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The 2022 Polarized Proton Run in the Injectors

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Introduction

The previous polarized proton (PP) run was in 2017. During the start up process this run the injectors were set up in the same configuration using Booster and AGS PPM user 4 (BU4/AU4).[1] Concurrently with this a new setup was established on Booster and AGS user 3 (BU3/AU3) called the split/merge. This new setup splits a single bunch into 2 in the Booster and recombines them on the AGS flattop in an attempt to improve polarization mainly by reducing the transverse emittance growth thought to be associated with higher peak beam current.

Although Gold beam from EBIS was used at times in RHIC for LEReC and CeC development, from the injector perspective there is little noteworthy about it and so this note will focus solely on PP. According to the OC log, STAR Physics was first declared on Dec. 22, 2021 and the run ended on April 18, 2022.

Initially, BU4/AU4 was used for RHIC. Then the split/merge setup was used from Dec. 27 until the Siemens motor generator failed on Jan. 12 and the Westinghouse motor generator had to be used in its place. The peak dB/dt available using the Westinghouse is half what it is with Siemens so the AGS required a different setup. Since the split/merge setup is more complicated than the standard one, and any benefit from it to polarization had not been demonstrated, a cycle was developed on AU6 for RHIC based on the AU4 setup but with a longer ramp. The split/merge was also set up with Westinghouse on BU3/AU7, but it was never used for RHIC. The switch back to the Siemens occurred on March 8th once again using BU4/AU4.

The BtA Vacuum Valve Problem

The Booster was ready for beam on October 25, 2021, about 2 weeks before the AGS was ready. In addition to re-establishing the standard BU4 setup during this time, the split cycle was established on BU3. On November 10th, the AGS was ready for beam and it was extracted from the Booster (BU4). However, BtA MW006 showed profiles in both planes that were unusually wide.[2]

There are no magnets between the F6 extraction septum and this multiwire, which is located 6 ft. downstream of it. There was a signal apparent on the AGS wall current monitor (WCM) that was correlated with beam at MW006 but it looked like the derivative of a typical bunch signal. There was only a very small signal on the AGS current transformer even in high gain (x10).[3] The transfer efficiency was on the order of 1%. There was not much evidence of beam on the other 3 BtA multiwires (MW060, MW125, and MW166) that are further

[1] The details of the setup in 2017 (Run 17) is described in K. Zeno, "An overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594 and other sources referenced there.
[2] See Booster-AGS-pp elog Nov.10 2021 1832 entry. The FWHM widths were similar in both planes, about 14 mm. Normally, the horizontal would be roughly half the width of the vertical. The horizontal width was about 3-4 times larger than normal.
[3] Booster-AGS-pp elog Nov.10 2021 1832 entry shows what the bunch looked like on the WCM. Instrumentation checked the WCM on Nov. 12 and determined it was in need of repair (Nov. 12 1625 entry Booster-AGS-pp elog). The snakes and their correctors in the AGS were off for the initial AGS setup.

downstream and there were large losses apparent on the first BtA loss monitor located at 23 feet.[4]

It was suspected that there was an obstruction upstream of MW006 in the BtA line. There are two flags upstream of it. One right at the beginning of BtA (F6) and the other at 5 ft. However, the pet page indicated that the flags were retracted. There is also a vacuum valve named SV009, which should be at 9 ft, which would make it downstream of MW006. There was a major incident with the Booster and BtA vacuum before startup began, and this valve had been damaged during it. The valve could not be controlled but the vacuum group believed that it was open. It seemed odd that a flag would have such a large effect on proton beam, and even if SV009 was closed, it was hard to understand how that would affect the MW006 profiles. There was no indication that there was anything abnormal with the beam in the Booster. When the beam was scraped horizontally or vertically in the Booster there was not an obvious change in the widths of the MW006 profiles as there normally would be.

On Nov. 11th the vacuum group confirmed as well as they could without breaking vacuum that SV009 was open, and the instrumentation group inspected the F6 and BtA005 flags in the ring and confirmed that they were retracted.[5] BtA optics and steering changes improved the profiles on MW060 and increased the amount of beam in the AGS. Afterwards the transfer efficiency was roughly 10% and beam was accelerated to the end of the flattop.[6] The transverse emittance on the flattop measured by the polarimeter target was very large.[7]

Although those possible obstructions had been checked and verified to be in a good state, it was still thought that there was an obstruction. It was decided to try to extract Au from the Booster, since if there was an obstruction, Au beam would not be able to get through it at all and so there should be no beam visible on MW006.[8] Establishing Au beam on MW006 using the standard setup is typically fairly straightforward and on Nov. 13th this was attempted unsuccessfully.[9] After the switch back to protons, the beam position at MW006 was scanned both vertically and horizontally to see if a position with smaller widths could be found which would suggest a partial obstruction. That scan was unsuccessful.[10]

Afterwards, it was learned that SV009 was actually located 2 feet upstream of MW006, not 3 feet downstream of it. An HP survey found radiation levels at the valve were also the

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[4] It was determined that plunging and/or retracting MW125 was causing a vacuum leak. Although this was unrelated to the transfer problem. The leak was repaired and MW125 was locked in the retracted position for the remainder of the run. See Nov. 12 OC log 0900 entry.

[5] See Nov. 11 1838 entry in the Booster-AGS-pp elog by D. Weiss and 1512 entry by H. Huang

[6] See Nov 12 Booster-AGS-pp elog 2133 entry for optics and steering changes.

[7] See Nov.12 2021 Booster-AGS-pp elog 2258 entry by H. Huang. Using a vertical target, the 95% normalized horizontal emittance was 63 mm mr, about 4 times what it normally is.

[8] Greg Marr suggested this.

[9] See Nov. 13th 2021 Booster-AGS-EBIS elog

[10] See Nov. 14 2021 Booster-AGS-elog entries from 1745 to 1826.

highest in the area.[11] It was also found that early in Run 17, with protons, the SV009 valve had been closed and the MW006 profiles were qualitatively similar to how they looked now.[12]

Subsequently, the vacuum group had a closer look at the valve. It required venting and opening the vacuum chamber to look at it directly. They found that the valve was almost completely closed and removed it from the beampipe. After being down for about 2 days for this AGS setup resumed on Nov. 21st, eleven days after the first attempt. Figure 1 shows MW006 profiles before and after the valve removal.

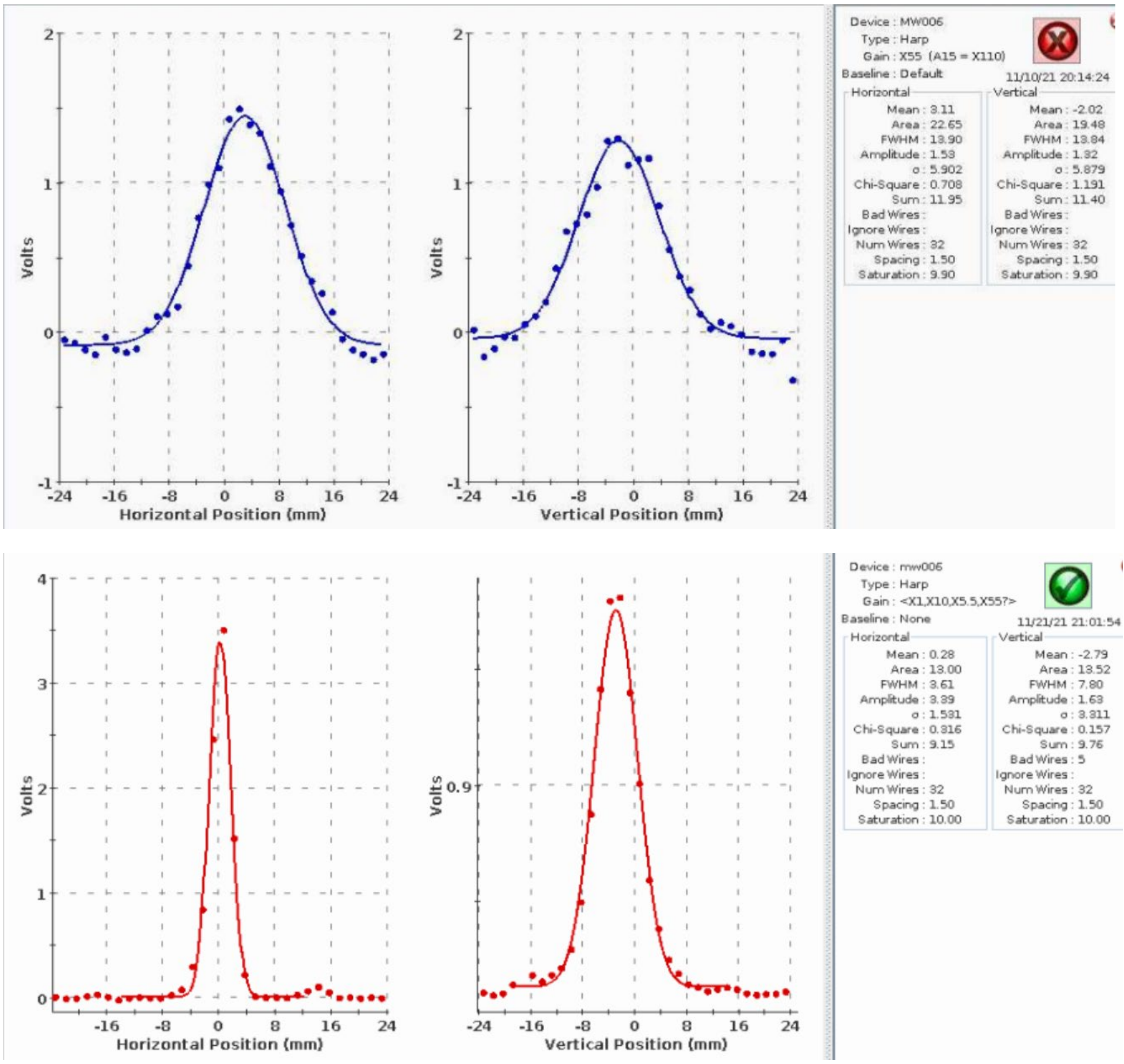

Figure 1: Comparison of BtA MW006 profiles before (top) and after (bottom) the SV009 valve was removed. There was no scraping in both cases but the Booster Late intensity in the case when the valve was in is about 3 times higher than after the valve was removed since the Linac pulse width was 300 μs for the former and 100 μs for the latter.

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[11] See H. Huang, Injector status, Time meetings, Nov. 16, 2021

[12] See the Nov. 17 2021 Booster-AGS-PP elog entries from 1710 to 1736

In the state with the valve closed, the AGS injection field measured with the hall probe was 872 g. The injection field, once the problem was resolved, was 878 g, 6 g higher than in the closed valve state[13]. Assuming the same injection radius this corresponds to a difference in energy of 14.2 MeV.[14]

Also, with the valve closed, the Booster extraction frequency was 1.3618 MHz (h=1) and the AGS injection revolution frequency (f_{rev}) was 339.994 kHz. Since the AGS is 4 times the circumference of the Booster one might expect the extraction frequency to be 4* f_{rev}=1.3600 MHz without energy loss between the Booster and AGS. After the problem was resolved, the injection f_{rev} was 340.546 kHz and 4 times that is 1.3622 MHz, 400 Hz higher than the extraction frequency instead of 1800 Hz lower. Assuming the same injection radius, this difference in f_{rev} corresponds to an energy difference of 20.5 MeV between the 2 cases and a kinetic energy that is a factor of 1.5% lower (1.391 vs. 1.412 GeV) for the valve inserted case.

The Split/Merge

Motivation

In 2013 there were studies performed capturing and accelerating in the Booster on h=2 instead of the usual h=1 and accelerating the 2 resulting bunches in the AGS. There were indications that, for a given AGS intensity, the polarization was higher and transverse emittances on the flattop were lower than if h=1 was used (AU4 was used for both cases with an RF harmonic of 8.).[15]

For a particular study performed in 2013 the AGS Late (flattop) intensity was 2.0e11. For the 1-bunch case the measured polarization was 66.5% and for the 2-bunch case it was 75.2%.[16] Using the (ion) IPM, the 95% normalized horizontal and vertical emittances (ε_x,ε_y) were (19, 20) mm mr for the h=1 case and (11, 15) mm mr for the h=2 case. The emittances in the h=2 case are much smaller and, if this were due to the lower peak current during the ramp, then accelerating 2 bunches and merging them into 1 on the flattop would provide that smaller emittance for a bunch intensity which is twice as high. It would presumably also provide the higher polarization that was measured for the h=2 case. On the other hand, there was concern about whether such a merge would take too long since the synchrotron frequency at the flattop energy will be low.

[13] See Nov 23 1646 entry in Booster-AGS-pp elog.

[14] The injection radius seems to have been -5 mm for valve closed and -4 mm once it was removed, nearly the same. The Booster extraction radius was near 0 in the former case and may have been near zero in the latter case since it was not intentionally changed between the 2 cases.

[15] See Booster-AGS-pp 2013 Apr 19 summary (dated Apr 22 2013 1802) and April 18 2013 1854 entry, comments by H. Huang for polarization measurements. The study considered here took place on 4/19/13 from 19:53 to 20:23. For transverse flattop emittance, the April 19th 2013 elog has 3 measurements during this time with RF off and using the “Refit” option (entries at 1931, 1949, and 2007). For the h=1 case, (εx,εy)=(12, 15.5) for 1e11 and (19,20) for 2e11. For h=2 (ε_x,ε_y)=(11,15) for 2e11. ε_x and ε_y are the 95% horizontal and vertical normalized emittances, respectively. The Booster Input intensity for this study was 5.0e11.

[16] See Booster-AGS-pp June 29 2022 elog 1533 entry from H. Huang.

A dual harmonic was first used in the Booster in 2015 and in the AGS in 2017. These dual harmonics have been shown to reduce intensity dependent transverse emittance growth. In fact, in 2017, using both dual harmonics, (ε_x,ε_y) on the flattop were about (12.2, 13) mm mr with an AGS late of 2.0e11.[17] This value is quite similar to the 2-bunch value obtained in 2013.

Scheme

Efforts were made to preserve the benefit of the dual harmonics while still merging 2 bunches on the AGS flattop. The scheme arrived at is as follows: In the Booster, inject with h=1 and the dual harmonic as usual. Once at a higher energy where space charge effects are less of an issue, split the bunch into 2 using h=2 and then squeeze those 2 bunches into h=3 buckets using h=3. These manipulations are performed at constant energy on a porch. Afterwards, accelerate to extraction energy using h=3.[18]

To inject the 2 bunches into h=6 buckets in the AGS the F3 extraction kicker is timed to rise between the 2 adjacent h=3 bunches. By doing so, the bunches enter the AGS with the same spacing as they would have to inject 2 bunches into h=12 buckets that are separated by an empty h=12 bucket. This spacing is the same as what's required to inject into 2 adjacent h=6 buckets. So, using an AGS harmonic of 6 instead of 12 these 2 bunches are injected into adjacent h=6 buckets. In that configuration the AGS dual harmonic works as it has, using h=12 to flatten the bunches.

If h=2 was used to capture and accelerate in the Booster then the dual harmonic could not be used there because of the frequency range of the cavities. Additionally, the bunches would have to be injected into the AGS in adjacent h=8 buckets which would preclude the use of a dual harmonic in the AGS because the other harmonic required (h=16) would be out of the frequency range of the cavities.

Merging the 2 bunches initially in h=6 buckets is not straightforward. A 6-3 merge using station KL for h=3 might be possible but the h=3 frequency is not far from station KL's lower limit and there is not a lot of h=3 voltage available when using only one cavity. This has 2 potential downsides: First, the merge would likely take substantially longer than if a 12-6 merge were performed since there is less voltage available. Secondly, it might be stressful on station KL because of the amount of time required with substantial voltage while on h=3.

But if a 12-6 merge were performed the bunches would have to be in h=12 buckets and that would preclude using a dual harmonic in the AGS and would make the peak current early in the AGS higher than if h=6 was used. Instead, station KL was used early on the flattop with h=3 to move the 2 adjacent h=6 bunches closer to each other until they had the same spacing as adjacent h=12 bunches would have (although this squeeze takes time too). Then the h=12 voltage

[17] See Figure 18 on pg. 21 of K. Zeno, "An overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594.

[18] In 2017 a Booster cycle with a squeeze from h=2 to 3 was made. Booster capture took place on h=2 and the 2 bunches were accelerated in the AGS on h=12. See K. Zeno, "An overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594, pgs. 37-41.

was turned on and the h=3 and h=6 voltages were turned off. Once the bunches were in h=12 buckets, a 12-6 merge was performed.

Peak Current Considerations

One can ask though how the peak current (I_{peak}) early in the Booster using just h=2 compares to what it is using h=1 and a dual harmonic. If there were 2 bunches instead of 1 the bunch intensity and emittance would both be cut in half. For simplicity, first I'll compare what happens to I_{peak} if the bunch intensity and longitudinal emittance (ε) are halved but the harmonic remains one. Approximating the shape of the beam in (ΔE, Δt) phase space as an ellipse whose shape and distribution are the same in the 2 cases, the half-length of a bunch (Δt) will be shortened by $\sqrt{2}$ since the emittance before (ε_B) would be,

$$\varepsilon_B = \pi\, \Delta E_B \Delta t_B \qquad \text{Eq. (1)}$$

and after (ε_A) would be,

$$\varepsilon_A = \pi\, \frac{\Delta E_B \Delta t_B}{2} = \pi\, \frac{\Delta E_B}{\sqrt{2}} \frac{\Delta t_B}{\sqrt{2}} \qquad \text{Eq. (2)}$$

The peak current in both cases will be proportional to the bunch intensity as well as $1/\Delta t$. If N is the initial bunch intensity then the peak current before (I_{peakB}) will be,

$$I_{peakB} = kN \frac{1}{\Delta t_B} \qquad \text{Eq. (3)}$$

and the peak current after (I_{peakA}) will be,

$$I_{peakA} = k \frac{N}{2} \frac{\sqrt{2}}{\Delta t_B} = \frac{1}{\sqrt{2}} I_{peakB} \qquad \text{Eq. (4)}$$

where k is a proportionality constant. So, I_{peak} will be about 29% lower after these changes.

Modeling of the dual harmonic in the Booster also indicates a 30% or so reduction in I_{peak} with h=1 as the accelerating harmonic vs. h=1 without the dual harmonic.[19] But the question remains, what effect does using h=2 instead of h=1 (with no dual harmonic) have on the peak current (for the same bunch intensity and ε)?

It turns out that for the same voltage, and the above approximations, the dependence of Δt on RF harmonic goes as $(h_m/h_n)^{1/4}$ where h_n and h_m are the 2 harmonics.[20] In the case where the harmonic is changed from 1 to 2 then h_m=1 and h_n=2 and so Δt decreases by a factor of $(1/2)^{1/4}$, which means I_{peak} will be factor of $2^{1/4}$ larger. Combining this effect with the $1/\sqrt{2}$ reduction in

[19] C. Gardner, "Booster double harmonic setup notes" C-A/AP note 535 , pg. 40.

[20]. This dependence can be gleaned from Eq. 10 in M.J. Syphers, "Some Notes on Longitudinal Emittance" April 9, 2002 together with $\Delta p/p = (1/\beta^2)(\Delta E/E_s)$ and the approximation that the distribution is elliptical and ε is the same in both cases. This dependence was also confirmed computationally using Bbat for h=1 and 2.

I_{peak} from Eq. (4) yields an overall reduction by a factor of $1/2^{1/4}$. This makes I_{peak} in the h=2 case only 16% less than if h=1 was used with no dual harmonic. So, it seems using h=1 with a dual harmonic reduces I_{peak} more than just capturing and accelerating on h=2, although just using h=2 does provide some reduction.

The dual harmonic on BU4 is not turned off abruptly. The h=2 voltage starts to go down not long before 103 ms and falls linearly until 127 ms. Judging from the WCM mountain range display its effectiveness has waned considerably by about 115 ms. By that time the h=2 voltage has dropped by about half while the h=1 voltage and dB/dt are unchanged. On BU3 the dual harmonic behaves similarly up to about 109 ms but then abruptly drops to 0. The BU3 and BU4 magnet functions are identical up until 116 ms at which point on BU3 it starts to rollover for the porch. Details of the split and squeeze into h=3 buckets will be described later but for now what the effect on I_{peak} is from acceleration in h=3 buckets will be considered.

From the discussion above it is apparent that when the bunch are split into 2 bunches of half intensity and ε that I_{peak} would be reduced by a factor of $1/2^{1/4}$. This would be true if the RF voltage is constant but during the split the voltages are not constant but they are lower, so this change shouldn't present I_{peak} problems.

Obviously, when the 2 bunches are squeezed into h=3 buckets I_{peak} will increase. For a constant voltage and energy, and assuming elliptical bunches, using the relation mentioned above, the Δt of a bunch in an h=3 bucket would be a factor $(h_m/h_n)^{1/4} = (2/3)^{1/4} = 0.90$ smaller than in an h=2 bucket. So, I_{peak} in the h=3 buckets will be a factor of $(2/3)^{1/4} = 1.11$ larger.

But still I_{peak} for the h=2 bunches was a factor of $1/2^{1/4}$ smaller than for the h=1 bunch. So, the I_{peak} of the bunches in the h=3 buckets would be a factor of $(3/2)^{1/4}/2^{1/4} = 3^{1/4}/\ 2^{1/2} = 0.93$ smaller than if all the beam was in an h=1 bucket for the same energy and voltage, etc. What can be inferred from this is that even with splitting and squeezing the beam from an h=1 bucket into 2 h=3 buckets the I_{peak} is still slightly lower than it would have been otherwise.

Recall that in this scheme bunches with half the emittance and intensity are injected into h=6 buckets in the AGS. To compare this to the case where only one bunch is transferred Eq. (4) can be used. This indicates a reduction in I_{peak} of $1/\sqrt{2}$, at least if no dual harmonic were used in the AGS and if the longitudinal match was good. But this is different than the Booster case considered above. In the Booster case the beam would be captured, but here fully formed bunches are injected. Although once the bunch is matched to the bucket the $1/\sqrt{2}$ reduction in I_{peak} is a useful way to look at things, I_{peak}, when first injected, is not determined by the above considerations.

In the standard setup quad mode pumping (QP) is used effectively at Booster extraction to flatten out the bunch injected into the AGS and match it to a dual harmonic bucket. For some reason, the QP is not nearly as effective with this scheme. The reasons for that are not entirely clear. One issue may be that the F3 kicker doesn't have enough time to rise during the time between the 2 adjacent bunches as the QP makes the bunches wider. When its modules are lined up properly, its rise time is about 100 ns, and the h=3 bucket spacing is 245 ns. In order for there to be at least 100 ns between the 2 bunches they must be no more than 145 ns wide.[21] Their length, measured on the first turn in the AGS, was around 90 ns. It also seems to be harder to drive the oscillations with h=3 than it is with h=1.

This I_{peak} analysis has been theoretical and rather simplistic. The intent of it is to see if there are any glaring issues with this scheme. One could conceivably just measure I_{peak} directly with the WCM. However, the Booster WCM's time response is limited and so many of the measurements would not be accurate and data for many of these cases is not available. The exception being the comparison of I_{peak} in the AGS for (BU3/AU3) and (BU4/AU4) using the AGS WCM which will be discussed later in this note.

Preliminary Work Before Run 22

Some time was allotted during the period from Jan.17th to 27th in 2021, mainly to establish the feasibility of the flattop merge. As time was limited, h=3 was initially used in the Booster for capture and acceleration (BU7) and h=12 was used for acceleration in the AGS (AU7). This precludes the use of a dual harmonic in either machine and results in 3 bunches in adjacent h=12 buckets on the flattop. This allowed work on a 12-6 merge to proceed without the need for a 6-12 squeeze.

At first a 500 ms long merge was established but it was soon extended to 700 ms because the extra time improved it.[22] The ε before and after the 700 ms long merge was 0.512 eVs and 0.67 eVs, respectively (31% growth).[23] But only 2 of the 3 bunches are merged, and so the equivalent for 2 split bunches would be 50% larger or 0.77 eVs before and 1.00 eVs after the merge.[24] The ε before the merge is lower than typically found with h=1 bunches (~0.9-1.0 eVs). One likely contributing factor for that was that the bucket area was limited in the Booster due to a lack of voltage and there was some associated loss there.[25]

After this, the split and squeeze into h=3 buckets were developed on a new longer magnet cycle with a porch (BU3), AU7 was reconfigured for acceleration on h=6, beam was transferred to AGS into adjacent h=6 buckets and accelerated to the flattop.[26] The Booster was later configured to capture into h=2 buckets and the split was removed due to issues with the A6 RF cavity.[27] The squeeze from h=6 to 12 at the beginning of the flattop was developed and took about 300 ms. So, the whole process, 6->12 and 12->6, took about 1 sec.[28]

[21] Close inspection of the F3 kicker module rise times shown in I. Zane, Booster-AGS-pp Dec. 17, 2022 1657 entry indicate this.
[22] See Booster-AGS-PP Jan 17 2021 elog 0120 entry for 500 ms case.
[23] As usual, I use Bbat and/or Bbrat to calculate longitudinal emittances in this note.
[24] See Booster-AGS-PP Jan 18, 2021 elog 1750 and 2010 entries.
[25] See Booster-AGS-PP Jan.16, 2021 elog 1626-1644 entries).
[26] See Booster-AGS-PP Jan 20, 2021 elog 2352 entry shows split and squeeze into h=3, and Booster-AGG-PP Jan. 21, 2021 1728 entry shows bunches injected into adjacent h=6 buckets. The squeeze into h=3 buckets was first performed in Run 17 (see K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594, pgs. 37-40)
[27] See Booster-AGS-PP Jan. 24 2021 elog 1628 entry.
[28] See Booster-AGS-PP Jan. 24 2021 elog 1730 to 2337.

In this state (no split) the total ε of the 2 bunches at Booster extraction was 0.81 eVs.[29] The 2-bunch ε at the beginning of the flattop (before the squeeze) was 1.10 eVs.[30] Measuring ε after the merge was particularly difficult because of the large synchrotron oscillations there, but after some effort trying to account for that I arrived at a value of 1.38 eVs, a factor of 1.25 larger than the early flattop measurement.[31] This is where the preliminary split/merge work concluded.

The Booster User 3 Cycle

Figure 2 is a series of Booster WCM mountain range displays extending from capture to when the split bunch is squeezed into h=3 buckets and Figure 3 shows the RF voltages, harmonics, cavities, and the main magnet field.[32] These are both from well into Run 22 and so more or less represent the final state of the BU3 setup.

