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The 2024 Run in the Injectors

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Introduction

The injectors provided polarized protons to RHIC for most of Run 24. That was followed by 3 weeks of Gold at 9.8 GeV/n using Tandem. Physics with PP was first declared on May 1st and the PP portion of the run ended on Sept. 30th. The standard BU4/AU4 setup was used for most of it. Although, from Sept. 7th to 30th the AGS skew quad setup (BU4/AU6) was used instead.[1] More work was done on the Split/Merge setup (BU3/AU3) initially developed in Run 22.[2] A two Linac pulse setup was also developed this run (BU4/AU2). As far as PP work in the injectors goes this note will focus on the standard, Split/Merge, and Two Linac pulse setups. The 9.8 GeV/n Tandem Au setup was essentially the same as in Run 23.[3] The injector setup for Helium-3 from EBIS (BU7/AU7), which was used for an APEX study in RHIC on August 7th, will be covered as well.

The Two Linac Pulse Setup

This setup was proposed by Kiel Hock. By using 2 Linac pulses instead of one more beam can be scraped off in the Booster for the same final intensity. This would allow for smaller transverse emittances coming out of the Booster for a given Linac pulse intensity. There are 2 Booster transfers of 1 bunch each, and these 2 bunches are accelerated to the flattop in adjacent h=6 buckets and merged into 1 on the AGS flattop (as with the split/merge setup). After the 2 bunches have been transferred to the AGS the cycle is essentially the same as the one for the split/merge setup (AU3). One drawback is that the longitudinal emittance is expected to be roughly twice as large as on the standard and split/merge cycles.

The shortest interval between successive OPPIS pulses is 1 second, so the first transfer will have to sit on the injection porch for at least a second before the last transfer occurs. The same Booster setup is used as in the standard setup (BU4), but the time between Booster cycles is longer (350 vs. 283 ms). There are also 5 Booster cycles instead of 2. The first pulse is injected on cycle 2 and the 2nd pulse is injected on cycle 5. With this configuration the 2nd Linac pulse happens 3*350ms=1050 ms after the first.

Another complication is that LtB DH1, the magnet that bends the Linac beam into LtB, is pulsed so that OPPIS beam can be sent to the 200 MeV polarimeter in HEBT on every supercycle. When DH1 is pulsed the bend it provides is a function of where on the pulse the beam falls. Consequently, the bend the first pulse encounters is slightly less than it is for the 2nd pulse which passes through it a second later. With the normal DH1 timing the horizontal profile

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[1] New AGS skew quads are used to correct weak horizontal depolarizing resonances. This method is intended to replace the tune jump quads for polarization preservation. For more information see V. Schoefer et al, "Correction of Horizontal Partial Snake Resonances with Pulsed Skew Quadrupoles at the Brookhaven AGS" in IPAC2024, Nashville, Tennessee, 2024, pgs. 1000-1002. Progress on commissioning the skew quad setup is covered in the Injector RHIC retreat talk given by Vincent Schoefer. The slides from that presentation are here. Pages 9-18 are about the skew quad commissioning.

[2] For information on the Split/Merge setup in Run 22 see K. Zeno, "The 2022 Polarized Proton Run in the Injectors", C-A/AP/685, October 2022. Some preliminary work was also done in Run 21, ibid., pgs 8-9.

[3] See K. Zeno, "The 2023 Gold Run in the Injectors", C-A/AP/706, March 2024

on the LtB MW035 multiwire is about 18 mm further to the left than it is when the start of the DH1 pulse occurs 1050 ms earlier.[4]

Initially, the timing for DH1 was changed so that it pulsed twice to get the same bend for the 2 pulses.[5] Although this worked, it wasn't stable over long periods and there was some concern as to whether pulsing it like this would be good for the supply.[6] A simpler solution was provided by John Morris. This allowed the DH1 setpoint to be changed by a small amount between the first and 2nd injections which solved the problem.[7]

The supercycle length for the standard supercycle is 4.2 sec. For the 2-pulse setup it was extended to 4.8 sec to accommodate a long injection porch.[8] Initial setup with beam in AGS began on March 13th. The cold snake was not available until March 27th, so the initial setup was done without it. The snake setup for AU2 became active on Mar 29th. The AU2 settings are derived from the split/merge settings. For the most part, AU2 was loaded with AU3 timing and functions shifted 1050 ms later making the injection porch 1050 ms longer. The first transfer occurs at the same time after At0 as it does on AU4 (144 ms) and the second occurs 1050 ms later (1194 ms).

Two longitudinal emittance (ε_L) measurements were made for the 2 pulse setup. On March 15th, without the snakes, ε_L after the merge at At0+3000 ms was 2.08 eVs (40.33 ns bunch length) in h=12 buckets and using the H- source.[9] On April 5th, 2.17 eVs (40.7 ns bunch length) was measured at 3000 ms. The latter was measured with the snakes on and beam from OPPIS.

Table I contains six transverse emittance measurements with RF shutting off at 2050 ms, which is on the flattop after the 6-12 squeeze and right at the beginning of the merge. The AGS Late intensity range of these is from about 1.9 to 4.0e11. These measurements have different pulse lengths and scraping settings varied a little.[10]

The damper was often used for AU2, but it seemed to behave inconsistently. At one point anti-damping was tested which caused significant beam loss. But when set to damp (Hard-Normal) it would sometimes damp after a tunemeter kick and other times the oscillations seemed

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[4] See Jan 11, 2024 15:14 and 15:16 entries in the Booster-AGS-pp elog. Moving the start of the DH1 pulse 40 jiffies earlier reduced this to 8 mm (see Booster-AGS-pp March 21, 2024 12:24 entry).

[5] To get the same bend angle for the 2 pulses 1050 ms apart DH1 was pulsed twice. BU8 was active for NSRL and LGB on BU8 with an 810 ms delay was used as the start trigger for the first DH1 pulse. The first stop trigger was BC2+250ms (event 239) on BU4. The second start trigger was BC4 (event 242) on BU4 and the last stop trigger was BC5+250 ms (event 243) on BU4. See Jan 11 and 12 2024 Booster-AGS-pp elog.

[6] See Booster-AGS-pp elog March 15, 2024 13:44 entry.

[7] See Booster-AGS-pp elog entries on Apr 3 2024 from 10:15 to 11:11 by J. Morris and entries from 15:13 to 15:44.

[8] See Booster-AGS-pp elog March 13, 2024 15:25 entry

[9] See Booster-AGS-pp elog March 15, 2024 18:06 entry (merged bunch was about 0.9e11) and April 5, 2024 entries from 18:46 to 19:50 (the merged bunch was about 2e11).

[10] The amplitude of the B6 dump bump at 102 ms controls the amount of horizontal scraping and it was increased from 176 to 191A between measurements 3 and 4. The amplitude of the vertical harmonic bump, used to control the vertical scrape, was set to 8.0A for cases 1, 2, 3, and 5. It was larger for cases 4 and 6, 8.3 and 8.4A respectively.

to not damp at all and there was significant beam loss.[11] This was investigated on the injection porch where the beam may just become too unstable after a tunemeter kick for the damper to work effectively. It was set to damp for the measurements in Table I.

	Date	Time	# of cycles	ε_x (π mm mr)	ε_y (π mm mr)	Pulse length (μs)	Booster input ($x10^{11}$)	Booster Late ($x10^{11}$)	AGS Early ($x10^{11}$)	AGS Late ($x10^{11}$)
1	4/9	18:16:29	3	17.3	18.0	200	7.4	4.3	4.0	3.27
2	4/9	18:18:21	6	19.4	19.4	250	9.0	5.0	4.7	3.98
3	4/9	18:18:54	5	15.2	18.0	100	3.9	2.6	2.1	1.99
4	4/9	19:54:59	5	17.6	17.3	300	11	4.7	4.5	3.80
5	4/10	13:37:20	5	15.8	17.5	110	4.1	2.4	2.0	1.87
6	4/10	18:51:10	4	16.5	17.2	300	9.3	3.9	3.6	3.20

Table I: AGS IPM 95% transverse emittances, ε_x and ε_y on the flattop for the 2-Linac pulse setup. RF is shut off at 2050 ms. Each measurement is the average of 3 data points typically at 2108, 2141, and 2174 ms. For each case there were multiple measurements made and ε_x and ε_y are the average of those measurements. The "# of cycles" column contains how many measurements were taken. They are from consecutive AGS cycles. The time column indicates when the first measurement was taken. This is from logged data accessed using the AGS IPM program. The Refit option is used.

The 6 to 12 Squeeze

Figure 1 shows the merge on AU2, together with the 6 to 12 squeeze and rebucketing into h=12 as viewed on a mountain range display of the wall current monitor. How the 6-12 squeeze transitions into the merge is complicated and so I will look at it in some detail here. It is basically the same as it is on AU3. The process is also shown in Figure 2 in terms of RF harmonics and voltages.

At 1850 ms KL (h=3), used to move the bunches in adjacent h=6 bunches closer to each other, reaches its maximum value. The h=6 voltage also stops ramping down and then sits at a constant value. The h=12 voltage starts to rise at 1850 ms as well. The h=3 voltage starts to fall from its constant value at 1920 ms and the h=6 voltage starts to fall at 1931 ms. Both h=3 and 6 reach zero voltage at 1960 ms and the h=12 voltage reaches its maximum there. At the same time the h=6 voltage that is used for the merge starts to ramp up. This h=6 voltage has a different phase than the h=6 used for the squeeze.

During the squeeze, the bunch on the left seems to move to the right more than the bunch on the right moves to the left. As mentioned in a previous note this is suspected to be an artifact of poor delay compensation.[12]

The force on a particle as a function of RF phase, $F(\varphi)$, where φ is the h=3 phase, is given by,

[11] See Booster-AGS-pp elog April 10, 2024 elog entries from 17:47 to 18:29.
[12] See K. Zeno, "The 2022 Polarized proton Run in the Injectors" C-A/AP/685 pg. 21

$$F(\varphi) = A_3 \sin\varphi + A_6 \sin 2\varphi + A_{12} \sin 3\varphi$$

where A_3, A_6, and A_{12} are proportional to the RF voltage amplitudes for h=3, 6, and 12, respectively.[13] Since $F(\varphi) = -dU(\varphi)/d\varphi$, then $U(\varphi)$, the potential energy, can be found by integrating the above equation, which results in,

$$U(\varphi) = A_3 \cos\varphi + \frac{1}{2} A_6 \cos 2\varphi + \frac{1}{3} A_{12} \cos 3\varphi$$

Figure 3 shows $U(\varphi)$ at different stages in the squeeze where A_3, A_6, and A_{12} are all set to 1. The green trace is just h=6. The orange trace is where KL has ramped up (i.e.-1850 ms). The blue trace is after that, where the h=12 voltage has also been ramped.

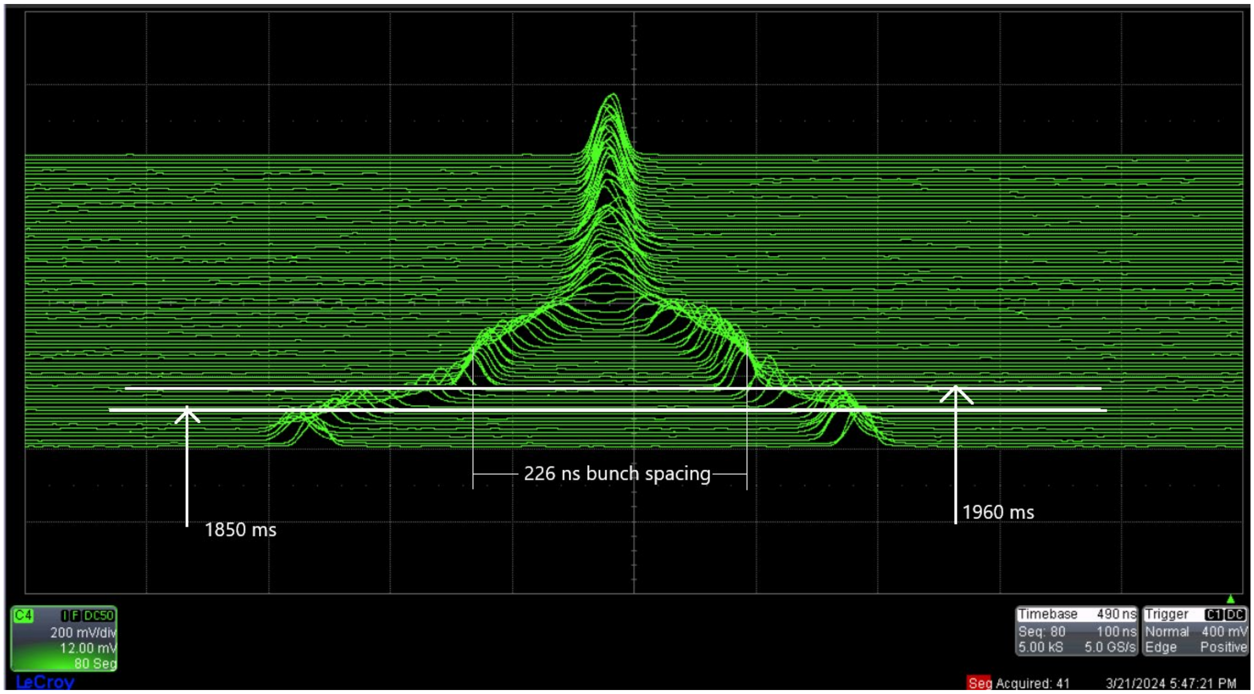

Figure 1: G5 wall current monitor mountain range display of the AGS 6-12 squeeze, 12-6 merge, and rebucketing into h=12 for the 2 Linac pulse setup (AU2). Looking from At0+1650 to 3250 ms. Since the AGS cycle has been extended by 1050 ms this corresponds to 600 to 2200 ms on the normal split/merge cycle (AU3). There are 80 traces and the spacing between traces is 15 ms.[14] Also shown are where KL (h=3) reaches its maximum value in the 6 to 12 squeeze (1850 ms) and where the merge begins (1960 ms). The bunch spacing is expected to be 226 ns (the width of an h=12 bucket) at the beginning of the merge.

Three cavities are used for h=6 during the squeeze (D, DE, and IJ). The h=6 gap volts from 1850 to 1920 ms are set to 3*1167V=3501V. The h=3 gap voltage during that time is about

[13] See C.J. Gardner "Preservation of the distribution of beam particles with respect to longitudinal oscillation amplitude in a 3 to 1 bunch merge", pg. 43, Sept. 3, 2019. Specifically, A_3, A_6, and A_{12} are each equal to the proton charge times the voltage amplitude per gap (V) times the number of gaps and divided by the gap length (L) since this equation is for the Lorentz force, F=qE, and E=V/L.

[14] Taken from Booster-AGS-pp elog March 21 2024 17:48 entry.

the same (3820V). So, having A_3 and A_6 both set to 1 may not be far off from what is in the machine. In Figure 3, from the symmetry of the locations of the potential wells in the h=3 + h=6

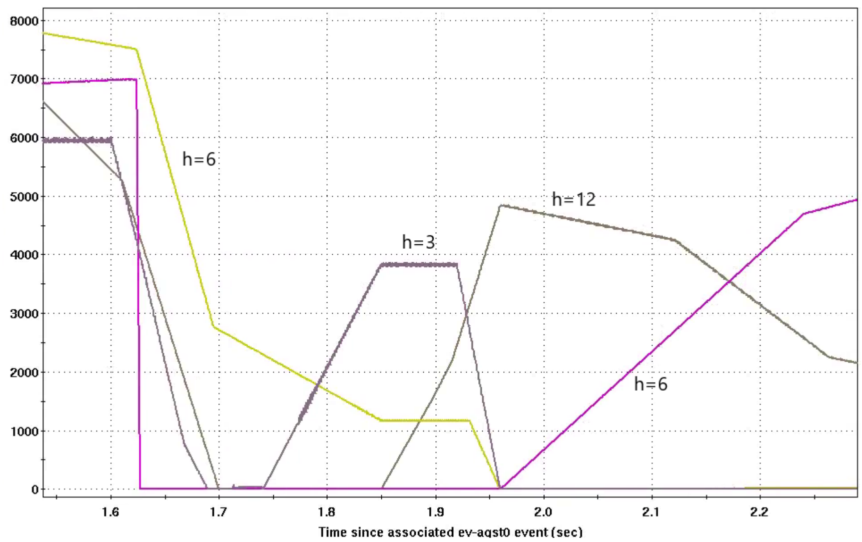

Figure 2: The RF harmonics and voltages involved in the 6 to 12 squeeze and the 12-6 merge. The voltages shown are for single cavities, they are not the total voltages.

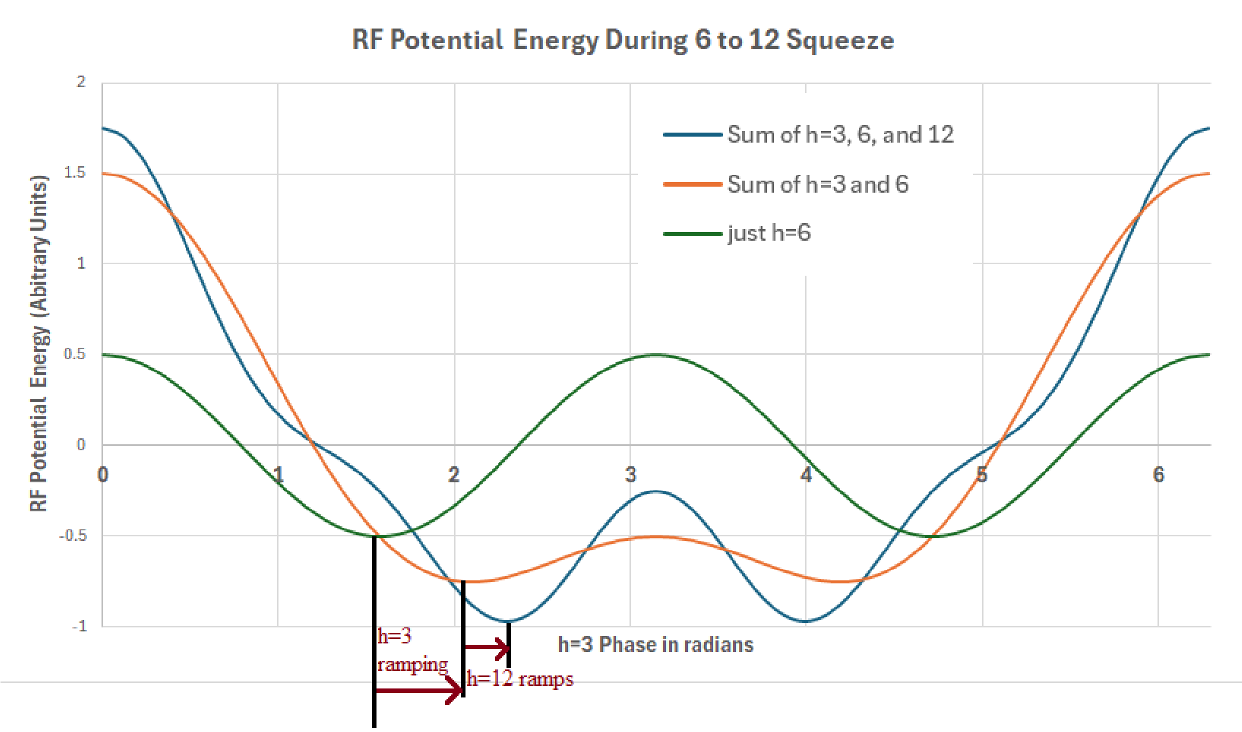

Figure 3: $U(\varphi)$ at different points in the squeeze. The green trace is where only h=6 voltage is present, the orange trace is where h=3 has also been ramped, and the blue trace is where h=12 has also been ramped (to some degree).

case, it seems that the phasing of the h=3, 6, and 12 cavities should all be the same for the squeeze to be setup properly. The actual relative phasing was not zero. The h=6 cavity phases were set to 0°, KL was set to 20°, and the h=12 cavities were set to -70°.

Note that the potential wells for the orange trace are closer together than they are in the green trace. The h=3 voltage moves those 2 wells closer to each other. Later, as the h=12 voltage ramps, those wells gradually move even closer to each other eventually reaching h=12 spacing as h=3 and 6 are ramped down.

In Figure 3 the wells in the orange trace are shallow, but the depth can be increased by lowering the h=3 voltage at the expense of moving them closer to where the wells are for the green h=6 trace. For AU3, after the bunch has been extracted, there is no beam left in the AGS. Whether this is true for AU2 is unclear because those bunches were not extracted. However, it doesn't seem to me that it is critical to have the wells in the orange trace as close as possible to each other for the squeeze to work properly.

The h=12 bucket spacing on the flattop is 226 ns and the measured bunch spacing at 1850 ms was 283 ns.[15] The spacing between the bottom of the wells for the orange trace in Figure 3 is 302 ns. This is a lot closer than the h=6 well spacing of 452 ns and not that far from 283 ns. If the h=3 voltage were raised by 9% to make the h=3 and 6 voltages the same the spacing would become 272 ns.

It's rather obvious that the h=12 phasing could be adjusted to put the beam directly into 2 h=12 buckets without any h=3 voltage, but they would not be adjacent buckets.

