

The 2019 Gold Run in the Injectors

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In the injectors, RHIC run 19 used Gold at four different AGS flattop energies (3.85, 4.59, 7.30, and 9.8 GeV) and with several different bunch merges in the AGS. The Westinghouse motor generator was used for the AGS main magnet for the entire run. Although in all cases EBIS provided beam for RHIC there was some time spent setting up the injectors with Gold from Tandem.

Injector setup with beam began on Feb 1 and Table I gives a chronology of this somewhat more complicated than normal startup period.¹ Table II shows when the different setups were used for RHIC and Table III shows the chronology for the Tandem setups.²

Flattop Longitudinal Emittance for Different Setups

Table 4 shows some longitudinal emittance (ϵ) and bunch intensity measurements on the flattop for all these setups together with similar measurements made last year (Run 18).³ The measurements from last year are generally under similar but not the same conditions. One difference is that last year the AGS motor generator was Siemens. Although the ramp rate is generally the same on the F bank, it is slower on the P bank with Westinghouse. The 7.3 and 9.8 GeV cycles use both banks, and the others only use the F bank.

The 7.3 and to a lesser extent the 9.8 GeV ϵ calculations are also affected significantly by the value of the slip factor (η) at the time in the cycle where the measurement is taken, and η 's value depends on several factors not only the energy, but also on γ_t since $\eta=1/\gamma_t^2-1/\gamma^2$. The values quoted here for those energies simply assume a γ_t of 8.50.

An attempt at estimating γ_t for flattop ϵ measurements given a particular setup has been made, and perhaps a more accurate value for ϵ at those energies can be obtained using this method.⁴ This year, in the 7.3 GeV case, an estimate for the ϵ has already been made this way and a value of 0.689 ± 0.04 eVs was found.⁵ This is essentially the same value as that obtained assuming γ_t is 8.50 (0.693 eVs). However, this seems to just be a coincidence.

A similar estimate for the 9.8 GeV ϵ this run can also be made. The parameters that affect γ_t are the trim Q_h and ξ_h settings and the radius (ΔR). In this case, the estimated value of γ_t is 8.347 ± 0.029 which results in an ϵ of 0.724 ± 0.013 instead of 0.817 eVs.⁶

¹ See [Booster-AGS-EBIS 2019 elog](#) from dates indicated in the table for more details.

² See [Booster-AGS-EBIS 2019](#) and [rhic-AuAu 2019](#) elogs for more details.

³ See [Booster-AGS-EBIS_2019 elog](#) and K. Zeno, "[AGS Longitudinal emittance measurements for upcoming RHIC low energy gold runs](#)", C-A/AP/615 for more details.

⁴ See K. Zeno, "[Estimating longitudinal emittance near transition energy in the AGS](#)", C-A/AP/624

⁵ *Ibid.*, pg. 12.

⁶ For the 9.8 GeV cycle this year the flattop Q_h setting was 8.758, the ξ_h setting was -3.0 (little or no sextupole current), and ΔR (from AGSOrbitDisplay) was +4mm. Using the technique developed in *Ibid.* and this information the estimate for γ_t is 8.347. Bbrat is used to calculate ϵ in this case as it allows γ_t as an input. The uncertainties

Date	Setup	Notes
Feb 1	EU1/BU1	Initial Booster setup with EBIS Au32+
Feb 4	EU1/BU1	Initial Booster setup continues
Feb 5	9.8 GeV, AU1	AGS setup, beam accelerated to flattop with 6-3-1 merge in AGS.
Feb 6	9.8 GeV, AU1	Problems develop with the Westinghouse, exciter P.S. trips. Confusion regarding magnet parameters to use for the Westinghouse. A slower ramp down than initially used was implemented (-4500 vs. -5000V). Supercycle extended from 6.0 to 6.2 sec. At end of the shift it had tripped again and was left off for the night.
Feb 7	9.8 GeV, AU1 7.3 GeV, AU2	After further adjustment to magnet parameters (VEpsilon), injection field is no longer flat. Supercycle was extended from 6.2 to 6.6 sec. After changes by P.S. group and adjustment of the rollover, flatness of the flattop field improved. The amplitude of down ramp voltage decreased further to -4200 V. Then 7.3 GeV was setup with 6-3-1 merge.
Feb 8	3.85 GeV, AU5	No merge in the AGS. Issues with the beam control that were later found to be related to phase loop.st turning on after beam_control.st. 6 EBIS requests and bunches on flattop with bunch intensity of about 4.9e8 (Mar 7) and ϵ of about 0.15 eVs (Feb 13)
Mar 7	3.85 GeV, AU5	Implemented 2-1 merge in AGS. In this state there are 6 EBIS requests and 3 bunches on flattop, each about 8.5e8 and 0.30 eVs (Mar 8).
May 31	3.85 GeV, AU6	12 EBIS requests, still 2-1 merge in AGS. Used for RHIC 3.85 GeV run. 6 bunches on flattop
Jun 14	3.85 GeV, AU8	12 EBIS requests, 3-1 merge in AGS using h=24,16, and 8. Provides 4 bunches on flattop. ϵ was 0.50 eVs.
Jun 17	4.59 GeV, AU5	12 EBIS requests and 6 bunches on flattop, derived from 3.85 GeV AU6 cycle, still 2-1 merge in AGS. Used for RHIC 4.59 GeV run. *
Jul 10	4.59 GeV, AU2	12 EBIS requests, 3-1 merge in AGS with h=24,16, and 8. Provides 4 bunches on flattop.

*- On May 15, a 3-1 merge was also set up on 3.85 GeV cycle. This merge could be turned on or off as could the 2-1 merge so that either only a 3-1 or a 6-3-1 merge could be used. For 3.85 GeV all 3 variations were employed, and for 4.59 GeV the 3-1 and 2-1 were. Although for both energies the nominal merge was 2-1.

Table 1: Chronology of injector setups used for Run 19. The same Booster cycle (BU1) and preinjector (EBIS) were used for all these setups. The Booster setup is the same as the one used last run for Au32+, which has a 4-2-1 bunch merge, an injection kinetic energy of 1.98 MeV, and an extraction kinetic energy of 107.8 MeV. BtA stripping foil 6 (Al+C) was used exclusively this run.

shown are those related to the estimation method and not from other factors such as the uncertainty in the bunch length measurement.

Flattop energy	Start	Stop	Notes
9.8 GeV	Feb 24	Apr 3	collisions, 2 bunches, 6-3-1 AGS merge
3.85 GeV	Feb 21	Near end of run	LEReC, initially no merge then 2-1 merge (Mar 7), and briefly 3-1 and 6-3-1 merges
7.30 GeV	Apr 4	Jun 3	collisions, 2 bunches, 6-3-1 AGS merge
3.85 GeV	Jun 3	Jun 27	collisions, 6 bunches, 2-1 AGS merge, briefly 3-1
4.59 GeV	Jun 28	Jul 8	Collisions, 6 bunches, 2-1 AGS merge, briefly 3-1. Also used by LEReC until July 15.
9.80 GeV	Jul 8	Jul 12	100 GeV collisions, 6-3-1 merge
7.30 GeV	Jun 18	Jun 18	Fixed target, 6-3-1 merge

Table 2: Chronology of the injector setups used for RHIC.

Date	Setup	Notes
Feb 11	TU1/BU3	Booster setup and extraction to BtA of Tandem beam (Au31+). First use of 6-3-1 merge in Booster with Tandem beam.
Feb 12	9.80 GeV on AU3	Accelerated to flattop with a 2-1 merge in AGS using h=12 and 6 (station KL) and a 6.0 sec supercycle. Bunch intensity was about 1.5e9.
Feb 13	9.8 GeV, AU1 3.85 GeV, AU5	Westinghouse trips. Lowered the peak voltage on the up ramp from 5000 to 4700 V and moved the flattop 100 ms later. Then 3.85 GeV (AU5) with 6 unmerged bunches on flattop of about 2.7e8 and 0.15 eVs each.
Feb 27	9.80 GeV on Au3	Continue 9.8 GeV setup. Only 2 Tandem pulses were used resulting in 1 bunch on flattop. AGS extraction was not setup. 2.18e9 bunch intensity and 0.42 eVs on flattop.
Mar 6	9.80 GeV on AU3	Continue 9.8 GeV setup. Still 2 Tandem pulses were used resulting in 1 bunch on flattop. AGS extraction still not setup. 1.96e9 bunch intensity and 0.38 eVs on flattop.
Mar 19	3.85 GeV on AU7	No AGS merge, 4 Tandem requests and bunches on flattop. About 1.0e9/bunch and 0.15 eVs.

Table 3: Chronology of the Tandem Au31+ injector setups. Extraction was not set up for these setups.

For 9.8 GeV in run 18 the estimated γ_t is 8.2976 ± 0.032 which changes the calculated ϵ from 0.782 to 0.685 ± 0.014 eVs.⁷ An estimate for γ_t for the Run 18 7.30 GeV measurement is unavailable because ΔR is not known for this case. Note that the best estimates for the ϵ on the 9.80 GeV and 7.30 GeV flattops are about the same. If this is true than the ϵ growth typically

⁷ In this case set Q_h is 8.71 with essentially no current in the sextupoles ($\xi_h = -3.0$) and $\Delta R = +4$ mm. Q_h and ξ_h were obtained from archives the day of the measurement (Jun 16 2018) and ΔR from AGSOrbitControl data files for AU3 saved with Snap ramp (ex.- run_fy18fil18May29-2251_U3).

seen between the beginning of the ramp and the flattop occurs below 7.30 GeV. For 3.85 and 4.59 GeV, the emittances measured this year are quite close to those measured in Run 18.

Energy	Merge	Date	ϵ (eVs/n)	Bunch intensity	Run 18 ϵ	Notes
with EBIS						
3.85 GeV	None	4/1	0.14	0.48e9	N/A	6 bunches
	2-1	5/6	0.25	0.92e9	0.25	3 bunches
	3-1	6/6	0.37	1.45e9	0.36	3 bunches
	6-3-1	5/15	0.61	2.37e9	0.62	2 bunches
4.59 GeV	2-1	7/2	0.27	0.95e9	N/A	6 bunches
	3-1	7/3	0.41	1.46e9	0.40	3 bunches
7.30 GeV	6-1	5/7	0.693	2.50e9	0.64	2 bunches
9.80 GeV	6-1	7/8	0.817 ⁸	2.66e9	0.78	2 bunches
with Tandem						
3.85 GeV	None	3/19	0.15	1.0e9	N/A	3 bunches, could be as much as 6 or 8
9.8 GeV	2-1	2/27, 3/26	0.40	2.1e9	N/A	1 bunch, could be as many as 3 or 4.

Table 4: Some longitudinal emittance measurements on AGS flattop at the different energies. Also shown, when available, are ϵ measurements from last run for similar setups.

Evolution of Longitudinal Emittance in the Injectors

ϵ of Au³²⁺ from EBIS at Booster Injection

In order to find the ϵ just after Booster injection a debunching measurement, which measures $\Delta p/p$, was performed. This measurement has been done several times over the past few years using somewhat different methods.

In 2014, an EBIS pulse shorter than the revolution period (~ 7.3 vs. $10.35 \mu\text{s}$) was used so that the time it takes the beam to debunch could be measured. A typical EBIS pulse is $30 \mu\text{s}$ or more. The debunching time was found using a mountain range display of the D1 PUE sum signal on the injection porch. A (half width) $\Delta p/p$ of $0.22e-3$, corresponding to an ϵ of 0.018 eVs, was found.⁹ This method was problematic for 2 reasons. First, since the pulse was shorter than the normal pulse, its $\Delta p/p$ may have been different. Secondly, the edges of the pulse were not sharp, which makes them difficult to see.

⁸ Note that the bbat calculation shown in the Jul 8 elog is wrong (0.797 eVs) because it uses the wrong synchrotron frequency.

⁹ See K. Zeno, "[Longitudinal Emittance measurements in the Booster and AGS during the 2014 RHIC Gold run](#)", C-A/AP/523, August 2014, pgs. 19-20.

In 2016, a typical EBIS pulse was used and an approximately 3 μs hole was kicked out of the injected beam using the F3 extraction kicker on the injection porch.¹⁰ Although this method provides a bunch with sharp edges, I was unable to get the mountain range display to work and there was barely enough time on the injection porch for the trailing and leading edges of the bunch to cross before the beam was lost. This was partly because I was unable to get the kicker to fire earlier than 5 ms after injection.

However, I was still able to measure the time it takes for the edges to cross and obtained a $\Delta p/p$ of $4.9\text{e-}3$, about twice the value I obtained in Run 14. I also treated the hole as a bunch and measured its debunching time, as it seemed to be an equally valid means of determining it and obtained a $\Delta p/p$ of $4.2\text{e-}4$. The emittances corresponding to these 2 $\Delta p/p$ values are 0.040 and 0.034 eVs, respectively.

This year I used the kicker at injection again but was able to get the mountain range display to work. I also used a flat magnet cycle so that the beam survived until long after the trailing and leading edges of the hole has crossed. In this case, I treated the hole as a bunch, and it took 7.6 to 7.9 μs (see Figure 1) for the edges to cross which corresponds to a $\Delta p/p$ of $0.50\text{-}0.52\text{e-}3$ and an ϵ of $0.041\text{-}0.042$ eVs.¹¹ This is not far from what was found in 2016.

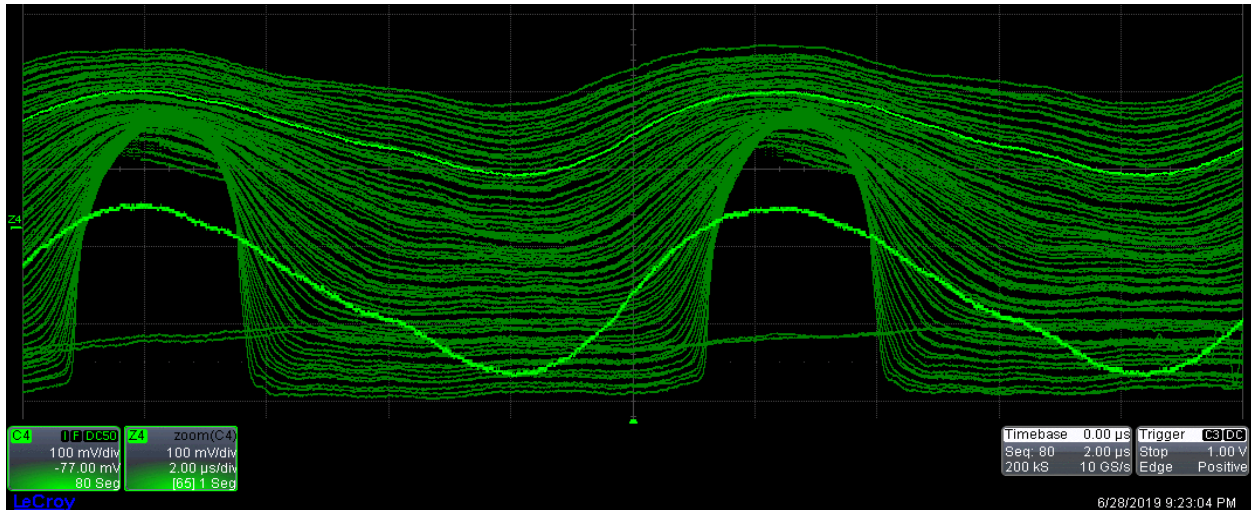


Figure 1: Mountain range display of the hole kicked in the Booster beam at injection energy seen on the D1 PUE sum signal. There are 80 traces and the kick occurs between the 2nd and 3rd traces from the bottom. The leading and trailing edges appear to cross no earlier than trace 65 and perhaps as late as trace 68. The traces are 120 μs apart. Trace 65 is highlighted and is also shown in a higher gain (channel Z4). The 65th trace is therefore about $63 \times 120 \mu\text{s} = 7.56$ ms and trace 68 is about $66 \times 120 \mu\text{s} = 7.92$ ms from when the beam is kicked.

¹⁰ See K. Zeno, “[Overview and analysis of the 2016 Gold Run in the Booster and AGS](#)“, C-A/AP/571, September 2016, pgs. 23-26. Calculating $\Delta p/p$ from the debunching time is described in some detail here. The equation that relates debunching time to $\Delta p/p$ is derived here: K. Zeno, “[Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Merge](#)“, CA/AP/596, December 2017, pgs. 7-8.

¹¹ See [Booster-AGS-EBIS Jun 28, 2019 elog](#) entries from 1804 to 2123.

Booster ϵ Near the End of the Injection Porch

On Jun 26 the ϵ 8 ms after injection (Bt0+18.5 ms), using the normal capture setup, was measured using the Wall Current Monitor (WCM).¹² The Rf at this time in the cycle is h=4. On one Booster cycle the average length of the 4 bunches was 1042 ns with $\sigma=11$ ns. A measurement using a 12-cycle average of the 4 bunches was also done and the length averaged 1054 ns with $\sigma=55$ ns.

The bunches are not in equilibrium at this time in the cycle but they do not have a lot of structure. Figure 2 shows a mountain range display of the first 8 ms after injection together with the one and 12-cycle average length measurement of the “first” bunch.

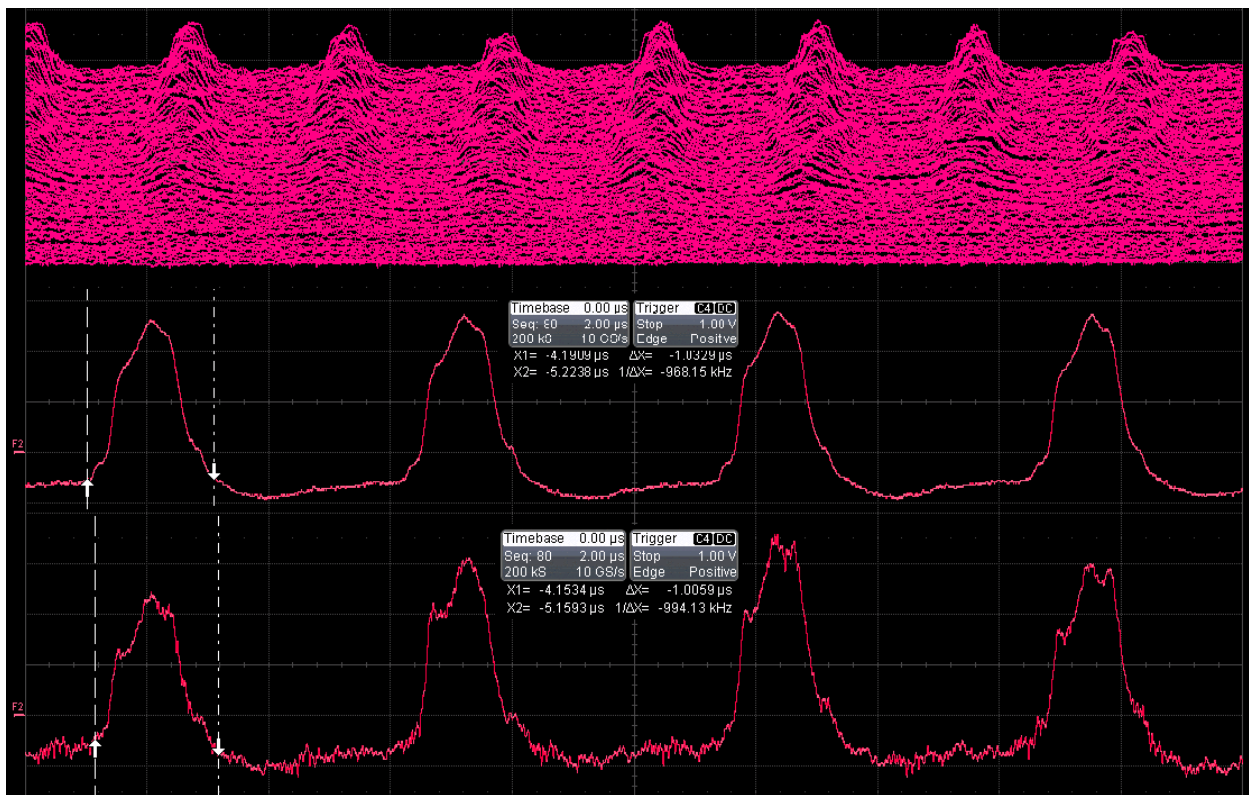


Figure 2: An 80 trace mountain range display of the first 8 ms after Booster injection using the WCM (top). A 12-cycle average (middle) and 1 cycle (bottom) length measurement of the bunch on the left on the 80th trace (8 ms after injection) is also shown. Here the measured bunch lengths are 1032.9 ns (middle) and 1005.9 ns (bottom).