Figure 4 is a comparison of the BU4 and BU3 magnet cycles. The BU4 cycle is 283.33 ms long and BU3 is 2 jiffies longer (316.67 ms). The porch is 59.8 ms long, extending from 119.3 to 179.1 ms. The BU3 magnet cycle needs to be longer because of the porch, but the beam also needs to be transferred at the same time relative to At0 that it is on AU4 so that the B(t) at AGS injection to the flattop can be the same as on AU4.

dB/dt at extraction time is 27 g/ms. the same as it is on BU4.[33] Extraction occurs at Bt0+210.76 ms, 4 jiffies later than on BU4 (144.0 ms).[34] At0 is shifted 4 jiffies later on the supercycle to account for this difference. But the BU3 dummy cycle is also 2 jiffies longer than the BU4 one is so the first BU3 Bt0 is also shifted earlier by 2 jiffies. With these supercycle changes beam is injected into the AGS at At0+144.4 ms about 400 μs later than it is on AU4.

The 2 magnet references are identical up until 116.9 ms where the rollover to the porch begins. The field on the porch was set halfway between Gγ=3 (3.03 kG) and Gγ=4 (4.50 kG) at 3.75 kG. For the first 15 ms after the porch (179.1-194.0 ms) the dB/dt as a function of B is somewhat lower than on BU4 and it is the same as it from 194.0 ms to extraction. The h=3 RF frequency for Gγ=4 (at R_0) is 3.984429 MHz which happens near 195.77 ms.[35] From 194 ms to well after Gγ=4 dB/dt is the same as on BU4 and is about 63g/ms at 195.77 ms.

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[29] See Booster-AGS-PP Jan. 27 2021 elog 1614 to 1633

[30] See Booster-AGS-PP Jan. 27 2021 elog 1704-1808 and 1810.

[31] See Booster-AGS-PP Jan.27 2021 elog 2000 to 2022

[32] Mountain ranges taken from Booster-AGS-PP March 1 2022 elog 1623 entry and Figure 3 is taken from April 18, 2022 archived functions for BU3. Normally A6 and E6 would be used for h=1 during the dual harmonic but A6 was unavailable this run so B3 was used instead. Initially h=1 was also used during the squeeze but it was found to be unnecessary (see Booster-AGS-PP Nov. 3 2022 entries from 1738 to 1741).

[33] See Booster-AGS-PP Feb 18 2022 elog 1536 entry for BU4 extraction dB/dt. I can't find a similar measurement for BU3 but the dB/dt as a function of B is the same as it is on BU4.

[34] See Booster-AGS-PP Dec 17 2022 elog entry at 1313 to 1750. The RF frequency at extraction was measured to be 4.0875 MHz (Booster-AGS-PP Nov. 18 2022 1421 entry). This is an f_{rev} of 1.3625 MHz. Recall that f_{rev} for BU4 was 1.3618 MHz.

[35] See Booster-AGS-PP Jan 3 2022 elog 1617 entry. This measurement was performed on a scope. See also Dec. 31 2021 0101 entries where the RF frequencies for Gγ=3 and 4 are found and Dec. 31 2021 0115 and 0118 entries

When determining the timing of these imperfection resonances, the effect of the radius is generally neglected. So, I'm just going to check here to make sure this is OK. Near $G\gamma=4$, dB/dt is about 63 g/ms ramp which causes a change in $G\gamma$ of 0.045 in a ms. A change in radius of +1 cm at constant field corresponds to a change in $G\gamma$ of 0.0126.[36] So, say the radius was +1 cm from R_0, then $G\gamma$ would be 4.023 at 195.77 ms. However, 0.0126/0.045=280 μs earlier $G\gamma$

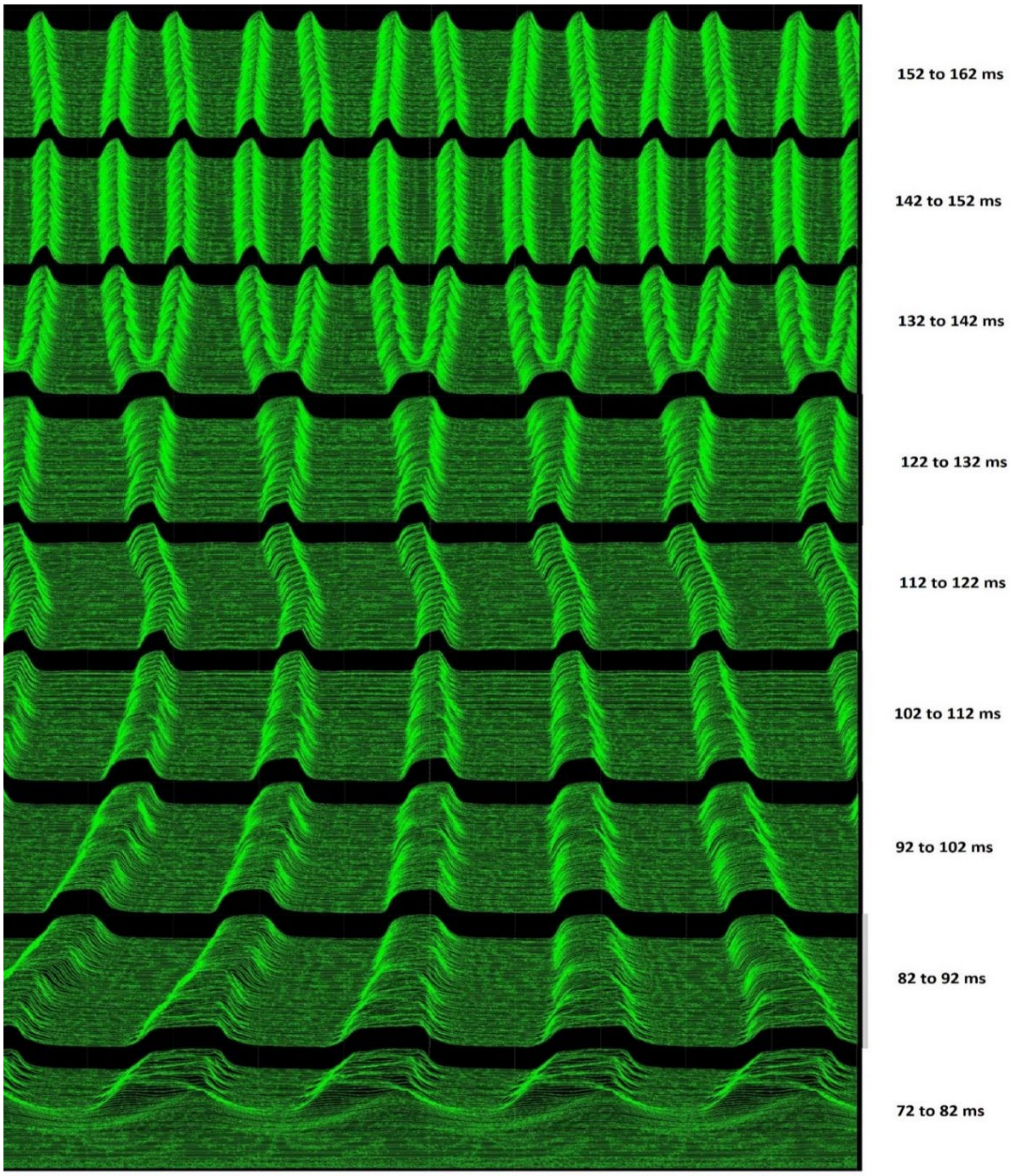

Figure 2: Mountain Range displays of the Booster WCM on BU3 showing capture, the dual harmonic, 1 to 2 split, and squeezing the 2 h=2 bunches into h=3 buckets. 500 ns/box and 500 mV/div. Each of the nine 10 ms intervals contains 80 traces, each separated by 125 μs.

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where the times in the cycle where they occur are measured using an RF GPM. Note that the time that $G\gamma=4$ occurs is 195.73 ms, only 40 μs earlier than the value obtained on the scope. $G\gamma=3$ occurs near 106.73 ms.

[36] To find *Δf/f* I use the *B(f,R)* differential relation setting *ΔB* to 0. Then I use the *p(f,R)* differential relation with the value found for *Δf/f* (=0.0012) together with *ΔR/R* (=0.0003) to find *Δp* and find the change in $G\gamma$ from that.

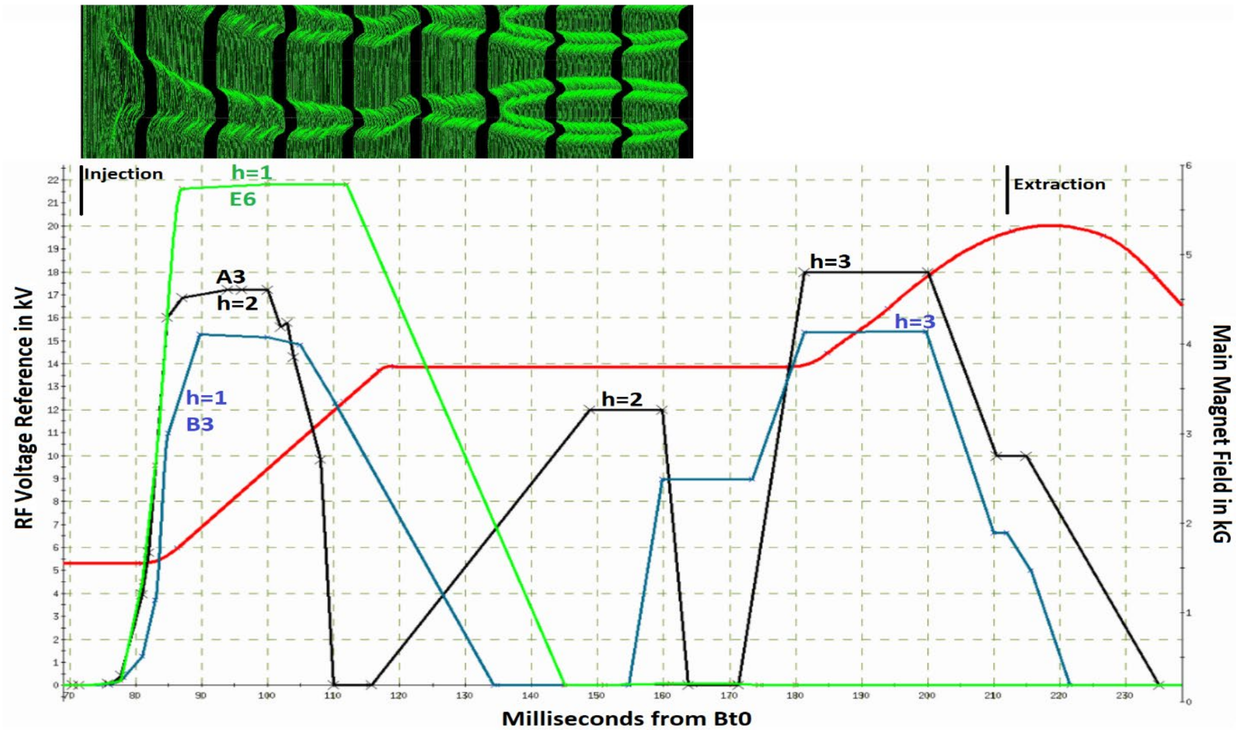

Figure 3: RF cavity voltage and Main magnet field references for the Booster (BU3) setup. Also shown are the cavity harmonics as well as where injection and extraction occur, 71.5 ms and 212 ms respectively. Above it is a portion of the mountain range display from Figure 2 scaled to roughly match the time axis.

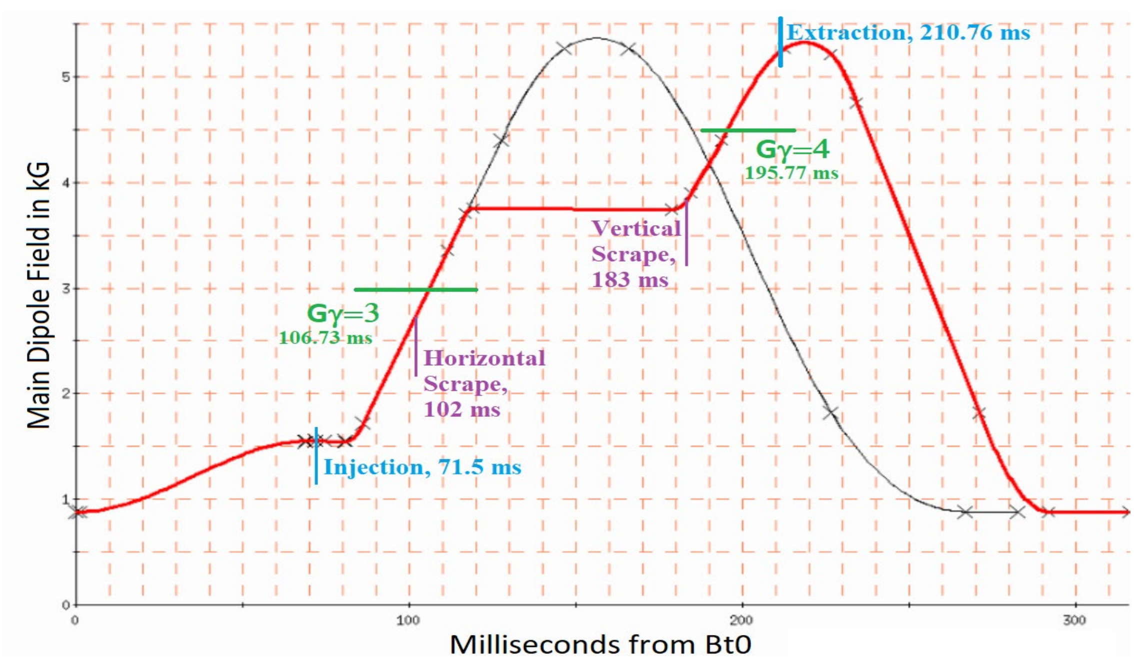

Figure 4: The Booster Main magnet field reference for the standard user (BU4, in black) and the one used for the split/merge cycle (BU3, in red). The timing of Gγ=3 and 4, the vertical and horizontal scrapes, and injection and extraction for BU3 are also shown.

would've been 4.00, so any shift in Gγ from the one calculated above for R_0 due to an off-center radius should be tolerable if the Gγ=4 bump is left on for a few ms centered around the Gγ crossing time for R_0. For BU3 it is on for 8 ms, from 191 to 199 ms. Similarly, for Gγ=3, where dB/dt is about 65 g/ms, Gγ changes by 0.0416 in a ms and a change of +1 cm at constant field changes Gγ by 0.0143. So, Gγ changes by 0.0143 in 344 μs which should also be tolerable. These considerations also apply to BU4.

The vertical scrape was set to occur at 183 ms, which is just 4 ms after the end of the porch while dB/dt is ramping up. The field reference is 3.81 kG which is nearly the same as it is on BU4 (3.77 kG). The horizontal scrape occurs about 5 ms before Gγ=3 at the same time and field reference as on BU4 (102 ms and 2.74 kG).

Perhaps of greater concern than the effect of an off-center radius on the resonance crossing times is the slew rate of the correctors. The vertical scrape is set to occur about 12-13 ms before Gγ=4. Two positive sin5v harmonic bumps are used to scrape and a negative sin4v bump is used to flip the spin at Gγ=4. Correctors at locations that are both sin4v-like and sin5v-like will have to change current the most between the scrape and Gγ=4. The F7 corrector is one of these as its sin5v component has a coefficient of -0.939 and its sin4v component has a coefficient of -0.829. Figure 5 shows its setpoint and readback during the time of interest. The situation on BU4 is similar. The readback lags the setpoint considerably but it still appears that the output gets there in time for Gγ=4. This amount of scraping is typical for normal running conditions (~2e11 late in Booster). Since the time that the vertical scrape is done can be moved, it probably makes sense to scrape a little earlier (on both users).

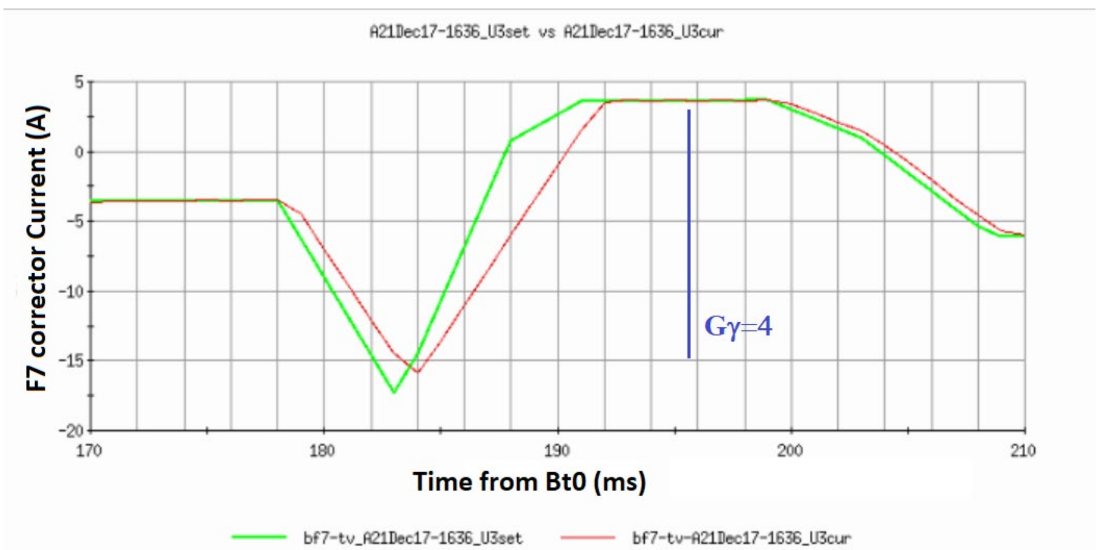

Figure 5: The setpoint (green) and readback (red) of a vertical corrector (F7) from before the vertical scrape until after Gγ=4 on BU3.[37]

[37] This is from Injpscompare. The setpoints and readbacks for a Dec. 17, 2022 at 1636 snapramp on BU3 are compared. Note that this is the dummy cycle. The readback for the 2nd cycle is missing in the program. I'm assuming it behaves the same on cycle 2.

As alluded to earlier, dB/dt (as a function of B) for the first 15 ms after the porch is somewhat lower than on BU4. It is set that way to reduce a loss near the time where peak dB/dt was reached. Before lowering it, even with the maximum RF voltage (A3 and B3 set to 18 kV) there was still a rather sharp ~5% loss near 190 ms.[38] This is perhaps not surprising because the total ε is in only 2 of the 3 h=3 buckets. Using an RF voltage calibrated from the synchrotron frequency (f_{synch}) and the maximum reference in both A3 and B3, the bucket area when the peak dB/dt was reached would be 0.42 eVs before the dB/dt there was lowered.[39]

Transfer to the AGS

Since there are 2 full h=3 buckets and 1 empty one at Booster extraction there are 2 ways that the F3 kicker can be timed to kick the 2 bunches out. One way is to have the kicker rise when the empty bucket is passing by it. This will kick both bunches out and the time between their centers passing some point in BtA will be a third the revolution period so they will be spaced correctly for injection into adjacent h=12 buckets. The other way is to have the kicker rise between the 2 full buckets, then the centers of the extracted bunches will be twice as far apart and they can be injected into adjacent h=6 buckets. The latter kicker timing is what is used for the split/merge so the dual harmonic can be used and is shown in Figure 6.[40] Although the transfer efficiency and transverse emittance seem unaffected by whether the A5 kicker pulse is in narrow (proton) or wide (ion) mode, in proton mode it does not look wide enough and there is little to no room for error in timing it correctly.[41]

The G5 WCM, which is what has been used in MCR, was broken the entire run. Instead, on Nov. 22nd the F20 WCM used by the RF system was split and sent to the mux in its place.[42] The F20 mux signal was much slower than the G5 signal. On Dec. 10th the F20 WCM was also connected to a scope in the AGS RF control room and configured for use through the RemoteScope application. This version of the F20 WCM had a time response that was faster than even the G5 WCM. It was fast enough to accurately measure the full length on the flattop, whereas with G5 it had been necessary to use twice the first half's length as the full length.[43] However, at injection there was a significant tail on the trailing edge and including that in a bunch length measurement leads to unrealistically large ε values.[44] Regardless, all the bunch length measurements from Run 22 quoted in this note are made using the F20 WCM scope in the

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[38] See Booster-AGS-PP Nov. 5, 2021 elog entries from 1226 to 1510. Also, with 18 kV in both A3 and B3 there was no loss evident at about 1e11 Booster late with no scraping (50 μs Linac pulse). Presumably this is because the ε is smaller for a shorter pulse since less time is spent on the foil, see Booster-AGS-PP Nov.28 2022 elog 1719 entry.

[39] See Booster-AGS-PP Jan. 24 2021 elog 1656 entry for f_{synch} measurement at extraction. The h=3 voltage references from logged data are A3=17 kV and B3=11 kV. The measured f_{synch} was 1008 Hz and dB/dt=34.5 g/ms. According to Bbat this requires an RF voltage of 21.45 kV. So, the calibration factor is 21.45/28=0.768.

[40] From Booster-AGS-PP Apr. 11 2022 elog 1343 entry.

[41] This was not recognized as an issue until Jan. 8 2022, it was in proton mode before that. Afterwards it was generally in ion mode. See Booster-AGS-PP Jan. 8 2022 elog entries from 1530-1605.

[42] See Booster-AGS-PP Nov. 22 2022 elog 1916 entry. Nov. 22 was when AGS setup started after the BtA vacuum valve problem.

[43] Booster-AGS-pp Dec.10 2022 elog 1911 entry and comment below it.

[44] Booster-AGS-pp Dec.10 2022 elog 1256 entry. This entry shows an BU3/AU3 injected bunch with the long trailing edge on the 'RF scope'.

RF control room unless otherwise noted. On Dec. 29th an amplifier (~13 dB) was added to the F20 WCM mux signal to get more signal for Gold.[45] With the increased gain the signal generally had to be unterminated to make it small enough to fit on the display.

A BU3/AU3 bunch length measurement at Booster extraction was made using the first turn in the AGS with and without the trailing edge. When omitting the trailing edge, where the bunch ends is not clear. Figure 7 consists of measurements with and without the trailing edge with the same bunch. Without the trailing edge its length was 87.4 ns and with it 117.5 ns. Using the RF voltage calibration discussed above (0.768) and a dB/dt of 27 g/ms the resulting emittances are 0.456 and 0.696 eVs, respectively.[46]

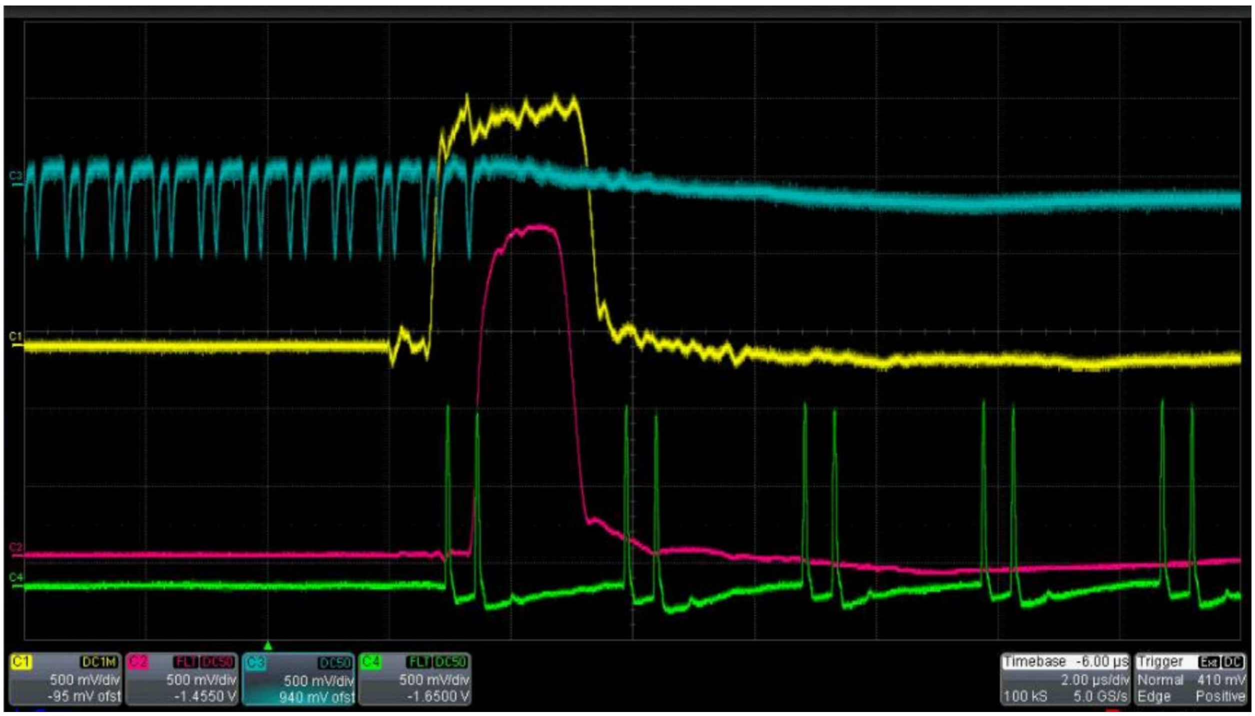

Figure 6: Kicker timing for transfer into 2 adjacent h=6 buckets showing the Booster and AGS WCMs in blue and green, respectively. The F3 (yellow) and A5 (red) discharge current signals are also shown. All but F3 are terminated into 50Ω. The trigger is the F3/A5 kicker trigger and the sweep speed is 2 µs/div. The A5 kicker is in wide (ion) mode here.

Bunch length measurements at Booster extraction were also made on BU4 and a similar trailing edge was evident. Neglecting the trailing edge, the bunch length was 134.79 ns and with it it was 154.5 ns. These correspond to emittances of 0.835 and 1.088 eVs, respectively. A BU4

[45] See AGS-RF-stay 1416 Dec.29th 2021 elog 1416 entry by. K. Hernandez. The F20 RF scope signal was unaffected by this.