Some Issues with 2-Linac Pulse Setup

By injecting only one of the BtA transfers the merge can be studied with only 1 of the 2 bunches present. It was noticed that the optimal h=12 phasing when using only the first transfer was different than for only the 2nd transfer. To optimize the merge for the first injected bunch the h=12 phase was +5 degrees from the optimal for both and to optimize the 2nd it was -5 degrees from the optimal for both.[16] It was not obvious that optimal phasing for the squeeze had this dependence. Figure 4 shows the case where the 2nd transfer is optimized. Unfortunately, the scope gain for the 2 bunches is different.

Ideally, beam control would be turned on immediately after the first transfer but turning it on then disrupts synchro for the 2nd transfer. This is because synchro relies on a constant AGS RF frequency, but with beam control on, the RF frequency is not constant on the porch. With it off, the phase and energy match for the first transfer needs to be closely monitored because it drifts over time. If the first transfer is not well matched its longitudinal emittance will grow because beam control isn't on. Figure 5 shows an example of the result when it was not well matched.

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[15] See Figure 5 and Booster-AGS-pp March 25, 2024 elog 15:14 entry

[16] See Booster-AGS-pp-March 22 2024 elog 17:40 and 17:54 entries.

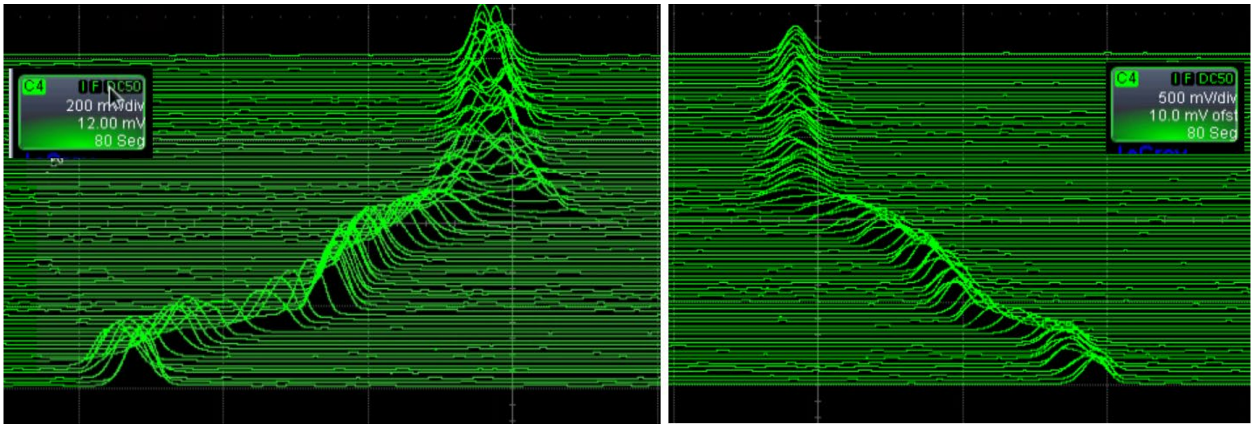

Figure 4: WCM mountain range display of the squeeze and merge with only 1 Booster transfer. Only the first transfer is on the left and has a gain of 200mV.div. On the right is just the second transfer, which has a gain of 500 mV/div. The sweep speed is 100ns/box in both cases. Looking at 80 traces from 1650 to 3050 ms.

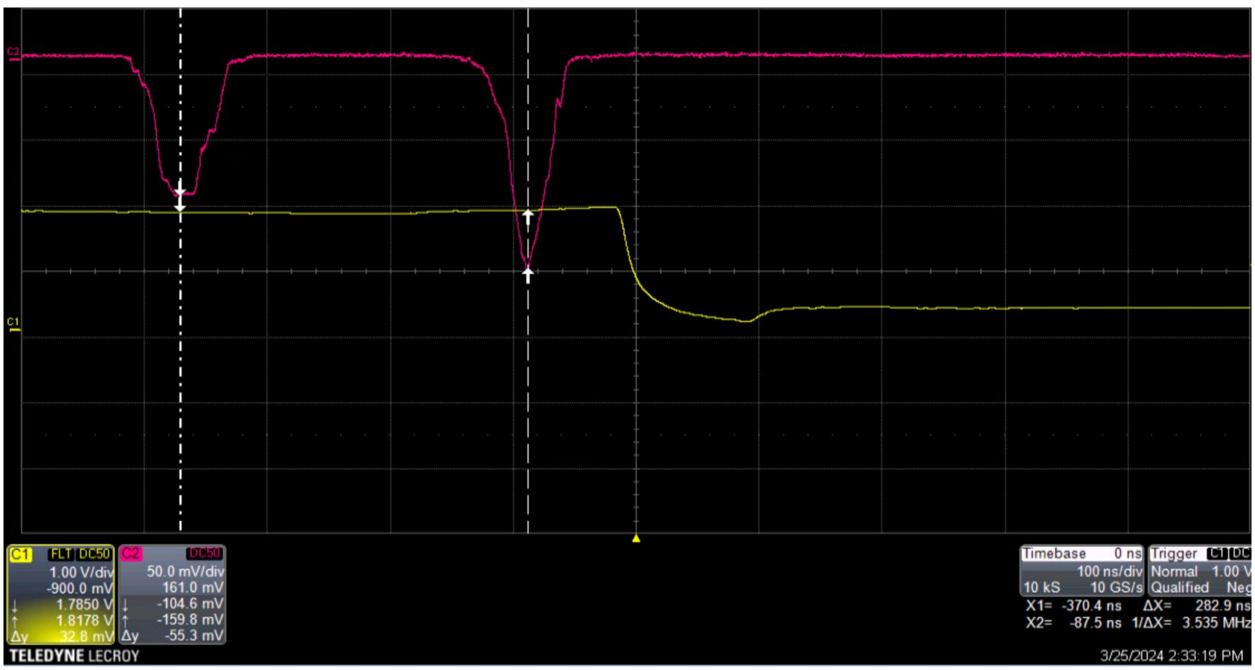

Figure 5: The first (left) and second (right) transfers on the WCM (red trace) at At0+1850 ms. The bunch from the first transfer is much larger than the one from the second because it was not well matched at injection and beam control is not on before the 2nd transfer. 100 ns/div. The yellow trace is the Rev tick. Also, the bunches are 283 ns apart.

Figure 6 shows how the first transfer looks when it is well matched and shows what the first transfer looks like at the 2nd transfer together with the 1st transfer. These are not on the same cycle but are under the same conditions. It appears that the first transfer may have deteriorated somewhat after spending 1050 ms on the porch without beam control on even when it is well matched when injected.[17] There is some cycle-to-cycle variation as well. The dual harmonic is

[17] See Booster-AGS-pp April 10 2024 elog 17:35 to 17:38 entries.

also used throughout the injection porch and the bunches are quad pumped to reduce the peak current when the bunch is injected.

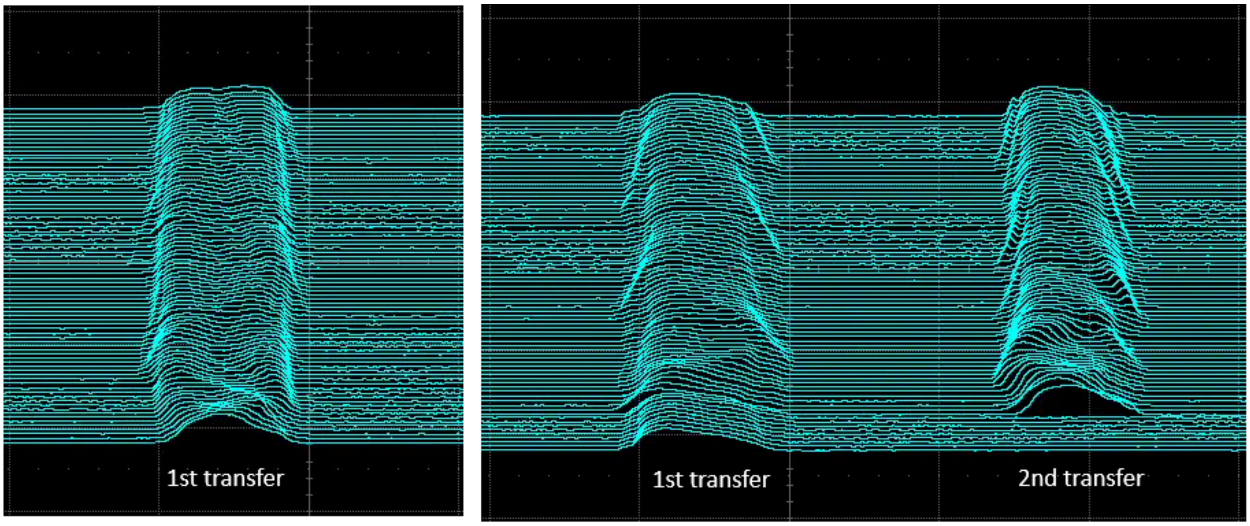

Figure 6: WCM Mountain range displays for the 10 ms after the first transfer (left) and for 10 ms after the 2^{nd} transfer showing both bunches (right).

There were a few polarization measurements taken on AU2 and the polarization was quite low. The source polarization was also low and the tune jump quads were off but that is not enough to account for how low they were. The vertical tune at the major resonances and the "36+ bump" were OK.

The average of 10 measurements was 29.2% with a standard deviation 6.0%. The average AGS Late for the measurements was 1.64e11. The source averaged 69.9% for these measurements with a standard deviation of 0.8%.[18] The first 5 were taken with vertical target 3 and the last 5 were taken with horizontal target 1. The averages for the 2 sets were 34.2% (σ=5.2%) and 25.7% (σ=3.2%), respectively. The target profiles for the latter set did not look good, they had double peaks. The day before on AU4, with jump quads off, it was 57%.[19]

Figure 7 shows the A15 normalized current transformer on AU2. This is taken with the nominal snake setup except with tune jump quads off. There is some acceleration loss, which is typical for the snake setup on any user. There is also some slow loss on the injection porch. The AGS Late intensity here is about 3.5e11.[20]

The AGS IPM can be used to look for emittance growth on the injection porch. The beam is bunched and the β functions are distorted due to the snakes but an increase in the reported values across the porch should be indicative of growth. Figure 8 shows the transverse emittances across the injection porch for the cycle shown in Figure 7. ε_y is about 5.5 π mm mr and shows no sign of growth, but ε_x gradually grows from about 14 to 18 π mm mr. This growth may be

[18] See Booster-AGS-pp April 10, 2024 elog entries from 20:55 to 22:41 by T. Dankworth and E Becker.
[19] See Booster-AGS-pp April 10, 2024 elog 13:56 entry by H. Huang
[20] Taken from the Booster-AGS-PP April 10, 2024 elog 15:52 entry

correlated with the loss shown in Figure 7 which is more or less representative of AU2. Whether it could be reduced is unclear, although there was some effort to reduce the injection porch loss there was no direct attempt to reduce the growth.

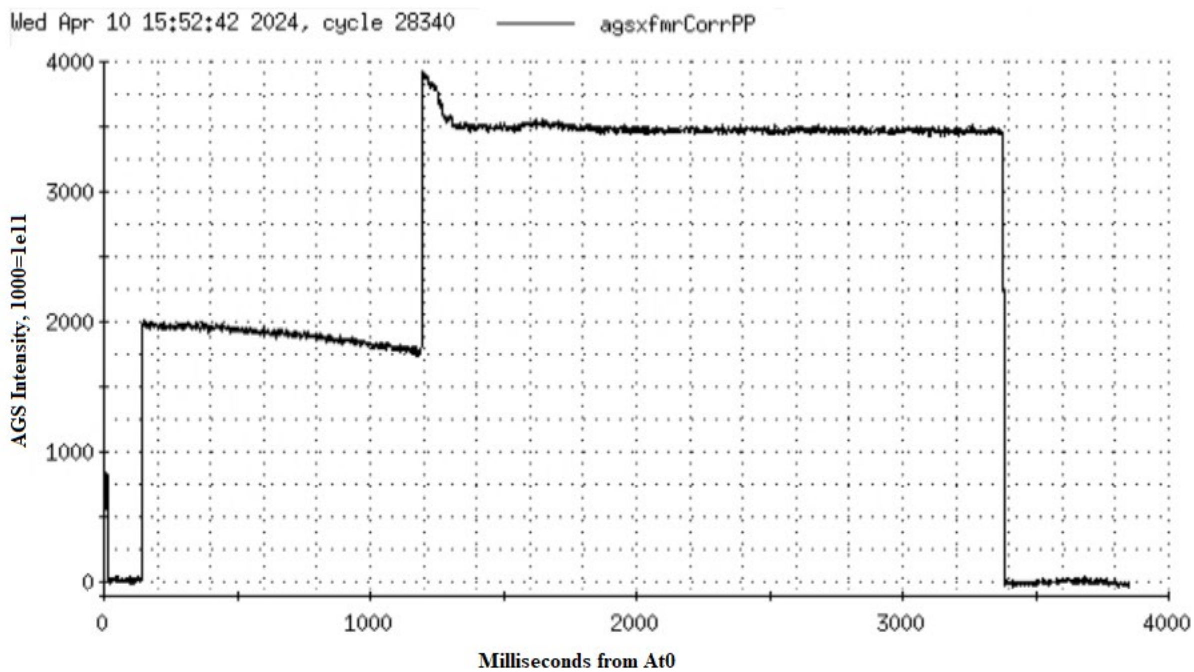

Figure 7: The A15 normalized current transformer on AU2. This is with the snakes on setup.

More IPM data is available to look at this growth as a function of injected bunch intensity. The IPM data in Figure 9 is at a much lower bunch intensity, 0.8e11 vs. 2.0e11. The intensity was lowered by reducing the pulse width. In this case, not only is growth not apparent in either plane but the reported emittances are smaller, (12, 3.5) π mm mr. The latter may just be the case because of the space charge effect bunched beam has on the measurement. The slow loss is still there.[21] At a bunch intensity of 1.3e11 there is still no growth but the emittances are again larger than the 0.8e11 case and smaller than the 2.0e11 case.[22] At a bunch intensity of about 1.6e11 though there is horizontal growth, from about 11.5 to 15 π mm mr, and again no vertical growth. So, there may be a threshold between a bunch intensity of 1.3 and 1.6e11 where horizontal growth starts to appear.[23] In all these cases the pulse width was used to change the bunch intensity.

AU2 was also used in September to measure the asymmetry at injection energy. For some reason the measurements were intensity dependent. There were 2 sets of measurements. The injected bunch intensity was about the same (3e9) for both, but the beam survival was not as good for the first set. In that case the asymmetry was about -570 and for the second set it was

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[21] The Booster-AGS-PP April 10, 2024 elog 17:35 entry has a plot of the current transformer for that cycle (17:36:37). Although there is still a slow loss on the porch the acceleration losses are much smaller than for the higher intensity case.

[22] They are about (14,4.5) π mm mr. See AGS (AU2) IPM logged data April 10, 2024 15:16:32 and Booster-AGS-PP April 10, 2024 15:16 entry.

[23] See Booster-AGS-pp April 10, 2024 elog 18:51 entry.

about -490.[24] The source polarization was about 76%. In 2017 an average of 4 measurements at injection was -769 (σ=3.3) and the average source polarization was 86.1%.[25] The lower source polarization, 76 vs. 86% is not enough to account for this difference. -769*(76/86)=-680.

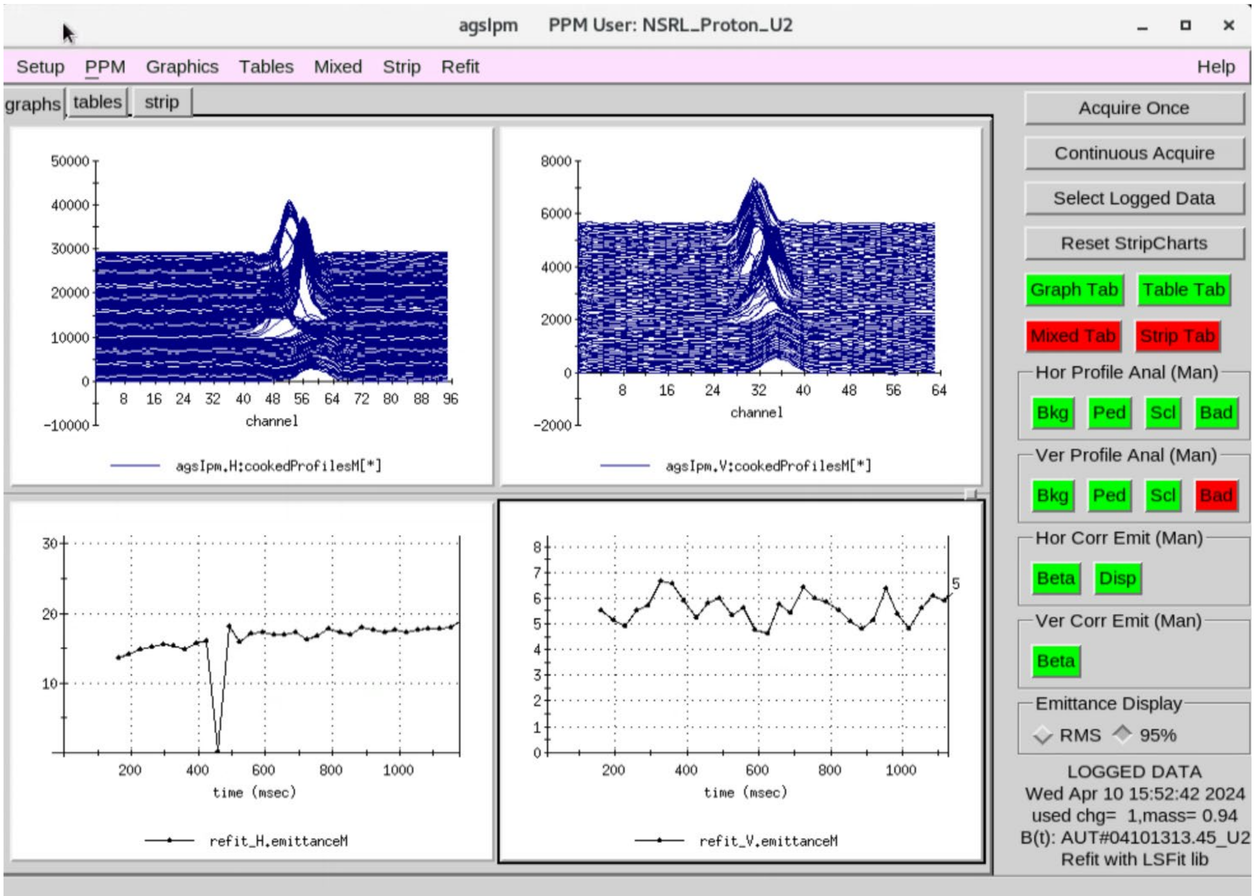

Figure 8: The AGS IPM emittances on the AU2 injection porch for the cycle shown in figure 7. The bunch intensity is about 2.0e11.

To improve the beam survival on the porch the RF voltage was lowered. Before it was improved the intensity near the end of the porch was about 2.0e9, and afterwards it was about 2.75e9. This intensity dependence was not expected. If say, particles with a larger emittance were preferentially lost, one would expect the asymmetry to be higher (more negative) in the first case only if the asymmetry were dependent on the particle emittance (i.e.-there is a polarization profile). But measurements from years ago have not shown this dependence and it is not theoretically expected at AGS injection energy.[26]

[24] See Booster-AGS-pp Sept. 16, 2024 elog 23:16 entry by H. Huang.
[25] See Booster-AGS-pp Sept. 16. 2024 elog 17:44 entry by H. Huang
[26] See comments attached to Booster-AGS-pp Sept. 16, 2024 elog 23:16 entry by H. Huang.

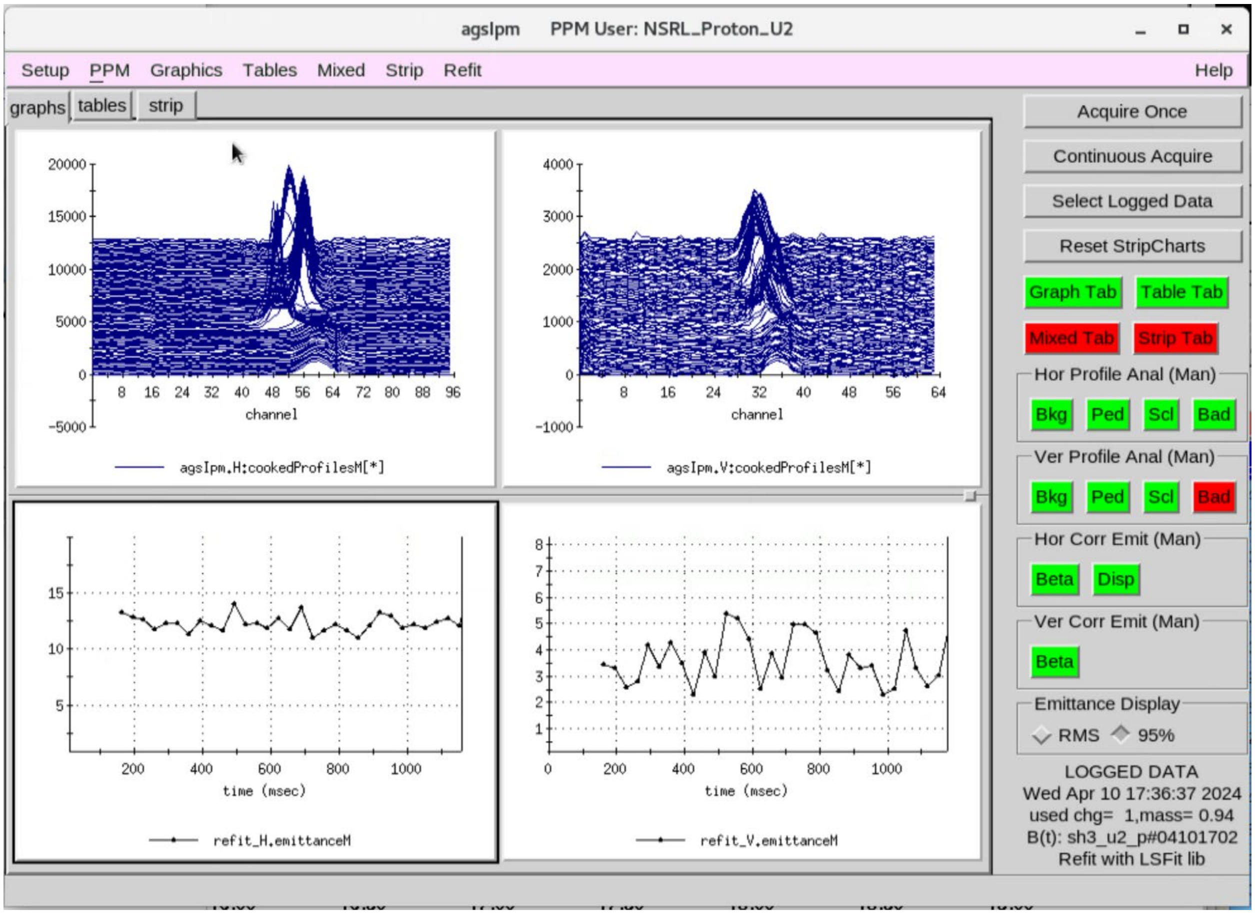

Figure 9: The AGS IPM (95%) emittances on the AU2 injection porch for a bunch intensity of about 0.8e11. The RF is on. $(\varepsilon_x,\varepsilon_y)=(12, 3.5)\ \pi$ mm mr. Snakes are on.

