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Overview and analysis of the 2016 Gold Run in the Booster and AGS

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Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

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Introduction

Run 16 differed from preceding Au runs in that during most of it a 12:6:2 merge was employed in the AGS instead of an 8:4:2 merge. This was done to provide higher bunch intensities for RHIC. Since the approach to providing higher bunch intensities is, and has been, to merge more Booster bunches of the same intensity into one final bunch, detailing the longitudinal aspects of this setup seems quite relevant. So, aside from providing an overview of the Au portion of Run 16, this note also contains a series of emittance measurements in the Booster and AGS. Comparisons of these to similar measurements in previous runs are also made in hopes of gaining a better understanding of what factors contribute to the emittance of a bunch at AGS extraction. The note also tries to provide some context in which to understand the various merge schemes and describes a potential 8 to 1 type merge.

Some History and Context

Prior to the use of EBIS as the pre-injector for Au, the Tandem delivered Au beam to the Booster. By the time the pre-injector was switched to EBIS, the intensity at booster extraction using Tandem was around 3.3e9 Au+31 ions. Because of the frequency range of the Rf cavities and the revolution frequency of the Tandem Au beam at Booster injection, the lowest Rf harmonic achievable in the Booster was h=6. Every AGS cycle, 4 Booster transfers of 6 bunches each were injected into the AGS into h=24 buckets.[1] The 24 bunches were merged into 12 bunches and then they were merged again into 4 bunches. These 4 bunches were then accelerated in h=12 buckets. So, for each AGS cycle there were 4 bunches available for RHIC injection. About 52% of the beam at Booster extraction survived to AGS extraction, which corresponds to about 3.3e9*0.52=1.72e9 Au+77 ions per AGS bunch.[2]

In 2007, the total longitudinal emittance of the 6 bunches from 1 booster cycle after injection into the AGS was measured to be 0.082 eV*s/n, and the final emittance of 1 bunch at extraction was measured to be 0.23 eV*s/n.[3] Another extraction emittance measurement from 2009 gave a result of 0.37 eV*s/n.[4] And other bunch width measurements from 2011 suggest a typical value was around 0.30 eV*s/n. It was also found in 2007 that the emittance increased by a factor of 1.8 from Booster extraction to AGS injection due to scattering in the BtA stripping foil.

[1] Unlike AGS extraction, Booster extraction to the AGS does not occur on a flattop. Whatever beam is present at extraction time is kicked out of the machine in 1 turn.

[2] There could also be beam in the so-called ‘satellite’ or ‘baby’ bunches that results from not all the merged beam fitting into the main h=12 buckets. But when optimized there was a few percent of less of the beam in these satellite bunches.

[3] L. Ahrens et al., “Setup and Performance of the RHIC Injector Accelerators for the 2007 Run with Gold Ions”, pg. 1864, Proceedings of PAC07, Albuquerque, New Mexico, USA.

[4] L. Ahrens, A series of entries in the Dec 14 2009 Booster-AGS Au 2010 elog

Scattering through the stripping foil contributes to emittance (ε) growth by increasing a bunch's energy spread (ΔE/E). This contribution adds in quadrature to the ΔE/E of the incoming bunch.[5] If the bunch's ΔE/E is relatively small, this contribution will be relatively large, and vice versa. So, the more bunches extracted from the Booster for a given total ε in the Booster the greater the increase in the total ΔE/E and therefore the total ε of the beam injected into the AGS. So from the perspective of ε conservation, it would be preferable to have only one bunch to transfer to the AGS.

There is also a subtle issue that arises when injecting multiple bunches from one Booster cycle into the AGS through a stripping foil. In order for Booster bunches to be matched to the AGS buckets the spacing between those bunches must be the same in the AGS as it is in the Booster. Because the stripping foil causes a net energy loss, the bunches slowdown after passing through it. Because of this, when they reach the AGS, the distance between them is smaller than it was in the Booster. For example, the last bunch to pass through the foil has been traveling at a higher speed than the first for a bit more than a microsecond and so it is a little closer to it than it would have been if the first bunch had not slowed down. It may seem that this effect would be insignificant, but dipole oscillations associated with it can be seen on the AGS mountain range, and it has been speculated that these oscillations contributed to emittance growth during the merge.[6] Whether this was a significant contributor to ε growth or not, it's not an issue if only 1 bunch is injected per Booster cycle.

So, there are 2 reasons to favor injecting a single bunch into the AGS. But those are not the only reasons. The AGS circumference is 4 times that of the Booster, so if there is more than 1 bunch in the Booster at extraction, then there is a maximum of 4 Booster transfers per AGS cycle. This is the case because the AGS harmonic has to be 4 times the Booster harmonic to maintain the proper bucket spacing in the AGS. But if there is only a single bunch being transferred per Booster cycle, then this bucket spacing constraint is removed. From a purely Rf perspective, the number of transfers allowed is then limited only by how many buckets the AGS Rf can generate, which for the present Au transfer energy can range from 12 to 27.[7] The AGS buckets can also be populated in any sequence and pattern that's desired.

With EBIS Au operation there is only about 1.0e9 Au ions at Booster extraction. This is slightly less than a third of the amount when Tandem is used. Consequently, beginning in Run 12

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[5] In this case, by in quadrature I mean, $\frac{\Delta E}{E}_{final} = \sqrt{\left(\frac{\Delta E}{E}\right)^2_{initial} + \left(\frac{\Delta E}{E}\right)^2_{foil}}$

[6] See Footnote #3 and K. Smith, "AGS Bunch Merging for Au2007" Presentation. The latter also gives a good description of the 6:3:1 type bunch merge.

[7] I think the use of only one bunch in the Booster to defeat the constraint that the AGS harmonic must be 4 times the Booster harmonic was first employed in high intensity proton operation so that 6 Booster transfers could be injected into the AGS instead of 4. I believe it was suggested by Mike Brennan. See L.A. Ahrens et al., pg. 1, "High Intensity Performance of the Brookhaven AGS", 1999 Particle accelerator Conference.

(the beginning of EBIS injection) multiple bunches were merged into one bunch in the Booster. For most of this time an AGS harmonic of 16 was used with 2 sets of 4 opposing buckets populated, i.e.- {1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0}. Each set of 4 bunches is merged into 2, and then into 1 in the AGS to provide sufficient bunch intensity for RHIC (8:4:2 merge). The bunches are arranged in 2 sets of 4 consecutive buckets to allow for these AGS merges to occur. This setup requires 8 EBIS pulses per supercycle. Up until Run 16, this was the maximum number of pulses EBIS was comfortable with delivering, which set a limit on the maximum number of bunches that could be merged in the AGS to provide 2 bunches at AGS extraction.

The single bunch at Booster extraction was created by merging the multiple bunches required by the Rf system at Booster injection energy. In the case of EBIS, the lowest Rf harmonic possible at injection is 4 not 6 (as it is for Tandem Au). The 4 bunches are first merged into 2 and then into 1 when the energy is high enough to allow for the corresponding Rf harmonics in the Booster to be operational.

But having only one bunch in the Booster does not solve all the problems. For instance, there are still often limitations associated with the AGS (A5) injection kicker’s rise and fall times. For example, it is sometimes the case that due to the finite fall time of the kicker it is preferable not to inject into a bucket that is immediately followed by a bucket that has already been populated. Depending on the details, this could result in the bunch that follows the most recently injected bunch receiving a kick.

It’s also possible that the bunch may be too wide to fit into an AGS bucket. This is a particular issue because the 4 bunches created at Booster injection are merged into 1, which results in a much wider bunch. And, even if it fits, if there is a bunch in the preceding bucket, the A5 kicker has to start rising after it has passed, and also get up to current before the injected bunch passes through it.

There are also power supply constraints that can limit the number of Booster cycles. The most notable power supply constraint is the PPMR limit for the Booster main magnet P.S. which limits the amplitudes of different harmonics in its power spectrum, thereby limiting what the Booster magnet cycle may be, and how many of them there can be per AGS cycle (or equivalently, per supercycle).

Despite the lower EBIS pulse intensity EBIS Au injection has some advantages:

1) Booster injection from EBIS is quite stable. That is, the EtB line does not have to be adjusted frequently to keep injection optimized.

2) EBIS does not depend on stripping foils, which are a source of intensity fluctuations.

3) Compared to Tandem Au, the Booster injection energy is higher, the intensity is lower, and the injection and early acceleration efficiencies are better. So, there are no significant issues with space charge or vacuum degradation. Therefore, the intensity in the Booster is largely proportional to the EBIS injection intensity. Such is not the case with Tandem injection at the higher Booster intensities that were used. At the higher Tandem intensities, the Booster intensity is well into saturation due to these effects.

4) The EBIS beam characteristics are such that they result in a beam at AGS injection that is comparable in size to the beam that results from Tandem (not really an advantage, but if it wasn't that would be a problem).

5) EBIS seems to be able to deliver more pulses per supercycle than Tandem has been able to. Up until Run 16 the maximum number of EBIS pulses was 8 spaced 200 ms apart. The maximum was increased to 12 in Run 16. Tandem regularly delivered 4 pulses spaced 200 ms apart at the higher intensities they used to run. On short notice, they were able to deliver 6 per supercycle at somewhat lower intensities in Run 16, and perhaps they could deliver more pulses at relatively low intensity given enough setup time.

The Evolution of AGS Merge Schemes

The 8:4:2 bunch merge scheme employed from Run 12 to early in Run 16 for EBIS injection eventually provided about 20% more Au bunch intensity for RHIC as that provided when Tandem was used with the 24:12:4 merge. But there are only 2 bunches instead of 4 per AGS cycle, the AGS cycle length is longer (5.4 vs 4.0 sec), and the longitudinal emittance is 2 or 3 times greater than with Tandem (about 0.3 vs. 0.7 eV*s/n).[8]

With the Tandem 24:12:4 merge, only the beam from one Booster cycle goes into 1 AGS bunch, and with the EBIS 8:4:2 merge the beam from 4 Booster cycles goes into 1 AGS bunch. Measurements made during Run 14 indicate that the ε of the one bunch at AGS injection was in the 0.09-0.10 eV*s/n range.[9] This isn't much different than the total of the 6 bunches from one Booster cycle that was measured with Tandem (0.082 eV*s/n).[10] But why then isn't the ε at extraction of an AGS bunch 4 times what it was with the Tandem scheme? At least part of the reason may the dipole oscillations mentioned previously that result from multiple bunches per transfer. Since these oscillations did not damp out, they were thought to contribute to ε growth

[8] K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pg. 26, CAD Note 523, August 2014. In Run 14 the longitudinal emittance was about 0.69 ± 0.06 eV*s/n, but in Runs 15 and 16 it seems to have been smaller, about 0.60 eV*s/n.
[9] Same as 8
[10] L. Ahrens et al., "Setup and Performance of the RHIC Injector Accelerators for the 2007 Run with Gold Ions", pg. 1864, Proceedings of PAC07, Albuquerque, New Mexico, USA.

during the 24:12:4 merge. However, I am unable to find any ε measurements made just after the merge that would help distinguish any growth there from other growth during the acceleration ramp.

Emittance measurements of the 8:4:2 scheme do not show much ε growth from the merge, but do indicate significant growth during the acceleration ramp. In particular, they suggest that significant ε growth occurs while the AGS main magnet power supply is on the pulsed voltage bank (P-bank) which is used for the higher dB/dt part of the ramp.[11] A further complication is that these ramp measurements, especially when done on the P-bank are difficult to make and provide some inconsistent results (i.e.-in some cases the measured ε during parts of the ramp is significantly larger than the flattop value). It does seem pretty clear however that there is ε growth between the early ramp (before the P-bank) and the AGS flattop.

In order to provide more bunch intensity to RHIC, S.Y. Zhang asked me to look into the feasibility of a 12:6:2 merge in Feb 2014.[12] This would merge 6 Booster transfers of 1 bunch each into 1 final AGS bunch, and would also provide 2 bunches per AGS cycle for RHIC. This setup uses the same AGS merge scheme as in the Tandem case. That is, injection into h=24 buckets, a 12:6 merge using h= 24 and 12, and a 6:2 merge using h=12, 8 and 4:

{1,1,1,1,1,1,0,0,0,0,0,0,1,1,1,1,1,1,0,0,0,0,0,0}->{1,1,1,0,0,0,1,1,1,0,0,0}->{1,0,1,0}

It would require 12 EBIS pulses, something that EBIS was not ready to provide at the time. It would also require at least 4 more Booster magnet cycles per AGS cycle, and that configuration would have to satisfy the PPMR constraints. At the time, I tried finding such a supercycle that would satisfy the PPMR constraints. Simply adding 4 more of the Booster cycles used for 8:4:2 did not satisfy them. I found that 2 sets of 7 magnet cycles, each set with a different merge porch field and separated by about 500 ms did.[13]

However, a setup that fills only 1 set of 6 AGS buckets to make 1 final AGS bunch (6:3:1) is less demanding from the EBIS and PPMR standpoint than even 8:4:2 and could be checked to see what bunch intensity and emittance it could provide. This was done in Run 15. For convenience, the same AGS magnet cycle was used as for the 8:4:2 case. The same Booster magnet cycle was also used.

There are several things that running the 6:3:1 setup would help to clarify. How large will the losses during the acceleration cycle be? How well will the Booster bunches fit into narrower

[11] K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pg. 15-18, CAD Note 523, August 2014.
[12] S.Y. Zhang, private communication.
[13] See Booster-AGS-EBIS Feb 12 2014 elog Feb 15 1714 entry. Much later I found that 13 consecutive Booster cycles could be used if the Booster merge porch was raised from 4.5 to 5.5 kG on all cycles (See Booster-AGS-EBIS Jun 23 2015 elog, Aug 4 entries). However, this setup was not actually tested with the Booster main magnet pulsing until 2016. The latter configuration was eventually used for 12:6:2 operations.

AGS buckets at injection (h=24 vs h=16)? And how well will the merged bunch fit into an h=12 bucket? With regard to the latter, if any of the merged bunch is outside the h=12 bucket it tends to wind up in the other h=12 buckets, forming 'baby' bunches that are also accelerated to flattop. The final bunch emittance could also be measured.

The 6:3:1 Merge in Run 15

There were only a few days dedicated to this setup in Run 15. An increase of about 17% in the bunch intensity over the 8:4:2 scheme was achieved.[14] Of the 5.9e9 ions at Booster extraction about 2.6e9 ions survived to AGS extraction. Of that, about 2.3e9 was in the main bunch. So, the amount of beam in the baby bunches was about 1-(2.3/2.6)=0.12 or 12% (a typical baby bunch percentage for 8:4:2 is 3%). The BtA transfer efficiency was about 53% (AGS intensity just after the last transfer divided by the total intensity late in the Booster). So about 0.53*5.9e9-2.6e9=5.3e8 ions were lost between the end of injection and the AGS flattop or never captured into h=24 buckets (which is 17% of the beam present after the last injection).

Figure 1 shows the last three transfers and 800 ms or so of the acceleration cycle. The first sharp loss occurs around the time the field starts to ramp, and the 2nd around the time of the transfer from flattop to pulsed AGS main magnet V bank (F to P transfer). The total of these 2 losses is about the same as the size of single transfer. The amount of beam in a single transfer is 1/6 (~17%) of the total injected beam. Then there is 12% of the total beam at extraction in the baby bunches, or about 72% of one injected bunch. So, the amount of beam in the main bunch at extraction is only the equivalent of about 4+0.28=4.28 transfers. But not all the beam injected in the 8:4:2 case is in the main bunches at extraction either. There is some loss at these 2 places in that case as well, but far less. There is also beam in the baby bunches (about 3%). The result is that there was perhaps 17% more beam for the 6:3:1 setup than for the 8:4:2. The bunch in the 6:3:1 case is also slightly wider and has a different shape (see figure 2).

The 2nd sharp loss, at F to P transfer, is mainly associated with a transient that occurs in the voltage, and therefore the dB/dt, at this time. Because of the transient, the Rf must accelerate the beam quickly and there is apparently not enough voltage to do that without some beam spilling out of the buckets. A similar loss occurs with 8:4:2, but it is much smaller. The loss can generally be reduced by moving the F to P transfer later, so that it occurs at a higher field. It's not surprising this can reduce it since for one thing; the transient the beam sees is related to $\Delta B/B$, not just ΔB. It had already been moved later to reduce it for the 8:4:2 scheme, which was the magnet cycle used here.[15] It's also important to point out, regarding this loss, that this setup was far from optimized, and it's quite possible the loss could have been reduced given more time. For example, in Figure 1 there is a large amount of fuzz on the BPM signal just before the

[14] See the Booster-AGS EBIS May 26 2015 elog. I'm using 2e9=32.74 nVs as the calibration for the WCM to measure the bunch intensity. This calibration was found in Run 16 (see Booster-AGS-EBIS 2016 elog Feb 9 1955 entry).
[15] K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pg. 14, CAD Note 523, August 2014.

F to P transfer. This could be indicative of emittance blowup, which could make the loss at the transfer worse than it would have been otherwise.

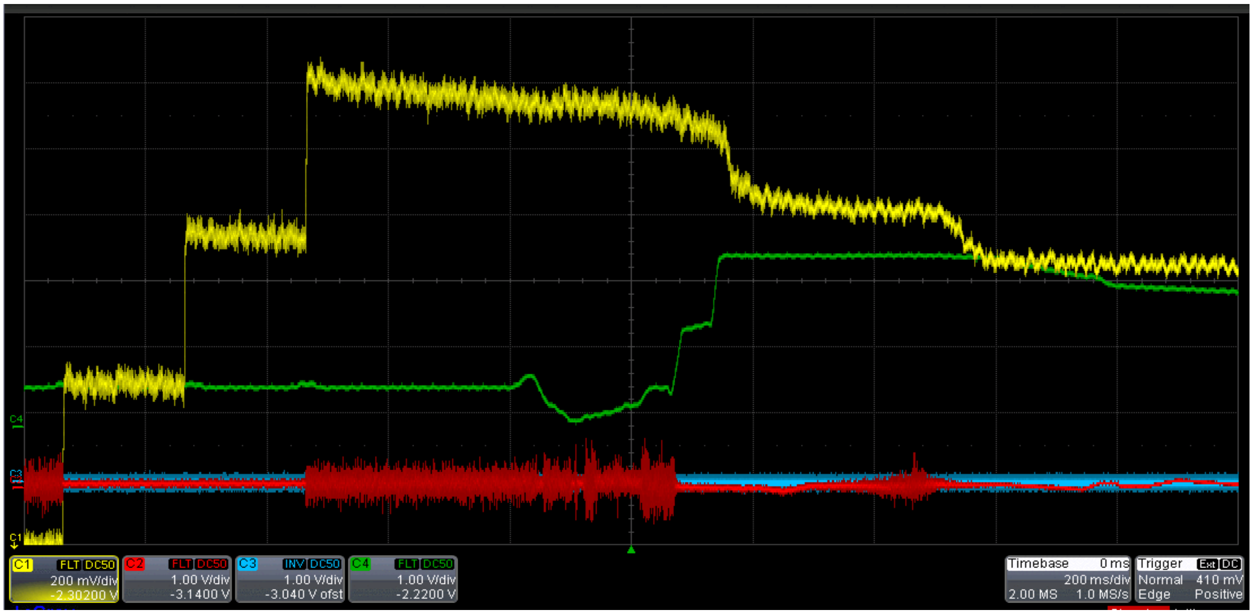

Figure 1: AGS Normalized Current Transformer (yellow) with 6:3:1 setup from Run 15. Also shown is the Rf Vector Sum (Green), and a horizontal AGS BPM. The trigger is AT0+1600 ms, 200 ms/div.