[46] An f_{synch} measurement was also made at extraction on BU3 this year when the references for A3 and B3 were 7 and 12 kV, respectively (see Booster-AGS-pp Dec. 1 2022 1550 entry). It was 789 Hz which corresponds to 14.05 kV. So, the calibration would be 14.05/18=0.781. This is close to the calibration found above (0.768). In the case considered here the references are 7 and 11 kV, quite similar. Using this calibration, the resulting emittances are 0.441 and 0.658 eVs. The length measurement is found in the Booster-AGS-pp Dec. 10 2022 elog 1256 entry.

flattop ε measurement from the same day was 0.97 eVs, smaller than the injection measurement that includes the trailing edge.[47]

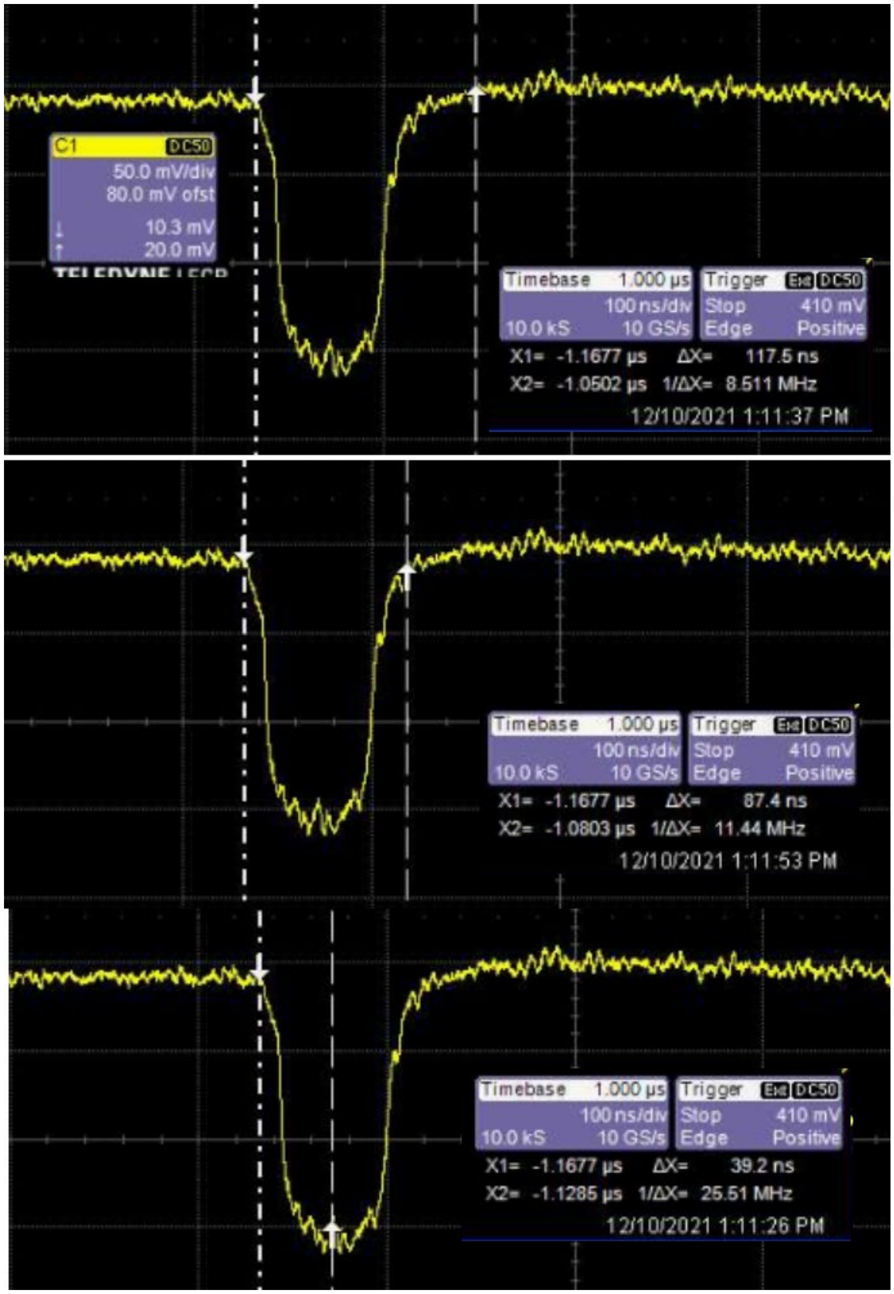

Figure 7: BU3 length measurements of the same bunch on the first turn in the AGS including the trailing edge (top, 117.5 ns) and omitting it (middle, 87.4 ns) using the F20 WCM RF scope. At the bottom is a measurement of the first half of the same bunch (39.2 ns). 100 ns/box, 50 mV/div, 50 Ω termination.

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[47] See Booster-AGS-pp Feb. 18, 2022 elog entries at 1533 (f_{synch}), 1536 (dB/dt), 1538 (bunch lengths with trailing edge tail), 1550 (ε calculation with tail), 1552 (bunch lengths without tail), 1624 (ε calculation without tail). See 1628 to 1636 for flattop measurement.

However, the dB/dt is 27 g/ms at Booster extraction so one would expect the bunch to have a longer 2nd half than 1st half. The first half of the bunch was also measured as shown in Figure 7 and was 39.2 ns. According to Bbat, the 2nd half should be about 35% longer than the first half for a 39.2 ns first half and so its full length should be (39.2ns)(1+1.35)=92 ns. That is still much smaller than the length when the trailing edge is included (117.5 ns) but is not that far from what was measured omitting the trailing edge (87.4 ns). It results in an ε of 0.50 eVs. Perhaps that is the most accurate measurement since measuring the first half is relatively straightforward.

0.50 eVs is quite large, but there is a further complication. The split in the Booster can slowly drift and so 1 bunch can be more intense and presumably have a higher ε than the other.[48] Unfortunately, I only measured 1 of the bunches here. There is however a trace containing both from Jan. 8 2022 during the time when AU3 was used to fill RHIC. The lengths of the first half of each bunch are 32.9 and 38.3 ns. Again using Bbat, the bunch with a half length of 32.9 ns will be (32.9ns)(2.28)=74.3 ns long and the other will be (38.4ns)(2.358)=90.5 ns. These correspond to emittances of 0.335 and 0.471 eVs for a 2-bunch ε of 0.806 eVs. These 2 bunches have about the same peak current and upon casual inspection look to be about the same length.[49] The error due to bunch length uncertainty for these is perhaps ±0.05 eVs.

Peak Current in the AGS

Figure 8 shows a WCM mountain range display of the first 10 ms after injection (144-154 ms). It is for the Westinghouse cycle (AU7), but that setup during that time in the cycle is essentially the same as on AU3 since the B(t) function is essentially the same up until 235 ms.[50] As opposed to AU4/AU6, there is no QP at Booster extraction and so the bunches are peaked when they are injected. That is the way BU3 was normally configured.[51]

By looking at the bunch envelope during this period it is easier to see how long it takes for the bunches to flatten out from the effect of the dual harmonic. Figure 9 shows the envelope using the WCM over the first 9 ms after injection for BU4/AU6 which has QP and only 1 bunch and BU3/AU7 both with a Booster late of 2.4e11. The peak currents right at injection are comparable for the 2 cases but after about 500 μs the peak current on AU7 has reached about the value it has when the bunches have flattened out. At about 4 ms after injection, when the AU7 bunches have flattened out, the ratio of the peak currents for the 2 setups is about 0.62. This is somewhat smaller than the predicted ratio of $1/\sqrt{2}$ =0.71.

[48] See Booster-AGS-PP Dec.10, 2021 elog 1302 entry. This shows the first turn on the F20 WCM mux signal and shows both bunches. Their intensities are clearly unequal and this is only a few minutes after the entry about the bunch length using the RF scope (1256), so the bunches were likely unequal then too. Also note that the shape of the bunch is quite different than it is on the RF scope.

[49] Booster-AGS-pp Jan. 8, 2022 elog entry at 1603. The A3 and B3 voltages from logged data were 11.485 and 7 kV respectively. The 0.768 calibration factor was used.

[50] The only significant differences are that the F-P transfer, which happens near 190 ms, and the voltage ripple afterwards, are gentler with Westinghouse.

[51] Booster-AGS-pp March 4,2022 elog entries 1959 and 2000.

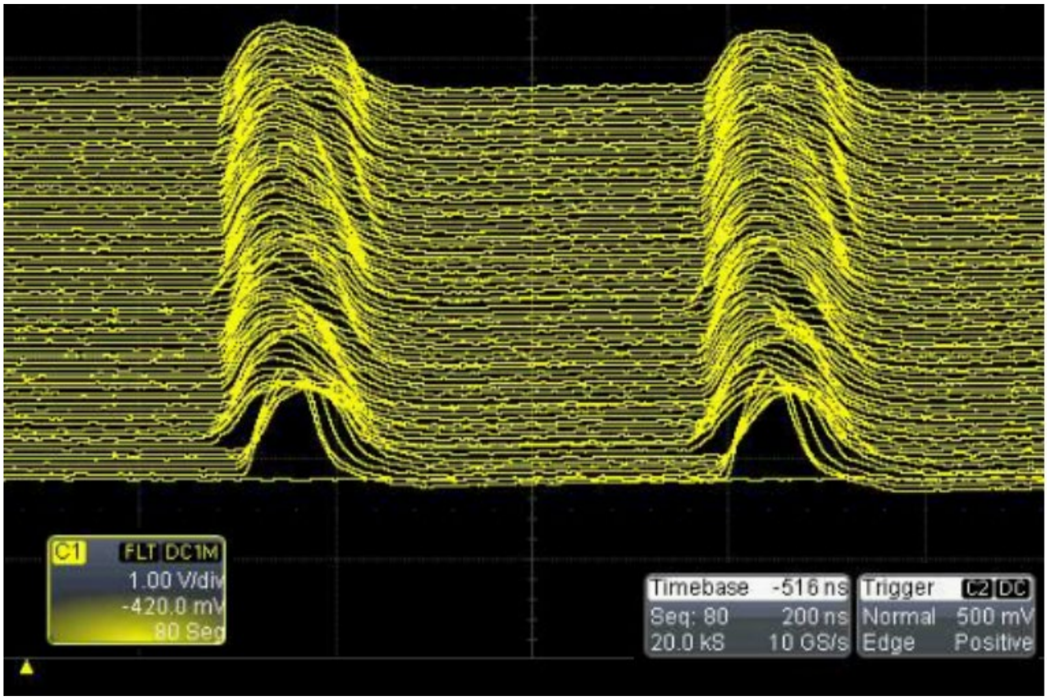

Figure 8: Mountain range display of the F20 WCM mux signal from At0+144 to 154 ms, the 1st 10 ms after injection. There are 80 traces. 1V/div and 200 ns/box. 1 MΩ termination.

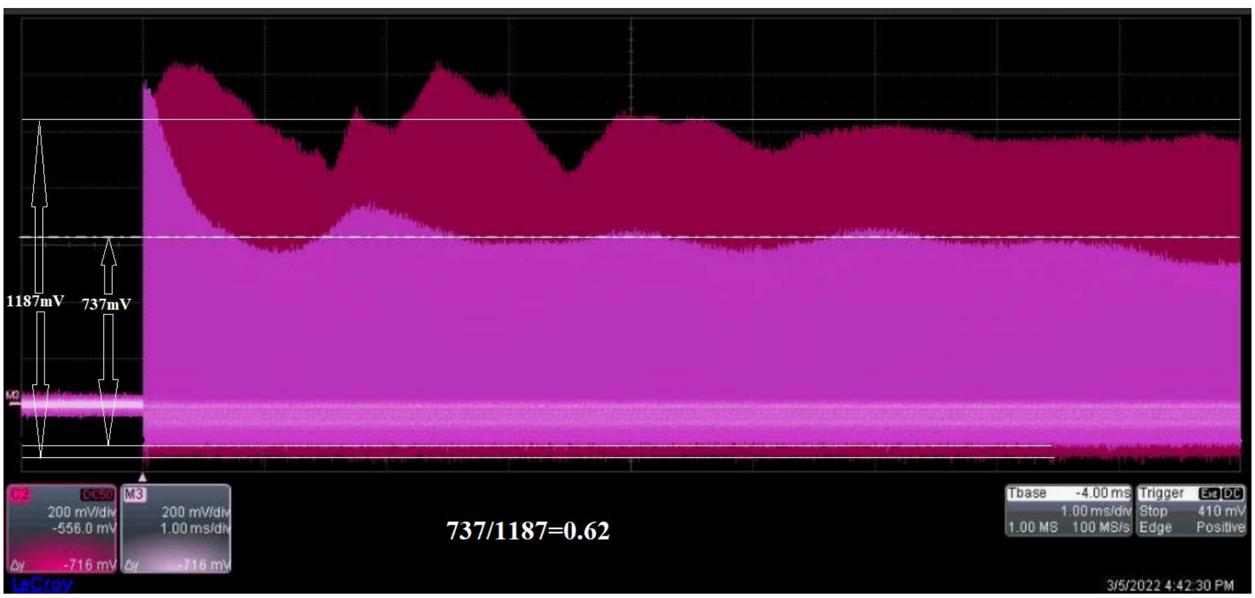

Figure 9: The bunch envelope in the AGS as seen on the F20 WCM mux signal over the first 9 ms after injection for AU6 (red, 1 bunch) and AU7 (purple, 2 bunches). Also shown are the amplitudes around 4 ms after injection. Booster late was 2.4e11 in both cases. Their ratio is about 0.62. The trigger is the F3/A5 kicker trigger which occurs at about At0+144ms. 1 ms/box, 200 mV/div, and 50 Ω termination.[52]

[52] Adapted from Booster-AGS-pp Mar. 5 2022 elog 1648 entry.

Figure 10 shows these envelopes over the first 90 ms after injection, from 144 to 234 ms for a Booster Late of about 2.4e11. Again, these are Westinghouse setups. The dual harmonic is on during the entire period, but on the corresponding Siemens setups (AU3 and AU4) it starts to turn off at 227 ms even though the B(t) functions are the same over this interval. Roughly speaking, the ratio of the 2 seems rather constant. An attempt at measuring it over the interval from 187 to 211 ms or so yields a ratio of 0.63.

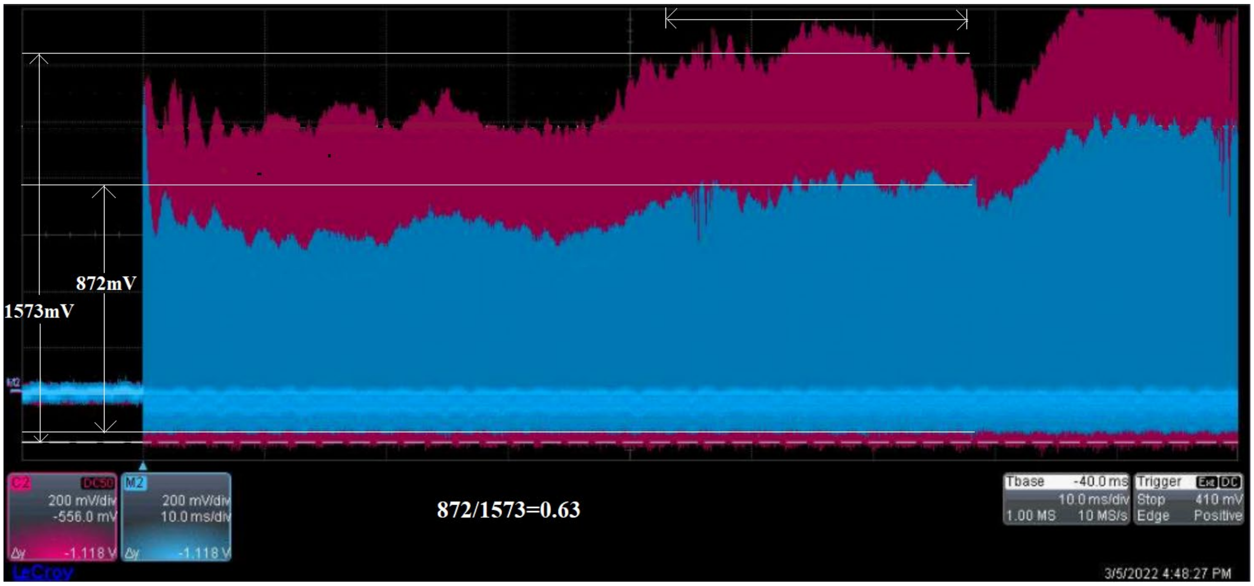

Figure 10: The bunch envelope in the AGS as seen on the F20 WCM mux signal over the first 90 ms after injection for AU6 (red, 1 bunch) and AU7 (blue, 2 bunches). Also shown are their approximate average amplitudes over the indicated interval (from about 187 to 211 ms). Their ratio is about 0.63. The trigger is the F3/A5 kicker trigger (At0+144 ms). 10 ms/box, 200 mV/div, and 50 Ω termination.[53]

Figure 11 shows the cavity voltages and harmonics for AU3 from about 140 to 280 ms. This encompasses injection, the dual harmonic, and the harmonic jump to just h=6. $G\gamma=0+\eta_y$ happens near 262 ms and the peak dB/dt, according the gauss clock, happens near 274 ms. This is essentially the same as AU4 except right near injection where the RF voltage is high to better match the incoming bunches and is rapidly lowered.

With this voltage right at injection the quadrupole oscillations in Figure 9 do not seem worse than on AU4 once the voltage has been lowered. If I infer from that that the bunch is matched coming in and neglect the relatively small h=12 voltage there (~5% of the h=6 voltage) I can calculate the ε of an injected bunch. Using the bunch length of 92 ns discussed earlier and an h=6 RF voltage of 88.2 kV I get 0.470 eVs.[54]

[53] Adapted from Booster-AGS-pp Mar. 5 2022 elog 1654 entry.

[54] I get the h=6 calculated vector sum (Vsum) of 119.5 kV from logged data for Mar 4, 2022 1958 (Figure 8). I use the calibration, V=0.759(Vsum)-2.473=88.2 kV to estimate the actual h=6 voltage (See K. Zeno, "Run 21 in the Injectors", September 2021, C-A/AP/653, pg. 15)

ε Before the AGS Flattop

It is difficult to measure ε accurately for the split/merge cycle on the flattop before the 6 to 12 squeeze because the RF voltage is changing rapidly and the f_{synch} is low. So, I opted to measure it 40 ms before the flattop at 540 ms instead, while still at full dB/dt. ε measurements made while the field is ramping are typically not that reliable, but this measurement can be compared to measurements made there on AU4 where the flattop ε can be measured reliably. The ε at 540 ms for both AU3 and AU4 was measured on Dec. 23, 2022. It was 1.10 eVs on AU4 and 1.09 eVs (0.543*2 eVs) on AU3. An AU4 flattop measurement of 0.96 eVs was also made then.[55]

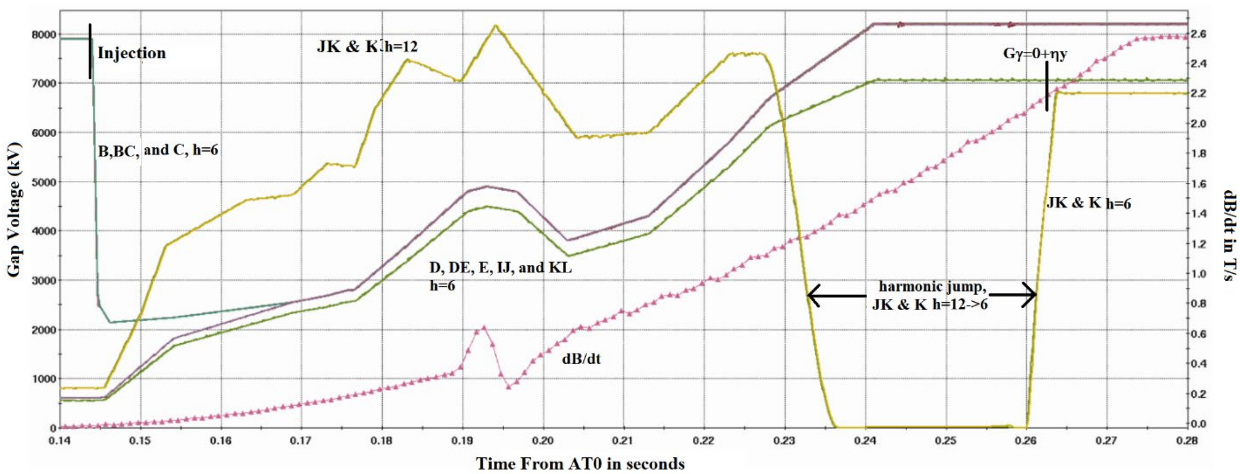

Figure 11: Cavity gap voltages reported by RF system and RF harmonics early in the AGS cycle (there are 4 gaps in each cavity). The dB/dt from the gauss clock is also shown using the right y-axis. This is the Siemens cycle (AU3) from Jan. 7 2022.[56]

For AU4 it is unlikely that the ε is smaller on the flattop than it is at 540 ms, and assuming the flattop measurement is correct then it can be no larger than 0.96 eVs at 540 ms. Also, one might be inclined to infer that at 540 ms, since the measured AU3 2-bunch ε is similar to the AU4 ε that their actual emittances are nearly the same and ≤ 0.96 eVs. Admittedly, there are assumptions involved in this such as that the errors in the 540 ms measurements do not depend on bunch length.

The 6 to 12 Squeeze and 12 to 6 Merge

Figure 12 is a schematic of the RF manipulations on the flattop. It includes RF gap voltages, harmonic jumps and other relevant events (the cavity phases are not shown). Although all 10 cavities are in use here, the entire cycle can work with only 9 as long as KL is one of them

[55] See Booster-AGS-pp Dec. 23 2022 elog entries from 1341 to 1523 (AU4 flattop), from 1525 to 1535 (AU4 at 540 ms), and from 1549 to 1605 (AU3 at 540 ms).

[56] Cavity voltages are from the Jan. 7, 2022 1334 and are in the log file AGS/RF/AGS_CavityVoltagesSnapshot.logreq. dB/dt is for the same time but from the Ags/RF/LLRF/agsDspAll.logreq/B_dot(T/s).

and 2 cavities can be configured for the dual harmonic (h=12). The squeeze starts at 690 ms and the merge ends at 1630 ms, but the whole process can be considered to start when the first

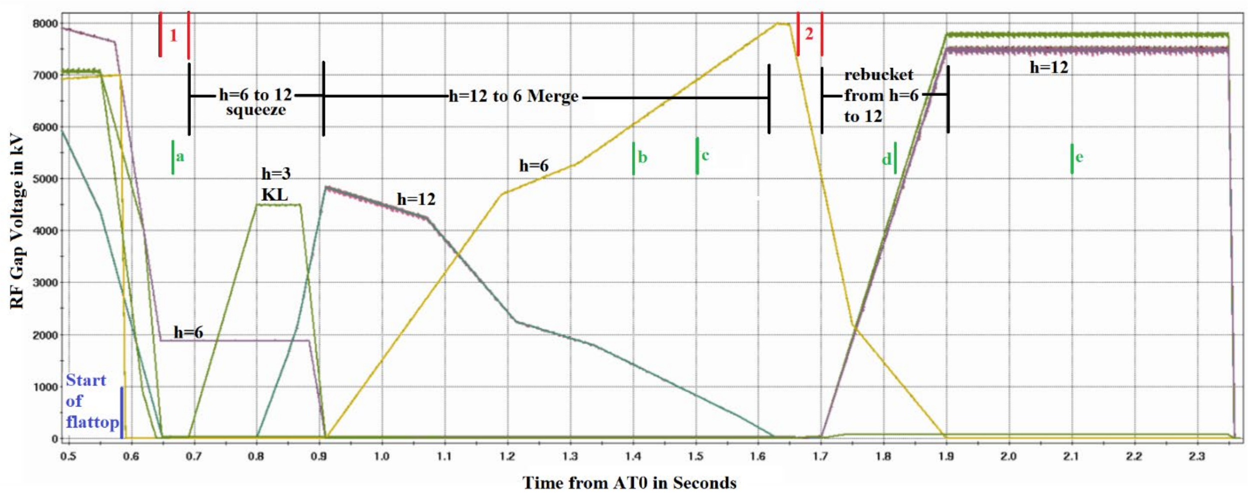

Figure 12: Typical RF cavity voltages and harmonics for the h=6 to 12 squeeze and 12 to 6 merge on the flattop for AU3. The numbers in red show the harmonic jumps. Relevant events are lettered in green and described below. All of the those events (except ags.feb_req.rt) can be found on the AGS/Rf/cfe-929-rfll1/Timing/delayV202Dsp pet page.[57]

- Cavities used for 6 to 12 squeeze: D, DE, and IJ are used for h=6, KL is used for h=3, and B, BC, and C for h=12. Each group of cavities takes the same phase and voltage functions.
- Cavities used for 12 to 6 merge: B, BC, and C are used for h=12 and JK and K for h=6. Each group of cavities takes the same phase and voltage functions.
- Cavities used for rebucketing from h=6 to 12: JK and K are used for h=6 and B, BC, C, D, DE, E and IJ are used for h=12
- Harmonic Jump 1 at 650 ms (SEQ 2): Stations B, BC, and C jump from h=6 to 12 and KL jumps from h=6 to 3.
- Harmonic Jump 2 at 1660 ms (SEQ 3): Stations D, DE, E, and IJ jump from h=6 to 12.
- a: *AGS HOLD RF Track* and *Loop Hold #1* are both turned on at 665 ms after AT0.
- b: *AC Phase Loop Start #1* occurs at 1400 ms after AT0.
- c: *AGS ReStart RF Track* occurs at 1500 ms from At0.
- d: *Loop Hold for AtR Synchro* occurs at 1825 ms from At0.
- e: ags.feb_req.rt occurs at 2100 ms from AT0.
- The rollover on the main magnet function begins at AT0+572 ms and the flattop extends from AT0+580 to 2369 ms.

[57] As with Figure 11, the cavity voltages are from the Jan. 7, 2022 1334 and are in the log file AGS/RF/AGS_CavityVoltagesSnapshot.logreq. The event and harmonic jump settings are from archives later that day.

harmonic jump occurs and end when the rebucketing to h=12 is completed at 1900 ms, 1.25 sec later. The rebucketing is performed to make the bunches narrower for injection into RHIC but even if there was no rebucketing the RF voltage would have to be raised after the merge and it probably would still be desirable to switch the h=12 cavities (B, BC, and C here) to h=6, so it would take about the same amount of time.

The rollover to the flattop begins at 572 ms, only 8 ms before it is reached. Seven of the 10 (h=6) cavities are brought to 0 by 650 ms. Two of those cavities (JK & K) are brought from close to full voltage to 0 in just a few milliseconds right at the beginning of the flattop to try to keep the restoring force constant as the dB/dt goes to 0 and thereby minimize quadrupole oscillations. Figure 13 shows the WCM during this time.

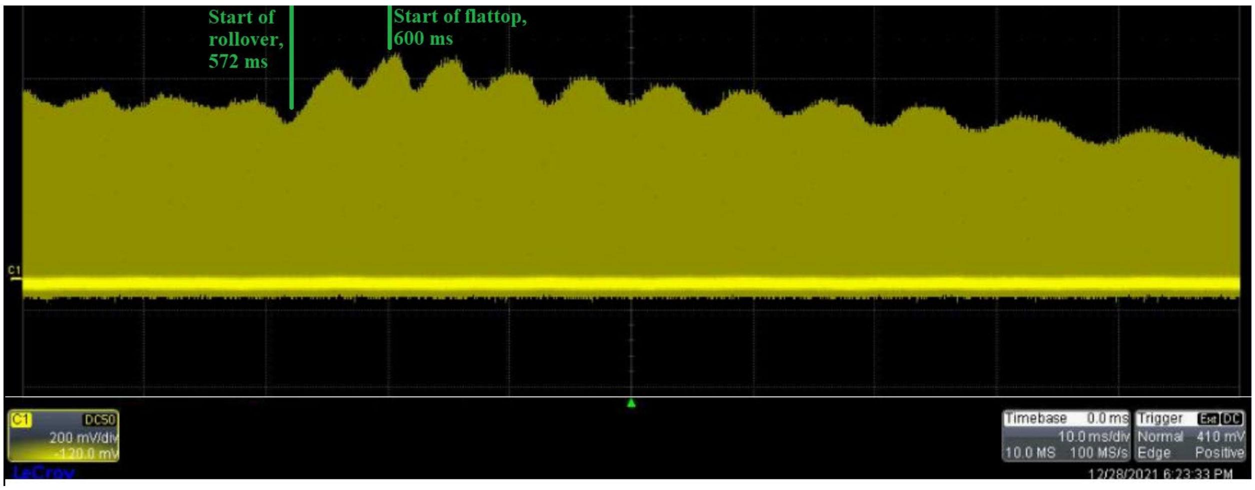

Figure 13: Mux version of the F20 WCM signal looking over the interval from 550 to 650 ms. The rollover begins at 572 ms and lasts 8 ms. It shows what happens to the quadrupole oscillations during this time.[58] 10 ms/div, 200 mV/box, 50 Ω termination.