In order to find the ϵ the Rf voltage at this time in the cycle is needed. This was found from the synchrotron frequency (f_{synch}). It is changing quickly at this time in the cycle but f_{synch} 's that were clearly too low and too high were found (936.2 and 1020 Hz) which correspond to Rf voltages of 3.76 and 4.46 kV, respectively.

¹² See [Booster-AGS-EBIS Jun 26 2019 elog](#) entries from 1900 to 1930.

Using the average of these 2 voltages (4.11 kV) the ϵ for the non-averaged data is 0.0199 eVs and for the averaged data it is 0.0204 eVs. These correspond to total, or 4-bunch, emittances of 0.0796 and 0.0816 eVs, respectively. The upper and lower bounds on the Rf voltage correspond to a range in total ϵ of ± 0.0036 . In Run 16 the measured total ϵ at this time in the cycle ($\sim \text{Bt0}+18$ ms) was 0.083 eVs.

Booster ϵ at Extraction

Determining the ϵ at Booster extraction is difficult because the merged bunch is far from matched to the bucket. Were it to stay in the Booster longer it would eventually match the bucket through filamentation. It's likely that a magnet cycle could be constructed which would make it possible for this measurement to be made.

There are 2 reasons why the ϵ at extraction is important. First, because it could be used to determine how much growth occurs from the Booster merge. Secondly, it could be used to determine how much growth occurs from the BtA stripping foil. One can still just assume the bunch is matched to the bucket and make the measurement, as it is presumably better than nothing.

So, this measurement was made on Jun 16th.¹³ The Quad mode Pumping (QP) that is used at Booster extraction was turned off and the lengths of 5 bunches were measured on the 1st turn in the AGS using the WCM. The average length was 264 ns with a σ of 6.9 ns. An f_{synch} measurement near extraction with the QP on was 974 Hz and with it off it was 959 Hz.

The difference between the peak and valley amplitudes of the quadrupole oscillations with the QP off divided by the average amplitude of the WCM envelope gives some idea of how well the bunch is matched to the bucket and was about 23%. The bunch length should be measured when the amplitude of the WCM envelope at extraction is halfway between the peak and the valley. The phase of the oscillation at which extraction occurs does not vary much from cycle to cycle and was perhaps a third of the way from the valley to the peak a couple minutes before the measurements were made.

Using an f_{synch} of 974 Hz gives an ϵ of 0.0878 eVs and using 959 Hz gives 0.0864 eVs. Changing the bunch length by $\pm\sigma$ changes the calculated ϵ by ± 0.0045 eVs. Note that these ϵ values are only slightly higher than those measured 8 ms after injection. This measurement has been made several times in the past with results varying from 0.066 to 0.089 eVs.¹⁴ In 2017 the ϵ at extraction without a merge was 0.068 ± 0.005 eVs.¹⁵

¹³ See [Booster-AGS-EBIS Jun 16 2019 elog](#) entries from 1352 to 1512.

¹⁴ See K. Zeno, "[Overview and analysis of the 2016 Gold Run in the Booster and AGS](#)", C-A/AP/571, September 2016, pg 28.

¹⁵ See K. Zeno, "[Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Merge](#)", CA/AP/596, December 2017, pgs. 3-4.

A 264 ns bunch matched to a bucket with $f_{\text{synch}}=974$ Hz at Booster extraction has a $\Delta p/p$ of $1.046\text{e-}3$ and one with $f_{\text{synch}}=959$ Hz has a $\Delta p/p$ of $1.030\text{e-}3$.

ϵ at AGS Injection

Debunching Measurements

On June 14th, debunching measurements were taken at AGS injection with and without QP at Booster extraction.¹⁶ Due to difficulties with triggering the mountain range display an alternative method was used. The scope was triggered with both a 1000 and 2000 μs delay from the Booster F3/A5 kicker trigger and, using a 10-cycle average, the time between the leading and trailing edges was measured for both the QP off and on cases (see Figure 3).

For each case the rate at which the trailing and leading edges approach each other was calculated. In the QP off case the time between the edges was 3.95 μs at 1000 μs and 2.12 μs at 2000 μs , so the rate at which the edges approached each other was $(3.95-2.12) \mu\text{s}=1.83 \mu\text{s}$ per ms. Since the spacing at 2000 μs was 2.12 μs it would take another $2.12/1.83$ ms for the edges to reach each other. Therefore, the debunching time would be $2.000 \text{ ms}+(2.12/1.83) \text{ ms}=3.16 \text{ ms}$. Similarly, in the QP on case the debunching time was $2.000 \text{ ms}+(0.99/2.58) \text{ ms}=2.38 \text{ ms}$. The bunch lengths on the first turn were measured a day earlier under the same conditions and were 264 and 221.1 ns for QP off and on, respectively. From this information, $\Delta p/p$ was $1.17\text{e-}3$ without QP and was $1.565\text{e-}3$ with it.¹⁷

Compared to the $\Delta p/p$ found for a matched bunch at Booster extraction without QP ($1.030-1.046\text{e-}3$) the value here is about 12-14% higher. The difference could naively be attributed to the BtA foil. ΔE should also increase by that amount and, if the injected bunch were matched to the bucket would cause the same amount of ϵ growth. When QP is used the growth should be somewhat less.

The bunch length for the QP on case was 221.1 ns, that together with a $\Delta p/p$ of $1.565\text{e-}3$ corresponds to a 0.0956 eVs bunch in an $h=24$ bucket, which is 9-11% larger than what was measured at Booster extraction.

It's not clear that averaging over cycles is the best way to measure the debunching time since, although it provides a cleaner signal, the edges could be washed out. On Jun 24th another

¹⁶ The $\Delta p/p$ measurements in the section were taken with BtA foil #6, the foil that was used exclusively this run.

¹⁷ Debunching measurements with foil 5, whose performance is usually indistinguishable from foil 6, indicated a higher $\Delta p/p$ as well as more energy loss. On June 12th the $\Delta p/p$ for foil 5 without QP was $1.30\text{e-}3$ (2.85 ms) and with QP it was $1.65\text{e-}3$ (2.25 ms). f_{rev} also had to be lowered 60 Hz from the value for foil 6 to match the f_{rev} of the injected beam. This measurement was taken using the typical mountain range display method. On that day with foil 6 $\Delta p/p$ without QP was $1.04\text{e-}3$ (3.60 ms) and with QP it was $1.31\text{e-}3$ (2.85 ms). See [Booster-AGS-EBIS Jun 12th 2019 elog](#). Another MR type measurement from Jun 25th with QP off for foil 5 was $1.38\text{e-}3$ (2.7 ms) and for foil 6 it was $1.13\text{e-}3$ (3.3 ms), See [Booster-AGS-EBIS Jun 25th 2019 elog](#) entries from 1550 to 1705. To get the MR to work properly the scope was smart triggered using the MR triggers as event A and the Rev Tick as event B.

debunching measurement without averaging and using the typical mountain range display method was performed for the no QP case and a similar debunching time of 3.0 ± 0.15 ms was obtained.¹⁸ Using the same bunch length (264 ns) as in the Jun 14th measurement gives a $\Delta p/p$ of $1.233e-3$.¹⁹

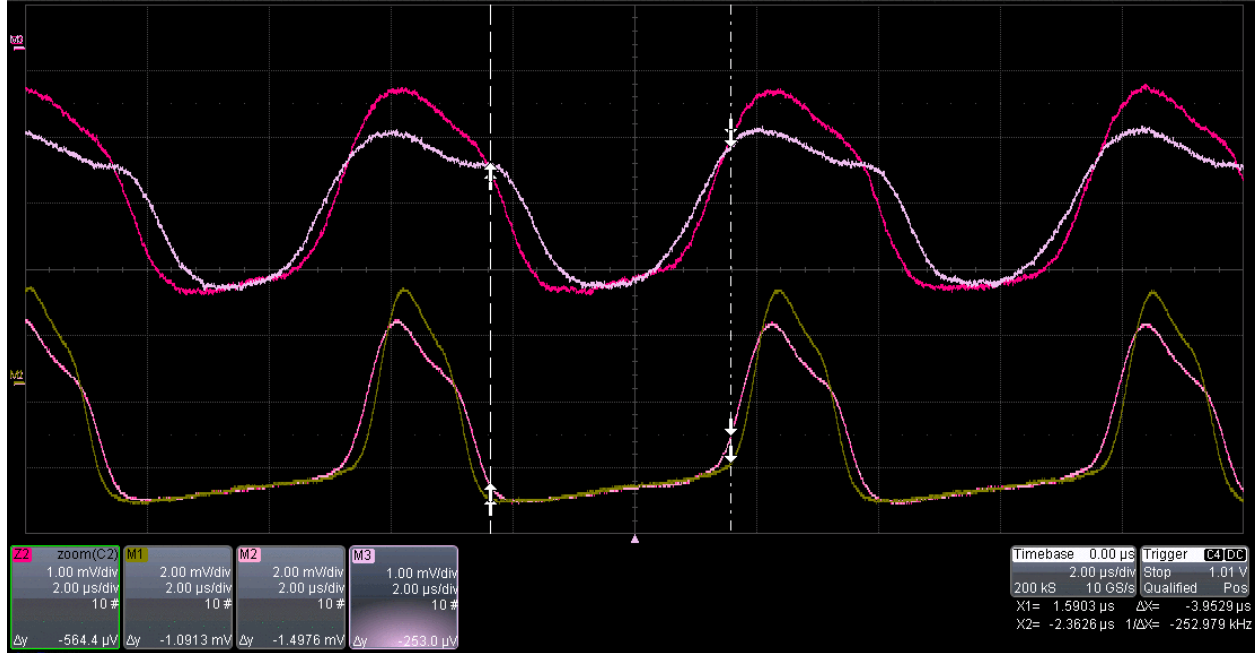


Figure 3: Debunching measurement at AGS injection for QP off and on (and Rf off) using the AGS WCM. The top 2 traces are taken at 2000 μ s and the bottom 2 at 1000 μ s after the kicker trigger. For each delay the wider bunches are with QP on. In this figure the time between the end of the trailing edge and beginning of the leading edge is being measured as indicated by the cursors (3.95 μ s). This is the QP off 1000 μ s case. The amplitude of the QP was 2.25 kV on B3. The gain is 1 mV/box for 2000 μ s and 2 mV/box for 1000 μ s. The sweep speed is 2 μ s/div.

ϵ after Filamentation on the Injection Porch

On June 13th five length measurements of the first injected bunch taken 400 ms after injection were measured under normal running conditions (i.e.-QP on).²⁰ That together with the measured f_{synch} (2.612 kHz) were used to find the ϵ of a matched bunch on the injection porch. The average bunch length was 210.1 ns with a σ of 3.7 ns from which the ϵ is 0.0956 ± 0.0018 eVs. Perhaps surprisingly, this ϵ is the same as what was found at injection for the measured $\Delta p/p$ and length with QP on mentioned earlier.

The observation that once the bunch is matched it has a similar ϵ to one constructed from its injected length and $\Delta p/p$, at least when $h=24$, has been noted before. In that analysis,

¹⁸ See [Booster-AGS-EBIS Jun 14 2019 elog](#) entries from 1853 to 1855.

¹⁹ The calculation does not depend strongly on the bunch length at injection. If 221 ns is used for the bunch length $\Delta p/p$ becomes $1.243e-3$.

²⁰ See [Booster-AGS-EBIS Jun 13 2019 elog](#) entries from 1601 to 1614.

significant growth was apparent with $h=16$. The conclusion was that because the bunch is about the same length as an $h=24$ bucket and scattering from the foil only increases the bunch's phase space area in the $\pm\Delta E$ directions, that the Rf voltage can be adjusted so that the shape of the bucket matches the shape of the injected bunch reasonably well.²¹

ϵ at After 2-1 Merge

Also on June 13th, when the 2-1 3.85 GeV cycle was active the ϵ after the 2-1 merge was measured.²² The merge occurs after the last injection while still at the injection field. The measurement was taken with only $h=12$ station K on at $At0+2300$ ms. f_{synch} was 1.273 kHz (20.5 kV) and 5 bunch length measurements had an average of 422.2 ns and σ of 7.7 ns. For an ϵ of 0.187 ± 0.004 eVs (where the uncertainty is from σ). With no growth one would expect the ϵ to be twice what was measured for a matched bunch on the injection porch (0.191 eVs), so there is no apparent growth from the 2-1 merge.

ϵ After Ramp to 3-1 Merge porch

On the same day, just after the previous measurement this ϵ was measured.²³ After the 2-1 merge is complete the AC phase loop is turned on and the beam is accelerated on $h=12$ to the porch where, if configured, a 3-1 merge can take place. The measurement was taken near the end of that ramp where the dB/dt was not yet zero (2.4 g/ms). An average of 6 bunch length measurements was 193.1 ns with a σ of 4.7 ns. With an f_{synch} of 2.727 kHz the ϵ is 0.189 ± 0.008 eVs, so there is no apparent growth from this part of the cycle.

ϵ at the End of the Merge Porch

Although the 3-1 merge was not active at the time the Rf was setup to easily accommodate it. Once the porch was reached the AC phase loop and Rf track were set to hold mode and all the Rf cavities except for station K were zeroed. The average of 6 bunch length measurements made before the loops were turned on and Rf voltage was raised ($At0+2690$ ms) was 339.3 ns with a σ of 6.2 ns.²⁴ With an f_{synch} of 1.172 kHz this gives an ϵ of 0.202 ± 0.004 eVs. This corresponds to a 7% higher ϵ than just before the porch.

ϵ early in the Ramp

For the 3.85 GeV cycle configured to allow switching between the 2-1, 3-1, and 6-3-1 merges on the same user (AU6), the voltage ramps up quickly and nearly to full voltage after the merge porch. Beam control is used for the entire ramp to the flattop. An ϵ of 0.228 eVs (170.4

²¹ See K. Zeno, "[Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Merge](#)", CA/AP/596, December 2017, pgs. 12-15.

²² See [Booster-AGS-EBIS June 13 2019 elog](#) entries from 1622 to 1638

²³ See [Booster-AGS-EBIS June 13 2019 elog](#) entries from 1641 to 1703

²⁴ See [Booster-AGS-EBIS June 13 2019 elog](#) entries from 1713 to 1740

ns, $\sigma=3.2$ ns, 3.42 kHz) was measured at At0+2740 ms, about 20 ms after beam control is turned on and where dB/dt=2.3 g/ms.

Following this, the ramp to high Rf voltage was slowed down and the ϵ was measured again and was 0.210 ± 0.007 eVs (162.9 ns, $\sigma=3.0$ ns, 3.42 kHz).²⁵ In this state, it may ramp too slowly to allow for a lossless 3-1 merge. There is 11% apparent growth from before the merge porch to here. For the 2-1 merge it is not necessary to raise the voltage this much.

This measurement has been taken in previous runs with 6-3-1 and 8-4-2 merges, but in those cases the bunch is already larger than the bucket, so even if there was growth it wouldn't be evident. The measurements here indicate that there is some growth that seems to depend on the rapid increase in the Rf voltage.

ϵ on flattop for 3.85 GeV

For the 2-1 setup on the flattop the average of 10 bunch length measurements was 53.48 ns ($\sigma=1.67$ ns), which with an f_{synch} of 218.6 kHz corresponds to 0.243 ± 0.015 eVs.²⁶ So, the growth from just after the beginning of the ramp (0.210 eVs) to here was about 16% which is about the same as the growth observed last year with a similar setup.²⁷ The Rf voltage early in the ramp was also lowered to 5 kV/gap instead of 7.3kV/gap and the flattop ϵ was measured again.²⁸ No improvement was observed so if was left at the higher voltage.

Table 5 summarizes the results described in this section and Figure 4 is a plot of the ϵ data.

	Time	Length (ns)	σ (ns)	f_{synch} (kHz)	Total ϵ (eVs)	Notes
1	Bstr. injection	10380	-	-	0.0415 ± 0.0005	From $\Delta p/p$ measurement
2	Bt0+18.5 ms	1054	55	4.11	0.0816 ± 0.036	h=4, near end of injection porch
3	Bstr. extraction	264	6.9	0.959	0.0864 ± 0.0045	QP off
4	AGS injection	222.1	5.3	-	0.0956 ± 0.0012	h=24 with $\Delta p/p=1.565e-3$, QP on
5	Injection porch	210.1	3.7	2.612	0.0956 ± 0.0018	After filamentation, h=24
6	After 2-1 merge	422.2	7.7	1.273	0.187 ± 0.004	h=12
7	After 1 st ramp	193.1	4.7	2.727	0.189 ± 0.008	End of ramp to 3-1 merge porch
8	End of porch	339.3	6.2	1.172	0.202 ± 0.004	Before raising Rf voltage
9	Early ramp	162.9	3.0	3.42	0.210 ± 0.007	After raising Rf voltage
10	AGS flattop	52.48	1.67	0.219	0.243 ± 0.015	ϵ to RHIC

Table 5: Emittance measurements at different times in the injectors for the 3.85 GeV cycle while using a 2-1 merge in the AGS. Also included are emittances derived from $\Delta p/p$ measurements at Booster and AGS injection. Uncertainties in ϵ correspond to variations in the bunch length of $\pm \sigma$.

²⁵ See [Booster-AGS-EBIS June 13 2019 elog](#) entries from 1743 to 1821

²⁶ See [Booster-AGS-EBIS June 13 2019 elog](#) entries from 1830 to 1837

²⁷ See [Booster-AGS-EBIS_2019 elog](#) and K. Zeno, "[AGS Longitudinal emittance measurements for upcoming RHIC low energy gold runs](#)", C-A/AP/615, pg. 7.

²⁸ See [Booster-AGS-EBIS June 13 2019 elog](#) entries from 1901 to 1909

BtA Foil Stripping Efficiency

BtA foils 5 and 6 are typically used interchangeably to strip Au³²⁺ to Au⁷⁷⁺ and are located 23.4 ft from the start of BtA. Their stripping efficiencies were measured using BtA multiwire MW060 (located 60 ft from the start of BtA). The large bend (DH2-3), which is downstream of the foil, is used to move the different charge states onto the multiwire. The area of the Gaussian fit of the horizontal profile for each charge state is displayed in the ProfileDisplay application. Then, the fraction of beam that is Au⁷⁷⁺ is found by dividing the Au⁷⁷⁺ area by the sum of the areas for all the (visible) charge states.

One complication is that the profiles for the different charge states overlap. Attempts to reduce the overlapping were made by reducing the $\Delta p/p$ by turning off the Booster merge, by scraping the beam horizontally with the extraction bump, and by adjusting the injection bump timing. Ultimately though the BtA quad QF2 upstream of the stripping foil was adjusted to make the profiles narrower.²⁹ This did not seem to affect the transmission to the multiwire, at least for the normal DH2-3 setting.