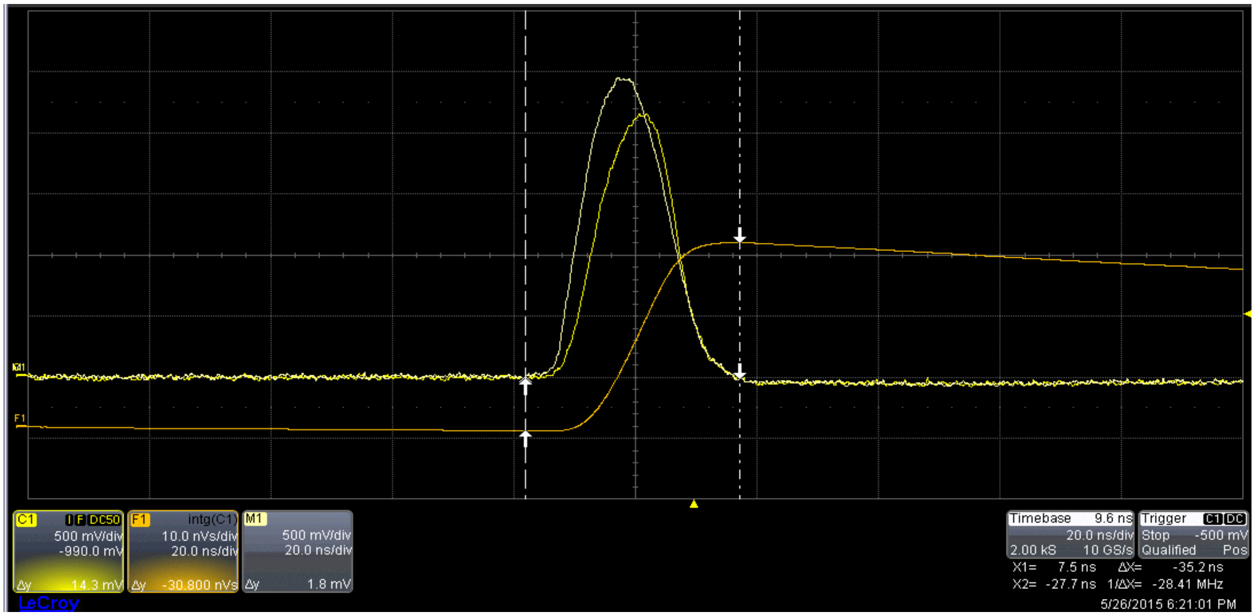

Figure 2: Comparison of 8:4:2 and 6:3:1 bunches on the AGS flattop using the WCM. The orange trace is the integral of the 8:4:2 bunch. Note that the 6:3:1 bunch is slightly wider and has a different shape.[16]

[16] Booster-AGS-EBIS May 26 2015 elog 1823 entry

There is also a loss during 8:4:2 early acceleration but it is much smaller too. This loss was once much larger for 8:4:2 as well, until it was noticed early in Run 14 that increasing the dB/dt right at the beginning of the ramp greatly reduced it.[17] Except for a capture loss, no satisfactory explanation for an Rf mechanism to account for the loss was ever put forth, and it had always been sensitive to octupole and tune adjustments. There was not significant capture loss with the 8:4:2 setup either, but given the difficulty in fitting the Booster bunches into h=24 buckets some of this loss could conceivably be attributed to beam that was never captured into h=24 buckets. Rf quad pumping (see Figure 7) at Booster extraction was used to make the bunches narrower at transfer so that they would fit better into the h=24 buckets, and it did seem to help with the final per bunch intensity.[18]

Initially it was very much a mystery why an increase in the early dB/dt could have such a dramatic effect on this loss. But while running Aluminum during Run 14 it became quite apparent that this loss was intensity dependent (see Figure 3), and also could be reduced by making the early dB/dt even higher.[19] The Aluminum setup was quite similar to the Au setup. They both use an 8:4:2 merge, but Al+13 was estimated by C. Gardner to have about a 25% larger space charge tune shift around this time in the cycle than Au for typical running intensities.[20]

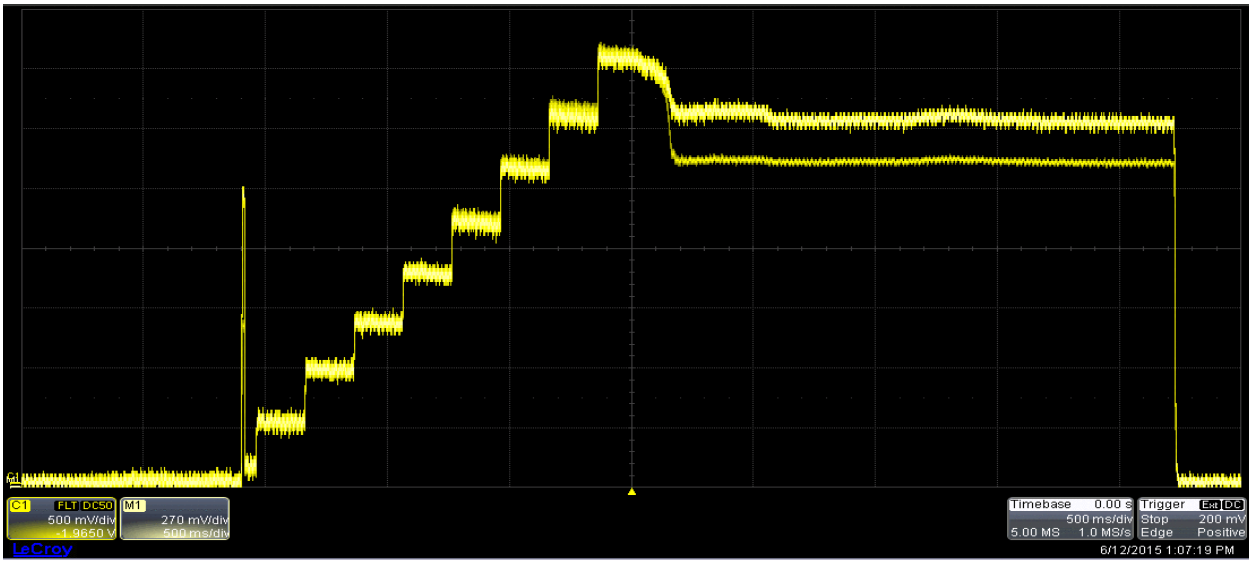

Figure 3: A comparison for Al+13 of higher (4.8e10 ions Booster Late)) and lower (2.6e10 ions Booster late) intensity on the AGS normalized current transformer with the gains adjusted so that they overlay before acceleration. The trace with the proportionally larger loss at early acceleration is the higher intensity case. [21]

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[17] K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pg. 14, CAD Note 523, August 2014. It also should be noted that even with Tandem operations there was a loss there that was sensitive to stopband correctors (Octupoles) and tunes.
[18] Booster-AGS-EBIS May 26 2015 elog 1654 entry
[19] Booster-AGS-EBIS elog Jun 8 2015 Jun 9 1413 entry
[20] C. Gardner, Booster-AGS-EBIS elog Jun 11 2015 1019 entry
[21] Booster-AGS-EBIS elog Jun 12 2015 1307 entry

As a result of this, new sextupole and additional octupole stopband correctors were installed in the AGS during the shutdown between Runs 15 and 16 to be used to try to correct the stopbands causing beam loss due to space charge effects. The peak space charge force likely occurs when the beam (which is from either 4 or 6 initial bunches) has been merged into 1 bunch and is then squeezed into the h=12 buckets and the h=12 voltage is raised to capture and accelerate it. Both the h=8 and h=4 cavities used for the 3:1 merge are also used immediately afterwards to make the merged bunches narrower so they will fit better into the h=12 buckets. This process is typically referred to as the bunch squeeze.

Up until this time, the energy that the merges (both 8:4:2 and 3:1) occur at was determined by the frequency ranges of the h=8 (KL) and h=4 (L10) cavities used for merging, which since the time of Tandem operation had been configured so that the merges occur at Au injection energy (which is largely why the EBIS Au and Tandem Au AGS injection energies are the same). In particular, the h=4 (L10) cavity has a very narrow frequency range.[22] But just prior to the beginning of Run 16, the Rf group offered to raise the frequencies at which these cavities operate. Raising the Booster extraction energy so that the merges could occur on the injection porch didn't seem feasible, but ramping up to the merge energy after injection seemed like a viable option.

The new L10 and KL frequencies were chosen so that the squeeze could occur into h=10 buckets instead of h=12 buckets if desired (at injection energy the required Rf frequency for h=10 operation is too low). The reason for wanting to use h=10 buckets is that they are larger, so in the 6:3:1 scheme more of the merged bunch would fit into them, thereby reducing the size of baby bunches. The drawback is that the bunch at extraction will likely be even wider and might have a larger ε. S.Y. Zhang in particular was a strong proponent of using h=10 for acceleration (as was I).[23] For the 6:3:1 scheme these frequencies would allow the 3:1 merge to occur at the higher energy, though the 6:3 part would still have to occur at injection energy because the frequency of the h=24 Rf would be too high for it to be used for the ramp to the merge porch. The frequency ranges of the Rf required for the 8:4:2 merges allowed both of them to occur at the higher energy.

This increase in the L10 and KL frequencies would require an increase in the rigidity that the 3:1 and 8:4:2 merges take place at of about 29%. Ramping up to the merge energy should be fine from the standpoint of space charge, because the bottleneck is after the final merge. Given the sensitivity of the early loss to changes to the dB/dt at that time in the cycle, it seemed likely that this rigidity/energy change would be more than enough to get away from any space charge related issues in the 6:3:1 case, and that the use of the stopband correctors would not be necessary after all.

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[22] K. Smith, Private Communication. The h=8 (KL) cavity tuning also had to be modified.

[23] S.Y. Zhang, private communication, and S.Y. Zhang, H Huang, "Au intensity enhancement for RHIC", Dec 2015, CAD Note 556.

Run 16

The Initial Setup with 8:4:2

Near the beginning of Run 16 (Jan 11 2016), the h=4 (L10) and h=8 (KL) cavities were modified to run at higher frequencies which would allow for the merge and squeeze to occur at an energy sufficiently high for injection into h=10 buckets.[24] Prior to this, the nominal 8:4:2 setup had been reestablished and worked as expected. Once the frequency change was made a new magnet cycle for 8:4:2 operation was made with a ramp to the porch where the merges would occur. Otherwise the cycle was quite similar with the F to P transfer occurring at the same field and around At0+2100 ms as it had before.

To merge the bunches now, the beam had to be accelerated up to the merge porch. This required Rf Track, which causes the Rf frequency to track changes in the magnetic field, to be turned on before that ramp as well as the AC phase loop. The AC phase loop needs to be put 'in hold' while the bunch merge is occurring because the phase information is not usable then. But it was found that when this was done the bunch structure became noisy (see Figure 4).[25] The speculation was that the noise was associated with Rf Track being on.[26]

In the past, AGS merges had been performed before Rf Track was turned on. When Rf track is on the frequency changes in response to gauss clock counts to keep the radius constant. Freddy Severino provided a way to turn Rf Track off for the merge and back on afterwards. Once this was done the noise went away and the merging proceeded normally. Empirically, it seems more critical that the Rf frequencies remain constant than the radius (assuming the gauss clock is accurately tracking the field). Rf track had always been on in the Booster during the 4:2:1 merge as well. Freddy also provided a way to turn it off and back on. This was implemented on Jan 13, and did not have an obvious effect on the quality of the bunches coming into the AGS.[27]

It might be enlightening to compare the 8:4:2 merge scheme at injection with it at the higher energy merge porch. In Run 15, AGS late intensities as high as 4.4e9 ions were obtained with an EBIS (xf108) total intensity of about 10e9 ions. The baby bunches at the time were about 3.5%. This corresponds to a bunch intensity of 2.12e9 ions.[28] The single flattop ε measurement recorded in the elog from Run 15 gave 0.60 eV*s/n.[29] On Feb 22 2016, the EBIS intensity was about the same as in the 2015 case, and bunch intensity was measured to be 2.14e9 ions.[30] The baby bunches for the 8:4:2 in Run 16 were about 2-3%. A flattop ε measurement gave 0.60

[24] These modifications change the L10 frequency from 628 kHz to 783 KHz, and KL from 1.26 MHz to 1.566 MHz.
[25] Booster-AGS-EBIS elog Jan 11 2016 1610 entries.
[26] Booster-AGS-EBIS elog Jan 11 2016, 1922 entry.
[27] Booster AGS-EBIS elog Jan 13 2016, 2228 entry
[28] Booster-AGS-EBIS elog May 29 2015, Jun 2 1258 and 1522 entries
[29] Booster-AGS-EBIS elog Apr 30 2015, May 1 2015 1617 entry
[30] Booster-AGS-EBIS elog Feb 22 2016, 1542 entry

eV*s/n.[31] These values are very similar to those in Run 15, so it doesn't seem like the higher energy merge porch affected the 8:4:2 performance significantly.

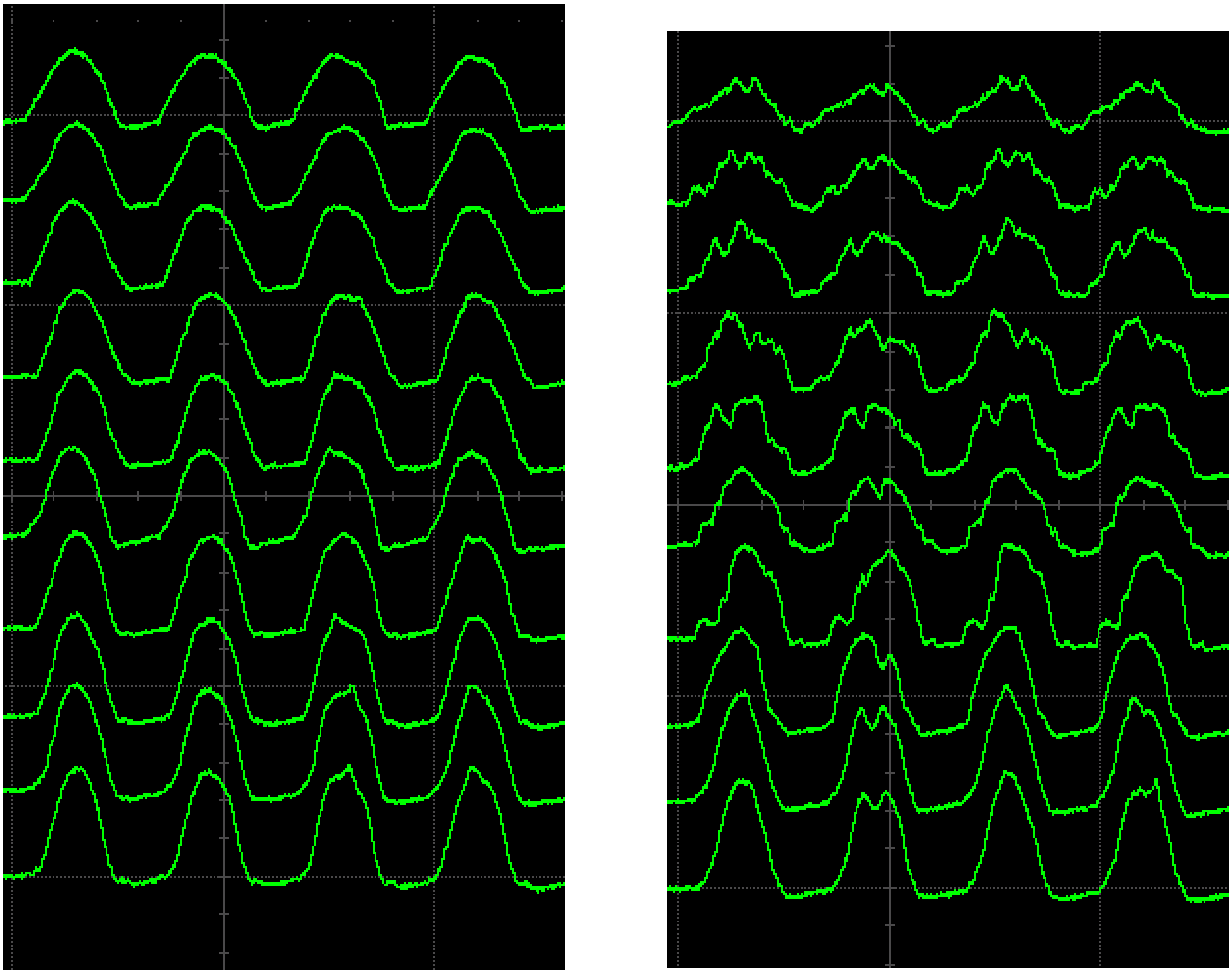

Figure 4: Comparison of bunches on merge porch using a mountain range display with AC phase loop on (left) and in hold (right). Both of these are with Rf Track on. There is no merge occurring here, station KL (h=8) which would be used for the 8:4 merge is at zero voltage. The time span is 50 ms (from At0+1615 to 1665 ms.

6:3:1 Merge

The initial setup of the 6:3:1 merge cycle began on Jan 14. This time the AGS magnet cycle was modified for only 6 transfers instead of 8 and the supercycle was shortened to 4.5 from 5.4 sec. The peak bunch intensity reached was 2.56e9 ions on Feb 3, about 12% higher than in Run 15. At that time the Booster late intensity was about 9% lower than at the time of the Run 15 intensity measurement (probably because the EBIS intensity was lower).[32] The baby bunches remained at about 12%. A few notable changes were made along the way:

[31] Booster-AGS-EBIS elog Jan 27 2016 1452 entry

[32] Given the noise and frequent drift in the EtB xf108 transformer baseline nominally used to determine the EBIS intensity and the difficulties associated with it also measuring different charge states, I find that the Booster

1) On Jan 19-21 the AGS main magnet function was modified so that the F to P transfer would occur at a higher field (1.10 vs. 1.66 kG). The later part of the ramp was also made faster to shorten the cycle to 4.0 from 4.5 sec. Although the supercycle was never shortened to 4.0 sec because of some timing issues with Rf, the magnet cycle remained the active one (see Figure 5).
2) On Jan 22 the Booster Rf was configured to use the Radial loop after the merge instead of the AC Phase loop. This was suggested by Freddy Severino and it reduced the dipole oscillations after the Booster merge.[33]
3) On Jan 25 the A5 injection kicker module timing was optimized.
4) On Jan 26 work with a higher merge porch in the Booster began. This was in preparation for a 12:6:2 merge setup which would provide 2 bunches at AGS extraction. It would require 13 Booster cycles and with the existing Booster magnet cycle that would exceed the PPMR limits. It was found that raising the merge porch from 4.5 to 5.5 kG would allow 13 consecutive Booster cycles without exceeding the PPMR limits.[34]
5) On Feb 1 the performance with the higher Booster merge porch was comparable to that with the initial merge porch so that cycle remained the active one for the remainder of the 6:3:1 setup.

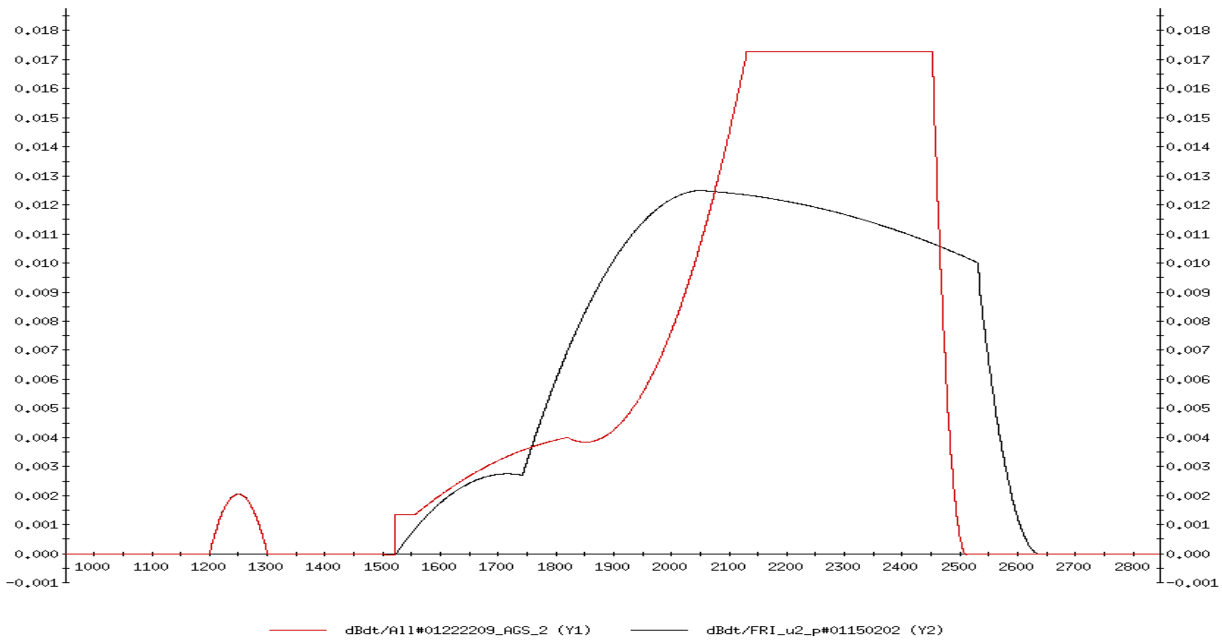

Figure 5: The AGS MMPS dB/dt before (black) and after (red) the modifications to the 6:3:1 magnet cycle during the ramp. X-axis is time from At0 in ms and the Y-axis is dB/dt in kG/ms (see item 1 above).

intensity is often a more reliable measure of the EBIS intensity than the xf108 transformer is. In this particular case the xf108 intensity was actually about 10% higher in the Run 16 case than in the Run 15 case, but I think it is suspect. The Booster late intensity is also more relevant because what mostly matters here is how much of the Booster beam is usable at AGS extraction.