Figure 14 is a mountain range display of the F20 WCM mux signal with the plot from Figure 12 adjusted so that the time scales match. It spans 1 second and shows the squeeze and merge. Note that the squeeze and merge do not appear symmetric as the bunch on the left moves to the right more than the one on the right moves to the left. This is likely an artifact of the instrumentation, perhaps related to delay compensation. Figure 15 shows the peak current as seen on the F20 WCM on the flattop (as well as the ramp).

When AU3 beam was first injected into RHIC the intensity was lowered to 0.7e11. The squeeze and merge had been set up prior to that with about 1.6e11. The quality of the bunches greatly deteriorated when the intensity was lowered. The merged bunch ε went from about 1.3 to 1.6-2.0 eVs.[59] Lowering the integral radial loop gain from 30000 to 1000 reduced the quadrupole oscillations during the ramp and the beginning of the flattop and reduced the intensity dependence to an acceptable level. With the lower gain the radius did not follow the radial

[58] Taken from Booster-AGS-PP Dec. 28, 2022 elog 1828 entry.
[59] The 1.6-2.0 eVs value was estimated using the RHIC WCM at injection. See Booster-AGS-pp Dec. 15 2021 1454 entry and Dec. 14 2021 1835 entry by V. Schoefer.

steering function nearly as well, especially at the rollover, but the radius was reproducible so it was left this way (it remained 30000 on BU4).[60]

Before the squeeze starts the AC phase loop is set to hold by turning on “Loop Hold #1” before the squeeze begins.[61] For some reason the amount of dipole and quadrupole oscillations during the squeeze/merge and hence the quality of the merged bunch depends strongly on when it goes to hold and the optimal value tends to drift. It is typically put to hold after the 1st harmonic jump (650 ms).

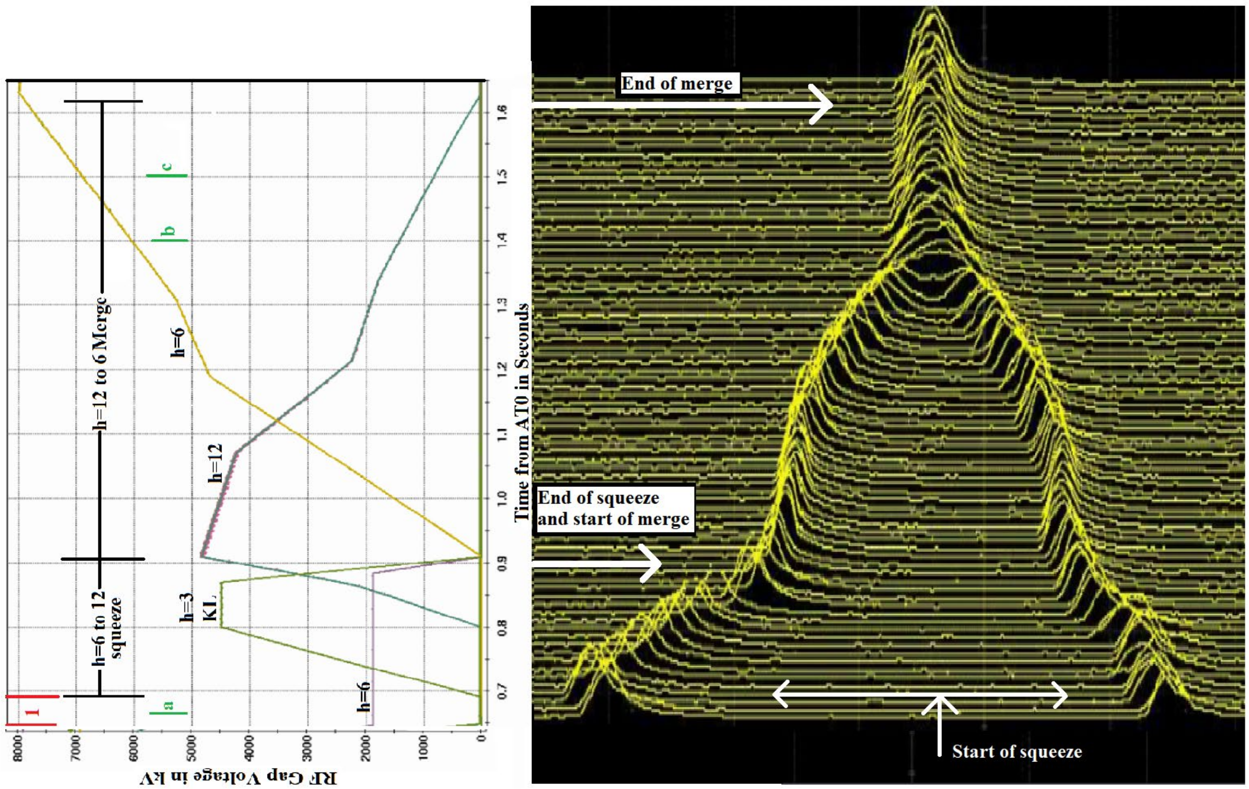

Figure 14: A mountain range display of the F20 WCM (mux) signal on the flattop made of 80 traces spanning from just before the beginning of the squeeze until just after the end of the merge (650 to 1650 ms) with an AGS late of about 2e11.[62] On the left is part of Figure 12 scaled to match the timing on the mountain range. 500mV/box, 50 Ω termination.

Looking at the bunch to bucket phase logged data and considering 2 cases, one where it is set to a time (693 ms) that results in poorly merged bunches and one where they are merged relatively well (663 ms), there are no dipole oscillations apparent before it goes to hold, but they

[60] The Booster-AGS-pp Dec. 27 2022 1136 entry is a comparison of radii, as seen through AGSOrbitDisplay, with the integral loop gain set to 30000 and 1000 on AU4. Just below it (1142 and 1143 entries) are comparisons of the radial steering and radial average for the 2 cases. It seems the integral gain was raised in 2015 after the rollover was shortened so that the radius would follow radial steering better there (see Booster-AGS-pp 2015 March 17 entries from1754 to 1758).

[61] Found on AGS/Rf/cfe-929-rfll1/Timing/delay202Dsp pet page. Initially this was moved around a lot but eventually settled down.

[62] Taken from Booster-AGS-pp Dec. 23 2021 1608 entry. This is before gain was added to the signal.

do develop afterwards in both cases. It appears from the logged loop status data that loop hold actually comes on about 11-12 ms after where it is set to come on. If that is the case then when set to 693 ms it was going to hold when the KL voltage was considerable, about 600 V. Maybe that was part of the problem. Another difference I see between the 2 cases is that in the 663 ms case the oscillations begin as a negative sine and in the 693 ms case they begin as a positive sine.[63]

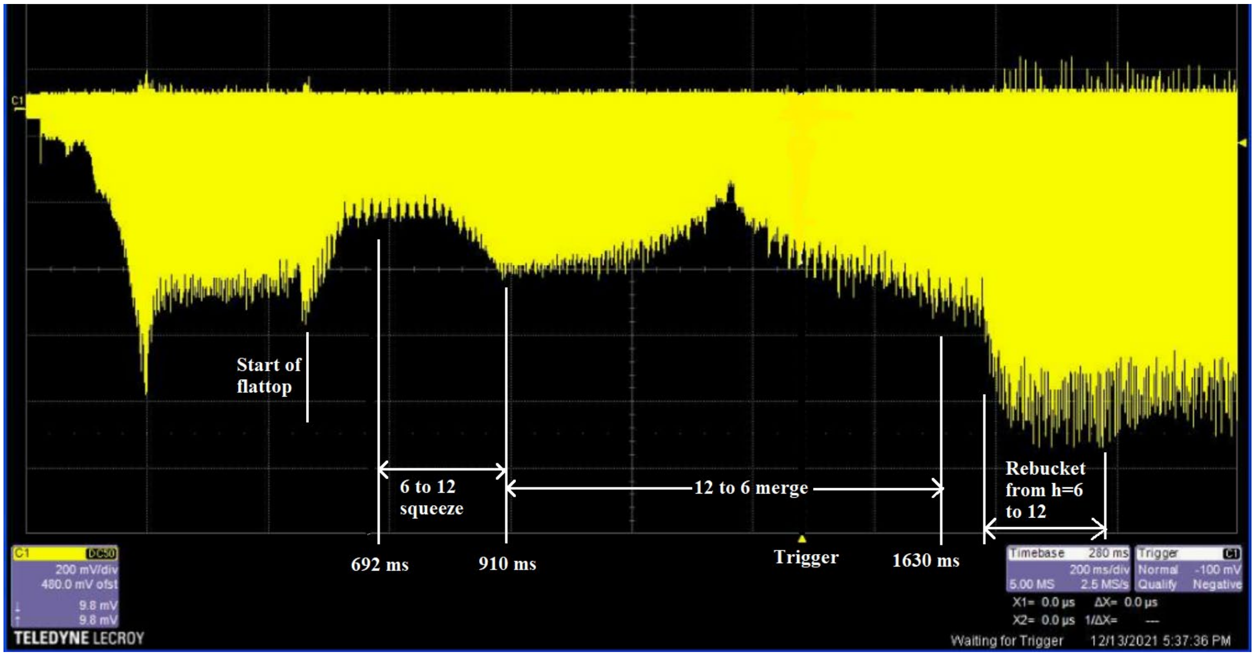

Figure 15: The envelope of the F20 WCM RF scope signal during the entire ramp and most of the flattop on AU3. The trigger is at 1400 ms. 500ms/box and 200 mV/div.[64]

Longitudinal Emittance Measurements after the Merge

Table I contains ε measurements made on the flattop after the AGS merge in January 2021 and during Run 22. A dual harmonic was not used in either machine in January 2021. For the first and second measurements the beam was captured in the Booster into h=3 buckets and only 2 of those 3 bunches were merged. So, one would expect the merged bunch ε to be only 2/3rd of what it would be if all the beam captured went into 2 bunches. There was also no 6 to 12 squeeze for those. For the remainder of the Jan. 2021 measurements (rows 3 to 5) the beam was captured into h=2 buckets and those bunches were squeezed into two h=3 buckets. For rows 4 and 5 there was a flattop ε measurement made before the 6 to 12 squeeze so the amount of growth is also indicated.

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63 See Booster-AGS-pp July 27 2022 elog 1719 entry which shows B2B phase data for the 2 cases from Dec. 22 2021.

64 From Booster-AGS-pp Dec. 13 2021 1722 entry.

row	Date	Time	*h*	Length	ε	Notes
1	1/18/21 17:53	1600	6	43.26	0.94	No AGS squeeze, only h=3 in Booster, h=12 for AGS ramp, AU7
2	1/18/21 20:10	1700	6	36.4	0.67	No AGS squeeze, only h=3 Booster, h=12 for AGS ramp, AU7
3	1/24/21 22:07	1800	6	54.7	1.54	h=2 Booster capture, h=2 to 3 and AGS squeezes, h=6 for AGS ramp, AU7
4	1/27/21 18:04	1800	6	56.05	1.61	Same as above. 1-bunch ε at start of flattop 0.553 eVs so growth on flattop is factor of 1.61/1.106=1.46
5	1/27/21 20:22	1800	6	51.64	1.38	Same as above, but growth on flattop a factor of 1.38/1.106=1.25
6	12/10/21 14:33	2000	6	42.0	1.80	Full split/merge setup, BU3/AU3, no rebucketing
7	12/11/21 20:41	1900	6	35.52	1.31	Full split/merge setup, BU3/AU3, no rebucketing
8	12/20/21 14:07	1900	12	31.04	1.35	Rebucketing from h=6 to 12 for extraction since Dec. 16
9	12/21/21 21:04	1900	12	32.23	1.54	
10	12/22/21 16:28	1900	12	31.02	1.34	Average of peak and valley lengths, 29.41 and 32.63 ns
11	12/22/21 16:44	1900	12	31.67	1.40	0.7e11
12	12/22/21 20:03	1901	12	29.63	1.23	Lower Radial loop integral gain & Loop hold #1 moved earlier, 663 ms
13	12/23/21 16:19	1901	12	28.56	1.14	checking at 0.7e11
14	12/28/21 18:58	2100	12	29.27	1.20	used for RHIC
15	12/29/21 14:10	2100	12	28.45	1.13	used for RHIC, 1.7e11
16	12/29/21 1621	2100	12	30.08	1.25	used for RHIC, 1.9e11
17	1/4/22 13:06	2100	12	31.74	1.39	used for RHIC, 2.3e11, as found after long weekend
18	1/4/22 17:45	2100	12	30.78	1.31	used for RHIC, 2.4e11, before phase loop gain lowered
19	1/4/22 17:51	2100	12	29.61	1.21	used for RHIC, 2.1e11, phase loop gain lowered due to possible intensity dependence
20	1/12/22 16:15	2100	12	29.01	1.17	used for RHIC, 2.2e11
21	2/8/22 19:45	2400	12	30.14	1.22	Westinghouse, AU7

Table I: Compilation of AGS flattop longitudinal emittance measurements after the merge from Jan. 2021 and Run 22. The time column is in ms from At0, the *h* column is the RF harmonic, the length column is the bunch length in ns, and the ε column is (full) longitudinal emittance in eVs. The bunch lengths were measured using the G5 WCM in Jan. 2021 and the F20 WCM RF scope signal in Run 22. The data is taken from the Booster-AGS-pp elog for the dates and times indicated. The intensities quoted in the Notes section are at AGS Late and have been corrected for the low calibrate pulse by multiplying them by 4.64/5=0.928.

The Run 22 data (rows 6 to 21) was all taken with a full split/merge setup. Rows 14 to 20 are measurements that were taken while it was being used for RHIC. The last measurement was taken while Westinghouse was the motor-generator. This required shifting everything associated with the AGS squeeze/merge and extraction later by about 465 ms. This setup (AU7) was not used to inject into RHIC because there was not an obvious difference in the RHIC polarization between AU3 and AU4. While the motor-generator was switched back to Siemens on March 8th and the split/merge cycle was active then, it was not used for RHIC for the same reason.[65]

On March 23rd it was found that the calibrate pulse used to calibrate the AGS intensity scalers was not the advertised 5 mA but was instead 4.64 mA. Judging from the fact that the amplitude of calibrate pulse on the unnormalized version of the current transformer did not change significantly through the run it is likely that the cal. pulse current had been this way for at least the entire run. This means that all the AGS intensity data up until that point was reading about 7.7% high. All AGS intensities from Run 22 quoted in this note are adjusted to correct for this.

Although there are no proper ε measurements on AU3 at the beginning of the flattop for Run 22, there is the estimated value discussed above, 0.96 eVs. There are also ten AU4 flattop measurements. So, the ε before extraction on AU3 and AU4 can be compared. Table II contains the AU4 flattop measurements that were made during the run. There is not much variation and the average of the 10 measurements is 0.99 eVs with a σ of 0.062 eVs.

Date & Time	f_{synch} (Hz)	Length (ns)	ε (eVs)	AGS Late intensity
12/10/22 19:24	123.6	29.1	1.00	1.9e11
12/17/22 14:57	123.2	28.34	0.95	0.6e11
12/17/22 15:52	123.6	29.4	1.02	1.1e11
12/22/22 13:20	123.7	28.03	0.93	1.7e11
12/23/22 15:23	123.9	28.51	0.96	1.8e11
3/10/22 13:50	120.0	31.18	1.11	2.4e11
3/15/22 12:53	118.7	30.62	1.06	2.1e11
3/16/22 18:25	116.9	28.19	0.88	2.2e11
3/28/22 18:50	123.8	28.97	0.99	2.2e11
3/29/22 17:07	117.8	29.44	0.97	2.4e11

Table II: AU4 flattop longitudinal emittance measurements during Run 22. They were measured at At0+900 ms. Data is taken from the Booster-AGS-pp elog for the dates and times noted. The lengths were measured using the F20 WCM RF scope signal.

Many of the split/merge setup's ε measurements were made during its development and are not representative of the optimized state although the measurements taken while using it for RHIC could be considered as such. The average of those measurements (rows 14 to 20 in Table

[65] See pg. 41 of V. Schoefer's 2022 RHIC retreat presentation "RHIC Polarized Proton Operation in Run 22".

I) is 1.24 eVs and the σ is 0.08 eVs. So, ε at extraction was about 25% larger on AU3 than on AU4. In Run 17, the previous PP run, the average flattop ε was 0.92 eVs with a σ of 0.07 eVs.[66]

AU3 and AU4 Transverse Flattop Emittance Measurements using the Ion IPM

Tables III and IV contain flattop 95% normalized transverse emittance (ε_x,ε_y) measurements made on the AU3 and AU4, respectively, during Run 22 using the Ion IPM with the RF shutting off at 1000 ms.[67] Although these aren't all the measurements taken, it is most of them. They were taken under a variety of conditions, and I don't find that just plotting them to compare the 2 users is particularly enlightening. The intensity data has been rounded off to the nearest 0.1e11, so it can be binned with a bin size of ±0.05e11. I decided to pick the lowest average emittance, $\varepsilon_{avg} = \sqrt{(\varepsilon_x^2 + \varepsilon_y^2)/2}$, for each AGS late from 1.9 to 2.5e11 for AU3 and AU4. This data is shown in Figure 16 together with IPM data from Run 17.[68]

The ε_{avg} data from Run 17 are consistently smaller than AU4, which is nominally the same setup. The AU3 data is a little smaller than both except at 2.5 and 2.6e11 where it is a bit larger than the Run 17 data. Although this may simply be due to the AU3 setup not being optimized for those intensities, it is still a bit surprising since, naively, one would expect the benefit of the split/merge to be more evident at higher intensities.

Figures 17 contains similar plots for ε_x and ε_y. For intensities less than 2.5e11, ε_x data for AU3 is consistently smaller than the AU4 or 2017 data, but that is not the case for ε_y. For ε_y the 2017 data is often smaller than the AU3 data. As regards ε_x, it may be that the AU3 data is this small because the maximum Δp/p when the RF is shut off is smaller, resulting in a smaller dispersion contribution to the horizontal width for AU3. It is evident from Figure 14 that at 1000 ms there are still 2 distinct bunches which would normally have a significantly smaller Δp/p than a single bunch with (roughly) twice the longitudinal emittance as is the case on AU4. In addition, the RF voltage is only generated by 5 of the cavities and, unlike on AU4 where 9 or 10 cavities are typically used, the cavity voltages are far lower than their maximum values.

BU3 and BU4 BtA Transverse Emittance

At least in the case of Run 22, even on AU3, the flattop (ε_x,ε_y) would be expected to increase even if there was no intensity dependence in the AGS since the scraping was generally relaxed in the Booster to raise the intensity. That is not the case for the Run 17 data in Figures 16

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[66] See K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594, pg. 35. These measurements were made using the G5 WCM.

[67] Note that all IPM emittance data quoted in this note uses the Refit option.

[68] See Figure 18 on page 21 of K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594 for the Run 17 IPM data. The 2017 (ε_x,ε_y) data is interpolated from the dual harmonic (AU2) data in that figure and ε_{avg} is calculated from that. For this data, the intensity was varied by adjusting the Linac pulse width while keeping scraping constant. Booster input was about 6.9e11 with the full 300 μs pulse.

and 17 since the pulse width was changed to vary the intensity. (ε_x,ε_y) in BtA also depends on Booster input since the higher it is the more scraping can be used for a given Booster late intensity. The Booster input intensity in Run 17 averaged about 6.9e11.[69]

	Date & Time	ε_x	ε_y	ε_{avg}	AGS Late ($x10^{11}$)	Notes
1	12/22 17:01:48	12	12	12	1.4	
2	12/22 17:04:07	12.5	15	13.8	1.9	BtA efficiency only 85%
3	12/23 16:23:52	11.5	12.5	12.0	2.0	
4	12/23 16:36:41	14	15	14.5	2.6	Only vertical scrape
5	12/23 16:38:51	11.5	13	12.3	1.9	Only vertical scrape
6	12/23 17:46:07	11	11.5	11.3	1.9	
7	12/23 18:31:38	11	12	11.5	1.9	
8	12/28 18:13:58	10.5	12	11.3	2.0	AU3 used for RHIC from here to 1/12
9	12/30 16:44:20	11	12	11.5	1.9	
10	1/5 15:23:15	12	13.5	12.8	2.4	
11	1/5 16:11:50	12.5	13	12.8	2.3	
12	1/5 17:10:22	12	13	12.5	2.3	
13	1/5 17:59:35	11.5	13.5	12.5	2.3	
14	1/7 13:50:29	10.5	14	12.4	2.1	
15	1/7 19:14:10	10.5	13	11.8	1.9	BtA MW006 (ε_x,ε_y)=(9.6,3.1) mm mr
16	1/7 19:25:14	9	12.5	10.9	1.5	
17	1/7 19:31:45	8.5	13	11.0	1.0	
18	1/10 18:27:47	10	13	11.6	1.9	BtA MW006 (ε_x,ε_y)=(8.0,2.3) mm mr
19	1/12 15:51:10	11	14	12.6	2.2	Last measurement before Siemens failure, BtA (ε_x,ε_y)=(9.9,3.5) mm mr
20	3/21 18:30:13	14.5	15.5	15.0	2.3	First measurement after Siemens repair
21	3/22 18:32:56	13	16	14.6	2.2	
22	3/22 18:54:13	14.5	14.5	14.5	2.2	
23	4/8 15:49:34	13	15	14.0	2.2	BtA MW006 (ε_x,ε_y)=(7.9,2.8) mm mr
24	4/8 15:52:39	13	15	14.0	2.5	
25	4/8 15:54:32	12.5	14	13.3	2.2	
26	4/8 18:59:00	12.5	14	13.3	2.2	
27	4/11 13:38:38	13	14	13.5	2.2	
28	4/11 14:15:14	13	14	13.5	2.2	
29	4/14 17:26:24	13	14	13.5	2.3	
30	4/15 17:38:00	12.5	13.5	13.0	2.1	

Table III: AU3 (split/merge) transverse 95% normalized emittances (ε_x,ε_y) in mm mr on the flattop using the ion IPM with RF shutting off at 1000 ms. Also shown is ε_{avg} for each case. The rows highlighted in yellow contain the data plotted in Figures 16 and 17.

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

	Date & Time	ε_x	ε_y	ε_{avg}	AGS Late ($x10^{11}$)	Notes
1	12/8 16:48:57	13.5	14	13.8	1.9	
2	12/13 12:16:35	14.5	13	13.8	1.8	
3	12/20 12:50:35	13	14.5	13.8	2.0	
4	12/23 13:35:14	15	16.5	15.8	2.4	Not much horizontal scrape
5	12/23 13:38:06	13.5	14	13.8	1.9	More horizontal scrape
6	12/23 21:22:51	14	15	14.5	1.9	Last measurement before Siemens failure
7	3/8 15:29:09	14	16	15.0	2.0	Switched back to Siemens. AU4 used for RHIC
8	3/8 18:25:56	13	16	14.6	2.2	
9	3/8 19:12:25	13	15	14.0	2.0	
10	3/8 19:28:02	12	14	13.0	1.9	
11	3/8 19:40:25	13	15	14.0	2.2	
12	3/9 19:01:32	12.5	14.5	13.5	2.2	
13	3/9 19:41:01	13.5	14	13.8	2.2	
14	3/10 19:36:49	13.5	14.5	14.0	2.2	
15	3/11 14:56:52	13.5	14.5	14.0	2.3	
16	3/20 17:52:30	13.5	15	14.3	2.4	
17	3/22 14:30:44	15	14.5	14.8	2.4	
18	3/22 16:18:02	15	14	14.5	2.1	
19	3/23 18:22:39	13	15	14.0	2.4	
20	3/24 14:12:34	13.5	14	13.8	2.2	
21	3/25 14:26:43	14	15	14.5	2.4	
22	3/25 14:49:57	13	15	14.0	2.5	
23	3/27 13:27:31	13.5	15	14.3	2.3	BtA MW006 (ε_x,ε_y)=(8.2,3.1) mm mr
24	3/28 15:47:24	13	15.5	14.3	2.4	
25	3/31 17:32:27	14	15.5	14.8	2.4	
26	3/31 18:39:12	11.5	12.5	12.0	1.3	
27	4/4 14:11:51	12.5	14.5	13.5	2.2	BtA MW006 (ε_x,ε_y)=(9.6,2.6) mm mr
28	4/4 14:19:29	11	12	11.5	0.9	
29	4/4 15:12:41	10.5	11.5	11.0	0.7	
30	4/5 14:08:53	13.5	16	14.8	2.3	
31	4/6 18:35:32	13.5	14.5	14.0	2.2	
32	4/8 16:12:24	13.5	15	14.3	2.2	
33	4/11 19:45:10	14	15	14.5	2.1	
34	4/12 16:19:02	13.5	15	14.3	2.1	
35	4/13 16:30:50	14	15.5	14.8	2.3	

Table IV: AU4 transverse 95% normalized emittances (ε_x,ε_y) in mm mr on the flattop using the Ion IPM with RF shutting off at 1000 ms. Also shown is ε_{avg} for each case. The rows highlighted in yellow contain the data plotted in Figures 16 and 17.

Although it varied, the Booster input intensity this run was generally lower than that. This was because there was a concern that higher current might reduce the source polarization.[70] On March 24th it was found that Booster input scaler gain had been set too high and its gain was lowered from 17 to 16.[71] Figure 18 shows the corrected Booster input for the entire run. During the time when AU3 was used to fill RHIC (12/28 to 1/12) it was about 5.7e11 except for the period from Dec 31 to Jan. 4 where it was around 7.0e11. Note that there are no measurements in Table III from that period.