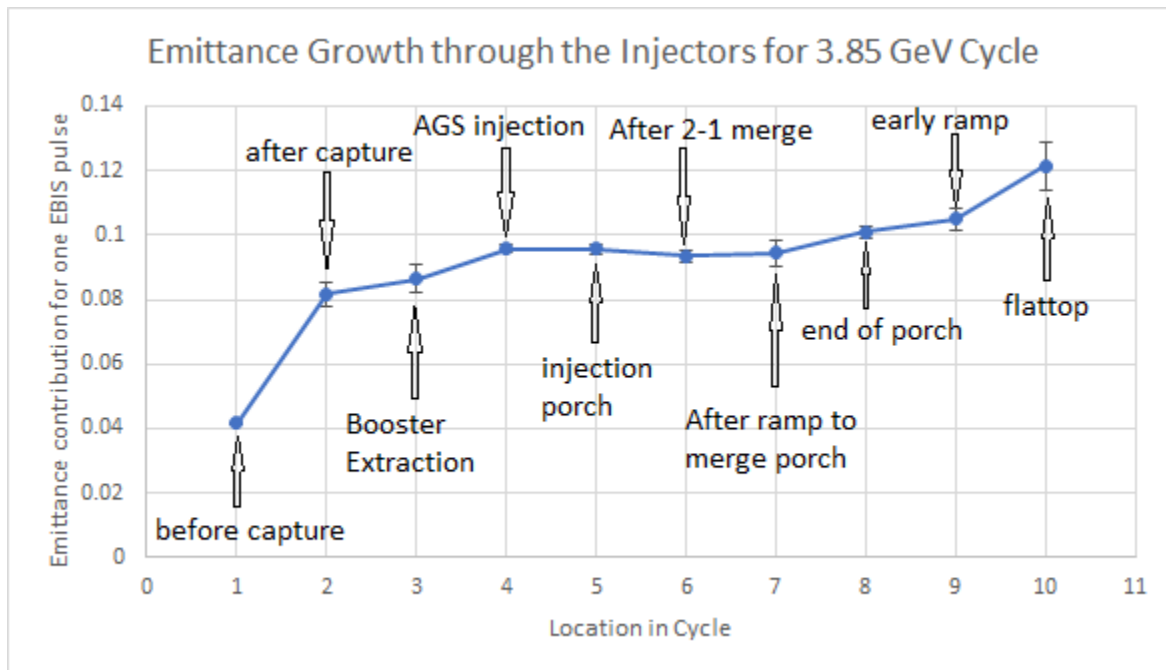


Figure 4: The 3.85 GeV cycle emittance data shown in Table 5. After the 2-1 merge in the AGS the ϵ and error bars are divided by 2 since the ϵ doubling there is expected (locations 6 to 10).

Figure 5 has part of the ProfileDisplay application window which shows an example of a Gaussian fit together with its area. The measured stripping efficiencies to Au⁷⁷⁺ were 63.7% for foil 6 and 63.9% for foil 5 (see Table 6). In 2007, when this type of foil (A1+C) was first

²⁹ See [Booster-AGS-EBIS June 12 2019 elog](#) entries from 1406 to 1428 and associated logged MW060 ProfileDisplay data.

introduced into BtA their measured stripping efficiency to Au77+ was slightly higher (65%).³⁰ Foil 6 was used exclusively this run.

Figure 6 is a composite of 3 different MW060 data acquisitions using foil 6 (though the foil 5 data look very similar). The 76+ and 77+ profiles are from the same acquisition and each of the 75+ and 78+ profiles are from another.

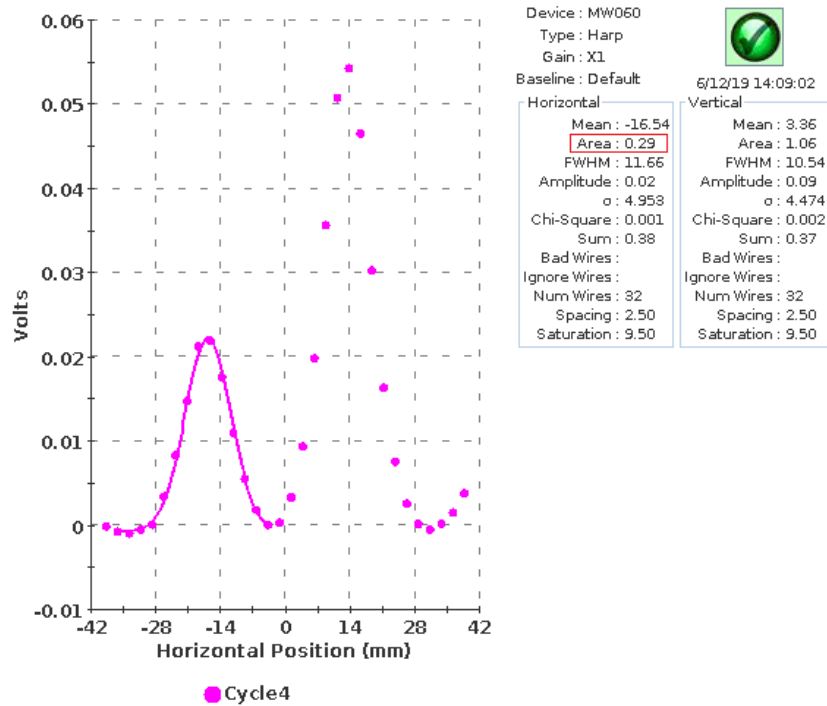


Figure 5: An example of how the area of a Gaussian fit of the profile of a particular charge state appears. Shown here is the Gaussian fit for Au76+ and its area (0.29). The profile to the right of Au76+ is Au77+ and has not been fit in this case. Note that the profiles for 76+ and 77+ do not overlap. To the right of the 77+ profile is the beginning of the 78+ profile. The DH2-3 current would be lowered to move that profile into the multiwire. This is foil 6.

Charge State	DH2-3 (A)	Foil 6 Area	Foil 5 Area
75+	1895	0.054±0.005 (7)	0.05±0 (2)
76+	1867	0.270±0.011 (5)	0.28±0 (2)
77+	1867	0.728±0.015 (5)	0.725±0.005 (2)
78+	1842.5	0.09 (1)	0.08 (1)
Sum	-	1.142	1.135
Area(77+)/Sum	-	0.637	0.639

Table 6: Gaussian fit areas for the only Au charge states visible on BtA MW060 with BtA DH2-3 setting for each case. The number of measurements is shown in parentheses. The uncertainty is the σ for the cases where statistics are available.

³⁰ P. Thieberger et al, “Improved gold ion stripping at 0.1 and 10 GeV/nucleon for the Relativistic Heavy Ion Collider” Phys. Rev. Spec Topics, 2008, pg. 011001-8. However, that was with Au31+ (from Tandem) and had a slightly lower energy.

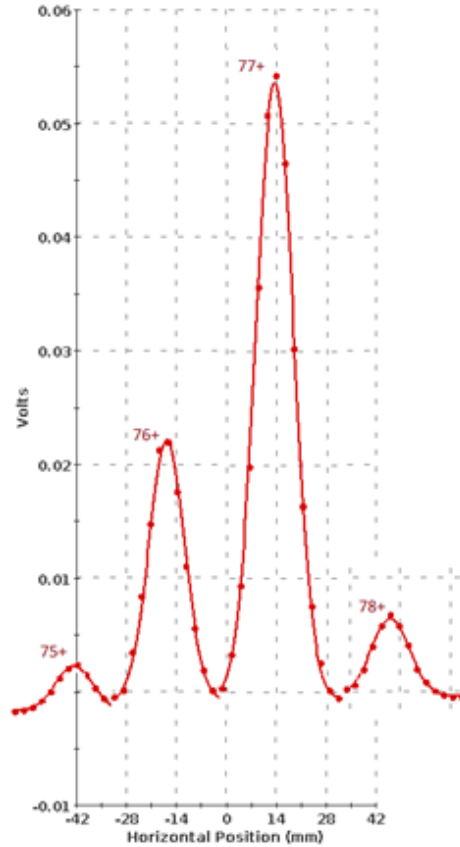


Figure 6: A composite of 3 data acquisitions using foil 6 which shows the relative size of the profiles for each of the 4 visible Au charge states on BtA MW060 as well as their Gaussian fits. The profiles for 76+ and 77+ are from the same acquisition.

As in Figure 6, the data for the 76+ and 77+ areas is taken from the same acquisition. So, if the intensity varied the ratio of their areas would be unaffected. And since only about 12% of the beam is comprised of 75+ and 78+, intensity variations between those and the 76+/77+ measurements should not have a dramatic effect on the 77+ stripping efficiency.

The largest variations in the Booster late intensity scaler during these measurements was about $\pm 3.5\%$. The area of the vertical profile varied by a similar fraction from 1.06 to 1.14 over the course of the seven 76+/77+ measurements. If say, the intensity of the 76+/77+ data was 7% higher or lower for all the 75+/78+ measurements than for the 75+/78+ ones that would change the 77+ stripping efficiency by $\pm 0.5\%$ but evidence from the foil 5 data suggest that the intensity variation is likely less than that (at least for foil 5).³¹

³¹ For the foil 5 data there was only one Booster cycle per AGS cycle so Booster Late is the same as the intensity on that cycle. This data is logged, and the area data can be adjusted to account for any cycle to cycle intensity variations. The σ of the Booster Late over the 5 data sets is 1.2% and the adjusted area data give a stripping efficiency of 63.7% instead of 63.9%. Much of the variation in Booster Late may simply be due to noise. The fact that the area data has only 2 significant digits likely introduces as much uncertainty as the intensity variations do.

Booster to AGS Transfer Efficiency

A couple other factors that affect the BtA transfer were investigated on June 21st for the 3.85 GeV cycle. First, because of the merge employed at the time (12-6), the cogging pattern on the injection porch can be (and was) different than it would be for the more typical 12-6-2 merge.

In the 12-6-2 case there are 2 sets of 6 bunches injected. Except for the last bunch kicked in of each set, each bunch is in the machine when a bunch is kicked into the adjacent bucket just in front of it. The kicker is timed to provide the best transfer efficiency which, because each bunch nearly fills an $h=24$ bucket and the kicker rise time is finite, may entail that when a bunch is kicked into this adjacent bucket that the bunch already in the machine will receive a kick from the rising edge of the kicker.

In the 12-6 case there are 6 sets of 2 bunches each injected. In each set, the first bunch kicked in may receive a kick from the rising edge when the 2nd bunch is kicked in. So, in this case, only half the bunches injected might receive an additional kick instead of 5/6ths of them.³² If this additional kick caused beam loss the transfer efficiency would be better with the 12-6 setup and other than that the setups are essentially the same.

In the 12-6 case, the AGS fast transformer was used to measure the injected intensity when the 1st of the 2 bunches is injected and also when the last of the 2 is injected. The 1st bunch is injected when there is no beam in the AGS and the 2nd is injected 200 ms later when the 1st is still in the machine. If some of the 1st bunch is lost when the 2nd is kicked in one might expect to see some fast loss on the transformer.³³ There is typically no fast loss evident on the slow transformer, but it might be too fast to see on that, so the fast transformer was used.

There was no fast loss visible on the fast transformer at the 2nd injection. However, there still might be a loss that is too fast for the fast transformer to see. If there is such a fast loss the transfer efficiency when the 1st bunch is injected should be higher than when the 2nd is injected. Using a scope, the intensity on the Booster current transformer at extraction was measured on the same Booster transfer as the intensity increase on the AGS fast transformer was measured.

There were 9 efficiency measurements of the first bunch transferred and 5 of the second. Three of those measurements were the average of 10 cycles, each of which I 'weight' as 10 measurements and the others were single measurements. The stability of the EBIS intensity was less than ideal. The average transfer efficiency for the 1st injection was 59.2% and for the 2nd was 57.9%. Table 7 shows the data. The efficiency for the first transfer is slightly higher though it's

³² Specifically, in the 12-6-2 case the cogging pattern is (0, 180, 15, 195, 30, 210, 45, 225, 60, 240, 75, 255) and for 12-6 it is (0, 15, 180, 195, 60, 75, 240, 255, 120, 135, 300, 315) where the numbers are degrees of azimuthal angle around the ring and injection is into $h=24$ buckets which are $360/24=15$ degrees apart. The numbers in red represent bunches that have a kick in the adjacent bucket.

³³ A study on Apr 26, which looked at losses in the integral of the WCM signal for a bunch already in the machine over the period between the turn just before a bunch is injected into an adjacent bucket and 300 μ s later, did not see any loss there. See [Booster-AGS-EBIS 2019](#) Apr 26th 1638 entry.

hard to know if this difference is significant. Because of the averaging over 10 cycles a σ for these measurements is not available.

A 10 AGS cycle average of both the intensity at Booster extraction for the 12 Booster cycles in each AGS cycle and the intensity in the AGS just after the last transfer was measured on the same 10 AGS cycles. The average intensity at Booster extraction for the 10 cycles was 105.58e8 and the average intensity in the AGS after the last transfer was 58.08e8 so this efficiency was 55.1%.

	1 st transfer eff. (%) & B. cycle #		Average of...	2 nd transfer eff. (%) & B. cycle #		Average of...
	58.6	2	1	58.1	5	10
	58.9	2	10	58.2	5	1
	59.9	4	10	57.9	5	1
	58.9	4	1	56.5	9	1
	59.6	4	1	56.8	9	1
	59.1	4	1			
	59.1	4	1			
	58.2	8	1			
	57.3	8	1			
Weighted average	59.2			57.9		
# of measurements			27			14

Table 7: BtA transfer efficiency for 1st and 2nd bunches transferred for the 12-6 merge cogging pattern. Different Booster cycles were used because the EBIS intensity was systematically lower on some cycles, especially the first (cycle 2).

There is a slow loss on the injection porch, and assuming it has a constant value across it, the loss rate is 4.6%/sec using a 10-cycle average of the AGS current transformer with baseline subtracted and measuring the fraction of beam lost during a 600 ms interval (between the 4th and 5th transfers) where no beam is injected (see Figure 7).³⁴ One can also measure the change in amplitude at each transfer, sum all of those, and measure the difference between the baseline and the amplitude just after the last transfer and find the loss rate that way. Using that method, one obtains a value of 4.4%/sec.

The fraction of the beam at Booster extraction injected into the AGS is 59.2 or 57.9% depending on which bunch it is. There are an equal number of ‘first’ and ‘second’ bunches, so the average fraction is 58.55%. Each one of those bunches spends a different amount of time on

³⁴ See [Booster-AGS-EBIS Jun 21 2019 elog](#) 1450 entry. Note that the 1522 entry is the same kind of measurement and gives a beam loss rate of 3.1%/sec, but it was taken while beam was being extracted from the AGS. It has been noticed that when the beam is not dumped at the end of the flattop the BtA efficiency (AGS after last transfer/Booster late) is sometimes better than when it is (see [Booster-AGS-EBIS Jun 12 2019 elog](#) entries 1657 and 1700). This is likely because the dumped beam deteriorates the vacuum on the next cycle and that is likely related to the slow loss. Efficiency measurements are generally taken when the beam is being dumped. Also, the 1801 and 1805 entries are also similar measurements and would be preferable except that the baseline is not subtracted properly on them.

the injection porch before the last transfer occurs and so loses a different amount of beam from the slow loss before that time. If one assumes all the Booster bunches have the same intensity, $105.58e8/12$, then one can estimate that the intensity at the last transfer over Booster Late will be 55.6% (using 4.6%/sec), slightly higher than what was measured (55.1%). A detailed measurement like this was not done with the 12-6-2 setup this run although its transfer efficiency seemed no better than in previous years.

The measured slow loss rate in 2016 for the 12-6-2 setup was slightly higher than measured here (5.2 vs. 4.6%/sec).³⁵ In 2016, when this slow loss was removed from the efficiency calculation the fraction of the beam injected into the AGS for a 12-6-2 setup was estimated to be 55.1% vs. the 58.1% one might expect from the measurements above.³⁶ A typical 12-6-2 efficiency from Booster late to just after the last transfer in AGS is about 52%, as it was in the case referenced here.

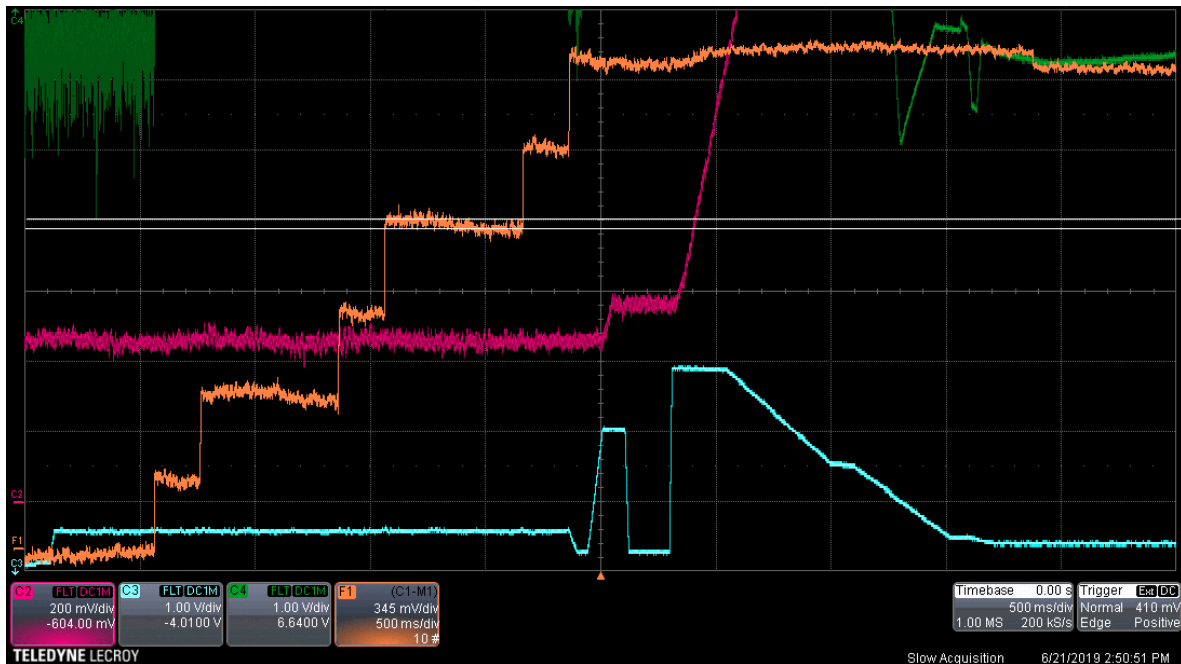


Figure 7: Slow loss rate measurement in the AGS. The orange trace is the AGS normalized transformer with baseline subtracted, the red trace is the AGS main magnet current, and the blue trace is the AGS Rf vector sum. The bright white horizontal lines are placed to measure the beam loss between the 4th and 5th injections which occur 600 ms apart. The measured loss is 45 mV out of 1622 mV ($\sim 1.8e9$ ions) or 4.6%/sec. Sweep speed is 500 ms/div. The trigger is at At_0+2400 ms.

The transfer efficiency does seem better with 12-6 than 12-6-2 (55.1 vs. 52%). Perhaps the effect of the additional kick not only causes a fast loss but also more slow loss. This is not

³⁵ See [Booster-AGS-EBIS Apr 27 2016 elog](#) 1814 entries.