[33] See Booster-AGS-EBIS Jan 22 2016 elog 1758 entry

[34] See Booster-AGS-EBIS Jun 23 2015 elog, Aug 4 entries.

Figure 6 shows the state of the setup on Feb 3. The spike in the AGS main magnet voltage (blue trace) around At0+1885 ms is the transient in the main magnet voltage at the F to P transfer. Note that, there is no longer any loss there. Before the F to P transfer was moved later, there was about a 5% loss there, not quite as much there had been in Run 15 (that was maybe 8%).[35] There is also only a small loss after the 3:1 merge around 1600 ms and another small loss at the beginning of the ramp to the merge porch at 1200 ms. In this setup any capture loss would now show up at the beginning of the ramp to the 3:1 merge porch (after the 6:3 merge), not after the final merge as it would have in Run 15. This makes it easier to distinguish a capture loss from other loss mechanisms (i.e.-space charge) as those losses would now occur at quite different times.

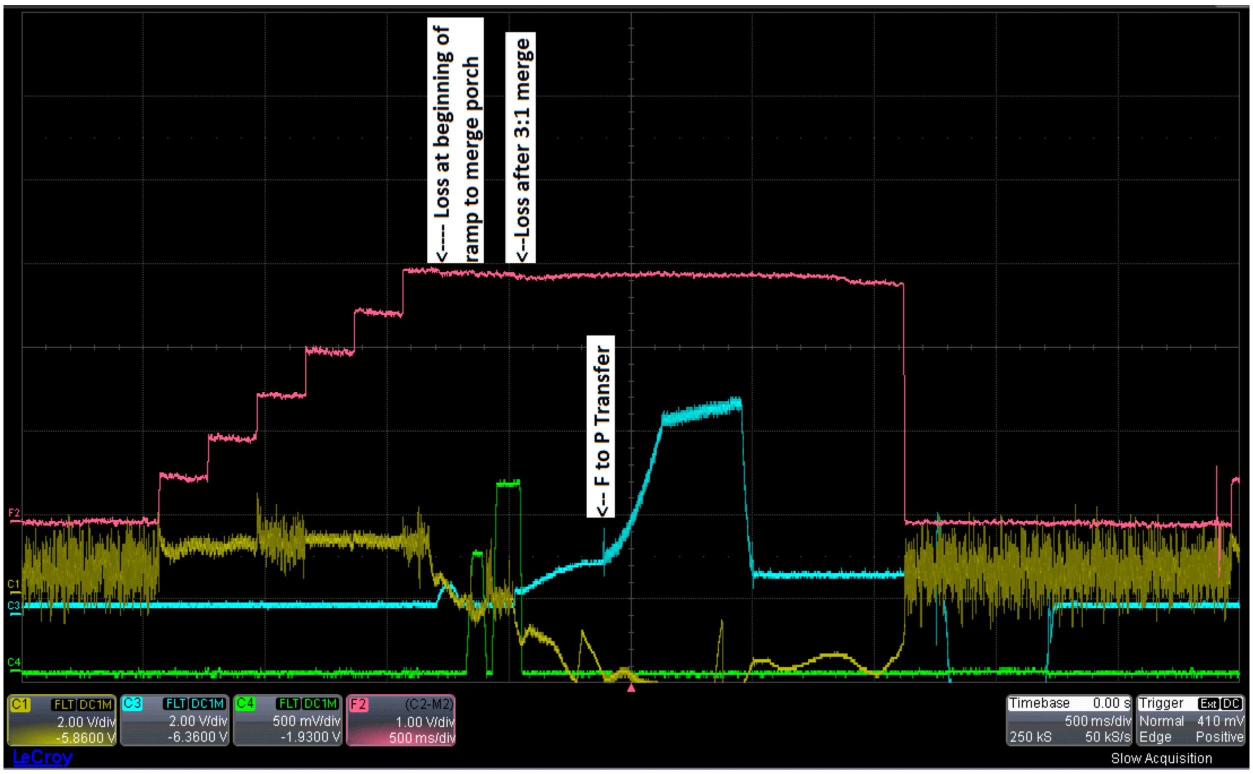

Figure 6: The AGS cycle with the 6:3:1 merge setup on Feb 3. The red trace is the AGS normalized current transformer, the yellow a horizontal BPM signal, the blue is the AGS main magnet voltage, and the green is the station KL (h=8) voltage. The scope is triggered at At0+2000 ms and has a sweep speed of 500 ms/div.

It's evident from this figure that the capture loss at 1200 ms is not large. In this case the Booster late intensity is about 5.4e9, and the AGS intensity after the last injection is about 2.75e9, giving a transfer efficiency of 51%. The transfer efficiency is typically about 3-5% lower for 6:3:1 than it is for 8:4:2.

As in Run 15, the bunches at Booster extraction are 'quad pumped' to make them narrower at transfer (see Figure 7). Without doing this a typical bunch would be roughly the

35 See Booster-AGS-EBIS 2016 elog Jan 19 1552 entry

same size as the bucket it needs to be injected into. Specifically, a typical bunch length at injection without quad pumping is about 250 ns, and an h=24 bucket at injection is 256 ns wide. But this is not the only problem. The 6 bunches need to be injected into adjacent buckets for the merges to work properly. Because of the width of the injection kicker and its rise and fall times the only viable way to proceed after the first bunch has been injected is to inject the next 5 bunches into buckets that directly follow a bucket that has already been filled. That means that the field in the kicker has to rise after the bunch in the adjacent bucket has passed through it, but before the injected bunch passes through it. Using the A5 kicker scope GPM Monitor, it appears that the kicker's 90% rise time is about 100 ns.[36] Another method, which looked at the change in bunch position due to the rising edge of the kicker, obtained a value of 90 ns or so for the rise time.[37]

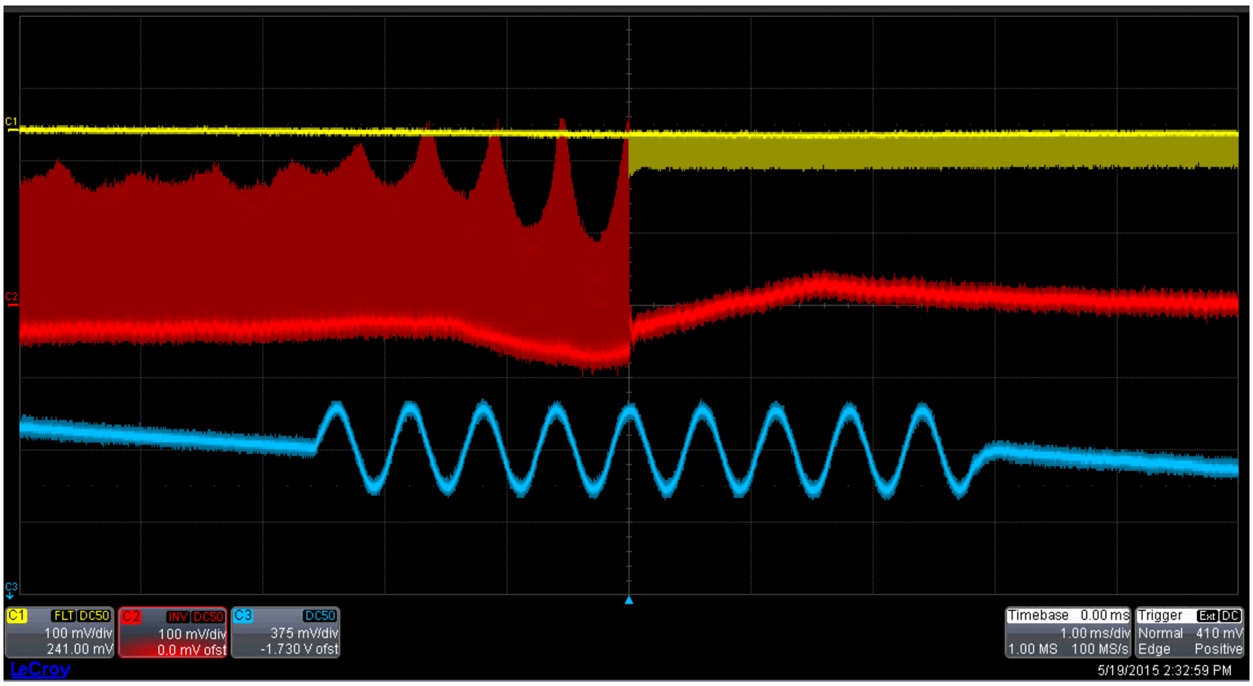

Figure 7: Rf 'Quad Pumping' at Booster Extraction. The Rf voltage in the Booster is modulated by a sine wave at approximately twice the synchrotron frequency to induce bunch shape (quadrupole) oscillations. The phase of the sine wave is adjusted so that extraction occurs when the bunch is narrow. Shown are the AGS WCM (yellow), the Booster WCM (red), and the Booster A3 Gap volts (blue). The trigger is the F3 /A5 kicker trigger, and the sweep speed is 1ms/div.[38]

By using quad pumping the bunch can be made narrow enough to fit in the bucket and also narrow enough so that there is enough time for the kicker to rise between bunches. Empirically, the injected bunch length that provides the highest bunch intensity at AGS extraction seems to be about 200 ns. Figure 8 shows the WCM at the time of the 2nd transfer. The bunch on the left is from the first transfer, and the one on the right is just being injected and has been narrowed to about 200 ns by quad pumping. According to the figure there is only about 70

[36] See Booster-AGS-EBIS Jan 25 2016 elog 1325 entry
[37] See Booster-AGS-EBIS Jun 16 2016 elog, 1842 entry
[38] See Booster-AGS-EBIS May 19 2015 elog, May 19 1431 entry

ns between the 2 bunches during which the kicker needs to rise. In the 8:4:2 case, which does not use quad pumping, the spacing is about 125 ns.[39]

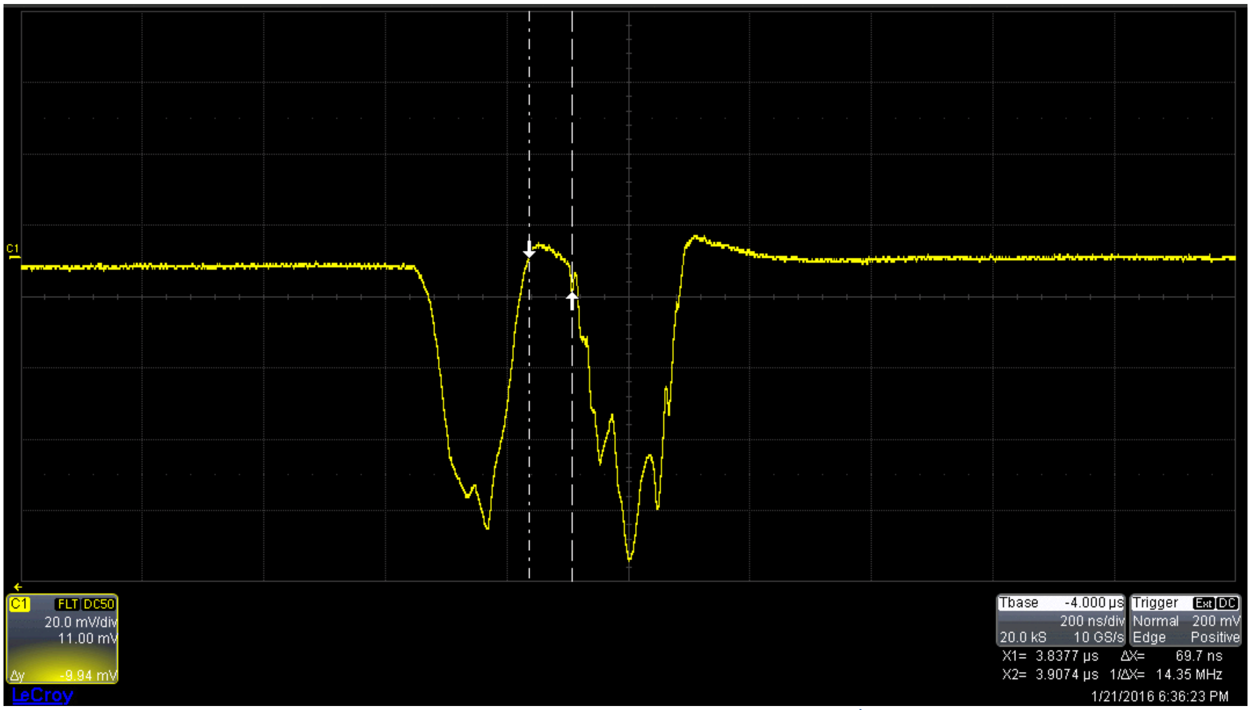

Figure 8: The AGS Wall Current Monitor at the second Booster transfer showing the 1st injected bunch (left) and the bunch just being injected (right). The sweep speed is 200 ns/div.

The drawback to using quad pumping to make narrow bunches is that at some point the beam will start to scrape during transfer because of the increased horizontal beam size associated with the increased momentum spread of the narrower beam. In the case of Au beam this is probably already occurring to some extent even without quad pumping. The 6:3:1 transfer efficiency is generally worse than it is for 8:4:2 because the bunches need to be made narrower to fit into the h=24 buckets and have enough time for the kicker to rise, but making them narrower makes the transfer less efficient because of this scraping.

The injected bunch length that corresponds to the highest bunch intensity at extraction comes about as a compromise between these competing factors. It's also the case that scraping using quad pumping preferentially scrapes higher Δp/p particles, and can thereby reduce the longitudinal emittance in AGS. This is important to consider when measuring longitudinal emittance in AGS and the size of baby bunches. Despite the fact that the kicker doesn't seem to have quite enough time to rise (70 vs. 100 ns), the transverse emittance on the AGS flattop measured with the IPM is comparable in the 6:3:1 and 8:4:2 cases.[40]

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[39] See Booster-AGS–EBIS Jan 22 2016 elog 1338 entry.

[40] In the 6:3:1 case (actually the 12:6:2 case) using the AGS IPM the 95% normalized 'refit' emittances were (ε_x, ε_y)=(9, 9.5) π, and in the 8:4:2 case they were (9,10) π. See Booster-AGS-EBIS Feb 16 elog 1530 and 1535 entries. A study using the A3 PUE also suggested that neither the incoming bunch nor the one already in the

The fact that there is only a small loss at the beginning of the ramp to the merge porch (1200 ms) means that nearly all of the beam successfully injected has been captured into the h=24 buckets. On Feb 1 the 6:3:1 extraction bunch width was measured at 30.1 ns corresponding to an ε of 0.86 eV*s/n.[41]

The 12:6:2 Merge

The 6:3:1 setup provided considerably more bunch intensity than the 8:4:2 but the filling time was about 50% longer even if the supercycle length could be brought down to 4.0 sec (which it probably could have been). A supercycle with 12 Booster transfers and a 12:6:2 merge was deemed to be a better option. There were 2 main hurdles that had to be overcome. First, could EBIS provide 12 pulses per supercycle without a significant reduction in pulse intensity? And secondly, could the Booster main magnet pulse 13 times with the higher merge energy without exceeding the PPMR limit or having other problems? [42]

On Jan 22 thirteen Booster magnet cycles were tested with the higher merge porch energy and a supercycle length of 7.0 sec. Although some of the harmonics were very close to the PPMR limits the supply stayed on, and the power supply group gave the OK to run it that way.[43] On Feb 4 the cycle was tested with 12 EBIS pulses and a 7.0 sec supercycle. There was little or no degradation in the EBIS performance. On Feb 11, EBIS personnel gave permission to shorten the supercycle length to 6.4 sec.[44] On Feb 22, the setup used for RHIC was changed from 8:4:2 to 12:6:2. At that time, an extraction ε measurement gave 0.69 eV*s/n, the bunch intensity was about 2.7e9 ions, and the EBIS xf108 intensity at the time was about 13.5e9 ions for 12 pulses.[45]

The supercycle was eventually shortened to 6.0 sec in early June to accommodate Linac protons for NSRL.[46] The AGS magnet cycle is shorter than that, and could probably allow for a 5.4 or 5.6 sec supercycle. For the most part the AGS main magnet cycle used for 12:6:2 is the same as the final 6:3:1 magnet cycle with the injection porch extended 1200 ms to allow for 6 more transfers (the Booster cycle length is 200 ms). The F to P transfer occurs at the same field. The only other difference is that the dB/dt at the very beginning of the ramp was raised in the 12:6:2 magnet cycle.[47]

The first measurement of the proportion of baby bunches with the 12:6:2 scheme was made on Feb 11 and it was 4.1%. This is substantially lower than the measurements made with

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machine were adversely affected by the kicker's rise time. See Booster-AGS-EBIS elog Jun 16 2016 1806-1844 entries.

[41] See Booster-AGS-EBIS elog 2016 Feb 1 1927-1928 entries and Jan 22 1619 entry.

[42] There is an additional Booster cycle required to account for hysteresis effects (the dummy cycle).

[43] See Booster AGS EBIS Jan 22 2016 elog 1435 entry

[44] See Booster-AGS-EBIS Feb 11 2016 elog 1425 entry

[45] See Booster-AGS-EBIS Feb 22 2016 elog, 1838, 1846, and 1849 entries.

[46] N. Kling, Booster-AGS-EBIS Jun 2 2016 elog 1202 entry

[47] This change was made on Feb 11.

the 6:3:1 setup which were typically about 12%.[48] Whether this is a consequence of the 12:6:2 setup, or some other unrelated change occurred to account for it is unclear. Particles with a higher Δp/p may be lost preferentially while sitting on the injection porch since they will tend to have larger excursions. That could be responsible for part of the difference since for 12:6:2 the injection porch is 1200 ms longer.[49] In May the rate of the slow loss across the injection porch was measured to be 6.0%/sec.[50] The average particle sits on the injection porch for 1.17 sec for 12:6:2 and 0.57 sec for 6:4:2. Regardless, their proportion throughout the rest of the run (which used the 12:6:2 scheme) was consistently much closer to 4% than 12%.

Figure 9 shows how the 12:6:2 setup looked in the AGS on Feb 18.[51] In this case there is negligible loss at the beginning of the first ramp. There is often some loss there though which can normally being reduced by improving the longitudinal matching at injection, or optimizing the Booster merge. So that loss is likely capture related. There is some loss at the start of the ramp, which is sensitive to the Rf voltage (which is typically as high as it can go here). That loss typically goes away if the squeeze is turned off. So, it seems likely related, at least in part, to fitting the squeezed bunch into a large enough bucket. The slow loss across the injection porch is also apparent especially during the latter part of the porch where there is more beam so it is easier to see.