Modification to the Split-Merge Setup in Run 24

Quad pumping is used at Booster extraction in the standard BU4/AU4 setup to reduce the peak current in a bunch at AGS injection. In Run 22, I was unable to make the peak current using quad pumping less than if just the RF voltage were reduced, and so the latter was used. In this state the peak current during the first 500 µs after injection was comparable to its value on the BU4/AU4 cycle. Since it may be that blowup occurs right at injection this is a problem. The peak current of the BU3/AU3 bunches a millisecond or more after injection is less than 70% of the peak current on BU4/AU4, but if it is higher before that there may be no benefit from the lower peak current then. So, this year the Booster magnet cycle was modified so that the bunches could be extracted at close to zero dB/dt so the RF voltage could be lowered more.[27]

After these modifications the bunch length right at injection could be made long enough to reduce the peak current to 70% or less of its value on BU4/AU4 for the same Booster Late

[27] K. Zeno, The 2022 Polarized Proton Run in the Injectors, C-A/AP/685, October 2022, see bottom of pg.16 for discussion of the peak current.

intensity.[28] Figure 10 is a comparison of the magnet cycle used in Run 22 and the one used this run. In Run 22 extraction occurred at Bt0+210.76 ms and that was moved about a jiffy later to Bt0+227.237 ms in Run 24. The new magnet cycle reference is identical up until Bt0+200.0 ms and Gγ=4 happens about 4.2 ms before that.

Before switching to the new magnet cycle effort was made to improve the quad pumping at extraction and some progress was made but it was decided to modify the magnet cycle anyway.[29]

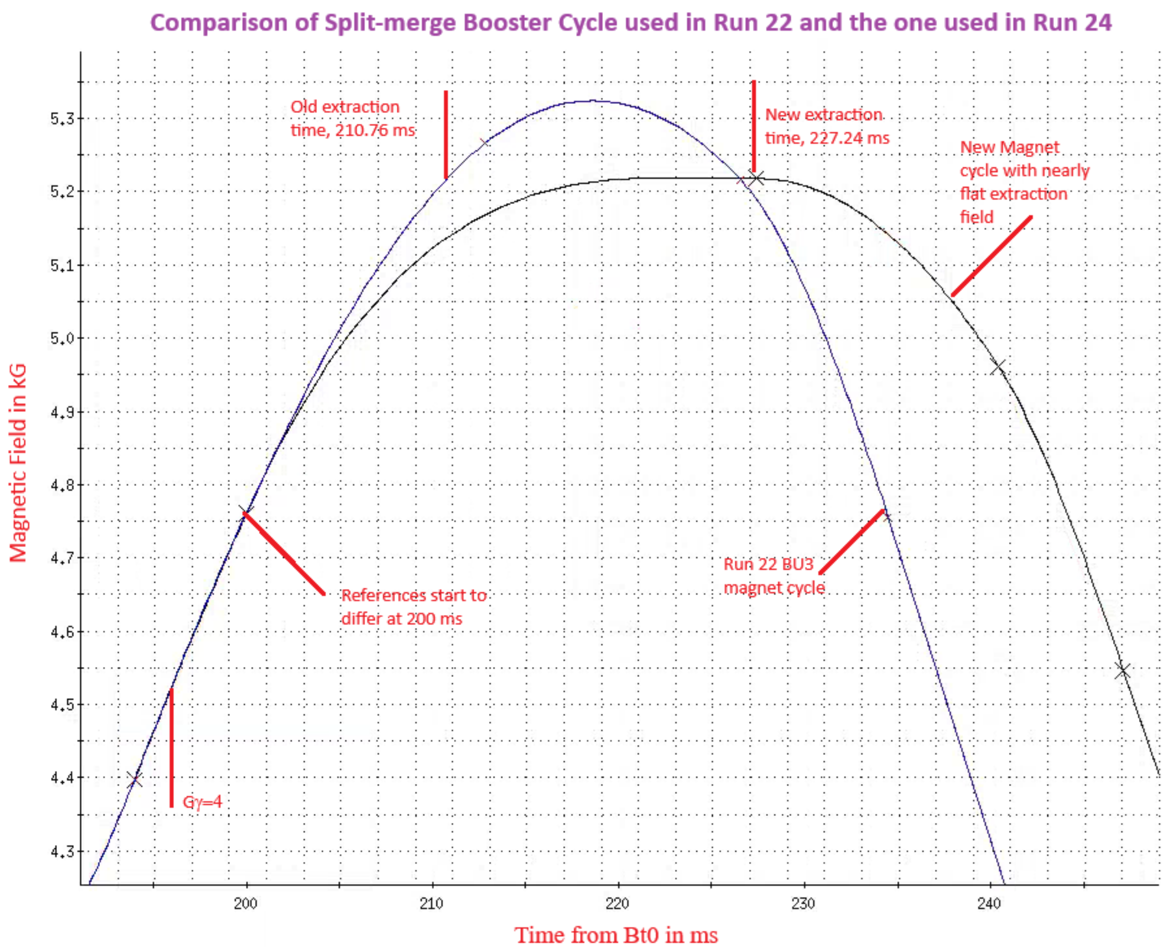

Figure 10: Comparison of the Booster magnet references used in Run 22 and 24 showing that, in Run 24, extraction occurs when the field is nearly flat which allows the RF voltage to be lowered more than in Run 22 to reduce their peak current.

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[28] Compare 15:40 and 18:39 entries in Booster-AGS-PP Mar 6 2024 elog. In both cases the WCM is shown over the first 5 ms or so after injection. In the 15:40 plot the top trace is BU3/AU3 in the Run 22 state. The bottom trace shows the WCM on BU4/AU4 over that interval with about the same (total) intensity. The 18:39 entry shows BU3/AU3 after the changes to the main magnet, extraction timing, RF voltage, etc at a similar total intensity.

[29] Booster-AGS-pp Feb 16, 2024 13:25 entry compares QP on BU3 then with how it looked in Run 22. The Booster WCM signal available to MCR is also rather poor and there may be some sort of saturation occurring which prevents proper display of the quad pumping.

Figure 11 shows the 2 bunches on the first turn with and without the voltage near extraction lowered. The narrower bunches in the saved trace are about 75 ns long, roughly about what they were in Run 22, whereas with the voltage lowered they are about 130 ns long and the peak current is greatly reduced.[30] There is another side of the coin though: If the bunches become too wide the F3 kicker will not have enough time to rise between the 2 bunches. The F3 kicker fine delay can be adjusted to minimize the horizontal width on MW006 and to see how sensitive the horizontal width is to longer bunches.

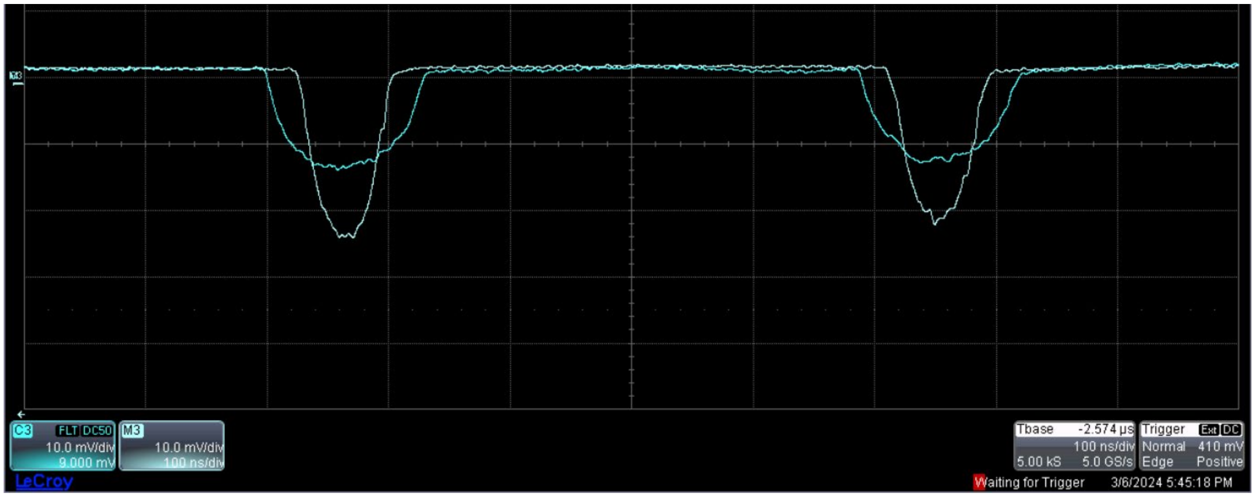

Figure 11: AGS WCM at injection on BU3/AU3 with near zero dB/dt at Booster extraction and RF voltage lowered (C3) and without it lowered (M1).

It is also important that the F3 kicker modules be lined up. This was done several times during the latter part of the run and in August the F3 setpoint was also lowered from 31 to 25 kV. In this state the 10 to 90% risetime of the kicker module sum signal was 110 ns. After some adjustments the transfer efficiency was the same for 25 kV as it was for 31 kV.[31]

The h=3 bucket length at extraction is 245 ns, so the time between the right side of 1 bunch and the left side of the other, in adjacent buckets, *R*, is equal to 2*[(245ns/2)-(*d*/2)] where *d* is the bunch length. *R* is the time the F3 kicker must rise in to not kick part of a bunch. As the bunches get wider *R* gets smaller and for a 130 ns long bunch it is 115 ns. The optimal bunch length is limited by the kicker rise time. The length can be varied by adjusting the RF voltage while watching the MW006 horizontal width and scanning the F3 fine delay.

It was scanned in this case and there was about a 40 ns window where the horizontal width was nearly constant. Within this range, it did not appear to be any wider (or narrower) on BU3 than on BU4. The fine delay was also checked frequently during the run.[32]

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[30] Figure 11 is from Booster-AGS-pp Mar 6, 2024 elog 17:46 entry. See also K. Zeno, The 2022 Polarized Proton Run in the Injectors, C-A/AP/685, October 2022, pg. 16 for length in Run 22. For the wide case the A3 RF voltage reference was 0.5 kV and the B3 reference was 1.7 kV.
[31] See Booster-AGS-pp Aug 9, 2024 elog 17:48 entry.
[32] See Booster-AGS-pp Jan. 3, 2025 elog for a record of changes to the fine delay on BU3 during the run.

Transverse Emittance vs. Intensity on Normal and Split-Merge Cycle Flattops

How the Flattop Emittance Measurements were Made

In Run 17 there were AGS Late vs. AGS flattop transverse emittance scans made, with and without the dual harmonic in the AGS.[33] Similar scans were made this year for the split-merge and standard BU4/AU4 cycles. BtA emittance data does not exist for the Run 17 scans but does for the scans made this year.

It is not straightforward to measure the flattop emittance with the AGS IPM. The RF needs to be turned off to eliminate the space charge effect of bunched beam on the measurement. However, when the RF is turned off the horizontal emittance drops to some minimum and then starts to increase, but if the intensity is low enough it does not start to increase. Many years ago this did not happen (maybe because the intensity was lower), but it has been happening since at least 2015.

Figure 12 shows logged data for the RF vector sum and radial average signal in the case where the RF is shut off at 940 ms and AGS Late is about 3e11. Although there is very little RF voltage apparent on the vector sum after the RF has been shut off, the radial average still has a signal from the beam indicating it is still bunched to some extent. The beam is dumped just after At0+2300 ms and it is only then that the beam signal disappears.

A working hypothesis for the observed behavior is that the horizontal emittance (ε_x) appears to increase across the flattop because the interaction with the cavities increases the beam's momentum spread. That is why it only grows in the horizontal. But regardless of the reason something is happening and there is no reason to think that the larger measurements are the better ones. In 2017, when the RF was shut off at 1000 ms, the reported ε_x reached its minimum near 1050 ms. That is the value that was used for ε_x then. In the vertical, the minimum was reached near 1100 ms, and the average value of ε_y on the flattop after that is what was used for ε_y.[34]

Figure 13 shows a typical set of measurements this year on AU4 with the RF shutting off at 940 ms (a few milliseconds after extraction time) and an AGS Late of 3e11. The average value of the data at 1014, 1030.5, and 1047 ms for both planes was used since in the AU4 case the vertical data generally had a minimum near 1050 ms or so and then would increase somewhat just after that (this may have had to do with the extraction bump collapsing). The same data points are used for the split-merge measurements. On AU4 the extraction bump collapses from 1000 to 1100 ms and it is not on at these times on AU3.

For both BU3/AU3 and BU4/AU4 AGS Late was scanned from 0.8 to 3.0e11 in steps of 0.2e11. For each intensity step ten of the measurements described above were taken.

[33] K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", C-A/AP/594, October 2017. See pgs. 19-21 and Figure 18 in particular.

[34] See footnote 38 (pg. 30) in K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", C-A/AP/594, October 2017 for an explanation of how the flattop emittance was measured in 2017.

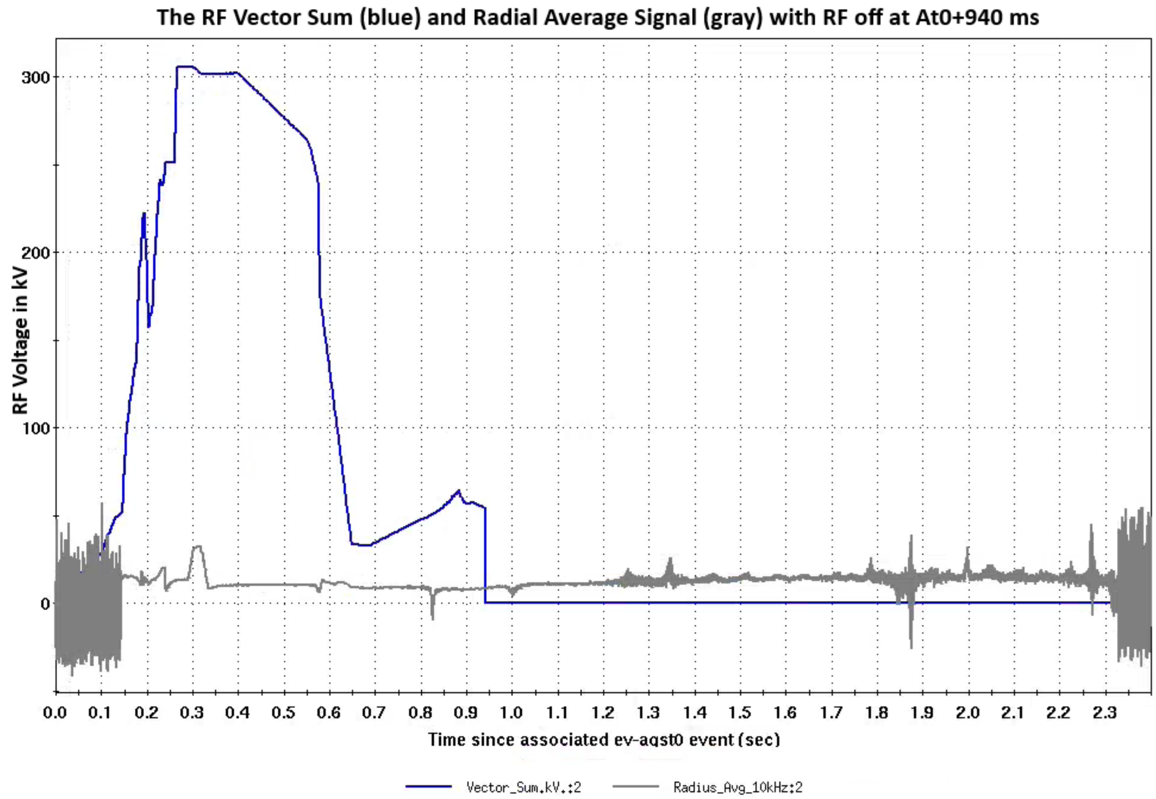


Figure 12: The vector sum (*Vector_Sum.kV,* in blue) and radial average signal (*Radial_Avg_10kHz,* in gray) on AU3 with RF shutting off at 940 ms and an AGS Late of about 3e11. Taken from Ags/RF/LLRF/agsDspAll.logreq . It is the cycle on Sept. 23, 2024 that starts at17:44:09.[35]

Flattop Emittance Measurements

Figures 14 and 15 show the results for BU4/AU4 and BU3/AU3, respectively.[36] The emittances on the split-merge cycle are smaller at higher intensities. For the standard setup with 3.0e11 (ε_x, ε_y) are (19.4, 18.6) π mm mr and for the split-merge they are (16.5, 15.8) π mm mr. However, in 2017, using the same basic setup as BU4/AU4 this year, (ε_x, ε_y) were about (14.3, 15.5) π mm mr somewhat smaller than even the split-merge setup.

Emittance measurements at BtA MW006 were also taken this year for both AGS setups and each intensity step.[37] Figure 16 shows the results which indicate that even though there was a fixed amount of scraping the emittances coming out of the Booster were intensity dependent and the dependence was strongest for BU4 and in the horizontal. For BU4, as AGS Late varies from 0.8 to 3.0e11, the fit for ε_x grows by a factor of (9.19/6.80)=1.35 and the fit for ε_y by a

[35] At lower intensities the beam signal on the radial average goes away when the RF is shut off. See Booster-AGS-pp Jan. 9, 2025 14:06 entry

[36] See Booster-AGS-pp 2024 elog. The BU4/AU4 scans are in the September 22nd elog (entries from 16:46 to 18:04). The BU3/AU3 scans are in the September 23rd elog (entries from 17:43 to 18:20)

[37] The BtA MW006 data can be found along with the IPM data for the scans in the elog (see footnote 36).

factor of (4.55/3.60)=1.28. For BU3, the ε_x fit grows by a factor of (7.61/6.33)=1.20 and ε_y, although the fit has a slightly positive slope, doesn't show a significant dependence.

The flattop measurements for each user and intensity can be scaled by the ratio of the emittance at 0.8e11 over the emittance at the intensity for a particular measurement to try to distinguish between growth in the Booster and growth in the AGS. For example, for AU3 and 3e11, ε_x for one of the measurements on the flattop was 16.13 π mm mr and at MW006 it was 7.83 **π** mm mr. ε_x for AU3 and 0.8e11 at MW006 was 6.475 π mm mr. So, the scaled ε_x measurement at 3e11 would be (6.475/7.83)(16.13) π mm mr=13.34 **π** mm mr. The same thing can be done for ε_y on the flattop but this only needs to be done for BU4, since ε_y on BU3 doesn't show obvious intensity dependence.