³⁶ Since for 12-6-2 ten out of 12 bunches might be affected by a 2nd kick the transfer efficiency one might expect is $(59.2+5*57.9)/6=58.1\%$. For the 12-6-2 slow loss measurement from 2016 see K. Zeno, “[Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Merge](#)”, CA/AP/596, December 2017, pgs. 13-14.

hard to imagine since if some beam is kicked out due to the additional kick, other beam that (initially) survives it must have its transverse ϵ increased and that beam is therefore more likely to be lost as it sits on the porch. The slow loss rate for 12-6 is roughly consistent with the measured single transfer efficiency, but the rate measured for 12-6-2, although it is larger, would have to be larger still to be consistent with the expected single transfer efficiency for that coggling pattern (58.1%).

Performing only a 3-1 Merge in the AGS

When just the 3-1 type merge is used in the AGS, the beam is injected into every other $h=24$ bucket so when a bunch is injected the adjacent bucket is never populated. Those bunches are then ‘rebucketed’ into $h=12$ and ramped to the merge porch where the 3-1 merge is performed. If it’s true that the coggling pattern affects the overall transfer efficiency, then one would expect it to be at least what it is with the 2-1 (12-6) merge. Unfortunately, a detailed study required to measure differences on this level was not performed with the 3-1 merge.

The A5 kicker pulse is at least $1.0 \mu\text{s}$ long³⁷ and an $h=24$ bucket at injection energy is $0.256 \mu\text{s}$ long or roughly a quarter of that. So, the time from when the kicker starts to rise until when it has fallen spans 4 buckets. Since the 12 bunches are injected into every other $h=24$ bucket for a 3-1 type merge, when the 12th bunch is kicked in there will be a bunch 2 buckets behind and one 2 buckets ahead of it. This means the kicker has only about $0.75 \mu\text{s}$ to rise, kick the bunch in, and fall. This is less than the length of the pulse, so when that bunch is kicked in a bunch in the machine will be kicked out. The bunches already in the machine are about 200 ns wide which buys another 100 ns but it’s still not enough.

So, this 3-1 merge provides only 3 bunches with the full intensity on the flattop. It is possible to inject 11 bunches (instead of 9) and have 3 merged bunches at full intensity and 1 at two-thirds intensity. When this was set up for 3.85 GeV the ϵ of the full 3-1 bunches was 0.43 eVs, but the ϵ of the other bunch was only 0.30 eV-s.³⁸ This is not much more than two-thirds of the ϵ of the full 3-1 bunches.

The ϵ for the full 3-1 bunches was eventually brought down to 0.37 eVs, but the ϵ of the other bunch was not measured in that state. Figure 8 is a mountain range display of the 3-1 merge when the full 3-1 flattop ϵ was 0.37 eVs.³⁹ It is evident that the merged bunch on the left, which results from merging only 2 bunches, is significantly narrower than the middle 2 which are composed of 3. For the merged bunch on the right there are 3 initial bunches but the one on

³⁷ See [Booster-AGS-EBIS Jun 30 2019](#) 2101 entry for example.

³⁸ See [Booster-AGS-EBIS Jun 4 and 5 2019 elogs](#)

³⁹ See [Booster-AGS-EBIS Jun 6 2019 elog](#) entries from 1825 to 1838. The MR display can be found in the 1829 entry on Jun 6th. In that display also note also that the bunch on the right is merged from 3 but the 1st of those 3 bunches has lower intensity and the merged bunch is also smaller.

the left has less intensity than the others. That merged bunch also looks narrower but has larger tails than the merged bunch on the left.

The behavior of this merge with only 2 initial bunches is reminiscent of the 8-4-2 merge used with He3+ in 2014. Because of kicker constraints then as well, a modified 6-3-1 type merge was used with only the inner 4 buckets populated without leading to ϵ growth. However, this is different in the sense that the bunches populated the buckets symmetrically then and here they do not.⁴⁰

If the adjustments which brought the ϵ down to 0.37 eVs also brought the ϵ of the bunch made from only 2 initial bunches down proportionately its ϵ would be 0.26 eVs, which is nearly the same as what was measured with the conventional 2-1 merge (0.25 eVs). Also, 0.37 eVs is 3/2 of the measured 2-1 ϵ on the 3.85 GeV flattop suggesting that the 3-1 merge is not causing significant ϵ growth.

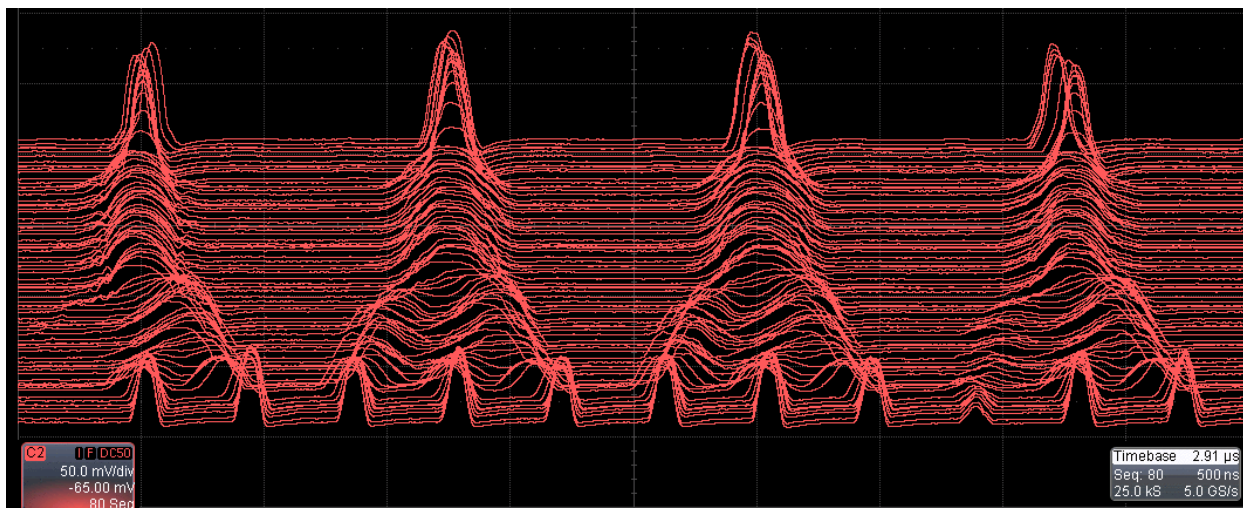


Figure 8: The 11-4 merge in the AGS on a mountain range display of the WCM.⁴¹

In order to provide 4 final bunches, each of which is the result of the merger of 3 bunches, C. Gardner suggested a merge using $h=24, 12,$ and 8 that could be performed at injection energy. It uses station KL for $h=8$, which is tuned to run on the merge porch but still can run at injection energy. I. Zhang set this up for 3.85 and 4.59 GeV.⁴² An ϵ measurement using this merge for 3.85 GeV was 0.50 eVs. This is higher than what was measured for the normal 3-1 merge, but it may have been improved after this measurement. It appears that the

⁴⁰ See K. Zeno, [Overview and Analysis of the 2016 Gold Run in the Booster and AGS](#). C-A/AP/571, September 2016, pgs. 37-40.

⁴¹ From [Booster-AGS-EBIS 2019 elog](#) Jun 6 1849 entry.

⁴² See I. Zhang's (Zane) entries in [Booster-AGS-EBIS 2019](#) Jun 4th, 14th, and 17th and July 10th elogs. The ϵ measurement is from the June 17th 1236 entry.

station KL voltage was noisy during this setup, since it was tuned for a higher frequency, which may have contributed to the higher ϵ .⁴³

Transverse Emittances in the Injectors

BtA

On June 24th the transverse emittances were measured in BtA using the MW006 multiwire under typical running conditions. Although no intensity dependence has been observed for Au32+ from EBIS, just for the record Booster Late was 1.11×10^{10} ions, or about 9.3×10^8 ions per Booster cycle. The full widths at half maximum (FWHM) of their Gaussian fits were $\Delta x = 5.17$ mm and $\Delta y = 8.21$ mm and using $\beta_x = 3.0$ m and $\beta_y = 16.0$ m at the multiwire the unnormalized 95% ϵ_x was $(2.08\Delta x/2)^2/3.0\text{m} = 9.63$ mm mr and $\epsilon_y = (2.08\Delta y/2)^2/16.0\text{m} = 2.25$ mm mr. These correspond to normalized 95% ϵ_x of 4.77 and ϵ_y of 2.25 mm mr. The normalized 1σ or RMS emittances are $\epsilon_x = 0.80$ and $\epsilon_y = 0.38$ mm mr where $\beta\gamma$ is 0.495. As can be seen in Figure 9, the profiles are reasonably Gaussian although the core looks a little denser than Gaussian in both planes.

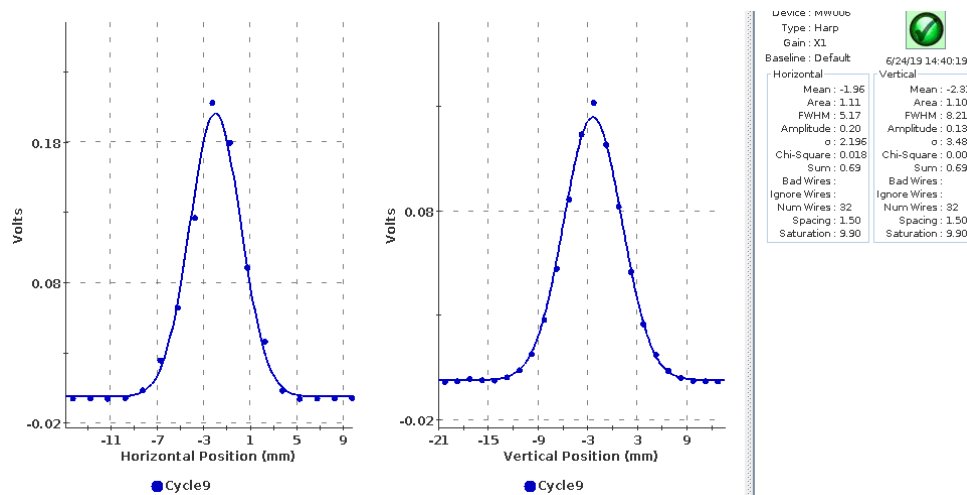


Figure 9: BtA MW006 multiwire profiles for Au32+ under typical running conditions.

Q_x and Q_y are close to each other at Booster extraction and if the set tunes are crossed just before extraction the normalized 95% ϵ_x becomes 2.24 mm mr and $\epsilon_y = 5.22$ mm mr. These values for ϵ_x and ϵ_y are close to those obtained above for ϵ_y and ϵ_x , respectively. That the values are similar but interchanged is a check on some level that the β function values for x and y are not unreasonable. Figure 10 shows the profiles after the tune change.

In Figure 10 the vertical profile appears to be quite far from Gaussian and the horizontal fit is very good. If only the core of the vertical profile is fit to a Gaussian, its FWHM is much

⁴³ See I. Zhang's [Booster-AGS-EBIS Jun 14th 2019](#) 1122 entry.

smaller than that of the fit to the entire profile (11.31 vs. 4.91 mm, see Figure 11). I would think this is some side effect of the tunes crossing since the horizontal profiles on MW060, where the horizontal profile is wider, are quite Gaussian (see Figures 5 and 6). If the tunes do not cross one might expect ϵ_x to be larger than ϵ_y because the multiturn injection process occurs in the horizontal plane and that is what's observed here.

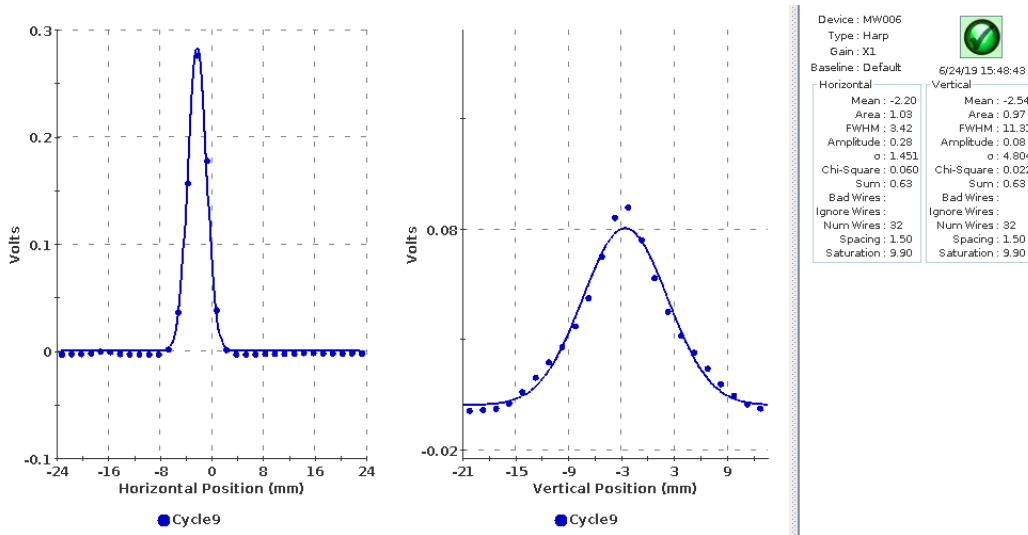


Figure 10: BtA MW006 multiwire profiles for Au32+ with Q_x and Q_y crossing just before extraction.

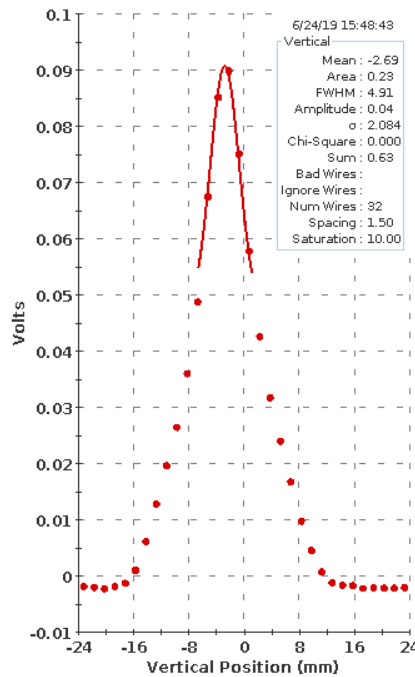


Figure 11: BtA MW006 multiwire vertical profile for Au32+ from Figure 9 except here the Gaussian fit is only of the center of the profile.

AGS Injection

AGS (ion) IPM emittance measurements from June 24th of the 12-pulse 3.85 GeV cycle on the 2400 ms long injection porch show significant growth in the vertical (see Figure 12). However, if the first beam is injected around 1200 ms after it is normally injected its measured emittance is the same at that time as it would have been if injection had begun at the normal time (see Figure 13). It is hard to imagine a physical mechanism that could account for this behavior although when the Rf is off on the porch there is not any apparent growth.

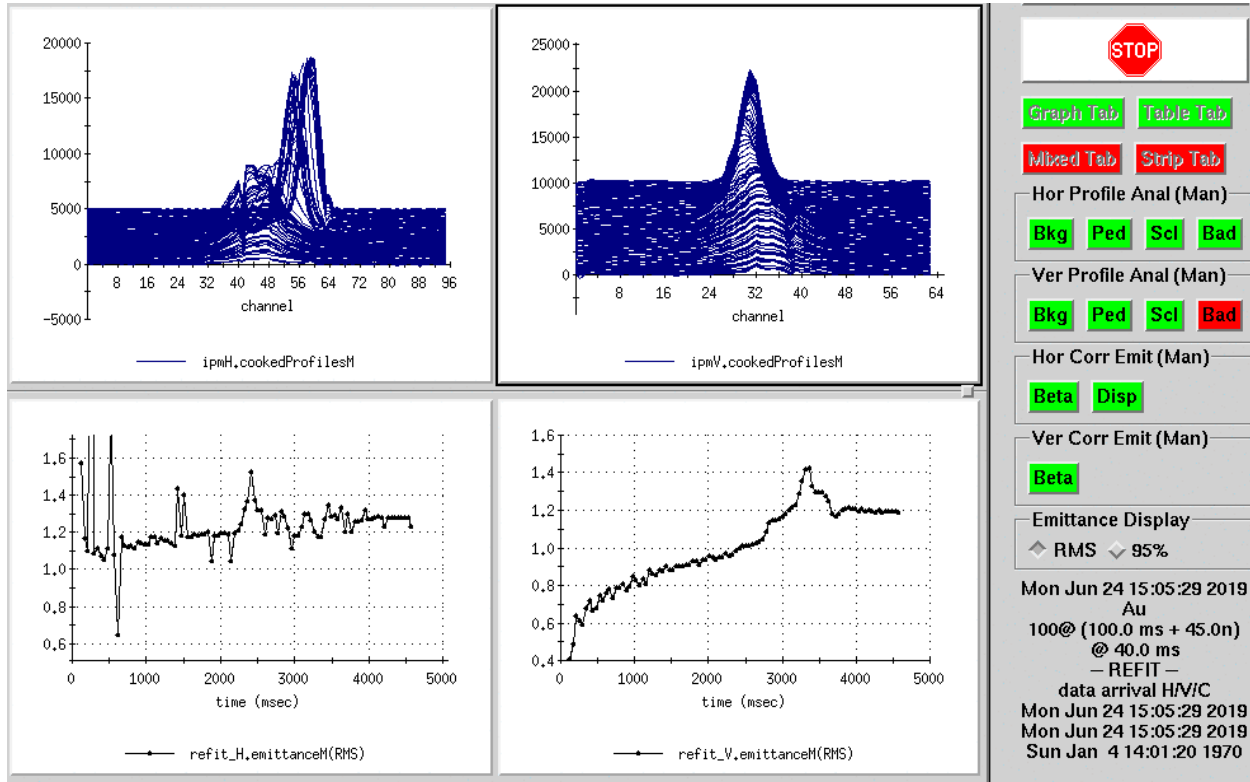


Figure 12: AGS IPM rms emittance on the 12 pulse 3.85 GeV cycle showing (apparent) emittance growth on the injection porch (which ends around 2400 ms).⁴⁴

As can be seen from Figure 14, the vertical profile just after the beam is injected at the normal time ($A_{t0}+120$ ms) is noisier than when it is injected 1200 ms later ($A_{t0}+1290$ ms) even though the intensity is likely about the same. Whatever the mechanism (was the baseline taken with the Rf off?), the profile when the beam is injected later is much cleaner. Even after this time the measured ϵ_y continues to increase from about 0.85 to 1.0 mm mr at the end of the porch. There was no attempt made to see what ϵ_y is reported if the first injection is moved even later. The horizontal profile is also less noisy when it is injected later.

⁴⁴ See [Booster-AGS-EBIS June 24, 2019 elog](#) 15:05 entry

Figure 15 shows what the vertical profile looks like at At0+120 ms just after the first injection at the normal time but with the Rf off. That profile looks a lot like the profile at At0+1290 ms in Figure 14. When the Rf is off the IPM program reports that ϵ_y is about 0.6 and ϵ_x is about 1.45 mm mr at the beginning of the porch and 0.7 and 1.45 mm mr just after the last transfer.⁴⁵ In the case where the Rf is on ϵ_x and ϵ_y are 1.2 and 0.95 mm mr, respectively, just after the last transfer (~2260 ms, Figure 12).