Figure 10 shows the timing and the various Rf harmonic voltages and cavities involved in the 12 to 6 (and also 6 to 3) merge, ramping to the merge porch, the 6 to 2 (also 3 to 1) merge, the squeeze, and final acceleration. Figure 11 shows the 12:6:2 merge as viewed on a mountain range display.

AGS Bunch Intensity with 6:3:1 and 12:6:2 Merges

Figure 12 shows the AGS bunch and Booster late intensity for the 6:3:1 merge setup from Run 15 and 16, and the 12:6:2 setup from Run 16. Note that the switch from 6:3:1 to 12:6:2 during the early part of February did not obviously reduce Booster Late (per cycle not total). There is also no obvious increase in the AGS bunch intensity after the switch to 12:6:2 even though the proportion of baby bunches with 12:6:2 is smaller (4 vs 12%). If there were solely a decrease in the proportion of baby bunches, there would've been an increase in AGS bunch intensity of about 0.2e9 ions. But there is more loss on the injection porch in the 12:6:2 case,

[48] See Booster-AGS-EBIS Feb 11 2016 elog 1849 and 2136 entries

[49] During Run 12 Copper operation it was noticed that raising the horizontal tune along the injection porch resulted in much smaller baby bunches (going from about 24% to 7%) and an increase in the main bunch intensity. The reduction in baby bunch size may be in part because the horizontal orbit became worse, which caused a disproportionate loss of far off momentum particles. There are clearly other things going on here to account for more intense main bunches though, such as space charge perhaps. See Booster-AGS-EBIS 2012 elog 1658 through 1939 entries.

[50] See Booster-AGS-EBIS May 26 2016 elog 1710 entry.

[51] See Booster-AGS-EBIS Feb 18 2016 elog 1417 entry

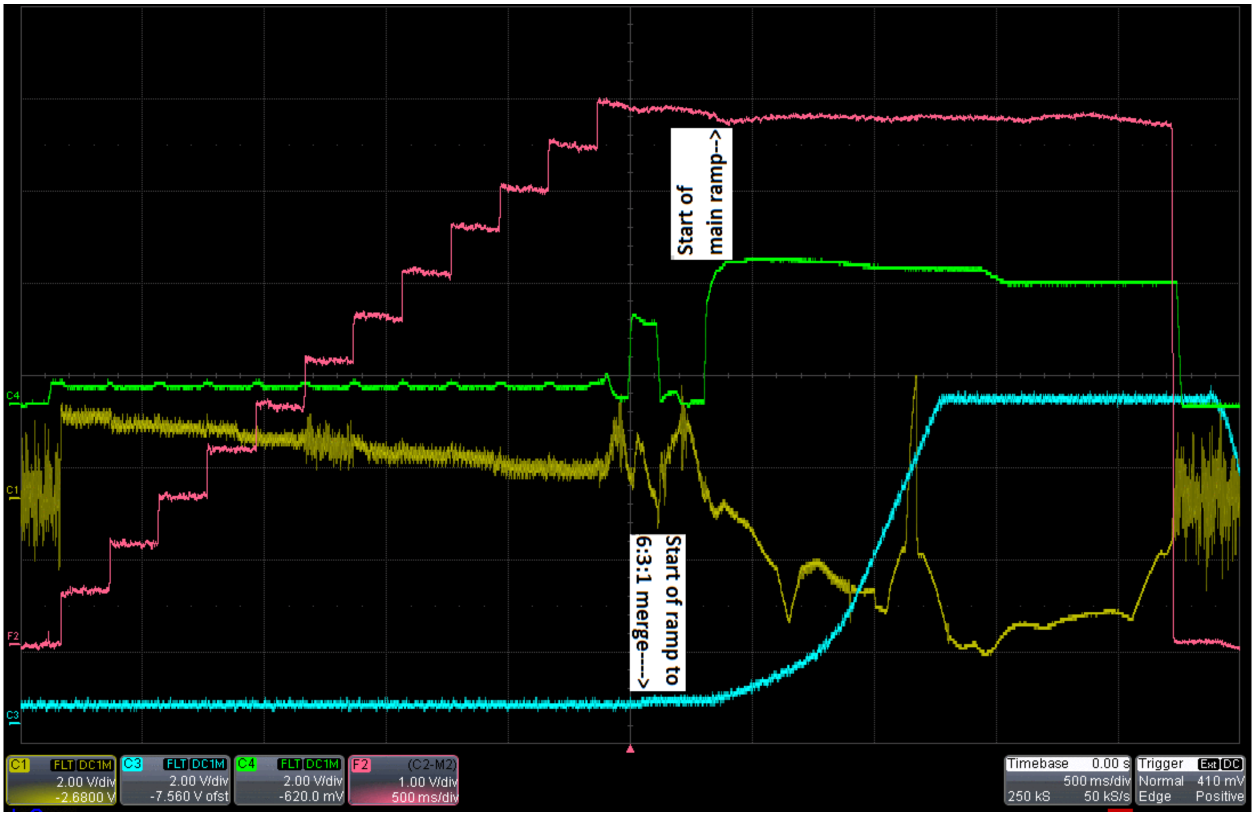

Figure 9: The 12:6:2 AGS cycle. The red trace is the normalized current transformer, the green trace is the Rf vector sum, the blue trace is the AGS main magnet current, and the yellow trace is a horizontal BPM. The AGS intensity on flattop is about 5.4e9 Au ions. The trigger is At0+2400 ms and the sweep speed is 500 ms/div.

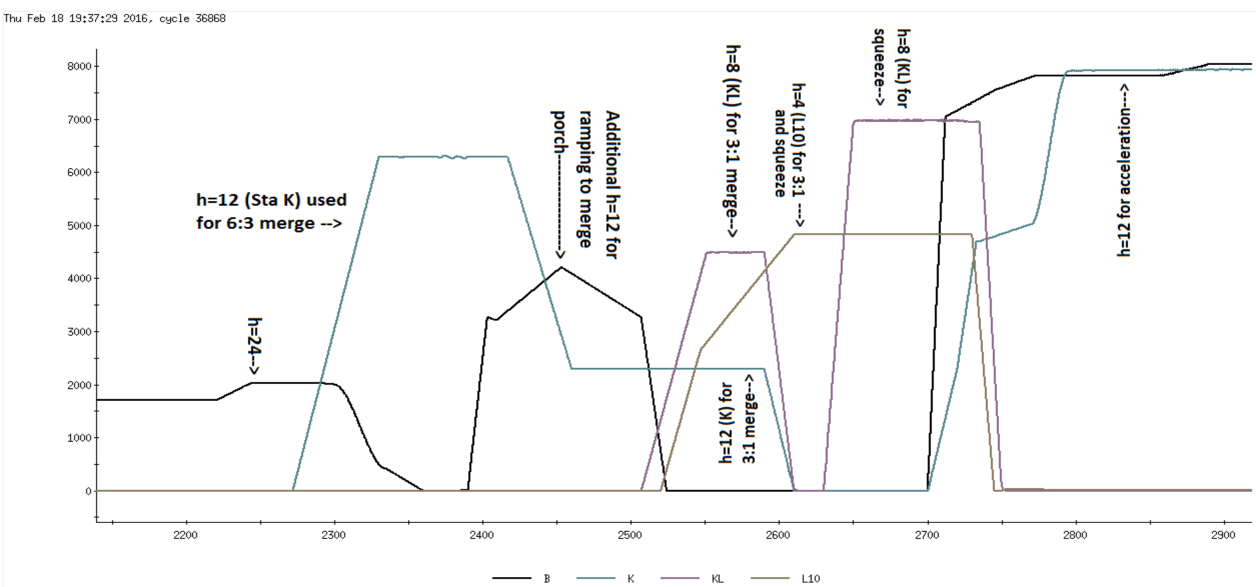

Figure 10; Rf harmonic voltages and timing for the 12:6:2, or equivalently 6:3:1 merge setups. The x axis is time in ms from AGS T0.[52]

[52] See Booster-AGS-EBIS Feb 18 2016 1937 entry

which helps to offset the effect of the decrease in the size of the baby bunches. The intensity of an AGS bunch is approximately constant until April when it increases from about 2.7 to 3.0e9.

The lack of data between Mar 5 and Apr 6 is due in part to Deuteron setup in Booster and AGS (Mar 7-Mar 17) and subsequent downtime associated with the RHIC diode problem (Mar 18-Apr 5). Around Apr 28 setup with Tandem Au began in preparation for the EBIS cathode replacement which occurred between May 4 and May 7. D-Au running began on May 9 and extended until Jun 17. Au-Au running went from then until Jun 27. There is a lot of data from RHIC fills that could be used to measure the bunch intensity in AGS but, aside from the fact that it would be a tedious process to filter out that data, most of the RHIC fills occurred with reduced intensity so that would not give an accurate representation of the full bunch intensities.

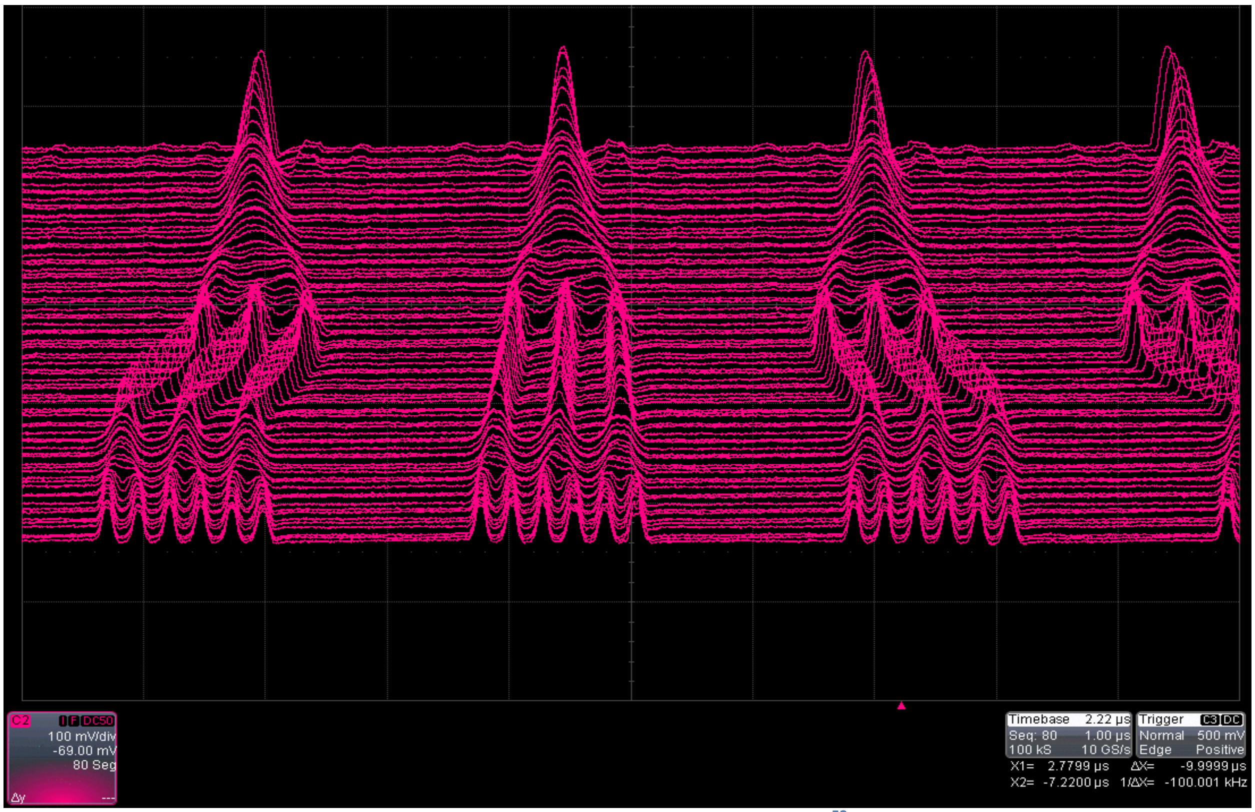

Figure 11: The 12:6:2 merge as viewed on the WCM with a mountain range display.[53]

On the evening of Mar 14 a problem developed with the Booster Main Magnet P.S. The problem, which involved the station II resistor bank, was fixed the next day. After the fix I. Marneris requested that I take the points on the merge porch out of the Booster main magnet function that were used to flatten it. This was requested in order to protect the power supply.[54] The points were taken out, and this is how the power supply ran for the remainder of the run.

[53] See Booster-AGS-EBIS Feb 4 2016 elog 1901 entry

[54] See Booster-AGS-EBIS Mar 15 2016 elog 1432 entry

Figure 13 shows the proportion of baby bunches through the run. This data was arrived at in two ways. When both bunches are extracted, this proportion can be found by measuring the amount of beam on the current transformer left after the last extraction and dividing it by the amount of beam before the first extraction.[55] When it is not being extracted, the area (which is proportional to intensity) of each bunch is measured on the WCM at flattop. The total area in the baby bunches divided by the total area of all the bunches is a measure of the proportion in the baby bunches.[56] These 2 methods generally agree well and the data shown in Figure 13 is a combination of both.

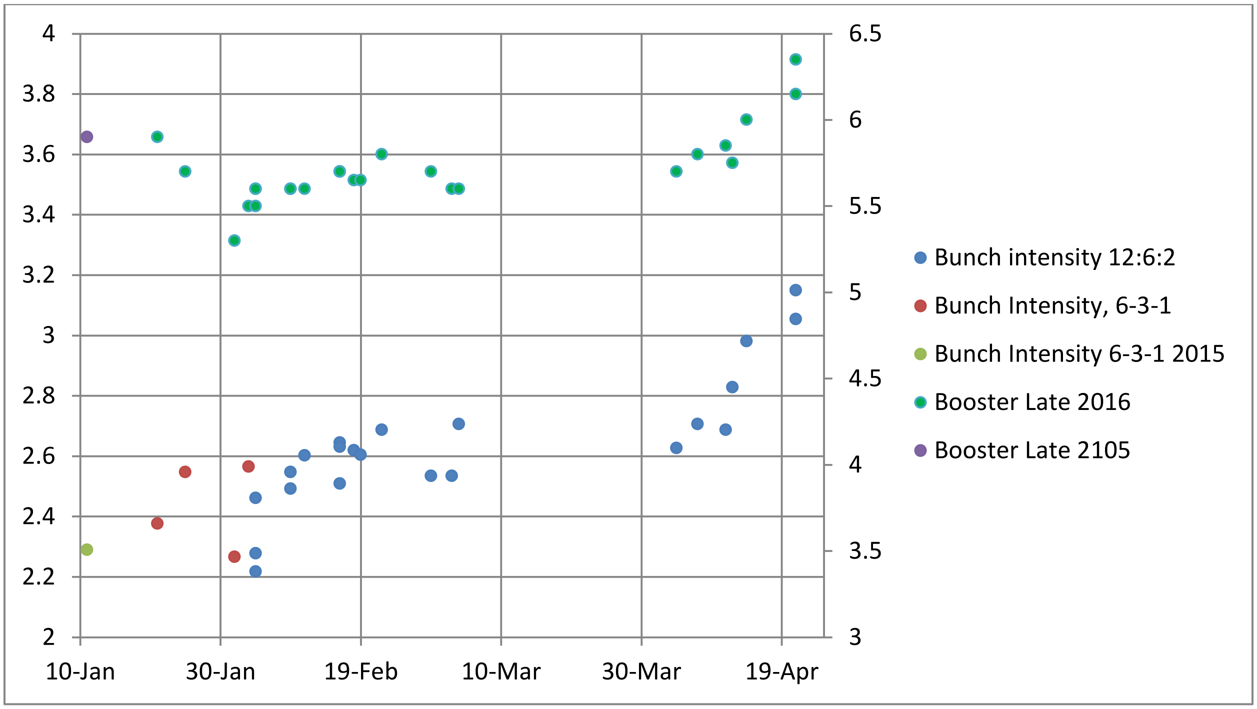

Figure 12: The bottom set of data (green, red, blue) is the AGS bunch intensity and is associated with the left y-axis (1=1e9 ions). The data is mainly obtained from the AGS WCM using the calibration 2.0e9=32.74 nVs. The top set of data (purple and green) is the Booster late intensity associated with the right y-axis (1=1e9 Au ions). In the cases where a 12:6:2 merge is being used the Booster late has been divided by 2. The data points from run 15 6:3:1 operation were put at Jan 11, they are actually from May 26 2015.

Note that before Feb 11 or so the proportion is 12% or more, and after that it drops to about 4%. This drop was coincident with the switch from 6:3:1 to 12:6:2. The point at 18% corresponds to the initial work on the higher Booster merge porch. There is some drift upwards after the switch to 12:6:2, and then a drop on Apr 12. After that it remains in the 4% range (sometimes even lower).

After the fix to the Booster main magnet on Mar 15 there were only a couple days of running before RHIC went down for the diode problem (Mar 18). After that downtime, it was

[55] See for example, Booster-AGS-EBIS Mar 1 2016 elog 1342 entry. There is also a GPM which does this calculation automatically that is also used (see Booster-AGS-EBIS Feb 11 2016 elog 1800 entry).
[56] See for example Booster-AGS-EBIS Jan 25 2016 elog 2010 entry.

noticed that the Booster extraction and injection field were both varying by significant amounts.[57] The problem was traced to the IIAB power supply module and on Apr 12 it was fixed by adjusting voltage limiting parameters in the BMMPS program.[58] Afterwards the baby bunches were smaller, averaging 3-3.5%, and the bunch intensity was higher than it had been previously (2.83e9 vs 2.7e9 or so, see Figure 12).[59] Figure 14, which shows the ratio of the AGS bunch intensity on flattop over the Booster Late intensity through the run, also shows a step at that time. It seems likely that this improvement was due to this change in the Booster MMPS, and judging by the fraction of Booster intensity per AGS bunch, it looks like it may have made its performance better than it had been all run.

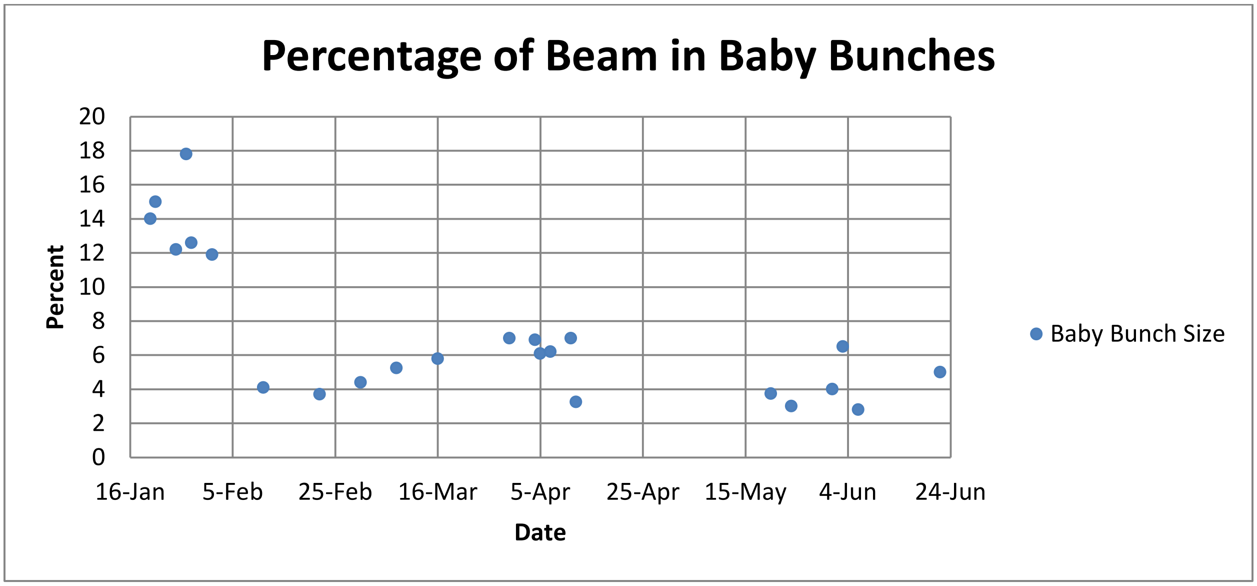

Figure 13: The percentage of the beam in the baby bunches at Booster extraction. See discussion in text.