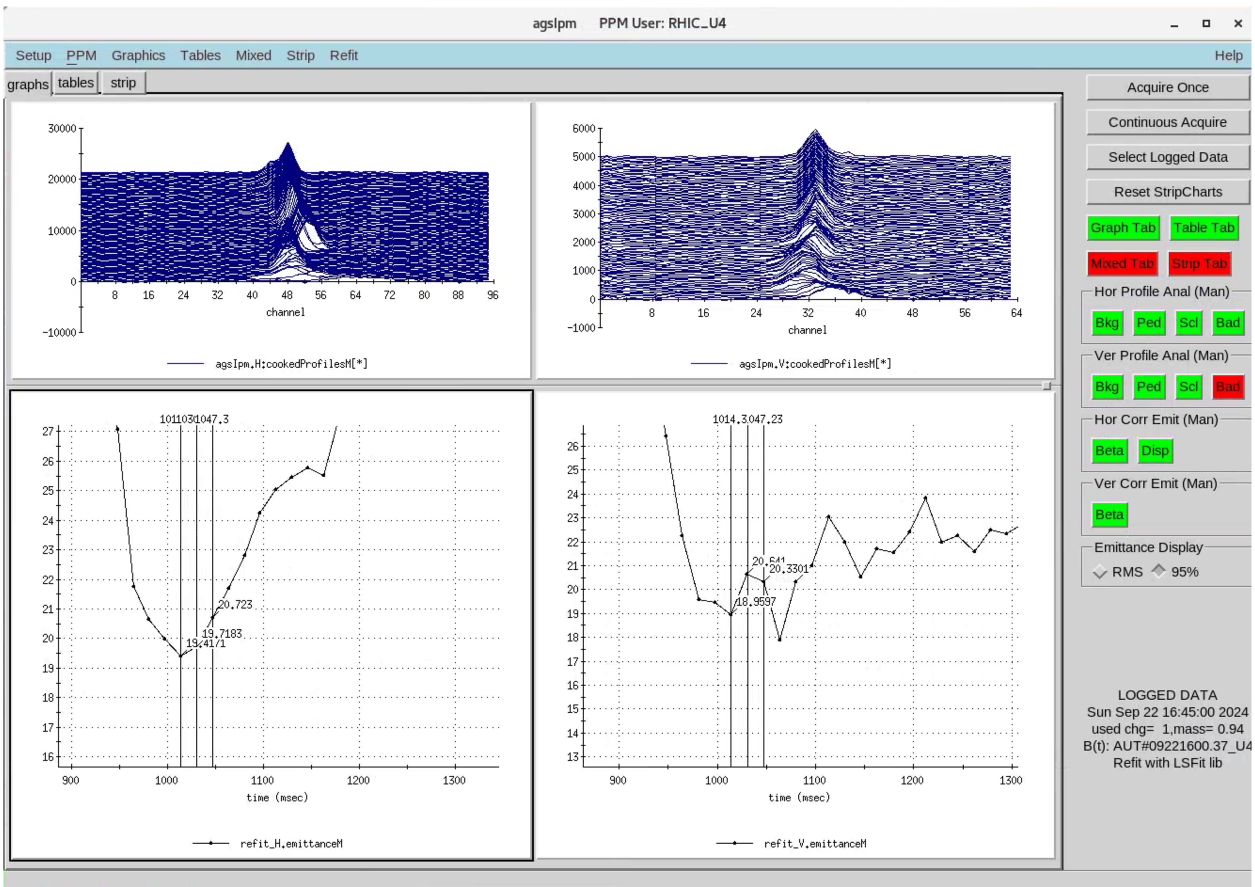


Figure 13: A set of AGS IPM measurements on AU4 with 3.0e11 AGS Late and RF shutting off at 940 ms. The vertical cursor lines indicate which data points are used for the measurements (1014, 1030.5, and 1047 ms). This logged data is from Sept.22 2024, 16:45:00 and it uses Refit.

Figure 17 contains the scaled flattop emittances for the standard and split-merge setups. When they are scaled there is less intensity dependence but there is still a fair amount. For the standard setup the scaled horizontal and vertical emittances are roughly equal independent of AGS Late. The horizontal is generally smaller than the vertical for the split-merge. The scaled emittances on the standard cycle are similar to those measured on the flattop in 2017. It is

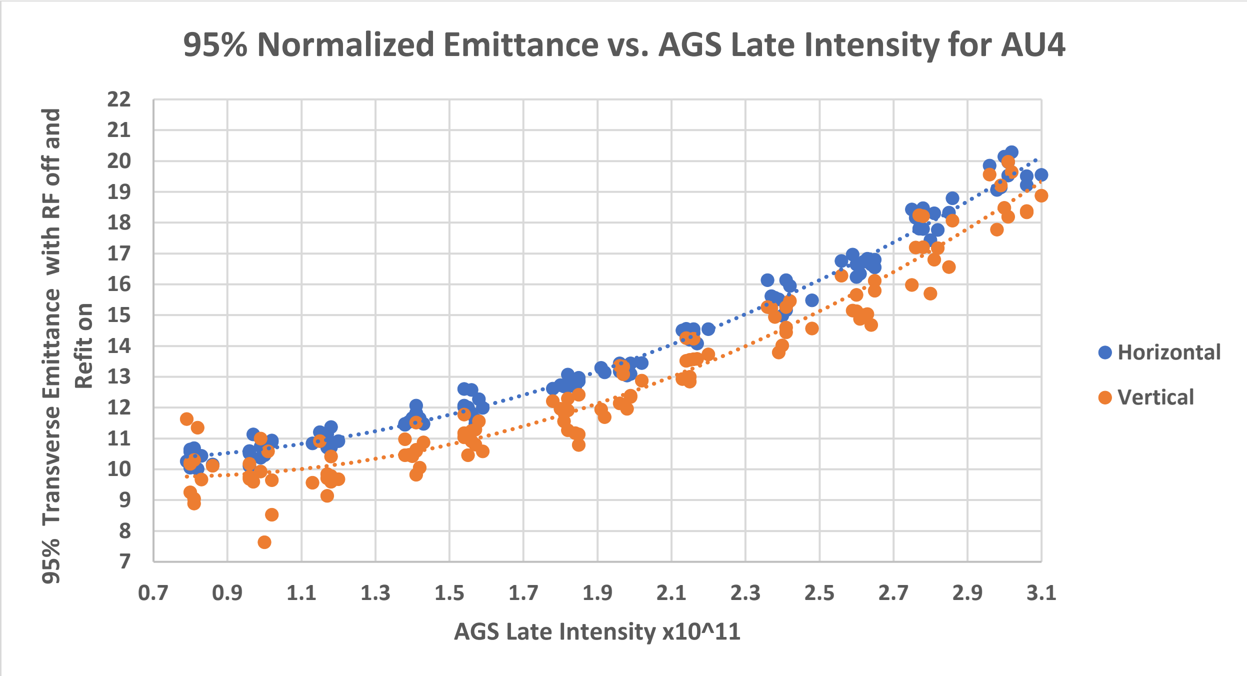


Figure 14: AGS IPM transverse 95% normalized emittances as a function of AGS Late for the standard BU4/AU4 setup (snakes on, tune jump quads on) in π mm mr. The dashed lines are quadratic fits to the data, $\varepsilon_x=1.44N^2-1.39N+10.61$ and $\varepsilon_y=1.68N^2-2.38N+10.60$, where N is AGS Late. The intensity was varied by adjusting the Linac pulse width with a constant amount of scraping.

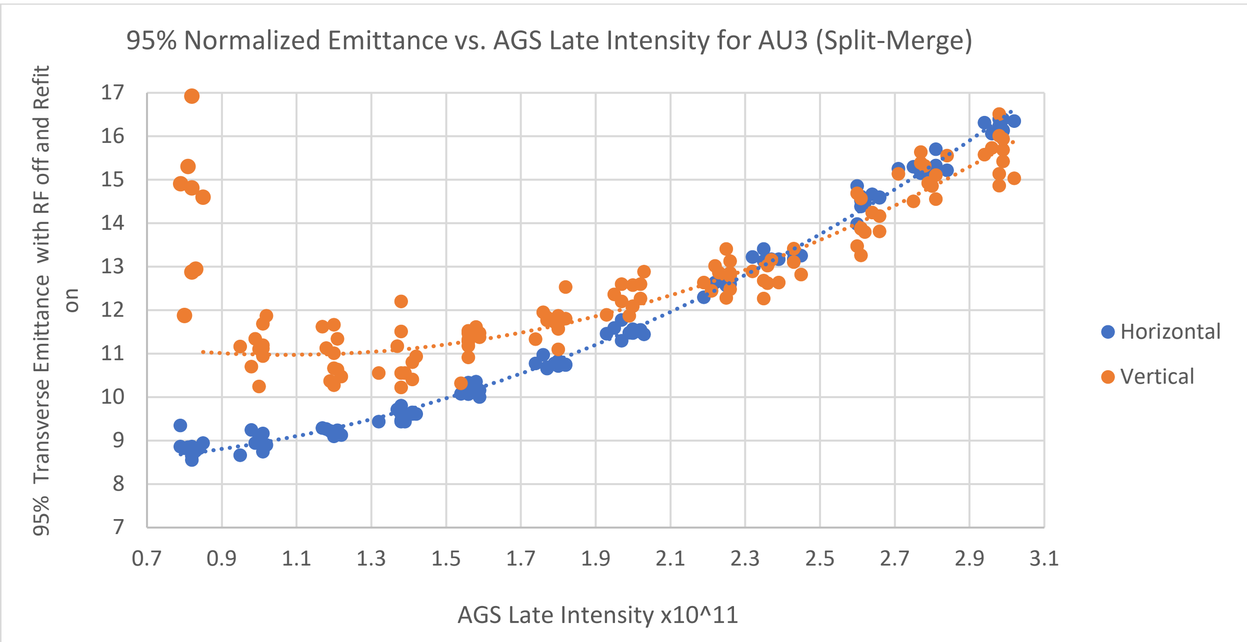
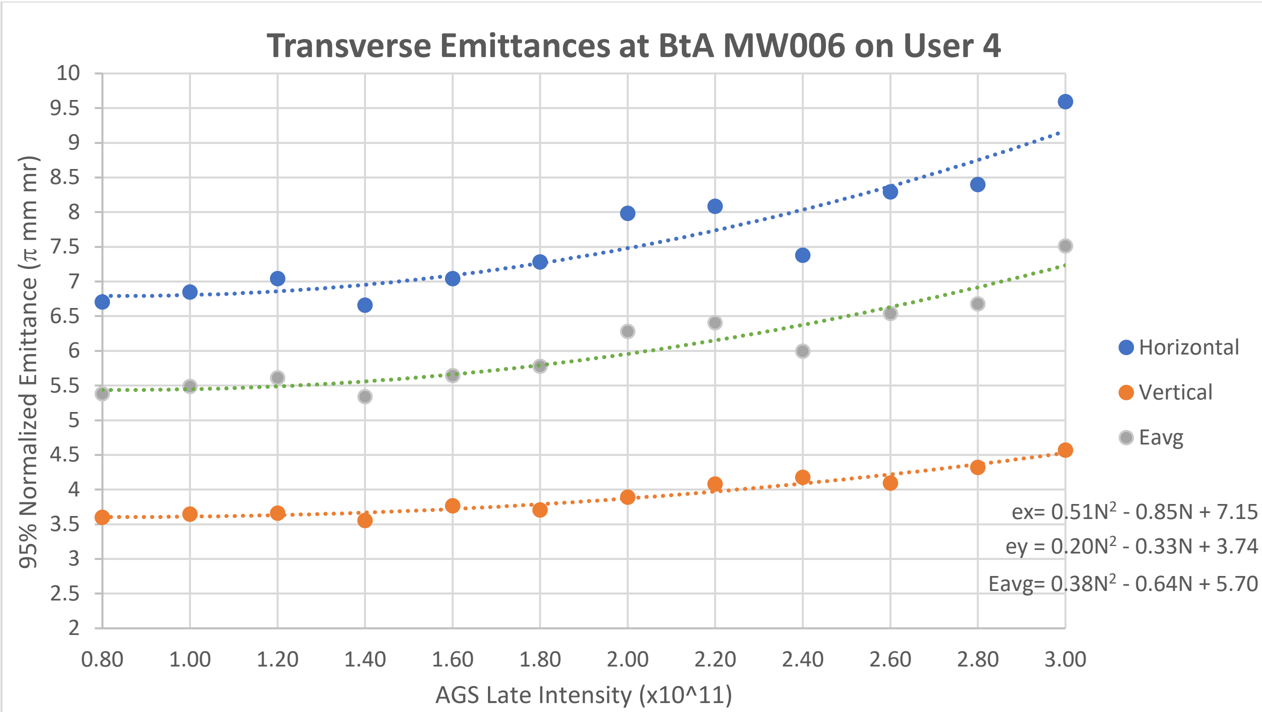


Figure 15: AGS IPM transverse 95% normalized emittances as a function of AGS Late for the split-merge BU3/AU3 setup (snakes on, tune jump quads on) in π mm mr. The dashed lines are quadratic fits to the data, $\varepsilon_x=1.15N^2-0.82N+8.61$ and $\varepsilon_y=1.30N^2-2.78N+12.46$, where N is AGS Late. The intensity was varied by adjusting the Linac pulse width with a constant amount of scraping. There was something wrong with the 0.8e11 vertical data so it was not included in the fit.



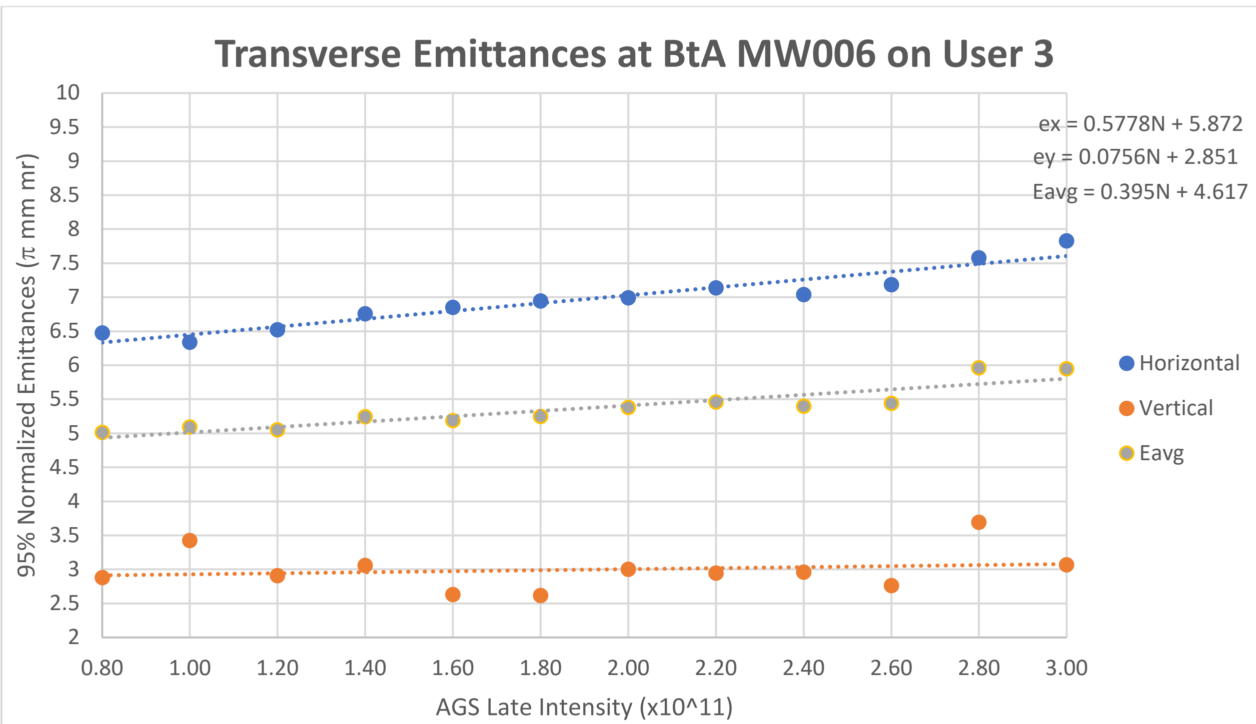
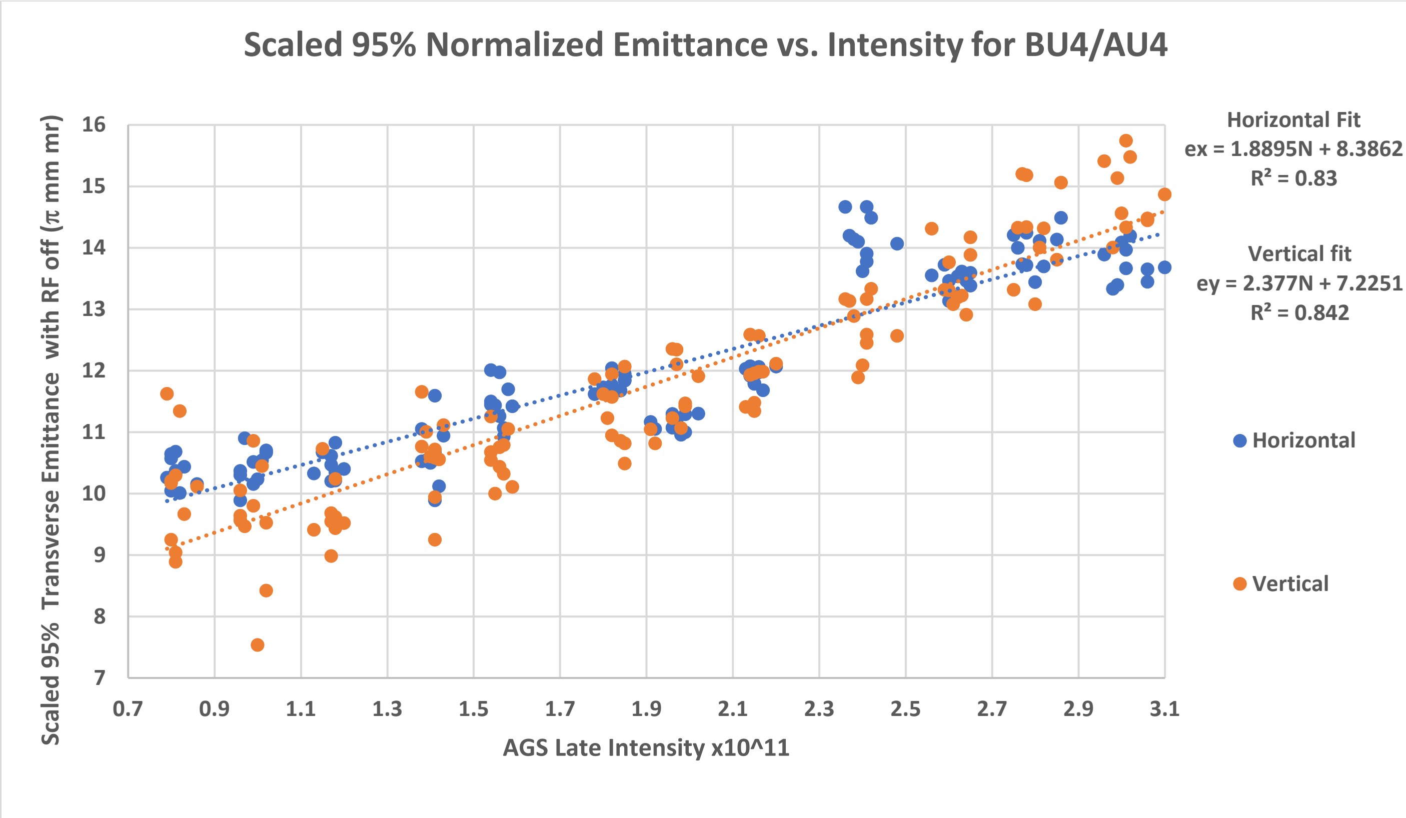


Figure 16: BtA MW006 multiwire horizontal and vertical 95% normalized emittances as a function of AGS Late for the BU4/AU4 (top) and BU3/AU3 (bottom) setups. Where the average emittance (E_{avg}) is defined as $\sqrt{(\epsilon_x^2 + \epsilon_y^2)/2}$ and ε_x=0.82($fwhm\_x$)^2 π mm mr and ε_y=0.155($fwhm\_y$)^2 π mm mr, where *fwhm_x* and *fwhm_y* are the Full Width Half Max (in mm) of the Gaussian fit of the horizontal and vertical profiles, respectively. Fits to the data are also shown



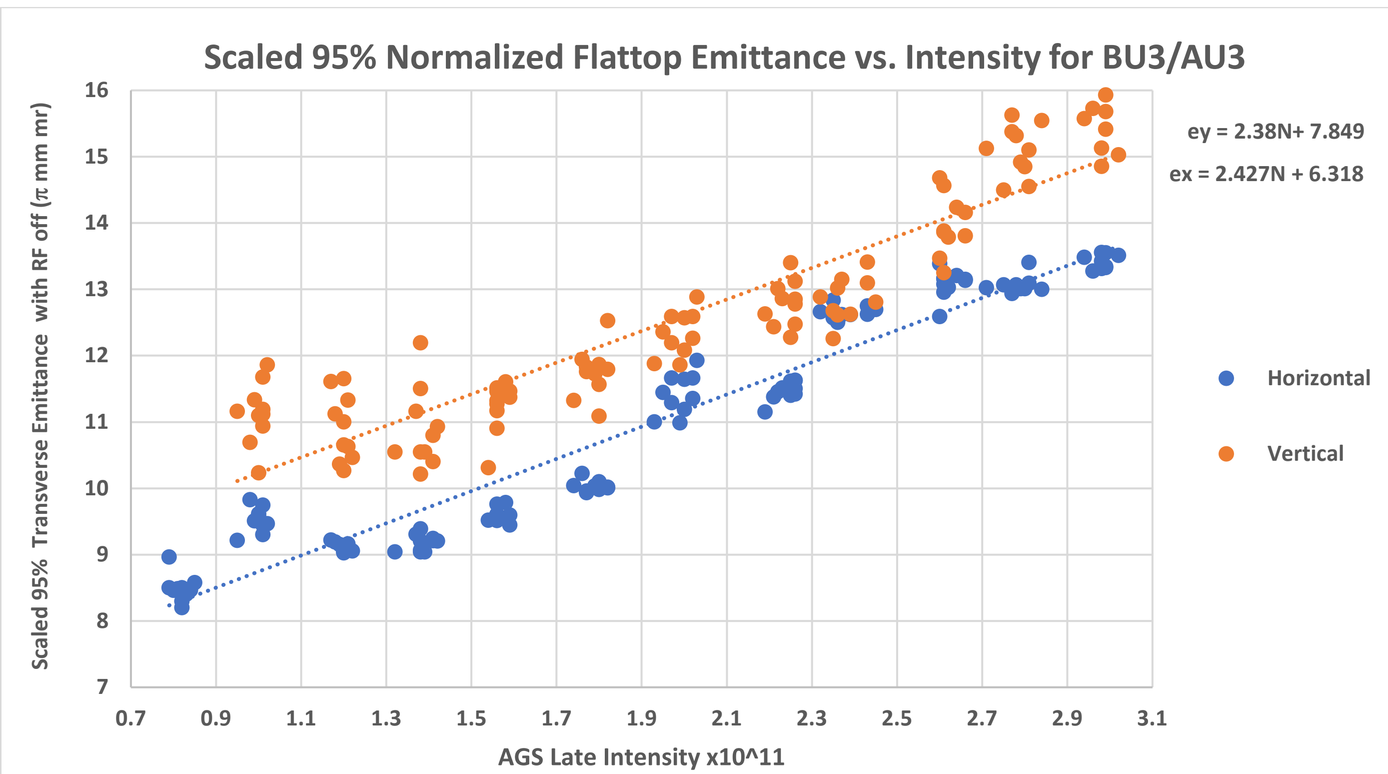


Figure 17: 95% Normalized flattop emittances scaled by BtA emittance growth for BU4/AU4 (top) and BU3/AU3 (bottom). Linear fits to the data are also shown.

tempting to speculate that the intensity dependence of the BtA emittance was significantly less then.

