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AGS Longitudinal emittance measurements for upcoming RHIC low energy gold runs

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Many longitudinal emittance (ε) measurements were made in the AGS towards the end of Run 18 with Au from EBIS at the flattop energies to be used for the upcoming RHIC low energy runs. The primary motivation for this was to determine what emittances and bunch intensities could be provided by the injectors. The measurements were also taken for many different configurations to try to gain a better understanding of the observed ε growth on the acceleration ramp in the hope of finding some way to reduce it.

The tentative requirements for the 5 energies are shown in Table I. Different parameters were varied depending on the requirements at each extraction energy and they included: The type of AGS merge, the main magnet voltage banks (Pulsed and Flattop) used for ramping, the ramp and flattop Rf voltages, and the amount of bunch squeezing after the merge.

Total Energy (GeV/n)	3.85	4.55	5.75	7.30	9.80
Bunch Intensity (e9)	0.6	0.8	1.3	2.1	2.3
Emittance (eV-s/n)	0.3	0.4	0.5	0.3	0.4

Table 1: Required Au bunch intensities and longitudinal emittances for the RHIC low energy runs.

The measurements were made over a period of a month (May 15 to June 15), starting with the lowest energy and generally working up to the highest. The measurements for each energy, from lowest to highest, are in Tables II through VI, respectively. Figures 4 through 7 also show some of the more relevant data for the first four energies. Table VII (and Figure 8) show the data for the best candidates for the different energies. Some of the setups may seem irrelevant, but at the time that was not clear. This is particularly true in cases where the ramping and flattop voltages were varied. On the other hand, with the benefit of hindsight, there are setups that should have been checked but weren't.

Description of the Measurements

The measurements of the ε of the entire bunch were made early in the main acceleration ramp (called early ramp ε) and on the flattop (flattop ε) and are somewhat subjective because the bunch length found from measurements made by eye using the wall current monitor (WCM) and the cursors on a scope are part of the calculation. The early ε measurements were made at the beginning of the ramp, just after the h=4 and h=8 Rf voltages used for the bunch squeeze come down to zero. For the early ramp ε measurements the full bunch length is measured and for the flattop ε ones the leading half-length is measured and doubled to get the full length. This is done because the frequency response of the WCM is such that for the shorter bunches on the flattop the trailing side is usually artificially longer than the leading side. These are the ways that the bunch lengths in the AGS are usually measured at these times in the cycle. Figure 1 shows typical early and flattop bunch length measurements.

For each of the measurements shown in the tables, 10 bunch length measurements were made, and the average of those was used to find the 'full' ε. For every setup the flattop ε was calculated from this (unless otherwise noted), but early ε measurements were only made in cases where there was a reason to believe its value differed from that of a previous setup for which it was measured. In cases where the bunch length early on the ramp was not measured, the value from that previous ε calculation was used. Take for example the early ε indicated in rows 11 and 12 of Table IV, since there was no difference between those setups up to the time in the cycle where the early ramp ε would be measured, the early ramp ε from row 11 was used for row 12 as well. In general, the ε was calculated from the bunch length, measured synchrotron frequency (f_s), and measured Rf frequency.

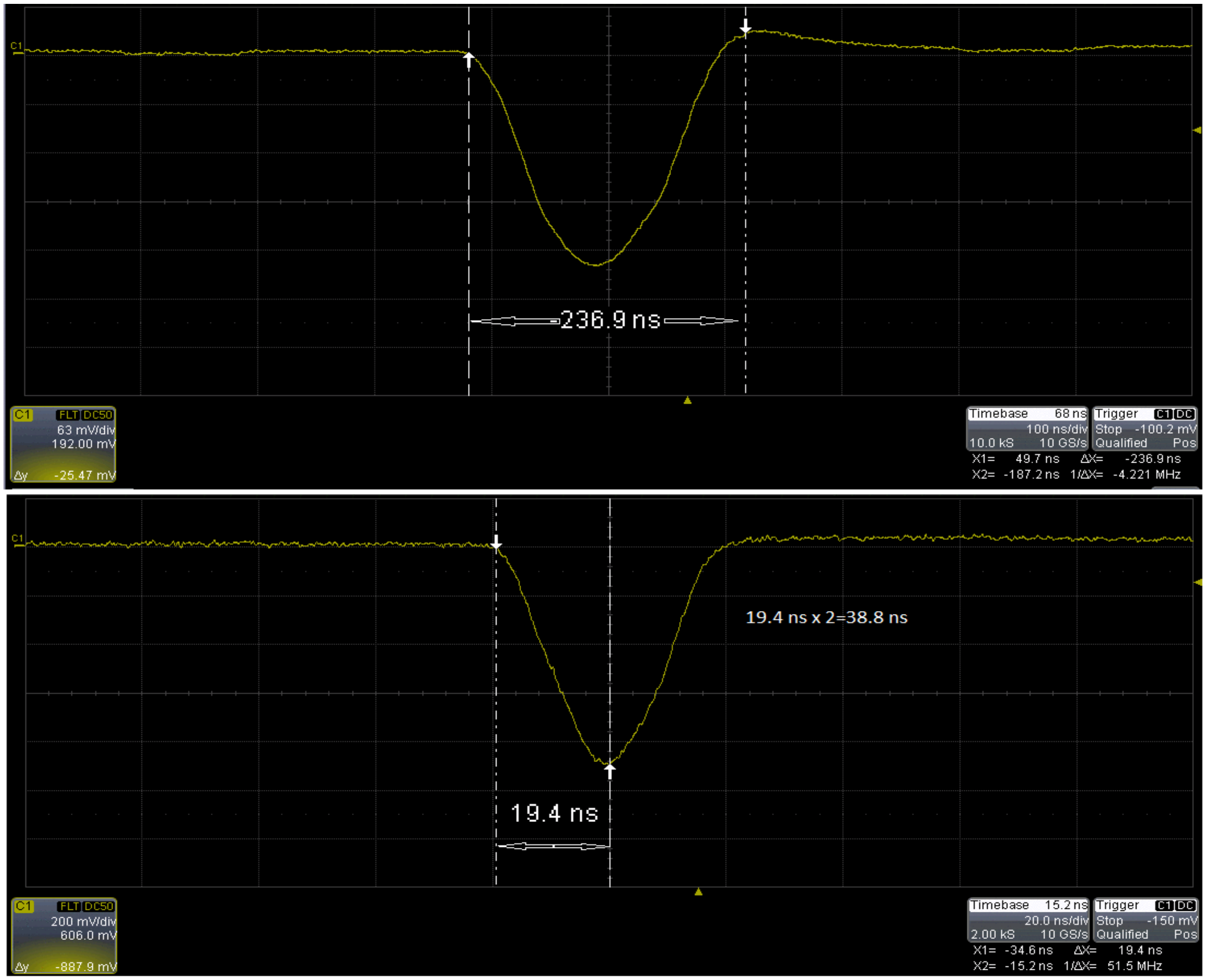


Figure 1: Typical bunch length measurements early in the ramp (top) and on the flattop (bottom). These measurements happen to be for a 5.75 GeV setup with a 6-3-1 merge (row 15 in Table IV).[1]

[1] There are many such examples in the Booster-AGS-EBIS 2018 elog. These are taken from the June 11th 1621 and 1635 entries.

Included in the table data is a column called signal amplitude which is the approximate amplitude, in divisions, of the WCM bunch signal on the scope for that set of measurements. It's relevant because there is some indication that the larger the amplitude is the larger the measured bunch length. I compared the bunch lengths in an extreme case (on the flattop) using the same setup, and for a 5.5 division amplitude the average of 4 measurements was 30.50 ns (σ=0.78 ns), but when the gain was lowered to provide an amplitude of about 2.3 divisions the average of 7 measurements was 29.43 ns (σ=0.92).[2] In the higher amplitude case the length was 3.6% longer, so the ε obtained would be 7.4% higher. I attempted to keep the amplitudes similar across the measurements, but I could have been more scrupulous about it. I think the error due to this should be significantly less than 7%, since the full range of the signal amplitude over all the measurements was less than for this extreme case.

On May 24th, about a week into the study, I also began to take measurements of the bunch's full width at half maximum (fwhm). The scope performs these measurements automatically, so they are not subjective. The bunch's fwhm is used to calculate the fwhm ε and the value used is also an average of 10 of these measurements. As with the full-length case, the early ramp fwhm is not measured for every different setup, but only when it's thought to be necessary. Figure 2 shows typical early and flattop fwhm bunch length measurements. Note that the flattop fwhm is not twice the width (or length) of the leading side as in the full-length data. I don't think this is a problem because the part of the bunch measured is generally quite symmetric.

f_s was found by measuring the period of bunch shape oscillations on the WCM near the time in the cycle that the bunch length measurements are taken. These oscillations are often visible, and if they're not they are induced by changing the Rf voltage non-adiabatically or turning off the Rf feedback loops. Figure 3 shows an example of such a measurement. The Rf frequency is determined using the GPM AGS/RF/LLRF/agsDsp_T0.mon from the value of *Frev_system* at the measurement time multiplied by the Rf harmonic. For the early ramp measurements the dB/dt is very small (~2 g/ms), but is typically included in the ε calculation.

The intensity at the time of the measurements was not measured since the EBIS intensity fluctuated a lot over the course of them and the ε has not given any indication that it depends on the bunch intensity in the AGS. So, recording the bunch intensities would be misleading and not really contribute anything beyond illustrating how much they vary. Instead the estimated bunch intensity found in the tables is just 4.5e8 times the number of bunches merged except where an 8-4-2 or 6-3-1 merge is used in which case that is reduced by 5% to 4.275e8 to account for the presence of baby bunches. These estimates will differ from the actual bunch intensity depending on the EBIS and injector performance, but the estimated values are not particularly optimistic. Also, the bunch intensities quoted are for the AGS flattop and because the transfer efficiency to

[2] This was done with the 5.75 GeV, F bank only, 3-1 merge (row 6 in Table IV). See Booster-AGS-EBIS 2018 elog Jun 8 2105 and 2106 entries.

RHIC is less than 100%, the bunch intensities in RHIC will be lower by some amount. That efficiency will tend to be lower for lower energies and higher emittances. Even so, it was as high as 90% or so for the 3.85 GeV setup. This was probably because the 2-1 merge produced bunches whose ε was only about 0.24 eV-s/n (see Table II).[3]

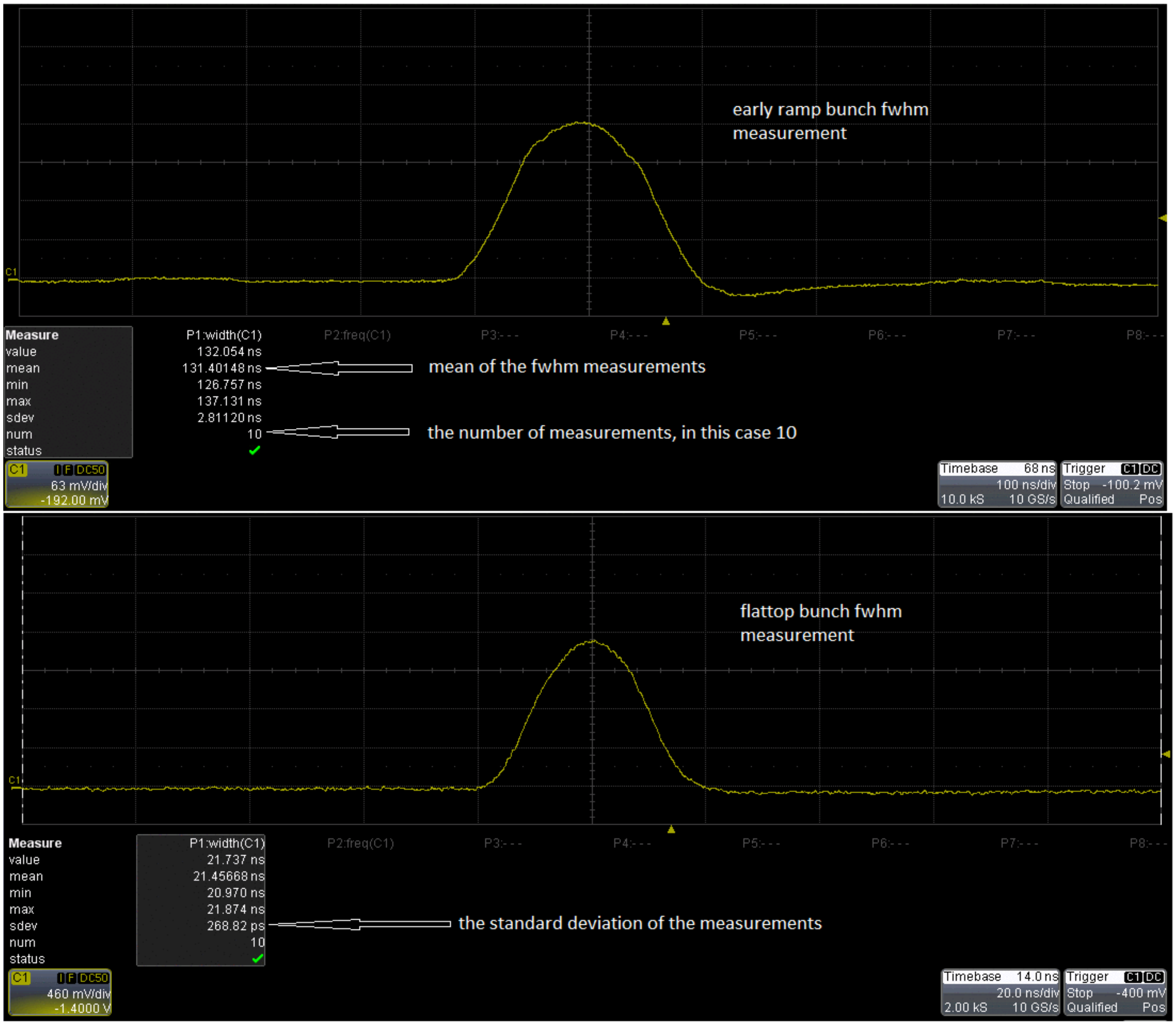


Figure 2: Typical bunch fwhm measurements early in the ramp (top) and on the flattop (bottom). These are the average of 10 measurements performed automatically by the scope. These measurements are also for the 5.85 GeV setup with a 6-3-1 merge (row 15 in Table IV).