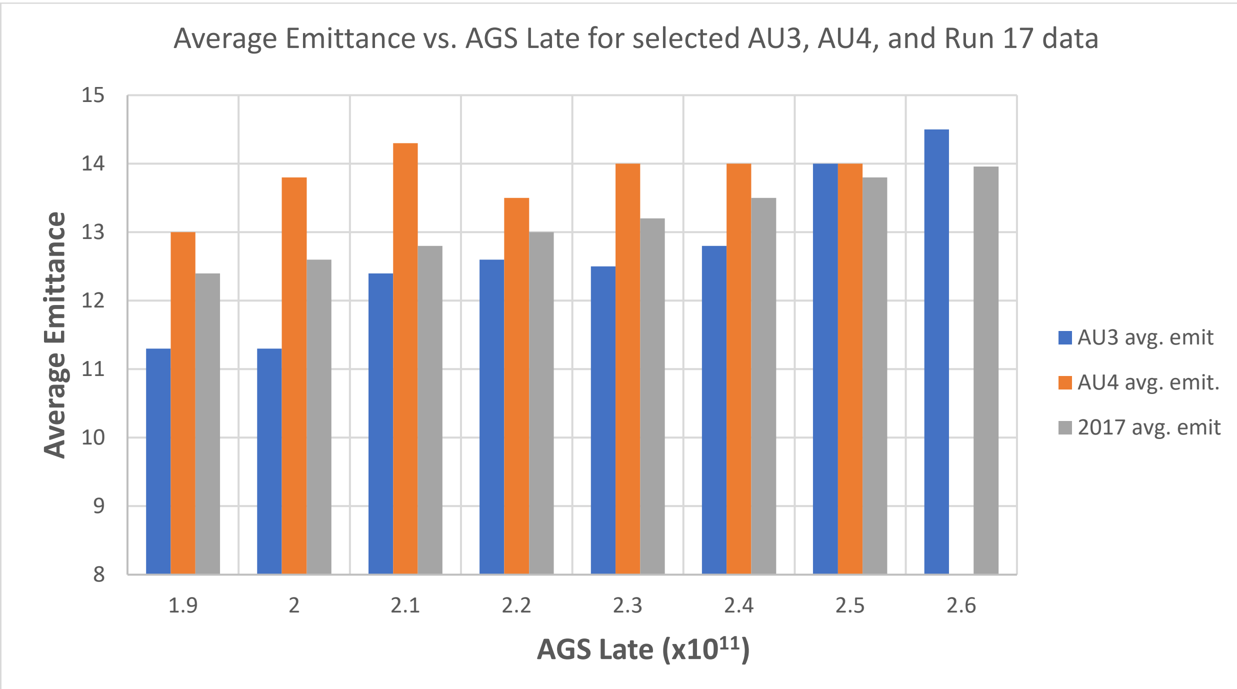

Figure 16: The 95% normalized transverse average ion IPM flattop emittance (ε_{avg}) data in mm mr while RF is off for AU3 (blue), AU4 (orange), and Run 17 (gray) for intensities from 1.9 to 2.5e11 (data for AU3 and 2017 at 2.6e11 is also included). The AU3 and AU4 data are from Tables III and IV, respectively.

Tables V and VI contain some BtA (ε_x,ε_y) measurements made during the run for BU3 and BU4, respectively. They were made using multiwire MW006 when the Booster Late intensity was roughly that used for filling (2.45 to 2.65e11). (ε_x,ε_y) are calculated from the profile FWHMs obtained from Gaussian fits using ε_x=0.82($FWHM_x^2$) and ε_y=0.155($FWHM_y^2$).[72] The average Booster Input and Late are quite similar for the 2 cases. ε_{avg} is somewhat smaller for BU4, 6.39 vs. 6.65 mm mr, but given the limited amount of data it is perhaps not a statistically significant difference.

[70] H.Huang, private communication.
[71] See Booster-AGS-PP Mar 24 2022 elog 1326 and 1327 entries.
[72] See footnote3 on pg. 3 of K. Zeno, "Booster and AGS Transverse Emittance During the 2006 and 2009 Polarized Proton Runs", C-A/AP#404, Sept. 2010

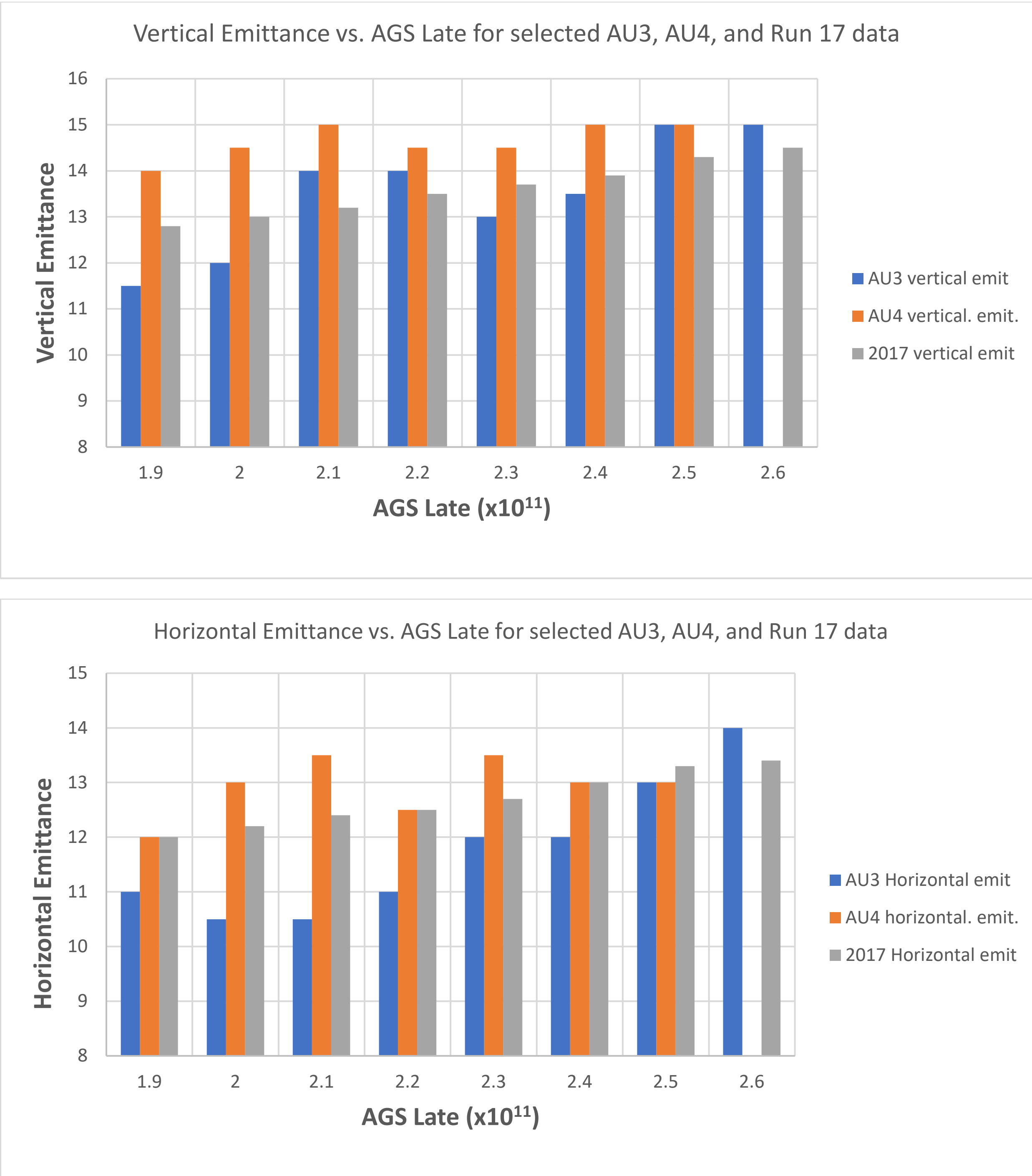

Figure 17: The 95% normalized transverse vertical (top) and horizontal (bottom) ion IPM flattop emittance data in mm mr while RF is off for AU3 (blue), AU4 (orange), and Run 17 (gray) for intensities from 1.9 to 2.5e11 (data for AU3 and 2017 at 2.6e11 is also included). The AU3 and AU4 data are from Tables III and IV, respectively.

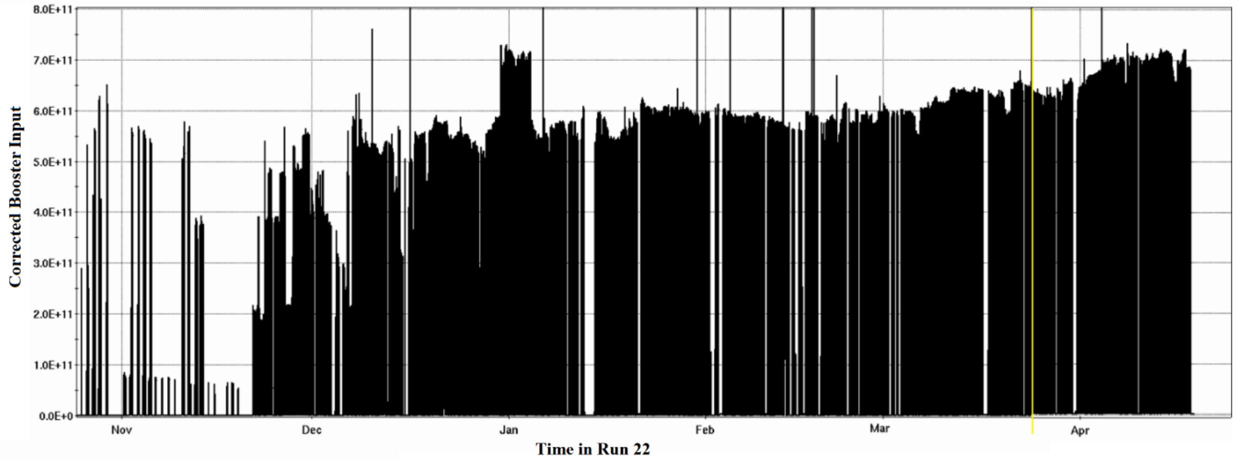

Figure 18: A plot of the corrected Booster Input during Run 22. Before the afternoon of Mar 24, what is displayed is the logged Booster input multiplied by 16/17. After that time the logged Booster input is displayed because the gain of Booster Input was lowered from 16 to 17. The time that change was made is indicated by the vertical yellow line.

In 2017, Booster Late at typical filling intensity was probably similar and ε_{avg} was in the 5-6 mm mr range. ε_x and ε_y from MW006 were typically in the ranges of 7-8 and 2-3 mm mr, respectively.[73] These values are somewhat smaller than this year, (8.9, 2.9) mm mr for BU3 and (8.4, 3.4) mm mr for BU4. The lower Booster input this year, averaging 6.1-6.2e11 in the Table V and VI data, could be partly responsible for the difference.

	Date	Time	x FWHM in mm	y FWHM in mm	B. Input ($x10^{11}$)	B. Late ($x10^{11}$)	ε_x	ε_y	ε_{avg}
1	Feb. 9	14:48:47	3.21	4.41	5.72	2.50	8.45	3.01	6.34
2	Mar. 4	17:26:51	3.12	4.98	5.76	2.52	7.98	3.84	6.26
3	Mar. 4	18:00:50	3.14	3.89	5.81	2.47	8.08	2.35	5.95
4	Apr. 8	14:25:52	3.67	4.07	6.69	2.58	11.04	2.57	8.02
5	Apr. 15	17:26:38	3.34	4.27	6.57	2.48	9.15	2.83	6.77
Average			**3.30**	**4.32**	**6.11**	**2.51**	**8.94**	**2.92**	**6.65**

Table V: BU3 BtA MW006 data for a few cases with typical Booster Late used for filling (2.45-2.65e11). The FWHM values shown are for Gaussian fits of the profiles. (ε_x, ε_y) and ε_{avg} are calculated as described in the text. The FWHM data can be found in the Booster-AGS-PP elog and the intensity data is from LogView.

The Δp/p at MW006 will have some effect on the horizontal width there and consequently the calculated ε_x. Given that the BU3 setup is quite different than the BU4 setup, it is not clear to me how their Δp/p's at MW006 compare.[74] Also, although there is no evidence that there is a

[73] See Figure 24 on pg. 31 of K. Zeno, "An Overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594.

[74] I have a Δp/p value for BU3 using 0.403 eVs at extraction with a 82.5 ns bunch. Bbat gives Δp/p =1.61e-3 but I don't have one for BU4 because there is QP, It could be found from a debunching measurement at AGS injection.

problem, the F3 kicker has to rise between the 2 adjacent bunches in h=3 buckets on BU3, and if it did not rise fast enough, or it was not timed optimally, it would contribute to the horizontal width at MW006 and so to ε_x as well.

It was noticed after the run that, on BU3, there had inadvertently been 5-10A in the drive sextupoles for the entire run mainly during the porch and the latter ramp (there was no appreciable current in them on BU4).[75] There was also some current in them earlier in the cycle. On March 23rd Q_x was lowered from 4.72-4.73 to 4.60 during the porch because it seemed that transmission through the vertical scrape, which happens just after the porch, improved.[76] Perhaps this was related to the current in the sextupoles, but Q_x was eventually raised back up on April 4th. There is no BU3 MW006 data in Table V from this period. For the period where BU3 was used to fill RHIC, Q_x was set around 4.72-4.73 and Q_y was set to 4.78 or so. Neglecting any space charge induced tune spread, one would expect these tunes to keep the beam reasonably far away from any normal or skew sextupole resonances. In general, the sextupole stopband correctors were not very sensitive on either user this run. This is perhaps because the Booster input was generally relatively low.

	Date	Time	x fwhm	y fwhm	B. Input	B. Late	ε_x	ε_y	ε_{avg}
1	Feb. 24	14:47:07	3.14	5.02	5.65	2.45	8.08	3.91	6.35
2	Feb. 24	15:23:45	3.16	4.90	5.60	2.47	8.19	3.72	6.36
3	Mar. 4	14:38:53	3.16	4.94	5.87	2.55	8.19	3.78	6.38
4	Mar. 4	20:36:56	2.97	4.85	5.65	2.55	7.23	3.65	5.73
5	Mar. 8	15:57:57	2.95	4.79	5.99	2.54	7.14	3.56	5.64
6	Mar. 10	14:23:41	3.06	4.86	5.93	2.65	7.68	3.66	6.01
7	Mar. 14	15:38:39	3.36	4.75	6.22	2.58	9.26	3.50	7.00
8	Mar. 14	15:40:32	3.15	4.83	6.18	2.59	8.14	3.62	6.30
9	Mar. 22	16:13:23	3.33	4.19	6.54	2.49	9.09	2.72	6.71
10	Mar. 24	14:21:29	3.09	4.40	6.31	2.55	7.83	3.00	5.93
11	Mar. 28	17:51:42	3.19	4.49	6.27	2.46	8.34	3.12	6.30
12	Mar. 29	12:47:11	3.24	4.72	6.45	2.61	8.61	3.45	6.56
13	Mar. 29	14:08:06	3.23	4.63	6.47	2.65	8.55	3.32	6.49
14	Mar. 31	16:23:01	3.27	4.63	5.76	2.45	8.77	3.32	6.63
15	Apr. 4	14:13:57	3.42	4.11	6.82	2.46	9.59	2.62	7.03
16	Apr. 13	17:10:52	3.49	4.29	7.02	2.59	9.99	2.85	7.34
17	Apr. 15	12:53:42	3.12	4.61	6.52	2.65	7.98	3.29	6.11
Average			**3.20**	**4.65**	**6.19**	**2.55**	**8.39**	**3.36**	**6.39**

Table VI: BU4 BtA MW006 data for a few cases with typical Booster Late used for filling ($2.45\text{-}2.65\times10^{11}$). The FWHM values shown are in mm and are for Gaussian fits of the profiles. (ε_x, ε_y) and ε_{avg}, (in mm mr) are calculated as described in the text. The FWHM data is from the Booster-AGS-PP elog and the intensity data is from LogView. Booster Input and Late are $\times10^{11}$.

[75] See Booster-AGS-PP May 10, 2022 elog entries at 15:35 and 16:17.

[76] See Booster-AGS-PP March 23, 2022 elog entries at 1619 and 1621.

Single Bunches in the AGS on AU3

The AGS Transverse Damper

The vertical transverse damper was used on AU3 and AU4. However, the way its electronics are configured, using h=8, one would naively expect that it could only be timed properly to damp one of the two AU3 bunches. For one thing this is because the bunches are in h=6 buckets. It has also not been used to damp more than one bunch since high intensity protons were run, about 20 years ago. It would not just be a question of changing its settings to configure it properly but would require different code.

A study was performed on April 11th (using Siemens) to determine whether or not both of the AU3 bunches were being damped.[77] By adjusting the F3 kicker fine delay it is possible to transfer only one bunch to the AGS and to select which one. The 2 fine delay settings required to kick one of the 2 bunches were 1900 and 2140 ns.[78] The resulting single bunch can be looked at on a mountain range WCM display on the flattop. When the fine delay is set to 1900 ns there is only a bunch on the left side of the display that undergoes the squeeze-merge. Set to 2140, the bunch is on the right side and setting it to 2020 ns shows the the normal squeeze-merge. This confirms that there is no bucket hopping occurring in the single bunch cases which would interfere with this study.

Using the Ion IPM, (ε_x,ε_y) was measured for each case. For the 1900 ns bunch (1.1e11), they were (12, 13) mm mr and for the 2140 ns bunch (1.1e11) they were (13, 13.5) mm mr. When set to 2020 ns both bunches are kicked into the AGS and (ε_x,ε_y) on the flattop was (12.5,14.0) mm mr and AGS Late was 2.26e11. Row 19 in Table III also contains an AU3 (ε_x,ε_y) measurement from Jan. 12 of (11,14) mm mr with an AGS Late of 2.2e11.

For both the 1900 and 2140 ns cases, when the damper was put into hard-inverse mode (maximum anti-damping), about 3 quarters of the beam was lost near injection. With the damper off there was a loss at about 570 ms, the location of the $36+Q_y=G\gamma$ resonance, for both the 1900 and 2140 ns cases and there was none with it on in hard-normal mode (maximum damping). One might expect, in the maximum damping case, that if only one of the bunches were being damped that there would be a loss there but it would be half the size.

Perhaps the damper pulse is long enough that a single kick kicks both of the adjacent h=6 bunches. If the 2 bunches have similar oscillations about the closed orbit and they get a similar kick, one would expect the damper to be effective for both bunches. There is no

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[77] See Booster-AGS-PP April 11, 2022 elog entries from 1339 to 1623. The 1356 entry shows what the squeeze-merge looks like for F3 kicker fine delays of 1900, 2020, and 2140 ns. The 1407 and 1408 entries contain the IPM data for the single bunches and the normal case (2020 ns) data is contained in the 1416 entry (RF off at 1000 ms). The current transformer traces for the anti-damping cases are in entries 1411 and 1412. The transformer traces for the damper off cases for each bunch are in the 1413 entries. For the damper on in hard-normal mode the 2140 ns case is in the 1414 entry and the 1900 ns case can be found in logged current transformer data from 14:06:50.

[78] The 1349 and 1351 entries in Booster-AGS-PP April 11, 2022 elog contain scope traces of the survival of a bunch in the AGS when the kicker is mistimed as does the WCM mountain range display of the first 10 ms after injection in the 1822 entry in the Booster-AGS-PP April 4, 2022 elog where there is no sign of it after 10 ms.

instrumentation available in MCR, like a signal of the damper output, to check for something like this.

Optimizing the Squeeze-Merge Using Single Bunches

If the squeeze and merge are set up properly, the left (1900 ns) and right (2140 ns) bunch should look the same after the merge. Figure 19 contains WCM mountain range displays of the 2 single bunches from April 11th. After the merge, the left bunch clearly looks worse than the right one. At the time I adjusted the h=12 phasing, which made the bunches more similar but not as good as the right bunch case. In hindsight, the h=3 phase may not have been phased properly to squeeze the 2 bunches symmetrically. In any event, using single bunches may help in optimizing the 6-12 squeeze and merge.

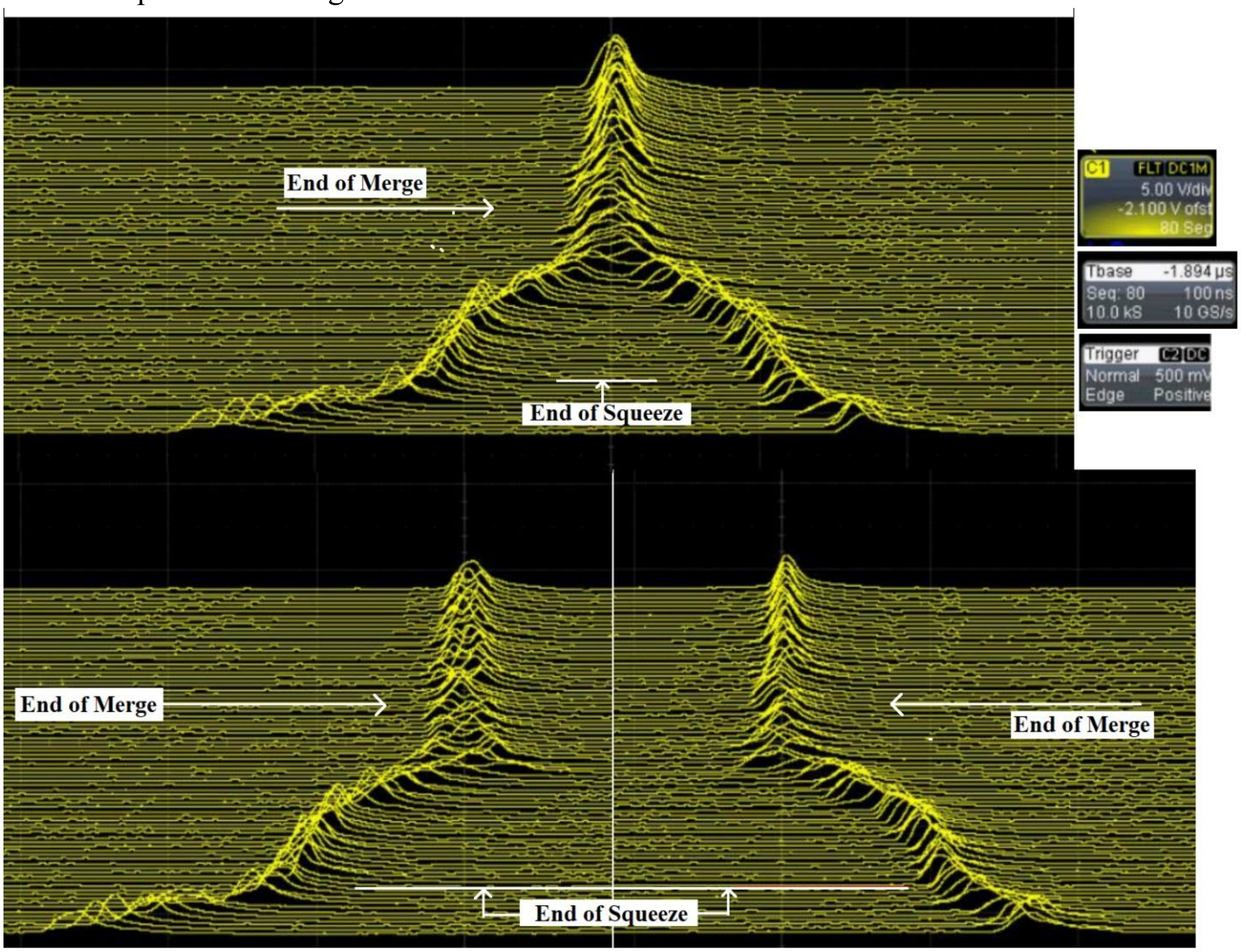

Figure 19: WCM mountain range displays with both bunches (top), only the 1900 ns bunch (bottom left), and only the 2140 ns bunch (bottom right). This is looking from 700 ms (10 ms after the beginning of the squeeze) to FEB Request (2100 ms). There are 80 traces each separated by 17.5 ms.[79]

[79]Taken from Booster-AGS-PP April 11, 2022 elog 1356 entry. Note that the termination here is 1 MΩ and the gain was 5V/division. The 1 MW termination was required to prevent saturation at normal intensities after the amplifier was added to the F20 WCM mux signal on Dec. 29th.

Booster Scraping

A GPM monitor was made this run to keep track of Booster scraping on BU4.[80] Figure 20 is the logged Booster Early, intensity just after the horizontal scrape (at 102 ms), and just after the vertical scrape (at 117 ms).[81] Figure 21 shows the intensity after the scrapes over the intensity just before the scrapes (in percent) for BU4 from the Siemens failure until the end of the run. It can be thought of as the fraction of the beam not (intentionally) scraped off. As is evident from Figure 21, as the run progresses this fraction decreases from about 55% to 35% but for much of the run it is around 45%. Part of this decrease is likely due to the gradual increase in Booster Input which is reflected in Booster Early. Figure 20 also shows that the vertical scrape is usually much larger than the horizontal.

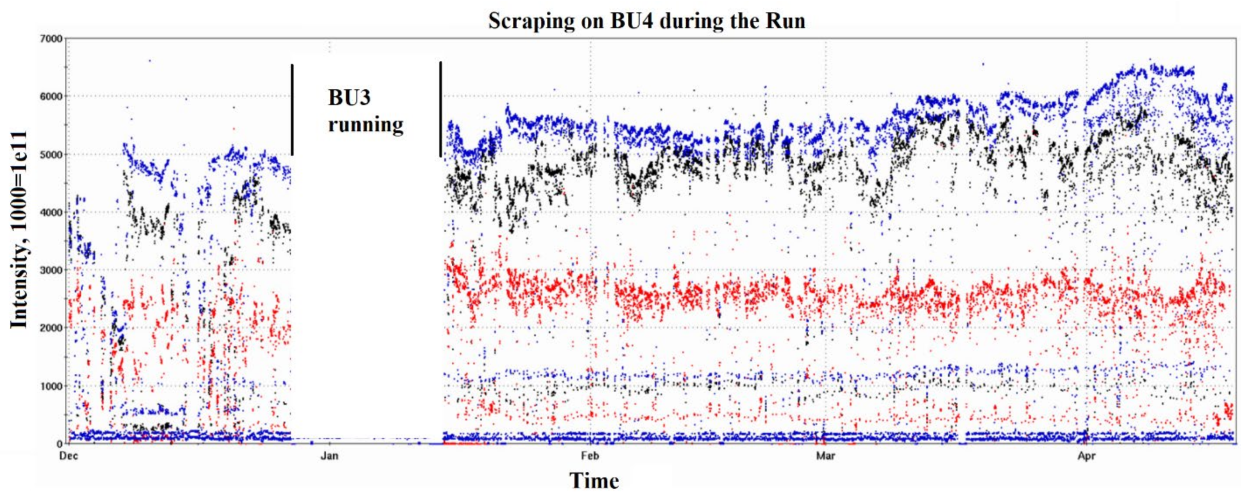

Figure 20: The Booster Early scaler (blue), the intensity after the horizontal scrape (PostHscrape, black), and after the vertical scrape (PostVscrape, red) on BU4 during Run 22.