Figure 18 is a plot of the scaled data but as a function of *E_{avg}*, which is defined as $\sqrt{(\epsilon_x^{*2} + \epsilon_y^{*2})/2}$ where ε_x^* and ε_y^* are the scaled horizontal and vertical emittances, respectively. The fits for the 2 sets of data are also shown and are nearly identical and the split-merge E_{avg} does not seem to benefit at higher intensities. So, if this intensity dependence is real it would seem that it depends on the total intensity not a bunch's peak current.

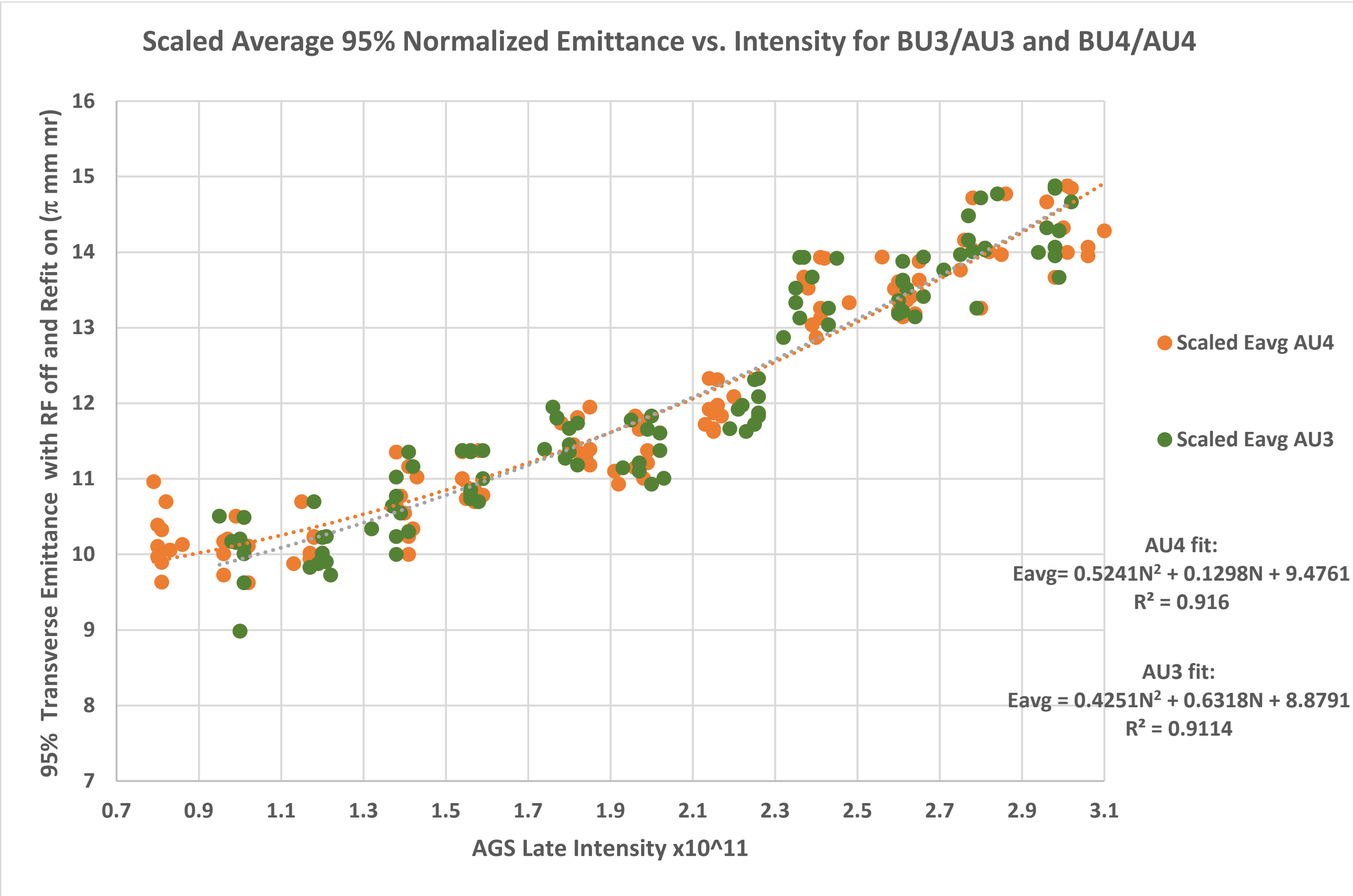


Figure 18: The average emittance, defined as $E_{avg}=\sqrt{(\epsilon_x^{*2} + \epsilon_y^{*2})/2}$, for the AU3 and AU4 flattop emittance data where ε_x^* and ε_y^* are ε_x and ε_y scaled by the BtA MW006 emittance growth.

The fields where the scrapes occur are the same for both setups and the horizontal scrape occurs at a lower field than the vertical one does (see Figure 19). For both cases the vertical scrape was relaxed to provide an AGS Late of 3.0e11 with a 300 µs pulse. The BU4/AU4 setup needed less scraping than BU3/AU3 did to be able to provide 3.0e11. It seems there are at least 2 reasons for this. The first was that when the BU3/AU3 measurements were performed Booster input was about 10% higher (6.0 vs. 6.6e11) for a 300 µs pulse. The second reason is that the efficiency through the AGS was better with BU3/AU3. This efficiency will also tend to be better if more scraping is used in the Booster, but in general the AGS efficiency is better with BU3/AU3 perhaps because the bunches have a lower momentum spread.

Table II shows the intensities through the injectors for the 2 setups at 0.8e11 and 3.0e11.

Setup	BU3/AU3	BU4/AU4
Booster Input	6.6e11	6.0e11
Booster Early	5.5e11	5.0e11
Booster Late	3.45e11	3.65e11
AGS Early	3.15e11	3.55e11
AGS Late	3.0e11	3.0e11

Setup	BU3/AU3	BU4/AU4
Booster Input	1.57e11	1.2e11
Booster Early	1.4e11	0.97e11
Booster Late	0.85e11	0.85e11
AGS Early	0.9e11	0.87e11
AGS Late	0.8e11	0.8e11

Table II: Intensities at different times in the injectors for BU3/AU3 and BU4/AU4 in the AGS Late equals 3.0e11 case (left) and equals 0.8e11 case (right).

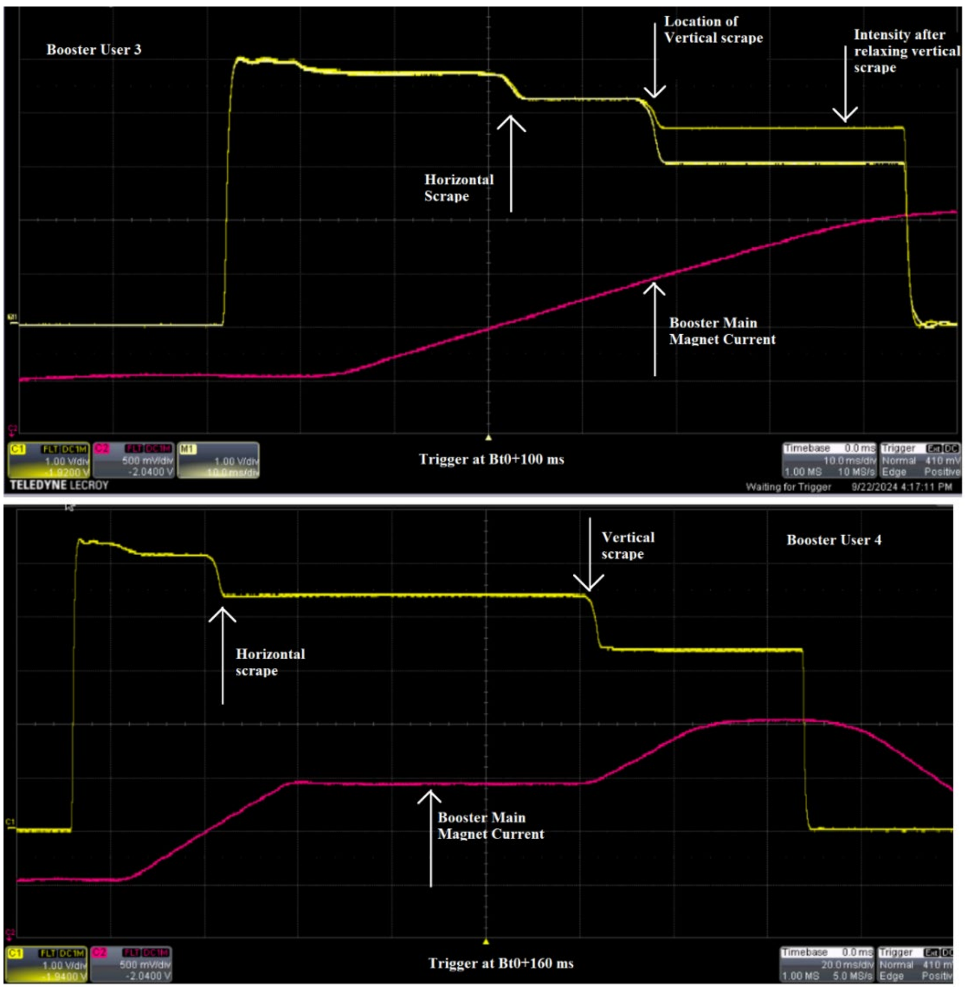


Figure 19: The horizontal and vertical scrapes used for the scans on BU3 (bottom) and BU4 (top). The yellow traces are the Booster normalized current transformer. The AGS Late intensity in both cases is about 3.0e11 and the Linac pulse width is 300 µs. The sweep speed for the top plot is 20 ms/div and it is 10 ms/div for the bottom plot. The red traces are the Booster magnet current. The yellow traces are 1V/div.

Booster Input

The Booster Input during the 2017 intensity scans was about 6.9e11 for a 300 µs pulse.[38] Recall that Booster input was 6.6e11 for the BU3/AU3 scan and 6.0e11 for the BU4/AU4 scan. The calibration of the Booster input scaler was checked on July 10th against the HEBT transformer on a scope and it read 5.15e11 when the scope read 4.85e11.[39] So, the scaler was reading 6% high then. The granularity of the scaler gain leaves something to be desired. This means that instead of 6.0 and 6.6e11 the input may have been lower than that, say 5.7 and 6.2e11 respectively. Since the Booster input scaler gain was not changed during the run, it may have been lower than the actual Linac intensity by a similar amount. Figure 20 shows the Booster Input adjusted for this, Booster Late, and AGS Late through the run.

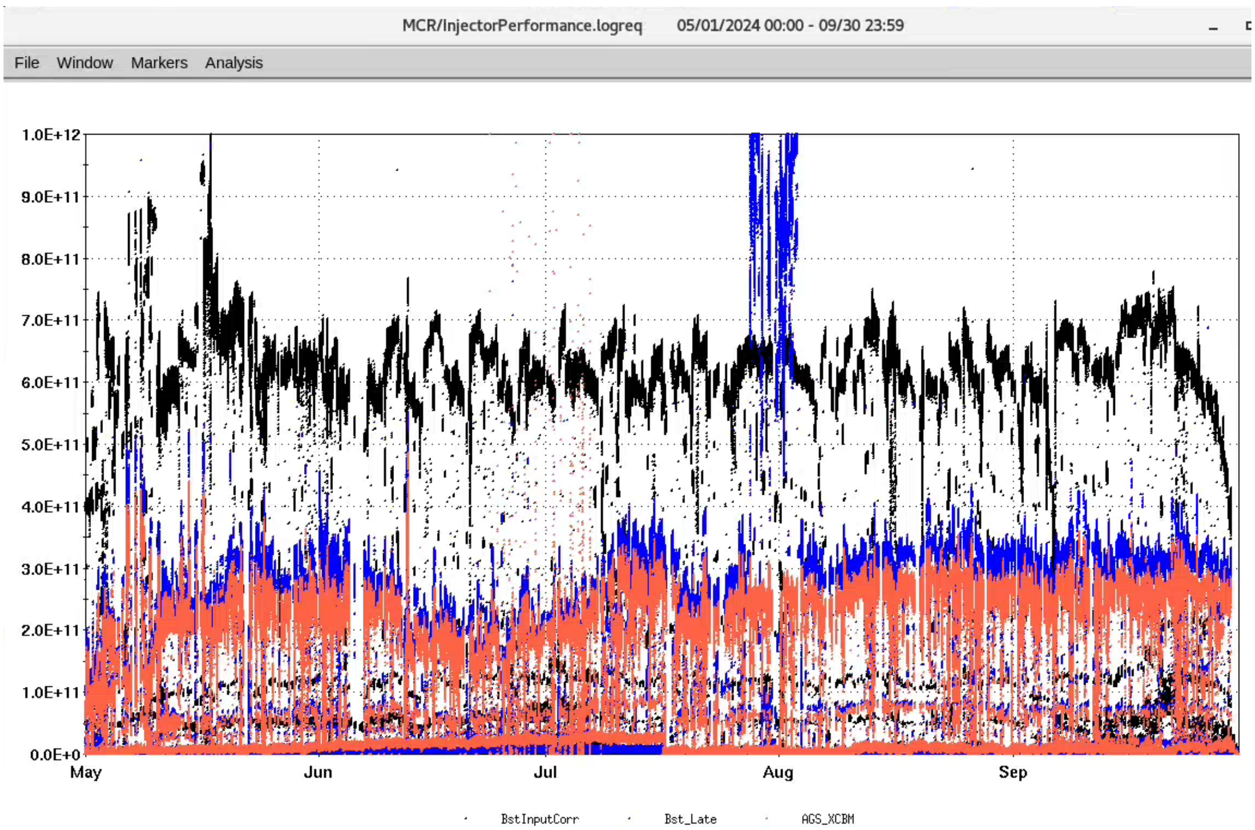


Figure 20: The "adjusted" Booster Input (black), Booster Late (blue), and AGS Late (red) intensity scalers during the PP run (May 1 to Sept. 30). The "adjusted" Booster Input is the actual Booster Input multiplied by 0.94.

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[38] See K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", C-A/AP/594, October 2017. Bottom of page 19.

[39] This is with a gain setting of 9. See Booster-AGS-pp July 10, 2024 elog entry at 14:36. The granularity could be reduced by changing the counts per volt parameter but then the Booster input would saturate at about 1.0e12 (for a 300 µs pulse) which is not OK because there needs to be a way to detect and log it if the intensity goes higher than that since the Booster proton intensity limit is 1.5e12 per cycle. In this configuration it saturates at 1.5e12, see Booster-AGS-pp Feb. 14, 2024 elog entry at 15:13. There were other problems with Booster input during the early part of the run that are summarized in the May 22, 2024 14:30 elog entry.

The input averaged about 7e11 for most of Run 17[40], and judging from Figure 20, it looks like it averaged between 6.0 and 6.5e11 for most of this run. In Run 22, Booster input trended upward from about 5.5e11 at the beginning (in December) to nearly 7.0e11 near the end of the run (in April).[41] A higher Booster Input allows for more scraping which should provide a smaller transverse emittance at Booster extraction.

Booster Late vs. Booster Input

In my note summarizing the 2017 PP run I argued that although there was no MW006 data for the flattop emittance vs. AGS Late scans that were performed then that the fact that Booster Late vs. Booster Input during the scans was linear indicated that the emittance at Booster extraction was likely nearly constant as the Linac pulse width was varied.[42] For this year's scans there is MW006 data available and there is intensity dependent growth observed at Booster extraction. So, Booster Late vs. Booster input can be checked to see if it was linear this year. Figure 21 contains this data. Linear fits for the BU3 and 2017 BU4 data are very good. A quadratic does a better job fitting the 2024 BU4 data than a linear one but the difference is subtle.

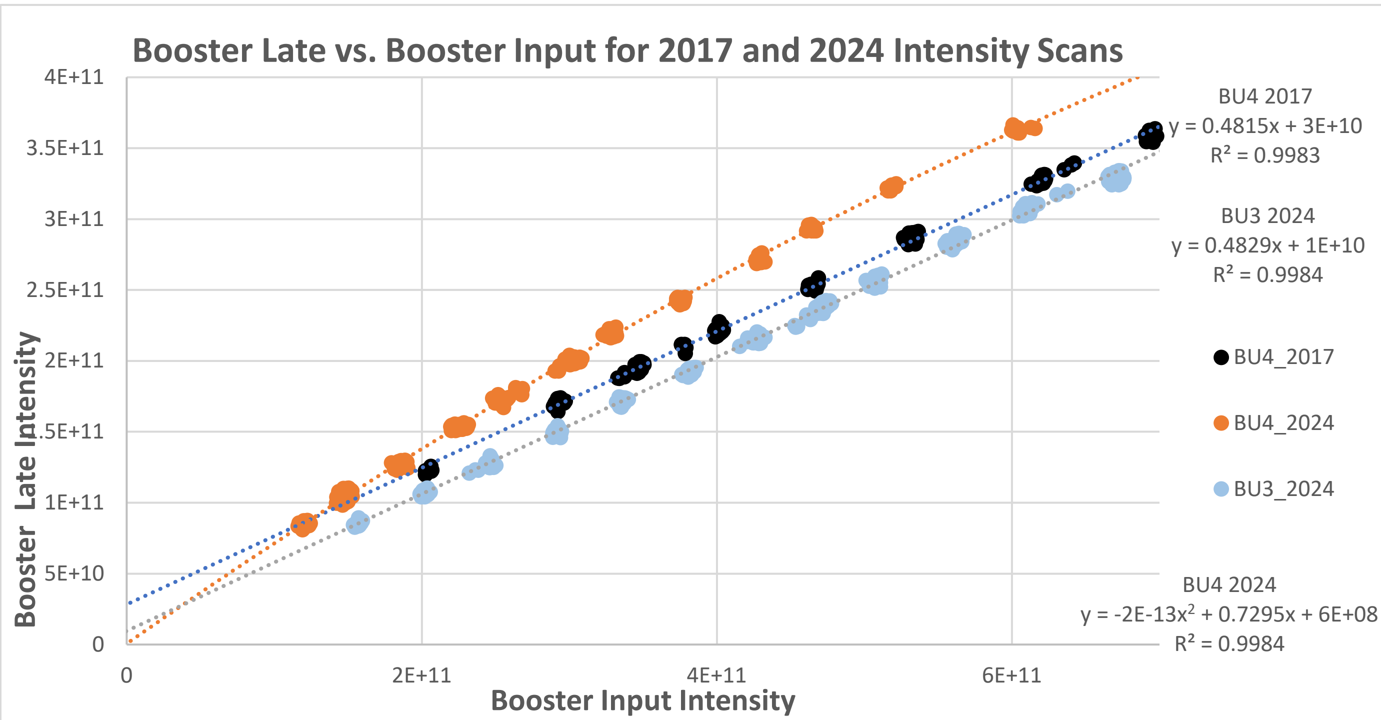

Figure 21: Booster Late vs, Booster Input for the Flattop emittance scans this run (BU3 in blue and BU4 in orange) and in 2017 (black) together with fits, linear for BU3 and 2017 BU4 and quadratic for BU4 this run.

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[40] K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", C-A/AP/594, October 2017. See pgs. 30-31.

[41] K. Zeno, The 2022 Polarized Proton Run in the Injectors, C-A/AP/685, October 2022, Figure 18 on page 31.

[42] K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", C-A/AP/594, October 2017. See pg. 23.

Although there is not as much intensity dependent growth on BU3 as BU4 there still is growth on BU3 and Booster Late vs. Booster Input is linear. So, it is not true that if it is linear there will be no intensity dependent growth observed at Booster extraction.

If there is intensity dependent growth only in the horizontal between the 2 scrapes and there is not much coupling occurring in that part of the cycle, then the vertical scrape would not scrape any of the horizontal growth off and Booster late vs. Booster input would still be linear.

