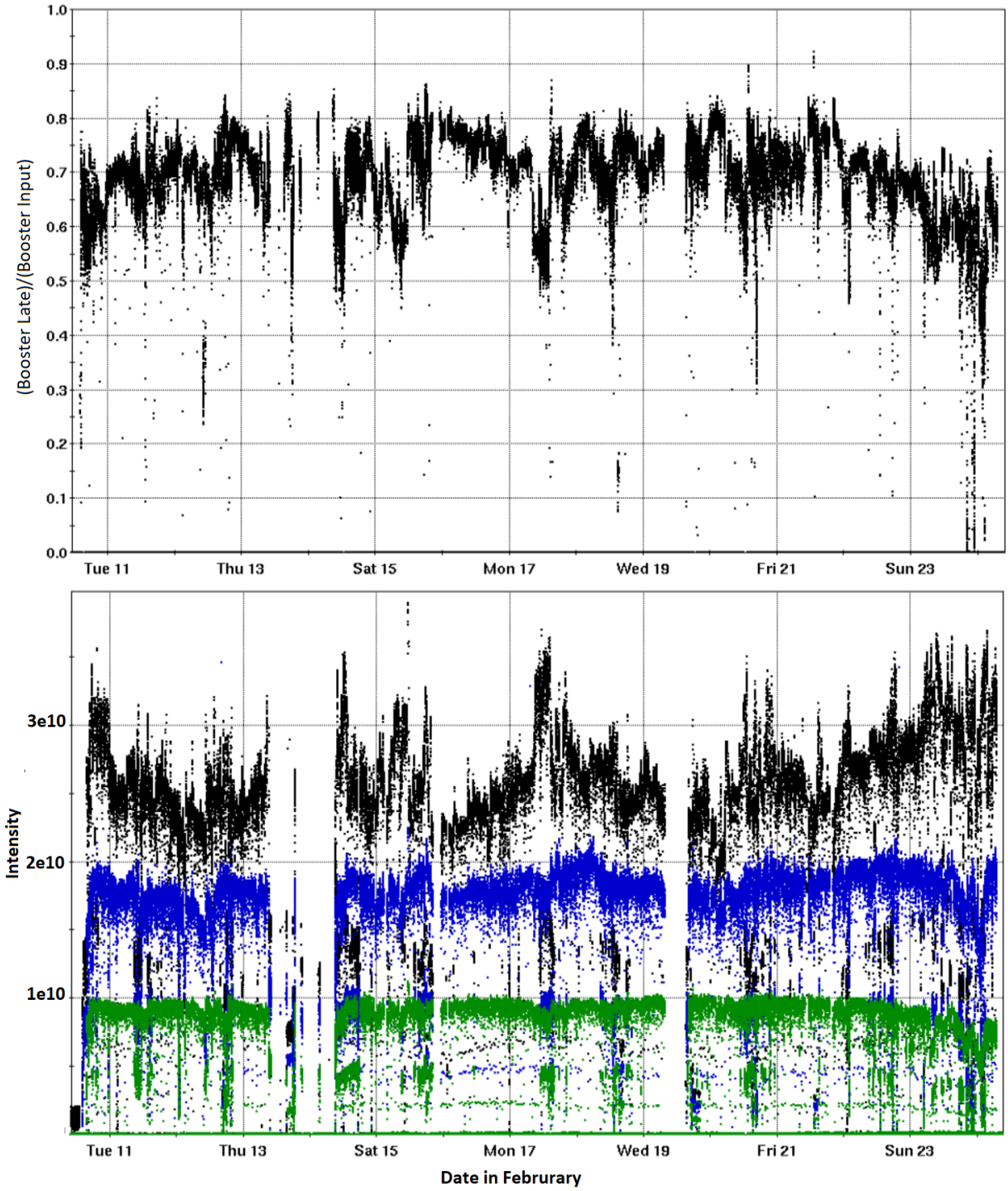

Figure 15: The Booster efficiency, (Booster Late)/(Booster Input), and intensities through the cycle for the last 2 weeks of 5.75 GeV running using the scalers. The intensities shown (bottom graph) are Booster input (black, TtB section 29 transformer), Booster Late (blue), and AGS Late (green).

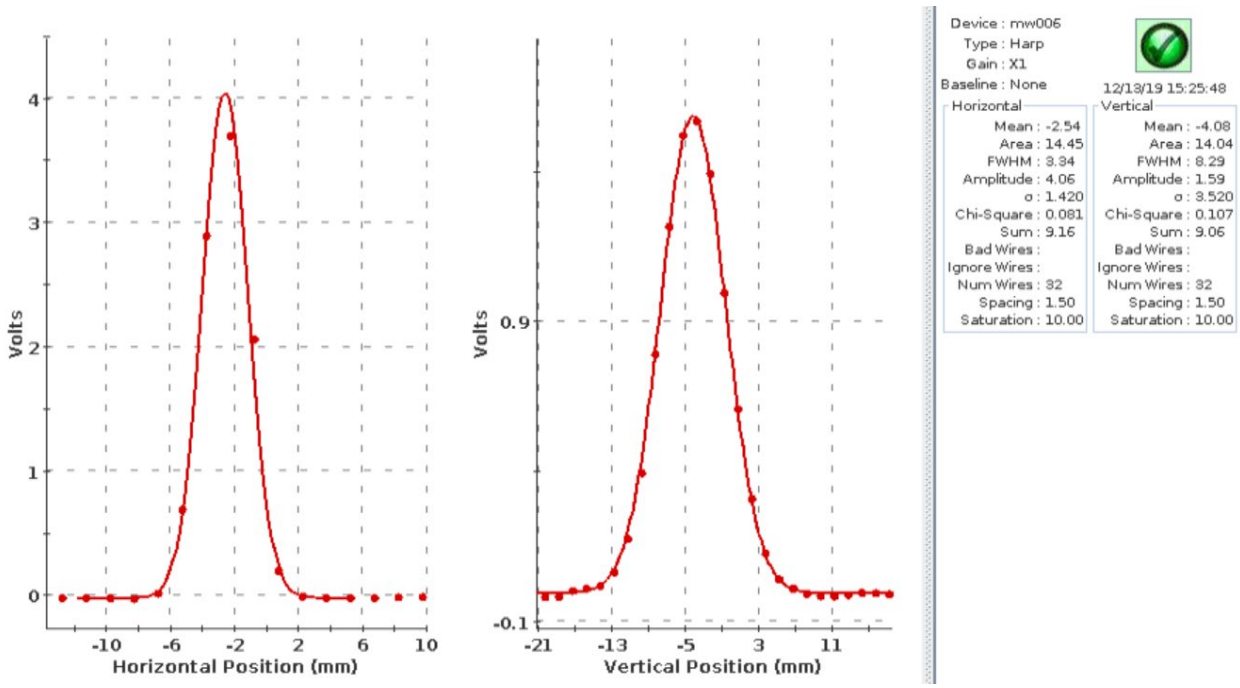

Figure 16: BtA MW006 profiles from Dec 13th using Tandem Au31+. Gaussian fits give a horizontal FWHM of 3.34 mm, and a vertical one of 8.29 mm. Using β_x=3.0 m, β_y=16.0 m, and $\beta\gamma$=0.482 yields ε_{xRMS}=0.32 and ε_{yRMS}=0.37 mm mr corresponding to 95% values of 1.94 and 2.24 mm mr, respectively.

AGS (ion) IPM data from Dec 9th when AGS late was about 5e9 (330 μs Tandem pulse) indicate an ε_{xRMS} of 2.0 and an ε_{yRMS} of about 1.1 mm mr with Rf shutting off on the flattop[33] On Dec 20th, when AGS Late was about 7e9 ions, but with only 6 BtA transfers, the IPM indicates that both ε_{xRMS} and ε_{yRMS} were about 1.0 mm mr on the injection porch and about 1.3 and 1.4 mm mr, respectively, on the flattop after the Rf shut off. Also on Dec. 20th, with the same AGS Late but now with the usual 8 BtA transfers, ε_{xRMS} and ε_{yRMS} are both 0.9 mm mr on the injection porch, and on the flattop, with Rf off, they were 1.4 and 1.1 mm mr, respectively.[34]

More IPM data, this time from Jan 23rd and with about 8.4e9 at AGS Late indicate an ε_{xRMS} of 1.85 and ε_{yRMS} of about 1.7 mm mr. However, this data is with the Rf still on.[35] The Dec. 20th data indicates that if the Rf was off, ε_{xRMS} would drop to 1.44 and ε_{yRMS} to 1.34. Data from Feb 11th with 9.6e9 at AGS Late indicate ε_{xRMS}=2.05 and ε_{yRMS}=1.7 mm mr with Rf on.

[33] See 1506 to 1509 entries in the Booster-AGS-EBIS Dec 9 2020 elog.

[34] In the 6 transfer case (Dec.20th, 1735 entry), where the bunch intensity is the same as an 8 transfer intensity of 7e9*4/3=9.3e9, the indicated ε_{xRMS} drops by about 74% going from about 1.7 to 1.3 when the Rf is shut off and the indicated ε_{yRMS} drops by about 87% from 1.6 to 1.4 mm mr when the Rf is shut off. In the 8 transfer case (1747 entry), 7e9, ε_{xRMS} drops from 1.8 to 1.4 mm mr (78%) and ε_{yRMS} drops from 1.4 to 1.1 mmm mr (79%).

[35] See 1343 entry in the Booster-AGS-EBIS elog from Jan 23 2020 and the logged IPM data for 20:21:24 on Jan 20th.

Again, these values would be expected to drop to about 1.8 and 1.3 mm mr respectively if the Rf were shut off on the flattop.[36]

Table III summarizes the flattop IPM measurements. In cases where data only exists for the Rf on case, estimates are also given for what it would be if it was off. The data in the table does not show a clear dependence on bunch intensity, though there is more of a trend if the Dec.9th data is excluded. If excluded ε_{total} goes from 1.8 mm mr for 1.75e9/bunch to 2.2 mm mr for 2.40e9/bunch. It's not clear if there's any dependence on pulse width since, except for Dec. 9th case, the pulse widths are all about the same.

The Rf was left on for the Jan. 23rd and Feb 11th cases because of the concern that the beam dump with the Rf off could be poor and potentially cause damage to the beam pipe or other equipment. All the data discussed here is calculated using the AGSIPM program's Refit option.

Date	**AGS Late**	**Bunch Intensity**	**Pulse Width**	ε_{xRMS}	ε_{yRMS}	**0.78*ε_{xRMS}**	**0.79*ε_{yRMS}**	ε_{total}
Dec. 9	5e9	1.25e9	330 ms	2.0	1.1	-	-	2.3
Dec. 20	7e9	1.75e9	780 ms	1.4	1.1	-	-	1.8
Jan. 23	8.4e9	2.10e9	820 ms	1.85	1.7	1.44	1.34	2.0
Dec. 20	7e9	2.33e9	800 ms	1.3	1.4	-	-	1.9
Feb. 11	9.6e9	2.40e9	860 ms	2.05	1.7	1.8	1.3	2.2

Table III: AGS (ion) IPM flattop emittance measurements for the 5.75 GeV Tandem cycle at different bunch intensities using the Refit option. The Dec 9th and Dec 20th data are taken after the Rf has been shut off. The Jan 23rd and Feb 11th data have the Rf on and so are also multiplied by correction factors to compensate (0.78 in the horizontal and 0.79 in the vertical, see footnote 34) using the Dec 20th 8 transfer Rf on and off data as a guide. Also shown is the total emittance, which is calculated using the corrected emittances, $\varepsilon_{total} = \sqrt{(0.78 \cdot \boldsymbol{\varepsilon_{xRMS}})^2 + (0.79 \cdot \boldsymbol{\varepsilon_{yRMS}})^2}$ in the cases where the Rf was on and $\sqrt{(\boldsymbol{\varepsilon_{xRMS}})^2 + (\boldsymbol{\varepsilon_{yRMS}})^2}$ otherwise.