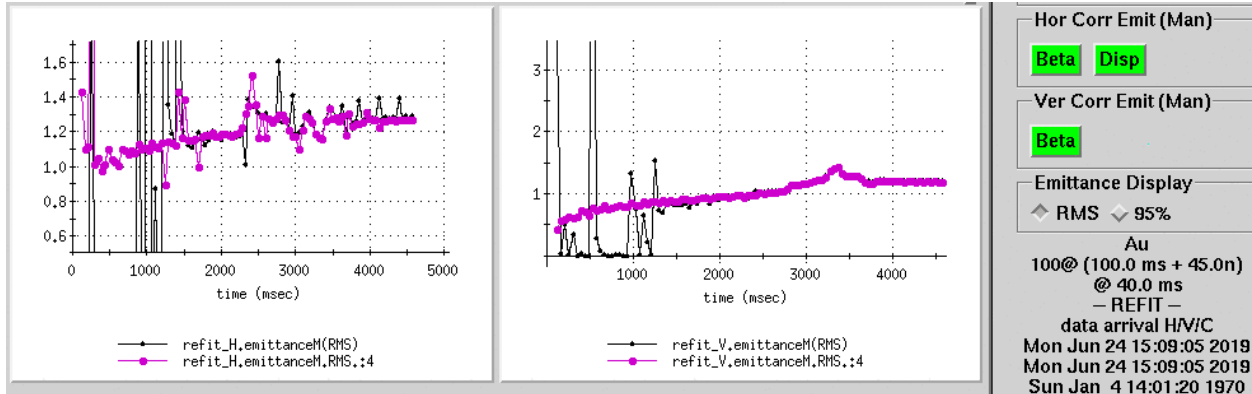


Figure 13: AGS IPM rms emittance on the 12 pulse 3.85 GeV cycle. The purple trace is when the first injection occurs at about 60 ms after At0 and the black trace is when it occurs 1260 ms after At0. Note that when it is injected later its emittance is the same as if it had been sitting on the injection porch for 1200 ms.⁴⁶

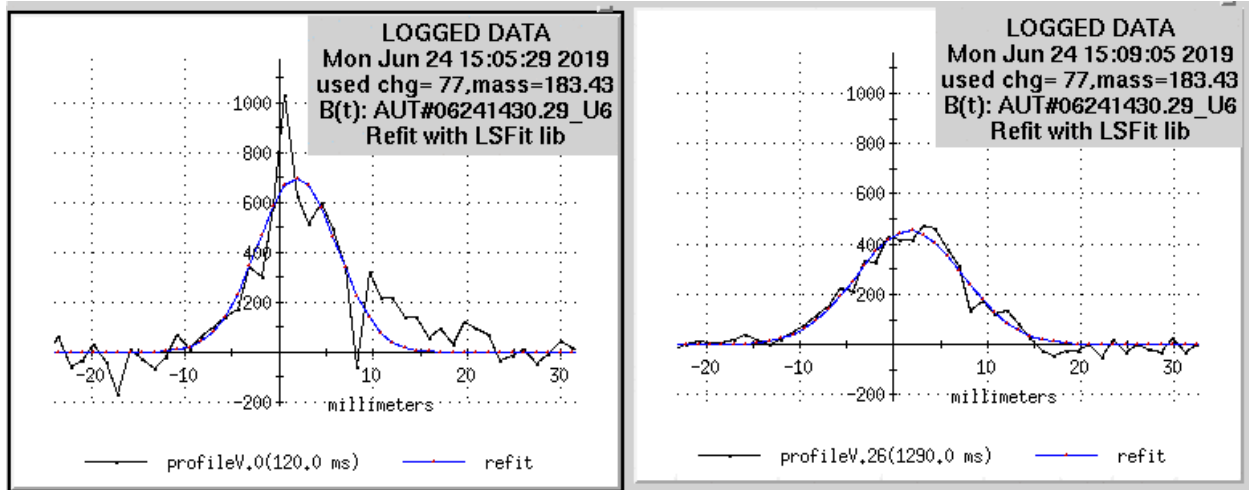


Figure 14: Vertical AGS ion IPM profiles and fits of the first bunch injected when injection occurs at the normal time (left, At0+60 ms, profile at 120 ms) and when it is injected 1200 ms later (right, profile at 1290 ms). The scales are approximately the same.

⁴⁵ See [Booster-AGS-EBIS June 24, 2019 elog](#) 15:12 entry.

⁴⁶ See [Booster-AGS-EBIS June 24, 2019 elog](#) 15:11 entry

If one considers the total ε , defined as $\sqrt{\varepsilon_x^2 + \varepsilon_y^2}$, with 12 transfers, its value after the last transfer is 1.61 mm mr with Rf off and 1.53 mm mr with Rf on. So, since the Rf on case is suspect early in the cycle, the growth can perhaps be estimated using the Rf off case since both cases roughly agree after the last transfer. The Rf off case indicates that there is 2.6% growth in total ε between these 2 times. This suggests only a little growth up until that point except from what might occur from an injection mismatch.

The fact that the ε indicated in the AGS is larger than in BtA is not necessarily due to an injection mismatch since the stripping foil lies between MW006 and the AGS. In the Rf off case, ε_x is larger than ε_y at MW006 and in the AGS just after injection. The growth in ε_x between those two places is $1.45/0.80=1.81$ and in ε_y it is $0.6/0.38=1.58$ (using foil 6).

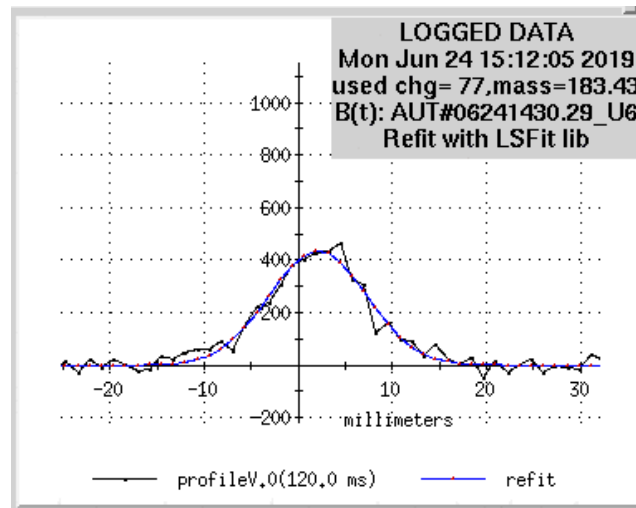


Figure 15: AGS ion IPM profile and fit of the first bunch injected when injection occurs at the normal time (At0+60 ms, profile at 120 ms) and the Rf is off.

The AGS eIPM doesn't look at all the bunches so I was unable to perform the same measurements with it. However, on the injection porch ε_y appears to grow as well from 0.7 to 1.6 mm mr except when the Rf is off in which case it remains constant at about 0.7-0.8 mm mr.⁴⁷

AGS Flattop

Table 8 shows representative emittances at the end of the injection porch and on the flattop using the ion IPM for different setups. Although there is not a clear trend ε_x at the end of the injection porch may be slightly larger for cycles with the longer 12-transfer porch. Although it is not clear if there is growth from the end of the porch to the flattop for the 3.85 and 4.59 GeV cycles, it is clear that it occurs for the 7.3 and 9.8 GeV cycles.

⁴⁷ See [Booster-AGS-EBIS June 26, 2019 elog](#) entries 1955 to 1959.

Should beam from the profile to the right of the main profile on EtB MW096 be included in Booster Input?

There is typically a profile visible to the right of the main Au32+ profile on EtB multiwire MW096 located at a high dispersion point between the 2 magnets that comprise arc146 (see Figure 16). The xf108 current transformer, used for Booster input, sees current from this beam if it is not collimated out.⁴⁸ The collimator was inserted for this run so that its profile was not visible and xf108 only saw current from the main Au32+ beam. Naively it would seem unlikely, but one nagging question has been, is this extra profile Au32+ at a different energy? It could be that the EBIS Rf has been configured improperly and if configured properly that beam could be incorporated into the main Au32+ beam (EBIS personnel did not discount the possibility that it could be Au32+).⁴⁹

Energy (GeV)	Date and Time	ϵ_x @ inj.	ϵ_y @ inj.	ϵ_x @ flattop	ϵ_y @ flattop	Final Bunch Intensity	Merge	Cycle type
3.85	Mar 15, 15:21:15	1.05	0.92	1.0	0.92	0.82e9	6-3	6 transfer
	Apr 12, 16:23:10	1.25	1.05	1.16	1.1	0.87e9	6-3	6 transfer
	May 6, 13:52:31	1.15	1.15	1.1	1.05	0.92e9	6-3	6 transfer
	Jun 12, 15:59:00	1.25	1.0	1.29	1.20	0.94e9	12-6	12 transfer
4.59	July 5, 22:44:57	1.30	1.13	1.26	1.08	0.95e9	12-6	12 transfer
7.3	Jun 17 19:15:26	1.18	0.95	1.5	1.4	2.7e9	12-6-2	12 transfer
9.8	Jul 8 18:48:15	1.34	1.03	1.5	1.45	2.7e9	12-6-2	12 transfer

Table 8: AGS ion IPM at the end of the injection porch and flattop transverse RMS emittance measurements for different setups (in mm mr using Refit option). For the flattop, all but one of these (4.59 GeV) are obtained after turning the Rf off because those measurements are more accurate with debunched beam. The 4.59 GeV flattop emittances shown here are 10% lower than measured with Rf on, (1.4, 1.2) mm mr, since there is about a 10% reduction when the Rf is shut off for 3.85 GeV. When the Rf is turned off for 7.3 GeV, the flattop ϵ_x is about 2.1 not 1.5 mm mr, but before the Rf is shut off it is the same as it is for 9.8 GeV, which drops from about 2.7 to 1.5 mm mr when shut off. So, the actual flattop ϵ_x should be close to what it is in the 9.8 GeV case. The values are from logged data with the indicated date and time, and most instances are also shown in the elog.

On May 13th an attempt was made to put this question to rest. If that beam could be injected into the Booster and accelerated on the nominal magnet cycle it would likely be possible to answer it. In order to do so, the EtB arc146 was raised from 2218A to 2248A to move that profile to the same position that the main profile normally occupies on MW096. Once the injection field was raised 6 g and the inflector lowered from 59.78 to 59.38 kV spiraling beam was visible on the injection transformer.⁵⁰ Although bunching was visible on the D1 PUE sum signal as well, if the phase loop was turned off that bunching disappeared. Then the injection f_{rev}

⁴⁸ See K. Zeno, “[Run 18 in the Injectors](#)”, C-A/AP/610, pgs. 24-25 for more on this.

⁴⁹ E. Beebe, private communication.

⁵⁰ See [Booster-AGS-EBIS May 13, 2019 elog](#) 1918 entry.

was lowered from 96650 to 95000 Hz and the beam bunched with the loop off. In this state the beam survived for about 20 ms (the magnet starts to ramp about 8 ms after injection).

At this point, the charge state the Rf system uses to calculate f_{rev} as the magnet ramps was changed from 32 to 31. The charge state is used by the low level Rf system to calculate the frequency required to keep the beam's radius constant as the B field changes. If it is wrong the beam's radius may eventually move far enough from R_0 that the beam will be lost. After changing this parameter, the beam survived for more than 50 ms (see Figure 17).⁵¹

So, this beam appears to be Au31+ not Au32+, and its presence is not due to a misconfiguration of the EBIS Rf. It is just another Au charge state coming from EBIS and collimating it out so that the xf108 signal does not include current from it is appropriate. Although the size of this profile varies (over days), when this study was done collimating it out reduced Booster input by about 4-5%, which changed the Booster efficiency (Booster Late/Booster input) from 82 to 86%.

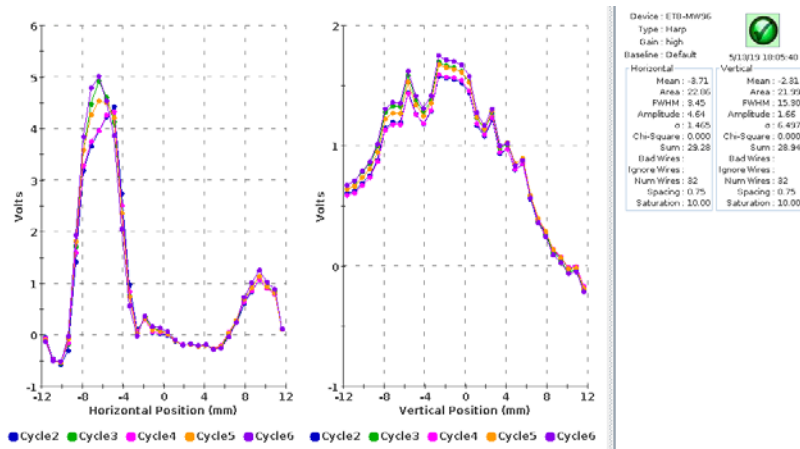


Figure 16: EtB Multiwire MW096 showing main Au32+ profile centered around -6 mm and the other profile centered around +9 mm. This is with the collimator retracted so that the profile on the right is visible.⁵²

Baby Bunches and $h=10$

For 7.3 GeV, the RHIC bunch intensity and longitudinal emittance requirement of $2.1e9$ and 0.3 eVs could not be provided by the injectors. Beyond that, just to fit an entire bunch from the AGS into a RHIC bucket its ϵ would need to be about 0.5 eVs.⁵³

The fully squeezed ϵ of about 0.69 eVs had a bunch intensity sometimes as high as $2.8e9$, but usually much lower. The longitudinal emittance can be reduced by relaxing the bunch

⁵¹ This is accomplished by changing the ADO parameter “charge state” on the Booster/Rf/914-rfl11/dsp_4 page from 32 to 31.

⁵² [Booster-AGS-EBIS May 13, 2019 elog](#) 1805 entry.

⁵³ See C. Gardner, [Booster-AGS-EBIS April 5, 2019 elog](#) 1320 entry.

squeeze after the 3-1 merge, but this doesn't increase the resulting bunch's brightness which, it seems, is the figure of merit.

During the beginning of the Run the bunch squeeze was relaxed to provide bunches that come closer to fitting into the RHIC bucket since having a lot of unbunched beam is perhaps not the best way to run. When the bunch squeeze is relaxed the beam that doesn't go into the main buckets winds up in satellite, or baby, bunches. Figure 18 shows the percentage of beam in the baby bunches during RHIC fills in the 7.3 GeV run. Note that up until April 12th or so it was

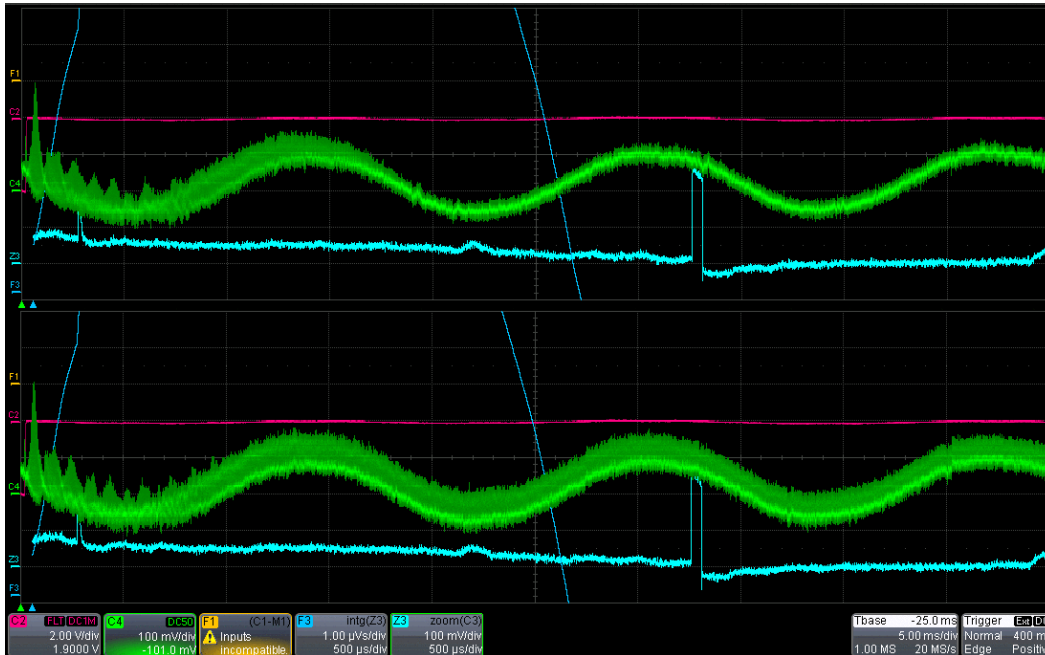


Figure 17: The Booster D1 PUE sum signal (green) with the Au charge state set to 32 (top) and set to 31 (bottom). In the top signal there is no bunching evident after about 20 ms from injection (which occurs at the far left). On the bottom signal bunching is evident throughout the 50 ms shown in the display. The sweep speed is 5ms/box.

around 11 or 12%. This is because the bunch squeeze was relaxed at that time. Afterwards it was decided to use the full bunch squeeze even though the bunch was larger than the RHIC bucket.

This was the configuration for most of the next month, where the baby bunches averaged 4-5%, and were sometimes as low as 3-4%. This also represents typical 9.8 GeV running since the cycles are basically the same, it's just that 9.8 GeV goes to a higher field.

Usually the size of these baby bunches is mainly determined by the quality of the Booster merge and the energy match between bunches injected into the AGS and the AGS Rf. The Booster extraction energy tends to drift, which is most likely a result of the extraction field drifting which causes the Booster to AGS energy match to drift (the Rf frequency at extraction is constant because of BtA synchro).

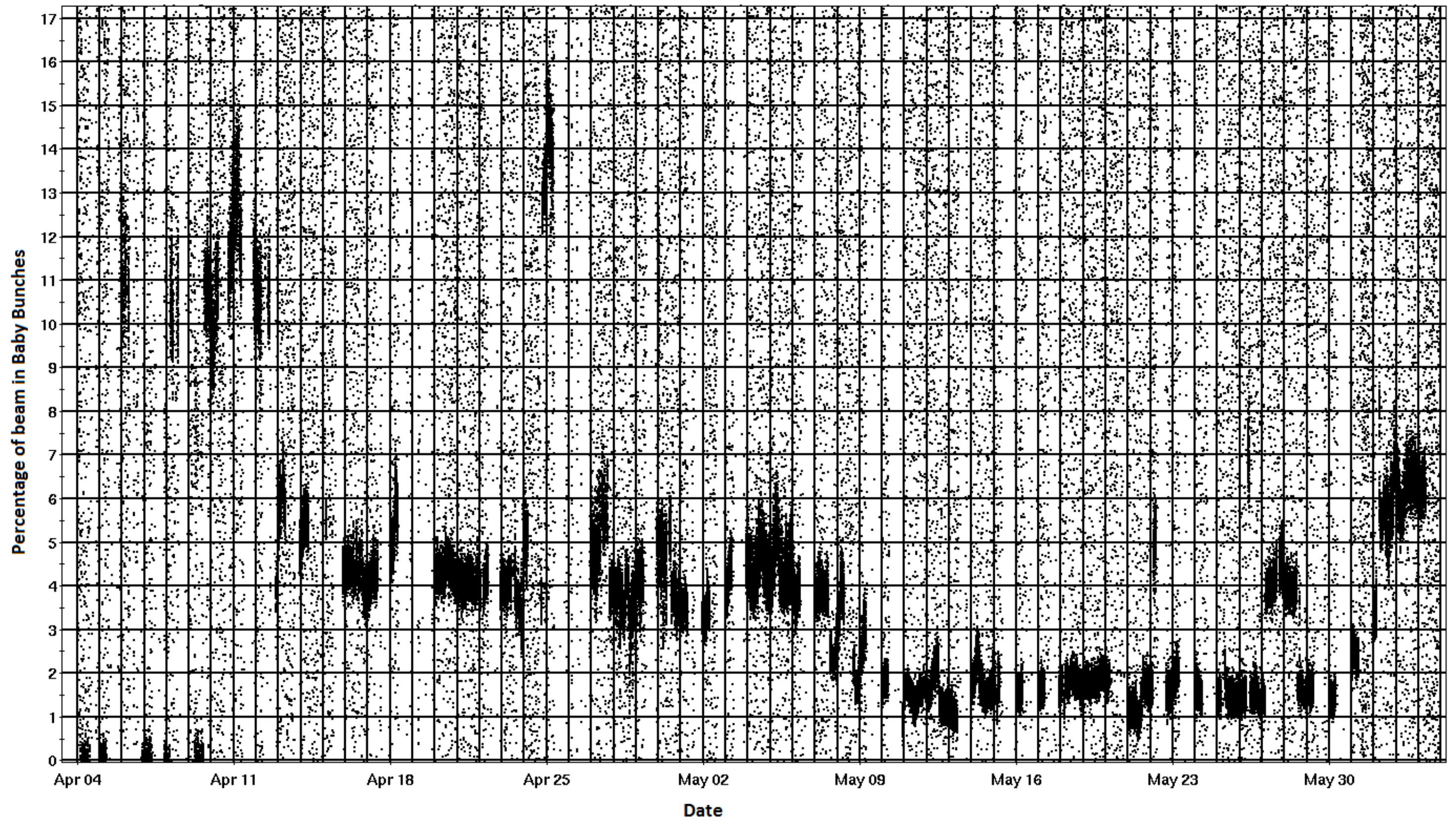


Figure 18: The percentage of beam remaining in baby bunches during RHIC fills in the 7.3 GeV Run. The randomly scattered black dots are between fills where the measurement doesn't work and should be ignored. Between April 4th and 9th there are some periods with little or no baby bunches, those measurements are in error.