Loss Patterns when Scraping

Figure 22 shows BU4 vertical scrape losses using scraping that was fairly representative of what was used to fill RHIC. This includes losses from extraction as well, which seem to be minimal. Figure 23 shows the losses from the horizontal scrape for this case. For both figures, the Booser Early intensity was 6.0e11, after the horizontal scrape it was 5.0e11, and after vertical scrape it was 2.5e11. So, the vertical scrape was 2.5 times the size of the horizontal scrape and, in total, about 58% of the beam was scraped off. The loss patterns were checked throughout the run and seemed quite stable. The loss pattern was also checked on BU3, and like BU4 the

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[80] It was also logged for BU4 and can be found in LogView under MCR/Personal/kelz/BoosterPPScrape.logreq.

[81] The MADC version of the normalized Booster circulating current transformer is sampled to measure the injected intensity and the intensity before and after the vertical and horizontal scrapes. The location of the cell file is /operations/app_store/Gpm/CellFiles/PPScraping.cells. In the GPM there is an "Injected intensity" sampled from the MADC signal but Booster Early is a more accurate representation of the initial intensity and so it is shown in instead. The other samplings shown in Figure 20 seem to be consistent with the scalers and scope signal for the transformer. The Booster-AGS-PP Nov. 26 2021 1312 entry shows the monitor.

scraping losses were highest near the dump and significant losses extended downstream of it until C4 or so.[82]

The horizontal scrape is created using the dump bump and with it, it is easy to scrape near the dump. The scrape occurs on the inside of the ring. With the bare vertical orbit the beam will scrape (vertically) around E7 as Q_y is raised. To move the loss to the dump, vertical harmonic bumps are used (sin5θ and cos 5θ). The sin5θ component is used to adjust the amount of vertical scraping and typically has a large amplitude. For the scraping shown in Figure 22 the sin5θ amplitude is about +16A (the cos5θ amplitude normally remains fixed at -7A). Although the timing of the vertical scrape is different on BU3, these considerations hold for it as well (see Figure 4). These bumps also have to ramp down before Gγ=4 so those harmonic corrections can be active for the crossing (see Figure 5).

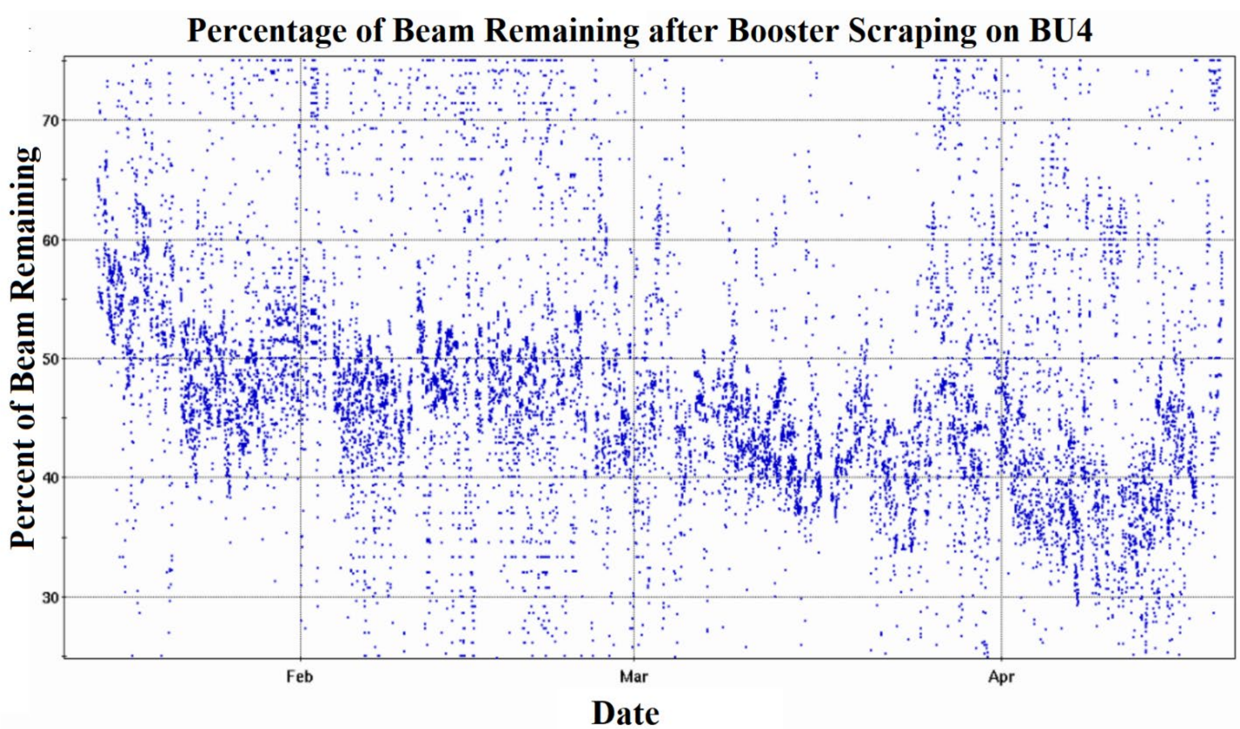

Figure 21: The intensity after the vertical scrape divided by the intensity before the horizontal scrape in percent (TotalScrape) on BU4 from the Siemens failure (Jan. 12) until the end of the run (Apr. 18).

The Stability of Booster Scrapes

One thing that differs this year from previous PP runs is that the D6 extraction septum magnet, used for NSRL, is new. It seems that the circulating beam is more sensitive to its fringe field than it was with the previous magnet. The problems with that magnet were mainly with its remanent field. NSRL also often makes more frequent species and energy changes (mode

[82] See Booster-AGS-PP Nov. 3 2021 elog 1552 and 1553 entries and 1623 entry on Apr. 11 2022 for the BU3 loss pattern.

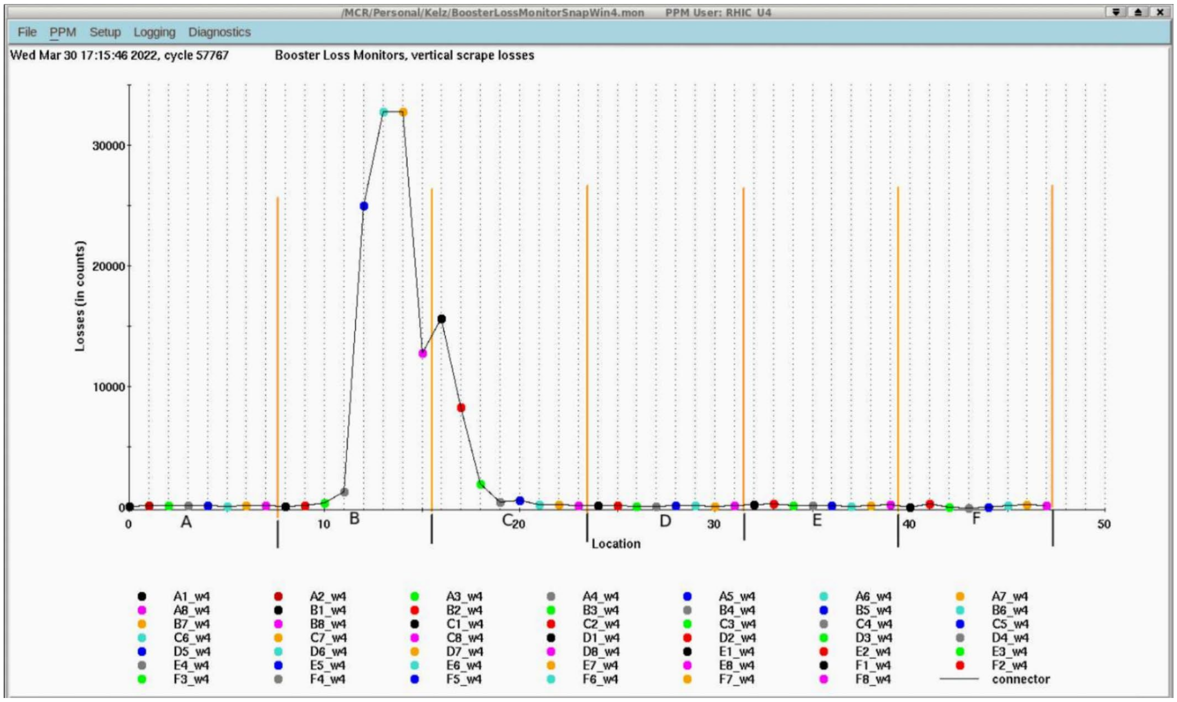

Figure 22: The losses from the vertical scrape at 117 ms and extraction. The window extends from 110 to 150 ms (extraction is at 144 ms). The extraction loss should be minimal and about 2.5e11 is being scraped off. Note that the B6 and B7 loss monitors are saturating.[83]

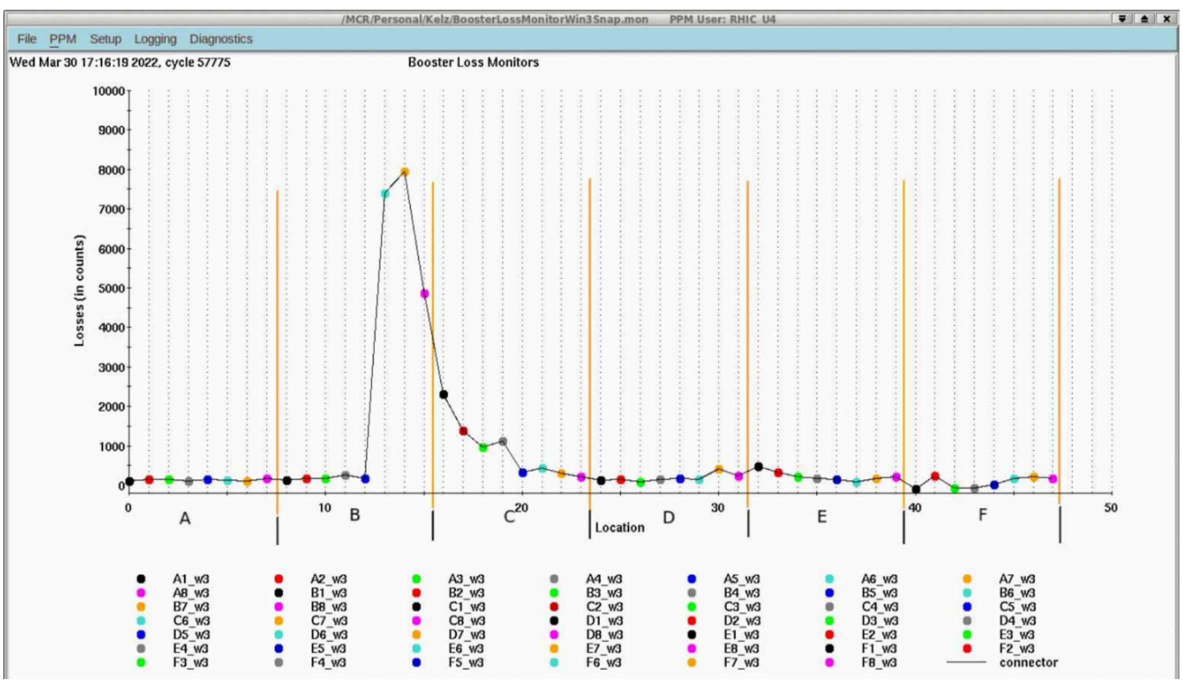

Figure 23: The losses from the horizontal scrape at 102 ms. The window extends from 95 to 110 ms. In this case about 1.0e11 is being scraped off.

[83] Figures 20 and 21 are taken from the Booster-AGS-pp March 30 2022 elog entries at 1715 and 1716.

switches) associated with the Galactic Cosmic Ray (GCR) simulator, which did not exist in Run 17.

Additionally, during an NSRL mode switch the D6 septum undergoes a hysteresis cycle where its setting is ramped to 0 and then ramped up to the new setting. Sometimes the effect on the amount of beam scraped can be dramatic and other times it has little effect. Although it varies, the hysteresis cycle takes on the order of 30 sec, or 7 AGS cycles. Among other things, this can cause variations in the bunch intensity during filling. Figure 24 shows a rather extreme example (on BU4) of what can happen to the scraping during frequent NSRL mode switches. Efforts were normally made to coordinate RHIC filling with GCR running.

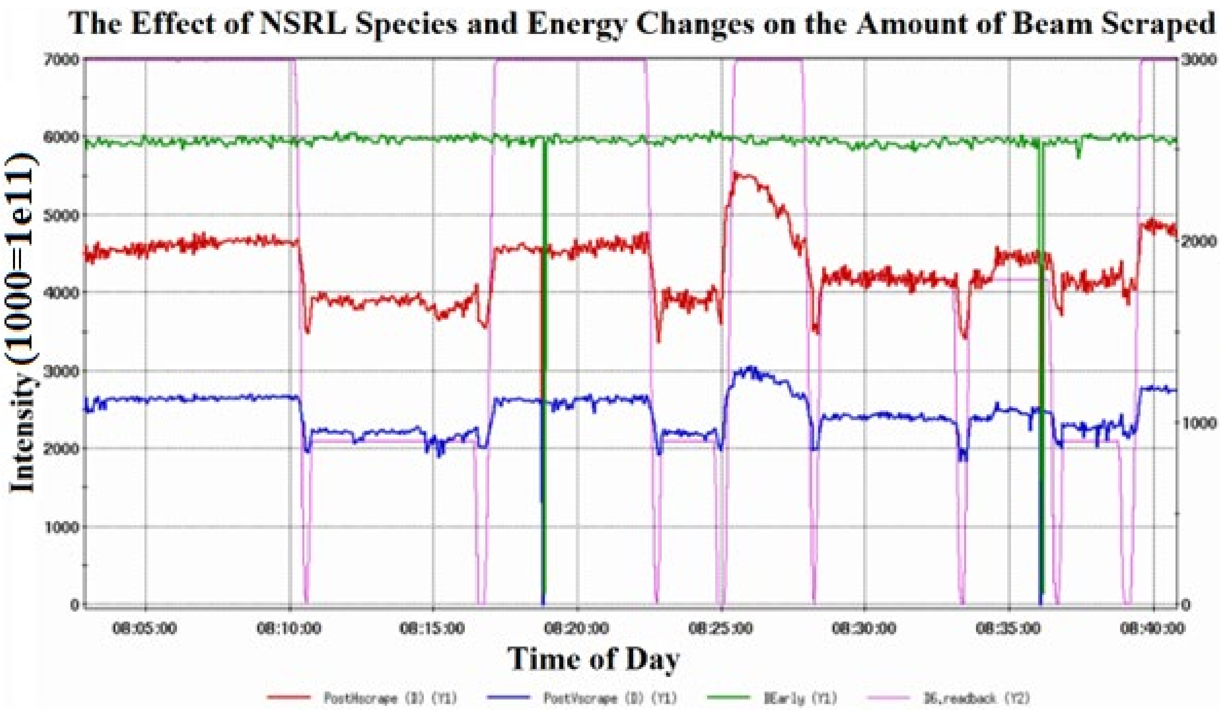

Figure 24: The Intensity after the horizontal (red) and Vertical (blue) Scrapes during frequent NSRL mode switches over a 40-minute interval on March 30, 2022. The green trace is Booster Early and the magenta trace is the D6 septum current readback (in Amps). The right y-axis is for the D6 septum current. This is BU4. The radial loop is in use.

Note that Booster Early is unaffected by the septum's output and the amount of beam scraped is different for different NSRL modes. The horizontal scrape has clearly changed, whether it's because the horizontal emittance is larger, the circulating beam moves further to the inside at the dump, or both. But it is not clear that the vertical scrape changes because there is less beam to scrape there when more is scraped horizontally.

Figure 25 shows the fraction of beam remaining after scraping during the same time period as in Figure 24. In this case at least, it is clear that the vertical scrape is largely unaffected by the mode switching. This is perhaps surprising since the septum fringe field changes the (horizontal) injection orbit, and there is significant coupling at injection, so the vertical emittance should also be affected. It also seems largely unaffected even by the hysteresis cycle. In this case the radial loop is in use.

To distinguish between the D6 septum and the host of other parameters that are changed during an NSRL mode switch, only the septum current was varied to see if the scraping still changed. Figure 26 shows the results. The fraction of beam scraped horizontally as the septum current is increased still decreases. It is not clear if there is any change in the vertical. The radial loop is also in use for this case.

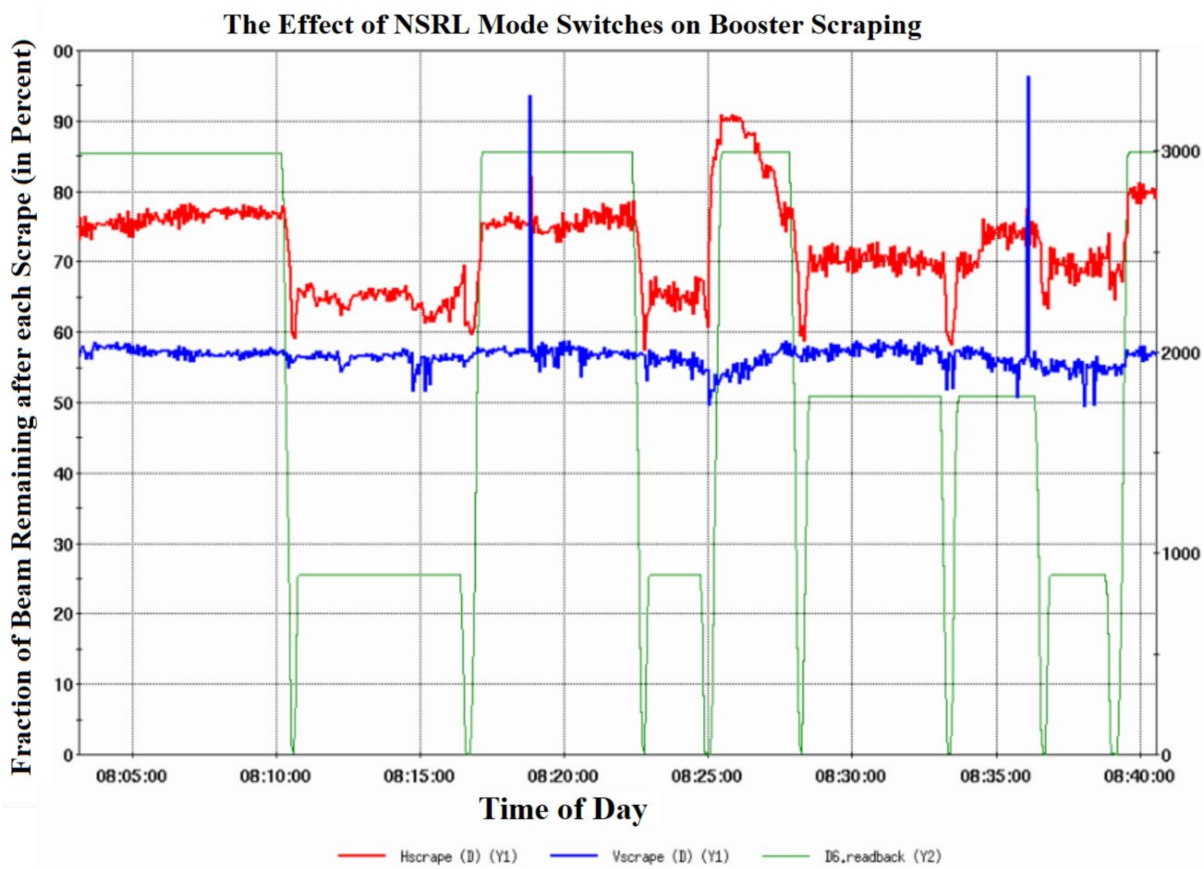

Figure 25: The Red trace is the amount of beam after the horizontal scrape over the amount just before the horizontal scrape (Hscrape). The blue trace is the amount of beam after the vertical scrape over the amount just before the vertical scrape (Vscrape). The green trace is the D6 septum current and it uses the right y-axis. This is for the same time interval used in Figure 24.

Using BoosterOrbitDisplay it appears that, in the case where only the septum current is changed, and it is increased, that the average horizontal orbit at the horizontal scrape moves to the outside. In going from 3200 to 900 A it moved 0.97 mm to the inside and that could explain why the horizontal scraping would change, but why would the average orbit change?[84] The

[84] See Booster-AGS-PP March 30 2022 entries at 1233 and 1234.

radial average signal did not noticeably change when the septum current was changed.[85] Again, the radial loop is in use for this.

One could argue that the average position at the BPMs could change even if the radius doesn't because the septum distorts the orbit and the BPMs do not sample the orbit well enough to get an accurate measure of the average horizontal position of the orbit. Then it would just so happen that the distortion the septum makes, when sampled by the BPMs, looks like a radial shift but is not.

On April 15th the Gauss clock counts from Bt0 to 1 ms before extraction (143 ms) were measured on 4 cycles with the D6 septum current at 0 and 4400 A. The average of the four 0A measurements was 42845.75 counts with a σ of 0.433 gcc and for the four 4400A measurements it was 42846.25 counts with a σ of 0.433.[86] These values are nearly identical and lead one to conclude that the septum current probably does not affect the main magnet field, at least if the gauss clock is an accurate measure of it. One could argue that the dwell field might be changing but Booster injection was stable so it couldn't be moving around by much.

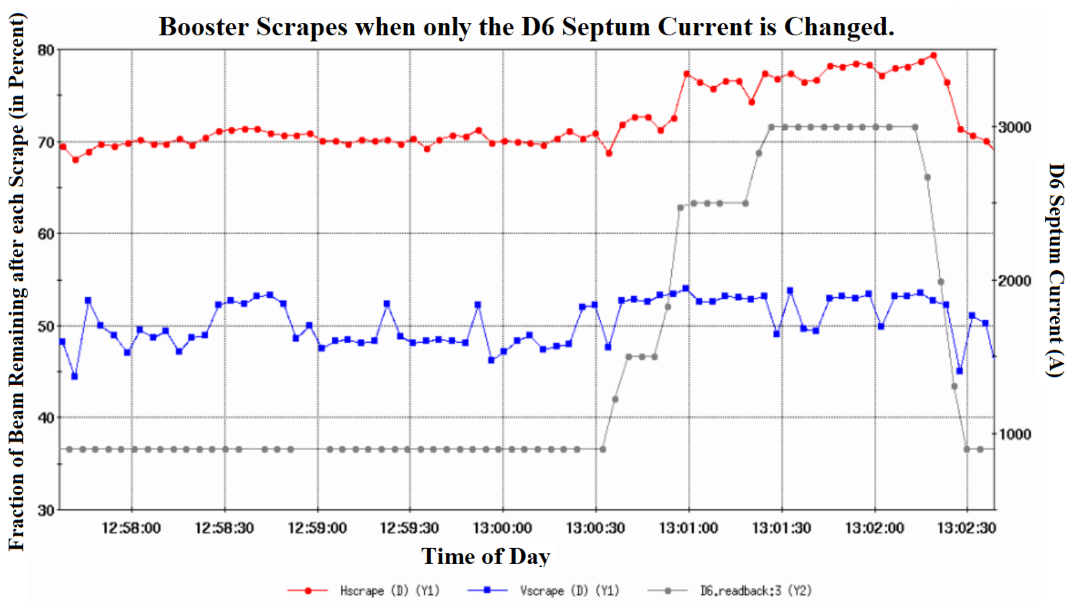

Figure 26: As in Figure 25, the red trace is the amount of beam after the horizontal scrape over the amount just before the horizontal scrape (Hscrape) and the blue trace is the amount of beam after the vertical scrape over the amount just before the vertical scrape (Vscrape). The gray trace is the D6 septum current and it uses the right y-axis. This is also from March 30th, 2022, but in this case only the D6 current is changed and the radial loop is on. This is BU4.[87]

[85] See Booster-AGS-PP March 30 2022 1253 entry. Also, closer inspection of the logged radial average and the 2 radial PUEs (A2 and A8) indicates that the logged radial average signal agrees with the average of the logged A2 and A8 positions calculated in LogView except that the latter lags the logged radial average by 2 ms. This is true whether the AC phase or radial loops is used. See Booser-AGS-PP Aug. 22, 2022 elog 1458 entry.

[86] See Booster-AGS-PP April 15 2022 1700 entry. Orbits from March 30 also shows negligible 'radial' dependence on the septum output with the AC phase loop (1613 and 1614 entries).

[87] See Booster-AGS-PP March 30, 2022 1301 entry.

On April 15th, while using the AC phase loop, not the radial loop, the average horizontal orbit on the BPMs at the horizontal scrape did not have the same dependence. It changed by +0.22 mm in going from 4400 to 0 A.[88] Not only is this a much smaller change but it is in the opposite direction. Also, the effect on the scraping was minimal. Could it be that with the radial loop a larger orbit distortion from the septum moves the beam outward at the dump during the horizontal scrape? But the radius is just as reproducible when using the AC phase loop, so maybe when the radial average signal (the average of the A2 and A8 PUEs) is held constant by the radial loop the actual radius changes? If nothing else, the AC phase loop does not feed back on any radial input.

Figure 27 shows the effect of an NSRL mode switch on Apr. 14th. The AC phase loop was in use. Again, increasing the septum current is correlated with reducing the horizontal scrape, but this time the vertical scrape was affected as well. Also shown (in black) is the fraction of beam remaining after both scrapes, which more or less remains unchanged. One might conclude after comparing Figures 25 and 27 that the effect of mode switching is different depending on whether the AC phase or radial loop is in use, but unfortunately, after switching back and forth between the 2 loops during the run, it was not clear which resulted in more stable scraping. Overall though I think the AC loop may be a bit better, maybe because of the lack of a radial input.

Since the horizontal scrape occurs near the dump what happens to the position at B6 when the septum current is changed is critical. On March 30th on the radial loop when D6 was changed from 3200 to 0 A the position at B6 changed by -1.85 mm. Later that day, on the AC phase loop, it changed by +0.5 mm when D6 was changed from 500 to 4100 A. In both cases a higher D6 current moves the beam away from the dump though it seems to move more when on the radial loop.[89]

It's clear that the septum field can have an effect on the scraping, but the scraping also varies when it is not changed. There are a number of possible causes which were investigated during the run. The readbacks for the DC supplies in LtB and HEBT steerers, are accurate enough to rule them out as culprits, but the readback for DH1, which is pulsed, is not. The horizontal position on the LtB MW035 multiwire can vary from cycle to cycle by 2 or 3 mm and when investigated the variation was pretty clearly correlated with the total scrape losses. There is also a mux signal for DH1, but I could not conclusively correlate the MW035 variation with variations in that signal either. Varying the DH1 setpoint by 0.6 A (out of 190 A) produces a similar motion at MW035.[90] The fraction of beam remaining after the vertical scrape decreased from 48 to 33% but the amount of beam scraped off at the horizontal scrape barely changed.[91]

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[88] See Booster-AGS-PP April 15, 2022 elog entries at 1528 and 1529. See also Aug. 18, 2022 entries at 1636 and 1726.