Longitudinal Emittance for 5.75 GeV

The debunching measurements discussed earlier can be used to estimate the emittance of the incoming bunch when it is injected into an AGS Rf bucket. The 5.75 GeV setup uses h=12 on the injection porch. Looking at the Sept. 3rd case, a 268.4 ns bunch matched to an h=12 bucket, that has a $\Delta p/p$ half width of 1.10e-3 will have an ε_{long} of 0.0844 eVs. This is only slightly larger than the ε_{long} found earlier at Booster extraction (0.0820±0.022 eVs). However, considering the bunch shape variations evident in Figure 5, on some level the shape of this bunch

[36] See 1755 entry in the Booster-AGS-EBIS elog from Feb 11 2020 and the logged IPM data for 17:54:21 on that day.

will not be matched to the bucket. Also, one would expect the bunch to be elongated along the ΔE axis because of the interaction with the foil and filament out.

The matching h=12 voltage for a bunch with that length and $\Delta p/p$ is only 17.0 kV. On Feb. 20th ε_{long} measurements of 'equilibrated' bunches, which had been on the injection porch long enough that they had filamenting out, were made.[37] At that time the voltage used, as determined from the synchrotron frequency (f_{synch}) was 35.3 kV, about twice that. This was the nominal operating voltage at injection then. The amplitude of quadrupole oscillations just after injection were fairly small (about ±6% of total WCM amplitude).[38] With that voltage and a bunch length of 268.4 ns a matched bunch would have a $\Delta p/p$ of 1.58e-3 and an ε_{long} of 0.122 eVs. The measured ε_{long} of the equilibrated bunches, which were 272.5 ns long, was 0.125 eVs.

Unfortunately, the debunching measurement was not taken at the same time as these other measurements. In order for the $\Delta p/p$ to be 1.58e-3, the debunching time would have to have been 2.40e-3. In Figure 6, this would correspond to 50 traces before the edges meet up instead of 70. From the figure, that looks too early, but one could perhaps imagine they cross at the 60th trace, which would correspond to a $\Delta p/p$ of 1.29e-3 and a 'matched' ε_{long} of 0.0982 eVs.

It is not clear to me though that the observation that the quadrupole oscillations are minimized at a much higher voltage than 'the matched one' is necessarily inconsistent since in reality there is no matched voltage. A matched voltage exists only if the injected bunch has the same shape as a bucket that can be made by adjusting the voltage, which is not the case here.

Right after the equilibrated bunch measurement was made on Feb. 20th an ε_{long} of 0.24 eVs was found after the 12 to 6 merge and rebucketing into h=12, right at the beginning of the ramp. An ε_{long} of 0.305 eVs on the flattop was also measured then.

The Feb. 20th results are summarized in Table IV. It appears there is no significant growth from when the bunches have equilibrated until after the merge and the growth up the ramp is about 28%. The 5.75 GeV cycle uses both the F and P banks of the AGS main magnet power supply. Two years ago, with EBIS Au, 7 measurements of ε_{long} growth on a ramp to 5.75 GeV were made when using both banks. The average growth was 35% with a σ of 7%, which is a bit more than what was observed here.[39] The magnet cycle had a lower merge porch and Siemens was used in those cases. The merges themselves were also different (3-1 and 6-3-1).

Flattop ε_{long} measurements taken during the 5.75 GeV portion of the run are compiled in Table V.[40] The data suggests that ε_{long} increased as the run progressed, but it also appears to

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[37] For all the ε measurements made on Feb 20th see the entries from 1543 to 1645 in the Booster-AGS-EBIS Feb 20, 2020 elog.

[38] See entries from 1551 to 1601 in the Booster-AGS-EBIS Feb 20 2020 elog

[39] See "AGS Longitudinal Emittance Measurements for the Upcoming RHIC Low Energy Gold Runs", C-A/AP/615, November 2018, pg. 9.

[40] The raw data can be found in the Booster-AGS-EBIS elogs from the dates and times in Table V. Note that the Rf frequency used for the ε_{long} calculations in the elog for the Nov. 21st, 22nd, and 23rd instances is wrong. The correct frequency (4.398585 MHz) is used for the Table V calculations.

depend on the bunch intensity. It may be that ε_{long} is intensity dependent but the BtA foil's worsening condition as the run progressed may also be a factor. Also, the RHIC requirement was 0.30 eVs so there was no need to work on reducing it.

Measured at	f_{synch} (Hz)	length (ns)	ε_{long} (eVs)	Total ε_{long}	Notes
7th transfer	1685 Hz	272.5±7.3	0.125±0.006	0.250±0.012	Length 266 ms after injected
At0+2410 ms	2168 Hz	126.5±3.9	0.240±0.013	0.240±0.013	Just after merge, 2.76 g/ms
At0+3300 ms	158.8 Hz	29.36±0.74	0.306±0.015	0.306±0.015	On flattop

Table IV: Summary of Feb. 20th ε_{long} measurements in the AGS. The first measurement was of an equilibrated bunch, specifically, the bunch from the 6th transfer measured at the 7th transfer. The uncertainties reflect the σ of the bunch length measurements. Since there is a 2-1 type merge (12-6), the 'Total ε_{long}" after the merge is the same as ε_{long} but before the merge it is twice that.

Date & Time	f_{synch} (Hz)	length (ns)	ε_{long} (eVs)	Bunch Intensity
Nov. 20 21:06	190.8	24.36±0.59	0.253±0.012	1.1e9
Nov. 21 17:04	160.5	26.30±0.30	0.248±0.005	1.1e9
Nov. 22 18:18	159.3	26.92±1.16	0.258±0.022	1.7e9
Dec. 3 16:53	162.3	23.87±1.15	0.228±0.021	0.8e9
Dec. 13 15:14	160.0	27.68±1.06	0.274±0.021	1.7e9
Feb 18 16:02	158.9	29.76±1.16	0.314±0.024	2.4e9
Feb. 20 16:38	158.8	29.33±0.78	0.305±0.016	2.0e9

Table V: ε_{long} measurements taken on the 5.75 GeV flattop. The uncertainties in the bunch lengths are the standard deviations of each set of measurements and are the source of the ε_{long} uncertainties.

The 4.59 GeV Part of the Run

Since EBIS was used for 4.59 GeV, the Booster setup was the same as it has been in the preceding years' Gold runs. Unlike the 5.75 GeV case, the AGS main magnet only used the F voltage bank because measurements have indicated that ε_{long} may be somewhat smaller that way.[41] 4.59 GeV was initially set up with a 3-1 type merge occurring on a merge porch that only provided 3 bunches on the flattop with 9 Booster transfers (setup 2 in Tables I and II). That merge was replaced with a new 3 to 1 type merge in the AGS which produced 4 bunches on the AGS flattop with 12 Booster transfers (setup 7 in Tables I and II). With the previous 3-1 merge, because of the required cogging pattern and length of the A5 kicker pulse, there was not enough space on the injection porch for the 12 transfers needed to produce 4 final bunches.

The new merge takes place on the injection porch instead of a merge porch and uses h=24, 16, and 8. It was set up by Iris Zhang and was used for LEReC commissioning for 4.59 GeV running.[42] The ε_{long} of these bunches on the 4.59 GeV flattop was essentially the same as

[41] See Figure 13 in K. Zeno, "AGS Longitudinal Emittance Measurements for the Upcoming RHIC Low Energy Gold Runs", C-A/AP/615, November 2018, on pg. 19.
[42] See I. Zane's entries in the Dec. 5 Booster-AGS-EBIS 2020 elog . See also K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pgs. 18-20 about "Performing only a 3-1 Merge in the AGS".

for the previous 3-1 merge this run, as well as measurements taken using it in 2018, about 0.40 eVs.[43]

Once the STAR 4.59 GeV program began the AGS merge was changed to a 4-2-1 type merge to provide more bunch intensity. This merge was also different than the previous 4-2-1 type merge which was 16-8-4. In this case the merge is 24-12-6, where the 24-12 part takes place on the injection porch and the 12-6 part takes place on a relatively high merge porch, the same energy porch used for 5.75 GeV.

This 4-2-1 type merge was chosen for a few reasons. First, injection occurs into h=24 buckets and there are indications that less longitudinal emittance growth occurs when the bunches are injected into h=24 than occurs using lower harmonic buckets.[44] Secondly, because of the similarity with the 5.75 GeV setup that was already operational it was easier to set it up by loading archives from that user and modifying them than it would have been to set up the 16-8-4 merge. Additionally, the 24-12-6 merge does not require the L10 cavity but the 16-8-4 does.

Intensities During the 4.59 GeV Part of the Run

Figure 17 shows the intensity scalers during the period of STAR data taking for 4.59 GeV. It was not uncommon to have an AGS Late intensity greater than 6.0e9. Ignoring the baby bunches, which were generally 1-2% of the beam, this corresponds to more than 2.0e9 per bunch. It is evident that AGS Late largely scales with Booster Input, which at times reached as high as 14.5e9.[45]

As you can see from the figure, there was a period near the restart in June where Booster Input was not working. After it was repaired the data from it was far less noisy than it had been. The xf108 integration window was changed to get it to work, though it is not understood why that worked. After this change Booster Input required a significantly different gain for it to agree with the xf108 intensity measurement on a scope. Up until this point, although the Booster Input baseline was not stable, the gain was quite stable. The gain has been stable since the change and the baseline is likely more stable as well. However, to obtain a good linear fit of the xf108 intensity measured on a scope vs. Booster input that also has a y-intercept near zero, the baseline needs to be about -300 counts or -3e8.[46]

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[43] See 1409 to 1416 entries in the Dec. 5 Booster-AGS-EBIS 2020 elog.

[44] See K. Zeno, "Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Bunch Merge", C-A/AP/596 Dec. 2017, especially pgs. 12-15. Also, ε_{long} after 3-1 (with injection into h=24) and 4-1 (with injection into h=16) type merges are shown in Figure 5 of "AGS Longitudinal Emittance Measurements for the Upcoming RHIC Low Energy Gold Runs" (C-A/AP/615, November 2018) and indicate that ε_{long} (called Early Ramp ε in the figure) divided by the number of merged bunches after the merge is smaller in the h=24 cases (0.108 vs. 0.125 eVs).

[45] From Figure 17 it appears that the input was a bit higher (15e9) on Feb 28 to Mar 2nd but close inspection indicates that the xf108 baseline was too high during that time (see Nov 30th 1407 and 1409 entries in Booster-AGS-EBIS 2021 elog). Compare this with Booster Input in 2016 where it appeared to reach about 15.0e9 and remained there for about a week (Figure 15 on pg. 22 in "Overview and analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, Sept. 2016).

[46] See 1307 entry in Booster-AGS-EBIS July 23rd 2020 elog.

Booster and AGS Efficiencies during the 4.59 GeV part of the Run

Figure 18 shows the Booster efficiency over a two-month period from just after the Booster Input problem was fixed until the end of the 4.59 GeV part of the run. It averages about 85%, which is typical. As was the case with 5.75 GeV, the BtA and AGS acceleration efficiencies found from (AGS Early)/(Booster Late) and (AGS Late)/(AGS Early), respectively, are not very accurate because of the baseline offset on the AGS Early scaler and less than ideal normalization.

Scope measurements were made on Aug 26th to get more accurate values: The AGS acceleration efficiency was 97.8% and the BtA efficiency was 58.6±1.5%.[47] These were taken with an AGS Late intensity of 6.0e9 and 1.9% of the beam in the baby bunches. The baby bunches could be eliminated by raising Rf station KL's voltage while the h=12 voltage is coming up after the 12-6 merge, but this wasn't done because the size of baby bunches is a useful diagnostic when trying to reduce ε_{long} prior to the end of the final merge.

This BtA efficiency is higher than what has been see before with injection into h=24 buckets. The efficiency seems to depend on the cogging pattern, and the fewer bunches injected into adjacent buckets the worse it may be due to issues with the A5 kicker rising between bunches. Last run, when a 2 to 1 type merge was used with only 2 adjacent h=24 buckets filled the BtA efficiency was 55.1%. Here there are 4 adjacent buckets filled, so if anything, the efficiency should be lower than that.[48] It has been about 52% for the 6-3-1 type merge where injection occurs into 6 adjacent buckets.

One contributing factor to the rather high BtA efficiency found this year is that it was measured while filling RHIC. Figure 19 shows AGS Early and the BtA efficiency on the 4.59 GeV cycle (AU3) around a time where the beam was extracted from the AGS continuously over a period of 3 minutes. Note that the BtA efficiency is about 1.5% higher during this period.[49] So, if RHIC was not being filled, as with the case last run, one would expect the BtA efficiency to be 57.1±1.5%.