On May 7th the AGS accelerating harmonic was switched from h=12 to 10, It is easier for the merged (and squeezed) bunches to fit into h=10 buckets because they are wider and so there was less beam in the baby bunches (1-2%) from that time until June 1st when the A6 (h=2) Rf cavity in the Booster failed. The E6 cavity was used in its place, but the quality of the bunch merge could not be restored to what it was with A6.

Note also that the baby bunches were larger on May 27-28th because AGS Rf station KL was off during this time. Station KL is used for the 3-1 merge and bunch squeeze, but still the baby bunches were not any larger than when the full squeeze and nominal merge were used with h=12 (3.5-4.5%). The higher baby bunch intensity on April 25th was because the squeeze was relaxed.

Perhaps surprisingly the measured ϵ on the flattop did not change noticeably when using h=10. Naively one might expect it to increase since more of the squeezed bunch fits into h=10 than h=12 buckets. Perhaps the increase was just too small to see, or since the mechanism for growth on the ramp is not understood, the growth might be less with h=10. However, the flattop ϵ is more sensitive to variations in the AGS injection energy match with h=10 because there is more room in an h=10 bucket for a larger bunch to fit.⁵⁴

Figure 19 shows the AGS to RHIC transfer efficiency for the fills during the 7.3 GeV run together with when the switch from h=12 to h=10 occurs. When h=10 was used the baby bunch intensities were about 1.5% instead of about 4.5% of the total intensity. So, since there are 2 bunches destined for RHIC on the flattop, the intensity of each of those would be about $(4.5\% - 1.5\%)/2 = 1.5\%$ higher with h=10 and if that extra beam were injected into RHIC buckets the bunch intensity in RHIC would also be 1.5% higher. Since the flattop intensity includes the intensity of the baby and RHIC bunches the transfer efficiency, as it's defined here, would be 1.5% higher as well. Given all the other things going on it would be hard to see that difference even if it was there and it is not apparent.⁵⁵

Tandem Au31+ in the Injectors

Given the plan to use Tandem for the 5.75 GeV run next year it seems worthwhile to go over the work that was done with Tandem Au in some detail. In Run 16 Tandem was used for a

⁵⁴ See [Booster-AGS-EBIS May 8, 2019 elog](#) entries from 1819 to 1857.

⁵⁵ There was a problem with the AGS Late (or xcbm) scaler where it consistently read about 3% high during the first two thirds or so of the 7.3 GeV run. On May 16th, after fill 23477, the V to F convertors for the injection and extraction scaler channels were switched and the problem stopped occurring. See Iris's Zhang's 0933 entry in the May 16th [Booster-AGS-EBIS 2019 elog](#). I confirmed that it stopped happening by comparing logged data for the AGS before transition and the AGS late scalers throughout the 7.3 GeV Run. Prior to that the AGS before transition scaler was calibrated to reflect the flattop intensity. After the fix the scaler gain was adjusted so that AGS Late was calibrated correctly. Prior to that, AGS late read about 3% higher than before transition. In the figure, the transfer efficiency data up to fill 23477 has been multiplied by 1.03 to correct for this. See also, May 14th [Booster-AGS-EBIS 2019 elog](#) entries from 1345 to 1424.

few days to supply RHIC with beam. This was because of an EBIS failure and so the setup was done without any planning and as simply as possible.

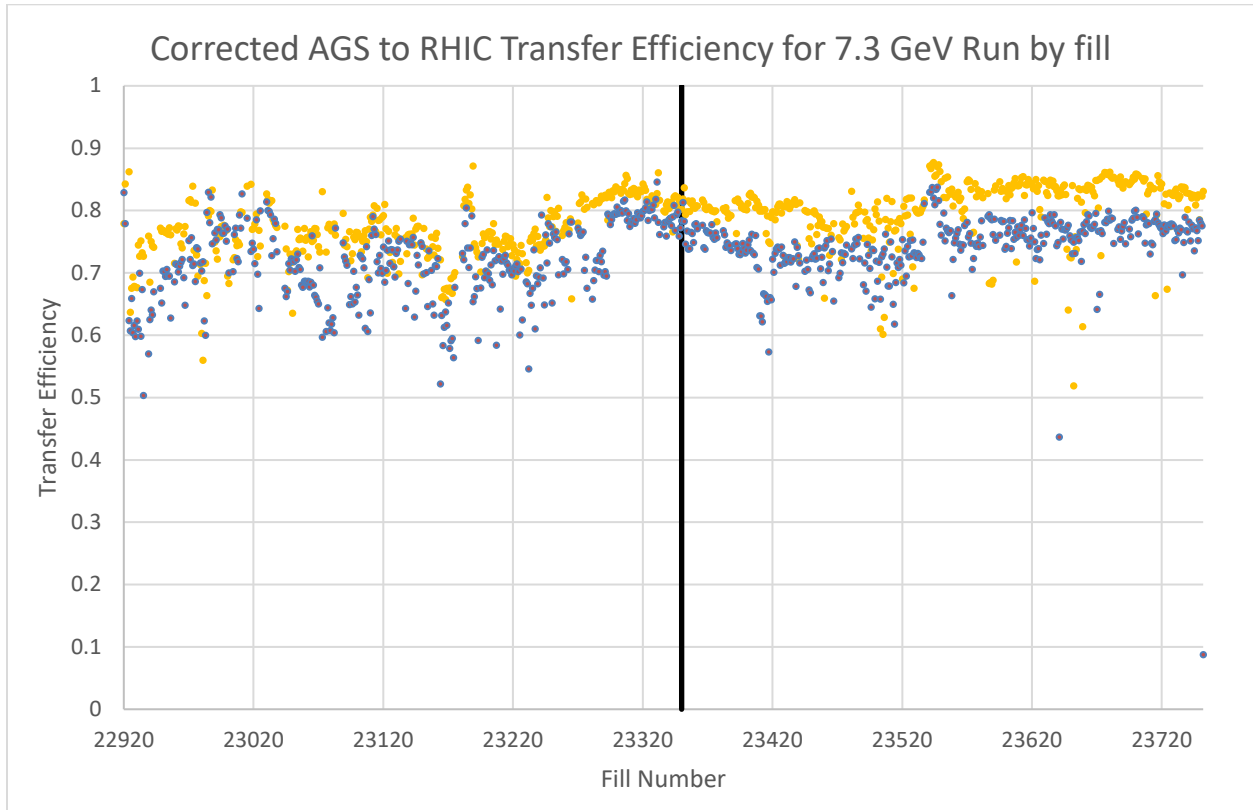


Figure 19: Fill number vs. average blue and yellow transfer efficiency from AGS to RHIC during the 7.3 GeV run. Each dot corresponds to a fill of the respective ring (typically 111 bunches). The transfer efficiency is defined here as (average RHIC bunch intensity) / (average AGSxcbm/2). The AGSxcbm is the AGS flattop intensity during the fill of that ring. The black vertical line signifies when the switch from $h=12$ to $h=10$ occurred (fill 23350). The data is taken from FDAView. Fill 22920 occurs on April 4th and fill 23752 on June 3rd. The yellow bunch data is in yellow and the blue bunch data is in blue.

One complication with using Tandem instead of EBIS is that the 4-2-1 Booster merge cannot be used because the lower f_{rev} at Booster injection requires the Rf harmonic there to be 6 or higher. In Run 16, a 6-2-1 merge was used with injection initially occurring into $h=24$ buckets. The BtA efficiency was poor and the baby bunches were large. The reason for this is thought to be the poor quality of the bunches coming from the Booster due to this merge.⁵⁶ A 3 to 1 merge was used in the AGS which, for 6 Tandem requests, provided 2 bunches for RHIC each AGS cycle.

This run a 6-3-1 merge, analogous to the one used in the AGS was employed to improve the bunch quality. The details of this merge have been described elsewhere.⁵⁷ It was also set up

⁵⁶ See K. Zeno, “[Run 16 Tandem gold performance in the injectors and possible improvement with AGS type 6:3:1 bunch merge in the Booster](#)”, C-A/AP/576, pgs. 2-5.

⁵⁷ See [ibid](#), pgs. 8-10 for a description of the merge.

in Run 18 using EBIS Au32+ to see if it would work, and it did, although those merged bunches were not injected into the AGS.⁵⁸

Another potential issue with Tandem beam is that if the Booster merge problem were resolved, space charge could become a problem in the AGS because of the lower ϵ and higher intensity available from Tandem. The bunch intensity on the AGS injection porch has the potential of being 3 or more times higher than what it is using EBIS.

It might be possible to reach the 5.75 GeV requirement of 1.45e9/bunch without a merge in the AGS, but that would require everything to work optimally. A more practical choice, performing a 2-1 merge in the AGS, was used during this run (AGS User 3). These bunches, for the 9.8 GeV cycle, had an intensity of about 2.0e9 and ϵ of about 0.38 eVs (Figure 20 shows a bunch on the flattop).⁵⁹ The 5.75 GeV ϵ requirement is 0.30 eVs.

The ϵ just after the 2-1 merge in the AGS was not measured but for EBIS Au the ϵ after a 2-1 merge is 0.19 eVs (Table 5). About 45% growth is typical from there to the 9.8 GeV flattop so in the Tandem case one would expect the ϵ just after the 2-1 merge to be about $0.38/1.45=0.26$ eVs, which is still significantly larger than it is with the EBIS setup.

ϵ growth measurements up the ramp during Run 18 indicate that it doesn't make much difference whether the 5.75 GeV cycle uses the P bank (a factor of 1.35 ± 0.07) or just the F bank (a factor of 1.33 ± 0.07), so it probably makes sense to use the P bank since the cycle would be significantly shorter even if Westinghouse is used. With the same ϵ just after the merge (0.26 eVs) this would give a flattop ϵ of $(0.26\text{eVs}\cdot 1.35) = 0.35$ eVs on a 5.75 GeV flattop using the P bank.⁶⁰

The AGS was also setup with a 3.85 GeV flattop without any merges (AGS user 7) and the measured flattop ϵ was 0.146 eVs. Table 5 indicates about 20% growth on the 3.85 GeV ramp, from which it could be inferred that the ϵ at the end of the injection porch would be about 0.122 eVs. This is not much different than the estimate just above ($0.26/2$ eVs= 0.13 eVs).

The bunches were injected into h=12 buckets in the AGS and accelerated on h=12 to a relatively high merge porch (~915 vs. 576 g used for the standard EBIS 3-1 merge). Station KL was set to h=6, and together with the h=12 Rf stations was used to perform the 2-1 merge. The merged bunches were then transferred back into h=12 buckets for acceleration to the flattop.

⁵⁸ See [Booster-AGS-EBIS 2018 elogs](#) from June 21-28 for entries about its implementation with EBIS Au32+ in Run 18.

⁵⁹ See [Booster-AGS-EBIS March 6th 2019 elog](#) 1958 entry and [March 7th elog](#) 1442 entry.

⁶⁰ K. Zeno, "[AGS Longitudinal emittance measurements for upcoming RHIC low energy gold runs](#)", C-A/AP/615, pg 12.

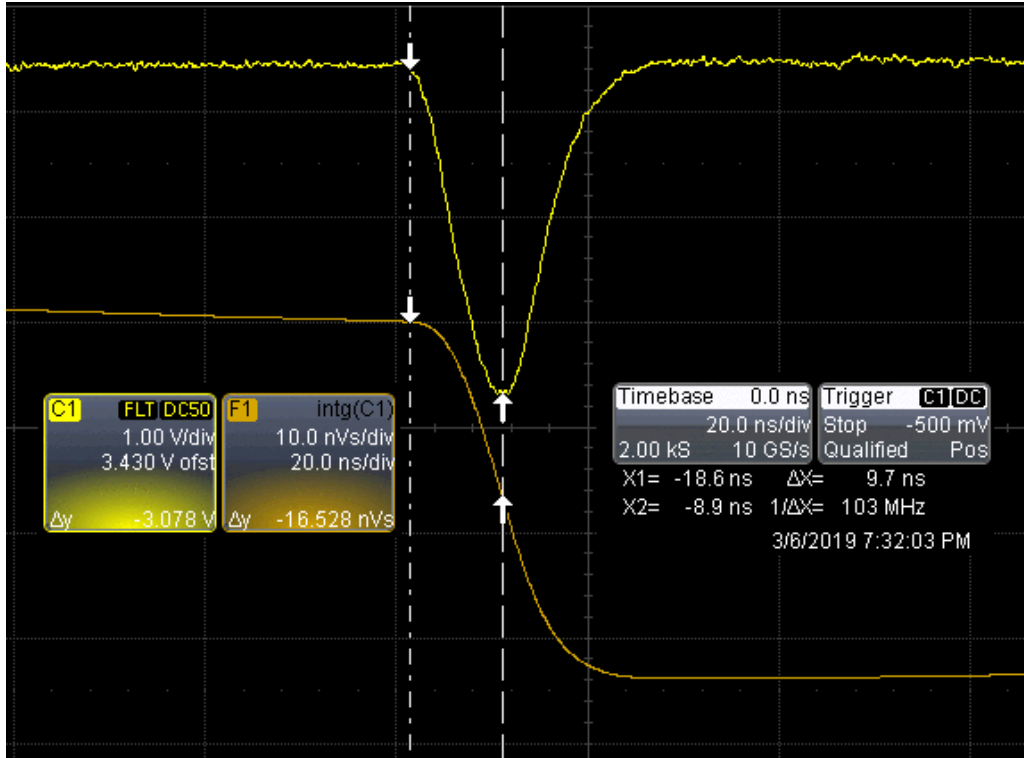


Figure 20: An Au bunch on the 9.8 GeV AGS flattop using Tandem as the preinjector (C1, yellow trace) as seen on the WCM. The bunch length measured here is $9.7 \text{ ns} * 2 = 19.4 \text{ ns}$. A typical bunch length using EBIS with a 6-3-1 merge in the AGS is about 28 ns. The bunch intensity here is about $2.0e9$ ions. The orange trace is the integral of the bunch current (C1) and is often used to measure the bunch intensity.

The injection harmonic was set to 12 instead of 24 mainly due to concerns about space charge effects. During Tandem Au running years ago, there was some intensity dependence after the 24 to 4 merge that occurred on the injection porch. After that merge the bunch intensity in $h=12$ buckets was as high as $1.8e9$ and the ϵ was likely about 0.17 eVs.⁶¹ If a 2-1 type merge was done at injection energy the resulting bunch intensity would be higher than that so the merge is performed at a higher energy where space charge effects are greatly reduced.

The beam could be injected into $h=24$ buckets and then accelerated to a merge porch corresponding to the maximum allowable Rf frequency and a merge could be performed there using $h=24$ and $h=12$. But when the $h=24$ voltage is increased to accelerate to the merge porch that could cause space charge problems and there also might be space charge problems after the merge since the porch would be lower than the one used for EBIS beam. With the merge setup used this year $h=24$ could still be used for injection and the bunches could be transferred to $h=12$ buckets before accelerating to the porch.

⁶¹ K. Zeno, "[Comparing the effect on the AGS longitudinal emittance of gold ions from the BtA stripping foil with and without a Booster Merge](#)", CA/AP/596, December 2017, pg. 20.

It is not clear why the ϵ is larger than it is with EBIS beam. It may be because there is more growth during the Booster merge, but it could also be because the injected bunches are not as well matched to $h=12$ buckets as they are to $h=24$ ones (see the section ‘ ϵ after filamentation on the injection porch’). Next year the option of injecting into $h=24$ buckets can be tried to reduce the ϵ if it is an issue. It would also be interesting to try it just to see what difference it makes.

Another option, since the bunch intensity is significantly higher than the RHIC requirement, is to reduce the ϵ at the expense of bunch intensity by reducing the station KL voltage when the $h=12$ comes on so that some of the merged bunch goes into the adjacent $h=12$ buckets creating baby bunches. This is like relaxing the bunch squeeze and I imagine it would have a similar effect on the ϵ of the main bunches. Although the AGS bunch intensity is higher than the requirement, the AtR transfer efficiency could be a factor.

On March 6th the flattop bunch intensity was about $2.0e9$ and Booster late was $4.1e9$ (48.8% efficiency from Booster late to a bunch on the flattop). This was with only 2 Tandem requests and a Booster input of about $8e9$ ions. For the 6 Tandem requests used in Run 16, the Booster input briefly reached $3e10$ for an average of $5e9$ per Booster cycle. From previous experience, if the Booster were optimized, the efficiency (Booster Late/Booster input) would be about $52.5\pm 3.5\%$ for this input intensity.⁶² With the same efficiency observed in this run (48.8%), this would give a bunch intensity on the flattop of $2.56\pm 0.17e9$ ions. It remains to be seen whether accelerating $1.3e9$ ions in a bunch with an ϵ of 0.13 eVs (or less) to the merge porch will present any problems with space charge. If there were any space charge problems this year with $1.0e9$ /bunch and 0.13 eVs, they were minor.

The Booster Cycle

The Booster cycle used this run is longer than it is for EBIS Au (233 vs. 200 ms). There are several reasons for this. First, since injection occurs at a lower rigidity for Tandem than for EBIS, the ramp rate would have to be increased, and/or the merge porch would have to be shortened, for extraction to occur at the same rigidity. Even with the same extraction rigidity the extraction energy is somewhat lower since Au31+ is used for Tandem and Au32+ for EBIS. The lower the extraction energy, the more the BtA efficiency will suffer from reduced stripping efficiency and larger beam and the more risk that space charge will be a problem in the AGS.