[89] In Booster-AGS-PP March 30 2022 elog see 1233 and 1234 entries for the orbits with the radial loop and 1613 and 1614 entries for the AC loop case.

[90] See Booster-AGS-PP Mar. 30 2022 elog entries at 1813 to 1923.

[91] See Booster-AGS-PP Aug. 19 2022 elog 1515 entry. Also shown is the DH1 setpoint and readback. Given the noise on the readback there is no indication of a change in the readback that's correlated with the change in DH1's

The DH1 mux signal is also not flat while the pulse is being injected.[92] If this variation was actually what the supply was outputting, the entire pulse might not be bent by the same amount causing transverse emittance growth. Of course, this is the DH1 current not B field, even if this current variation is real, the B field might change much more slowly.

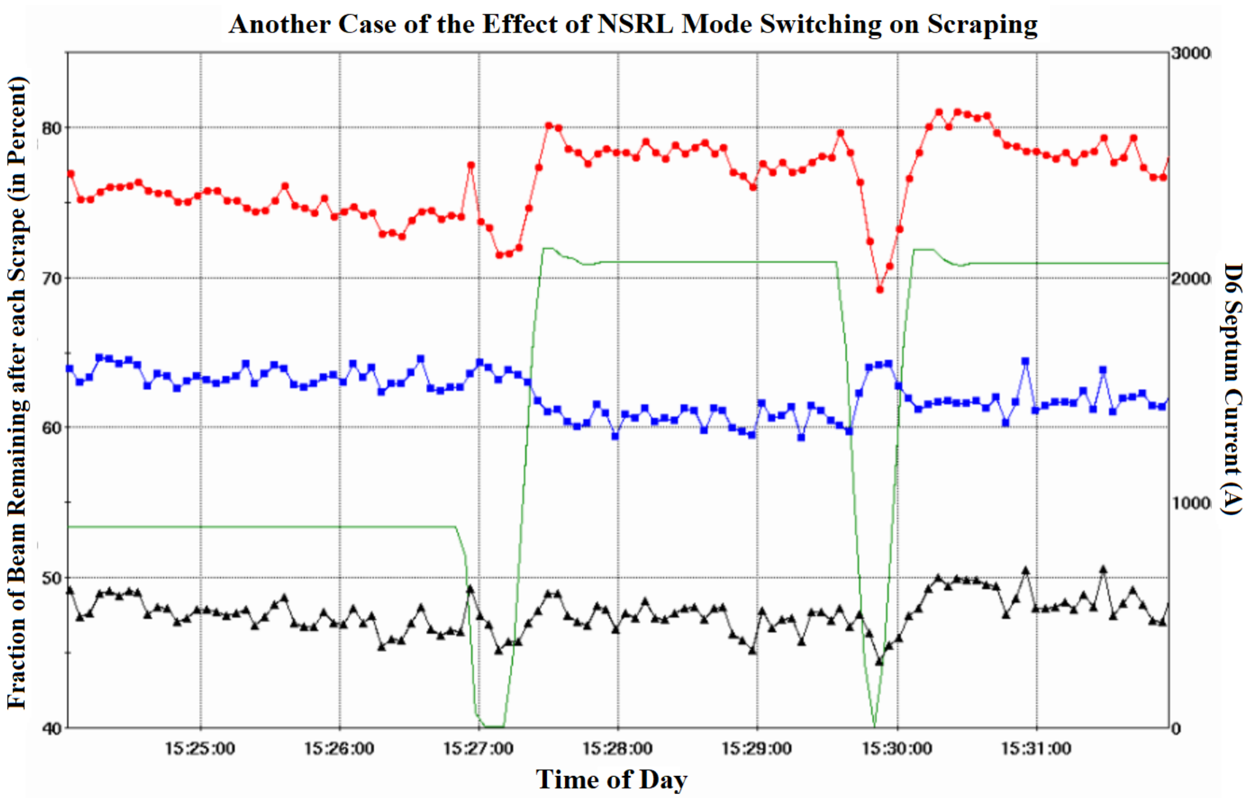

Figure 27: Another case of the effect of an NSRL mode switch on scraping. It is like Figure 25, but one thing that is different is that the AC phase loop is in use. The red trace is the amount of beam after the horizontal scrape over the amount just before the horizontal scrape (Hscrape) and the blue trace is the amount of beam after the vertical scrape over the amount just before the vertical scrape (Vscrape). The Total scrape (TScrape), is in black and is the intensity after vertical scrape over intensity just before horizontal scrape. The green trace is the D6 septum current and it uses the right y-axis. This is from April 14th, 2022 and is BU4.

Transverse Emittance When Using the Westinghouse Motor Generator

Table VII and VIII contain transverse emittance ion IPM flattop measurements using Westinghouse with the split-merge (BU3/AU7) and the standard BU4/AU6 setup, respectively. As with similar measurements made for AU3 and AU4, Tables III and IV, these measurements

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output. Perhaps it would be evident in an average over an extended period, but cycle to cycle variations would not be.

92 See Booster-AGS-PP March 30, 2022 elog 1908 entry.

were taken under a variety of conditions and the data doesn't lend itself to a simple interpretation.

	Date & Time	ε_x	ε_y	ε_{avg}	AGS Late
1	2/7 14:34:04	12.0	18.3	15.5	1.99
2	2/9 15:02:30	10.5	16.0	13.5	2.23
3	2/9 18:49:54	10.5	18.0	14.7	2.30
4	2/24 18:30:48	11.0	16.0	13.7	2.26
5	3/4 17:59:24	10.0	14.5	12.5	2.28
6	3/4 19:10:20	10.4	14.5	12.6	2.24
7	3/4 19:12:32	11.4	17.5	14.8	2.93

Table VII: Ion IPM transverse 95% normalized emittances (ε_x,ε_y) in mm mr on the flattop of the Westinghouse split-merge (AU7) cycle. The RF shuts off at 1500 ms. Also shown is ε_{avg} for each case. AGS Late intensity is x10^{11}.

	Date & Time	ε_x	ε_y	ε_{avg}	AGS Late
1	1/15 17:26:40	12.2	15.0	13.7	2.02
2	1/15 17:31:56	13.5	16	14.8	2.42
3	1/16 16:04:33	11.3	18.5	15.3	2.04
4	1/16 16:55:29	12.2	18.5	15.7	2.39
5	1/18 18:19:17	14.2	20.8	17.8	2.37
6	1/18 19:25:29	15.0	16.7	15.9	2.38
7	1/18 20:32:02	15.0	16.0	15.5	2.41
8	1/20 15:23:02	13.9	16.2	15.1	2.24
9	1/24 20:09:04	15.3	18	16.7	2.29
10	2/4 14:47:07	12.7	20.0	16.8	2.18
11	2/8 17:43:05	12.1	17.8	15.2	2.26
12	2/11 14:08:42	12.5	18.5	15.8	2.26
13	2/14 18:44:19	12.8	18.2	15.7	2.42
14	2/14 18:48:06	12.3	17.5	15.1	2.22
15	2/17 17:56:20	12.4	19	16.0	2.26
16	2/22 15:59:26	12.3	18.5	15.7	2.20
17	2/22 18:41:02	12.0	18.5	15.6	2.09
18	2/23 19:13:58	12.0	18.0	15.3	2.22
19	2/24 14:48:41	12.8	20.5	17.1	2.38
20	2/24 14:57:28	11.2	18.0	15.0	2.24
21	3/1 20:32:11	11.0	17.0	14.3	2.31
22	3/4 20:46:29	12.6	18.5	15.8	2.24
23	3/4 20:48:40	14.1	21.0	17.9	2.76

Table VIII: Ion IPM transverse 95% normalized emittances (ε_x,ε_y) in mm mr on the flattop of the standard Westinghouse cycle (AU6). The RF shuts off at 1500 ms. Also shown is ε_{avg} for each case. AGS Late intensity is x10^{11}. The data in rows 1 and 2 were taken without the jump quads pulsing.

There is plenty of data for AU6 with AGS Late intensities near the filling intensity of about 2.2-2.3e11 and some AU7 data, but there is no data for either at intensities lower than

2.0e11. ε_{avg} for the AU4 data from Table IV and the AU6 data from Table VIII are plotted together with linear fits in Figure 28. The plot indicates that the flattop ε_{avg} was higher for AU6 and also suggests it may have more intensity dependence than with AU4.

ε_{avg} for the AU3 data from Table III and the AU7 data from Table VII are plotted together with linear fits in Figure 29. I am comparing ε_{avg} for the standard setups separately from the split/merge setups because ε_x is smaller for the split/merge data and I suspect that at least part of the difference is due to the contribution from the dispersion component to the horizontal width and this contribution is smaller for the split/merge cases because $\Delta p/p$ is smaller. Unlike AU4 vs. AU6, when AU3 and AU7 are compared, it doesn't seem that ε_{avg} is larger for AU7. There are 2 linear fits shown for AU7, one is for all the data in Table VII (dotted line) and the other is only for the Mar. 4th data (solid line). I fit the March 4th data separately because it is over a significant range of intensity, it was taken on the same day, and it probably comes closest to an optimized state.

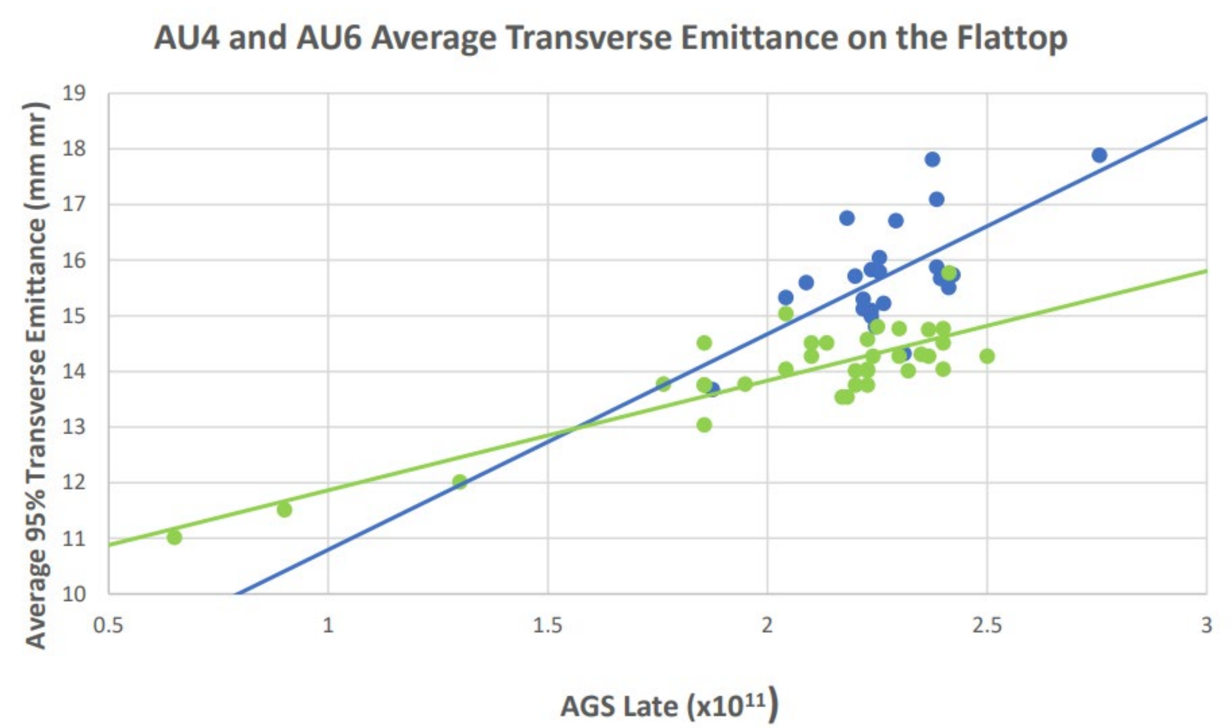

Figure 28: Plot of AU4 (green) and AU6 (blue) average 95% normalized transverse emittance (ε_{avg}) from the Ion IPM on the AGS flattop vs. AGS Late intensity. Linear fits to the data are also shown. The AU4 data is from Table IV and the AU6 data is from Table VIII. RF off at 1500 ms.

Although there is not much range in AGS Late for the data in Tables VII and VIII, the last row in each table is at higher AGS Late intensity than the rest.[93] That data indicates that ε_y is significantly smaller for AU7 than AU6 (17.5 vs. 21.0 mm mr) even at a higher AGS Late (2.93

[93] They were also taken on the same day (March 4) and in both cases the intensity was raised by relaxing the vertical scrape.

vs. 2.76e11). AU3 data exist for 2.5 and 2.6e11 (rows 24 and 4 in Table III). For 2.5 and 2.6e11 ε_{avg} were 14 and 14.5 mm mr, respectively. For AU7 ε_{avg} was 14.8 mm mr at 2.93e11, which considering the higher intensity, is not worse than those AU3 cases. This is another indication that although the AU6 ε_{avg} seems higher than it is on AU4, the same may not be the case for AU7 vs. AU3.

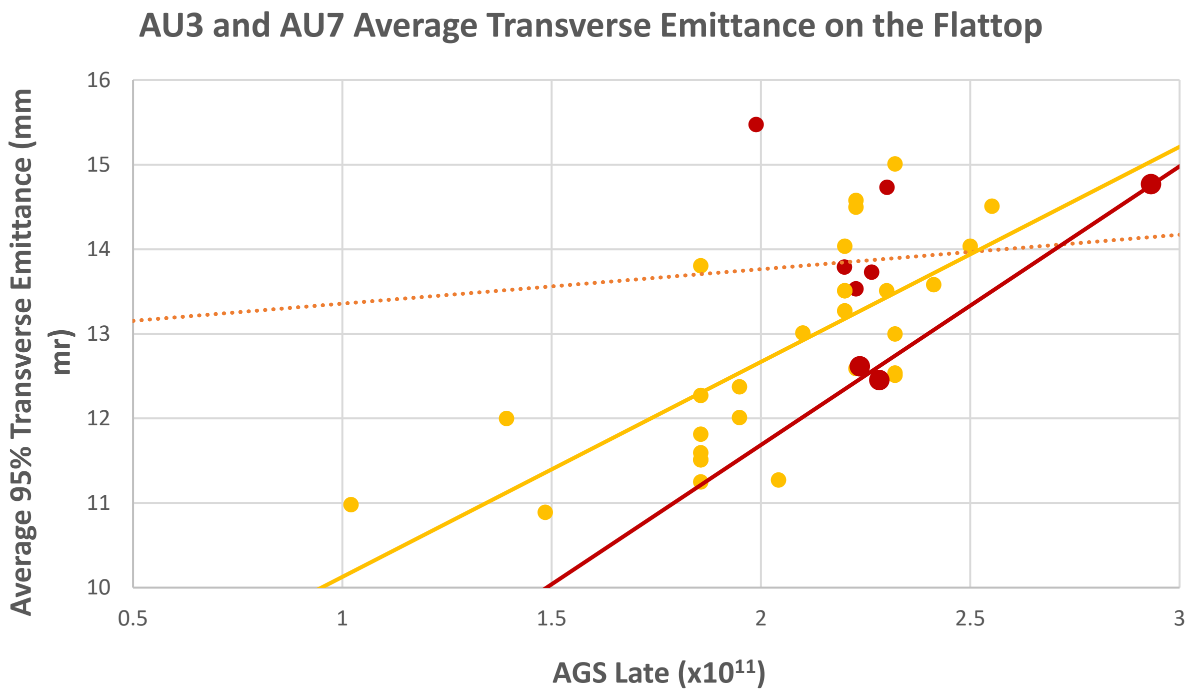

Figure 29: Plot of AU3 (yellow, Table III) and AU7 (red, Table VII) average 95% normalized transverse emittance (ε_{avg}) from the Ion IPM on the flattop vs. AGS Late intensity. The AU3 linear fit is for all the AU3 data in Table III, but there are 2 fits for the AU7 data. The solid red line is a fit to only the March 4th data (rows 5, 6, and 7 in Table VII) and the dotted red line is for all the data in Table VII. The three March 4th data points are larger than the others. RF shuts off at 1500 ms.

Extending the Dual Harmonic on the Westinghouse Cycles

The AGS main magnet functions for Westinghouse and Siemens are the same up until 235 ms. The dual harmonic is turned off around 230 ms on the Siemens cycle. It can remain on longer for the Westinghouse cycle since the dB/dt is lower after 235 ms so less h=6 voltage is required there. On Jan. 20th, it was extended past the $0+\nu_y=G\gamma$ resonance, which occurs near 272 ms instead of 262.5 ms for Siemens. Figure 30 shows the WCM bunch envelope with and without the extension on AU6.

There is enough voltage to extend it even further, perhaps through the entire ramp, although maintaining it through the transition phase jump probably would not be easy. It might be interesting to see what effect, if any, extending it through the entire ramp would have on polarization since $\Delta p/p$ would normally be smaller. Unfortunately, this can't be done on the

Siemens cycle unless the maximum ramp rate, which is used through most of the cycle, was lowered considerably.

Another difference between the Westinghouse and Siemens is that there is a smaller voltage transient at the F to P transfer with the Westinghouse and the voltage ripple after that is smaller. The F to P transfer and the P bank ripple are also evident in Figure 30 on the main magnet Station I voltage.

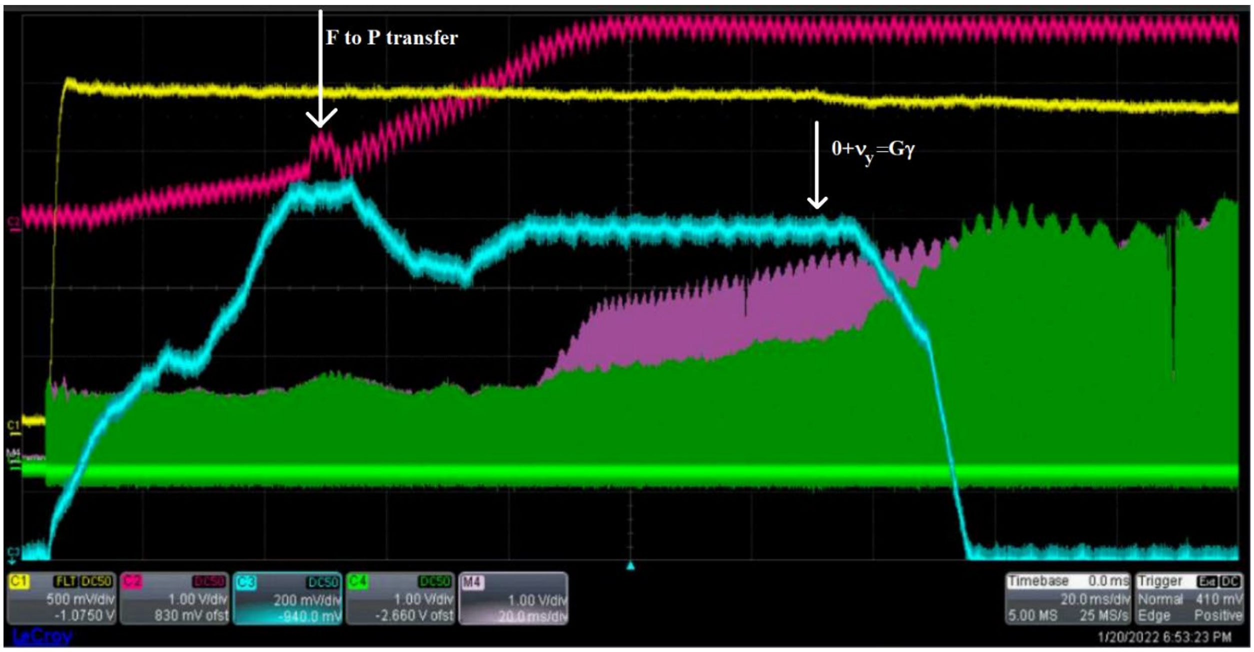

Figure 30: The WCM bunch envelope on the AU6 Westinghouse cycle with (green, C4) and without (purple, saved trace M1) the dual harmonic extension. The bunch intensity is nearly the same for both cases. The yellow trace (C1) is the A15 normalized current transformer, the blue trace (C3) is one of the 2 h=12 cavity voltages (JK) with the extended voltage function, and the red (C2) trace is the Station I main magnet voltage. The trigger is at 240 ms and the sweep speed is 20 ms/div.[94]

Given that the dual harmonic is on until a higher energy for Westinghouse than it is for Siemens, what would be the mechanism by which the flattop ε_{avg} would be higher for AU6? Transition can be a source of transverse emittance growth and dB/dt is slower for Westinghouse. On Jan. 15th, the day after beam was established in the AGS with Westinghouse, the γ_t jump was set up on AU6. It is on for all the AU6 data in Table VIII. When the γ_t jump was first set up on AU6 there was nothing unusual about the behavior of the bunch envelope near transition that might have indicated a potential issue.[95]

The function sent to the γ_t jump quads was modified to account for the slower dB/dt but the start time was moved later making the duration of the γ_t jump quad pulse nearly the same

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[94] Taken from Booster-AGS-PP Jan. 20, 2022 elog entry at 1648.

[95] A scope trace of the WCM around transition on AU6 can be found in the Booster-AGS-PP Feb 8, 2022 elog 1723 entry. AGS Late was about 2.4e11 then.

length it has on AU4, about 24 ms. This was done to reduce quad oscillations and any losses. Although the γ_t jump quad function has a slower rise time on AU6, their output is not that different from AU4. Their average current just before the jump was about 7% higher on AU4.[96] Looking back at the elog and archives from when Westinghouse was used in 2013 it does not appear that the γ_t jump was used at all.[97] The intensity was lower then, AGS Late was around 1e11 and AGS Early was near 2e11. The majority of the beam loss between AGS Early and Late occurred before transition. The intensity at transition was typically around 1.0e11 but did at times reach 1.4e11 or so.[98]

Transverse Emittance on the Westinghouse Ramp and Early Flattop

Figure 31 shows vertical ion IPM data from 5 ms after injection until just after the RF is shut off on the flattop. The top plot is AU7 data from March 4 with AGS Late intensities of 2.24 and 2.93e11 and the bottom plot is AU6 data from the same day with 2.24 and 2.76e11. Determining if or where emittance growth occurs during the ramp is difficult because of the space charge effect bunches have on the measurement and β function distortions due to the snake setup. The green vertical lines indicate where the γ_t jump quads are pulsing. It is not obvious to me that there is growth there between the lower and higher intensity AU6 cases when compared to the AU7 cases which presumably have little or no growth because of the lower bunch intensity.

The space charge effect causes the ions created from the residual gas interacting with the beam to take a curved path to the collector in the IPM.[99] This makes the beam appear wider than it actually is. The effect gets stronger as the bunch intensity increases. The error also gets larger as the transverse bunch width becomes smaller, such as during acceleration due to adiabatic damping.

Since, for AU6 and AU7 the B(t) and the overall setup is the same for both intensities, I attempted to compensate for these effects so that the vertical emittances on the ramp at the 2 intensities could be compared qualitatively. The lower intensity data (2.24e11) for AU6 and AU7 was scaled by the ratio of the measured ε_y at the beginning of the flattop (990 ms) for the higher intensity case over the lower intensity case. I scaled it from injection to where the RF shuts off (1500 ms). Once the beam is no longer bunched the effect is greatly reduced so it was not scaled after the RF shuts off.

The scaled lower intensity data is plotted in Figure 32 together with the unaltered higher intensity data. The plots from very early in the cycle until where the RF shuts off overlay

[96] Using archived readbacks from April 1st for AU4 (run_fy22 sh3_u4_T#04011904) and March 4th for AU6 (run_fy22 sh3_u6_S#03041732)
[97] See for example Booster-AGS-pp 2013 elog Feb. 7 2128 entry and comment.
[98] See logged intensity scaler data from Jan. 30 to Feb 8 2013 found in MCR/InjectorPerformance.logreq.
[99] See R.E. Thern, "Space Charge Distortion in the Brookhaven Ionization Profile Monitor", 1987 Particle Accelerator Conference, Washington, D.C., March 16-19, 1987. See also H. Huang et al, "Measurement of Proton Transverse Emittance in the Brookhaven AGS", Proceedings of IPAC 2017 pgs. 494-496.

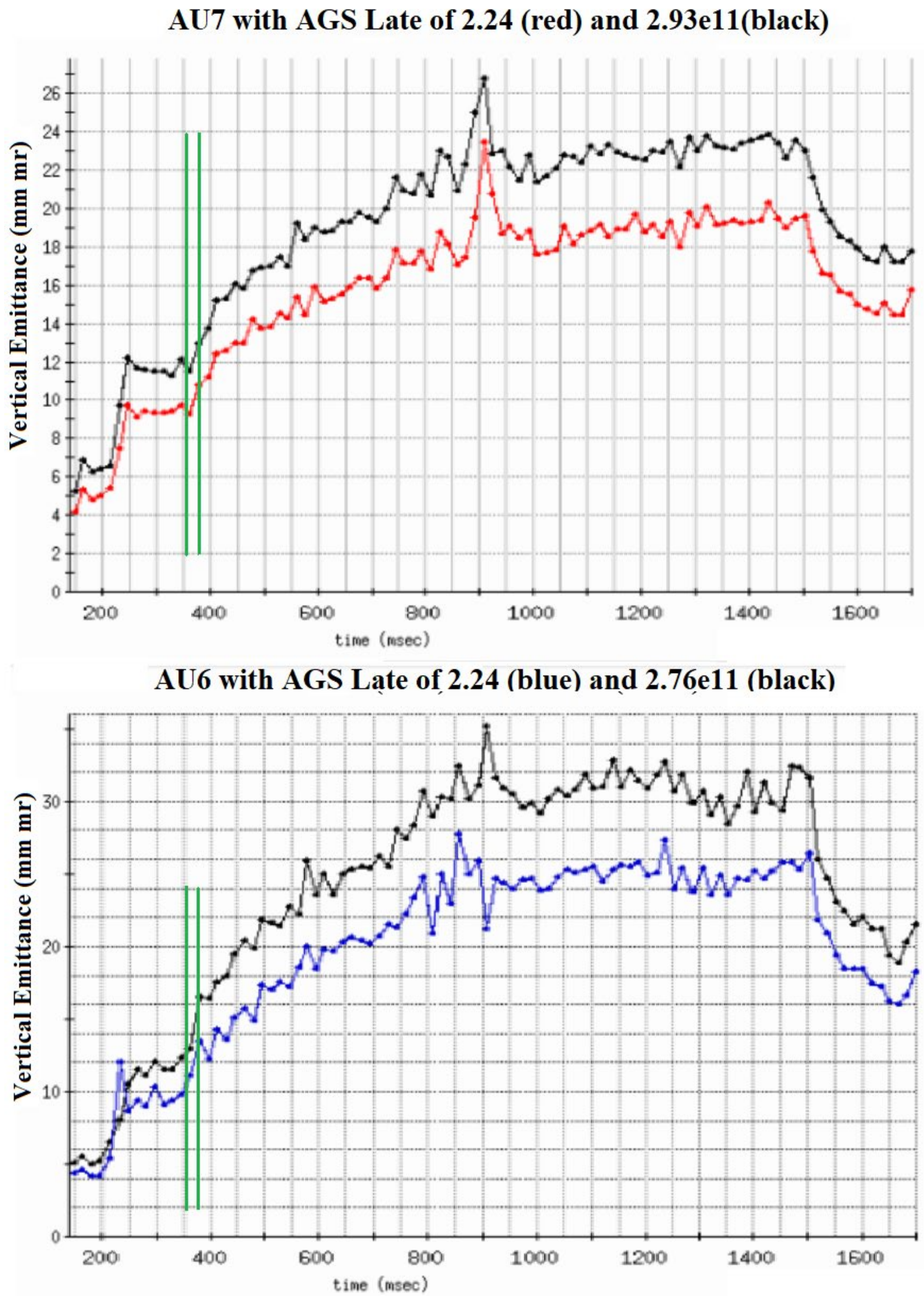

Figure 31: Vertical Ion IPM data for AU7 (top) associated with rows 6 (red, 2.24e11) and 7 (black, 2.93e11) in Table VII and AU6 data associated with rows 22 (blue, 2.24e11) and 23 (black, 2.76e11) in Table VIII. The green vertical lines indicate the start and stop times for the γ_t jump quad pulses. The x-axes are in milliseconds from At0.