It's also worth noting that the merge porch in the Booster had been far from flat since the changes made to it on Mar 15. Before the change the field variation across the merge porch was about 3 g, and afterwards it was about 22 g (out of about 5500 g).[60] It seems that this increased variation did not adversely affect the merge. Although there may be some subtle stability issues that make the initial setup preferable.

Figure 15 shows the Booster input (xf108) and Booster late during the period of highest EBIS intensity. At this time the EBIS pulse intensity got about as high as the highest it had been for 8:4:2 running, about 1.3e9 ions. Note that although the EBIS intensity goes up during the first part of the plot, the Booster intensity does not. I don't recall why this is though on April 21 when the Booster late intensity went up several things were changed: a bump for the H- injection foil

[57] See for example Booster-AGS-EBIS Apr 6 2016 elog 1948 entry.
[58] At I. Marneris's suggestion, see Booster-AGS-EBIS Apr 12 2016 1405 entry.
[59] See Booster-AGS-EBIS Apr 12 2016 elog 1612, 1613, 2015, and 2018 entries
[60] See Booster-AGS-EBIS elog, Jan 27 2016 1605, and Mar 16 1715 entries, respectively.

was removed, the horizontal orbit near injection, and the tunes early in the Booster cycle. In any event, that period accounts for the highest bunch intensities in Figure 12. The Booster efficiency (Booster Late/xf108) was about 83%. The period of highest Booster late intensity lasted for about a week. After that the EBIS intensity started to go down, and the cathode had to be replaced. One can't help but wonder if this was merely coincidental.

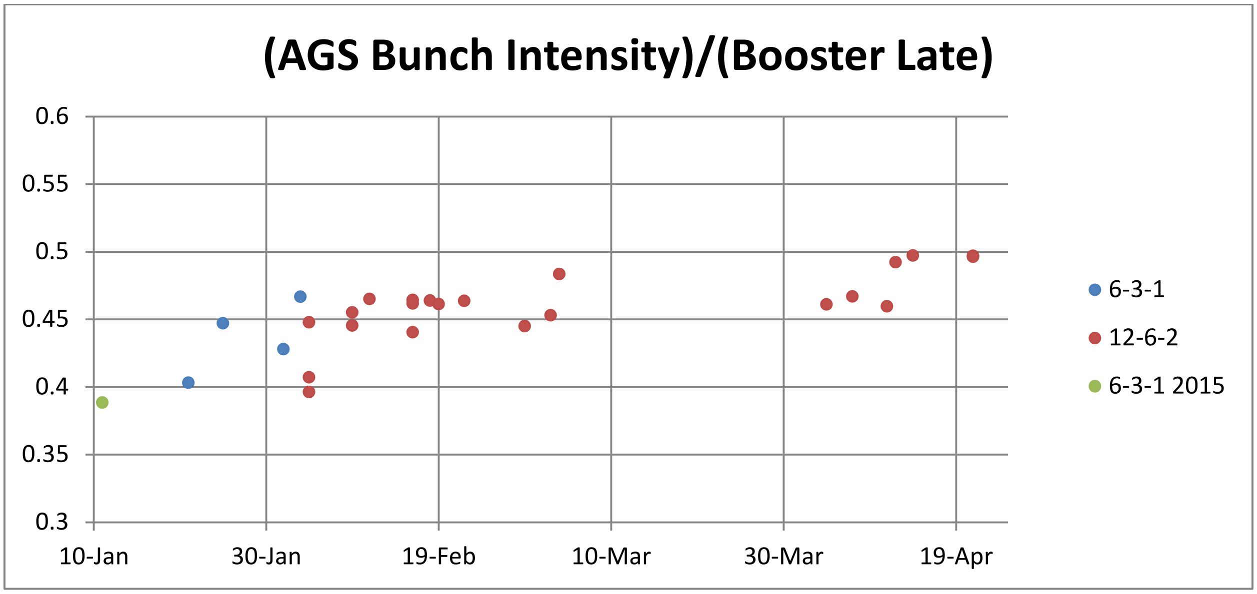

Figure 14: AGS bunch intensity on flattop divided by Booster intensity near extraction (Booster Late). In the cases where the 12:6:2 merge is being used what's called Booster Late here is actually Booster Late divided by 2.

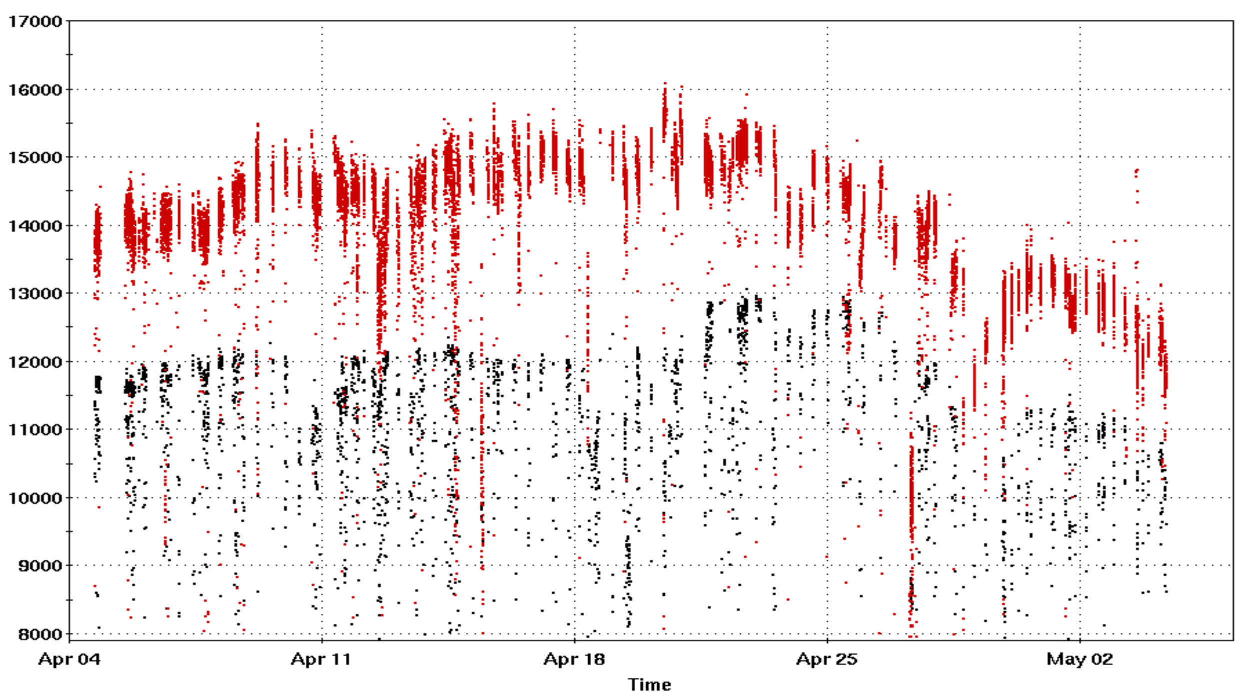

Figure 15: Booster input (xf108-red) and Booster late (black) during the part of Run 16 with the highest EBIS intensity. On the y-axis 10000=10e10 Au Ions.

Using h=10 Instead of h=12

On Jan 28, while still using the 6:3:1 setup, the proportion of baby bunches was 12.6%. Then the accelerating harmonic was switched to 10 and the proportion of baby bunches was 9.1%, a reduction of 3.5%.[61]

On March 4th, when using the 12:6:2 setup the proportion of baby bunches was 4.5% for h=12 and 2.1% for h=10.[62] It was also noticed that the early acceleration loss with h=10 was reduced. This is presumably because there is more bucket area there. Since the loss was already small, the effect could not be large, and only contributed to an intensity increase of about 1%. In total then a bunch intensity increase of about 3-3.5% over the h=12 case was realized. This corresponds to about 1e8 ions more per bunch at typical running intensities. The h=10 bunch width was 29.7 ns on flattop, about 1 ns wider than when the bunch is in h=12 buckets. The flattop ε was 0.77 eV*s/n, which is not noticeably different than in the h=12 case.

The h=10 setup was not used to fill RHIC because there was already sufficient intensity. Although it only improved bunch intensity slightly the ability to use it in the future might prove useful.

Longitudinal Emittance Measurements during Run 16

Quite a few longitudinal emittance (ε) measurements were made during the run in both the Booster and AGS. I might as well go through them sequentially starting at Booster injection.

EBIS Δp/p Measurement

A typical Δp/p measurement involves watching a bunch spread out on a mountain range display with a flat field and the Rf off. The time it takes for the trailing edge of the bunch to cross the leading edge is indicative of the momentum spread of the bunch. A measurement like this was done in Run 14 at Booster injection using a narrow pulse from EBIS.[63] Although this pulse is narrow for EBIS it still occupies about 3 quarters of the Booster ring and its edges, particularly the trailing one, are not sharp. These factors contribute to the uncertainty in the measurement. At that time a Δp/p (half width) of 2.2e-4 was measured. This can be associated with an emittance in the Booster of 0.018 eV*s/n. The error in this measurement was estimated to be ± 0.08 eV*s/n due to the above mentioned factors.

A different approach was used in Run 16. On April 19 the F3 extraction kicker was timed so that it fired on the Booster injection porch about 5 ms after injection. The F3 kicker pulse is

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[61] See Booster-AGS-EBIS Jan 28 2016 elog, 1908 through 1932 entries.
[62] See Booster-AGS-EBIS Mar 4 2016 elog
[63] K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pgs. 19-20, CAD Note 523, August 2014.

about 3 μs long and the revolution frequency is about 10 μs. It is strong enough to completely kick the beam out, and the edges of the resulting hole are quite sharp. Figure 16 shows what the hole looks like just after the kicker has fired. The width of the hole at that time is 2.83 μs, consistent with the width of the kicker pulse.

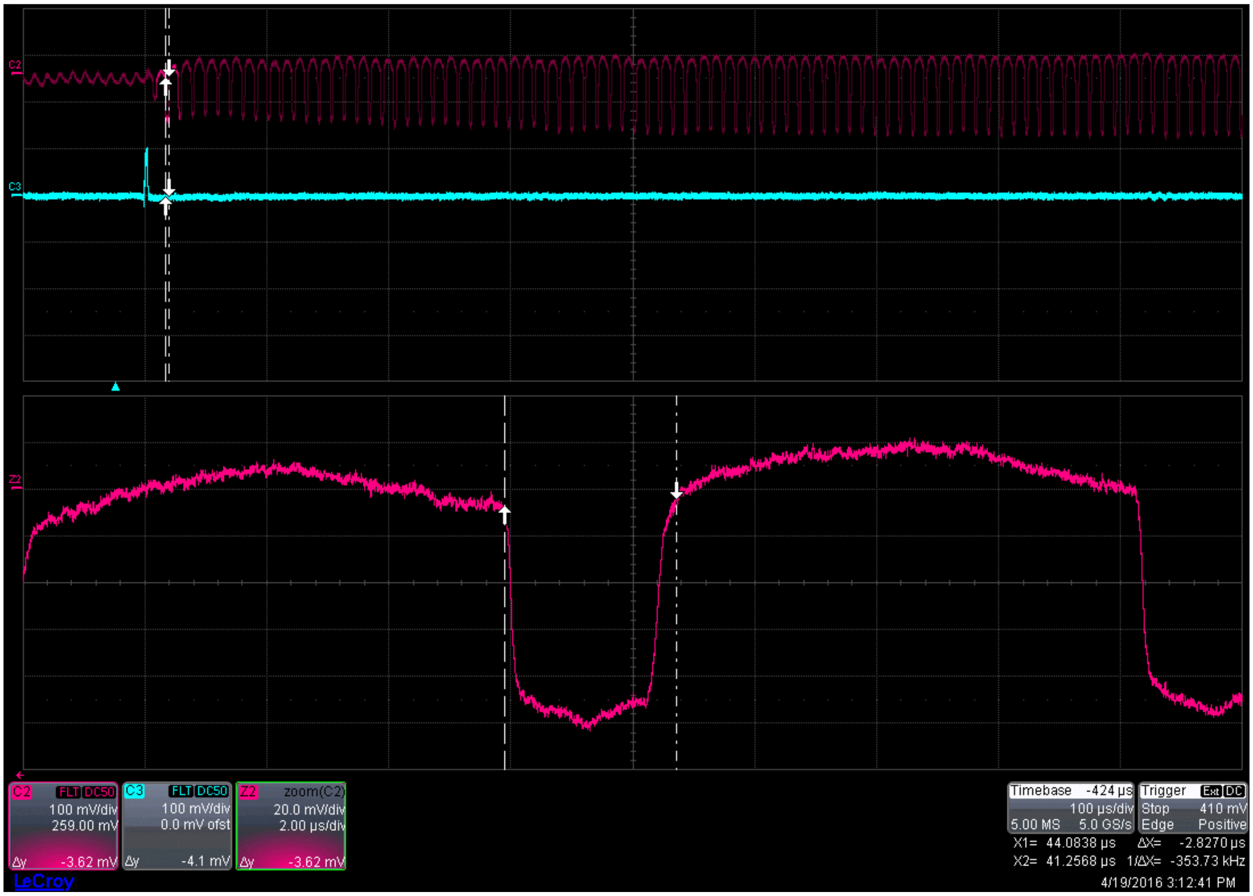

Figure 16: The F3 kicker kicking a hole in the beam on the injection porch. The blue trace is the F3 kicker current, the red is the D1 PUE Sum signal. The upper traces have a sweep speed of 100 μs/div and the bottom trace is zoomed in on where the cursors are for the upper traces. The sweep speed there is 2 μs/div. The trigger is Bt0+15 ms.

Unfortunately, due to details associated with getting the F3 kicker to fire at this time in the cycle the mountain range display does not work and I was also unable to get it to fire earlier on the injection porch so more time could be left for the hole fill in. But I can still try to find when the leading and the trailing edge of the bunch meet by looking later on the injection porch. Figure 17 shows what the bunch looks like 3.0 ms later (just before beam loss associated with the field ramping starts to occur). Judging from the zoomed trace, the leading and trailing edges have either already crossed or are just about to cross.

The time it takes for the leading and trailing edges to meet is called the debunching time, denoted by t_d. Using the formula below, Δp/p can be found from that,[64]

[64] AGS Studies Report #356, "Linac Beam Momentum Spread", S.Y. Zhang, June 8-9, 1996

$$t_{db} = \frac{\pi - \Delta\phi}{2\pi f_0 h|\eta| \; \Delta p/p}$$

where $\Delta\phi$ is the initial half bunch width (in radians), f_0 is the revolution frequency, h is the number of bunches, η is the slip factor, and Δp/p is the half-width momentum spread.

The width of the hole was initially 2.83 μs, and the revolution period is 10.38 μs, so the width of the bunch is 10.38-2.83=7.55 μs. The azimuthal angle this bunch spans is 2π*7.55/10.38=4.57 rad, and half of that, $\Delta\phi$, is 2.29 rad. f_0=96.34 kHz, h=1, and η=-0.954. Setting t_d to 3.0 ms, plugging these numbers in, and solving for Δp/p (half) gives 4.9e-4. This is roughly twice the Δp/p that was measured in 2014.

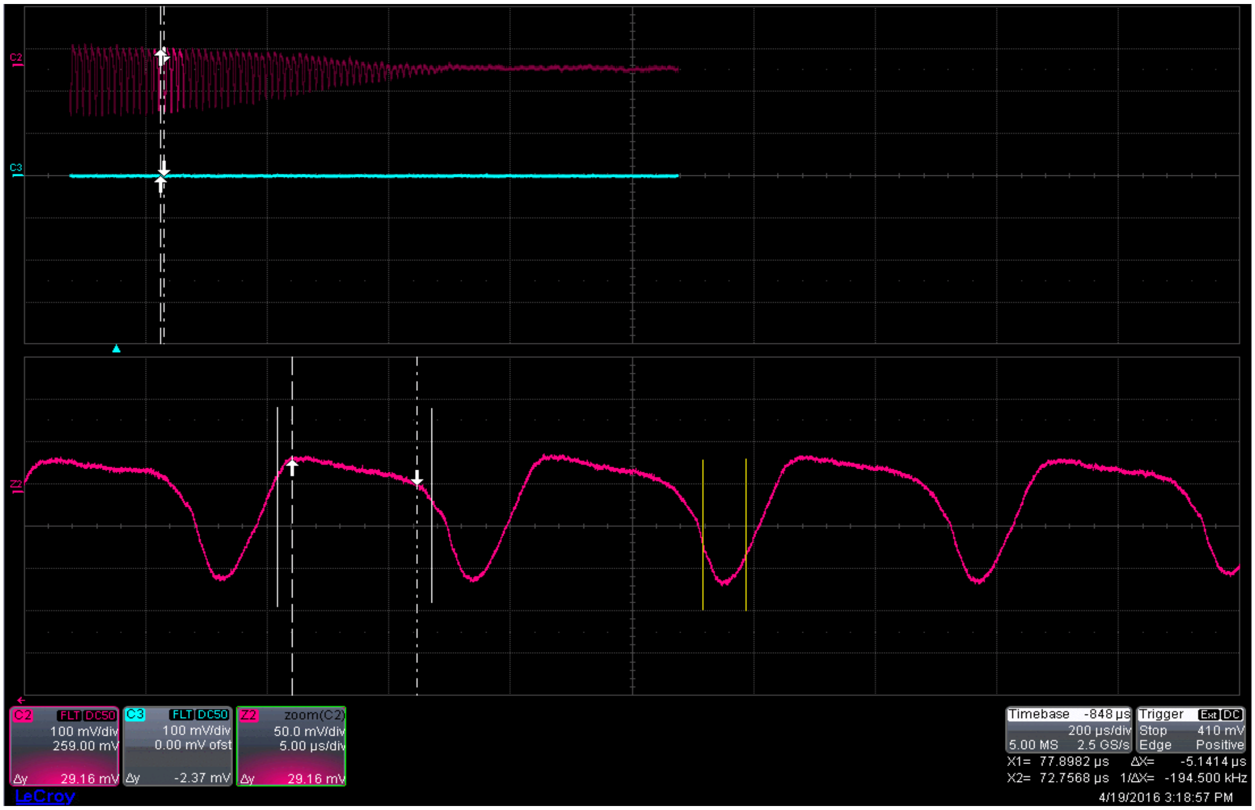

Figure 17: On the bottom is the D1 PUE sum signal 3 ms after a hole was kicked in the beam by the F3 kicker. The upper traces have a sweep speed of 100 μs/div and the bottom trace is zoomed in on where the cursors are for the upper traces. The cursors (dotted vertical lines) show the width of the space between the hole, 5.14 μs. The solid white vertical lines are where the edges of the hole would need to be to give the emittance measured in Run 14. The yellow vertical lines are where the edges of the bunch would need to be for the ε measured in 2014. The sweep speed there is 2 μs/div. The trigger is Bt0+18 ms.

I think it's also valid to think of the hole as a bunch that's spreading out, and a debunching time can be assigned to it. 3 ms after the kick the space between the edges of the hole is 5.14 μs (see Figure 17). It was initially 7.55 μs wide so it has shrunk 2.43 μs in 3 ms, so it will take 3 ms*(7.55/2.43)=9.32 ms for the 'edges' of the hole to cross. Using 9.32 ms for t_d and 2.83π/10.38=0.86 rad as the hole's initial half width in radians gives Δp/p (half)=4.2e-4.

A Δp/p (half) of 4.2e-4 corresponds to a ΔE (half) of 0.33 MeV at injection energy. From that ΔE the ε of the injected beam is approximated as 2ΔEτ/A, where τ is the revolution period (10.38 μs) and A is the number of nucleons in an Au atom (197).[65] This results in ε=0.034 eV*s/n. In the first case, where Δp/p (half)=4.9e-4 and ΔE=0.38 MeV, the result is ε=0.040 eV*s/n. These values for ε are roughly twice the value found in 2014 (0.018 eV*s/n) and they fall outside the uncertainty range given there too (± 0.08 eV*s/n).