I imagine the efficiency is worse when the beam is dumped in the AGS because the dump spoils the vacuum. Also, the injection porch occurs not long after the beam has been dumped and the poorer vacuum causes more slow loss there.

---

[47] See entries from 1614 to 1628 in the Booster-AGS-EBIS Aug. 26, 2020 elog. The AGS acceleration efficiency, (AGS Late)/(AGS Early), measured from the unnormalized transformer is unrealistically high (99.8%) since there are some losses evident and is greater than 100% using the normalized one with baseline subtracted. But looking at the latter there is a 1.7% loss from AGS Early to the start of the ramp to the merge porch. There is also a loss near 3000 ms of about 0.5%. So, the acceleration efficiency is about 97.8%. From Logview, (AGS Late)/(Booster Late) was 0.573 and so the BtA efficiency is about 0.573/0.978=0.586 using the fact that Booster Late and AGS Late scalers are calibrated. Given the uncertainties in the height of the AGS calibrate pulse, discussed in the 5.75 GeV section, and other factors, there is likely at least a ±1.5% uncertainty in the BtA efficiency.

[48] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pgs. 15-18.

[49] See also the 1527 entry in the July 20th Booster-AGS-EBIS 2020 elog.

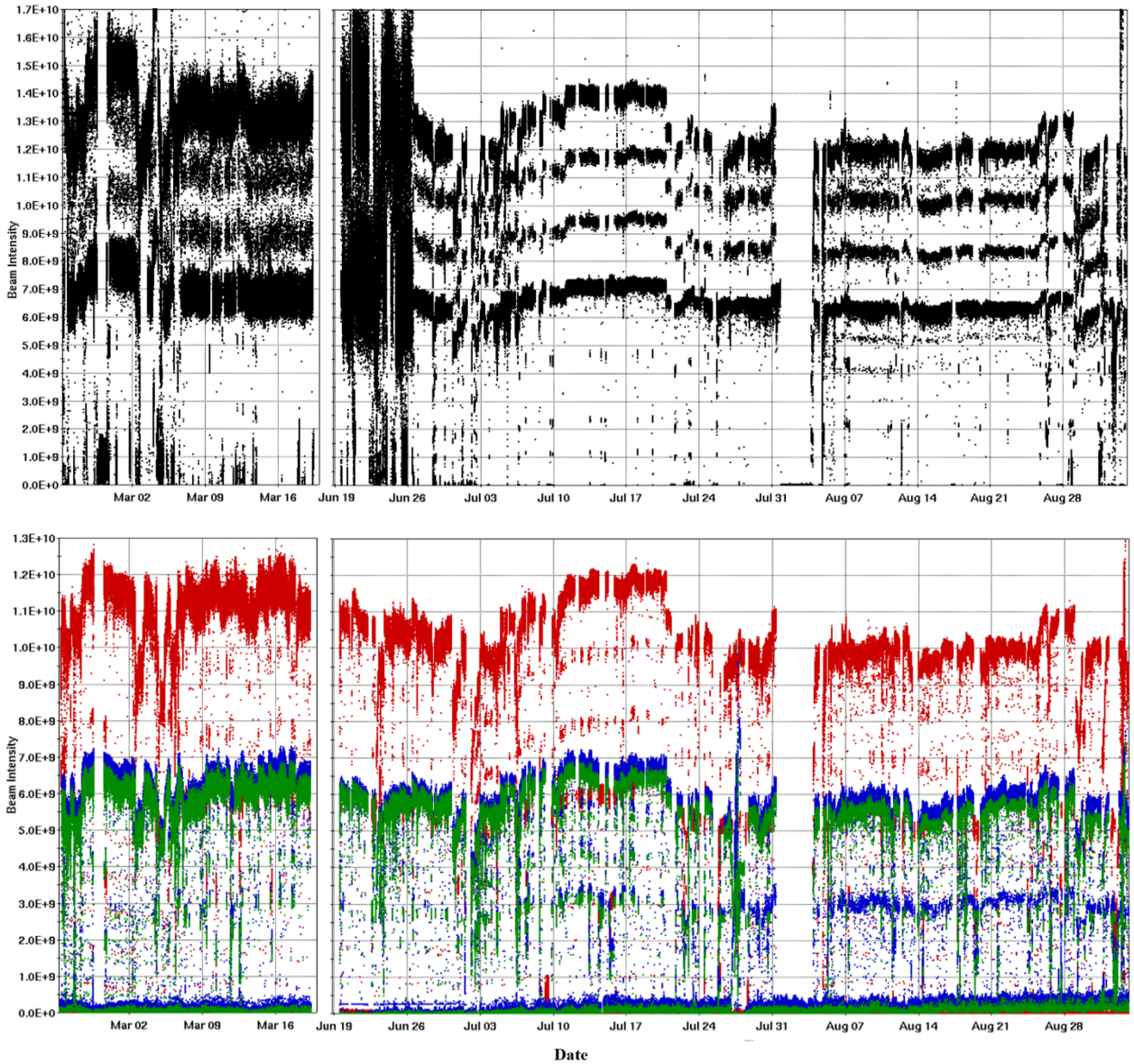

Figure 17: Intensity Scalers during STAR 4.59 GeV data taking (Feb. 24th to Sept. 1st). On the top is Booster Input which measures the intensity at EtB xf108. On the bottom are Booster Late (red), AGS Early (blue), and AGS Late (green). There is a gap from Mar 20th to Jun 21st corresponding to the COVID-19 shutdown. The Booster Input is displayed separately because if it wasn't the plot would be much harder to read. The 4 steps in Booster Input are from when a different number of pulses are requested (6, 8, 10, or 12). When filling RHIC 12 pulses were generally requested.

Beam Related Vacuum spikes at D5

There were problems last run with beam related vacuum spikes centered around D5, the location of the horizontal eIPM, which would sometimes cause sector valves to close. Although there were no similar valve closures this run that I'm aware of, the D5 eIPM vacuum log indicates that at times the vacuum there had spikes that were just as high, 1e-6 Torr (as high as

the gauge can report).[50] However, the spikes on the nearby vacuum gauges, which do not sample as frequently, only reached 5e-7 Torr, whereas they reached 1e-6 Torr last run. Perhaps this is why the valves did not close. The spikes were particularly large from March 15th to 20th and from July 29th until the end of the run. The BtA efficiency measurement above was not taken during this time, but most of the time when there were large spikes was during 4.59 GeV running.

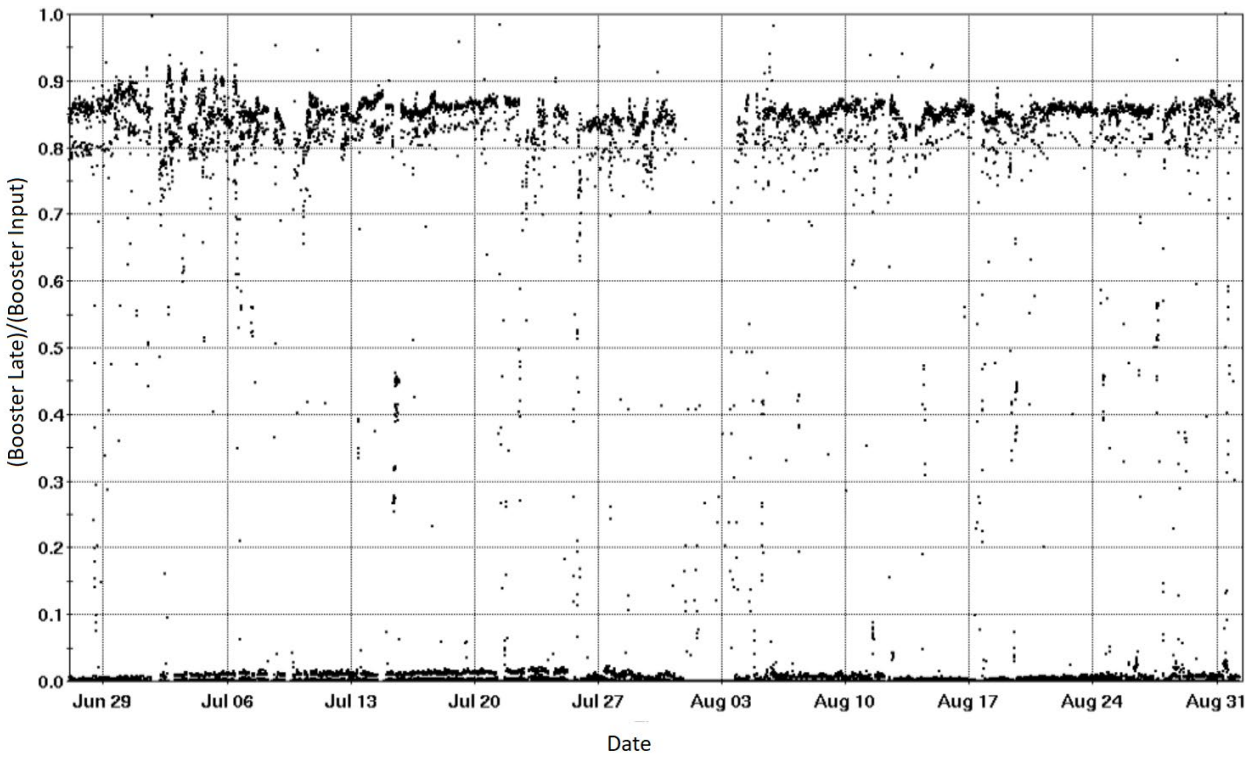

Figure 18: The Booster efficiency, (Booster Late)/(Booster Input), after Booster input was fixed until the end of the 4.59 GeV run (Jun 27th to Sept. 1st).

Last run, to reduce these spikes, horizontal and vertical bumps at D5 were put into the orbit. This was not done this year because I did not notice any valve closures. From the vacuum log it looks like the symptoms are the same as they were in 2019. The spikes occur when there is beam in the AGS, but the Rf is off. Like last year, the vacuum is the worst at D5 and drops off on either side.

Figure 20 shows the vacuum at D5 before, during, and after a fill on July 29th together with the AGS Rf voltage. Note that when the beam is being dumped on the flattop the vacuum at D5 does not appear to be affected. From the analysis done last year, it seems likely that on the injection porch the A5 kicker is somehow kicking debunched beam into D5 when the Rf is off and that causes the vacuum to deteriorate there. However, that doesn't necessarily mean that the vacuum there should be affected as much as it is.

[50] The log is found in LogView under Ags/Instrumentation/eIPM/BiasVoltageWithVacuum.lvdisp and the gauge is called d5h-eipm-vac:measurement:value. See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pgs. 37-42 for last year's discussion of the problem.

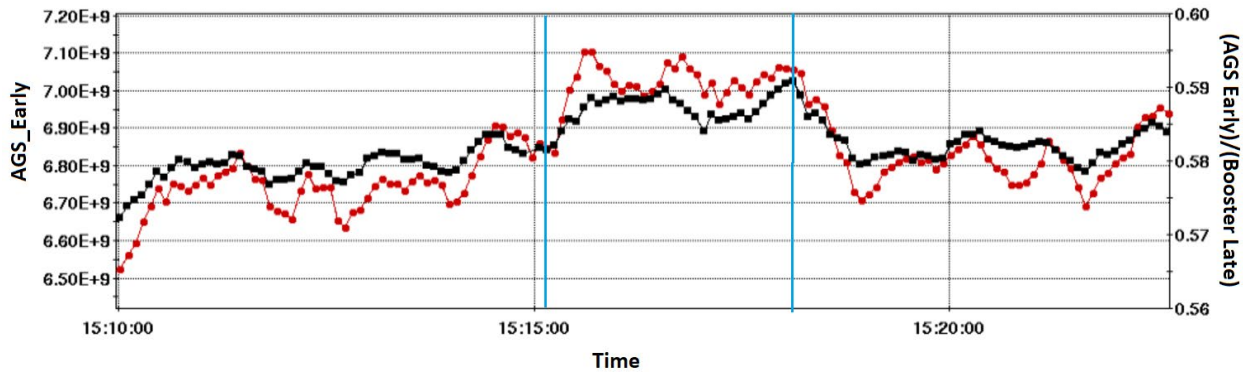

Figure 19: A 5 cycle running average of the AGS Early scaler (in black, left y-axis) and BtA efficiency (in red, right y-axis). Filling RHIC starts at 15:15:10 (left blue vertical line) and ends at 15:18:07 (right blue vertical line). The data is from July 20th. Note that the apparent lag between when filling starts and stops and the changes in efficiency is at least partly because it's a running average.