Second, the 6-3-1 merge will need more time than the 4-2-1 merge does so the merge porch needs to be lengthened. Since there will be fewer bunches merged into one in the AGS required to reach the desired bunch intensity there are fewer Booster cycles needed so the PPMR constraint which would prohibit a cycle longer than 200 ms is relaxed. The constraint is satisfied

⁶² See [Booster-AGS-Au_2010 elog](#) 1426 entry.

for 7 Booster cycles but for 9 Booster cycles the cycle would have to be lengthened to 267 ms.⁶³ For the latter the merge porch would be lengthened another 33 ms. Seven Booster cycles (6 with beam) with a 2-1 merge in the AGS would provide 3 bunches on the AGS flattop and 9 would provide 4 bunches. The Tandem has not run with 8 beam requests so how well it would perform is uncharted territory.⁶⁴

An AGS Westinghouse 5.75 GeV magnet cycle using the P bank with 6 transfers from the Booster (233 ms cycle), 3 extractions placed 200 ms apart (the spacing used for 4.59 GeV), leaving 500 ms for the rollover on the flattop to flatten, and 500 ms for the field to recover after the magnet reference reaches dwell would be about 4.6 sec long. If 8 transfers are used the cycle would be about 5.6 sec long.

If the supercycle length was the same as the AGS magnet cycle length, the ‘duty cycle’ for the 3 bunch setup would be $(4.6\text{sec})/(3\text{ bunches})=1.53\text{ sec/bunch}$ and for 4 bunches it would be $(5.5\text{sec})/(4\text{ bunches})$ or 1.38 sec/bunch. With 3 bunches it would take 2 min and 50 sec to fill one RHIC ring with 111 bunches and with 4 bunches it would take 2 minutes and 39 sec to do so. So, the 4-bunch setup would be 12% faster. There are other constraints besides the AGS cycle length that ultimately determine the supercycle length though (ex.- NSRL, EBIS, LINAC) so it might be that it would have to be 5.5 sec or more anyway. If it were longer than 5.5 sec, regardless of the number of bunches, then the 4-bunch setup would be 33% faster.

Figure 21 shows the (233 ms long) Booster magnet cycle together with the Rf voltage references and their harmonics. Note that the merge porch is 34 ms long whereas for the EBIS cycle it is 15 ms long and is also at a lower field (4.0 vs. 5.5 Kg) so that all the cavity frequencies fall within their operating ranges.⁶⁵

⁶³ See [Booster-AGS-EBIS Aug 1, 2019 elog](#)

⁶⁴ Note that the pre-EBIS Tandem injector setup with no Booster merge would nominally satisfy the 5.75 GeV requirements since the bunch intensity was as high as $1.8e9$ ions and the ϵ would probably be around 0.23 eVs. The AtR efficiency would need to be >80% and the Booster and Tandem performance would be more critical. It would provide 4 bunches with only 4 Tandem requests and 5 Booster cycles. It would also require the AGS merge to occur at injection energy or no higher than on a porch where the $h=24$ frequency would not exceed the limits of the Rf system and would likely require L10 to be reconfigured to operate at a lower frequency. The latter would not be compatible with the standard EBIS 4.59 GeV setup if a 3-1 (or 6-3-1) merge were used but in the 3-1 case a 4.59 GeV setup with the merge occurring with L10 at the reconfigured frequency would work. Presently, the 4.59 GeV requirements are $1.05-1.10e9$ and greater than 0.30 eVs, perhaps as much as 0.4 to 0.5 eVs (H. Huang, personal communication). To reliably obtain this RHIC bunch intensity with EBIS would likely require a 3-1 merge in AGS.

⁶⁵ The approximate Rf frequencies on the porch are 2.4 MHz for $h=6$, 1.2 MHz for $h=3$, 800 kHz for $h=2$, and 400 kHz for $h=1$. The allowable frequency range for $h=6$ and $h=1$ (A3/B3) is 350 kHz to 5 Mhz and for $h=2$ and 3 (A6/E6) it is 770 kHz to 1.45 MHz. From K. Zeno, “[Run 16 Tandem gold performance in the injectors and possible improvement with AGS type 6:3:1 bunch merge in the Booster](#)”, C-A/AP/576, pgs. 3 and 10.

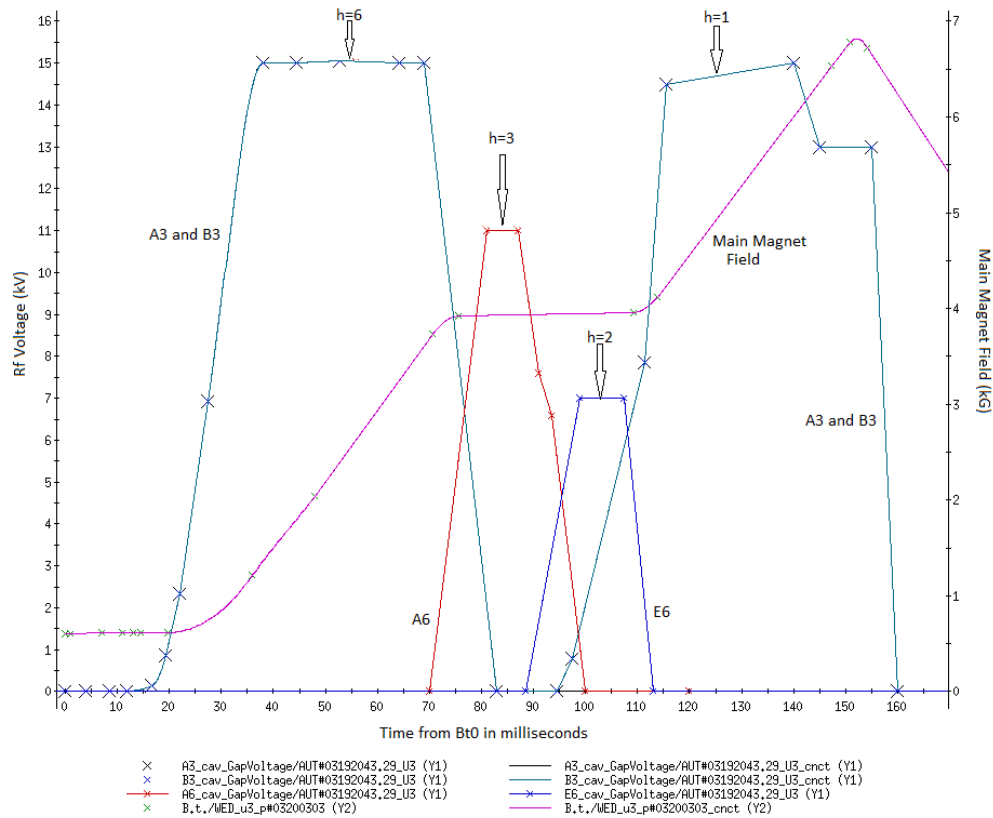


Figure 21: The Booster magnet cycle used with Tandem Au31+ together with the voltage references for the 4 Rf cavities and the harmonics at which they operate for the 6-3-1 merge. The A6 and E6 references are intentionally double the reference functions because they have 2 voltage gaps whereas A3 and B3 have only one. These functions were those used on March 19th.

Note that with the longer merge porch, even if a 6-2-1 instead of a 6-3-1 merge were used the quality of the merged bunches would very likely also be better than it was in Run 16 (when a 6-2-1 merge was used with the 15 ms porch). Also, as alluded to in the section “Baby Bunches and $h=10$ ” above, experience in the AGS has shown that a 6-3-1 type merge can also be performed without the $h=8$ cavity (station KL), which corresponds to $h=2$ in the Booster.⁶⁶ The resulting bunches are not as small but might be smaller than those using a 6-2-1 merge if for some reason either A6 or E6 become unavailable.

However, the relative timing of the cavity voltage functions used for the Booster 6-3-1 merge is still quite different than it is in the AGS and performing the merge without $h=2$ would probably give a different result. Hopefully, with more time working on the merge (with $h=2$) the relative timing will become more like it is in the AGS.

⁶⁶ In terms of Rf harmonics the AGS merge is 24-12-4, but there are only 2 sets of 6 bunches in the $h=24$ buckets before the merge begins. Each set of 6 bunches is merged into a set of 3 bunches and then into 1 bunch. In the Booster all the buckets are filled before the merge so in terms of Rf harmonics it is 6-3-1. In the AGS, $h=24$ is analogous to $h=6$ in the Booster, $h=12$ (station K) is like $h=3$, $h=8$ (station KL) is like $h=2$, and $h=4$ (L10) is like $h=1$. Unlike in the AGS there is no ‘rebucketing’ for acceleration after the merge.

Figure 22 shows a mountain range display of the 6-3-1 merge from the last day working with Tandem beam, March 19th, and Figure 23 is an AGS mountain range of an injected bunch

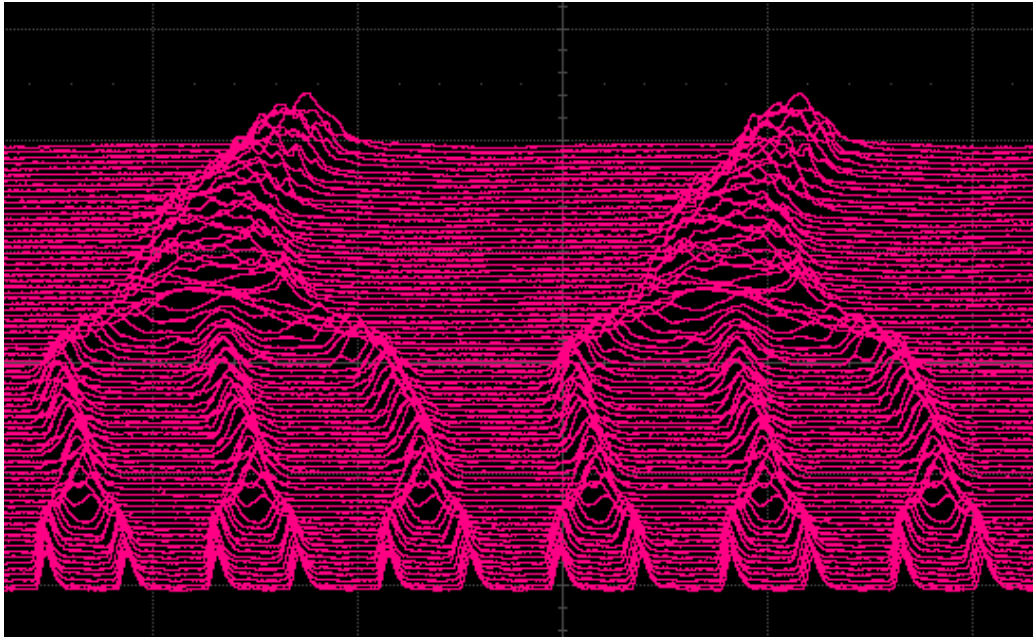


Figure 22: Mountain range display of the Booster 6-3-1 merge using the WCM. The sweep speed is 500 ns/box and the gain is 200 mV/div.

the length of which appears to be about 240 ns.⁶⁷ This is without QP, and although the bunch appears to have more structure than an EBIS Au one, its length is no longer and may be even shorter.⁶⁸

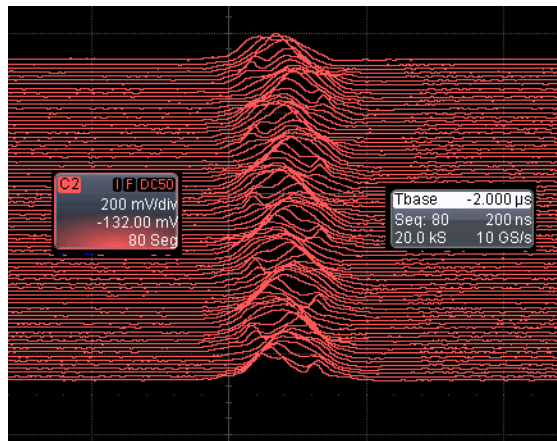


Figure 23: Mountain range display of a Tandem Au bunch just injected into the AGS using the WCM. Close inspection shows that it is about 240 ns long. 200 ns/box and 200 mV/div.

⁶⁷ [Booster-AGS-EBIS 2019 March 19th elog](#). Figure 22 is from the entry at 2006 and Figure 23 is from the 2051 entry.

⁶⁸ The Rf voltage at Booster extraction for the EBIS and Tandem cases is the same (13 kV), The EBIS bunch width was 264 ns with QP (see pg. 7).

Beam Dependent Vacuum Deterioration in the AGS D Superperiod

The Symptoms

From about the beginning of June onward pressure spikes in the D superperiod began to occur. Sometimes the pressure reached 10^{-6} Torr and the spikes were large enough to cause the sector valves to close. The deterioration was localized around D5, which is also the location of the horizontal eIPM. Since they occur where the eIPM is, it was initially thought that its controlled vacuum leak was the cause, but this possibility was ruled out.⁶⁹

Figure 24 is a LogView plot of such a spike on some of the ion gauges in the vicinity. For this case the vacuum was worse at D5 than at the other two gauges to begin with. The size of the spike at D5 looks about the same as it does at D2, but the scale is logarithmic, so it is actually 10 times larger at D5.

Figure 25 shows that the vacuum half a superperiod away from D5 was nearly unaffected. The D12 ion gauge is also shown because the sector valves probably closed in this case, the gauge is between them, and the vacuum looks like it does at D15. So, it is not because the valves closed that the vacuum half a superperiod away is nearly unaffected.

Figure 26 shows the D5 pressure throughout the run. There are some spikes prior to the beginning of June but the vast majority occur afterwards. They also seem to occur only when there is beam in the AGS and are correlated with high losses at injection energy. Take for example the spike that occurred on June 14th. That spike occurred during the time when the AGS debunching measurements discussed previously were being taken. When these are taken, the Rf is off and the beam is lost when the field starts to ramp up at the end of the injection porch. Judging from the logged intensity scaler data, just before the spike there were 12 transfers occurring and the beam was being accelerated to the flattop. The spike is correlated to when the Rf was shut off.

Another spike occurred on Jun 30th, in that case the A5 kicker was in wide pulse (ION) mode (not intentionally, but probably the result of a power dip). Normally, it is set to narrow (PRO) mode so it does not kick out bunches that are already in the machine. In this state, the beam was accelerating to flattop but 4 of the 12 bunches that were already injected into the AGS were being kicked out by the A5 kicker. Even though the Rf is on in this case it is like the June 14th case because in that case unbunched beam is also kicked out on the injection porch. So, the thought was that the spikes might be caused by, at least sometimes, beam that is already in the machine being kicked out by the kicker and perhaps into D5.

⁶⁹ H. Huang, private communication.

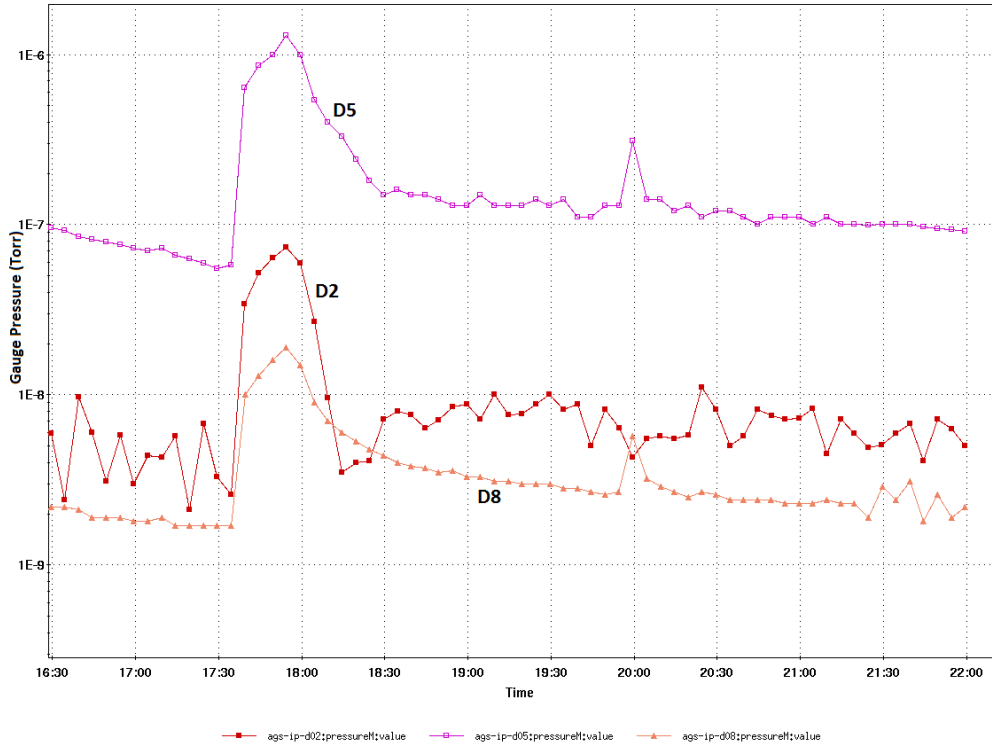


Figure 24: AGS ion gauge pressures when a vacuum spike occurred on June 14, 2019 at 17:30. For easy readability only the D2, D5, and D8 pressures are shown. The pressure scale is logarithmic. The sector valves are located at D3 and D13.

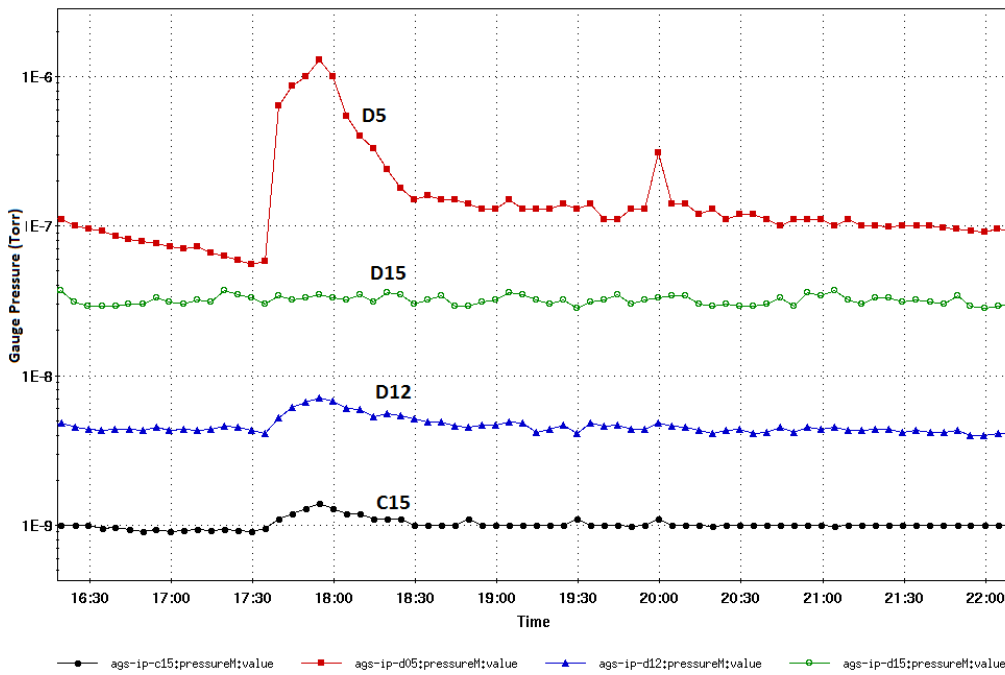


Figure 25: AGS ion gauge pressures for the same spike as in Figure 24. D5 is where the pressure spike is centered and C15 and D15 are both half a superperiod away. The D12 pressure is also shown. The pressure scale is logarithmic. The sector valves are located at D3 and D13.