Using the latter method, t_d would have to be 22 instead of 9.3 ms to get the Δp/p value corresponding to ε=0.0018 eV*s/n. That would correspond to a space between the edges of the hole of 7.55μs-3ms*(7.55μs/22ms)=6.52μs at 3 ms after the kick. The solid white vertical lines in Figure 17 show where the edges of the hole would be to give that ε value. It seems pretty clear that the hole has spread out more than that. Similarly, in the first case, for the Run 14 ε value, the hole would still be 1.8 μs wide after 3 ms.[66] The positions of the leading and trailing edges would then correspond to where the yellow vertical lines are in Figure 17.

So, it seems that the result is significantly different this year. The measured emittances later in the Booster and in the AGS were not any large this year than in Run 14 (which will be detailed below). So, the simplest explanation appears to be that the EBIS narrow pulse has a smaller Δp/p than the normal wider pulse and the incoming ε appears to be in the 0.34-0.04 eV*s/n range.[67] In Run 14 emittance measurements at the end of an extended capture porch were made with much lower capture voltage than normal and a value of ε=0.035 eV*s/n was obtained for the case of lowest voltage at the end of that porch.[68]

Booster Emittance Measurements

Figure 18 shows the Booster magnet cycle used for 12:6:2 running (i.e.-with the higher merge porch). Injection occurs at Bt0+10.5 ms, the merge porch extends from 91 to 109 ms, and extraction is at Bt0+131 ms. A series of measurements was taken on Apr18-20 from the injection porch to Bt0+85 ms (just before the merge porch) and at extraction.[69] Table I shows the results.

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[65] For a more complete description of how I arrive at these values see: K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pgs. 19-21, CAD Note 523, August 2014.

[66] A Δp/p (half) of 2.2e-4 corresponds to a t_d of 8.2 ms. So, it would take 8.2 ms for the distance between the edges to change from 2.83 μs to 0 μs, 2.83μs/8.2ms=0.345μs/ms. After 3 ms the edges would be 2.83μs-3*0.345 μs=1.8 μs apart.

[67] M. Brennan suggested this possibility a while ago, and C. Gardner reminded me of it this run.

[68] K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pg. 24, Table IV, CAD Note 523, August 2014.

[69] Data is in the Booster-AGS-EBIS elogs from those dates. Initially, I didn't account for the bunch shape asymmetry during acceleration. Once accounted for, I found that the ramp measurements gave inconsistent results.

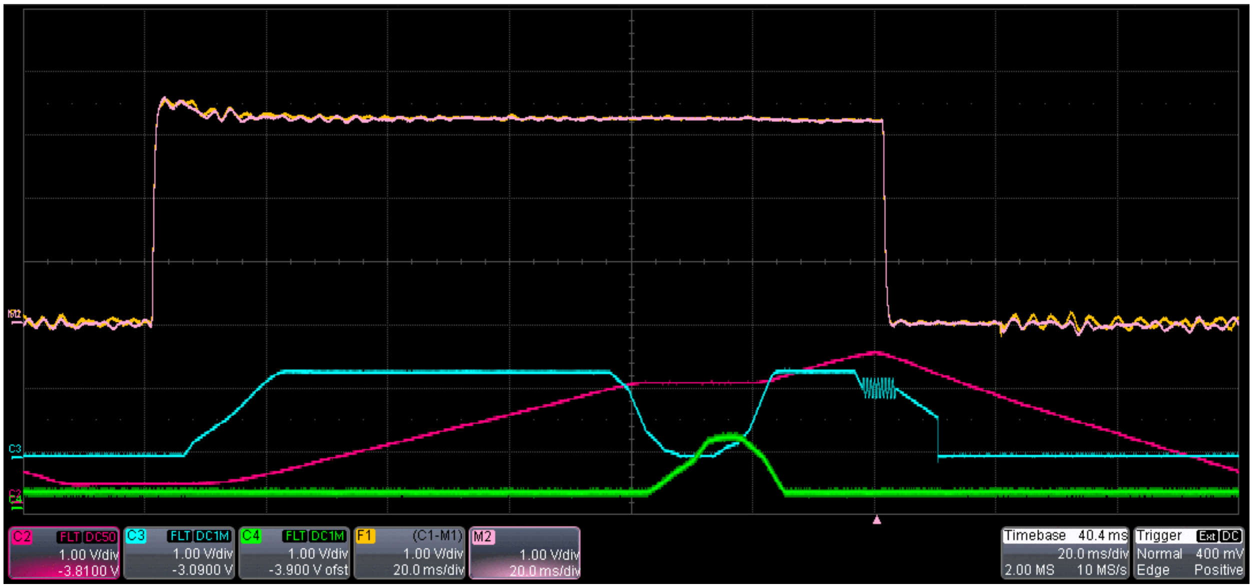

Figure 18: The Booster cycle. The two top traces that overlay are 2 traces of the Booster Normalized transformer. The red trace is the main magnet current. The blue trace is the A3 Rf cavity voltage which is used for h=4 before the merge and h=1 after it. The green trace is the E6 Rf cavity voltage used for h=2. The trigger is Bt0+130 ms and the sweep speed is 20 ms/div.

Time from Bt0 (ms)	Synch freq. (Hz)	1st half length (ns)	Rf V from Synch Freq (kV)	DB/Dt (T/s)	Bunch ε (eV*s/n)	Total ε (eV*s/n)
18.2	1082	1006	5.02	0	0.0207	0.083
24	1620	624	11.2	0.37	0.016	0.064
35	2042	170	27.65	7.5	0.0234	0.0936
45	1981	136	25.95	6.9	-	-
65	1825	84	25.3	7.1	-	-
85	1758	72	25.48	7.1	-	-
131 (ext.)	877	239.6	18.38	0	-	0.066

Table I: Booster emittance measurements (calculated with Bbat) from Apr 18-20 using the WCM. The bunch length is the width of the first half of the bunch. The Rf voltage is determined from the synchrotron frequency. The bunch ε is for a single bunch, the total ε is that multiplied by 4. The dB/dt was measured using the gauss clock. The measurement at 18.2 ms uses an average of 2 measurements around that time to compensate for quad. oscillations at that time in the cycle. The full length of the first turn on the AGS WCM is used for the extraction measurement (without quad pumping).

The first measurement is actually the average of ones taken at 17.9 and 18.5 ms, and is about twice what was obtained from the injection debunching measurement (0.037 vs. 0.083 eV*s/n). The difference is likely due to ε growth during capture. It is also larger than the next one at 24 ms (0.083 vs 0.064 eV*s/n). As can be seen in Figure 18, there is some beam loss between these 2 measurements which is associated with early acceleration. So, perhaps the scraping off of larger Δp/p particles could account for that difference.

For the remaining measurements that use the Booster WCM, the value for ε is either too large or can't be found because the full bunch width determined from the first half bunch width is larger than the bucket width. For the 35 ms case, the only one that gives a result, the ε is already 40% larger than that measured at extraction using the AGS WCM. The measurements after that require the voltage to be larger than what's inferred from the synchrotron frequency, and would give even larger ε values. At 65 ms, the ε would be 0.116 eV*s/n and the voltage would have to be 27.5 kV for that bunch to barely fit in the bucket. Similarly, at 85 ms the ε would be 0.176 eV*s/n and that voltage would have to be 31 kV. It seems likely that this behavior is due to the limited time response of the Booster WCM signal available in MCR.

The width of the bunch at extraction was measured using the first turn width in the AGS to obtain an ε at extraction of 0.066 eV*s/n (quad pumping off). If I compare it to the value at 24 ms, this suggests that there is little or no growth during the ramp or from the merge, though another measurement (Jun 17, quad pumping off) gave 0.077 eV*s/n. But the ε measurement at extraction is rather subjective; there are some (very small) blips of beam far from the main distribution that were ignored, so there may be some ε growth yet. In Run 14, a measurement of the unmerged bunches at extraction gave 0.080 eV*s/n (total of the 4 bunches). And a measurement of the merged bunch gave 0.089 eV*s/n, suggesting about 10% growth from the merge then.

Debunching Measurements at AGS Injection

Several Δp/p measurements at AGS injection were done during the run. These debunching measurements used the incoming bunch from the Booster and a mountain range display of the AGS WCM as in Run 14. Table II contains the results.[70] Since these were done during the course of the run the conditions over which they were taken vary. The first measurement was actually done during 8:4:2 running so there is no quad pumping and the Booster merge porch was the lower one. Although the quad pumping was on for all the others, the amount of it varied. Generally, there was more quad pumping early in the run, and it was somewhat reduced during the latter part.

Date	**Bunch Length (ns)**	**t_d (ms)**	**Δp/p (half)**	**ε (eV*s/n)**	**Notes**
Feb 10	250	3.44	1.07e-3	0.078	Low merge porch, QP off
Mar 1	211	2.35	1.59e-3	0.095	High merge porch, QP on
Apr 14	180	3.0	1.25e-3	0.065	High merge porch, QP on
Apr 20	203.6	2.69	1.39e-3	0.08	High merge porch, QP on
Jun 16	208.2	3.195	1.12e-3	0.066	High merge porch, QP on

Table II: AGS debunching measurements during Run 16 using the AGS WCM with Rf off at injection. 'QP" stands for Quad pumping. The porch that's mentioned is the Booster merge porch.

In Run 14, 2 debunching measurements were made which gave ε=0.087 and 0.086 eV*s/n. The first measurement listed in the table was made without quad pumping and was taken with basically the same setup as in Run 14, except that Rf track is off during the merge, and the radial loop, not the AC phase loop, is on after the merge. In that case, a value of 0.078 eV*s/n was obtained, which is about 10% smaller than the Run 14 values. The average of the 4

[70] Data is in the Booster-AGS-EBIS elog for those dates.

measurements taken with pumping on and the 12:6:2 Booster cycle is 0.077 eV*s/n, which is essentially the same as the value obtained for the pumping off case. I might have expected that value to be smaller than the one with pumping off due to preferential scraping of large Δp/p particles, but there's no evidence of that here.

If one had to pick a value for the run, 0.077 eV*s/n seems like a reasonable one. On average the value is only slightly larger than the Booster extraction ones (0.066 and 0.077 eV*s/n). There was not a significant difference between the values obtained for the Booster extraction and AGS injection ε using debunching in Run 14 either, suggesting that there is very little growth from the foil.

Measurements of 'Equilibrated' Bunches on the AGS Injection Porch

As in Run 14, measurements of the emittance of bunches that have been sitting on the injection porch and have stopped filamenting were also made. Table III shows the results.[71] The debunching measurements above were made with bunches that are far from equilibrium but these 'equilibrated' values include growth from any longitudinal injection mismatch there might be.

Date	t on porch (ms)	Synch freq. (Hz)	Bunch length (ns)	Rf V (kV) from S.F.	Bunch ε (eV*s/n)	Total ε (eV*s/n)	Notes
Feb 10	200	1799	233	30.8	0.10	0.60	h=16, 8:4:2
Feb 11	200	1500	271	21.5	0.10	0.60	h=16, 8:4:2
Apr 14	600	2553	194	41.3	0.085	0.51	h=24, 12:6:2
Jun 16	600	2190	195.4	30.5	0.074	0.44	h=24, 12:6:2
Jun 24	2210	2540	191.7	40.9	0.0873	0.524	batch of 6
Jun 24	2210	2540	194.2	40.9	0.0887	0.532	other batch of 6

Table III: Emittances of 'equilibrated' bunches on the AGS injection porch calculated with Bbat. In each case the synchrotron frequency was measured and the Rf voltage was obtained from that. The first 2 measurements were done with 8:4:2, so there's no quad pumping. The last 2 (Jun 24) are the averages of each of the 2 sets of 6 bunches that will go into 1 bunch just after the last transfer. The total ε is the bunch ε multiplied by 6.

The first 2 (Feb 10 and 11) were done with the 8:4:2 setup which has no quad pumping. The value obtained, 0.10 eV*s/n, is the same as that obtained in Run 14. The others were done with the 12:6:2 setup, which has quad pumping, and give somewhat smaller values. It's tempting to attribute the difference to the fact that quad pumping is used for the 12:6:2 cases, even though there was no evidence of its effect in the debunching measurements. The last 2 measurements on Jun 24 are each an average of 1 of the 2 sets of 6 bunches taken just after the last transfer that are to be merged into 1 later in the AGS cycle. They give an average bunch ε of 0.088 eV*s/n, and a total ε of 0.528 eV*s/n. If there is a decrease in ε associated with sitting on the injection porch for extended periods of time it is not evident from these measurements since the bunch ε is not any smaller than it is in the April 14 and June 16 cases where the bunches were sitting on the

[71] Data is in the Booster-AGS-EBIS elog for those dates.

injection porch for much less time.[72] 0.088 eV*s/n is taken as the ε of a set of 6 bunches going into the merges. It's about 14% larger than the ε obtained from the debunching measurements (0.077 eV*s/n). In Run 14 a value of 0.10 eV*s/n was obtained for an equilibrated bunch on the injection porch. So, that would suggest that the bunches on the injection porch in Run 16 (with 12:6:2) were about 100*(1-0.088/0.10)=12% smaller than in Run 14.

Measurements after the 12:6 Merge through the 6:2 Merge

Emittance measurements after the 12:6 merge, both before and after the ramp to the 6:2 merge porch were done, as well as measurements after the 6:2 merge. Table IV contains the results.[73] At0+2400 ms is just after the 12:6 merge, and the value of ε there was 0.576 eV*s/n, about 9% larger than the value before that merge (0.528 eV*s/n). After the ramp to the 6:2 porch, ε was 0.608 eV*s/n. Two measurements (taken on April 14 and June 17) of ε after the 6:2 merge but before the h=8 voltage associated with the bunch squeeze is turned on were taken. In these cases, the ε of a merged bunch in an h=4 bucket was found to be 0.57 and 0.61 eV*s/n, respectively. So, there is no growth apparent from the 6:2 merge.

The same type of measurement gave 0.428 eV*s/n in Run 14 with only 4 bunches being merged.[74] The ε after the merge then was 7% larger than before it (0.428/0.40=1.07). The post merge ε of 0.428 eV*s/n would be equivalent to 1.5*0.428=0.642 eV*s/n if 6 bunches were being merged. Everything else being equal, and using the average of the 2 h=4 only measurements, that would suggest that the h=4 bunches are effectively 100*(1-0.59/0.642)=8% smaller than in Run 14. The reason for that could be from a combination of factors. In particular, a smaller Booster extraction ε, quad pumping, and more preferential Δp/p scraping due to a longer time on the injection porch.

Date	Time (ms)	Synch Freq. (Hz)	Bunch length (ns)	Rf V (kV) from S.F.	Bunch ε (eV*s/n)	Total ε (eV*s/n)	Notes
Jun 24	2400	2806	250.5	99.8	0.192	0.576	After 12:6 merge, h=12
Jun 24	2500	3018	205.9	126	0.202	0.608	After ramp to 6:2, h=12
Apr 14	2630	575	748.5	14.9	0.57	0.57	After 6:2, h=4 only
Jun 17	2620	587	773	15.5	0.61	0.61	After 6:2, h=4 only
Jun 17	2720	3404	325.3	175.2	0.55	0.55	Only h=12, before ramp

Table IV: Emittance measurements from just after the 12:6 merge to just before the main acceleration ramp.

[72] The injected bunches alternately fill the 2 sets of 6 buckets that will eventually go into the merge. That is, the sequence that the buckets are filled is: {1,3,5,7,9,11,0,0,0,0,0,0,2,4,6,8,10,12,0,0,0,0,0,0}. So even if preferential Δp/p scraping was a factor one wouldn't expect one set of 6 bunches to have a smaller emittance than the other. A mountain range display showing the order in which the bunches are injected is shown here.

[73] Data is in the Booster-AGS-EBIS elog for those dates.

[74] K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pgs. 13-14, CAD Note 523, August 2014.

A measurement after the squeeze, now in h=12 buckets, but before ramping was also taken (the h=4 and h=8 voltages were turned off earlier than they normally would be to allow for this measurement). In that case, ε was 0.55 eV*s/n. This is smaller than the bunch in the h=4 bucket, and that may be due to the fact that not all of a merged bunch fits into an h=12 bucket, even when squeezed.

The baby bunches with the 12:6:2 setup were generally about 4%. In Run 14 with the 8:4:2 setup they were around 3.5%. There is not much difference between these. How is that possible? Well, for one thing the emittance after the merge is about 8% smaller than one might have naively expected from a 12:6:2 setup if it had occurred in Run 14.

Also, although it was not a motivation for my opting to go to a higher merge energy, it turns out that the bucket area for a given Rf voltage and harmonic (i.e.-4, 8, and 12) is 9.2% larger at the merge porch energy than at injection energy. For a given ε, if the bucket areas for the harmonics involved in the bunch squeeze are larger, it would seem to make sense that more of the merged bunch will successfully be squeezed into an accelerating bucket. That is, the longitudinal acceptance of the bunch squeeze increases as the merge porch energy is raised.[75]

C. Gardner has done modeling of the merge and squeeze. His calculations with an h=8 voltage of 22 kV and an h=4 voltage of 15 kV for the squeeze, which are very similar to the measured values, indicate that the expected proportion of baby bunches would be 6 to 12%, which is somewhat larger than what's measured (~4%).[76] The discrepancy could be due to the phase space distribution he uses in his model being different from the actual one.[77] He also found a longitudinal acceptance of 0.55 eV*s/n for the squeeze, which is the same as the ε of the bunch that was measured in the h=12 bucket immediately following the squeeze.[78]

Measurements during the Main Acceleration Ramp

On April 14th a series of measurements were made up the main acceleration ramp. Table V shows the results.[79] The first entry is just the h=4 only case which is also in Table IV. The width of the first half of the bunch is measured using the WCM in each case. The measured full width is not used because the time response of the WCM causes a significant tail to develop on the trailing edge as the bunch gets narrower. This tail will tend to make the full width measurement wider than the actual bunch width. This is easiest to see on the flattop, where the bunch should be symmetric. For example, in the 3750 ms case, which is on the flattop, the

[75] This kind of effect is alluded to in S.Y. Zhang, H Huang, "Au intensity enhancement for RHIC", Dec 2015, CAD Note 556.
[76] C. Gardner, "Simulation of 6 to 3 to 1 merge and squeeze of Au77+ bunches in AGS", C-AD Note 563, Figure 36. In the figure I'm using the ε range 0.58 to 0.62 instead of 0.57 to 0.61 eV*s/n because his model predicts 2% growth from the merge and the x-axis is the ε of bunches before the merge.
[77] C. Gardner, private communication.
[78] C. Gardner, "Simulation of 6 to 3 to 1 merge and squeeze of Au77+ bunches in AGS", C-AD Note 563, Figure 37
[79] See Booster-AGS-EBIS April 14 2016 1911 entry

measured full width was 33.3 instead of 29.0 ns obtained by multiplying the width of the first half by 2. 33.3 ns corresponds to an ε of 1.05 instead of 0.80 eV*s/n for the first half width times 2.

Using the measured synchrotron frequency, dB/dt, and Rf frequency at each time in the cycle, it turns out that the full width of the bunch can found using Bbat. The emittance shown is for that full width. The full width is found by adjusting the bunch length parameter until the first half of the graphically displayed bunch is the same length as the measured first half width. The peak of the bunch is assumed to be at the synchronous phase.

If just the half width of the bunch times 2 were used for the bunch width then for times before transition the calculated ε would be smaller than it actually is, and after transition it would be larger. This is because the accelerating bunch is not symmetric: Below transition the first half of it is narrower than the trailing half, and the opposite is true after transition. Despite accounting for this to try to get an accurate measure of the bunch's full width, the ε value for 3620 ms is still higher than that obtained on the flattop at 3750 ms when the bunch is symmetric. The reason for this is unclear (could it be that because they are actively growing, the bunches are in some excited state for which these measurements give values which are larger than their actual ε?). If only twice the first half was used at 3620 ms ε would be 1.02 instead 0.91 eV*s/n.