Figure 22 is a plot of the percentages remaining after scraping during the BU4/AU4 flattop emittance vs. AGS Late scan. The percentage of the beam remaining after being scraped horizontally, vertically, and in both planes are shown.[43]

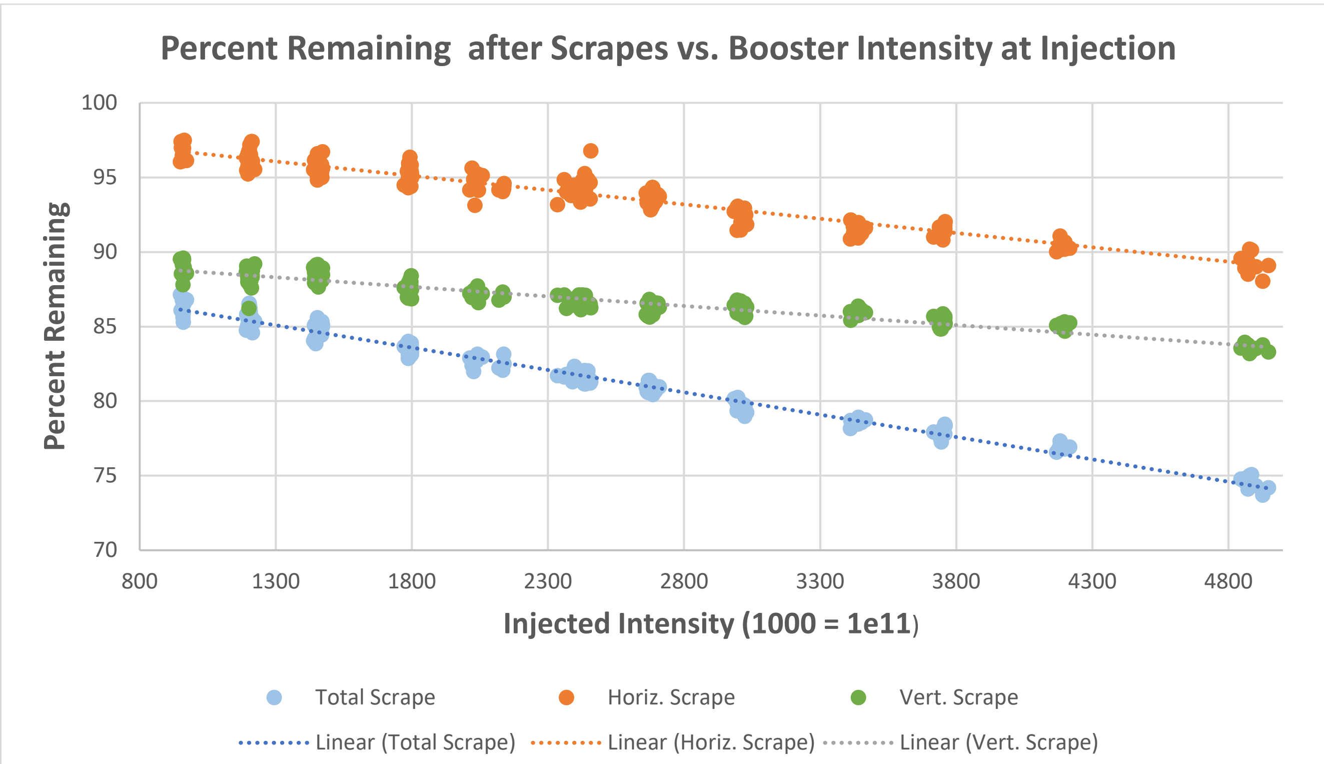

Figure 22: The percentages of beam remaining after scrapes as a function of the injected intensity (basically Booster Early) on BU4 this run. The Horiz. Scrape data (orange) is the intensity just after the horizontal scrape divided by the intensity just before it, and similarly for the vertical (green). The total scrape (blue) is the intensity just after the vertical scrape divided by the intensity just before the horizontal scrape. The only significant losses between those 2 times are from the scrapes (see Figure 19).

The Effect of NSRL Mode Switches

NSRL mode switches typically affect the amount of beam that gets through the scrapes, but this run the effect seemed significantly less than it has been. In fact, it was at times not noticeable. The D6 septum is thought to be the main culprit. Its current goes to zero during a

[43] This data was logged for BU4 and is found in Logview under "MCR/Personal/Kelz/BoosterPPScrape.logreq". Unfortunately, this data is not available for BU3.

mode switch and then usually ramps up to a different current.[44] During this hysteresis cycle the amount of beam that makes it through the scrapes typically varies. Also, the amount of beam that gets through the scrapes after the mode switch is complete is often different than before it as well. But Figure 23 shows the scraped intensity during a mode switch on Sept. 16. In this case the scrapes appear to be unaffected.[45] In another case (see Figure 24), the vertical scrape drops about 3% during a D6 hysteresis cycle, but afterwards Booster Late returns to what it was before it even though the D6 current has changed significantly.

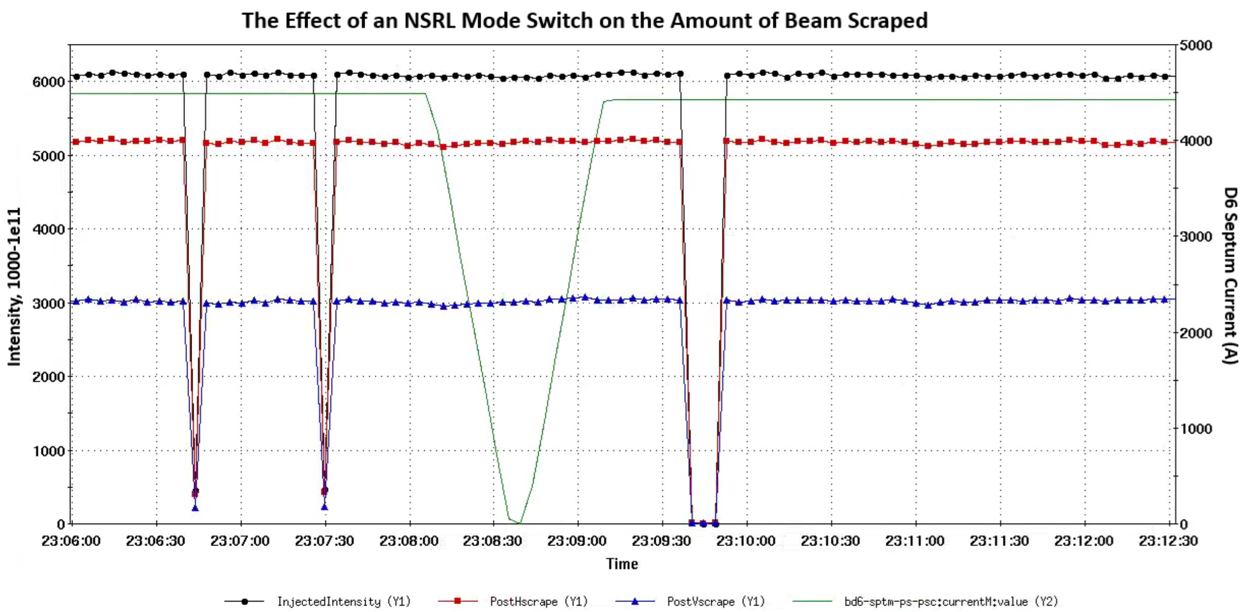

Figure 23: The intensity just after injection (black), just after the horizontal scrape (red), and just after the vertical scrape (blue) together with the D6 current (green, y-axis on right) during an NSRL mode switch on Sept. 16th.

AGS Flattop Polarization vs. AGS Late Intensity for Split-Merge and Standard Setup

Scans of the polarization vs. AGS Late were performed on Aug. 24th for both users. There was some bad data noticed after the fact on AU3 which has been removed so there is not as much data for AU3. The intensity was varied in steps of 0.5e11 from 3e11 to 0.5e11 by changing the vertical scraping. For AU4 this was done 3 times for a total of 18 data points. For AU3 the same is true except there are only 15 data points because for one set the points at 0.5, 1.0, and 1.5e11 are missing. Figures 25 and 26 show the data together with fits for AU4 and AU3, respectively. It is evident that the slope of the AU3 data is less steep, the AU3 data has

[44] K. Zeno, The 2022 Polarized Proton Run in the Injectors, C-A/AP/685, October 2022, Figure 26 on page 40.
[45] Compare Figure 24 on pg.38 of K. Zeno, The 2022 Polarized Proton Run in the Injectors, C-A/AP/685, October 2022.

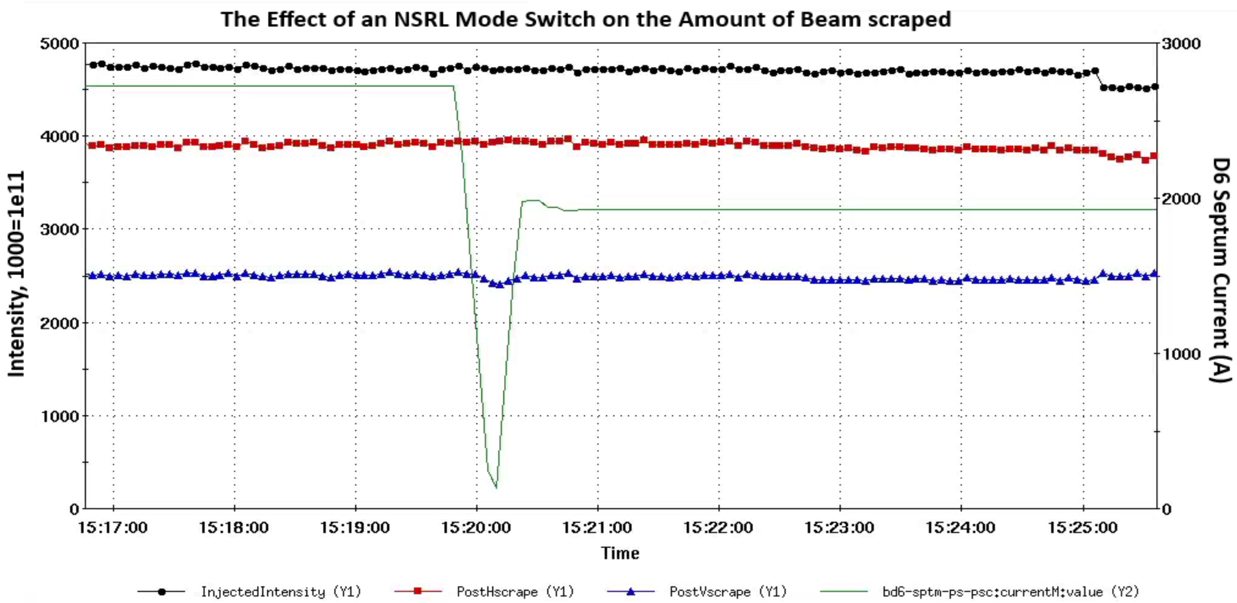

Figure 24: The intensity just after injection (black), just after the horizontal scrape (red), and just after the vertical scrape (blue) together with the D6 current (green, y-axis on right) during an NSRL mode switch on Sept. 5th.

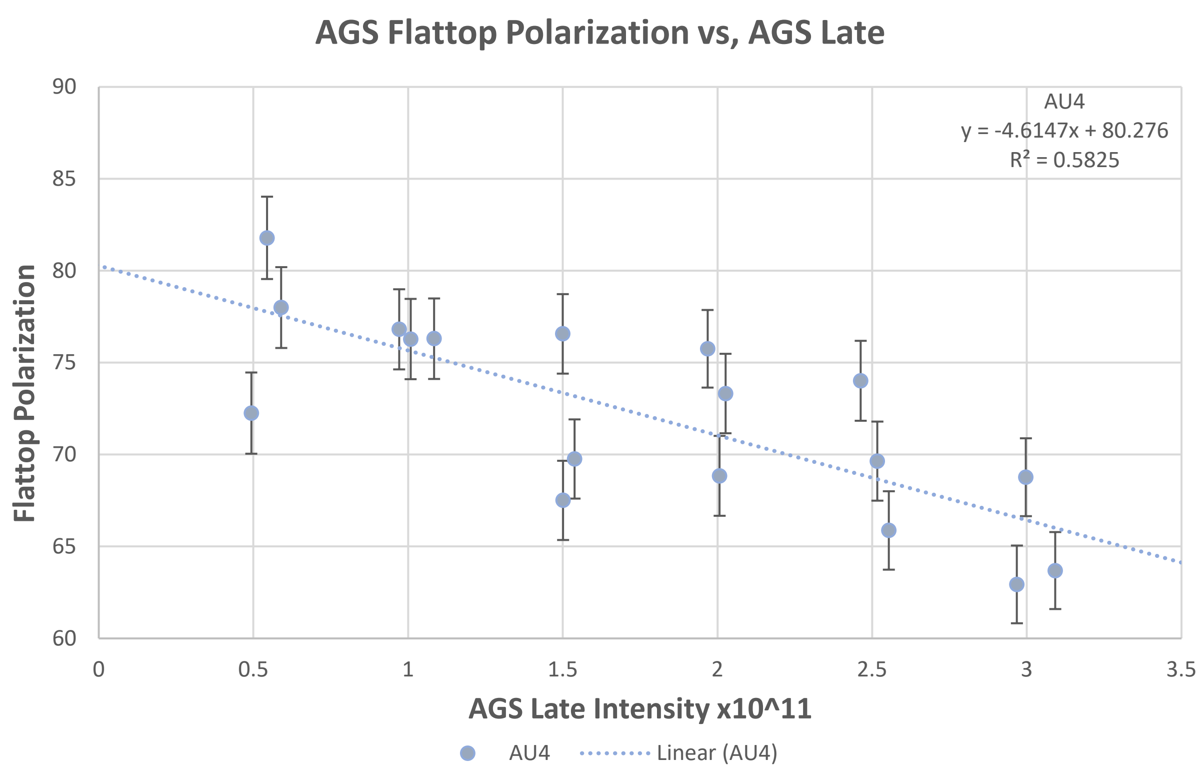

Figure 25: The AGS Flattop Polarization vs. AGS Late intensity scans for AU4 together with a linear fit, *P(I)=-4.6147(I)+80.276*. Intensity was varied using vertical scraping and the pulse width was set to 300 μs. Vertical target 3 was used. The error bars are +/- the ErrFit parameter in the Krisch display. The data was taken on Aug. 24th by T. Dankworth.

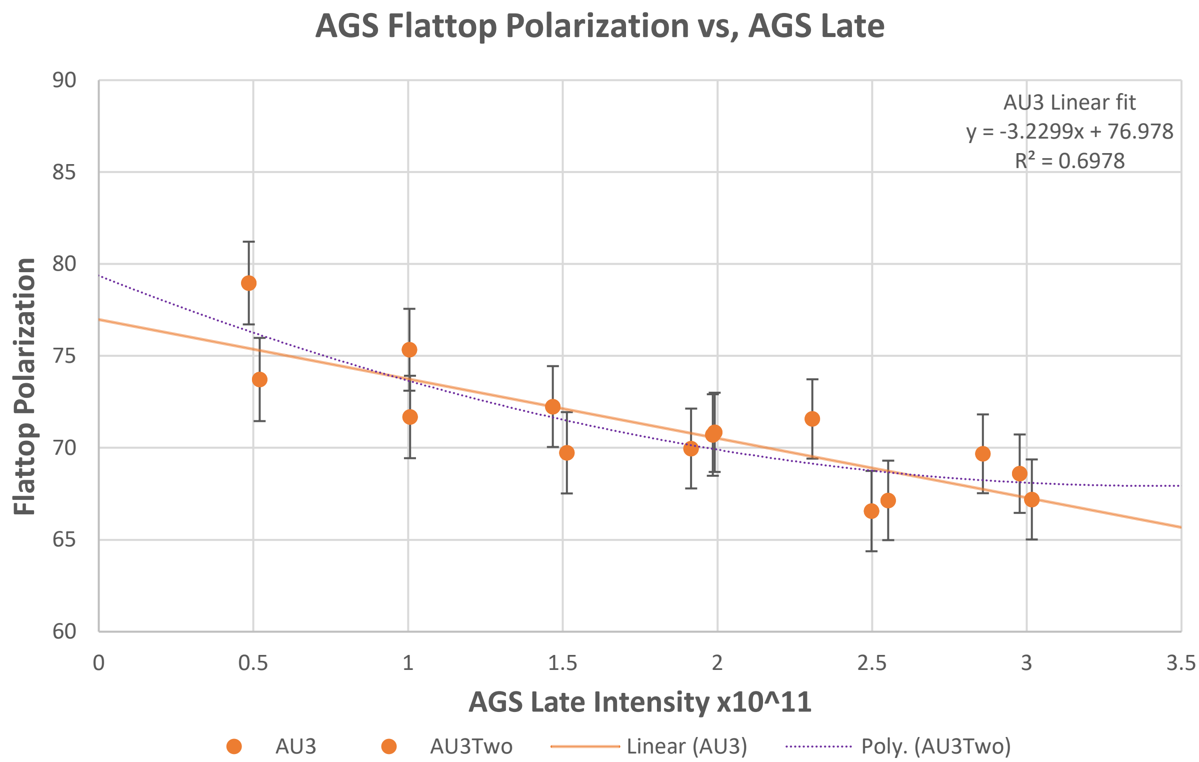

Figure 26: The AGS Flattop Polarization vs. AGS Late intensity scans for AU3 together with a linear fit, *P(I)=-3.2299(I)+76.978* (orange). A quadratic fit is also shown in faint purple. Intensity was varied using vertical scraping and the pulse width was set to 300 μs. Vertical target 3 was used. The error bars are +/- the ErrFit parameter in the Krisch display. The data was taken on Aug. 24th by T. Dankworth.

less scatter, and the y-intercept, *P(0),* is quite a bit lower on the AU3 linear fit than AU4, 77.0 vs. 80.3%, respectively.[46] A quadratic fit is also shown in Figure 26 for AU3 as it has a lower R^2, 0.733 vs. 0.698. Although far from conclusive, the AU3 data for higher intensities seems like it might be leveling off. This is also suggested by the quadratic fit.

There is an extra set of AU4 data that was taken earlier on Aug. 24th.[47] If that data is included in the AU4 fit *P(0)* becomes 80.6% instead of 80.3% and the slope becomes -4.98 instead of -4.62.

I don't have an explanation for why *P(0)* for the AU3 fit is so low compared to AU4, 77.0 vs. 80.3%. But I can't help but wonder if the lack of AU3 data, there are only 2 data points at 0.5, 1.0, and 1.5e11, may be a contributing factor. If more data at these early intensities happened to raise *P(0)* it would also make the slope more negative. On the other hand, on Aug.

[46] See Booster-AGS-pp Aug. 24, 2024 elog entries from 06:03 to 0738 (AU4 scan) and 19:31 to 22:14 (AU3 scan) by T. Dankworth.

[47] See Booster-AGS-pp Aug. 24, 2024 elog entries from 01:31 to 02:01 by T. Dankworth

22, four polarization measurements were made on AU3 with about 2.8e11 and the average was 66.7% (σ=0.70%) which agrees well with the intensity scan fit of 66.9% for 2.8e11.

The variation in the source polarization is a little greater for the AU4 data than for the AU3 data. The source polarization for the AU4 data was 81.75% with σ=2.42% and for AU3 it was 81.4% with σ=1.75%.

Let d_n be the difference between the measured polarization at data point n, called P_n, and the polarization value from the fit for that intensity (I_n). That is, for each user let $d_n = P_n - [m \cdot I_n + P(0)]$ where m is -3.229 for AU3 and -4.6147 for AU4. *P(0)* is 76.978 for AU3 and 80.276 for AU4. The amount that d varies is a measure of the scatter of the data points. The σ of d_n for the AU3 data is 1.75% and for AU4 it is 3.31%. The σ of d_n for the AU4 data is nearly twice what it is for AU3. σ for the source polarization on AU4 is larger than for AU3 but not nearly by as much as the σ for d_n on AU4 is larger than it is on AU3. So, I would think the difference in σ for the source polarizations is not enough to account for the difference in scatter between the 2 users. The Chi squared's for each user's set of data are all less than 1.7 and average around 0.9 on both users.

Helium-3 From EBIS

A new ^{3}He setup was developed for an APEX experiment in RHIC that eventually took place on Aug. 7th. $^3He^{2+}$ was first injected into the Booster and spiraled on June 6th. Booster and AGS user 7 were used and the supercycle was 5.4 sec long.

RHIC had used ^{3}He back in 2014. At that time a 12-4-2 merge was used in the AGS to merge 8 bunches into 2. But this required the L10 cavity for h=2 and it has been reconfigured to run at a higher frequency since then, so that this merge could not be used without L10 being reconfigured again.[48]

Initially, an 8-4-2 merge was attempted in 2014. This did not work for 8 transfers because the A5 kicker pulse was too long. But since this is just an APEX experiment only 1 final bunch instead of 2 would have been OK and only 4 transfers would really have been needed. With only 4 transfers the kicker length would not have been an issue. However, L10 would still need to be reconfigured so a 12-8-4 merge, which merges 3 bunches into 1, was used instead this run. The frequencies of the h=12, 8, and 4 RF during the merge, which occurs on the injection porch, were 3.765, 2.51, and 1.255 MHz, respectively. The h=12 and 8 frequencies were handled by normal RF cavities and KL was used for h=4.

Until this run, $^3He^{2+}$ from EBIS had the lowest rigidity of any species injected into the Booster.[49] The injection field, as measured on the hall probe, was about 196 G when beam first spiraled. The inflector setting was about 14.8 kV that day but eventually settled to about 14.4 kV.