[3] For example, on Jun 2 for the fill around 320 AM (#21938) during the low energy run, the AGS xcbm was about 1.5e9 (for 2 bunches, LogView file MCR/InjectorPerformance.logreq) and the average RHIC bunch intensity was 0.682e9 (see I. Zhang, Booster-AGS-EBIS elog Jun 29 1456 entry). This gives a transfer efficiency of 0.682/0.75=91%.

Emittance Calculation for Flattop Energies near Transition and the value of γ_t

It was noticed during the data taking for 7.30 GeV that the Rf voltage determined from the measured f_s was more than 20% higher than it was for similar Rf voltage settings at the other energies. This prompted me to try to measure the transition energy since if it was different from what's used in the ε calculation the voltage required to yield a given f_s would be different and this effect would be greater the closer one is to transition energy (γ=7.84 for 7.3 GeV) and that would affect the calculated ε.

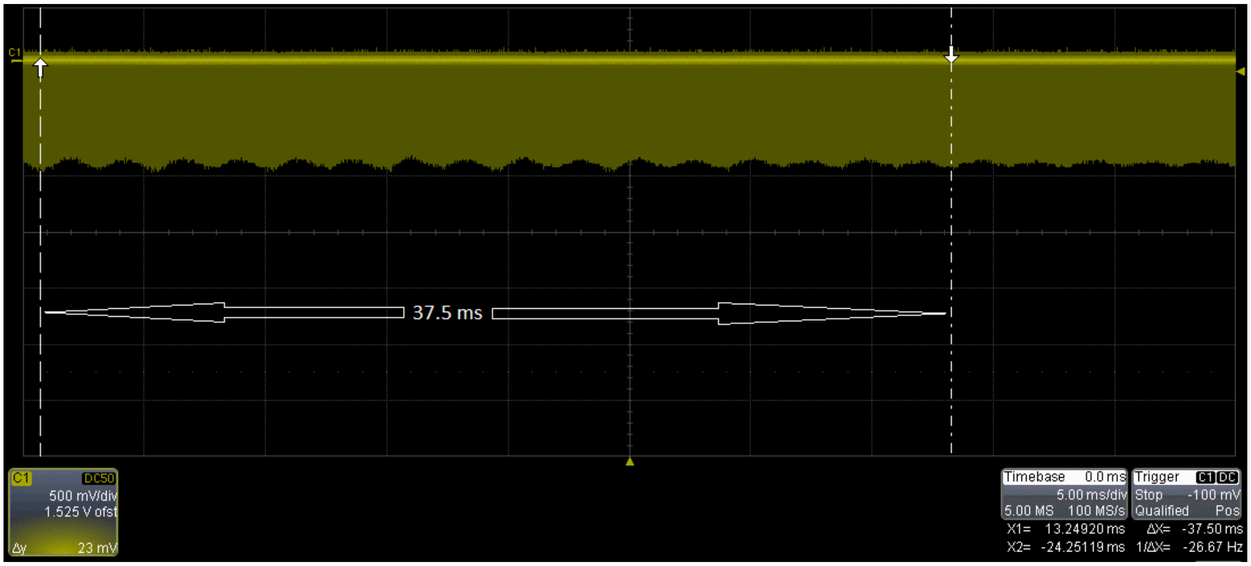


Figure 3: Typical synchrotron frequency measurement using the WCM. Once again this was performed on the 5.75 GeV flattop with the 6-3-1 merge setup (row 15 in Table IV). There are 8 bunch shape oscillations in 37.5 ms, so the synchrotron frequency is 8/(37.5 ms)=213 Hz. These oscillations were not intentionally induced.

The curious thing however is that the next day f_s was significantly lower, and I was unable to reproduce the higher frequency again.[4] The reason for this is not known, perhaps the scope was triggering at the wrong time. I made the measurement anyway and obtained a value for γ_t of 8.407.[5] The BBat program, which is used to calculate the ε, uses a value for γ_t of 8.50 and using a value of 8.407 instead increases the calculated ε for 7.30 GeV by about 15%.[6] This

[4] See Booster-AGS-EBIS 2018 elog Jun 12th for the high f_s measurement (1826 entry in particular, 92.2 Hz) and Jun 13th 1922 entry for the lower measurement (76.1 Hz).
[5] See K. Zeno, "Run 18 in the Injectors", C-A/AP/610, September 2018, pages 34-37. The difference between these 2 energies (8.407 and 8.50) corresponds to about 6 ms on the normal 9.8 GeV cycle, and changes in the timing of the transition phase jump on the order of a ms are probably significant so this discrepancy is significant. The beam barely survives when γ_t is set to 8.50 (of course, this measurement was taken with the γ_t jump off).
[6] To calculate ε using a γ_t other than 8.50 I use the program bbrat which takes γ_t as an input.

change also increases the calculated ε at 5.75 GeV (γ=6.18) but to a lesser extent (~2.5%). On the other hand, it reduces the calculated ε at 9.80 GeV (γ=10.52) by about 5%.

The calculated ε values shown in Table V for 7.30 GeV use γ_t=8.407 and the ones for 3.85, 4.55, and 5.75 GeV use γ_t=8.50 since the effect is much smaller at these energies. It's also true that γ_t, or more accurately the momentum compaction factor, is not constant through the cycle. However, since 7.30 GeV is not far from transition it is probably reasonable to use the measured value of γ_t for that data. As for 9.80 GeV cycle, the AGSModelViewer program was used to find γ_t from the model, which indicated 8.496 near transition time and 8.485 on the flattop. So, there is no indication that γ_t is much different at the two times and the model disagrees substantially with the measurement.[7]

When this value for γ_t is used (8.407) for both the 7.30 and 9.80 GeV data there is little difference between the flattop ε in both cases suggesting that very little ε growth occurs between the 2 energies.[8] For a similar setup using the 6-3-1 merge the flattop ε for 7.30 GeV is 0.77 eV-s/n and for 9.80 GeV it is 0.735 eV-s/n.[9] For the 6-3-1 merge the flattop ε is already 0.721 eV-s/n for a similar setup with 5.75 GeV. Nominal 6-3-1 data do not exist for the 4.55 GeV setup or 3.85 GeV cases, but it seems like, at least when the Pulsed, or P, voltage bank is used most of the growth occurs before 5.75 GeV.

Data Analysis

At first glance, there seems to be little advantage in using only the Flattop, or F, voltage bank for the energies above 4.55 GeV (for example, compare rows 15 and 16 in Table IV for 5.75 GeV). If the working hypothesis is correct, that the growth when on the P bank is due to resonance conditions when f_s and a large amplitude frequency component of the main magnet voltage are near each other, then it may be that f_s has already dropped low enough by the time the beam reaches 5.75 GeV that there are no longer any more important resonances to pass through. Although these resonance conditions would be expected to occur when only on the F bank as well, it was initially thought that their effect would be much less because the voltage ripple on the F bank is much less.

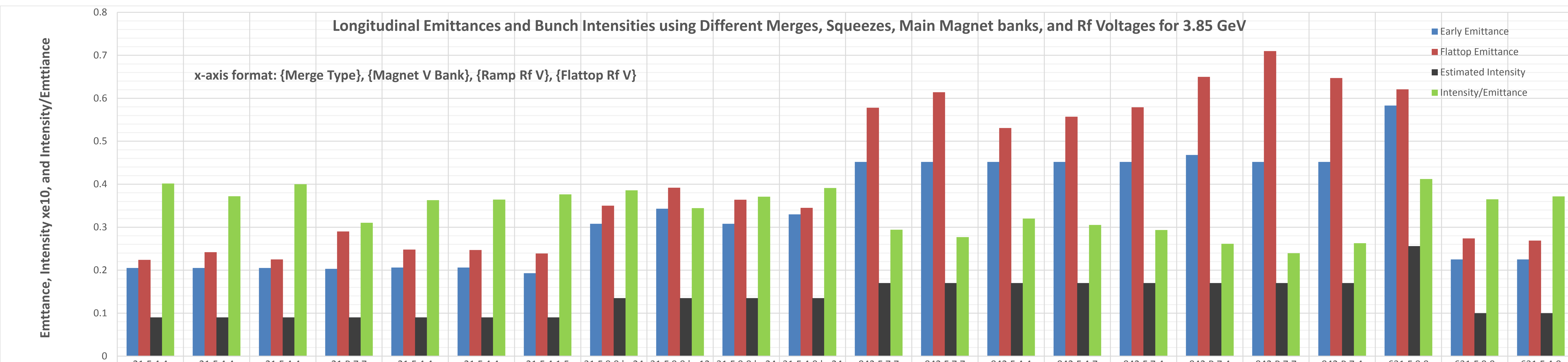
In Run 15, using the polarized proton magnet cycle some of the frequency components of the spectrum of the P bank voltage were measured: 360 Hz was the largest component, 720 Hz was about half of that, and 1440 Hz was about a tenth of the 720 Hz component.[10] In the low ramping voltage case (a setting of about ~4 kV/gap and ~95 kV total gap voltage) f_s crosses 720 Hz around 2.3 kG and in the high ramping voltage case (7-8 kV/gap and about ~170-195 kV total) around 2.8-2.9 kG. Note that f_s is high early in the ramp (~3 kHz) and for a constant Rf voltage continues to drop until the flattop is reached, except for the 9.80 GeV cycle where the beam passes through transition.

[7] See K. Zeno, "Run 18 in the Injectors", C-A/AP/610, September 2018, page 34.
[8] When the ε or growth is discussed I am referring the full ε and its growth unless otherwise noted.
[9] The 7.30 GeV data is from row 3 in Table V and the 9.80 GeV data is from row 2 in Table VI.
[10] See Booster-AGS-pp 2016 elog of June 19th, entries 1531 to 1534