Transverse Emittance for 4.59 GeV

Figure 21 shows the BtA MW006 profiles from Feb. 26th used to calculate the transverse emittances which yielded ε_{xRMS}=0.81, ε_{yRMS}=0.32, and $\varepsilon_{total}=\sqrt{\varepsilon_{xRMS}^2+\varepsilon_{yRMS}^2}$ = 0.87 mm mr. These results are quite similar to values found in 2019 (ε_{xRMS}=0.80 and ε_{yRMS}=0.38 mm mr).[51] The vertical is similar to what was found for a Tandem Au pulse width of 530 μs (0.32 vs. 0.37 mm mr) but the horizontal is more than twice as large (0.81 vs. 0.32 mm mr). The 700 μs pulse gave ε_{xRMS}=0.48, ε_{yRMS}=0.51, and ε_{total}=0.70 mm mr, which is closer to but still a bit smaller than the EBIS case.

On July 13th, ε_{xRMS} and ε_{yRMS} on the flattop using the AGS (ion) IPM, with an AGS Late of about 6.7e9, were 1.45 and 1.2 mm mr, respectively (ε_{total} =1.88 mm mr).[52] These measurements are with the Rf on but with only about a third the voltage present when the Dec. 20th 5.75 GeV Rf off and on data were taken. The bunch lengths for the 4.59 GeV flattop are more than twice what they are at 5.75 GeV (see Table V and VII), so the space charge effect, which can artificially raise the indicated emittances, is likely less.

The emittances near the end of the injection porch, where the signal to noise ratio is largest and the Rf voltage is still low, were (1.32, 1.15) mm mr. According to the IPM then, since ε_{total} on the porch is 1.77, the growth from there to the flattop is at most 6% (1.88/1.77). For a similar bunch intensity, ε_{total} on the 5.75 GeV flattop (Table III, Dec.20th case with bunch intensity of 2.33e9) was 1.91, which is about the same as measured for 4.59 GeV. Yet in the 5.75

[51] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, pg. 20.

[52] See 1519 entry in Booster-AGS-EBIS July 13th 2020 elog. The values near 4000 ms are used because the Rf voltage is lower there, so the space charge effect is probably less. The voltage goes down from 8 to 1.8 kV from 3800 to 3950 ms. At 3800 ms the measured ε_{xRMS} is about 0.1 mm mr (7%) higher than at 4000 ms and ε_{yRMS} is not significantly different at those 2 times.

GeV case, since ε_{xRMS} and ε_{yRMS} were both about 1.0 mm mr on the porch, there appears to be about 35% growth from the porch to the flattop (1.91/1.41).

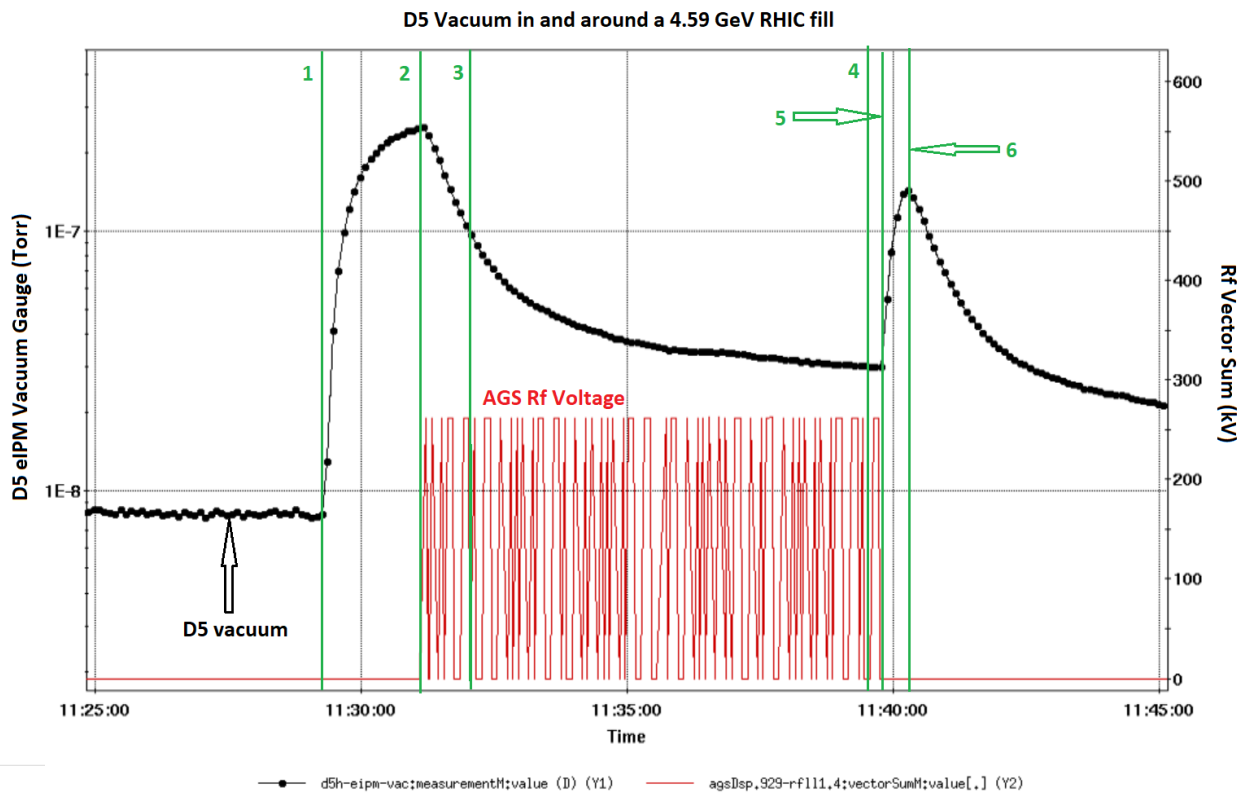

Figure 20: The response of the AGS D5 eIPM vacuum gauge to beam during a RHIC fill sequence for 4.59 GeV from July 29th. The D5 eIPM gauge (black) uses the y-axis on the left and the Rf voltage (red) uses the one on the right. There are 6 numbered green vertical lines denoting different stages in the process:

1- Beam starts being injected into the AGS with the Rf off.
2- The Rf is turned on so beam is now accelerating to, and being dumped on, the flattop.
3- The fill begins so beam is no longer being dumped at the end of the flattop.
4- The fill ends so beam starts being dumped at the end of the flattop.
5- The Rf is turned off. Beam is now dumped at the end of the injection porch.
6- Beam is no longer being injected into the AGS.

Longitudinal Emittance for 4.59 GeV

A series of ε_{long} measurements were made through the AGS cycle on March 5th and 6th. The results are shown in Table VI including a flattop measurement made on March 2nd. Note that the ε_{long} of an equilibrated bunch on the injection porch is significantly smaller than for the 5.75 GeV setup, 0.096 vs. 0.125 eVs, even though the ε_{long} at Booster extraction appears to be similar (see pg. 4). As discussed, this could be because there is less growth due to filamentation when

injection occurs into h=24 vs. h=12 buckets. Also, the value for ε_{long} of an equilibrated bunch on the injection porch this year is the same as last run using h=24 (0.0956±0.0018 eVs).[53]

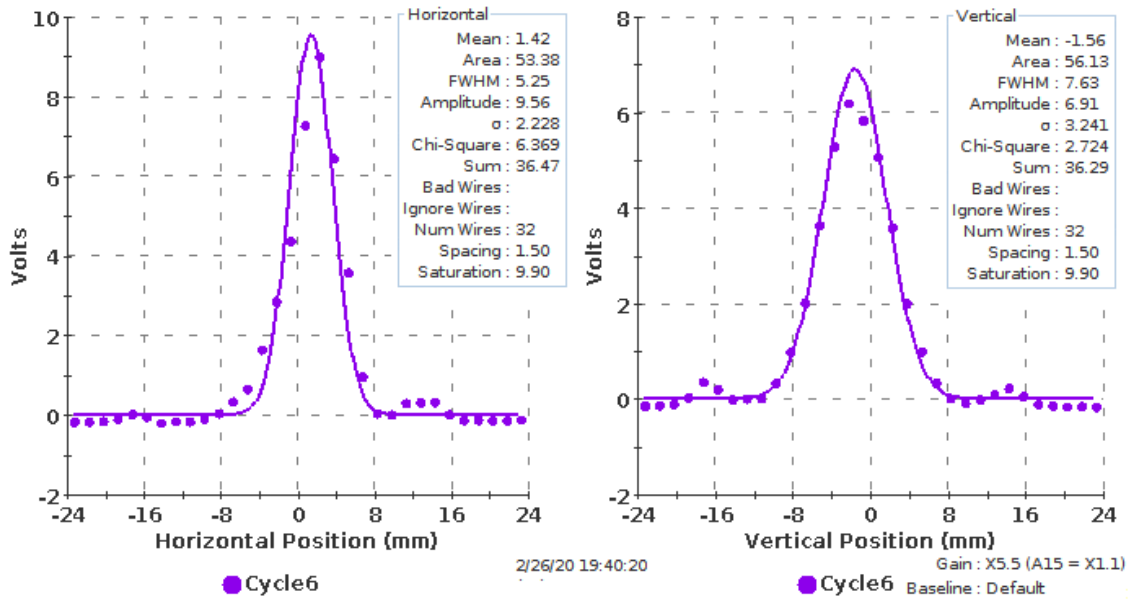

Figure 21: BtA MW006 profiles from Feb. 26th using EBIS Au32+. Gaussian fits give a horizontal FWHM of 5.25 mm and a vertical one of 7.63 mm. Using β_x=3.0 m, β_y=16.0 m, and $\beta\gamma$=0.492 yields ε_{xRMS}=0.81 and ε_{yRMS}=0.32 mm mr corresponding to 95% values of 4.89 and 1.94 mm mr, respectively.[54]

At least for this group of measurements, the growth of an equilibrated bunch on the injection porch to the flattop is a factor of 0.460/0.386, or 19%. The ε_{long} of the bunch grows about 11% from the injection porch to just after the last merge and it only grows 7% from just after the last merge to the flattop. In the majority of setups, most of the growth occurs on the ramp after the merge porch, but not in this case. This merge porch is higher than usual though and about 5% growth occurs from the end of the injection porch to the beginning of the merge porch (0.414/0.394). Yet there is no growth evident there in the 5.75 GeV case even though the merge porch is at the same field. The flattop is also lower than it is in most setups so one would expect less growth up the ramp.

When the 4-2-1 type merge was first set up on Feb. 7th, the AGS main magnet was inadvertently set to also use the P-bank. This was the case until it was noticed on Feb. 28, four days into the 4.59 GeV STAR data taking.[55] When this was discovered, flattop ε_{long} measurements were made for both cases. In the F-bank only case it was 0.437 eVs and in the

[53] See K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, Nov. 2019, Table 5 on pg. 11. The values at other stages of the cycle are also similar, except in last year's case only a 24-12 merge was performed, the merge porch was lower, and the data is for a 3.85 GeV cycle.
[54] See the1951 entry in the Feb. 26th Booster-AGS-EBIS 2020 elog.
[55] I. Zhang discovered this. See 1407 entry in the Feb. 28th Booster-AGS-EBIS 2020 elog.

case with the P-bank on as well it was 0.455 eVs.[56] Although these values are close to each other, the main magnet settings were changed so that it would only use the F-bank for the remainder of 4.59 GeV running.

Measured at	f_{synch} (Hz)	length (ns)	ε_{long} (eVs)	Total ε_{long}	Notes
4th transfer	2609 Hz	211.5±3.3	0.096±0.002	0.386±0.008	Bunch from 1st transfer
At0+2410 ms	3470 Hz	217.9±3.3	0.197±0.005	0.394±0.01	Just after 24-12 merge, 3.1 g/ms
At0+2560 ms	1841 Hz	140.2±3.6	0.207±0.009	0.414±0.018	Just before 12-6 merge, 1.6 g/ms
At0+2740 ms	2674 Hz	170.7±4.6	0.428±0.019	0.428±0.019	Just after 12-6 merge, 1.2 g/ms
At0+4000 ms	127.9 Hz	68.8±2.3	0.460±0.029	0.460±0.029	Flattop (March 2)

Table VI: Summary of early March ε_{long} measurements in the AGS for the 4.59 GeV cycle (setup 10). The first was of an equilibrated bunch, specifically, the bunch from the 1st transfer measured at the 5th transfer. The uncertainties reflect the σ of the bunch length measurements.[57]

There were problems with the Booster A6 Rf cavity, which is used for h=2 in the 4-2-1 merge, so starting on Feb. 24th the E6 cavity was substituted for A6.[58] This switch was difficult because E6, for whatever reason, required a substantially different voltage function. Once optimized, the flattop emittance was measured and compared to its value when A6 was used. They were nearly the same, 0.475 eVs using A6 and 0.486 eVs using E6. E6 was used for the remainder of the run.