[48] The frequency L10 runs at now is 783 kHz and for h=2 this corresponds to a velocity higher than the speed of light. The RF group could reconfigure it, but it is not a small job. Also, K. Zeno, "Overview and Analysis of the 2016 Gold Run in the Booster and AGS" C-A/AP/571, September 2016, contains a description of that merge. See pgs. 37-41.

[49] Protons from EBIS were injected into the Booster for NSRL this run, and their rigidity is 2/3 the $^3He^{2+}$ rigidity.

The $^3He^{2+}$ Booster main magnet cycle this run was the same one used in 2014. This setup took place while NSRL was running which introduced some complications because the NSRL dwell field was set to the EBIS Au^{32+} injection field (~830 G on hall probe) and the $^3He^{2+}$ dwell field is the same as its injection field. NSRL uses many different main magnet functions and it was impractical to have a new set of them to be used only with $^3He^{2+}$.

The dummy cycle was initially relied upon to isolate the $^3He^{2+}$cycle from the effects of the NSRL dwell field but there were still issues. When the first BU7 Bt0 occurs the main magnet field starts dropping from the EBIS Au injection field value to the $^3He^{2+}$ injection field which is about 600G lower.[50]

EBIS species all have the same velocity and are usually captured with h=4 RF. The RF frequency in this case is not far above the lower limit for the A3 and B3 cavities. RF track is normally turned on several milliseconds after injection. RF track sets the time that the RF frequency starts tracking changes in the field. But the field on the dummy cycle was still falling where RF track was set to occur. As a result, there were problems with A3 and B3 because the requested frequency was below their lower limit. Eventually, the DAC timing for those cavities was changed so that they would not pulse on the dummy cycle.[51]

Another problem developed when multiple EBIS requests were made. It was found that the injection field on cycle 2 was about 1.5G higher than on subsequent cycles. So, the first cycle with a beam request became cycle 3 and cycle 2 was used as a second dummy cycle.[52]

Beam reached Booster extraction on June 13, spiraling in the AGS occurred on June 23, and on June 24 some beam reached the AGS flattop. However, the beam only sometimes made it to the flattop. The bunch-to-bucket phase signal was not working properly. Eventually, it became evident that, even with the 3-1 merge, there was not enough bunch intensity for the signal to work properly. Presumably, the wall current monitor signal could have been amplified to get the signal to work but more $^3He^{2+}$ from EBIS became available so that option was not pursued.[53]

Table III contains some intensity measurements for just 1 EBIS pulse per supercycle mainly made on a scope. When EBIS was used as the preinjector for Au^{32+} the xf108 intensity was about 1.0e9 per pulse and so the number of charges per pulse was about 3.2e10. This was with 12 pulses per supercycle. It is a rule of thumb with EBIS that the number of charges per pulse remains roughly constant across species. For $^3He^{2+}$, rounding off xf108 intensity to 1e10, that would be the equivalent of 2e10 charges per pulse, or about two-thirds what it was for Au^{32+} (with 12 pulses). In 2014, when $^3He^{2+}$ was used, a typical Booster input was 2.4e11 for 8 pulses or 3.0e10 $^3He^{2+}$ ions per pulse or 6.0e10 charges per pulse.[54]

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[50] See Booster-AGS-EBIS Jun 7 2024 elog entry at 19:25. It shows the main magnet current for the 2 BU7 cycles. The trigger is pseudopeaker +3500 μs and pseudopeaker occurs at 7000 μs.

[51] See Booster-AGS-EBIS June 10, 2024 elog entry at 15:28. A3 was more of a problem than B3.

[52] See Booster-AGS-EBIS Jun 23 2024 elog entry at 17:20.

[53] See Booster-AGS-EBIS Jun. 25 2024 elog entry at 20:54.

[54] See Booster-AGS-EBIS June 21, 2014 elog entry at 21:02.

Figure 27 is a plot of the intensity scalers on the day of the APEX experiment. The highest Booster input with 3 EBIS pulses is about 3.2e10, so roughly 1.07e10 per pulse. In 2014 the input was about 2.4e11 for 8 pulses or 3.0e10 per pulse. In 2014 a method for increasing the EBIS intensity called flooding was used which is no longer available. The AGS late intensity in 2014 was about 1.1e11 or 5.05e10 per bunch. This year there was about 1.8e10 in 1 bunch, but if it were a 4-1 instead of a 3-1 merge in the AGS then that would have been (1.8e10)(4/3)=2.4e10/bunch. That is 47% of the 5.05e10/bunch in 2014 even though the EBIS pulse intensity this year was about 36% lower.

Date	xf108 (1 pulse)	xf108, average of n	Injected	Booster Late
June 13	3.0e9	2.1e9, of 7		
June 14	1.88e9		1.67e9	
June 18		2.05e9, of 5		
June 20	5.0e9		3.65e9	2.36e9
June 21		3.68e9, of 10		2.7e9
June 23	8.3e9			
July 1	5.3e9			

Table III: Intensity measurements for a single pulse per supercycle of $^3He^{2+}$ from EBIS on EtB xf108, at the peak of the Booster injection transformer ("Injected"), and at Booster Late. These measurements were made on a scope. The "xf108 average of n" column contains averages of n xf108 measurements but still with a single EBIS request per supercycle and the "xf108 (1 pulse)" column is the measurement of a single pulse. These measurements can be found in the Booster-AGS-EBIS elog for those days.

That is to say that the efficiencies in the Booster and AGS are somewhat better than in 2014. This is not surprising because the EBIS pulse intensity was lower and, given the low injection rigidity, there may be some intensity related losses early in the Booster.

Figures 28 and 29 show $^3He^{2+}$ in the Booster and AGS, respectively. There is very little loss in the AGS on the injection porch or during acceleration. From Figure 27 the BtA efficiency is close to 100% and from Figure 28 there appears to be about a 20% early loss on the Booster normalized circulating transformer. However, the injection transformer, which has a faster time response than the circulating transformer, indicates that nearly half the beam is lost over the first 4 ms or so after injection. The xf108 sum is about 2.4e10 and Booster Late is about 1.3e10 so this is not inconsistent if the injection efficiency is near 100%.[55]

The longitudinal emittance on the flattop was 0.85 eVs/n on July 22nd when the bunch intensity was about 1.0e10. The bunch length was 28.6 ns.[56] On July 24th, with about 1.4e10 at AGS Late, the transverse 95% normalized emittances on the flattop from the AGS IPM were

[55] See Booster-AGS-EBIS Aug. 5, 2024 elog. The xf108 sum is found from the 18:11 entry and the loss near injection is shown in the 16:16 entry

[56] See Booster-AGS-EBIS July 22, 2024 elog entries from 17:08, 17:11, and 17:46.

about 10 and 8 π mm mr for the horizontal and vertical, respectively.[57] The profiles on BtA MW006 are very small but there is no Gaussian fit available for them.[58]

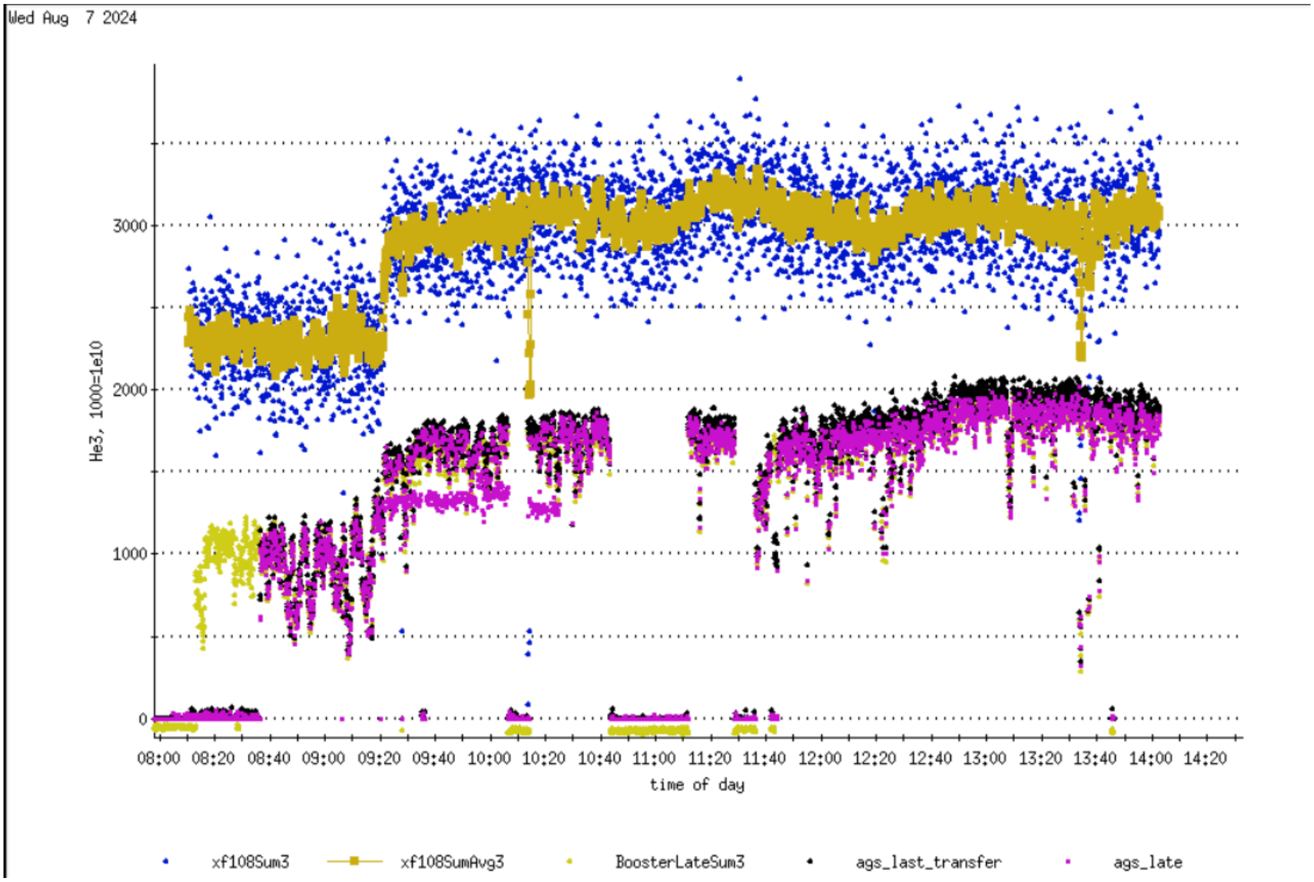

Figure 27: Intensity scalers for He3 on the day of the APEX experiment. Xf108Sum3 (blue) is the sum of the 3 EBIS pulses at xf108, xf108Sum3Avg (dark yellow) is a 10 supercycle running average of xf108Sum3, BoosterLateSum3 is the Booster Late intensity (lighter yellow), ags_last_transfer is the AGS intensity on the injection porch after the last transfer (black), and ags_late (purple) is the intensity just before extraction time (3300 ms).

The Tandem Au part of the Run

A single pulse of Tandem Au^{31+} was injected into the Booster on Sept. 18th and was accelerated to Booster extraction on the 19th in preparation for delivering Au to RHIC on October 1st. Initially, two Tandem Au Booster cycles were put on the supercycle after the NSRL cycle and before the next PP cycle. This allowed work with Au in the Booster to proceed while still supplying beam on the PP and NSRL cycles.

[57] This is with the RF on during the flattop and using the Refit option. With the intensity this low the fact that the beam is bunched probably doesn't corrupt the measurement. See Booster-AGS-EBIS July 22, 2024 elog 16:45 entry.
[58] ProfileDisplay appears to only log data from Booster users 1 through 4 so I am unable to access the BU7 data to fit it to a Gaussian. There are some pictures of the profiles in the Booster-AGS-EBIS June 21, 2024 elog, entries from 17:13 to 17:20.

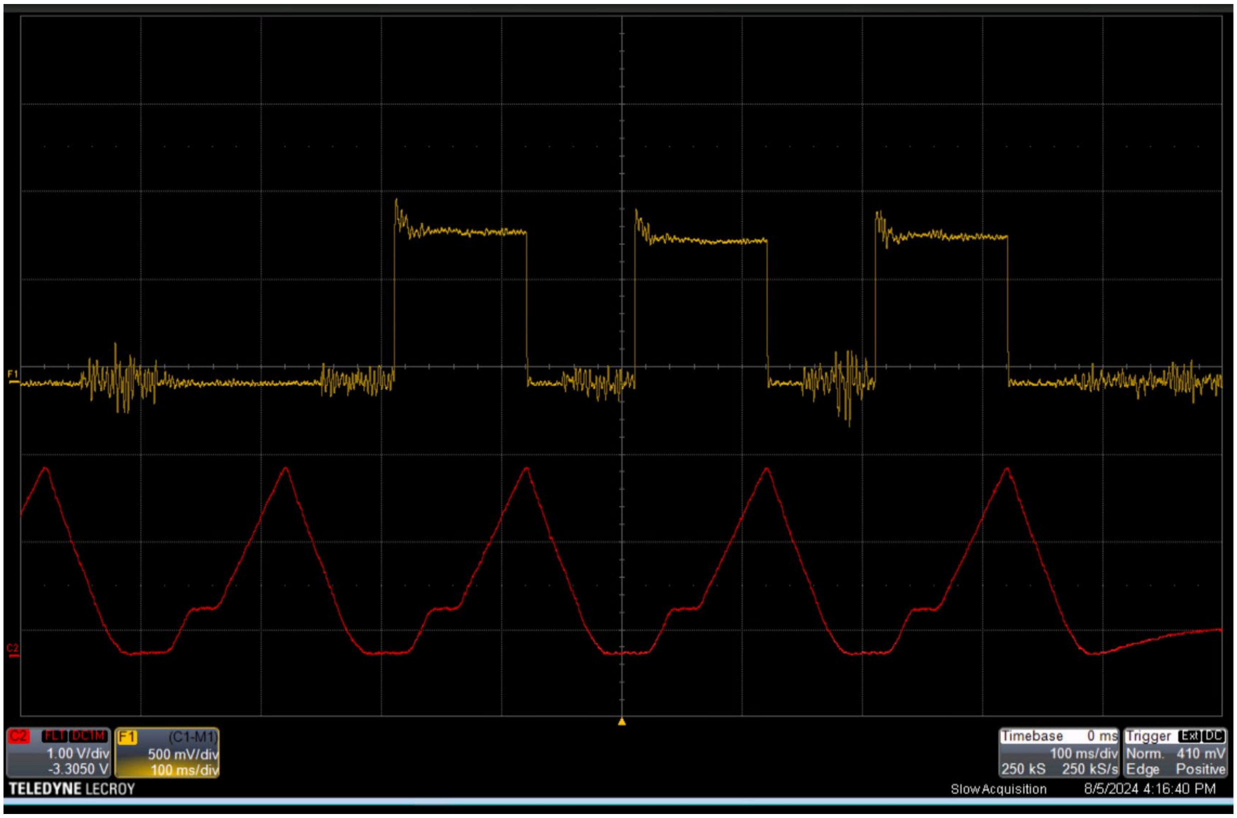

Figure 28: The 3 Booster $^{3}He^{2+}$ cycles with beam as viewed on the normalized circulating transformer (orange) and the Booster main magnet current showing the 5 magnet cycles (the first 2 are the dummy cycles). The trigger is Bt0 on cycle 4. The Booster late is about 1.3e10 and Booster input (xf108 sum) is about 2.4e10.[59]

The RHIC Au run was basically the same setup as the RHIC Au setup last year. There were 8 Tandem pulses, a 6-3-1 merge in the Booster, a 12-6 merge in AGS, further acceleration on h=12, and extraction at nominal energy (9.8 GeV/n). The setup was on BU1 and AU1. So, there is not much new to say about it. As in that run there were administrative limits put on the AGS and Booster Late intensity of 8.0e9 and 16e9, respectively. The AGS limit was established to protect the J7 plunging stripping foil and Copper absorber of the AGS dump and the Booster Late limit is to protect the BtA stripping foil. The supercycle length was 6.6 sec. No deterioration of the BtA foils was noticed.

Beam was accelerated to the AGS flattop on Sept. 25th on a nominal Au-NSRL supercycle. There was a vacuum leak in the AGS's D superperiod on the 27th which impacted the Au set up that day but was resolved.[60] There were problems with the G09 extraction bump which caused significant delays.

[59] Taken from Booster-AGS-EBIS Aug. 5, 2024 elog 16:16 entry
[60] See Booster-AGS-EBIS Sept. 27, 2024 elog entries from 17:06 to 20:04. See Oct 1 elog 14:20 entry by V. Schoefer as well.

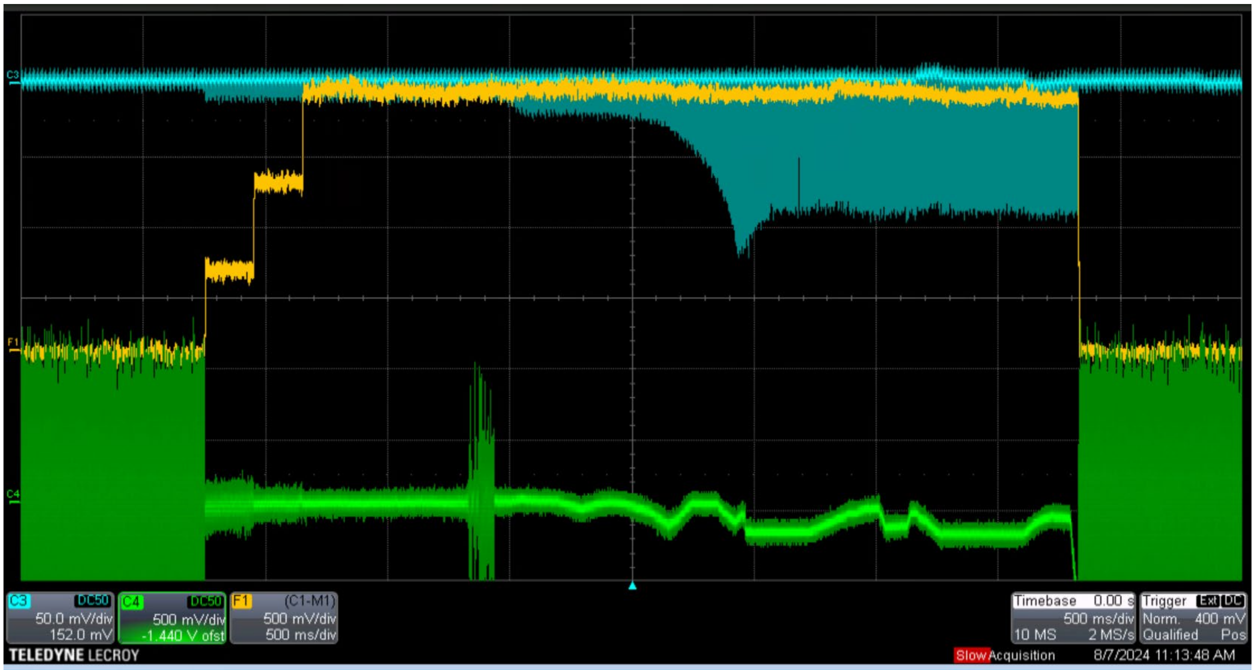

Figure 29: $^{3}He^{2+}$ in the AGS with 3 transfers. The A15 normalized current transformer (orange), the wall current monitor (blue), and the J12 horizontal BPM (green). The trigger is At0+2000 ms. The AGS Late intensity here is about 1.3e10.[61]

A longitudinal emittance measurement on the flattop yielded 0.22 eVs, which corresponds to a bunch length of about 16 ns.[62] On Oct. 11th, with an 800 μs pulse, and 2.0e9/bunch at AGS Late, the transverse emittances at BtA MW006 were $(\varepsilon_x.\varepsilon_y)=(1.88, 3.15)$ π mm mr.[63] This is about as long a Tandem pulse as is used and if there were 8 of these pulses the AGS Late would be near the administrative limit of 8.0e9. On the flattop with RF off, about 1.7e9/bunch at AGS Late, using Refit, and a 900 μs pulse $(\varepsilon_x.\varepsilon_y)=(15,9)$ π mm mr.[64] This is much larger than what was measured in BtA for a similar pulse width but there is a stripping foil.

There was a period where the G09 bump would not stay on long enough to extract more than 1 or 2 bunches so a 12-6-3 merge was developed to allow for more bunch intensity. With the 12-6-3 merge KL was still used for h=6 and L10 was used for h=3. There was enough room on the merge porch for the L10 cavity to pulse after the 12-6 merge was complete. After the 6-3 merge was complete the h=12 RF was brought up (see Figure 30). No squeeze was performed and there was about 2% of the beam in the satellite buckets. To switch from the 12-6 to the 12-6-3 merge a different KL voltage function was loaded, and the L10 DAC was turned on.

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[61] Taken from Booster-AGS-EBIS Aug. 7, 2024 elog 11:13 entry.
[62] See Booster-AGS-EBIS Oct. 10, 2024 elog entries from 17:58 to 18:14.
[63] See Booster-AGS-EBIS Oct. 11, 2024 elog entry at 16:20. The image on the right is with a Gaussian fit and the FWHMs are $(fwhm_x, fwhm_y)=(3.25\ mm, 9.77\ mm)$. Using the equations $\varepsilon_x=0.178(fwhmx^2)$ and $\varepsilon_y=0.033(fwhmy^2)$ gives $(\varepsilon_x,\varepsilon_y)=(1.88, 3.15)$ π mm mr.
[64] See Booster-AGS-EBIS Oct. 17, 2024 15:34 entry.