3.85 GeV

	Setup	Date	Rf har-monics	Voltage Bank	Early Ramp ε	Flattop ε	Growth	Ramp V (kV)	Flattop V (kV)	Flattop synch freq (Hz)	early fwhm ε	Flattop fwhm ε	Growth	Est. Int. ($x10^{10}$)	Intensity over flattop ε	Signal ampl.	Notes
1	21,F,4,4	5/15	24-12	F	0.205	0.224	1.09	4	4	340 Hz				0.09	0.40	2	DC phase loop without radial loop
2	21,F,4,4	5/15	24-12	F	0.205	0.242	1.18	4	4	340.6				0.09	0.37	2	AC phase loop only
3	21,F,4,4	5/16	24-12	F	0.205	0.225	1.10	4	4	340.6				0.09	0.40	2	DC phase loop without radial loop
4	21,P,7,7	5/16	24-12	P	0.203	0.290	1.43	7	7	448.6				0.09	0.31	3	AC phase loop only
5	21,F,4,4	5/17	24-12	F	0.206	0.248	1.20	4	4	343.6				0.09	0.36	2.5	DC phase loop with radial loop and radial and phase zeroing
6	21,F.4.4	5/17	24-12	F	0.206	0.247	1.20	4	4	343.6				0.09	0.36	2.5	DC phase loop without radial loop
7	21,F,4,1.5	6/1	24-12	F	0.193	0.239	1.24	3.9	1.5	210.7	0.0626	0.0685	1.09	0.09	0.38	2.8	AC phase loop only
8	31,F,8,8,h=24	6/6	24/12-4	F	0.308	0.350	1.14	8	8	464.9	0.112	0.126	1.13	0.135	0.39	3.5	AC phase -> b. control, h=24 injection, poor h=12 phasing post-merge, 3 bunch ε before ramp is 0.294. h=24 bunches have sharper edges.
9	31,F,8,8,h=12	6/6	12-4	F	0.343	0.392	1.14	8	8	464.9	0.112	0.123	1.10	0.135	0.34	2.1	AC phase then beam control, h=12 injection, h=12 phasing after merge not optimal, 3 bunch ε before ramp is 0.322
10	31,F,8,8,h=24	6/6	24/12-4	F	0.308	0.364	1.18	8	8	464.9	0.112	0.135	1.21	0.135	0.37	2.5	AC phase then beam control, h=24 injection, using early ramp ε meas. from (8) since this is before kicker adjustment.
11	31,F,4,8,h=24	6/6	24/12-4	F	0.330	0.345	1.05	4	8	464.9	0.126	0.131	1.04	0.135	0.39	3.5	AC phase then beam control, h=24 injection, adjusted (A5) kicker timing.
12	842,F,7,7	5/17	16-8-4	F	0.452	0.578	1.28	7	7	464				0.17	0.31	3	AC phase loop then beam control (DC phase and radial loops), early ε from (13)
13	842,F,7,7	5/18	16-8-4	F	0.452	0.614	1.36	7	7	461.5				0.17	0.29	3	Same conditions as (12) but on next day
14	842,F,4,4	5/18	16-8-4	F	0.452	0.531	1.17	4	4	360.1				0.17	0.34	3	AC phase loop then beam control (DC phase and radial loops), using early ε from (13)
15	842,F.4,7	5/18	16-8-4	F	0.452	0.557	1.23	4	7	465.4				0.17	0.32	2.5	AC phase loop then beam control (DC phase and radial loops), using early ε from (13)
16	842,F,7,4	5/18	16-8-4	F	0.452	0.579	1.28	7	4	360.1				0.17	0.31	3.5	AC phase loop then beam control (DC phase and radial loops), using early ε from (13)
17	842,P,7,4	5/21	16-8-4	P	0.468	0.650	1.39	7	4	367.5				0.17	0.28	3.5	Q.P. on at Booster extraction (normally off), AC phase loop then beam control
18	842,P,7,7	5/22	16-8-4	P	0.452	0.71	1.57	7	7	471.1				0.17	0.25	3.5	AC phase loop then beam control, 'hold for synchro' on, using early ε from (13)
19	842,P,7,4	5/22	16-8-4	P	0.452	0.647	1.38	7	4	360.5				0.18	0.28	3	AC phase loop then beam control, 'hold for synchro' on, using early ε from (13)
20	631,F,8,8	6/5	24-12-4	F	0.583	0.621	1.07	8	8	450.5	0.214	0.204	0.95	0.256	0.41	3	AC phase loop, beam control, Using normal (9.8 GeV) cycle early ε
21	631,F,8,8	6/14	24-12-4	F	0.225	0.274	1.22	8	8	489.9	0.085	0.094	1.11	0.10	0.36	2.3	No KL squeeze, L10 lowered to provide 1.0e9/bunch, AC phase then beam control
22	631,F,4,8	6/14	24-12-4	F	0.225	0.269	1.20	4	8	489.9	0.085	0.092	1.08	0.10	0.37	2.5	No KL squeeze, L10 lowered to provide 1.0e9/bunch, AC phase then beam control

Table II: ε measurements made with a 3.85 GeV flattop. Voltage bank: F indicates only the Flattop main magnet voltage bank was used for the ramp and P indicates that both the Flattop and Pulsed V banks were used. The early Ramp ε is measured at the beginning of the ramp, just after the merge and squeeze. Growth is (flattop ε)/(early ε). Ramp V is the Rf cavity voltage setting for most of the ramp and Flattop V is the Rf cavity voltage setting on the flattop where the ε and flattop synchrotron frequency measurements are taken. The early and flattop fwhm ε are the ε at full width half maximum. The 'growth' column to the right of those is (flattop fwhm ε)/(early fwhm ε). The Est. Int. is the estimated flattop bunch intensity usually, but not always, assuming that the bunch intensity is ($0.045x10^{10}$)*N where N is the number of bunches that have been merged. Signal amplitude is roughly the number of vertical divisions on a scope that the WCM signal occupied when the bunch length measurement was taken.



	21,F,4,4	21,F,4,4	21,F,4,4	21,P,7,7	21,F,4,4	21,F,4,4	21,F,4,1.5	31,F,8,8,h=24	31,F,8,8,h=12	31,F,8,8,h=24	31,F,4,8,h=24	842,F,7,7	842,F,7,7	842,F,4,4	842,F,4,7	842,F,7,4	842,P,7,4	842,P,7,7	842,P,7,4	631,F,8,8	631,F,8,8	631,F,4,8
Early Emittance	0.205	0.205	0.205	0.203	0.206	0.206	0.193	0.308	0.343	0.308	0.33	0.452	0.452	0.452	0.452	0.452	0.468	0.452	0.452	0.583	0.225	0.225
Flattop Emittance	0.224	0.242	0.225	0.29	0.248	0.247	0.239	0.35	0.392	0.364	0.345	0.578	0.614	0.531	0.557	0.579	0.65	0.71	0.647	0.621	0.274	0.269
Estimated Intensity	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.135	0.135	0.135	0.135	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.256	0.1	0.1
Intensity/Emittance	0.40	0.37	0.40	0.31	0.36	0.36	0.38	0.39	0.34	0.37	0.39	0.29	0.28	0.32	0.31	0.29	0.26	0.24	0.26	0.41	0.36	0.37

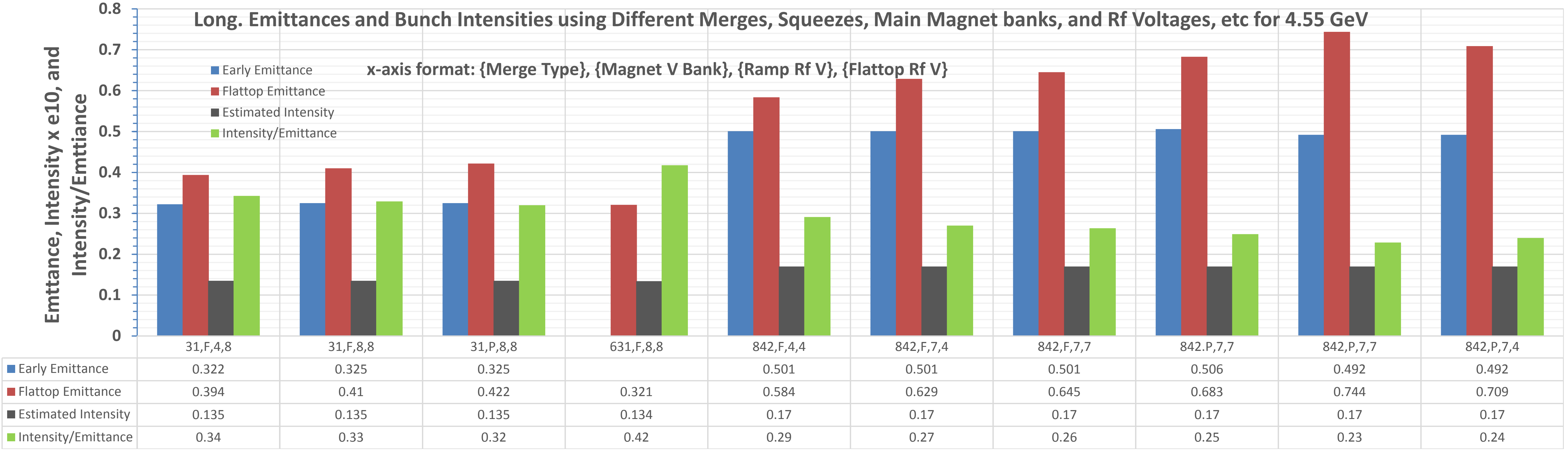
Row in Table I | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |

Figure 4: Selected data from the 22 3.85 GeV setups in Table II.

4.55 GeV

	Setup	Date	Rf harmonics	Voltage Bank	Early Ramp ε	Flattop ε	Growth	Ramp V (kV)	Flattop V (kV)	Flattop synch freq (Hz)	early fwhm ε	Late fwhm ε	Growth	Est Int. ($x10^{10}$)	Intensity over flattop ε	Signal Amplitude	Notes
1	31,F,4,8	6/8	24/12-4	F	0.322	0.394	1.22	4	8	343.3	0.124	0.132	1.06	0.135	0.34	3.2	Injection into h=24, AC phase then beam control, flattop measurement at 4200 ms
2	31,F,8,8	6/11	24/12-4	F	0.325	0.410	1.26	8	8	348	0.130	0.129	0.99	0.135	0.33	3	Injection into h=24, AC phase then beam control, scope gain matched to 4.55 GeV, 4200 ms
3	31,P,8,8	6/11	24/12-4	P	0.325	0.422	1.30	8	8	348	0.130	0.128	0.98	0.135	0.32	3	Same as (2) but P bank, 4200 ms
4	631,F,8,8	6/13	24-12-4	F		0.321		8	8	361.3		0.123		0.134	0.42	2.5	No KL squeeze, L10 lowered to get 1.34e9/bunch, AC phase then beam control, scope, 4200 ms
5	842,F,4,4	5/22	16-8-4	F	0.501	0.584	1.17	7	4	269.6				0.17	0.31	3	AC phase then beam control, ‘hold for synchro’ on, flattop measurements at 3200 ms
6	842,F,7,4	5/22	16-8-4	F	0.501	0.629	1.26	7	4	269.6				0.17	0.29	3	AC phase then beam control, ‘hold for synchro’ on, flattop measurements at 3200 ms
7	842,F,7,7	5/22	16-8-4	F	0.501	0.645	1.29	7	7	344.5				0.17	0.28	3	AC phase then beam control, ‘hold for synchro’ on, flattop measurements at 3200 ms
8	842,P,7,7	5/22	16-8-4	P	0.506	0.683	1.36	7	7	345.6				0.17	0.26	3	AC phase then beam control, ‘hold for synchro’ on, flattop measurements at 3200 ms
9	842,P,7,7	5/24	16-8-4	P	0.492	0.744	1.51	7	7	340.9		0.166		0.17	0.24	3.5	AC phase then beam control, ‘hold for synchro’ on, flattop measurements at 3200 ms
10	842,P.7,4	5/24	16-8-4	P	0.492	0.709	1.44	7	4	271.3		0.167		0.17	0.25	3.5	AC phase then beam control, ‘hold for synchro’ on, flattop measurements at 3200 ms

Table III: ε measurements made with a 4.55 GeV flattop. The organization is the same as in Table II.



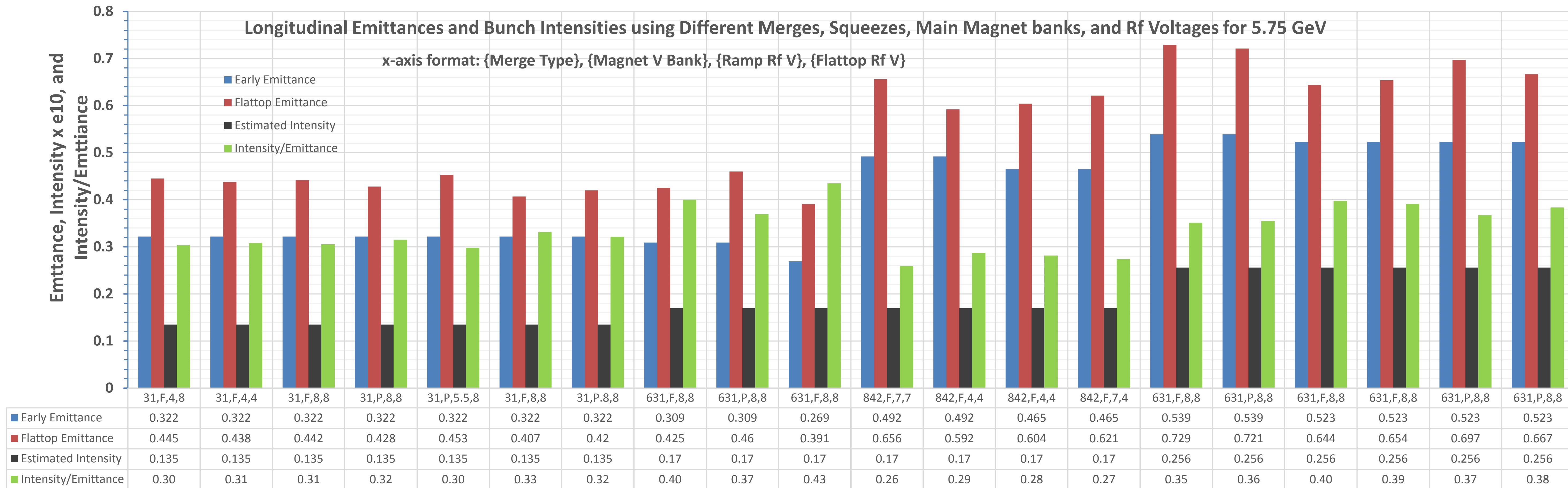
Row in Table III | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

Figure 5: Selected data from the 10 4.55 GeV setups in Table III.