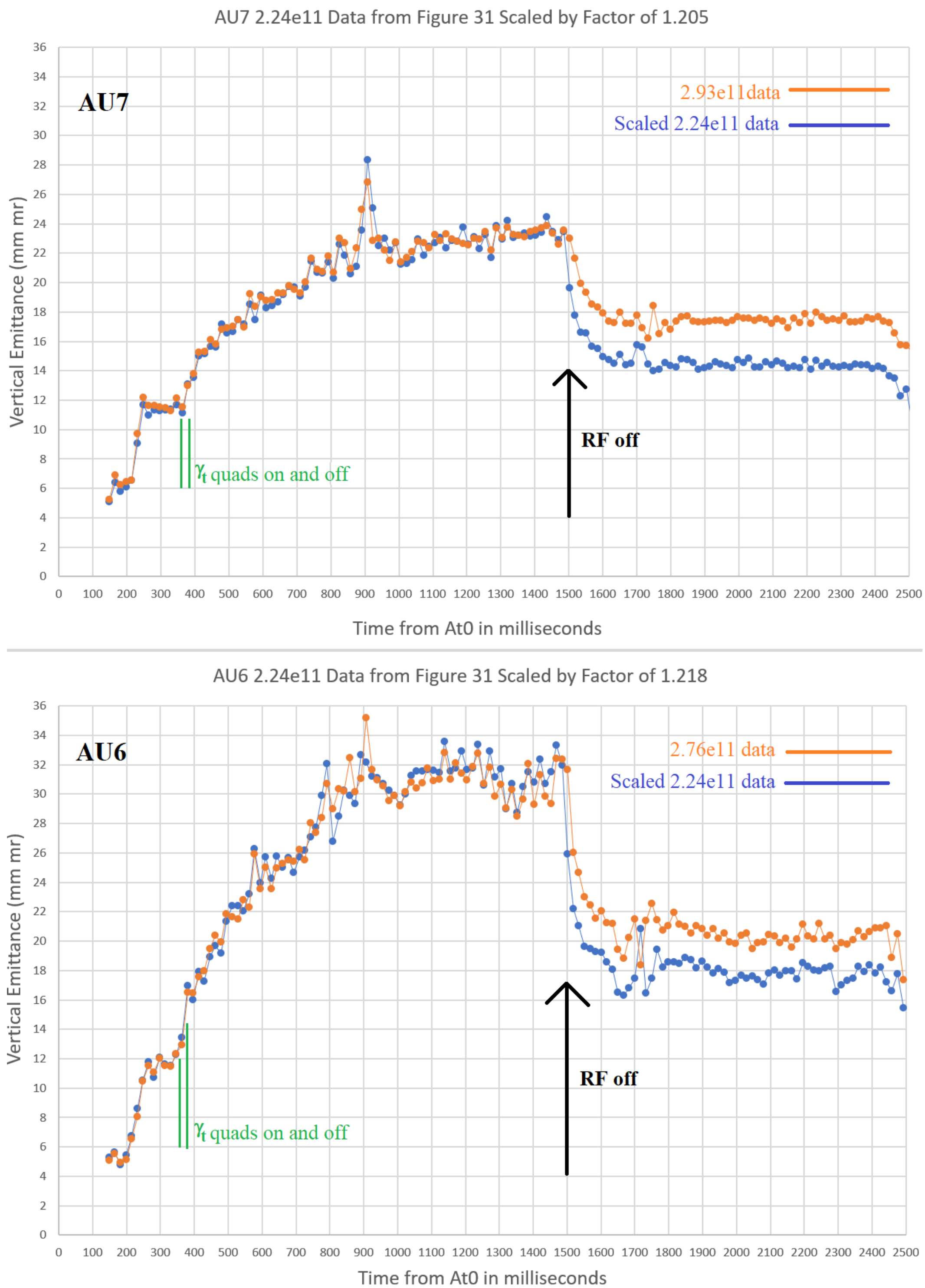

Figure 32: Ion IPM vertical emittance data shown in Figure 31 except that in the lower intensity cases (2.24e11, blue) the emittance data from injection until when the RF is shut off has been scaled so that in both the AU6 (bottom) and AU7 (top) cases the ε_y shown has the same value at the beginning of flattop. The data points at 990.5 ms are used and the scaling factor is 1.205 for AU7 and 1.218 for AU6. The higher intensity data (2.93e11 for AU7 and 2.76e11 for AU6) is in orange. The x-axis has also been extended to 2500 ms.

remarkably well, even around transition and for both users. Is it valid to conclude from this that there is no more ε_y growth in the higher intensity cases than the lower ones for the respective users?[100] In support of this conjecture is the fact that it is standard practice to identify emittance growth at particular points in the ramp by comparing IPM data with a saved trace from when that growth was not occurring.[101]

If it were valid then, if the scaled and higher intensity cases were to diverge at some point during the ramp or on the flattop before the RF is shut off, it would indicate that any emittance growth at that point differs for the 2 intensities. So, the fact that there is no divergence evident would indicate that there is at least no more growth in one case than the other. The other possibility would be that the growth occurs gradually throughout the cycle, not just at specific times such as transition, $0+\nu_y=G\gamma$, and $36+\nu_y=G\gamma$. But if that gradual growth were intensity dependent, the higher intensity case would start out lower than the scaled data and gradually converge with it as the flattop is approached.

The larger emittance after the RF is shut off in the higher intensity cases can still be attributed to a larger beam coming from the Booster. And the beam there should be larger since the vertical scraping was relaxed to provide the higher intensity.

Comparing AU4 and AU6 Transverse Emittance

It is difficult to compare IPM data through the cycle for AU4 and AU6, even at the same intensity, because the energy as a function of time differs for the 2. But the Westinghouse and Siemens functions have a fairly simple relationship to each other. They are the same up until 235 ms, and after that the time that a B field is reached on the Westinghouse function ramp (*t'*) is related to that time on the Siemens function ramp (*t*) by the formula t'=2.005t-254.6 where *t* and *t'* are in milliseconds from At0.[102] This is true until near where the rollover begins. The Siemens rollover is much faster. Regardless, on the flattop, since B is constant, the adjusted Siemens data times can be found by taking the time since the flattop started plus the time that it started on the Westinghouse cycle (912.34 ms). The Siemens flattop starts at 582 ms. So, for example, if the unadjusted Siemens time is 682 ms, the adjusted Siemens time would be 912.34+(682-582) ms, or 1012.34 ms.

Figure 33 contains IPM plots for AU4 and AU6 for a typical filling intensity (2.2e11) with the AU4 times adjusted as described above. In the vertical, I don't see a significant difference between the 2 on the ramp. What is different is that when the RF shuts off on the flattop the indicated ε_y does not drop as much on AU6 as it does on AU4. The horizontal is

[100] The model used in the R.E. Thern paper referenced in footnote 99 pertains to this question. Specifically, equation 5 in that paper, which relates the measured width to the actual width for bunched beam, seems to indicate it would be valid to compare them except that it would require one of the terms, K_2, to be the same at a particular time in the cycle for both the scaled and higher intensity cases. Unfortunately, the value of K_2 depends on the beam size and shape, so generally I don't think it would be valid. Although, it is unclear if the variation would be significant in the data considered here.

[101] For example see the Booster-AGS-pp Feb. 17 elog 1507 entry where there seems to be growth near transition that was not there when the blue trace was saved.

[102] See Booster-AGS-PP Jan 13 2022 elog entry at 14:51.

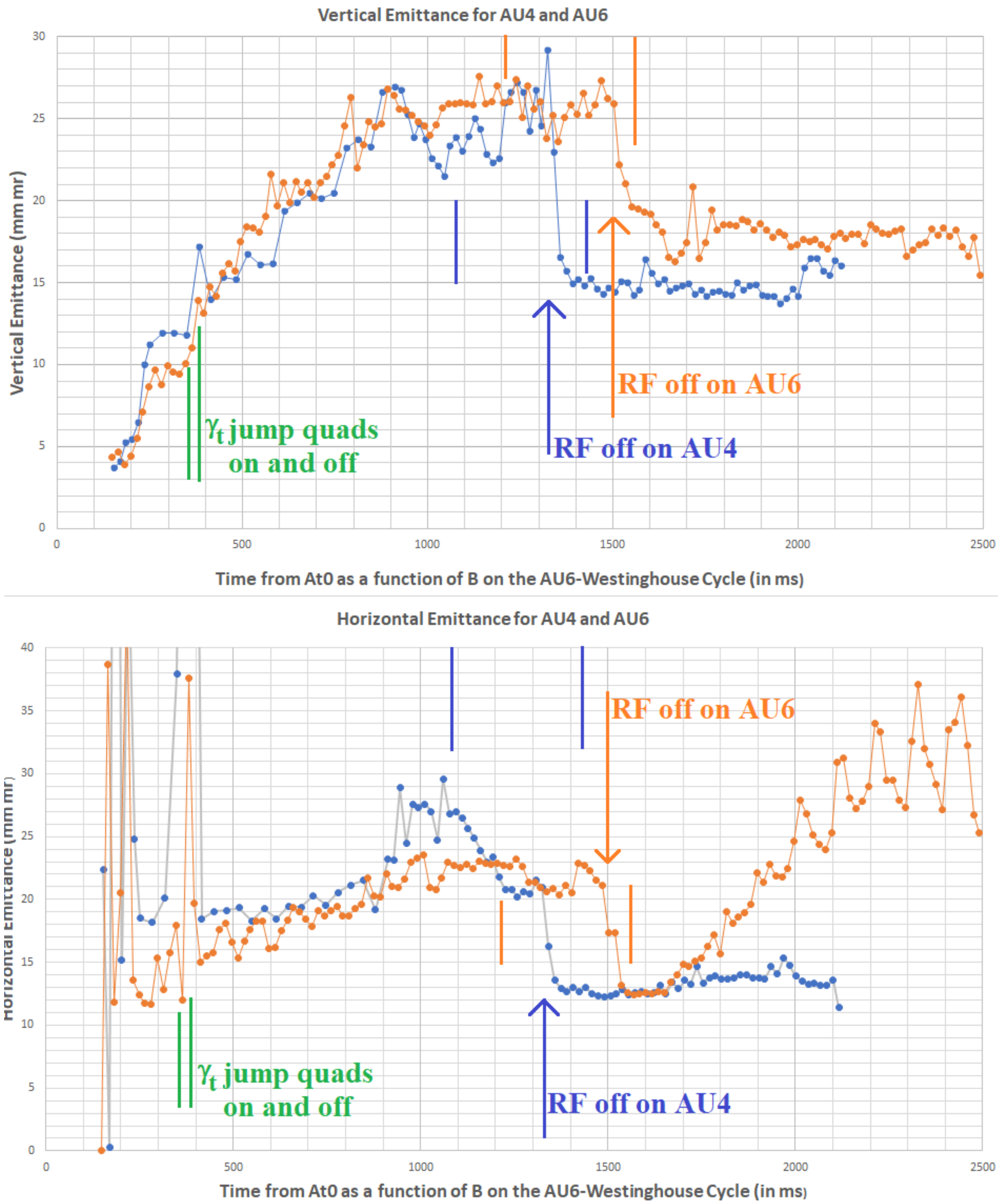

Figure 33; AGS Ion IPM (ε_x,ε_y) data for AU4 (blue) and AU6 (orange) with the AU4 times adjusted as described in the text. The AU4 data is from April 4 at 14:11:51 (row 27 in Table IV) and the AU6 data is from March 4 at 20:46:29 (row 22 in Table VIII). The intensity in both cases is about 2.2e11. The blue and orange vertical lines indicate when the extraction bumps start ramping (1080 ms, 1211 ms) and finish ramping down (1430 ms, 1561 ms) on AU4 and AU6, respectively.

generally smaller on the AU6 ramp but before the RF shuts off it is comparable and then it drops by the same amount resulting in the same flattop ε_x for both users.

So, perhaps the simplest explanation for the higher 'flattop' emittance on AU6 is that in the AU6 case there is some vertical growth near the time that the RF shuts off. In both the AU4 and AU6 cases extraction occurs before the RF is shut off. The blue and orange vertical lines in Figure 33 indicate when the extraction bumps start ramping and have finished ramping down on AU4 and AU6, respectively. In the AU7 (and AU3) case extraction would occur after the merge which would be much later than when the RF is shut off to take an emittance measurement.

It may be that in moving from the extraction configuration to one suitable for stability during polarization measurements that some vertical growth occurred on AU6 that did not occur on AU4. If that's the case, it is not a new problem, it is always a bit of an unknown whether growth occurs there or not.

Flattop Longitudinal Emittance on AU6

Table 9 contains four flattop longitudinal emittance measurements for the AU6-Westinghouse cycle. This data is of particular interest because the emittance might differ from what it is on AU4. The average of the 4 measurements is 0.91 eVs with a σ of 0.076 eVs. For AU4 the average of the measurements in Table II was 0.99 eVs with a σ of 0.062 eVs. The AU6 values may be a little smaller but not dramatically so, except for the Feb. 17th measurement, which is much smaller than the others, 0.78 eVs with a σ of 0.051 eVs. The logged scraping data from that time indicates that there was not much horizontal scraping. If there were a lot that would tend to reduce the longitudinal ε since far off momentum particles would be preferentially scraped off. There is also nothing unusual about the efficiencies in the Booster and AGS, or anything else that I can find.

Date &Time	**Length (ns)**	**# of measurements**	f_{synch} **(Hz)**	**ε (eVs)**	**AGS Late**
Jan 26 15:35	33.13 ±1.40	10	92.54	0.964±0.080	2.2e11
Feb 8 17:34	28.74±1.14	10	117.76	0.923±0.071	2.2e11
Feb 17 16:15	26.42±0.87	11	118.20	0.783±0.051	2.2e11
Feb 18 16:36	29.6±0.42	5	116.66	0.970±0.026	2.3e11

Table IX: AU6 flattop longitudinal emittance (ε) measurements during Run 22. Measurements were made at At0+1300 ms. Data is taken from the Booster-AGS-pp elog for the dates and times indicated. The full bunch lengths were measured using the F20 WCM RF scope signal. The "# of measurements" column contains the number of bunch length measurements made. The uncertainty in length is the σ of the measurements and the uncertainty in ε reflects that.

Summary and Conclusion

It may seem odd given that this is a note about a polarized proton run that there are few mentions of polarization in it. Especially given the difficulty this run with AGS polarization measurements, it seemed more worthwhile to focus on the parameters that may affect polarization, like transverse emittance, as well as the new split/merge setup. In particular, the effect on polarization of the slower Westinghouse cy cle was not discussed. Nor was the inferior stability of the Westinghouse compared to Siemens cycle and the implications for maintaining proper jump quad timing with Westinghouse.[103]

The BtA vacuum valve problem is described in some detail for reference purposes. Development of the split/merge cycle (BU3/AU3) took place while RHIC was set up using the standard setup (BU4/AU4). The Split/Merge development proceeded reasonably well, and the cycle was used for about two and a half weeks by RHIC until the switch to Westinghouse.

The split/merge setup was described in detail and an analysis of it was made to see if there are any issues with it that might explain why there was not a clear improvement observed in the polarization.[104] The motivation for the split/merge cycle was also discussed and it was noted that at least some of the data which motivated it, from 2013, was taken before a dual harmonic was used in either the Booster or AGS. A dual harmonic was first used in the Booster in 2015 and in 2017 in the AGS.

Whether the Booster correctors have enough time to get from the vertical scrape to the settings required for $G\gamma=4$ was investigated on the new BU3 cycle. Although it is less than ideal, there does appear to be a couple milliseconds to spare with a typical amount of scraping (Figure 5).[105] The sensitivity of the timing of $G\gamma=3$ and 4 to radial changes was also analyzed and the duration of their corrections looks sufficient.

As far as transverse emittance growth is concerned there is a potential issue with the peak current right at AGS injection. It is comparable to what it is on AU4 and AU7 for the same total intensity (see Figures 8 to 10).

To reduce the peak current at AGS injection quad pumping at Booster extraction was attempted but not successfully. It was possible to induce some oscillations there but the result did not seem any more effective in reducing peak current than just lowering the RF voltage at extraction as much as possible before beam loss occurs.[106] It would be complicated, but it should be possible to change the BU3 magnet cycle to reduce dB/dt and the RF voltage at extraction to make the bunches longer. As is evident in Figure 9, without QP the peak current drops to what it would be if QP were used in about 500 μs. Afterwards, the peak current during the dual harmonic is about 63% of what it is on the standard user for the same total intensity (Figures 9 and 10). This is about 10% lower than what was predicted.

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[103] These issues are covered in V. Schoefer's presentation at 2022 RHIC Retreat, "RHIC Polarized Proton Operation in Run 22", pgs. 29-33

[104] There were a lot of difficulties with the AGS polarimeter this run, mostly related to the high X^2 of the measurements, so the comparison between the standard and split/merge setup polarization is difficult. This makes it hard to say definitively that there was no improvement. There is some data that may indicate the polarization was higher on AU3. See the plot shown in the Booster-AGS-PP Sept. 30 2022 elog 1233 entry which was made by H. Huang.

[105] On BU4 the vertical scrape is at 117 ms and $G\gamma=4$ is expected to occur at 129.40 ms, 12.4 ms later. On BU3 the scrape is at 183 ms and $G\gamma=4$ is at 195.77 ms, 12.77 ms later. So, there is actually slightly more time between them on BU3. See Booster-AGS-pp_2015 March 16 2015 1756 entry for BU4 $G\gamma=4$ timing.

[106] For an example of QP on BU3 see Booster-AGS-PP March 7 elog 1603 entry. See Figure 10 in K. Zeno, "An overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594 for an example of QP at extraction on the BU4 cycle.

Another concern is whether or not the F3 kicker would have enough time to rise between the 2 adjacent bunches if they were longer. But when its modules are lined up properly, it seems like there should be room to make the bunches significantly wider.

Measurements of the AU3 longitudinal emittance of the merged bunch while AU3 was used to fill RHIC were about 25% higher than on AU4, 1.24±0.08 eVs (Table I) compared to 0.99±0.06 eVs (Table II). The average transverse emittance, ε_{avg}, on the flattop was generally smaller than on AU4 (see Figure 16). Although both ε_x and ε_y were generally smaller on AU3 than AU4, the difference in the horizontal was more pronounced than in the vertical (Figure 17). The larger difference in ε_x may have to do with the lower $\Delta p/p$ of the AU3 beam when the RF is shut off to take an IPM measurement.

The AU4 95% transverse normalized emittances, (ε_x,ε_y), were larger than the values found in 2017, especially ε_y. Part of the explanation for that may be the lower Booster input used this run, 6.0 vs. 6.9e11 (Figure 18). However, it seems unlikely that the lower input would be solely responsible. For AU3 (ε_x,ε_y) were generally smaller than the 2017 values except at the higher intensities (AGS Late > 2.4e11). It may be that at those higher intensities the machine was not optimized well. Again, the difference in ε_x was more significant than for ε_y.

In BtA, (ε_x,ε_y) for BU3 and BU4 were similar, (8.9, 2.9) and (8.4, 3.4) mm mr, respectively (see Tables V and VI). ε_x and ε_y in Run 17 were somewhat smaller, in the 7-8 and 2-3 mm mr range, respectively.

A study was described where a single bunch was transferred to the AGS using the split/merge setup to investigate the effectiveness of the AGS transverse damper in damping out oscillations on both bunches. It was found that both bunches were damped even though the electronics for the damper are not configured to do that. These single bunches were also looked at during the 6-3 squeeze and the merge and it was found that they behave differently (Figure 19), so it seems plausible that the merge could still be improved.

A GPM was made this run to monitor Booster scraping and the data was logged for BU4. Figures 20 and 21 are plots of that scraping throughout the run. Another GPM monitor was made to monitor the loss patterns from the scraping (Figures 22 and 23). These loss patterns for both the horizontal and vertical scrapes seemed stable throughout the run on both users. The losses extended from the B5 (just upstream of the dump at B6) to C4 or so with nothing of note elsewhere.

The stability of both the horizontal and vertical scrapes was worse than it was in 2017 (Figures 24-27). Historically, the vertical scrape has been quite stable, but not so this run. Possible reasons for the instability in both planes were explored. The D6 septum magnet is different than it was in 2017 and indications are that the fringe field from it has more of an effect on the horizontal orbit than the previous one, which had more issues with the remanent field. This, combined with the frequent NSRL mode switches associated with GCR running, contributed to the lack of stability.

The horizontal position on multiwire MW035 in LtB was also not stable. It appears that the variation is not due to any of the DC magnets in LtB but something upstream of them. The readback for LtB DH1, which is pulsed, is not accurate enough to conclude that it is responsible, but it is the prime suspect. It could also be a magnet further upstream although the HEBT steerers do not seem to be responsible.

Since the maximum dB/dt for Westinghouse is lower the dual harmonic in the AGS was extended past the $0+\nu_y=G\gamma$ resonance on those setups (Figure 30). Despite that the AGS flattop transverse emittance on the Westinghouse standard cycle (BU4/AU6) reported by the Ion IPM was larger than it was on AU4 (Figure 28). However, the AU7 transverse emittance did not seem to be larger than it was for AU3 (Figure 29).

An attempt was made to determine where in the Westinghouse AU6 cycle vertical emittance growth occurs relative to AU7 by comparing the IPM data on the ramp for 2 intensities (Figure 31). To make this comparison easier the lower intensity data on the ramp for each user was scaled so that it has the same value as the higher intensity data at the beginning of the flattop (Figure 32). In both the AU6 and AU7 cases the scaled ramp data overlayed remarkably well with the higher intensity ramp data. The fact that they overlay so well, and that emittance growth at various points during the ramp can often be observed using the ion IPM, suggests that this way of qualitatively comparing ramp emittances at different intensities is valid. If so, it would suggest that there was no more growth in the higher intensity case during the ramp on AU6 than on AU7.

It is tempting to take this speculation one step further and infer that if there is no difference in any growth between the 2 intensities on AU6, that there is generally little or no intensity dependent growth on the ramp on AU6 for intensities lower than the higher intensity case (about 2.7e11).[107] If true, this could help explain why the split/merge cycles (AU3/AU7) do not result in higher polarization. However, if that were true, then why is the flattop vertical emittance generally smaller on the split/merge cycles?[108]

As noted previously, the initial motivation for merging 2 bunches on the AGS flattop came from 2013 data which was before the dual harmonic was used in either the Booster or the AGS. In that case the flattop $(\varepsilon_x,\varepsilon_y)$ for the 2-bunch case at 2.0e11 was (11,15) mm mr so ε_{avg} was 13.2 mm mr. Although the AU4 flattop $(\varepsilon_x,\varepsilon_y)$ this run for 2.0e11 was (13,14.5) mm mr (Table IV, row 3), in 2017 it was comparable to the Run 13 values, about (12.2,13) mm mr for an ε_{avg} of 12.7 mm mr (see pgs. 4-5). The measured ε_x would also tend to be lower for the 2013 data since $\Delta p/p$ is smaller with 2 bunches and this year's ε_y is similar to the 2013 value.

Although the input intensity was lower in 2013, so not as much scraping could be used, it has been shown that the dual harmonics do help reduce emittance growth. Perhaps with their presence the split/merge may not improve things much at the intensities that are normally run. It at least should be the case that it will not improve things as much as would be suggested by the 2013 data. The 1-bunch 2.0e11 2013 $(\varepsilon_x,\varepsilon_y)$ was (19, 20) mm mr (see footnote 15).

[107] Assuming the setup is optimized for that intensity. For example, when the intensity is lowered to <0.5e11 or so it will usually become unstable which leads to growth.

[108] The reason the horizontal emittance is smaller on the split/merge setups may just be because $\Delta p/p$ is smaller.

On the other hand, a study performed in 2017 indicated that, even with both dual harmonics in use, that for AGS Late intensities above about 1.7e11 the flattop emittance does have considerable intensity dependence even though the BtA emittance is expected to be constant.[109] In order for the interpretation of the data from that study and the one considered here to both be true the intensity dependent growth would have to happen right after injection, before an IPM measurement is taken. If that is true then the fact that the peak current at injection is about the same on the split/merge cycle compared to the standard one (see Figure 9) would be a significant problem and more effort should be made to reduce it. To do so would require that the bunches be made longer at injection which may require a different Booster magnet cycle that has a lower extraction dB/dt.

AU4 and AU6 IPM data on the ramp and flattop were then compared. The AU4 time scale was adjusted so they could be compared during the ramp for an AGS Late intensity of 2.2e11 (Figure 33). It was found that up until the RF is shut off they are comparable but ε_y does not drop as much on AU6 when it shuts off. This suggests that the actual ε_y is about the same before then and that it may blowup around the time the RF is shut off. Extraction on AU6 occurs before the RF shut off time whereas on AU7 it happens well after this. It may be that the increase in ε_y for AU6 is associated with changing machine parameters to move from their state at extraction to the state it is put in afterwards so that the beam will be stable for polarization measurements.

Longitudinal emittance measurements on AU6 were compared with those made on AU4. The average value for AU6 was perhaps slightly smaller (0.91 vs. 0.99 eVs), but one of the four measurements was significantly smaller (0.78 eVs). The reason for this is unknown, the quality of that measurement looks to be comparable to that of the others (Table IX).

Acknowledgements: Thanks to Iris Zane for her help during the run.

[109] See K. Zeno, "An overview of Booster and AGS Polarized Proton Operations during Run 17", October 2017, C-A/AP/594 section called "AGS Flattop Emittance with and without the Dual Harmonic" pgs.19-21. The pulse width was changed to vary the intensity while the Booster scraping remained unchanged.