Table VII contains a compilation of AGS flattop ε_{long} measurements made while on the 4.59 GeV 24-12-6 merge cycle. Unlike with 5.75 GeV, the range of bunch intensities is rather small, so any intensity dependence would be harder to see. The average of these 14 measurements is 0.490 eVs.

Although there are fewer ε_{long} measurements before the COVID-19 shutdown, the values for ε_{long} before it are generally lower than after it. This could be for many reasons, but one thing that is different is that Westinghouse was used before the shutdown and Siemens was used after it. Of the 5 measurements taken before the shutdown, the first 3 were with the P-bank enabled. Only the Feb. 28th 19:13 and Mar. 2nd measurements were taken with the F-bank only and Westinghouse. So, if the change of motor-generators were the reason, say for example due to a difference in ripple on the F-bank, it is hard to understand why the Feb. 28th 19:19 measurement with the P-bank enabled is low as well.

Also, f_{synch} was generally lower before the shutdown and for the same actual ε_{long} the bunches would be wider with a lower f_{synch}. So, there might be some systematic error in the way bunch lengths are measured that could account for the difference. As in the 5.75 GeV case, one could suspect foil deterioration, but the most obvious symptom of that, degraded BtA efficiency, was not evident at all. Foil position 6.1 was used for the entire 4.59 GeV part of the run.

[56] See entries from 1913 to 1931 in the Feb. 28th Booster-AGS-EBIS 2020 elog.
[57] For the flattop measurement see the entries from 2048 to 2057 on March 2nd and for the others see entries on March 5th from 1936 to 2033 and on March 6th from 1449 to 1846 in the Booster-AGS-EBIS 2020 elog.
[58] See entries from 1817 to 1912 in the Feb. 24th Booster-AGS-EBIS 2020 elog.

Date & Time	f_{synch} (Hz)	length (ns)	ε_{long} (eVs)	Bunch Intensity
Feb 8 21:38	173.4	61.37±1.57	0.501±0.024	1.8e9
Feb 24 19:12	152.2	64.45±1.24	0.483±0.018	1.9e9
Feb 28 19:19	150.9	62.74±1.94	0.455±0.027	2.1e9
Feb 28 19:13	150.9	61.46±1.24	0.437±0.016	2.1e9
Mar 2 20:48	127.9	68.80±2.29	0.460±0.029	1.6e9
Jun 18 15:16	174.4	61.46±1.91	0.506±0.031	2.0e9
Jun 19 16:08	174.4	59.42±1.40	0.474±0.022	2.0e9
Jun 26 14:18	175.4	61.52±1.74	0.509±0.027	2.0e9
Jul 7 15:36	175.7	61.17±1.79	0.505±0.027	2.0e9
Jul 10 16:47	163.9	62.67±1.52	0.493±0.023	2.1e9
Jul 11 11:50	163.9	63.22±1.63	0.502±0.025	2.2e9
Jul 16 16:12	164.4	63.56±1.32	0.508±0.020	2.1e9
Aug 4 12:45	170.1	63.76±1.62	0.529±0.025	1.8e9
Aug 5 16:42	173.0	62.34±1.23	0.515±0.019	1.8e9

Table VII: AGS flattop ε_{long} measurements on the 4.59 GeV 24-12-6 cycle. The uncertainties shown in the bunch lengths are the standard deviations of each set of measurements and are the source of the ε_{long} uncertainties. The data can be found in the Booster-AGS-EBIS elog for those dates and times.

The 24-16-8 Merge with EBIS and Tandem

As discussed, setup 7 in Table I, where a 3-1 type merge occurs on the injection porch, was used for 4.59 GeV LEReC commissioning. EBIS beam was not always available for this so at times Tandem was used instead (setup 8).

Since there are only a maximum of 8 transfers with Tandem, in order to provide 4 final bunches, for each set of 3 buckets that are normally filled to produce 1 final bunch, only the two outside buckets were filled. Figure 22 shows the cycle with Tandem Au, about 0.8e9/bunch at AGS Late, with only the 2 outside buckets populated, and providing 4 final bunches. At the time, the Rf voltage vector sum during injection was about 53 kV and the baby bunches appeared to be in the 1-2% range.[59]

Note that there is a loss after the merge, when the h=12 voltage comes up and before the main magnet starts ramping. This loss was intensity dependent and, for a given bunch intensity, much larger with Tandem Au. This is likely due to space charge effects and the fact that it's worse with Tandem suggests those bunches are smaller.

On Dec. 6th, with a final bunch intensity of about 0.8e9, this loss was similar to what's shown in Figure 22 and, with only the 2 outside buckets populated, the flattop ε_{long} was 0.318±0.014 eVs.[60] On Dec. 5th the flattop bunch lengths with 2 of 3 and 3 of 3 buckets

[59] See 2049 entry on Dec. 6th in the Booster-AGS-EBIS 2020 elog

[60] See the 1903 and 1908 entries in the Dec. 6th Booster-AGS-EBIS elog. f_{synch} was 191.94 Hz and the flattop bunch length was 46.07±1.04ns.

populated were measured and they were similar.[61] A flattop ε_{long} measurement with EBIS Au made on Dec. 5th was 0.404±0.013 eVs with about 0.6e9/bunch.[62] The Rf vector sum at injection here was 67 kV and if there were baby bunches they were too small to see easily.

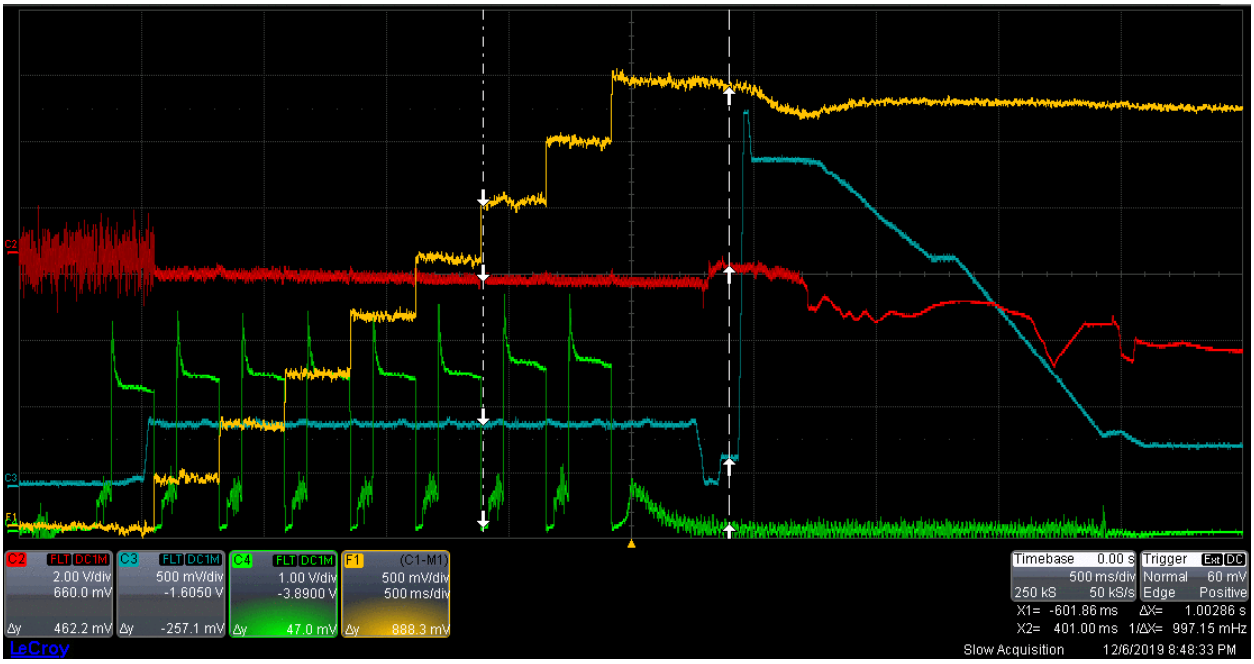

Figure 22: The AGS normalized transformer (orange) on the 24-16-8 merge 4.59 GeV cycle with Tandem Au (setup 8 in Table I). Also shown are the Booster normalized transformer (green), the AGS detected vector sum (blue), and the AGS J12 horizontal BPM (red). The magnet ramp begins at 2681 ms, and AGS Late is about 3.2e9. The trigger occurs at At0+2000 ms and the sweep speed is 500 ms/div.

For EBIS Au, f_{synch} has been measured at injection into h=24 buckets (see Table VI). At the time, the Rf vector sum was 61.28 kV, but the measured f_{synch} of 2609 Hz corresponds to an Rf voltage of 43.13 kV. This gives a calibration factor of 43.13/61.28=0.704 from which an actual voltage could be estimated from what the vector sum indicates since an f_{synch} measurement is not available.[63] This allows me to estimate actual voltages from the logged vector sum data.

When the Tandem Au flattop ε_{long} measurement was made, the vector sum at injection was 53 kV, which corresponds to a voltage of (53 kV*0.704)=37.03 kV. An h=24 bucket at injection energy using Tandem Au is 262 ns wide. On Feb. 21st the length of a Tandem Au bunch at injection was 268.4 ns (see bottom of pg. 3), about the same length as the bucket. The h=24 bucket area for a voltage of 37.03 kV is 0.10 eVs, so a bunch contained in such a bucket can only

[61] See Dec 5th 2201 and Dec 6th 1608 entries in Booster-AGS-EBIS 2020 elog. With 3 buckets filled the measured bunch length was 47 ns and with 2 of 3 filled it was 48 ns,

[62] See 1409 and 1414 entries in the Dec. 5th Booster-AGS-EBIS 2020 elog. This was taken on AU2, just before the setup was moved to AU5. The same value for ε_{long} was obtained on AU5 shortly after this (see Dec. 5th 1815 entry).

[63] One could argue that the value obtained for f_{synch} may be low because the bucket is full, but If I use the h=12 f_{synch} from Table IV, 1685 Hz, that corresponds to a voltage of 35.35 kV. The vector sum then was 54 kV. This gives a calibration factor of 0.655, even lower.

be that large. When h=12 was used the ε_{long} of an equilibrated Tandem bunch was 0.125 eVs (see Table IV).[64]

When this Dec. 6th ε_{long} flattop measurement was made, Booster Late was about 4.8e9 and AGS Early was about 2.6e9 for a BtA efficiency of 54%. AGS Late was somewhat lower (~2.35e9) but, as can be seen from Figure 22, there is a loss that can account for the difference. As noted earlier, the baby bunches were also small (~1-2%). The implication is that the ε_{long} of a Tandem Au bunch when injected is small enough to fit reasonably well into a 0.10 eVs h=24 bucket, which is also about the size of an equilibrated EBIS Au bunch (0.096 eVs). Although the ε_{long} of equilibrated bunches in h=24 buckets using Tandem was not measured, since the flattop ε_{long} is smaller than with EBIS (0.318 vs. 0.404 eVs) one can infer that it is smaller than it is using EBIS. There was no effort here to adjust its length, say with quad. pumping, to fit it into an h=24 bucket.

Although this Tandem Au setup was not used extensively for LEReC, the flattop ε_{long} was smaller than they had requested so effort was made to increase it. By detuning the BtA phase by four h=1 degrees the flattop ε_{long} was increased to 0.55 eVs, larger than the requested 0.40 eVs.[65] At that point there was about 5.3e8/bunch with 3 final bunches and AGS late was 2.3e9. So, about 31% of the beam was in the baby bunches in this state.

This growth must happen on the injection porch, but how does ε_{long} there increase beyond 0.10 eVs if the h=24 bucket area constrains it to that? One possibility is that, since the merge occurs on the injection porch, there is debunched beam and beam in other than the primary h=24 buckets that finds its way into all the h=12 buckets when that voltage ramps up after the merge. The ε_{long} would then be limited by the acceptance of the rebucketing process from h=8 to h=12, not the h=24 bucket area.