5.75 GeV

	Setup	Date	Rf har-monics	Voltage Bank	Early Ramp ε	Flattop ε	Growth	Ramp V (kV)	Flattop V (kV)	Flattop synch freq (Hz)	early fwhm ε	Late fwhm ε	Growth	Est Int. ($x10^{10}$)	Intensity over flattop ε	Signal amplitude	Notes
1	31,F,4,8	6/8	24/12-4	F	0.322	0.445	1.38	4	8	202.8	0.124	0.141	1.14	0.135	0.30	4	AC phase then beam control, injection into h=24, flattop measurements at 4400 ms
2	31,F,4,4	6/8	24/12-4	F	0.322	0.438	1.36	4	4	150.1	0.124	0.136	1.10	0.135	0.31	3.5	AC phase then beam control, injection into h=24, flattop measurements at 4400 ms, early ε measurements from (1)
3	31,F,8,8	6/8	24/12-4	F	0.322	0.442	1.37	8	8	202.8	0.124	0.139	1.12	0.135	0.31	4	AC phase then beam control, injection into h=24, flattop measurements at 4400 ms, early ε measurements from (1)
4	31,P,8,8	6/8	24/12-4	P	0.322	0.428	1.33	8	8	202.8	0.124	0.137	1.10	0.135	0.32	4	AC phase then beam control, injection into h=24, flattop measurements at 4400 ms, early ε measurements from (1)
5	31,P,5.5,8	6/8	24/12-4	P	0.322	0.453	1.41	~5.5	8	202.8	0.124	0.135	1.09	0.135	0.30	4	AC phase then beam control, injection into h=24, flattop measurements at 4400 ms, early ε measurements from (1)
6	31,F,8,8	6/8	24/12-4	F	0.322	0.407	1.26	8	8	202.8	0.124	0.133	1.07	0.135	0.33	3	AC phase->b. control, h=24 injection, flattop meas. at 4400 ms, early ε meas. from (1)
7	31,P,8,8	6/8	24/12-4	P	0.322	0.420	1.30	8	8	202.8	0.124	0.138	1.11	0.135	0.32	3.2	AC phase->b. control, h=24 injection, flattop meas. at 4400 ms, early ε meas. from (1)
8	631,F,8,8	6/11	24-12-4	F	0.309	0.425	1.38	8	8	213.8	0.154	0.158	1.03	0.17	0.40	2.5	No KL squeeze, L10 lowered to get 1.7e9, AC phase->beam control, with squeeze bunch intensity was ~2.2e9
9	631,P,8,8	6/11	24-12-4	P	0.309	0.460	1.49	8	8	213.4	0.154	0.160	1.04	0.17	0.37	2.5	No KL squeeze, L10 lowered to get 1.7e9, AC phase->beam control, with squeeze bunch intensity was ~2.2e9
10	631,F,8,8	6/14	24-12-4	F	0.269	0.391	1.45	8	8	190	0.141	0.136	0.96	0.17	0.43	2.5	L10 lowered, 1.7e9,4300 ms, new loop gains, full squeeze, gain matched, ac phase loop/beam control
11	842,F,7,7	5/24	16-8-4	F	0.492	0.656	1.33	7	7	203.2	0.151	0.181	1.20	0.17	0.27	3.5	AC phase then beam control, flattop measurements at 3500 ms, early fwhm ε is from (13)
12	842,F,4,4	5/24	16-8-4	F	0.492	0.592	1.20	4	4	159.7	0.151	0.180	1.19	0.17	0.30	3	AC phase then beam control, flattop measurements at 3500 ms, early ramp ε is from (11)
13	842,F,4,4	5/29	16-8-4	F	0.465	0.604	1.30	4	4	160.5	0.151	0.183	1.22	0.17	0.30	3.5	AC phase then beam control, flattop measurements at 3500 ms
14	842,F,7,4	5/29	16-8-4	F	0.465	0.621	1.34	7	4	160.5	0.151	0.180	1.19	0.17	0.29	3.5	AC phase then beam control, flattop measurements at 3500 ms
15	631,F,8,8	6/11	24-12-4	F	0.539	0.729	1.35	8	8	213.4	0.193	0.219	1.13	0.256	0.35	2.5	AC phase then beam control, flattop measurements at 4400 ms
16	631,P,8,8	6/11	24-12-4	P	0.539	0.721	1.34	8	8	213.4	0.193	0.228	1.18	0.256	0.36	2.3	AC phase then beam control, flattop measurements at 4400 ms
17	631,F,8,8	6/14	24-12-4	F	0.523	0.644	1.23	8	8	190	0.193	0.200	1.04	0.256	0.40	2.7	new loop gains, full squeeze, ac phase then beam control, early ramp ε from 6/15 normal cycle
18	631,F,8,8	6/14	24-12-4	F	0.523	0.654	1.25	8	8	190	0.193	0.207	1.07	0.256	0.39	2.5	old loop gains, full squeeze, ac phase then beam control, early ramp ε from 6/15 normal cycle
19	631,P.8,8	6/14	24-12-4	P	0.523	0.697	1.33	8	8	190	0.193	0.213	1.10	0.256	0.37	2.5	old loop gains, full squeeze, ac phase then beam control, early ramp ε from 6/15 normal cycle
20	631,P,8,8	6/14	24-12-4	P	0.523	0.667	1.28	8	8	190	0.193	0.203	1.05	0.256	0.38	2.5	new loop gains, full squeeze, ac phase then beam control, early ramp ε from 6/15 normal cycle

Table IV: ε measurements made with a 5.75 GeV flattop. The organization is the same as in Table II.



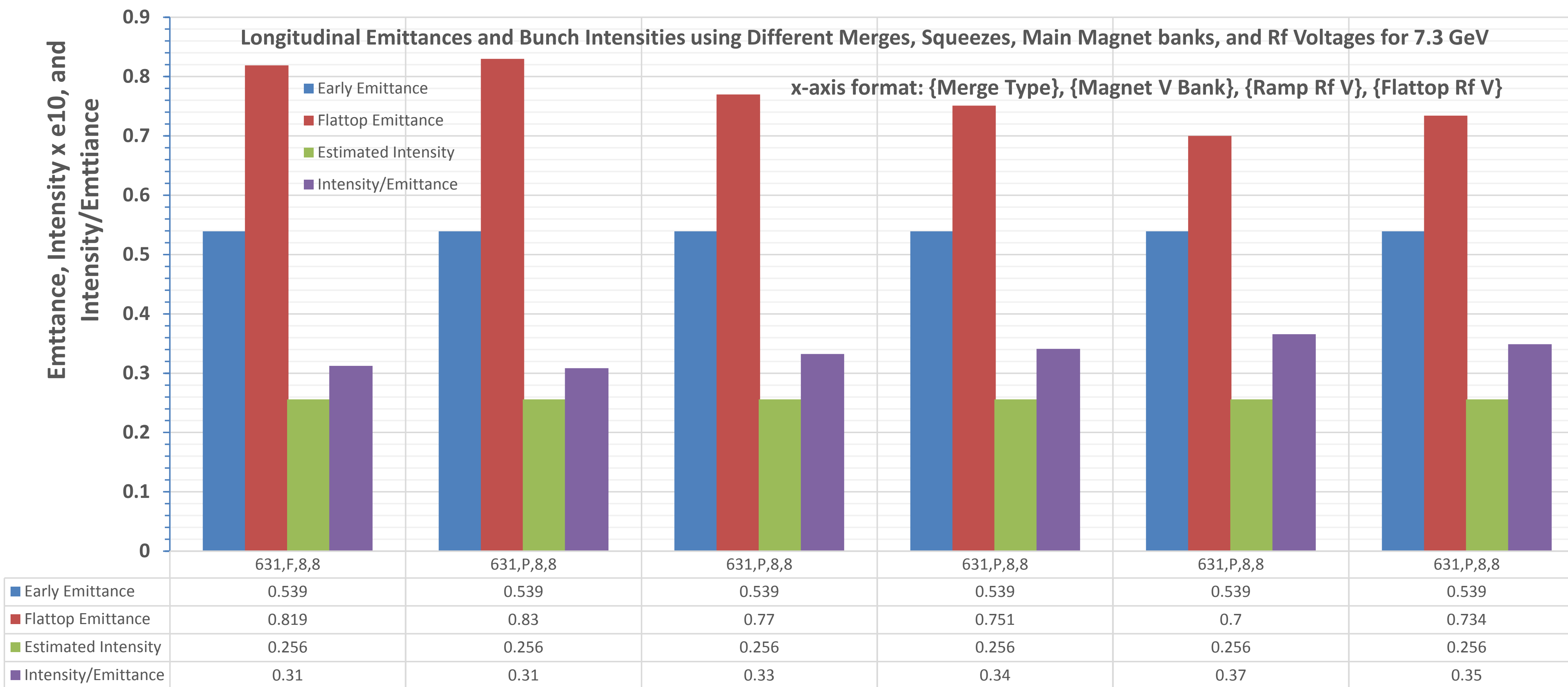
Row in Table IV | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |

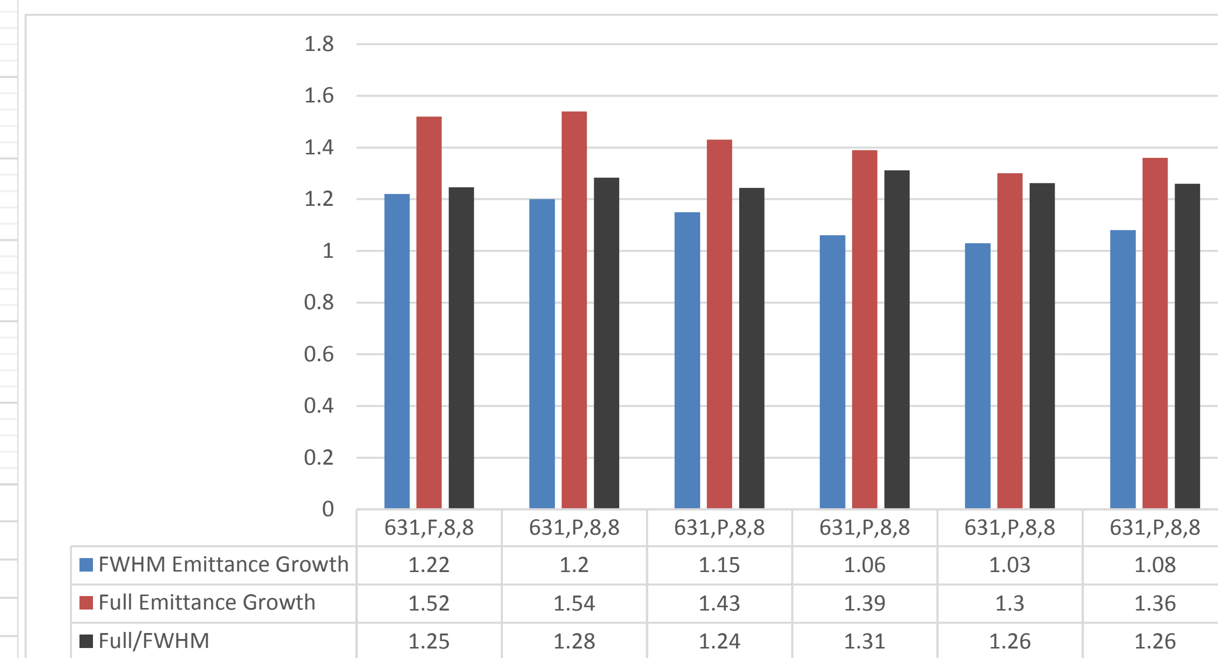
Figure 6: Selected data from the 20 5.75 GeV setups in Table IV.

7.30 GeV

	Setup	Date	Rf har-monics	Voltage Bank	Early Ramp ε	Flattop ε	Growth	Ramp V (kV)	Flattop V (kV)	Flattop synch freq (Hz)	early fwhm ε	Late fwhm ε	Growth	Est Int. (x10^{10})	Intensity over flattop ε	Signal Amplitude	Notes
1	631,F,8,8	6/13	24-12-4	F	0.539	0.819	1.52	8	8	76.1	0.193	0.236	1.22	0.256	0.31	2.7	AC phase to beam control, γt=8.407 in ε calculations, flattop measurements at 4900ms
2	631,F,8,8	6/13	24-12-4	P	0.539	0.830	1.54	8	8	72.3	0.193	0.231	1.20	0.256	0.31	2.5	AC phase to beam control, γt=8.407 in ε calculations, flattop measurements at 4200ms
3	631,F,8,8	6/14	24-12-4	P	0.539	0.770	1.43	8	8	72.6	0.193	0.222	1.15	0.256	0.33	2.6	early flattop measurements at 3800ms, AC phase to beam control, γt=8.407 in ε calculations
4	631,F,8,8	6/14	24-12-4	P	0.539	0.751	1.39	8	8	72.6	0.193	0.205	1.06	0.256	0.34	2.6	Still 3800 ms, different loop gains, AC phase to beam control, γt=8.407 in ε calculations
5	631,F,8,8	6/14	24-12-4	P	0.539	0.700	1.30	8	8	72.6	0.193	0.199	1.03	0.256	0.37	2.5	Still 3800 ms, more loop changes, AC phase to beam control, γt=8.407 in ε calculations
6	631,F,8,8	6/14	24-12-4	P	0.539	0.734	1.36	8	8	72.6	0.193	0.208	1.08	0.256	0.35	2.5	Same as (5) but measured later on flattop (4200 ms)

Table V: ε measurements made with a 7.30 GeV flattop. The organization is the same as in Table II.