Time (ms)	**Synch Freq (Hz)**	**dB/dt (T/s)**	**V from S.F. (kV)**	**Half width (ns)**	**Full width (ns)**	**ε (eV*s/n)**	**Notes**
2630	575	0	14.9	-	748.5	0.57	After 6:2, h=4 only
2900	2574	0.07	195.4	84.6	171	0.50	Early on ramp
3050	1489	0.384	189.4	59.9	120.8	0.52	Just before F to P transfer
3150	1101	0.50	152	47.5	101	0.51	Just after F to P transfer
3250	714.6	1.01	172.4	36.0	79.0	0.58	Before peak dB/dt
3350	343.2	1.68	185	26.4	60.0	0.67	Start of peak dB/dt
3500	94.4	1.68	170	16.2	35.0	0.78	Just before γ jump
3620	69.74	1.70	187	15.7	29.7	0.91	Near end of ramp
3750	95.85	0	182	14.5	29.0	0.80	flattop

Table V: Emittance measurements up the ramp. The time is from At0, The half width is the width of the first half of the bunch on the WCM. The full width is found using Bbat, it is the full width corresponding to the measured first half width, ε is the emittance corresponding to that full width.

Regardless, it seems apparent that there is ε growth between the end of the merge porch and the flattop. Figure 19 shows the ramp measurements together with the other AGS ε measurements already discussed (except for the debunching ones). After the squeeze the emittance drops from 0.59 to 0.55 eV*s/n, then it appears to drop a bit more to 0.52 eV*s/n or so. That's consistent with a small amount of beam spilling out of the bucket or being scraped off. In Figure 9 one can see that there is some loss during this time. Then it is fairly constant until around 3200 ms, afterwards it steadily rises at a rate of about 0.08 eV*s/n per 100 ms until the end of the ramp. It could be that some of the growth seen between 3500 and 3620 ms is due to transition (at 3570 ms) but it's not obvious, and if these measurements are to be believed (at least qualitatively) there is growth well before that.

In Run 14 the absolute amount of growth during the ramp (just before F to P transfer to flattop) was about 0.69-0.415=0.275 eV*s/n. But in Runs 15 and 16 the flattop ε was more like 0.60 eV*s/n, yet the early ramp ε was probably about the same.[80] In that case the absolute growth would be 0.60-0.415=0.185 eV*s/n. For 12:6:2, using the average value of flattop measurements through the run, not just the value from Apr 14th (see next section), it is 0.75-0.52=0.23 eV*s/n. So, compared to the most recent 8:4:2 measurements the absolute amount of ε growth appears to be somewhat larger in the 12:6:2 case (0.23 vs. 0.185 eV*s/n).

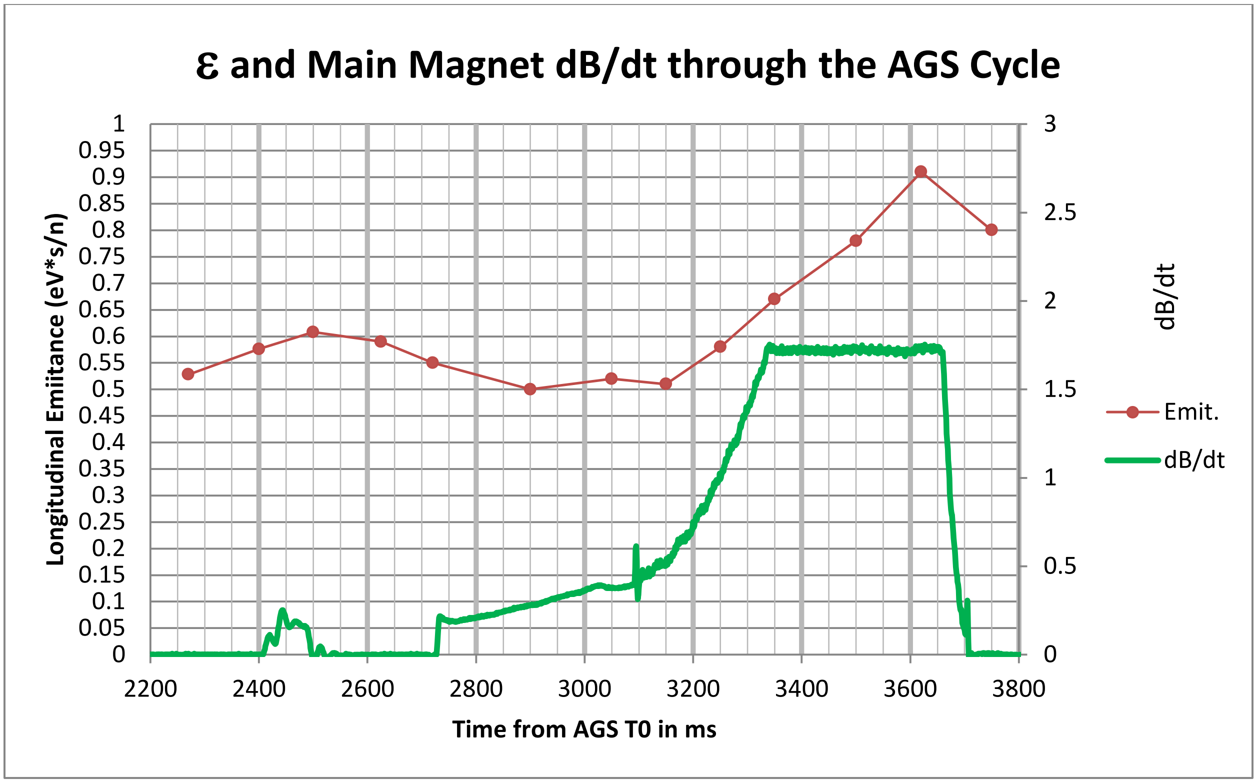

Figure 19: Emittance and the main magnet dB/dt (in T/s) during the AGS cycle. Before the merges, the emittance is the total that would go into 1 merged bunch. The F to P transfer occurs at 3100 ms and transition is at 3570 ms.

In Run 14, ε growth also appeared to start not long after the F to P transfer, but the Run 16 data indicates that it doesn't start right at F to P transfer since a measurement at 3150 ms (50 ms after it) does not show any growth. The synchrotron frequency is decreasing as the field ramps up and passes through 720 Hz just before the first measurement of increased ε (at 3250 ms).

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[80] Although the early ramp ε was not measured for 8:4:2 in either Run 15 or 16, in Run 16 the ε on the injection porch was and it was the same as in Run 14 (0.4 eV*s/n). So, there's no reason to believe that the early ramp ε was substantially different.

In Run 15, using the proton magnet cycle, some of the frequency components of the power spectrum of the P bank were measured. The sum of the station 1 and 2 voltage signals was used for the measurement. 360 Hz was the largest component, 720 Hz was about half of that, and 1440 Hz was about a tenth of 720 Hz component.[81] If the ripple was causing ε growth I might expect to see dipole oscillations on a WCM mountain range display while on the P bank, but I don't see any. There are some quadrupole oscillations visible on the envelope of the WCM, and their amplitude varies within some normal range. Yet when they are on the small side, the flattop ε is not substantially smaller.[82] The bunches do not look noisy either.[83]

Growth of Small Emittance Bunches

On May 26, both the AGS merges were turned off and the beam was injected directly into h=12 buckets to try to produce very small low intensity bunches at AGS extraction for the CeC experiment. The Booster Rf voltage after the merge was also lowered to reduce the Booster extraction ε via 'longitudinal scraping'.[84] That brought the AGS extraction ε down to 0.075 eV*s/n. In this case, 10 of the h=12 buckets were populated and the other 2 were left empty.

Although at the time I did not measure ε at AGS injection, I think there is enough information in the elog to piece together a measurement. That measurement gives an ε of 0.051 eV*s/n for a bunch after the last transfer.[85] This means the relative ε growth from injection to flattop is about 100*[(0.075/0.051)-1]=47%. It seems reasonable to think that the majority of this growth occurs while on the P bank. The ε growth for the 12:6:2 case ($\varepsilon_{flattop}/\varepsilon_{early\ ramp}$=0.75/0.52) is 44%. In the 8:4:2 case for Run 16 the growth would be 100*[(0.60/0.415)-1]=45%.

So, the data suggest that the relative growth on the P bank is independent of the initial ε over a very large range in initial ε. This seems counterintuitive to me, but if it's true maybe it's a hint as to the mechanism for the growth. One thing that's different about the small ε case is the

[81] See Booster-AGS-PP June 19 2015 elog 1530 to 1534 entries.
[82] For example, see Booster-AGS-EBIS Apr 12 2016 elog, 1854, 1903, and 1941 entries
[83] For example, see Booster-AGS-EBIS Apr 14 2016 elog, 1834, 1840, and 1900 entries
[84] Longitudinal scraping is the term used for lowering the longitudinal ε by reducing the Rf voltage so that the bucket becomes smaller than the bunch. In that case beam outside the bucket is lost and the ε decreases.
[85] From device history I found that this mountain range display of the bunches that produced the 0.075 eV*s/n bunches on May 26 was triggered at the last transfer. The beam has been injected into h=12 buckets using only station K. The trigger interval is 50 μs per trace, and there are 80 traces. The width of an equilibrated bunch is 200 ns. Looking at the bunch that hasn't equilibrated yet, one can see that there are 8 half synchrotron oscillations in 71 traces*50μs=3.55 ms. That makes the synchrotron frequency 4/(0.00355)= 1127 Hz. Using Bbat with h=12 this corresponds to ε=0.051 eV*s/n.

bunch intensity. But I have not seen much, if any, ε dependence on intensity with either one of the standard setups.[86]

The pre-EBIS Tandem Au setup, which merged the bunches in only 1 Booster transfer into 1 bunch, had a relative ε growth from injection to flattop of about a factor of 3 or 4 (0.082 eV*s/n at injection, and about 0.30 eV*s/n on flattop). Though, as mentioned earlier most of that growth may have occurred during the merge.

When running Deuterons in Run 16, there seems to have been very little emittance growth from injection to flattop. A bunch width measurement on March 14th of 125 ns at AGS injection corresponds to about 0.1 eV*s/n.[87] Four of these bunches were merged into 1, and the flattop emittance was about 0.41 eV*s/n.[88] A set of measurements during the 2015 polarized proton run indicated the growth from AGS injection to flattop was about 54% (0.72 to 1.11 eV*s).[89] But proton measurements from Run 13, when considerable effort was made to reduce the AGS extraction emittance, indicated the growth was only about 15% (0.66 to 0.76 eV*s).[90]

AGS Flattop Emittance

The average of 6 flattop emittance measurements taken during the run was 0.75 eV*s/n with σ=0.037 eV*s/n.[91] As alluded to above, this is a little smaller than in the April 14 measurement. The flattop ε can be reduced significantly from this at the expense of intensity. This is typically done by reducing or turning off the h=8 part of the squeeze. Turning it off reduces the bunch intensity by about 10%. To reduce the ε further the L10 voltage can also be lowered. For example, on April 25 RHIC was filled with the desired intensity (2.2-2.3e9 per bunch in RHIC) but with bunches that were about 0.53 eV*s/n.[92] The RHIC beam was lost at transition, probably because of problems with the yellow Landau cavity.[93]

Figure 20 shows the effect of turning off the h=8 part of the squeeze and lowering the L10 voltage. The fully squeezed bunch was 29.0 ns, with the h=8 squeeze off it was 27.6 ns, and

[86] For example the pilot bunch, which is about one sixth the intensity of a typical bunch has about the same width (at RHIC injection). See Booster-AGS-EBIS Jun 22 2016 1612 entry.
[87] See Booster-AGS-EBIS Mar 14 2016 elog 1704 entry. The synchrotron frequency was not measured here, but using the standard calibration of 0.80*the vector sum voltage (29kV) gives 23.2 kV and with that 0.10 eV*s/n is obtained. This measurement was done during the initial D setup, before the bunches were intentionally diluted for RHIC.
[88] See Booster-AGS-EBIS Mar 18 2016 elog 1027 entry by C. Gardner.
[89] See Booster-AGS-PP April 6 2015 elog, 1416 and 1439 entries. This was also with the new AGS LLRF Rf system.
[90] See Booster-AGS-pp elog Apr 19 2013, 1325 and 1559 entries.
[91] These are with the full squeeze on. See Feb 22 1838, Apr 13 1700, Apr 13 1709, Apr 14 1911, May 24 1537, and May 26 1614 in Booster-AGS-EBIS 2016 elog.
[92] With the L10 cavity (h=4) at ab·out 8 kV when the h=12 Rf comes on bunches at extraction were about 23.8 ns wide, the baby bunches were about 16%, and the bunch intensity at AGS extraction was about 2.4e9 ions.
[93] See N. Kling, rhic-AuAu April 25 2016 elog 1553 entry.

with the L10 voltage also reduced from 15 to 10 kV it was 25.6 ns. For the fill described above, the L10 was lowered further and the bunches were about 24 ns wide.

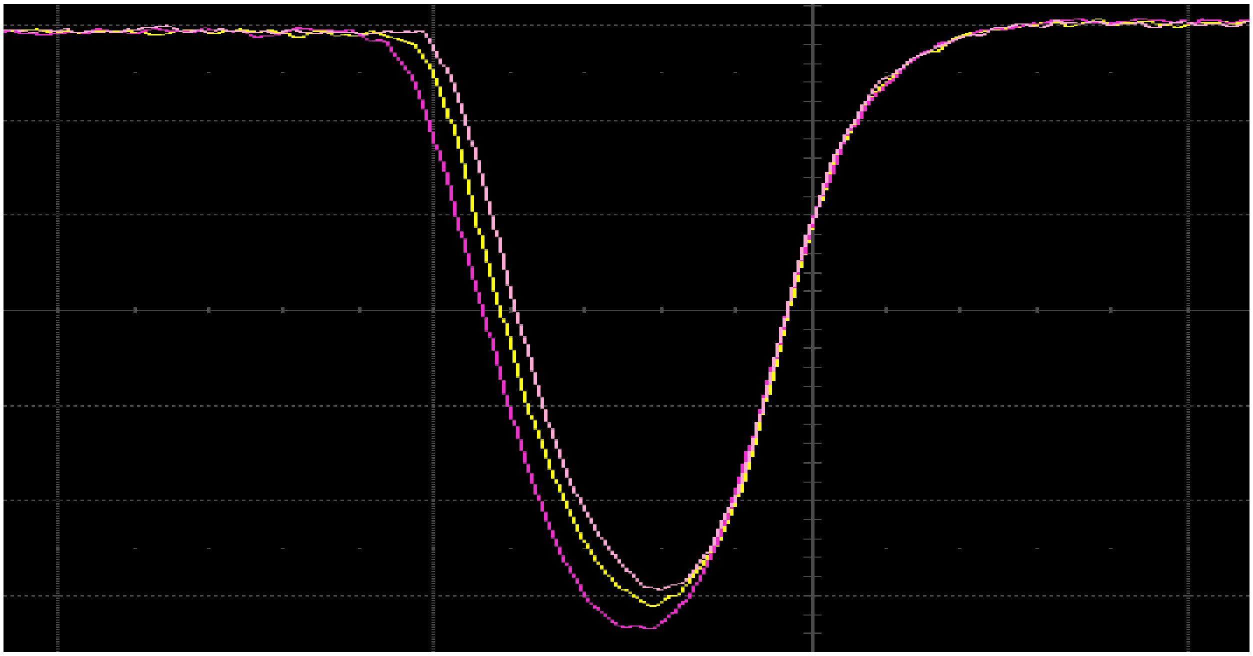

Figure 20: The bunch on the flattop as seen on the WCM in 3 different cases. The dark purple is a fully squeezed bunch, the yellow is with the h=8 part of the bunch squeeze off, and the light purple is with the h=8 squeeze off and the L10 cavity voltage lowered. The sweep speed is 20 ns/div and the gain is 500 mV/box.[94]

Comparing 12:6:2 and 8:4:2 Performances

It may seem that the extraction ε with the 12:6:2 setup was not any larger than it was for the 8:4:2 setup, but on closer inspection that doesn't seem to be true. It's nearly the case if compared to Run 14 (0.75 vs. 0.69 eV*s/n) but, although there's not a lot of data, the ε in Runs 15 and 16 appears to have been significantly smaller (0.60 vs. 0.69 eV*s/n). It's not clear what the reason for this decrease is, but it does seem like less growth occurred during the P bank. In Run 14 the growth from early ramp to flattop was about 66% and in Run 16, assuming the same early ramp ε, it seems to be about 45%. It seems reasonable to assume the same early ramp ε because the equilibrated bunch ε for 8:4:2 was measured to be the same in Run 16 as it was in Run 14 (Table 3).

If the amount of relative growth on the P bank were the same for 8:4:2 and 12:6:2, which appears to be the case, then one would expect the flattop ε to be about 45% larger than the early ramp ε. If the early ramp ε for 12:6:2 were simply 50% greater for 12:6:2 than 8:4:2 because there's 50% more Booster bunches per AGS bunch, than the flattop ε would be 0.86 not 0.75 eV*s/n. The reason it's smaller than that seems to be because the early ramp ε is smaller, 0.52 vs. 1.5*0.415=0.62 eV*s/n. So, the question becomes, why is the early ramp ε smaller?

[94] See Booster-AGS EBIS April 25 2016 elog, 1326 to 1606 entries.

As noted earlier, C. Gardner's modeling shows that the acceptance of the bunch squeeze is 0.55 eV*s/n, so the bunch at the beginning of the ramp cannot be larger than that. It is likely a bit smaller than that during the early ramp (0.52 eV*s/n) because there is not quite enough voltage to accelerate all of it. Indications for this are that any reduction in the early voltage causes more loss there, there is some loss there even when the voltage is at its maximum, using h=10 buckets, which are larger, also reduces that loss, and reducing the bunch squeeze also reduces the loss there. Bbat also indicates that the bucket is nearly full (ex.- at At0+2900 ms the bucket area is 0.59 eV*s/n).

So, then the question becomes, why are the baby bunches as small as they are? As was mentioned previously, the h=4, 8, and 12 bucket areas on the higher merge porch are 9.2% larger for the same voltages. So, for a given ε after the merges, the baby bunches should be smaller.

The ε after equilibration also seems to be smaller than in the 8:4:2 merge case (0.088 vs 0.10 eV*s/n). The most likely cause for this reduction is the use of quad pumping which reduces the injected ε because of momentum apertures in BtA. Although the quad pumping reduces the transfer efficiency, the beam that's lost would tend to wind up in the baby bunches anyway because it would tend to have a large Δp/p.

The Booster ε also seems smaller than it was, at least in Run 14 (0.71 vs 0.89 eV*s/n), although the Run 16 8:4:2 setup probably had those smaller bunches as well. Although not obvious, this may be due to some improvement in the Booster merge. There were changes made, for example, Rf track was turned off during it and the radial loop was used after it instead of the AC phase loop.

In the 12:6:2 setup less time was spent on the P bank than in the 8:4:2 case due to its higher ramp rate (643 vs. 872 ms). Yet, the relative ε growth from early ramp to flattop was essentially the same. This seems surprising since I would have thought that if the voltage ripple was driving the growth that spending less time on the P bank would result in less growth (45%*643/872=33% vs. 45%).

There is also some growth from just before the 12:6 merge to just after the ramp to the 6:2 merge porch which further complicates this analysis (see Table VI below).

16:8:4:2 Merge Scheme

As far as further increases to the AGS bunch intensity go, there is a merge that could possibly be used which would allow 16 Booster bunches to be merged into 2 bunches. This would use the same h=24 buckets at injection, but instead of 2 sets of 6, 2 sets of 8 bunches would be injected.[95] They'd be merged into 2 sets of 4 using h=12 and then, using the merge that

[95] There would be 4 empty buckets on either side of each set of 8 bunches. When the last bunch in either set of 8 is injected the kicker will have to rise to kick that bunch in and then fall before the first bunch in the other set passes

was found and employed during He3+ commissioning, each set of 4 bunches would be merged into 1. Figure 21 shows this schematically.