Figure 23 is from later in the run (Feb. 3rd) and it shows the cycle with EBIS Au, with about 1.5e9/bunch, with and without the octupoles on. The main magnet ramp starts earlier here, at 2480 ms. At this point in the run considerable effort has been made to reduce the loss which, with the octupoles on, is no longer significant. In mid-January the proportion of beam in the baby bunches was measured at 2.2%.[66]

The 3.85 GeV Part of the Run

3.85 GeV running is scheduled for next year, and towards the end of the run RHIC took both EBIS and Tandem Au in part at least in order to determine which pre-injector to use next year. Aside from the flattop energy, the EBIS setup was essentially the same as the 4.59 GeV 24-16-8 setup used for LEReC commissioning (setup 7). Similarly, aside from the flattop energy

[64] Note that even with EBIS Au, where f_{synch} was measured, and the equilibrated ε_{long} was 0.096 eVs (Table VI), the bucket area was only 0.109 eVs and so, if the voltage remained constant, that is the largest the bunch could be. In order for the bucket area to be 0.125 eVs the Rf voltage would need to be 57.6 kV.
[65] See entries from 1912 to 1955 in Dec. 6th Booster-AGS-EBIS 2020 elog.
[66] Jan 16th 1757 entry in the Booster-AGS-EBIS 2020 elog.

and the fact that only the F-bank was used, the Tandem Au setup is very similar to that used for 5.75 GeV (setup 6). They are setups 11 and 13 in Tables I and II.

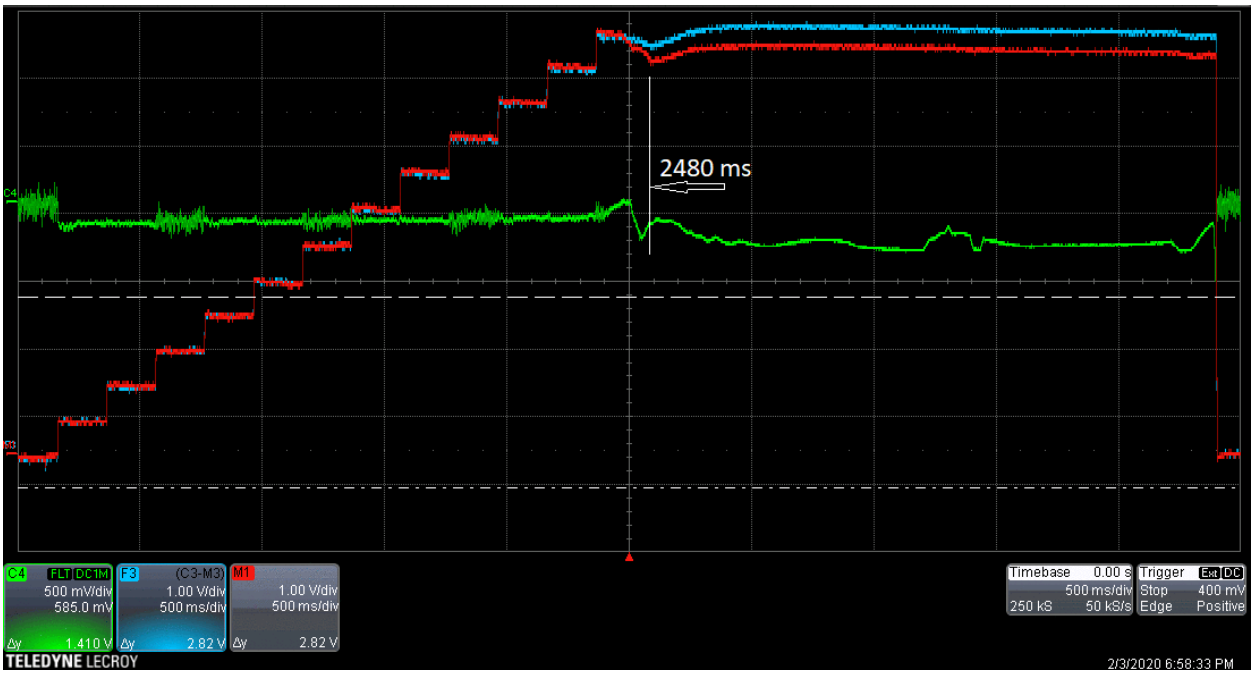

Figure 23: The AGS normalized transformer on the 24-16-8 merge 4.59 GeV cycle with EBIS Au (setup 7 in Table I) with octupoles on (blue) and off (red). The trigger is At0+2400 ms. The magnet ramp begins at 2480 ms. AGS Late is about 6e9.[67]

Transverse and Longitudinal Emittances

As regards EBIS Au, a couple flattop ε_{long} measurements were made on Sept. 1st. The first at a low flattop voltage of 23.6 kV yielded 0.352±0.025 eVs.[68] The other measurement, at 54.2 kV, yielded 0.388±0.029 eVs.[69] These are a little smaller than what was measured with this merge at 4.59 GeV (0.404 eVs), which is expected.

For Tandem Au, a flattop ε_{long} measurement was also made, at 53.8 kV, which yielded 0.240±0.022 eVs.[70] This is also a little smaller than what it was for 5.75 GeV (see Table V).

A Tandem Au AGS IPM measurement on Sept. 3rd at the end of the injection porch (1950ms) was (ε_{xRMS}, ε_{yRMS})=(1.22, 1.28) mm mr and ε_{total} was 1.77 mm mr for about 7.7e9 ions (600 μs pulse).[71] Recall that, at least on the injection porch, this is basically the same setup that

[67] See 1859 entry in the Feb. 3rd Booster-AGS-EBIS 2020 elog.
[68] See entries from 1353 to 1406 in the Sept. 1st Booster-AGS_EBIS 2020 elog. f_{synch} was 168.2 Hz and the bunch length was 74.36±2.75 ns. There was about 1.25e9/bunch.
[69] See entries from 1500 to 1510 in the Sept. 1st Booster-AGS-EBIS 2020 elog. f_{synch} was 254.9 Hz and the bunch length was 62.96±2.45 ns. There was about 0.9e9/bunch.
[70] See entries from 1237 to 1245 in the Sept. 3rd Booster-AGS-EBIS 2020 elog. f_{synch} was 254.7 Hz and the bunch length was 46.82±2.34 ns. There was about 1.6e9/bunch.
[71] See 1343 entry on Sept. 3rd in Booster-AGS-EBIS 2020 elog

was used for 5.75 GeV. On Dec. 20th, (ε_{xRMS}, ε_{yRMS}) was (0.9, 0.9) mm mr at the end of the 5.75 GeV porch with 7e9 (780 ms pulse). So, the 3.85 GeV measurement was a bit larger. The profiles and fits look good in both cases.

On the flattop (3500 ms), with Rf on, (ε_{xRMS}, ε_{yRMS}) were (1.37, 1.50) mm mr and ε_{total} was about 15% larger than on the porch, 2.03 mm mr. Given that the Rf is on, the bunch intensity is about 1.9e9, and the bunch length is somewhat narrow (~47 ns), this measurement is probably artificially high, and there is likely not much growth from the porch to flattop.[72]

Data from Sept. 2nd for the EBIS case give (ε_{xRMS}, ε_{yRMS})=(1.2, 1.05) mm mr on the AGS flattop (Rf on, ~5.3e9 ions in 4 bunches). However, the baselines are not good for this data. Even so, the horizontal fit looks OK. The vertical fit is dubious however.[73] For the 4.59 GeV 4-1 merge setup (ε_{xRMS}, ε_{yRMS}) were (1.45, 1.2) mm mr on the flattop (see bottom of pg. 27).

Tandem 3.85 GeV Running and the BtA Foil

Figure 24 shows the Booster Late and AGS Late intensities for Tandem 3.85 GeV running, which totaled about 5 days. Although AGS Late was on average not quite as high as it was during the latter part of 5.75 GeV running (compare Figure 15), the period on Sept. 10th was that high, yet no BtA foil deterioration was noticed. As with the rest of the run after the 5.75 GeV part, foil position 6.1 was used exclusively and BtA DH1 did not need to be changed.

Recall that foil 6 was different than foil 5 in that it had an additional layer of Carbon (see Figure 13). It is not clear if this layer was helpful or not in slowing down that foil's deterioration, but the fact that the beam's position relative to the foil didn't need to be changed during this time is not discouraging.

Beam Loading on the Injection Porch on the 3.85 GeV Tandem Cycle

During much of the summer there was a chronic problem with alarms for the AGS Rf overheating. In an attempt to alleviate this Rf cavities that were not needed were turned off. During the Tandem 3.85 GeV setup there was beam loading on the injection porch that caused the beam to become unstable. That is to say, the bunches were inducing voltage on the cavities that was in turn affecting the bunches themselves. At the time 3 Rf cavities were off (DE, IJ, and JK), and the solution was to turn them on with zero voltage on the injection porch.

Figure 25 is a mountain range display looking from the 6th transfer until a bit before the 7th transfer.[74] The injected bunch intensity here is about 0.65e9 and with 8 transfers AGS Early is about 5.2e9, but instabilities were observed with an AGS Early as low as about 3e9 (~0.4e9/bunch). The instabilities occur later on the porch, where more bunches and total intensity are present. This kind of behavior was not observed with the EBIS 3.85 GeV cycle even though

[72] In the Dec. 20th 5.75 GeV case considered above, (ε_{xRMS}, ε_{yRMS}) was (1.8, 1.4) with the Rf on (see footnote 34) and (1.4, 1.1) mm mr with it off on the flattop.
[73] See 1150 and 1156 entries in the Sept. 8th Booster-AGS-EBIS elog.
[74] See the entries from 1350 to 1832 in the Sept. 2nd Booster-AGS-EBIS 2020 elog

there are more bunches, and the bunch intensity reached as high as about 0.49e9 (an AGS Early of 5.9e9). The cogging and injection harmonic were different for EBIS though.

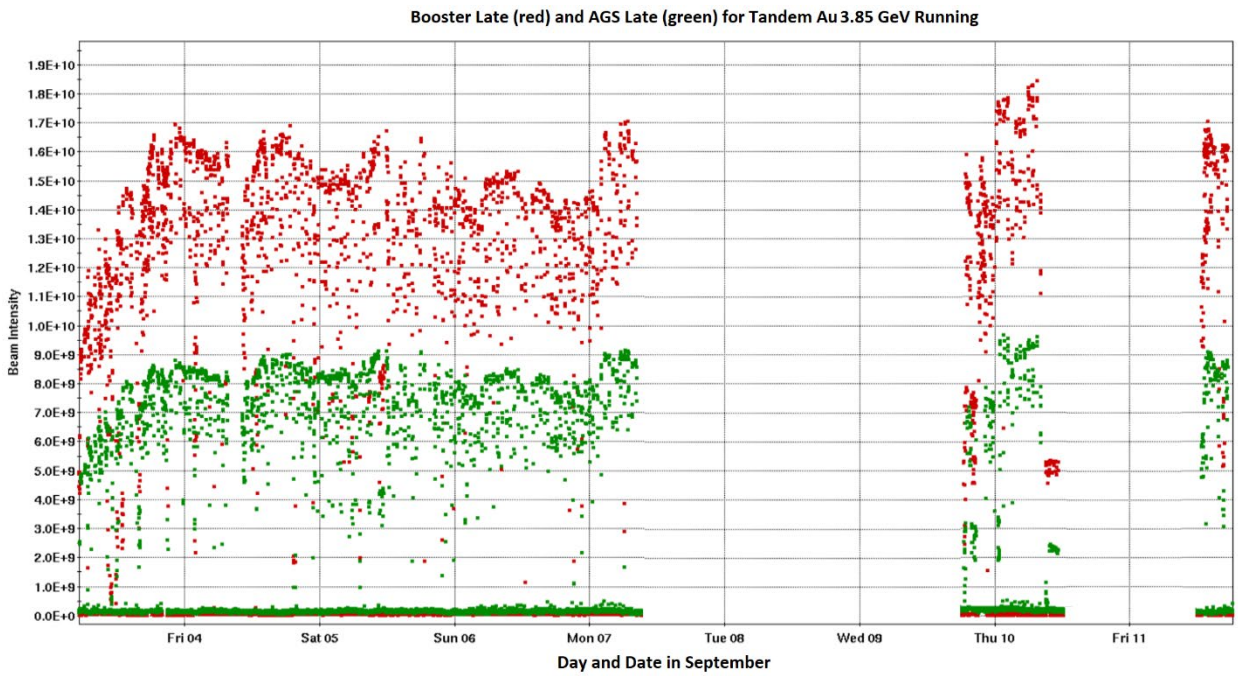

Figure 24: The Booster and AGS Late intensities during Tandem Au 3.85 GeV running.