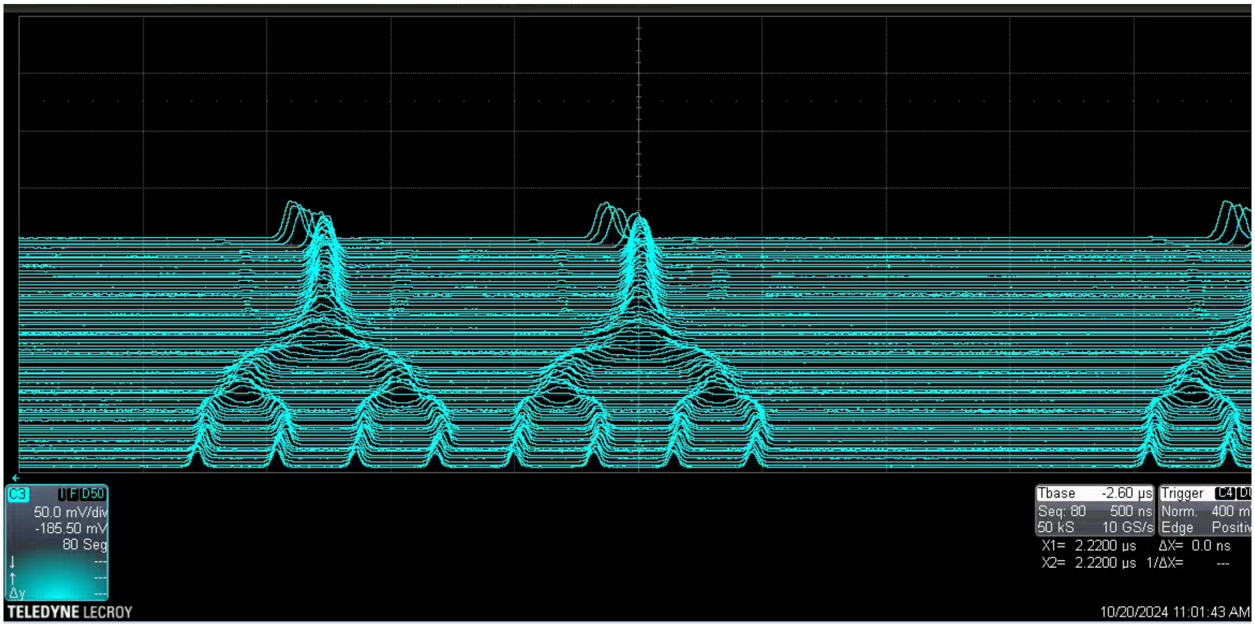

Figure 30: A WCM mountain range display of the 12-6-3 merge in the AGS where 8 bunches were merged into 2. There are 80 traces, and it is looking over an interval from At0+2200 to 2400 ms.

Figure 31 shows the AGS with the 12-6-3 merge.[65] There is a significant loss around 2400 ms. This is when the Main Magnet switches from the Flattop bank to the pulsed bank, the so-called F to P transfer. There is a transient in the dB/dt there and there is likely not enough RF voltage because of it. It is not much of an issue with the 12-6 merge because the merged bunches are smaller. It is likely that this loss could be eliminated by raising the energy at which it occurs as has been done for other merges (ex- the 24-12-4 EBIS Au merge).[66] The current transformer shows the case where both bunches have been extracted and there is a small amount of beam left in the machine from the baby bunches.

The flattop longitudinal emittance for the 12-6-3 setup was measured on Oct. 11th and 17th. On the 11th the average bunch length was 22.4 ns corresponding to 0.44 eVs with 1.5e9/bunch. On the. 17th, with a bunch intensity of about 2.8-3.0e9, the length was 24.4 ns corresponding to 0.52 eVs and was 0.54 eVs with 1.2-1.4e9 bunch intensity.[67] So, not much intensity dependence.

Pulse length vs. flattop emittance scans were done for both merges on Oct. 17th. Figures 32 through 34 show the results. The IPM emittance data was obtained from LogView and does not use the refit.[68] Because of this the reported emittances are smaller than when viewed in the

[65] Taken from Booster-AGS-EBIS Oct. 20, 2024 elog 14:12 entry.
[66] See also K. Zeno, "The 2023 Gold Run in the Injectors", C-A/AP/706, March 2024, pgs. 2-3.
[67] See Booster-AGS-EBIS Oct. 17, 2024 elog entries from 16:01 to 17:05.
[68] The RF is shut off at 3500 ms. For each pulse width there are 10 measurements made. Each of these measurements consists of an average of the emittance measured at 3535, 3580, 3625, 3670, 3715, 3760, 3805, 3850, 3895, 3940, and 3985 ms. The average of AGS Late is taken for each measurement and there is a

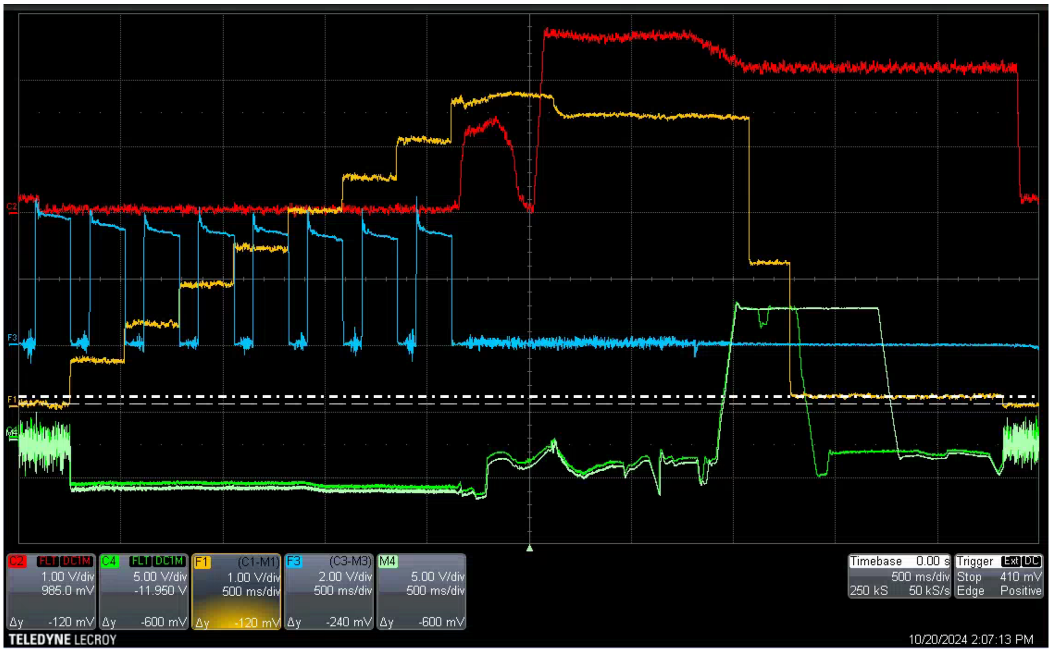

Figure 31: The AGS cycle with the 12-6-3 merge. F1 is the normalized current transformer (with baseline subtracted, orange), the red trace is the RF detected vector sum, the green traces are the G09 horizontal BPM with the G09 bump on long enough for 2 extractions (C4) and for 4 extractions (M4). The trigger is At0+2300 ms and the sweep speed is 500ms/div. AGS Late is about 5e9.

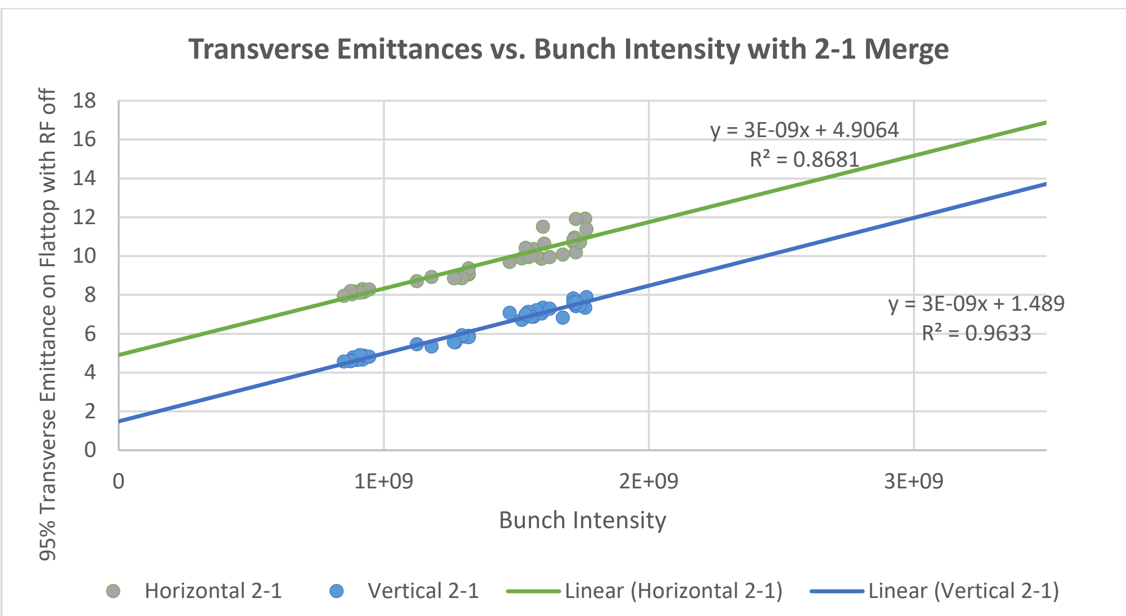

Figure 32: Flattop 95% IPM transverse emittances vs. flattop bunch intensity using the 12-6 (2-1 type) merge where the pulse width is varied to change the bunch intensity. Emittances are in units of π mm mr.

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measurement for the horizontal and the vertical. The measurements were taken for pulse widths of 300, 450, 650, and 900 μs for the 2-1 merge and 260, 300, 430, 550, and 800 μs for the 4-2-1 merge. The LogView data can be found in Ags/Instrumentation/IPM/AGSIPMStripChartSnapshots.logreq and is agsIpmH:emittanceM[.] and agsIpmV:emittanceM[.].

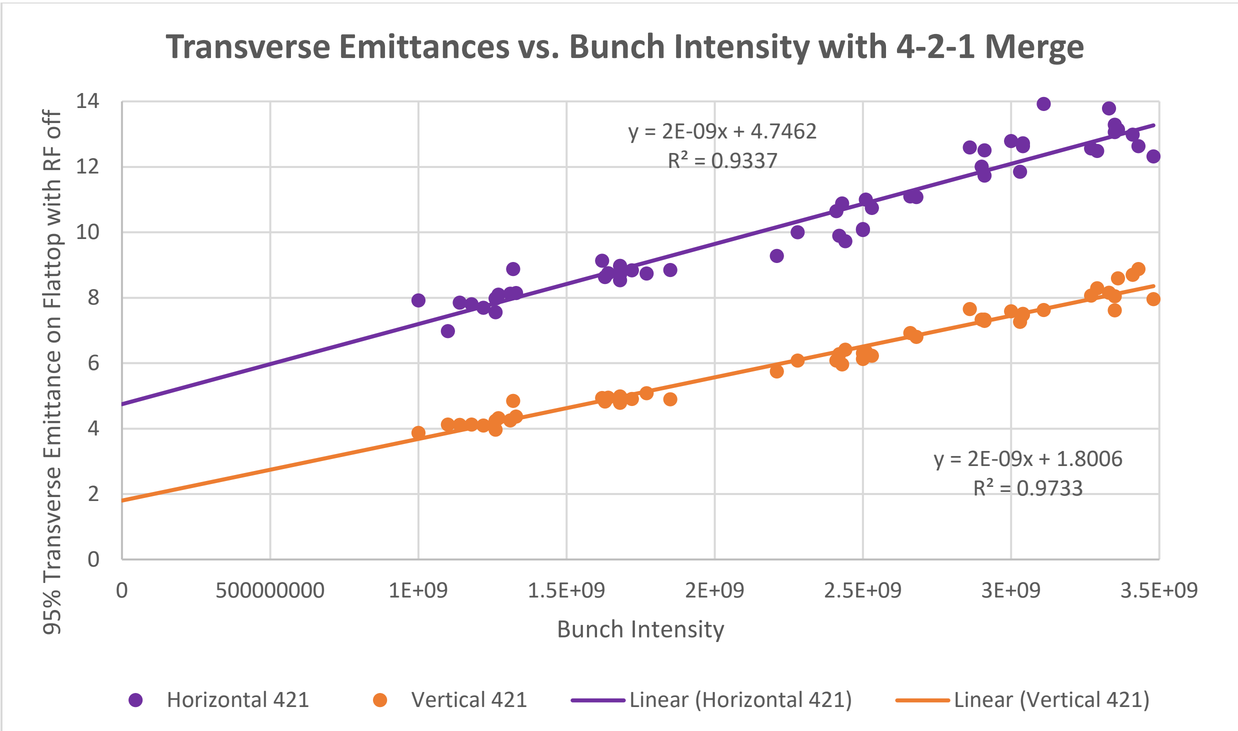

Figure 33: 95% IPM transverse emittances vs. flattop bunch intensity using the 12-6-3 (4-2-1 type) merge where the pulse width is varied to change the bunch intensity. Emittances are in units of π mm mr.

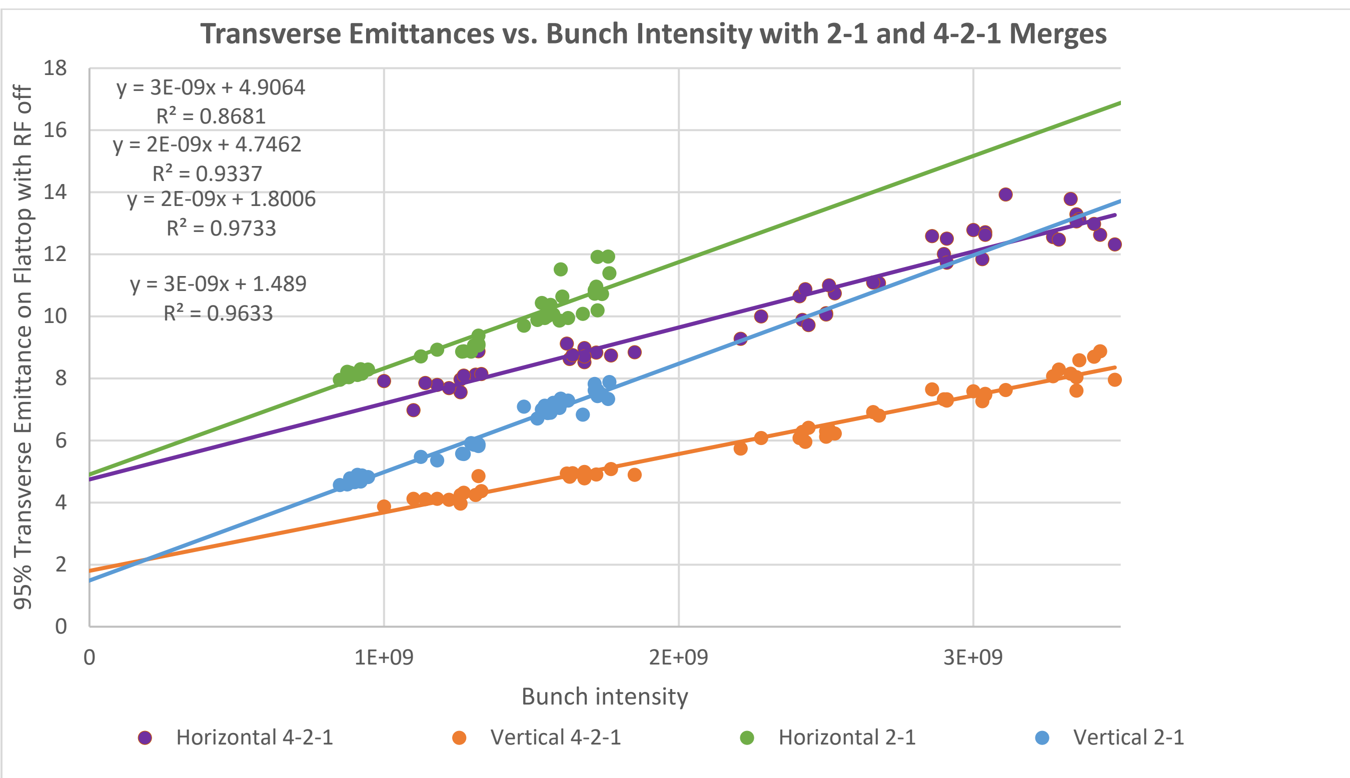

Figure 34: 95% IPM transverse emittances vs. flattop bunch intensity using the 12-6-3 and 12-6 merges where the pulse width is varied to change the bunch intensity. Emittances are in units of π mm mr.

agsIpm program which only shows “refitted” data. Since the kind of fit is the same for both scans it is reasonable to compare them. The intensity dependence is much less for the 12-6-3 case. These scans are reminiscent of the ones done with PP but they are different in the sense that although the intensity was also controlled with the pulse width, there is no intentional scraping. Due to the nature of multiturn injection, the transverse emittance is expected to increase as the pulse width is increased.

Summary

This RHIC run consisted of about 5 months of polarized protons (May through September) followed by 3 weeks of Gold. As far as protons go, this note gives a description of the new 2-Linac pulse setup (pgs. 1-11). The 6 to 12 squeeze on the flattop is discussed in some detail (pgs. 3-6), which pertains to both the 2-Linac pulse (BU4/AU2) and BU3/AU3 cases.

One issue with the 2-Linac pulse setup is that the first bunch injected sits on the injection porch for about a second without RF loops and can grow longitudinally because of this (pgs. 6-8). The flattop polarization was measured on the 2-Linac pulse setup and was only about 30% (pg. 8). The horizontal emittance on the second long injection porch showed some growth at higher intensity (2e11, figure 8) that was not evident at lower intensity (0.8e11, figure 9). The threshold for growth may be between 1.3 and 1.6e11 per bunch. The long injection porch was also used to measure the asymmetry at injection energy. It was significantly lower than in Run 17 and showed some intensity dependence, which was not expected (pgs. 9-10).

One significant change to the split-merge setup was made this year: The Booster main magnet function was modified so that extraction happens when the field is flat. This allows wider bunches to be made to reduce the peak current at AGS injection to the desired level (pages 11-13). Past a certain point, if the bunches at Booster extraction are made wider, there will not be enough time between them for the F3 kicker to rise. But indications are that the peak current can be reduced to the goal of 70% or less of its value for BU4/AU4, with the same intensity, while there is still enough time for the kicker to rise.

The intensity dependence of the flattop transverse emittance for the split-merge was also compared to the standard setup (pgs. 14-24). The BtA emittance as a function of pulse width was also measured. Even though the amount of scraping was fixed, the BtA emittance increased as the pulse width was increased, especially on BU4 (see figure 16). When the pulse width dependence of the BtA emittance was factored out, the pulse width vs. flattop emittance for AU3 and AU4 were similar and significantly less than with it included (compare figures 14 and 15 to 17 and 18). Surprisingly, at least when these scans were performed, the AU3 and AU4 flattop emittance when the BtA emittance dependence is factored out had rather similar emittance and intensity dependence. That is, there was no obvious benefit from the split-merge.

There has not been enough attention given to reducing the intensity dependence of the BtA emittance with constant scraping. It may be possible to reduce or eliminate this dependence and this is perhaps something that can be looked at in the upcoming run. I don’t know if it is related, but the Booster stopband correctors did not seem as sensitive this year as they normally are. I think it is important to optimize those corrections and the tunes using a higher Booster input than normal (i.e., ~1.0e12 or higher), and that was not done this year.

There is flattop emittance vs. AGS Late data from the standard setup in 2017 which, although measured somewhat differently, shows less growth than even the split-merge cycle (see pg. 15). However, there is no BtA emittance data for those scans so it is not known if the BtA emittance increased with pulse width then. The linearity of Booster Late vs. Booster input was compared for the 2017 and this year's scans. It is linear for the 2017 and BU3/AU3 data but does show some non-linearity for this year's BU4/AU4 data (Figure 21). This suggests that if there was any growth in the 2017 scan, it was not as large as it was for the BU4/AU4 scan this year.

The Booster Input (for a full 300 μs pulse) during the scans was lower than the 6.9e11 it was in 2017. For BU3/AU3 it was likely about 6.2e11 and for BU4/AU4 it was about 5.7e11 (pg. 22). This would be expected to make the flattop emittances somewhat larger for this year's scans than they were in 2017. The Booster input averaged about 7e11 in 2017 and this year it looks like it averaged a little below 6.5e11 (see figure 20).

The effect of NSRL mode switches on the PP user was less this year compared to the last PP run in 2022 (pgs. 24-25). Polarization measurements on the split-merge and standard setup are discussed (pgs. 25-28). The fit to the split-merge data has a lower polarization at 0 intensity, *P(0)*, than BU4/AU4 but the slope of the BU3/AU3 fit (dP/dI) is less steep than the fit for BU4/AU4. The BU3/AU3 scan is missing a few data points at lower intensity.

There is also a section on the ^{3}He setup developed for use in an APEX experiment (pgs. 28-31) and a section on the Tandem Au setup (pgs. 31-37). Part of the Tandem Au section contains an intensity scan comparing flattop transverse emittances for a 2-1 and 4-2-1 type merges (pgs. 34-38). The 4-2-1 merge data shows less intensity dependent growth than the 2-1 merge data does (Figure 34).