Row in Table IV | 1 | 2 | 3 | 4 | 5 | 6 | Row in Table IV | 1 | 2 | 3 | 4 | 5 | 6 |

Figure 7: Selected data from the 6 7.30 GeV setups in Table V (left) and FWHM and full emittance for the 6 setups (right).

9.80 GeV

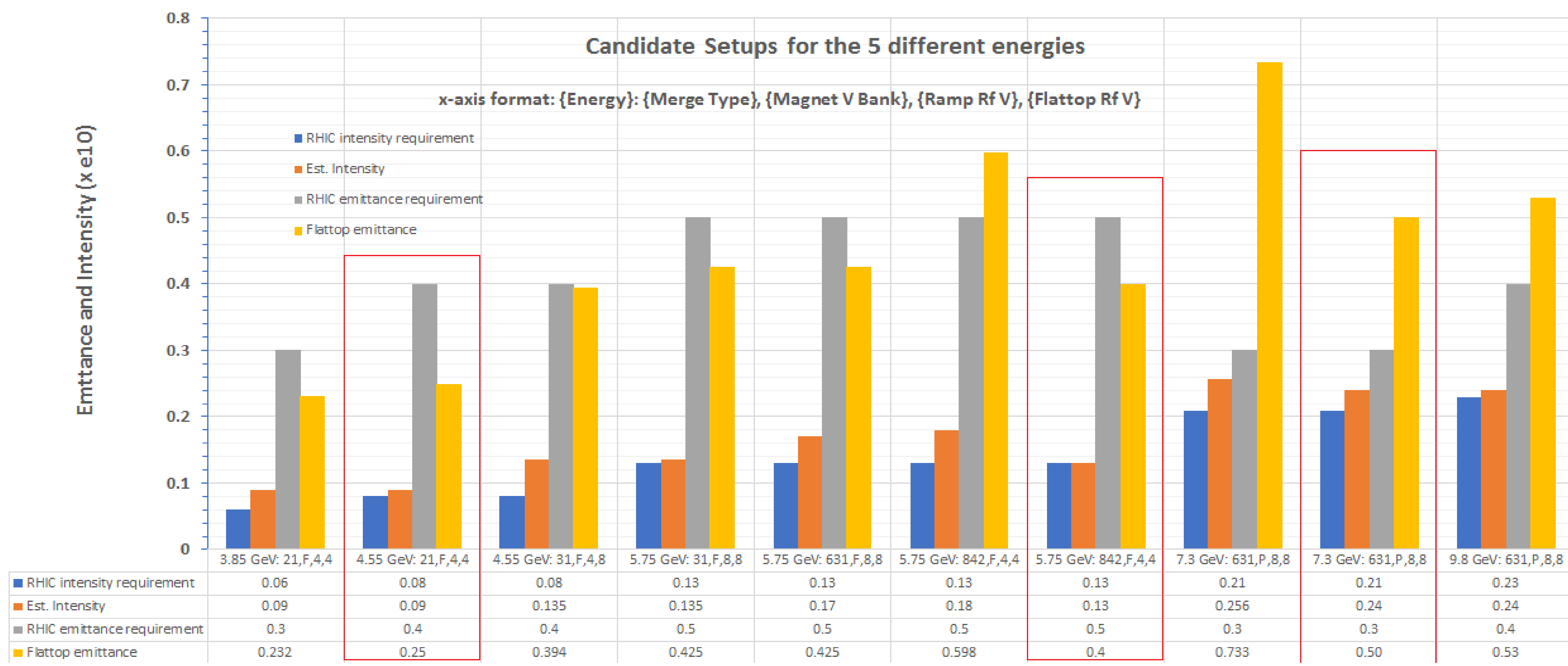
	Setup	Date	Rf har-monics	Voltage Bank	Early Ramp ε	Flattop ε	Growth	Ramp V (kV)	Flattop V (kV)	Flattop synch freq (Hz)	early fwhm ε	Late fwhm ε	Growth	Intensity (x10^{10})	Intensity over flattop ε	Signal Amplitude	Notes
1	631,F,8,8	6/15	24-12-4	P	0.523	0.782	1.50	8	8	97.2	0.187	0.224	1.20	0.21	0.27	2.3	Nominal setup for RHIC, using γt=8.50 for calculations
2	631,F,8,8	6/15	24-12-4	P	0.523	0.735	1.41	8	8	97.2	0.187	0.211	1.13	0.21	0.29	2.3	Same as above but using γt=8.407 for calculations

Table VI: ε measurements made with a 9.80 GeV flattop. The same organization as in Table II except the intensity is actual not estimated.

Candidate Setups to best meet RHIC requirements

	Energy: Setup	Date	Rf harmonics	Voltage Bank	Early Ramp ε	Flattop ε	Growth	Ramp V (kV)	Flattop V (kV)	RHIC ε and intensity req.		early fwhm ε	Late fwhm ε	Growth	Intensity ($x10^{10}$)	Intensity over flattop ε	Signal Amp.	# of bunches	Notes
1	3.85 GeV: 21,F,4,4	5/15-17	24-12	F	0.205	0.232	1.09	4	4	0.3	0.06				0.09	0.39	2	6	DC phase loop, average of 3 measurements
2	4.55 GeV:21,F,4,4		24-12	F	0.205	0.254	1.24	4	4	0.4	0.08				0.09	0.36		6	DC phase, estimated from (1) using the growth rate for 4.55 GeV (Table IX)
3	4.55 GeV:31,F,4,8	6/8	24/12-4	F	0.322	0.394	1.22	4	8	0.4	0.08	0.124	0.132	1.06	0.135	0.34	3.2	3	AC phase then beam control, h=24 injection
4	5.75 Gev:31,F,8,8	6/8	24/12-4	F	0.322	0.425	1.32	8	8	0.5	0.13	0.124	0.136	1.10	0.135	0.32	3.5	3	Avg. of 2 measurements, ac phase loop then beam control, h=24 injection
5	5.75 GeV:631, F,8,8	6/11	24-12-4	F	0.309	0.425	1.38	8	8	0.5	0.13	0.154	0.158	1.03	0.17	0.40	2.5	2	No KL squeeze, L10 lowered to get 1.7e9, ac phase then beam control
6	5.75 GeV:842,F,4,4	5/24,29	16-8-4	F	0.480	0.598	1.25	4	4	0.5	0.13	0.151	0.182	1.20	0.17	0.30	3.25	3	AC phase loop then beam control
7	5.75 GeV:842,F,4,4		16-8-4	F		0.40		4	4	0.5	0.13				0.13	0.35		3	Estimated for lowered L10 voltage, see caption.
8	7.30 GeV:631,P,8,8	6/14	24-12-4	P	0.539	0.734	1.36	8	8	0.3	0.21	0.193	0.199	1.08	0.256	0.37	2.5	2	new loop gains, ac phase loop then beam control, using γ_t of 8.407
9	7.30 GeV:631,P,8,8		24-12-4	P		0.50		8	8	0.3	0.21				0.24	0.48		2	See caption, optimistic estimate, γ_t=8.50
10	9.80 GeV;631,P.8,8	4/27/16	24-12-4	P		0.53		8	8	0.4	0.23				0.24	0.45		2	No squeeze, L10 lowered, measured under best running conditions (γ_t=8.50)

Table VII: The best candidates out of all ε measurements for meeting the RHIC requirements and estimates for setups that were not measured (in red). Concerning the estimates: Row 2 is derived from the early ε measurement for 3.85 GeV and finds the flattop ε by multiplying it by the growth up the ramp for a similar 4.55 GeV setup (i.e.- (0.205 eV-s/n)*1.22=0.250 where 1.22 is the growth for row 1 in Table III). Row 7 uses the 842 merge without the squeeze and with L10 lowered as in row 5 (which uses the 631 merge). The estimated intensity in that case is the (estimated) intensity for the nominal 842 merge (row 6) scaled by the ratio of the intensity for row 5 (0.17e10) and the full intensity when the row 5 data was taken (0.22e10). That is, 0.17e10*0.17/0.22=0.13e10. Similarly, the estimated ε is its value for the nominal 842 merge (0.604 eV-s/n, row 13 in Table IV) scaled by the ratio of the ε for row 5 (0.425 eV-s/n) and the full 631 ε (0.644 eV-s/n, row 17 in Table IV) or (0.604 eV-s/n)*0.425/0.644=0.40 eV/s/n. Row 9 is derived from the measured ε for the standard 9.80 GeV cycle that was measured with no squeeze and L10 lowered and taken during the best running conditions in Run 16. It uses the ε measured then adjusted for a γ_t of 8.407 (0.95*0.53eV-s/n=0.504 eV-s/n from row 10) multiplied by the ratio of the ε measured for 7.30 GeV (0.734 eV-s/n, see row 6 in Table V) and that measured for the typical 9.80 GeV cycle (0.735 eV-s/n, row 1 in Table VI) or (0.734 eV-s/n)*0.504/0.735=0.50 V-s/n. The estimated intensity used is that quoted in row 10.



Row in Table VII | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

Figure 8: Comparing the intensity and emittance for the candidate setups with the RHIC requirements. The cases framed in red are the estimates for setups where the actual intensity and emittance were not measured.

The time that the transfer from the F to P bank occurs is important because if the resonances occur after that then the beam will encounter the P bank voltage ripple. The transfer occurs on all cycles well below 2.3 kG so, in cases where there is a transfer, the magnet will be on the P bank when it crosses 720 Hz. This is not so for 1440 Hz, with the 2-1 and 8-4-2 type P bank magnet cycles the transfer will typically happen before 1440 Hz is crossed and for the 6-3-1 magnet cycles (with high Rf voltage, which is all but one of them) f_s crosses 1440 Hz too near the time of the transfer to determine whether it occurs before or after it.[11] All the magnet cycles, including what fields the transfers occur at on each of the P bank cycles, are shown in the Appendix.

There is a lot of data for different setups and it is hard to analyze it in a simple way. But one observation about the growth of the full ε up the ramp, at least when on the normal 9.80 GeV cycle which uses the P bank, that can be taken advantage of is that it is independent of the full ε at the beginning of the ramp.[12] With this in mind, data from all the different merges for a specific flattop energy can be put into two groups; one with and one without the P bank. First only sets of data where the ramp and flattop voltages are high (i.e.-7 or 8 kV/gap on most of the cavity gaps) will be considered.

With the 3.85 GeV cycle, when the Rf voltage is kept high on the ramp and flattop, f_s through the ramp and on flattop will remain higher than 360 Hz but it will pass through 1440 and then 720 Hz.[13] The average growth for the 7 measurements with only the F bank is 1.18 with a σ of 0.10. There were 2 measurements made using the P bank which were significantly higher (1.43 and 1.57).[14] In the P bank cases the Rf ramping voltage is high (~170 kV) and f_s passes through 720 and 1440 Hz while on the P bank. Evidence from Run 16, using the normal 9.80 GeV cycle, suggests the 720 Hz component has an effect and the 1440 Hz component does not.[15]

For 4.55 GeV, f_s always passes through 360 Hz, but when the P bank is used the growth for the 3 measurements taken is similar to that for 3.85 GeV: 1.38 with a σ of 0.10. Admittedly this seems odd since it is a larger component than 720 Hz. For the 8-4-2 cycles 1440 Hz is crossed while on the P bank and for the 3-1 cycle the crossing occurs too close to the F to P transfer to determine which bank it is on.

If it were true that the 720 Hz ripple was the only factor on the ramp that caused ε growth, the magnet cycles that use only the F bank should yield less ε growth regardless of the flattop energy. For 4.55 GeV, the average growth of the 3 setups that use only the F bank is 1.27 (σ=0.02) and, as mentioned above, the average growth for the P bank measurements is 1.38 (σ=0.10).[16] For 5.75 GeV, that average growth for the 8 cases that use only the F bank is 1.33 (σ=0.07) and for the 6 that also use the P bank it is

[11] The lowest field F to P transfer occurs at is on the 3.85 GeV 24-12 cycle (1.22 kG) and the highest is on the 4.55, 5.75, and 7.30 GeV 6-3-1 type cycles at 1.77 kG.

[12] See K. Zeno, "Overview and analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, September 2016, pgs. 33-35.

[13] The energy that the synchrotron frequency passes through 720 Hz depends on the Rf voltage, but in a typical high ramp voltage setup (~195 kV) it occurs near γ=3.28 or a field of 2.9 kG (3.85 GeV has γ= 4.13 and B=3.7 kG).

[14] The 3.85 GeV data for the F bank only and high Rf voltage is from rows 8,9,10,12,13,20, and 21 in Table II and with the P bank and high Rf voltage they're from rows 14 and 18.

[15] See K. Zeno, "Overview and analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, September 2016, pgs. 33-34. On the 6-3-1 type cycles the F to P transfer occurs at a somewhat lower field on the normal 9.80 GeV cycle (1.65 vs. 1.77 kG) than it does on all the other 6-3-1 type cycles (except for 3.85 GeV). This is because those cycles were constructed using a higher maximum F bank voltage of 1800 V instead of 1600V. But, if anything, the effect should be more noticeable if the F to P transfer were earlier.