The BtA Efficiency Without the F4 Extraction Bump Power Supply

There were problems with both the Booster F4 and A1 extraction bump power supplies during 3.85 GeV running.[75] A1 was repaired but F4 was not. Of the 4 windings around main dipoles that make up the extraction bump, F4 and A1 play the most critical role. Yet, when F4 failed, although some tuning of BtA was necessary to optimize, it was not hard to restore nominal BtA efficiency for either the Tandem or EBIS setups. This was surprising to me, and I thought it was worth looking into why that might be.

Since F4 is a winding around a main dipole, the main magnet field may be affected by it. After F4 had failed, that effect could still be quantified by comparing the main magnet field with A1 on and off since A1 also kicks to the outside and has a similar output. From logged data the outputs of A1 and F4 were about 465 A and 523 A, respectively, on the Tandem user (BU1) when they both were working, early on Sept. 10. The extraction field, about 6830 g, was 5.1 g lower with A1 off than with it on. So $\Delta B/B$ between the 2 states was -5.1/6830 or -7.5e-4.[76]

[75] See entries from Sept 9 1425 to Sept 11 1601 in the Booster-AGS-EBIS 2020 elog.
[76] This was measured using the gauss clock, See 1552, 1600, and 1601 entries on Sept. 11th in the Booster-AGS-EBIS elog.

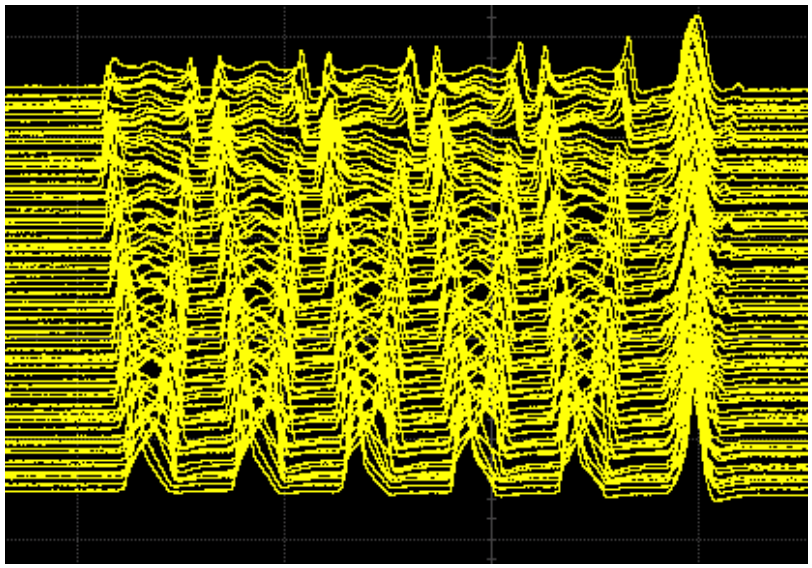

Figure 25: Mountain range display of the AGS WCM over a 240 ms interval starting at the 6th transfer, which is the bunch on the right. The display shows the effect on the bunches of the beam loading down the 3 Rf cavities that were off. There are 80 traces, each separated by 3 ms. The scope channel gain was 50 mV/div and the sweep speed was 1 μs/div.

After the failure, using the BoosterOrbitDisplay application, the average horizontal position at the BPMs (x_{avg}) near extraction was +8.2 mm on BU1.[77] It is normally only about 1 or 2 mm to the outside.

In order to determine whether the state of F4 affects the extraction radius, I can look at the logged radial average data.[78] On Aug. 31st, during the restoration of Tandem Au in the Booster on BU1, BoosterOrbitDisplay indicated that x_{avg} near extraction was about +3.0 mm.[79] On the same Booster cycle the radial average had a value of -11.5e5 at extraction. The radial average data with F4 on and off were -1.73e5 and 0.34e5 respectively. Since when x_{avg} was 8.2 mm the radial average was 0.34e5 and when it was -11.5e5 it was 3.0 mm, I estimate that x_{avg} would be +7.3 mm in the F4 on case on Sept 10th.

The extraction radius, relative to R_0, is different than x_{avg} because the average of the dispersion function at the BPMs (~1.99 m) is not the same as the average dispersion in the Booster (1.55m).[80] The change in x_{avg} indicated here, +0.9 mm, corresponds to a change in ΔR of +0.70 mm.

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[77] See 1430 entry on Sept 11th in the Booster-AGS-EBIS 2020 elog

[78] The radial average data is found in the Logview file Booster/RF/DedicatedLoggers/dsp_U1.logreq and is called radiusInAvgM:value[.]. The F4 on data is from Sept. 10th at 07:35:02 and the F4 off data is from Sept. 11th at 15:00:11. In each case they are the average of the 8 cycles within the supercycle occurring at that time. The standard deviations of the F4 on and off cases were 0.76e-5 and 0.35e5, respectively.

[79] See 1607 entry on Aug. 31st in the Booster-AGS-EBIS elog.

[80] See K. Zeno, "Fast Extraction from the Booster to R Line using Two Kicks from the F3 Kicker", C-A/AP/229, Feb. 2006, pg. 13-14.

Perhaps the oddest thing here is that, although the BtA phase changed by about one h=1 degree between the 2 states, the energy was still matched at AGS injection in both states. Using the differential relation for p as a function of R and B, with ΔR=0.7 mm, I find that Δp/p is -2.3e-4.[81]

Using $\frac{\Delta f}{f} = \eta \frac{\Delta p}{p}$, with f=158800 Hz and η=0.804, the change in f_{rev} at AGS injection, Δf, would be -46 Hz. A change of more than 20 Hz or so is noticeable, so this result is not exactly consistent with the observation that f_{rev} didn't change, but a change on this scale in the matched f_{rev} is typical going from one day to another. It is usually attributed to small changes in the extraction field (not associated with whether F4 is on or off). Note that the synchro loop was on so there was no radial loop being used to keep the extraction radius constant.

Nominally, with synchro on, the extraction frequency should not change between the 2 states. The logged Rf frequency data is not credible. The frequency at the peak, which is where extraction occurs, varies from cycle to cycle by about ±1.5 kHz. This amounts to a Δp/p variation of about ±3e-3, which is far too large to be real.[82] Perhaps this is because the 1 kHz sampling rate used is inadequate (the radial averaging sampling rate is 10 kHz).

Since there is no BPM at F6, the position there at extraction is not known, but there is a ±20 mm or so 5th harmonic in the orbit that, ignoring any cusps that may be present due to F2 and F7 pulsing, is phased such that it would have a maximum positive excursion near F6 (see Figure 26). Add to this that the extraction radius is about (1.55/1.99)*8.21 mm=6.4 mm, and it is not hard to imagine that the beam might be kicked out reasonably well.

Measuring ε_{long} on the 7.3 GeV Flattop

The 7.3 GeV setup used EBIS beam and the 24-12-4 AGS merge that has been used for several years now (setup 5 in Tables I and II). RHIC did not require anywhere near the intensity that it could provide and there is really nothing noteworthy about how it ran this year. However, its presence provided an opportunity to further study ways of estimating ε_{long} at a flattop energy not far from transition.

When making ε_{long} measurements I measure f_{synch} to find the Rf voltage because the Rf voltage indicated by the Rf system does not agree with the value I find from f_{synch}. The voltage obtained from f_{synch} is generally substantially lower. Figure 27 is a plot of Rf voltage obtained from f_{synch} (V_{synch}) vs. that voltage over the Rf vector sum (V_{sum}) for ε_{long} measurements taken throughout the run. Table VIII contains the data. Most of the measurements with lower voltages were taken on the flattop. For the most part, those at higher voltages were taken during the ramp, as noted in the Table.

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[81] *p(R,B)* is $\frac{\Delta p}{p} = \gamma_t{}^2 \frac{\Delta R}{R} + \frac{\Delta B}{B}$, in this case γ_t=4.88 and R=32.114 m.

[82] The Rf frequency data is found in the Logview file Booster/RF/DedicatedLoggers/dsp_U1.logreq and is called boosterRfDsp.914-rfll1.4:frevFbArrayM:value[*].

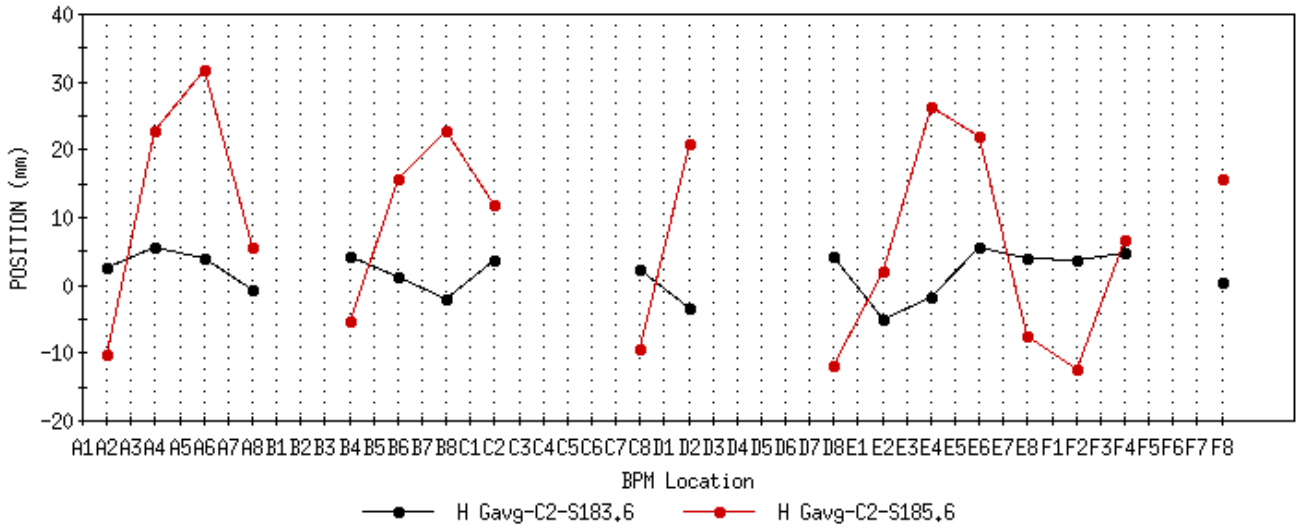

Figure 26: Horizontal orbits in the Booster on the Tandem Au cycle (BU1) at 183.6 ms (black) and 185.6 ms (red) with the F4 extraction bump power supply off, but with the other supplies on at their nominal settings. The BPM gate width is 100 μs and extraction occurs at 185.72 ms. At 183.6 ms the extraction bump supplies have not started pulsing, and at 185.6 ms they are nearly at their maximum amplitude. At 183.6 ms x_{avg} is 1.91 mm and at 185.6 ms it is 8.21 mm.[83]

Note that the ratio V_{synch}/V_{sum} is fairly constant and there is not a clear trend over the range of voltages and conditions. The average value of the ratio for the 17 measurements is 0.726 with a σ of 0.022. The Rf harmonic for all these cases was 12 and the range of frequencies over which the measurements were taken was 2.01 to 4.40 MHz. There is not an obvious dependence between frequency and V_{synch}/V_{sum} either.

On the 7.3 GeV flattop there is significant uncertainty in the value obtained for ε_{long} because of the uncertainty in the value of γ_t where the measurement is taken. The ε_{long} calculation contains a factor of $1/\sqrt{|\eta|}$ where $\eta = 1/\gamma^2 - 1/\gamma_t{}^2$ and so any error in γ_t becomes more important as γ approaches γ_t. A typical uncertainty in γ_t of ±0.05 around the nominal value of 8.50, changes $1/\sqrt{|\eta|}$ by ±3.6% at 7.3 GeV (γ=7.85). By contrast, at 5.75 GeV, the same error in γ_t will change the result by only ±0.7%. γ_t depends on a host of parameters (i.e.-Q_h, ξ_h, and ΔR), but if both the Rf voltage and f_{synch} are known then γ_t can be found by setting the Rf voltage in the bbrat application and adjusting γ_t there until f_{synch} agrees with what was measured.[84] The V_{synch}/V_{sum} data was taken at energies far from γ_t so the uncertainty should not be a factor and its average value, 0.726, multiplied by V_{sum} can be used as an estimate for the Rf voltage.