The 16:8 merge is straightforward, but this 8:4:2 merge is not.[96] After the 16:8 merge, each set of 4 bunches can be thought of as residing in a set of 6 buckets with the 4 bunches occupying the 4 innermost buckets, {0,1,1,1,1,0}. At this point, if only the h=4 voltage is raised as the h=12 voltage is lowered, 2 bunches would result, but each of those bunches would have an emittance that would be the same as in the case where the empty bucket is also populated (i.e.- a 6:2 type merge with two of the 6 initial buckets empty). So, there would be 50% (or more) emittance growth. But it was found that if the h=2 and 4 voltages are both raised as the h=12 voltage is lowered the 4 bunches merge into 2 bunches whose emittance is unaffected by the presence of the empty buckets. The h=2 voltage seems to act as a barrier which keeps the empty buckets separate from the populated ones. Once that merge is complete, the h=4 voltage can be lowered and the 2 sets of 2 bunches merge cleanly into 2 bunches.

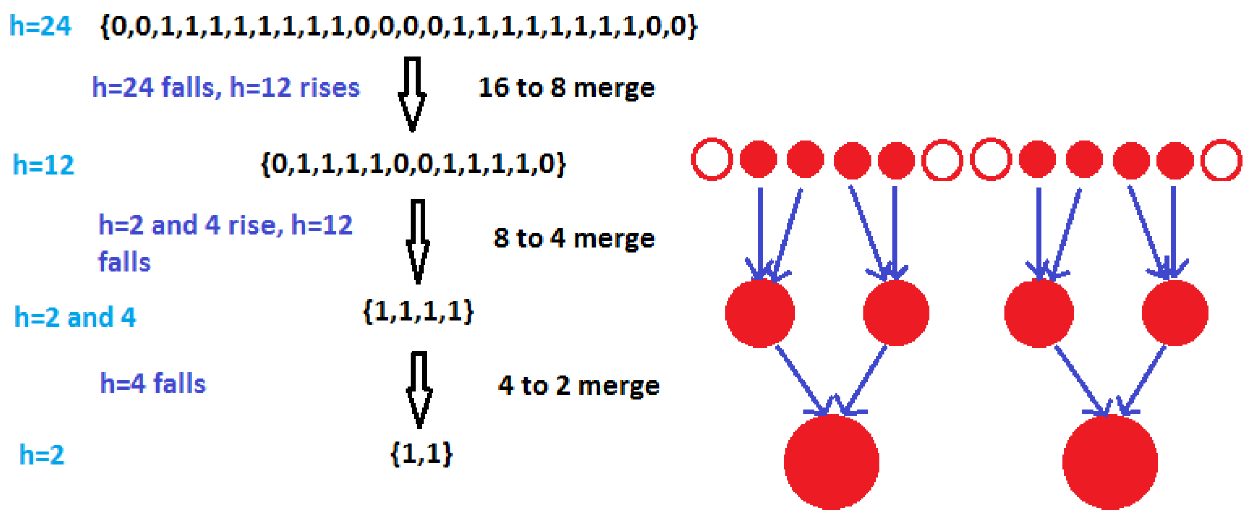

Figure 21: 16:8:4:2 merge scheme for merging 8 Booster cycles into 1. '0" or empty circles represent unpopulated buckets, 1 or filled in circles represent populated buckets.

Figure 22 shows this 8:4:2 merge with He3+. Aside from how it looks on this mountain range display, it also seems to be emittance conserving in the model developed by C. Gardner.[97] The harmonics of the special Rf cavities used for merges are h=2 and 4 instead of h=4 and 8. The L10 cavity is used for h=2 and KL is used for h=4. At their present frequencies this merge would

through it. So, the time between its rising edge and when it needs to have fallen will be about 5 h=24 buckets, or 5*256ns=1.28 μs. The kicker pulse, in proton (i.e.-narrow) mode, is about 1.16 μs long so it should have (barely) enough time to fall before the first bunch in the other set passes through it (See the kicker waveform in the Booster-AGS-He3 2014 elog, C. Gardner's May 22 2119 entry).

[96] This merge is different than the standard 8:4:2 merge. It requires the 2 sets of 4 bunches to be in h=12 not h=16 buckets. A standard 8:4:2 merge can't be done at the present injection energy because that would require the bunches to be injected into h=32 buckets. The Rf frequency required for that is too high, and the buckets are too short.

[97] C. Gardner shows a model of this 8:4:2 merge in the Booster-AGS-He3 elog, 1640 entry. See also, C. Gardner, "Simulations of Merging Helion Bunches on the AGS Injection Porch", 2014, CAD Note 527.

not work, their frequencies would need to be lowered, and the merge porch would have to be raised.

If the L10 frequency was lowered from the present 783 to 660 kHz, which is still higher than it was before it was raised (628 kHz), then the merge porch would be at about 1.80 kG.[98] This is a lot higher than it is now (0.577 kG), but is still far from transition (~8 kG). Assuming a similar ε evolution as there is in the 12:6:2 case, the merged bunch would be 0.59*(8/6)=0.79 eV*s/n (note that acceleration to the merge porch would be done on the F bank so there would presumably be no ε growth).

One issue with this higher energy and lower harmonic merge is that the synchrotron frequencies would be only about 27% of what they are on the present merge porch which might mean that the porch would need to be a lot longer. [99] The length of the 6:2 merge (from when KL starts to rise until when it has completely fallen) is about 100 ms. But when this merge was done with He3+ it took about the same amount of time (90 ms) even though the synchrotron frequencies for it were 45% of what they are for the 6:2 case.[100] So, it looks like the merge porch may have to be lengthened by perhaps a factor of 1.7 (i.e.-45/27), or from 150 to 250 ms, but probably not to the point where it would affect the cycle length.

As regards the bunch squeeze and baby bunches: In an h=2 bucket with 15 kV a bunch with ε=0.79 eV*s/n has a width of 358 ns at this energy. An h=4 bucket is 758 ns wide at this energy, more than twice as wide as the h=2 bunch. That means that the h=2 voltage could be lowered to zero while h=4 is raised and the bunch would easily fit in an h=4 bucket. With a final h=4 voltage of 22 kV that bunch would be 280 ns wide. The bucket area of both an h=2 bucket at 15 kV and an h=4 bucket at 22 kV are much larger than 0.79 eV*s/n, 7.5 and 3.2 eV*s/n respectively.

At this energy the regular Rf cavities can be set to have an even harmonic as low as 6. An h=6 bucket is 505 ns wide, an h=8 bucket is 379 ns, and an h=10 bucket is 303 ns wide. So, any one of these voltages could be raised and the bunch would fit in it since their bucket widths are greater than 280 ns even without the help of h=2 voltage. An h=12 bucket is 253 ns wide, and with h=2 on as well, the bunch might even fit into it.

If it didn't completely fit, 2 cavities set to h=10 could be brought on while the h=4 and 2 voltages are on. This would be about 44 kV of h=10 voltage and it would be enough to make a bunch 205 ns wide for an ε of 0.79 eV*s/n with a bucket area of 1.15 eV*s/n (if the h=2 and 4 voltages were zeroed, which they wouldn't be). That bunch would easily fit into an h=12 bucket.

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[98] I just picked that frequency because it is high enough to allow h=6 after the merge.

[99] For L10 at 14.9 kV, 660Hz, and h=2 gives synch. f=158 Hz. For the 12:6:2 it's 575 Hz, so 100*(158Hz/575Hz)=27%

[100] For He3+, if L10 is at 628 kHz, 14.9 kV and h=2, the synchrotron frequency calculated using bbrat is 260 Hz, so 100*(260Hz/575Hz)=45%. An ε measurement on the injection porch for He3+ gave 0.80 eV*s/n, and the ε after the merge was 0.83 eV*s/n. So, there seems to have been very little growth from it. See Booster-AGS-He3 Jun 16 2014 elog, Jun 18 1412 and 1641 entries. The flattop ε was 1.11 eV*s/n using h=6, so there was 34% growth on ramp.

It could also be accelerated to flattop with those 2 cavities on h=10 and the rest on h=12 so that no accelerating bucket area would be sacrificed. Those h=10 cavities could be switched back to h=12 once on the flattop. Also, any space charge issues will probably be negligible at this bunch squeeze energy.

Assuming the same relative ε growth on the P bank as in the 12:6:2 case, but no ε reduction from a limited acceptance of the bunch squeeze or from limited bucket area on the early ramp, the flattop ε would be 1.44*(8/6)*0.59=1.13 eV*s/n. This is 50 not 33 percent larger than the 12:6:2 case because of these assumptions (which imply that there would be no baby bunches or acceleration loss after this merge). If h=12 were used with a nominal flattop voltage of 180 kV, the bunch would be about 34.7 ns wide. As with the 12:6:2 setup, the ε could probably be reduced by lowering the voltages associated with the squeeze at the expense of bunch intensity.

The bunches might be too large and/or intense for nominal RHIC operation where transition crossing is required, but for lower energy runs this might not be the case. For very low energy runs (ex- 2.5 and 3.85 GeV), it might be practical to stay on the F bank. Presumably there would be little or no ε growth in those cases. This would also be possible with the present 12:6:2 setup.

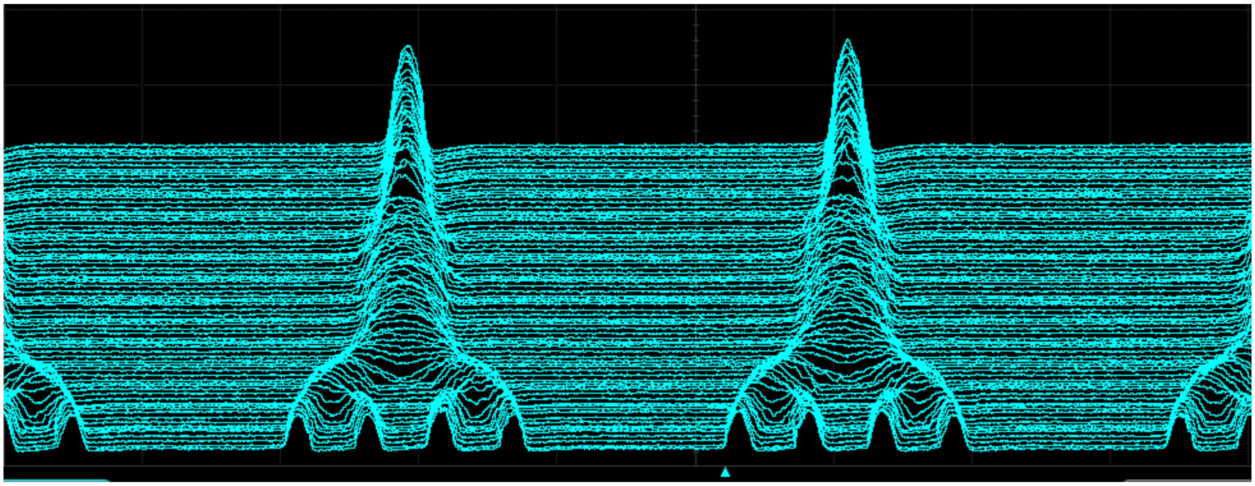

Figure 22: The He3+ 8:4:2 merge which could be used in conjunction with a preceding 16:8 merge to merge 2 sets of 8 Booster bunches into 2 bunches. The sweep speed is 500 ns/div, and the gain is 100 mV/box.[101]

There were errors found in the alarm levels for the PPMR this run, and the levels were subsequently raised significantly.[102] With the corrected levels a 17 Booster cycle supercycle with the present magnet cycle satisfies PPMR constraints (at least according to the calculation). As far

[101] Booster-AGS-He3 2014 elog, Jun 24 1552 entry.

[102] Thanks to N. Kling for pursuing this. See also John Morris' 1039 entry in the Booster-AGS-EBIS March 17 2016 elog.

as time required for the extra 4 injections, the supercycle length could stay the same as it was for most of Run 16 (6.4 sec), though there are probably other reasons why it might have to be extended (ex.-EBIS). There's a good chance that there will also be issues with the Booster main magnet power supply's duty cycle. This merge setup could be tested with only 8 EBIS pulses as in the 6:3:1 case, but the merge cavity frequencies would still have to be changed.

Summary

In Run 16, a 12:6:2 merge was employed in the AGS with a higher energy 6:2 merge porch to reduce losses associated with space charge that occur when the bunch is squeezed into accelerating buckets after merging and to allow for acceleration in h=10 instead of h=12 buckets (that capability was not used for RHIC operations this run). Raising the porch seems to have effectively avoided these space charge effects. This setup required 12 EBIS pulses and 13 Booster main magnet cycles per supercycle. The supercycle length was 6.4 sec for most of this time. A peak bunch intensity of about 3.1e9 ions was reached with an emittance of about 0.75 eV*s/n (vs. 2.1e9 ions and 0.60 eV*s/n for 8:4:2). At that time nearly 50% of the beam at Booster extraction wound up in the 2 main AGS bunches (see Figure 14).

Several changes were required to get this setup to work as it did. Most notably:

1) EBIS had to deliver 12 pulses, each separated by 200 ms, without a substantial decrease in pulse intensity.
2) The L10 and KL frequency ranges had to be increased by the Rf group so that the 6:2 merge could occur at the higher energy.
3) The Booster merge field had to be increased to satisfy the PPMR constraints. Except for the setup time, this did not have a negative impact on the Booster's performance.
4) A way to turn off Rf track during the 6:2 merge had to be implemented in order for that merge to work properly. This capability was also implemented for the Booster merges, and that proved helpful later in the run when the field on the merge porch was not flat.
5) Rf quad pumping at Booster extraction was used to reduce the width of the bunches so that they would fit into the h=24 buckets at AGS injection and also to allow for time for the injection kicker current to rise between bunches.
6) Changes to the AGS main magnet function were made. In addition to extending the injection porch, the F to P voltage bank transfer was moved to a higher field to eliminate losses there. The ramp rates while on the P bank and also during the down ramp were also increased to reduce the cycle length.

Table 6 is a summary of the emittance measurements detailed in previous sections. (Figure 19 is a plot of much of the AGS data).[103] The 2 places where the most emittance growth occurs appear to be Booster capture where it grows by about 124% (1->2) and the AGS ramp while on the P bank where it grows by about 47% (12->17). It doesn't seem like the growth at Booster capture will be an easy thing to reduce because there is not enough time in the Booster cycle to significantly slow down the capture process. There is also 15% or so ε growth that seems to occur during the 12:6 merge and ramp to the 6:2 merge porch. This needs to be investigated further.

t	**Part of the cycle**	**Total Booster Emittance (eVs/n)**	**AGS bunch emittance (eVs/n)**	**Emittance growth**	
				t_a->t_b	**Ratio**
1	Booster Injection	0.037 ± 0.003	0.222 ± 0.018	-	-
2	Booster after capture	0.083	0.498	1->2	2.24
3	Booster extraction (before foil)	0.071 ± 0.005	0.426 ± 0.03	2->3	0.86
4	AGS injection (debunching)	-	0.462 ± 0.084	3->4	1.08
5	After last transfer (equilibrated)	-	0.528 ± 0.004	4->5	1.14
6	Before 1st ramp but after 12:6	-	0.576	5->6	1.09
7	After 1st ramp, before 6:2	-	0.608	6->7	1.06
8	After 6:2 (h=4 only)	-	0.59 ± 0.02	7->8	0.97
9	After squeeze, before ramp	-	0.55	8->9	0.93
10	At0+2900	-	0.50	9->10	0.91
11	At0+3050 (before F to P xfer)	-	0.52	10->11	1.04
12	At0+3150 (50 ms after F to P xfer)	-	0.51	11->12	0.98
13	At0+3250 (before peak dB/dt)	-	0.58	12->13	1.14
14	At0+3350 (start of peak dB/dt)	-	0.67	13->14	1.16
15	At0+3500 (just before g jump)	-	0.78	14->15	1.16
16	At0+3620 (near end of ramp)	-	0.91	15->16	1.17
17	AGS Flattop	-	0.75 ± 0.037	16->17	0.82
-	Booster injection to extraction	-	-	1->3	1.92
-	Booster ext. to after last xfer	-	-	3->5	1.24
-	After last xfer to after 6:2	-	-	5->8	1.12
-	AGS after squeeze to early P bank	-	-	9->12	0.93
-	Early P bank to flattop	-	-	12->17	1.47
-	Booster injection to AGS flattop	-	-	1->17	3.38

Table VI: Summary of Emittances through the Booster and AGS cycles. "Total Booster emittance" is the sum of the emittances of all the bunches. "AGS bunch emittance" is the total emittance of the beam if it were in one final AGS bunch, or the beam in 1 final AGS bunch, as the case may be. The ranges given are the ranges in the different measurements taken or the standard deviation. Any values without ranges are from just one measurement. The emittance growth ratio is the ratio of emittance at t_b over that at t_a (t in the leftmost column) of the "AGS bunch" emittance.

In Run 14 a debunching measurement at Booster injection indicated the initial emittance was smaller by a factor of two compared to this year's measurement, but there's no evidence that the EBIS beam is any larger now than it was. This year's measurement seems more reliable since it used a full width EBIS pulse and looked at a bunch with sharp edges.

[103] This table is similar to Table V in K. Zeno, "Longitudinal Emittance Measurements in the Booster and AGS during the 2014 Gold Run", pg. 26, CAD Note 523, August 2014.

The injection and flattop emittances with a smaller Booster extraction ε and no AGS merges were also measured. Even though the ε on flattop was only about one tenth of the 12:6:2 ε, the relative amount of growth from early in the cycle to the flattop was about the same (45%), and it is also about the same for the 8:4:2 setup. So it appears that the relative ε growth while on the P bank may be independent of the initial early ramp ε.

If there were no ε growth while on the P-bank, the flattop ε would be 0.52 instead of 0.75 eV*s/n. Even so, the AGS was able to deliver about 2.4e9 ions/bunch with ε=0.53 eV*s/n by relaxing the bunch squeeze (see pg. 35). It's notable that in this case the bunches were smaller and of higher intensity than with the 8:4:2 setup which had at its best 2.14e9 ions/bunch and ε=0.60 eV*s/n. Since the relative ε growth on the ramp is constant, the absolute amount of growth is less if the ε on the early ramp is reduced and relaxing the bunch squeeze does that. For example, if the early ramp ε is 0.50 eV*s/n, then the flattop ε would be 0.725 eV*s/n, but if it's 0.40 eV*s/n then it would only be 0.580 not 0.625 eV*s/n.

For given voltages of the harmonics involved in the bunch squeeze, the bucket areas are 9.2% larger at the higher merge energy. This likely translates to a larger longitudinal acceptance of the bunch squeeze, and therefore smaller baby bunches than there would be if the 6:2 merge were performed at injection energy. But the longitudinal acceptance is still a little smaller than the ε of the merged bunch (0.55 vs 0.59 eV*s/n, see page 31). So, although the amount of gain would be small, if the L10 and KL frequencies were higher that would likely allow for smaller baby bunches (and larger final bunch ε).

A possible 8 to 1 type merge using a 2 to 1 merge followed by the 4 to 1 merge that was used for He3+ was also described. It doesn't appear that there would be any baby bunches with that setup. Assuming the same ε growth during the P bank as with the 12:6:2 merge, its ε on flattop would be 1.13 eV*s/n and its bunch width in h=12 buckets would be 34.7 ns. As with the 12:6:2 merge, the ε could probably be reduced at the expense of intensity by relaxing the squeeze

Even if the bunch intensity and ε with this merge were too high to accelerate through transition in RHIC, it could possibly be used for low energy runs. Also, if the flattop energy is low enough for these runs, it might be practical to stay of the F bank for the ramp, and then there would be little ε growth (which is also true for the 12:6:2 setup). In that case the flattop ε might be more like 0.79 eV*s/n.

Having the option to change the frequencies of the L10 and KL cavities was critical to the success of the 12:6:2 setup. Further progress, such as by using an 8 to 1 type merge, might call for them to be changed again.