[16] The 4.55 GeV data for the F bank only and high Rf voltage is from rows 1,2, and 7 and with the P bank and high Rf voltage they're from rows 3, 8, and 9 in Table III.

1.35 (σ=0.07).[17] For 7.30 GeV, there is only one measurement with only the F bank and it has a growth of 1.52 and the growth is 1.49 (σ=0.06) when the P bank is also used.[18] Table VIII summarizes the data.

So, it seems that using only the F bank for the 2 lowest energies is preferable, but that's not the case at the highest 2 energies. It seems reasonable to suspect that the extra time spent ramping when using only the F bank may be a drawback even if the growth mechanism isn't known. In fact, when the Table VIII data is plotted against flattop energy or just the time spent on the main acceleration ramp the growth is nearly linear (see Figure 9). Considering that, and the fact that the growth with the P bank cycles does not increase much between the lowest and highest energies, it may make sense for the magnet to stay on the F bank until f_s passes through 720 Hz and then switch to the P bank especially at the 2 or 3 highest flattop energies. It may also be the case that growth related to the length of the ramp occurs while on the P bank as well, in which case a high ramp rate on that bank would be preferable.

Energy	Full growth F bank only	Full growth with P bank
3.85 GeV	1.18±0.10 (7)	1.50±0.07 (2)
4.55 GeV	1.27±0.02 (3)	1.38±0.10 (3)
5.75 GeV	1.33±0.07 (8)	1.35±0.07 (6)
7.30 GeV	1.52	1.49±0.06 (2)
9.80 GeV	NA	1.41

Table VIII: Averages of full ε growths from early in the ramp to the flattop for all the data sets (i.e.-rows) where the ramp and flattop voltages are high. The uncertainties shown are the standard deviations of those measurements. The number of measurements for each case is shown in parentheses (where only one data set exists there are no parentheses). The raw data is in Tables II through VI. Only the 7.30 GeV P bank data set with the same loop gains as the F bank data set are used (rows 2 and 3 in Table VI).

Full versus fwhm ε

Now a similar analysis to that just above will be performed but, in this case, only using data sets that have both full and fwhm growth data. In what follows I'm assuming the fwhm growth is also independent of early ramp ε, like the full growth is thought to be, and that has not been demonstrated yet. Also, data sets will be included regardless of the ramp and flattop Rf voltages. Table IX shows the averages of the full and fwhm growth data for each energy.

Figure 10 shows the Table IX data plotted and for each case a data point has been added where the early ramp ε is measured (1.20 GeV), which is where the ε growth is 1 (all those points necessarily over lay and the location is indicated by a red dot).[19] For each case, linear fits to the data are included. The full ε growth F bank data is quite linear with flattop energy (as seen in Figure 9) and has the largest slope. The fits for both the F and P bank fwhm data sets are not as good, but the linear fits to those 3 sets cross at an energy very close to where the early ramp ε

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[17] The 5.75 GeV data for F bank only and high Rf voltage is from rows 3,6,8,10,11,15,17, and 18 and with the P bank and high Rf voltage they're from rows 4,7,9, 16, 19, and 20 in Table IV. For all the data with the P bank, the 1440 Hz crossing occurs near the F to P transfer.

[18] Again, the 1440 Hz crossing is to near the F to P transfer to determine which bank it is on when it happens.

[19] The 3.85 GeV 2-1 merge measurements were made at a somewhat lower energy (1.08 GeV) but I'm ignoring this the simplicity.

was measured and have a value near one there.[20] This is not the case for the linear fit of the Full growth with the P bank data, which can also be gleaned from a casual look at the Table IX.

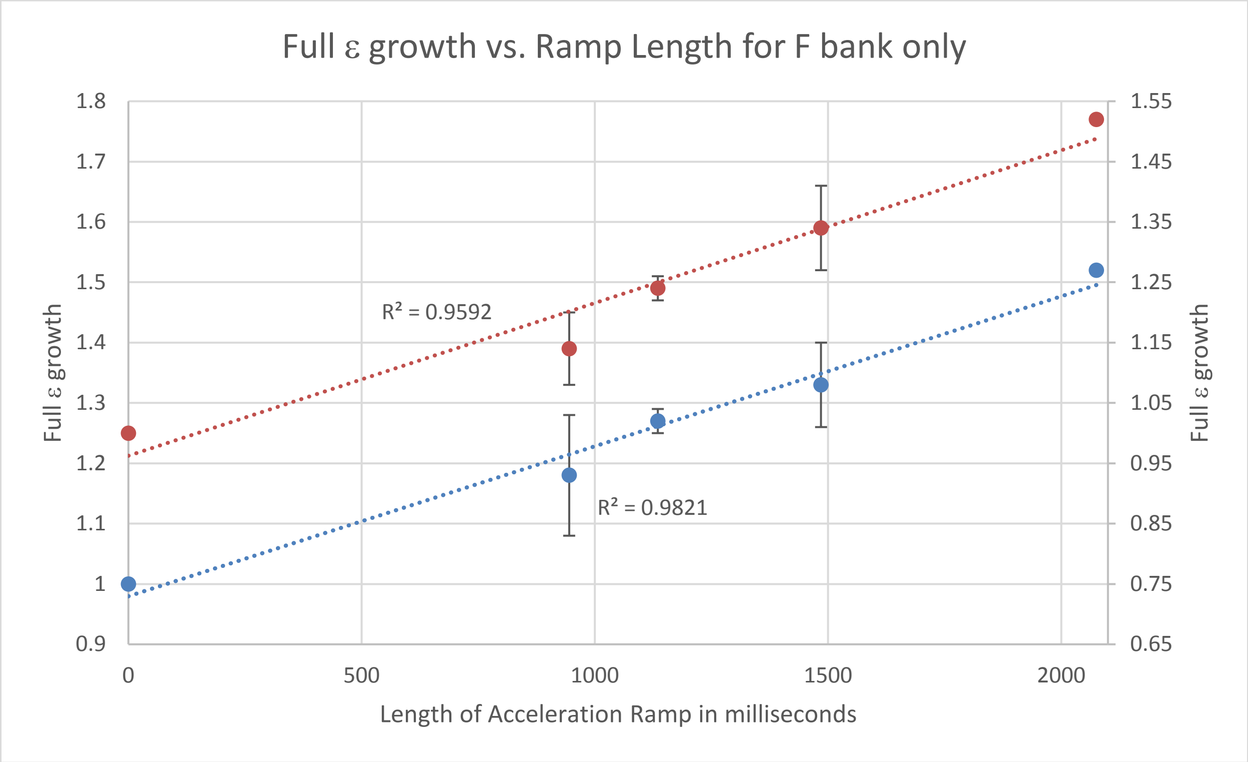

Figure 9: Full growth F bank only data from Table IX plotted against the 6-3-1 F bank main acceleration ramp length (the length of the 8-4-2 ramp is similar) in blue. In red is all the data that use the 6-3-1 type magnet cycles and so the ramp lengths for that data is not approximate (note it uses the y-axis on the right). The error bars are ± the standard deviations. The points at 0 ms are at the beginning of the ramp so they're equal to 1, 945 ms is 3.85 GeV, 1135 ms is 4.55 GeV, 1485 ms is 5.75 GeV, and 2075 ms is 7.30 GeV. Linear fits are also shown.

Energy	Full growth F bank only	fwhm growth F bank only	Full growth with P bank	fwhm growth with P bank
3.85 GeV	1.16 ± 0.07 (8)	1.09 ± 0.07 (8)	1.44 ± 0.08 (4)	NA
4.55 GeV	1.24 ± 0.02 (2)	1.03 ± 0.04 (2)	1.30	0.98
5.75 GeV	1.32 ±0.07 (13)	1.11 ± 0.07 (13)	1.35 ± 0.07 (7)	1.10 ± 0.04
7.30 GeV	1.52	1.22	1.49 ± 0.06 (2)	1.18 ± 0.03 (2)
9.80 GeV	NA	NA	1.41	1.13

Table IX: A similar format to Table VIII except only the averages of full and fwhm growths from early in the ramp to the flattop for all the data sets where full and fwhm data both exist separated by energy and magnet voltage banks are shown. The 3.85 GeV full growth with P bank is also shown even though no fwhm data exists for that case. The uncertainties shown are the standard deviations of those measurements. The number of measurements for each case is shown in parentheses (where only one data set exists there are no parentheses). The raw data is in Tables II through VI. Only the 7.30 GeV P bank data set with the same loop gains as the F bank data set are used (rows 2 and 3 in Table VI).

[20] If the points at 1.2 GeV are not included in the linear fits the fits for the three data sets cross around 2.0-2.6 GeV at about 0.96 and the R^2 values for Full growth F bank only, fwhm growth F bank only, and fwhm growth with P bank are 0.9832, 0.7353, and 0.4804, respectively. The R^2 value for full growth with P bank becomes 0.1041.

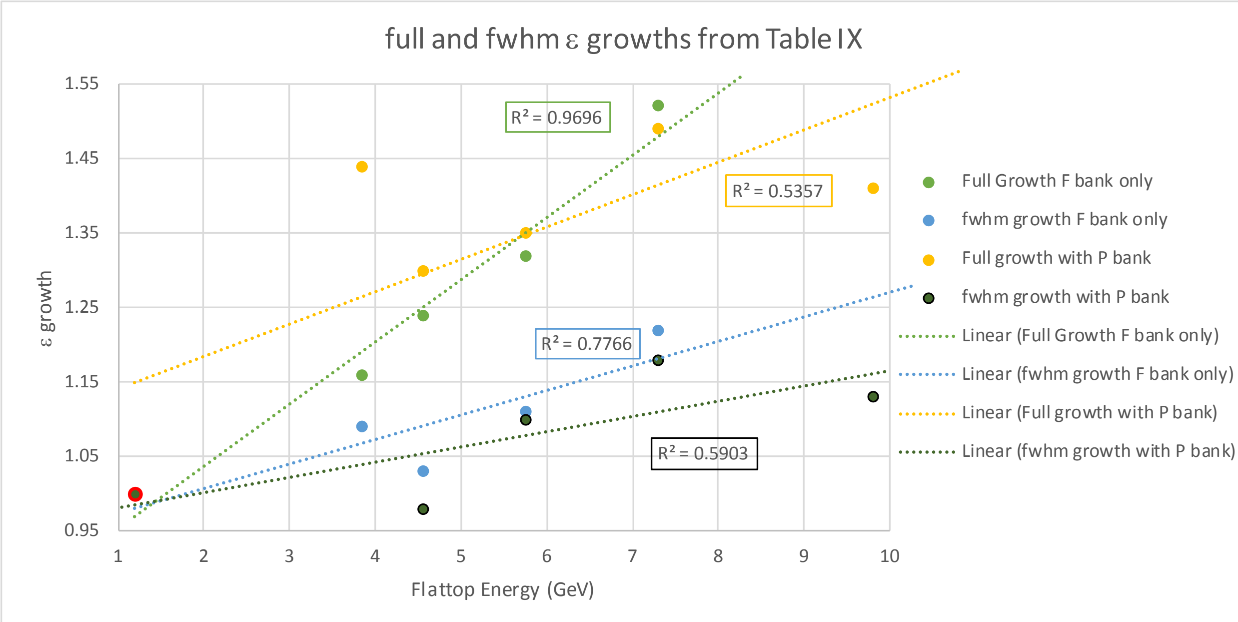

Figure 10: Full and fwhm data from Table IX with linear fits. Uncertainties are not shown, and each point is weighted equally in the linear fit. For each case a data point at 1.2 GeV has also been added (in red). This is the growth at the energy where the early ramp ε is measured, so it is just equal to 1. The R^2 linear fit values are also shown.

One is might infer from all this that the cause of the full ε growth for the P bank is different than it is for the other cases. Also, although the fwhm ε growth data leaves something to be desired, the fwhm growth rate on either bank is less than the full growth rate on the F bank, and for a given flattop energy, the amount of fwhm growth is less on the P bank than on the F bank. The latter is consistent with the idea that the amount of fwhm growth depends on how long it takes to ramp to the flattop. Also, since the fit to the full ε growth on the F bank data also intersects with the linear fits to both sets of fwhm data near the early ramp ε measurement it seems plausible to suppose that the growth mechanism is similar but the effect on the full ε is more pronounced.

As for the mechanism that causes growth in the full ε when on the P bank, the ε is already much larger at 3.85 GeV and doesn't obviously increase at higher flattop energies. So, from the full growth with the P bank data one could infer that whatever is causing that growth occurs at an energy lower than 3.85 GeV, which is consistent with the idea that the 720 Hz component of the P bank is responsible for it. From this data it is not apparent that the transfer from the F to P banks, which causes a spike in the magnet voltage and happens before 3.85 GeV, could not be responsible but measurements taken in 2016 using the normal cycle show no growth there.[21]

Since the full ε growth when using the P bank is much greater than the fwhm ε growth is, most of the growth must occur outside of the fwhm of the distribution. ε growth outside the

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[21] See Figure 19 and related discussion on pg.33 in K. Zeno, "Overview and analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, September 2016.

bunch's fwhm could merely be due to an increase in the size of the tails, and if so would not be as significant as growth that is not in the tails since the particle density in the tails is lower and so the number of particles that have that large ε increase will be relatively small. For that reason, maybe a bunch ε calculated from a bunch's full width at 10% of maximum height to the peak might be more meaningful than that calculated from the full bunch length. The scopes in MCR can automatically perform a rise time measurement from 10% to 95% and such measurements might be able to distinguish tail development from growth in the main part of the distribution.