Since the value of γ_t depends on Q_h, ξ_h, and ΔR, care must be taken to measure f_{synch} over an interval where not only the Rf voltage is constant but these parameters are as well. On July 14th, f_{synch} on the 7.3 GeV flattop was measured to be 38.29 Hz over a 180 ms interval where

[83] Taken from 1430 entry in the Sept. 11th Booster-AGS-EBIS elog. The 1434 entry shows the A1 extraction bump P.S. pulse relative to Bt0 and x_{avg} during the 5 ms or so before extraction.
[84] Both bbat and bbrat can be found in StartUp under Specialist tools/Rf Apps.

they were constant. At that time V_{sum} was 78.68 kV so the voltage estimate is 0.726*(78.68kV), or 57.12 kV. In bbrat, adjusting γ_t until I get 38.29 Hz for f_{synch} yields γ_t=8.4394. This measurement was taken at At0+4500 ms where the average of 10 bunch length measurements

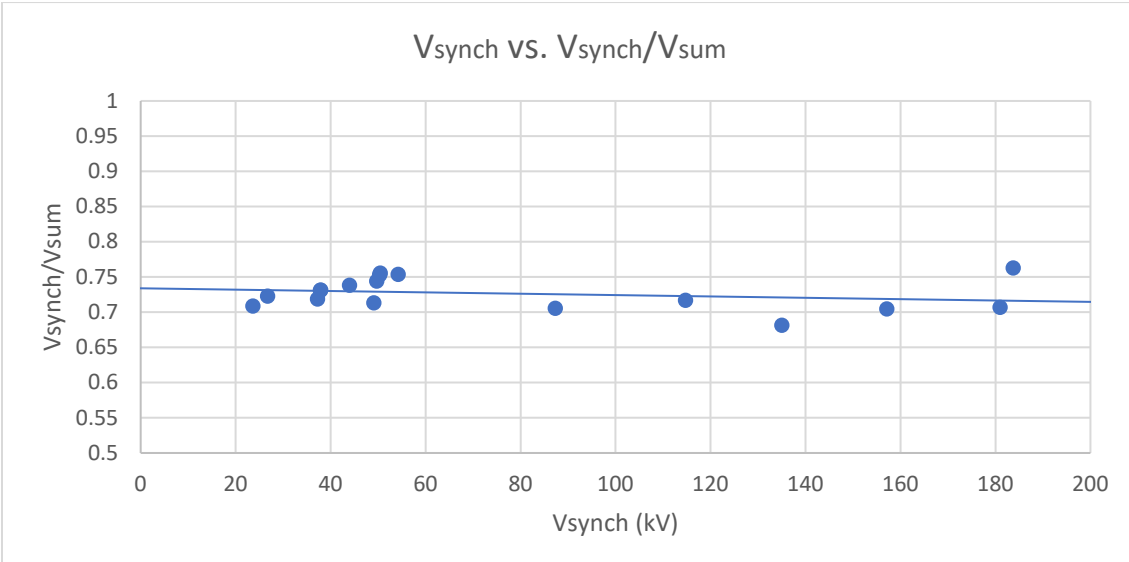

Figure 27: Vsynch vs. Vsynch/Vsum including a linear fit.

Date	**V_{synch} (kV)**	**V_{sum} (kV)**	**V_{synch}/V_{sum}**	**Rf freq. (MHz)**	**Notes**
Nov, 20	181	256	0.707	4.400664	5.75 GeV flattop
Feb 20	114.7	160	0.717	4.3985852	5.75 GeV flattop
Feb 8	49.13	68.9	0.713	4.3646184	4.59 GeV flattop
Feb 24	37.87	51.8	0.731	4.3646184	4.59 GeV flattop
Feb. 28	37.22	51.8	0.718	4.3646184	4.59 GeV flattop
Mar. 2	37.9	51.8	0.732	4.3646184	4.59 GeV flattop
Mar. 2	26.75	37.0	0.723	4.3646184	4.59 GeV flattop
Jun 18	49.71	66.8	0.744	4.364616	4.59 GeV flattop
Jun. 26	50.3	66.8	0.753	4.364616	4.59 GeV flattop
Jul. 7	50.48	66.8	0.756	4.364616	4.59 GeV flattop
Jul. 10	44	59.6	0.738	4.364616	4.59 GeV flattop
Sept. 1	23.6	33.3	0.709	4.3246356	3.85 GeV flattop
Sept. 1	54.2	71.9	0.754	4.3246356	3.85 GeV flattop
Mar 6	157.1	223	0.704	2.0064	4.59 GeV after 24-12 merge, 3.1 g/ms
Mar 6	87.33	123.8	0.705	3.121716	4.59 GeV before 12-6 merge, 1.6 g/ms
Mar. 5	183.76	240.9	0.764	3.12612	4.59 GeV after 12-6 merge, 1.2 g/ms
Feb. 20	135.0	198.1	0.681	3.2292	5.75 GeV after 12-6 merge, 2.8 g/ms

Table VIII: The data in Figure 27 together with the Rf frequency. The Rf harmonic is 12 in all cases.[85] $\Delta B/\Delta t$ is zero unless otherwise noted.

[85] The data can be found in the Booster-AGS-elog for the specified dates except for The Rf vector sum which can be found in Logview. It is called agsDsp.929-rfll1.4:vectorSum:value[.] and it is found in Ags/RF/LLRF/agsDspAll.logreq.

was 34.30 ns with a σ of 0.91 ns corresponding to an ε_{long} of 0.726±0.037 eVs (where the uncertainty reflects the σ of the bunch length measurements).[86]

The uncertainty in V_{synch}/V_{sum} also contributes significantly to the error. The σ of those measurements is 0.022, and if a value for V_{synch}/V_{sum} off by ±1 σ is used it changes the calculated ε_{long} by ±0.022 eVs.

A measurement was also taken at 4200 ms, and it can be used as a consistency check. In that case f_{synch} was 41.12 Hz, although the V_{sum} was the same, the radius was -2 mm instead of the +6 mm it was for 4500 ms, and the set Q_h was a little lower (8.64 vs. 8.67).[87] To match the measured f_{synch} a γ_t of 8.5427 was required. The average of 10 bunch length measurements was 35.60 ns with a σ of 1.07 ns. This corresponds to an ε_{long} of 0.727±0.043 eVs which is very close to the value obtained at 4500 ms despite a quite different value for ΔR.

Normally I would use bbat to calculate ε_{long}, which has γ_t hardcoded to be 8.5, and adjust the Rf voltage until f_{synch} agrees with the measurement. If I do that in the 4500 ms case, I obtain an Rf voltage of 52.28 kV and an ε_{long} of 0.660 eVs and in the 4200 ms case I get 59.95 kV and 0.763 eVs. Presumably, these 2 cases result in quite different values because instead of adjusting γ_t to get the right f_{synch}, γ_t is held fixed and the voltage is adjusted, even though the voltage is actually the same. Note that the bunch length is larger in the 4200 ms case, which contributes to the discrepancy as well.

If nothing else this exercise shows that, when the energy is close γ_t, adjusting the Rf voltage until the calculated f_{synch} matches the measured one is not a good recipe for finding the Rf voltage. Some other means has to be found, like the one used here. The Rf harmonic was 10 for these measurements, but V_{synch}/V_{sum} using h=10 and 12 has been compared and no obvious difference was found.[88]

Alternately, a model of how γ_t in the AGS varies as a function of Q_h, ξ_h, and ΔR could be used, and from that an estimate for γ_t could be found. Once it's found, it can be input into bbrat as above and then the Rf voltage can be determined by adjusting it until f_{synch} matches the measured value. Such a model is significantly more complicated and has been detailed elsewhere[89], but last year ε_{long} was calculated on the 9.8 GeV flattop using it.

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[86] See entries from 1728 to 1756 in the July 14th Booster-AGS-EBIS 2020 elog. The bunch length measurement is made at At0+4500 ms, and this measurement of γ_t is valid for that time.

[87] See entries from 1518 to 1727 in the July 14th Booster-AGS-EBIS 2020 elog. Note that I measured 40.67 Hz for fsynch in the 1516 entry, but later realized that the set Q_h was not constant after 4200 ms, so I measured f_{synch} for the 3.5 oscillations that precede that time and obtained 41.12 Hz. At 4500 ms f_{rf} was 3.684064 MHz (ΔR=+6 mm) and 3.684028 MHz at 4200 ms (ΔR=-2 mm). E_{long} is +0.003 eVs higher if the higher f_{rf} is used.

[88] See entries from 1625 to 1758 in Feb. 13th Booster-AGS-EBIS 2020 elog.

[89] See K. Zeno, "Estimating longitudinal emittance near transition energy in the AGS", C-A/AP/624, September 2019.

A value of 0.724 eVs was found and the value using the standard bbat method was much higher (0.817 eVs). If I use the method described here, I obtain γ_t=8.4395 and ε_{long}=0.783 eVs.[90] At that γ (10.53) the error associated with an uncertainty in γ_t of ±0.05 is ±1.7%. Although there is considerable uncertainty, if 0.783 eVs is accurate, then in going from 7.3 to 9.8 GeV, which includes crossing transition, ε_{long} increases by a factor of 0.783/0.726=1.08.

Summary

This note is divided into five sections. The first section contains an overview of the run and a chronology of the different injector setups that were used (Tables I and II). The other 4 sections cover the 5.75, 4.59, 3.85, and 7.3 GeV parts of the run, in that order, including both emittance and intensity data. The RHIC program was interrupted for about 3 months due to the COVID-19 shutdown.

The 2 principal energies used this run, 4.59 and 5.75 GeV, employed EBIS and Tandem respectively as the pre-injector. 3.85 GeV commissioning used 2 different setups, one for EBIS and one for Tandem.

The Booster cycle used with Tandem Au was extended from 233 ms to 267 ms by lengthening the 6-3-1 merge porch (Figures 1-3). This allowed for the use of 8 Booster transfers which, with a 12-6 merge in the AGS, provides 4 bunches to RHIC each AGS cycle. The 4.59 GeV setup used for data taking in RHIC employed a 4-2-1 type merge (24-12-6) that had not been used before which provided 3 bunches to RHIC per AGS cycle.

With 8 Tandem requests per supercycle the Booster Late intensity for 5.75 GeV was significantly higher than it had been with Gold, which likely contributed to damaging both of the BtA stripping foils used with Gold (Figure 13). Fortunately, this did not significantly impact the Run performance.

The BtA efficiency for the 24-12-6 4.59 GeV cycle is, at least sometimes, about 1.5% higher when filling than when the beam is dumped in the AGS. This seems like a vacuum related effect. Consequently, although probably not the cause, it was noticed that beam related vacuum spikes near the D5 eIPM, which were associated with frequent closures of sector valves last run, were still occurring on a similar scale at times this run.

A new 3 to 1 type AGS merge (24-16-8) was used for 4.59 GeV LEReC commissioning that allows for 4 bunches to RHIC per AGS cycle (Figures 22 and 23). This setup was used with both EBIS and Tandem beam and the difference in ε_{long} between the 2 cases was investigated.

The beam loading observed with Tandem beam on the injection porch during 3.85 GeV running was discussed. The Booster F4 extraction bump power supply failed during 3.85 GeV

[90] The bunch length was measured at 4200 ms. I measured f_{synch} over 4 synchrotron oscillations just after 4200 ms where the set Q_h, ξ_h, ΔR, and f_{rf} were nearly constant. I obtained a value for f_{synch} of 102.95 Hz for an Rf voltage of 0.726*279 kV=202.55 kV. See the July 8th entries from 1629 to 1638 in the 2019 Booster-AGS-EBIS elog and K. Zeno, "The 2019 Gold Run in the Injectors", C-A/AP/627, November 2019, pg.1.

running, but, surprisingly, the BtA efficiency could be restored without it, and this was investigated.

The 7.3 GeV setup was used to study a method for estimating ε_{long} when the flattop energy is close to transition.

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