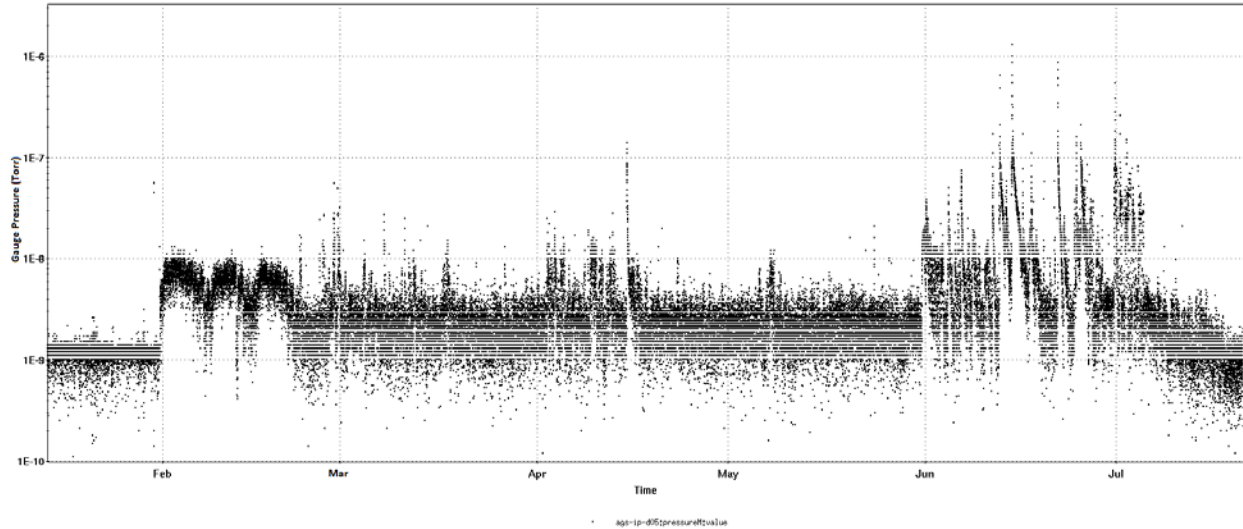


Figure 26: The AGS D5 ion gauge pressure throughout the 2019 Run.

As can be seen in Figure 26, aside from the spikes, the average vacuum at D5 increased around the beginning of June. Figure 27 shows the D5 vacuum from around this time and it indicates that this happened around noon on May 31st. At this time work was being done on the 12 transfer 3.85 GeV cycle with 6 extractions that was used during the majority of June for the 3.85 GeV RHIC run. Although the D5 pressure did always worsen when there was beam in the machine the effect seems to be greater after this time. The fast pressure fluctuations in the Figure are due to the beam turning on and off.⁷⁰

Improving Vacuum with Orbit Bumps at D5

On July 6th this problem was investigated on AU6, the 3.85 GeV 12 transfer cycle. There are no bmps at D5 but there are BPMs at D4 in both planes. At the time the horizontal position at D4 was +1.7 mm and the vertical position there was -4.6 mm. There was nothing in either plane around D5 that appeared unusual.⁷¹

Local orbit bumps were put in at D5 and the vacuum there was monitored using the D5 eIPM vacuum pressure gauge which updates every 6 seconds or so. Under normal running conditions (with 6 transfers) it was found that a vertical bump of an additional -9 mm improved the vacuum from 3.8 to 3.0e-8 Torr.⁷² When beam is off the pressure was 2.4e-8.⁷³

With the Rf off in this state the vacuum begins to deteriorate and with an additional horizontal bump to the inside of 6 mm it deteriorates faster.⁷⁴ With the same amplitude bump to

⁷⁰ There is typically no loss visible on the AGS loss monitors in the D superperiod, at least in low gain, the gain that is normally used. This is not to say there is no loss there since the Au beam deposits most of its energy in the beam pipe at this energy, so any losses are hard to see.

⁷¹ See “D5Bump” reference file in AgsOrbitDisplay for the this orbit.

⁷² [Booster-AGS-EBIS July 5 2019 elog](#) 1733 entry

⁷³ [Ibid.](#), 1710 entry

⁷⁴ [Ibid.](#), 1743 entry

the outside the vacuum is slightly worse with Rf on (3.1×10^{-8} Torr) but it does not deteriorate much when the Rf is off.⁷⁵ In this state the horizontal and vertical positions of the raw orbit at D5 were +7 and -14 mm, respectively.⁷⁶ Neither of these bumps caused any noticeable beam loss and the bumps in the opposite directions didn't either.

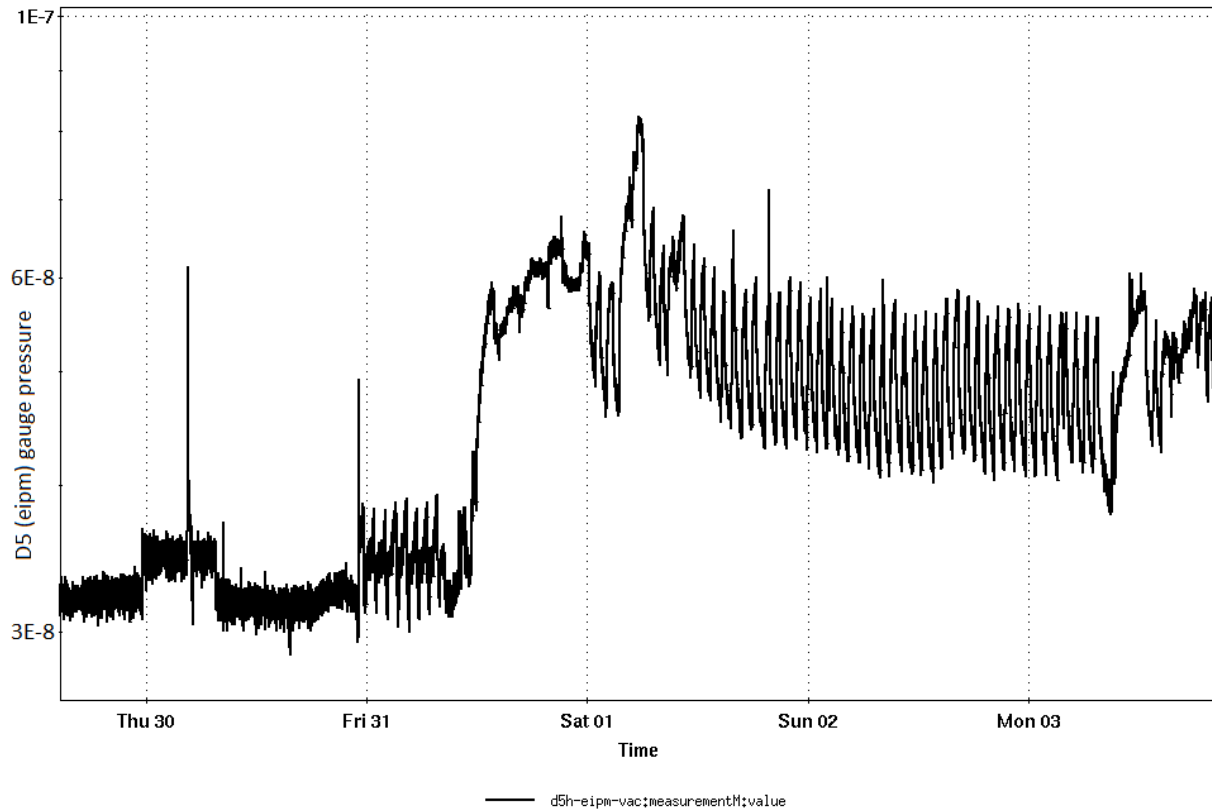


Figure 27: The D5 (eIPM) vacuum gauge showing the period around when the average vacuum at D5 deteriorated. Data is collected at a faster rate for this gauge than the ones shown in the earlier figures.

These bumps were left in on this user and installed on AU1 which began running July 8th. Figure 28 shows the D5 pressure before and after the bumps were installed. Afterwards there were no spikes, the vacuum's sensitivity to beam was reduced, and the average vacuum decreased to a lower level than before the change.⁷⁷

Why do these bumps reduce the D5 pressure's sensitivity to beam?

When the Rf is off most of the beam is lost at the beginning of the ramp to the merge porch, which on the 12-transfer cycle occurs at At0+2400 ms. A considerable amount of beam is also lost when the A5 injection kicker fires. It fires every 200 ms on the injection porch. The

⁷⁵ [Ibid.](#), 1758 entry

⁷⁶ [Ibid.](#), 1821 entry

⁷⁷ The vacuum improvement is also evident in Figure 26. There were a couple spikes after this period, but they were associated with setups that did not have the bumps installed.

horizontal bump that was installed ramps down to zero from At0+2300 to 2350 ms, which is after the last transfer and before the field starts to ramp. The vertical bump ramps down from 2700 to 2800 ms, well after the beam is gone.

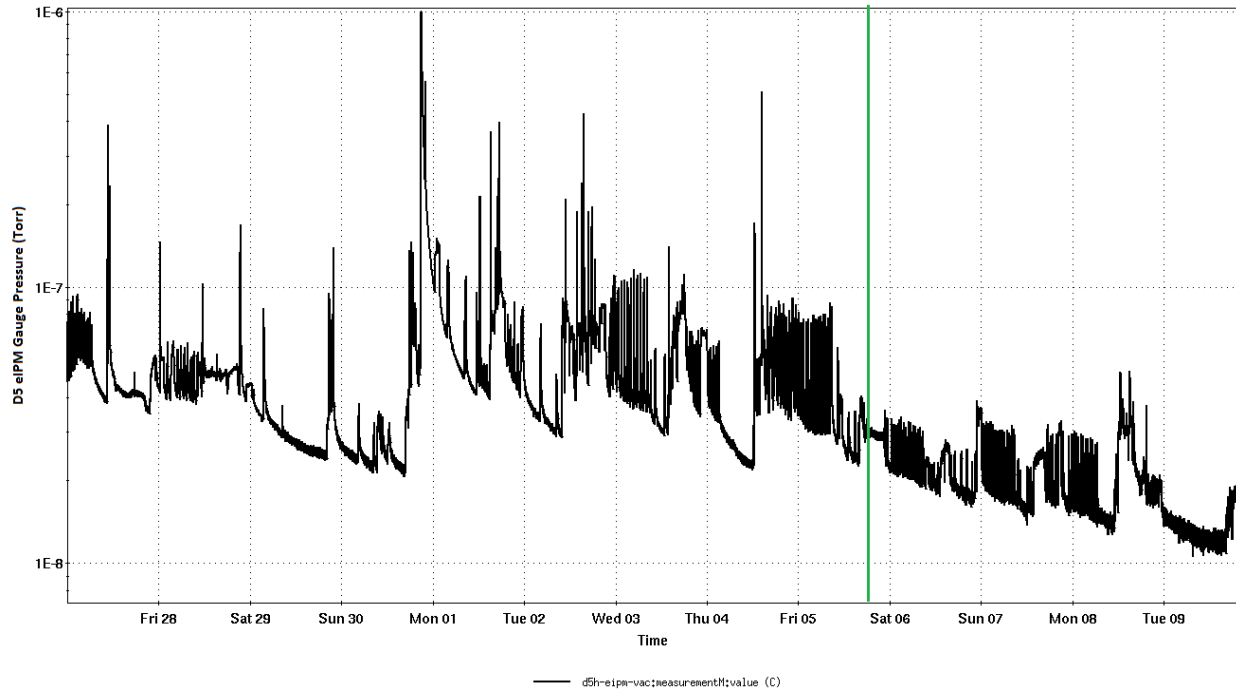


Figure 28: The D5 eIPM vacuum gauge before and after the installation of the orbit bumps at D5. The green vertical line marks when they were installed. The period is from June 27th to July 9th.

Since the horizontal bump is down before the field starts to ramp the possibility that the vacuum spikes occur when the beam spirals to the inside seems more unlikely. It could however be that there is some particularly sensitive spot on the inside which is above the midline and placing the orbit well below the midline helps the beam to avoid it. Adding to the complication, there is not just a beampipe there but there is also the eIPM inside that beam pipe.

As mentioned, on June 30th a spike did occur when the Rf was on and the A5 was kicking bunches out of the machine. In this case it is unlikely that a significant amount of beam was lost on D5 when the field starts ramping. It is tempting to blame that spike on beam getting kicked into D5 except that the A5 has a positive (horizontal) kick and the phase advance from A5 to D5 is very close to 2.25 oscillations, so the kick would translate to a large positive displacement at D5.⁷⁸ So naively, if the bump were there to prevent the beam from being lost it should be to the

⁷⁸ The A5 kicker delivers a positive kick to put the beam on the equilibrium orbit (See L.A. Ahrens and C.J. Gardner, “[Determination of the AGS Injection Kicker Strength from Beam Measurements](#)”, D-A/AP/91, December 2002, page 9). Since D5 is 3 superperiods from A5, using the set Q_h of 8.91, D5 is $8.91 * 3 / 12 = 2.228$ betatron oscillations from A5. The sine of $2\pi(2.228)$ radians is 0.99. I’m using the set Q_h not the measured one, but even if the actual Q_h was say 8.86 instead of 8.91, the phase advance would be 2.215 oscillations and the sine of that is still very close to 1 (0.976).

inside not the outside. Regardless, this spike occurred when the A5 was kicking beam out of the machine and the Rf was on, so it seems likely that there's a connection.

Summary

A chronology of the various setups used during the 2019 run can be found in Tables 1 through 3. Flattop longitudinal ϵ measurements for the different setups used are shown in Table 4. These measurements assume a γ_t of 8.5, but if an estimate for the actual γ_t on the flattop is made using the settings for Q_h and ξ_h as well as the radius, and that value is used to calculate the ϵ , it changes the calculated ϵ for 9.8 GeV from the value in the table, 0.817 eVs, to 0.724 eVs.

The longitudinal ϵ was measured at different times in the Booster and AGS cycles and the results are shown in Table 5 and Figure 4. These measurements indicate there is about a factor of 2 growth from Booster capture, there is little growth from there to Booster extraction, and the growth from the foil is about 11%. The growth on the 3.85 GeV F-bank only ramp to the flattop was about 20%.

The stripping efficiency from Au32+ to Au77+ in BtA was measured for foils 5 and 6 (Table 6). The efficiency for both foils was the same within the uncertainty, slightly less than 64%. It was noticed however that foil 5 introduced more energy spread than foil 6 this year, something that has not been apparent before (see footnote 17). Foil 6 was used for the entire run.

The BtA efficiency for single transfers and the slow loss rate on the injection porch were measured for the 12-6 cogging pattern used in the 3.85 GeV run because the overall transfer efficiency, (AGS after last transfer)/(Booster late), was better than it was for cycles with the 12-6-2 merge which uses a different cogging pattern. Before the time in the cycle the merges occur the 2 setups are basically the same except for this one difference.

The cogging pattern could affect the transfer efficiency since it determines if and how often a bunch is injected into a bucket adjacent to one that is already populated, and if there is a bunch there, it could receive a kick from the rising edge of the kicker. The 12-6-2 overall transfer efficiency from previous years is about 3% lower than it is for the 12-6 setup (52 vs. 55%). The analysis was inconclusive though, since if the higher overall efficiency with the 12-6 3.85 GeV setup were due to the different cogging pattern, the slow loss rate in the 12-6-2 case would have to be significantly larger than what has been measured.

The nominal 3-1 merge in the AGS, used briefly for 3.85 and 4.59 GeV, does not work for 12 Booster transfers because the injection kicker pulse is too long. It can only provide 3 bunches that are the result of merging 3 initial bunches into 1. It can provide 4 bunches, but the other bunch only has two-thirds the intensity. The ϵ of that bunch also appears to be about 2/3 of the ϵ of the other 3 bunches.

A different 3-1 type merge, which does work for 12 transfers and has four 3-1 bunches on the flattop was suggested by C.J. Gardner. It uses $h=24$, 16, and 8 at injection energy instead $h=12$, 8, and 4 on the merge porch. Station KL is used for $h=8$. This was setup for 3.85 and 4.59 GeV by I. Zhang.

Transverse emittance measurements were made in BtA and in the AGS. The Booster setup is the same for all the different AGS flattop energies. The normalized RMS emittances in BtA upstream of the foil are $\epsilon_x=0.80$ and $\epsilon_y=0.38$ mm mr. Table 8 shows the normalized RMS emittances in the AGS at injection and at flattop for the 4 flattop energies. For the lower energies (3.85 and 4.59 GeV) there is not any obvious growth during the ramp but for 7.3 and 9.8 GeV there is. Although the longitudinal emittance is larger, the bunch intensity for 7.3 and 9.8 GeV is about 3 times higher than it is for the lower energies.

There is another beam profile to the right of the main Au³²⁺ profile on multiwire MW096 in EtB. The EtB xf108 transformer, used for Booster Input, sees current from this beam. The amount of current it sees varies but is on the order of 5% of the total. It was not certain whether this profile is also Au³²⁺, a different charge state of Au, or another species. A study was performed which strongly suggests that it is Au³¹⁺ and so its current should not be counted in the Booster Input intensity. It had been collimated out this run and it remained so after the study.

About midway through the 7.3 GeV run the AGS acceleration harmonic was changed from 12 to 10 to increase the bunch intensity by reducing the size of the baby bunches. The baby bunch size dropped from about 4.5% to about 1.5% (Figure 18). Although one might expect the flattop ϵ to increase, the change did not have a noticeable effect on it. This change made the AGS bunch intensity about 1.5% higher, although an increase in the RHIC bunch intensity was not apparent (Figure 19).

There was work done with Tandem Au in the injectors. This work was described in some detail since Tandem is expected to be used for the upcoming RHIC 5.75 GeV run. At present the requirements are 1.45e9/bunch with an ϵ of 0.30 eVs. A 6-3-1 merge was used in the Booster together with a 2-1 merge in the AGS. The Booster cycle was extended from 200 to 233 ms for this setup.

On the 9.8 GeV flattop the bunch intensity using Tandem was about 2.0e9 and the ϵ was about 0.38 eVs. On a 5.75 GeV flattop one would expect a slightly lower ϵ (~ 0.35 eVs). Although this was done with only 2 Tandem requests, 6 requests should be possible. This would provide 3 bunches at AGS extraction of a similar intensity and ϵ . Using Westinghouse, and both the F and P banks, the supercycle length could be as short as 4.6 sec or so.

A supercycle with 8 beam requests also appears to satisfy the PPMR constraint if the Booster cycle length is increased to 267 ms. That supercycle would provide 4 bunches, although

Tandem has never run Au31+ with 8 Booster requests so it is not known how well it would perform. The supercycle could then be as short as 5.5 sec or so.

In the AGS, beam related pressure spikes and overall vacuum deterioration around D5, the location of the horizontal eIPM, began to occur in the beginning of June. The eIPM has a controlled leak which appeared to be functioning properly. After installing a negative vertical bump together with a positive horizontal bump at that location the spikes stopped occurring and the overall sensitivity of the pressure to beam was less.

Before the bumps were put in place the spikes would occur when there was a lot of loss at injection energy. Two cases where they occurred were looked at in some detail. In one case the Rf was off, and in the other the A5 injection kicker was unintentionally set to wide pulse mode so it was kicking out bunches that were already in the machine.

Since the beam debunches when the Rf is off, beam is kicked out of the machine when transfers occur, and so these kicks were initially thought to be responsible for a loss at D5. However, the phase advance from A5 to D5 is such that the kick at A5 becomes a displacement to the outside at D5. One would think then, if anything, a negative horizontal bump there should mitigate the problem and a positive one should make it worse. Which is the opposite of what was observed.

It is common to lose all the beam at injection energy, for example when the beam permit is pulled it shuts the Rf off and all the beam is lost there. There is nothing to suggest that the losses on the injection porch before and after the spikes started happening were significantly different which implies that something may have deteriorated at D5 itself.