In the analysis above I have ignored the fact that the ramp and flattop Rf voltages are not all the same. I can further restrict the setups that are included in the 2 groups by excluding all rows which do not have a high ramp and flattop voltage (either 7 or 8 kV). Table X shows the data when those rows have been removed from the 2 groups and that data is still quite similar to the data in Table IX.

These results are encouraging since they suggest that remaining on the F bank until just after 720Hz is crossed could result in substantially less full ε growth at the higher flattop energies and because using magnet cycles where the switch to the P bank occurs after 720 Hz should not make the cycle much longer or have other significant drawbacks. However, the 2016 data indicate that the full ε continues to increase on the normal 9.8 GeV magnet cycle after passing through 720 Hz.[22] On the other hand, measurements on the flattop and early in the ramp, where the dB/dt is very low, are more reliable than during the ramp and so can be compared with less uncertainty. Also, using an incorrect value for γ_t (8.50 vs. 8.407) could be responsible for at least part of the apparent growth later in the ramp.

Energy	Full growth F bank only	fwhm growth F bank only	Full growth with P bank	fwhm growth with P bank
3.85 GeV	1.15± 0.05 (5)	1.10±0.08 (5)	1.50±0.07 (2)	NA
4.55 GeV	1.26	0.99	1.30	0.98
5.75 GeV	1.33±0.07 (8)	1.08±0.07 (8)	1.35±0.07 (6)	1.10±0.05 (6)
7.30 GeV	1.52	1.22	1.49 ± 0.06 (2)	1.18 ± 0.03 (2)
9.80 GeV	NA	NA	1.41	1.13

Table X: The same as Table IX except only data sets (rows) with high ramp and flattop Rf voltages are included. Only the 7.30 GeV P bank data set with the same loop gains as the F bank data set are used.

The 5.75 GeV case (Table IV) probably has the most complete set of fwhm ε data for both the F and P bank cases. In Figure 11 the fwhm ε growth is plotted against the early fwhm ε for signs of a correlation in both cases and none is evident. This supports the assumption made in the above analysis that the fwhm growth is independent of the early fwhm ε in both cases.

[22] See Figure 19 and related discussion on pg.33 in K. Zeno, "Overview and analysis of the 2016 Gold Run in the Booster and AGS", C-A/AP/571, September 2016.

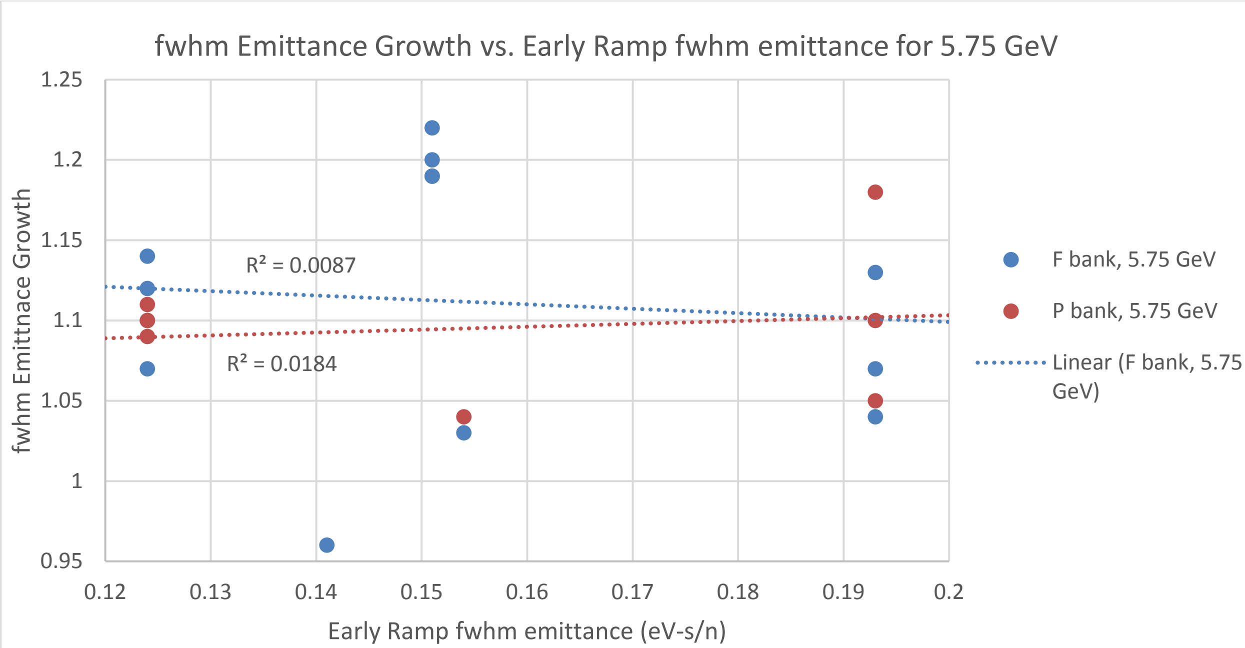


Figure 11: The fwhm ε growth as a function of the early ramp fwhm ε for 5.75 GeV for F bank only and with the P bank. Linear fits to the data are also shown. The data is from Table IV.

There is also a considerable range in the early fwhm in the 3.85 GeV case, but data only exists for the F bank only case (shown in Figure 12). The data does show a correlation but it is because of the one high early ε data point (row 20 in Table II) and the early ramp ε for that case is somewhat suspect because of difficulties encountered in measuring f_s.[23]

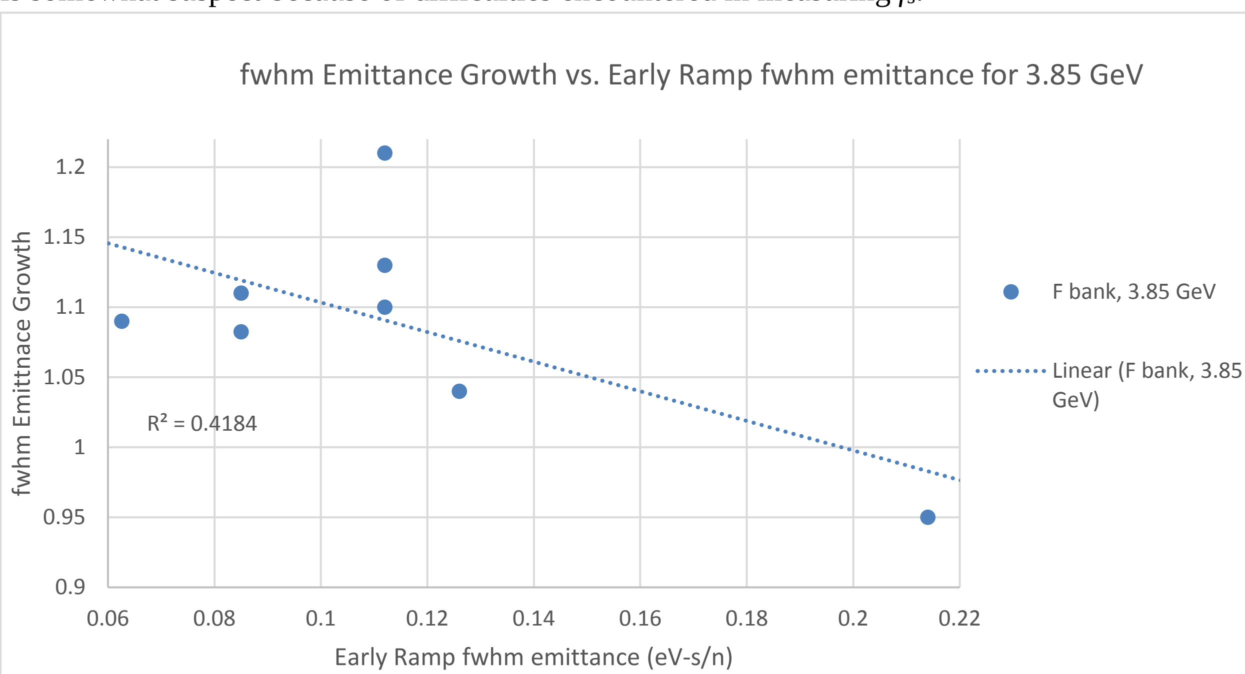


Figure 12: The fwhm ε growth as a function of the early ramp fwhm ε for 3.85 GeV for F bank only. A linear fit to the data is also shown. The data is from Table II.

[23] See Booster-AGS-EBIS 2018 elog June 6 entries from 1318 to 1403. This data is from a 6-3-1 type merge cycle and other early fwhm ε measurements exist for that case which give an early fwhm of 0.187 (Table VI) and 0.193 (Table V) which would give fwhm ε growths of 1.09 and 1.06, respectively. If either of those values are used instead of 0.95 the growth does not show any obvious dependence.

Another assumption that has been made to simplify the analysis is that the full ε growth is independent of early full ε for the F bank only cases as well as the cases where the P bank are used. As mentioned there is convincing evidence that that is the case when using the P bank, at least for the normal 9.80 GeV cycle.

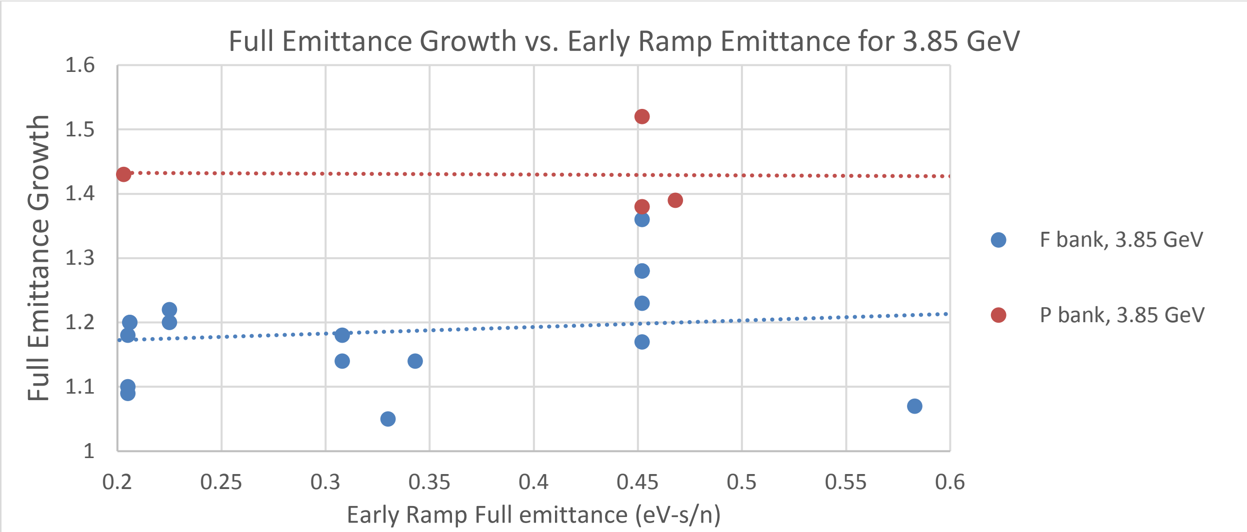
Figure 13 shows the full ε growth data for the 3 lowest energies separated into F bank only and P bank cases (there is no relevant F bank only data for the 2 highest energies). For 3.85 GeV there is no apparent dependence for either of the 2 cases, for 4.55 GeV the P bank data shows some increase in growth with increase in early ε (the F bank only data shows nothing), and for 5.75 GeV both sets of data show some decrease in growth with increase in early ε and the F bank only case shows more than the P bank case. The 5.75 GeV data is perhaps the most relevant because the flattop is at the highest energy for which data exist so there is more time for growth on the F bank. So, perhaps the assumption that the growth is independent of the early ε isn't true when only the F bank is used.

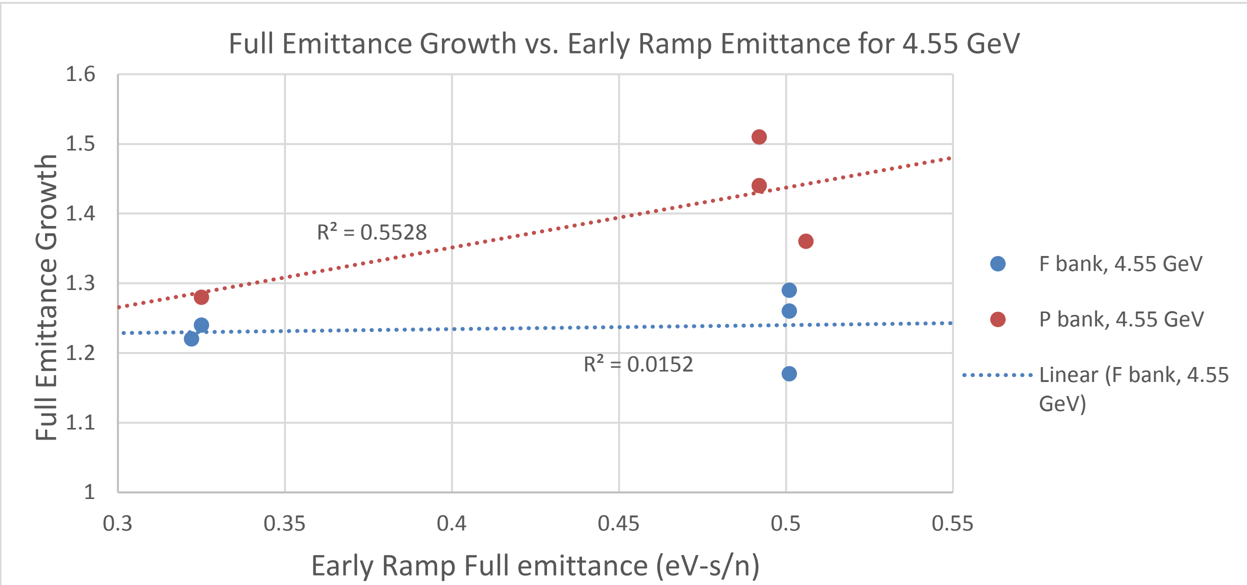
Relaxing the Bunch Squeeze

In what has been discussed thus far increasing the bunch intensity is accomplished by merging more bunches together, but merging more bunches together also increases the ε. One can also merge more bunches together than necessary to provide the required bunch intensity and only put part of that merged bunch into an h=12 bucket at the beginning of the ramp. In this way one can sometimes produce a smaller ε bunch than what would be possible using the above method and yet have the same intensity as one would obtain using that method.

After the last AGS merge the bunch is generally in an h=4 bucket but it needs to be put in a much narrower h=12 bucket. The higher the h=4 voltage is when this bucket switch is performed the more easily the h=4 bunch will fit into the h=12 bucket. In addition to the h=4 voltage, h=8 voltage is also used to squeeze the bunch further. If there is more bunch intensity than desired, first the h=8 can be lowered and if the intensity is still too high when that's zeroed the h=4 voltage can then be lowered. The resulting bunch has a lower ε than the fully squeezed bunch, and in some cases, for a given final bunch intensity, its ε can be smaller than what would have been produced using the standard method.

For example, 5.75 GeV has a bunch intensity requirement of 1.3e9 and an ε requirement of 0.50 eV-s/n. Although the ε requirement can be met by merging 3 bunches into 1 (0.425 eV-s/n), the estimated (flattop) intensity of that bunch is borderline (1.35e9). However, if six bunches are merged into one and the bunch squeeze is relaxed a bunch intensity of 1.7e9 with the same ε results (compare rows 4 and 5 in Table VII). However, there are drawbacks to this setup. First, with only a 3 to 1 type merge 3 bunches could be provided per AGS cycle and only 9 EBIS pulses would be required. With a 6 to 1 type merge, 12 EBIS pulses would be required to provide two final bunches and the AGS cycle would be 600 ms longer.





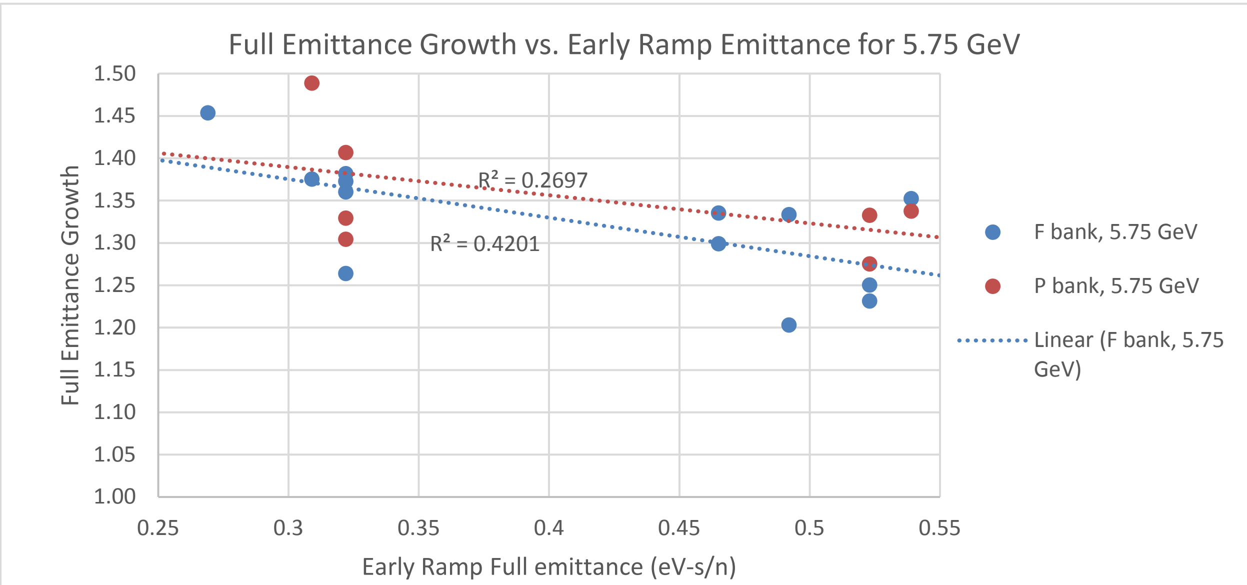


Figure 13: The full ε growth plotted against early ramp full ε for 3.85, 4.55, and 5.75 GeV for F bank only and with P bank. Linear fits to the data are also shown. The data is from Tables II, III, and IV.

Although this effect has only been studied with the 6 to 1 type merge, there is little reason to think it would not also work with a 4 to 1 type merge. An estimate was made for what one would expect if an 8-4-2 merge instead of a 12-6-2 type merge was used. For a bunch intensity of 1.3e9 an ε of 0.40 eV-s/n would be expected (row 7 in Table VII, see Table description for how the estimate was made). Although this does not provide a higher intensity than the original 3 to 1 type merge it could be preferable because the bunch intensity can be increased by squeezing more and there should still be some room until 0.50 eV-s/n is reached.

Relaxing the bunch squeeze seems to allow one to select the denser part of the bunch to put into the Rf bucket used for the ramp so one gets more intensity for a given ε. Although I'm just speculating, it may be that the more bunches are merged together the more effective this becomes. Although it has not been tried, it looks like it's possible to merge 8 bunches into 1 using a 24-12-6-3 merge without making hardware changes to the AGS Rf. The first 2 merges would be done on the injection porch (~480 g) and the last 2 not far up the ramp on a 900 g porch. This setup could be tried to see if there's any benefit. There would be only 1 bunch per AGS cycle.

Summary

Candidate Setups

Table VII has a list of possible setups taken from all the measurements that could best satisfy the RHIC requirements. Also included in the table are estimates for setups for which the ε wasn't measured but which might be viable as well.

3.85 GeV

For 3.85 GeV the requirements could be met using a 2 to 1 type merge, which in terms of Rf harmonics is 24-12, using only the F bank. If there were 12 EBIS pulses there could conceivably be as many as 6 bunches per AGS cycle available for filling RHIC. The measured ε on the flattop was 0.23 eV-s/n, less than the required 0.30 eV-s/n. Whether the bunch intensity requirement is met or not largely depends on the EBIS and injector performance, but it (6e8) was met during Run 18.

4.55 GeV

For 4.55 GeV the requirements could be met using a 3 to 1 type merge with injection into every other h=24 bucket (see row 3 in Table VII). The bunches are then 'rebucketed' into h=12 Rf, and then the 3 to 1 (12 to 4) merge is done. The bunches are injected into h=24 buckets because there seems to be less growth than when they are injected directly into h=12 buckets, which is probably because the injected bunch is better matched to h=24 buckets (compare rows 8 and 9 in Table II). The measured ε was 0.394 eV-s/n when only the F bank is used and the required ε is 0.40 eV-s/n. The estimated intensity is considerably more than required (1.35e9 vs. 0.8e9). For this setup there would be a maximum of 3 bunches on the flattop per AGS cycle.

Although the ε using a 2 to 1 type merge was not measured, the ε using only the F bank can be estimated by using the growth for the F bank with low ramp and high flattop voltage (1.22, from row 1 in Table III) and the early ramp ε for a 2 to 1 merge (0.205 eV-s/n, see row 1 in Table II) to get 0.254 eV-s/n (see row 2 in Table VII). The estimated bunch intensity is 0.9e9 which is only slightly higher than the requirement (0.8e9) but it would be possible to have as many as 6 bunches on the flattop per AGS cycle.

5.75 GeV

As discussed above, using a 3 to 1 merge provides a small enough ε but the estimated intensity (1.35e9) is very close to the RHIC requirement (1.30e9). A 6 to 1 merge with a relaxed bunch squeeze using only the F bank easily meets both requirements (for a measured intensity of 1.7e9 the flattop ε was 0.425 eV-s/n and the requirement is 0.50 eV-s/n, row 5 in Table VII). Although it wasn't tested, a 4 to 1 type merge with a relaxed bunch squeeze would also probably satisfy the requirements and would still allow 3 bunches on the flattop per AGS cycle (row 7 in Table VII).

7.30 GeV

For 7.30 GeV the ε requirement is much lower than it is for 5.75 GeV, and the bunch intensity requirement is much higher. So, there is no setup that meets these requirements (0.30 eV-s/n with 2.1e9/bunch). The measurement that comes closest is in row 8 of Table VII (0.734 eV-s/n with estimated intensity of 2.56e9/bunch) and uses a 6 to 1 type merge. This measurement uses different Rf loop gains than the other setups and the ε is calculated using γ_t=8.407.

During the best running conditions in Run 16 for the 9.80 GeV cycle and the bunch squeeze relaxed to provide 2.4e9/bunch the measured ε was 0.53 eV-s/n (this measurement used a γ_t of 8.50). From that an estimate of 0.50 eV-s/n at 7.30 GeV was obtained for the same conditions (with γ_t=8.407, see Table VII description for details on the estimate). Now, it is likely possible to get 2.1e9/bunch in RHIC with less than 2.4e9/bunch in the AGS, but the ε would still be too high.

9.80 GeV

The RHIC requirements for 9.80 GeV (0.40 eV-s/n at 2.3e9/bunch) are not quite as demanding as they are for 7.30 GeV. The ε obtained in Run 16 for the best running conditions and with the squeeze relaxed to get 2.4e9/bunch was 0.53 eV-s/n and if a γ_t of 8.407 is used this would become 0.50 eV-s/n.

Conclusions from Data Analysis

Before this task was undertaken it was suspected that the ε growth would be reduced if magnet cycles using only the F voltage bank were used but this turns out only to be partly true. The full ε growth between the beginning of the ramp and the flattop when using only the F bank seems to be proportional to the time spent ramping (see Figure 9). When the P bank is also used, the full ε growth is roughly comparable for all flattop energies (see Table IX and Figure 10). At higher flattop energies the full ε growth when only the F bank is used becomes comparable to the growth when the P bank is also used. At the 2 lowest energies though (3.85 and 4.55 GeV) it seems clearly preferable to stay on the F bank.

Given that the full ε growth on the P bank does not seem to depend strongly on the flattop energy, it seems plausible that whatever causes full ε growth on it occurs before the lowest flattop energy (3.85 GeV). There are 3 obvious things that are different about using the P bank: The dB/dt is higher, the voltage ripple is larger, and there is a voltage transient when the transfer from the F to the P bank occurs.

Full ε measurements from 2016 using the standard 9.80 GeV cycle indicate that full ε growth does not start until just after f_s crosses 720 Hz and there was no growth measured at the F to P transfer which occurs well before that. The 720 Hz crossing occurs before the lowest energy flattop (3.85 GeV). So, the prime suspect for full ε growth is a resonance between the 720 Hz component of the voltage ripple and f_s. It is important to note though that the observation that the full ε when on the P bank does not increase as the flattop energy increases contradicts the measurements taken in Run 16 which show that it continues to increase through the ramp after 720 Hz is crossed. Fortunately, it is not necessary to know which is true because this can be tested (see next subsection).

Not only is the full ε growth on the F bank proportional to the time spent on the ramp, but the fwhm ε using either just the F bank or both banks, seems proportional to it as well but much less so (see Figure 10). Also, the fwhm ε growth with the P bank seems to be less than it is when only the F bank is used. There are apparently two things that need to be sorted out here. First, the full ε growth when only on the F bank, although larger than the fwhm ε growth, seems to have the same dependency as it, so maybe the same mechanism is responsible for both. Secondly, the fwhm ε growth does not seem to be affected by the larger voltage ripple on the P bank since the fwhm growth is even smaller on the P bank than when only on the F bank (presumably because the ramping time is less). Continuing along this line, the full ε growth when using the P bank should also be a function of the time spent ramping, and maybe it is but, given the scatter in the data and the larger growth from the other mechanism, it's not surprising that it's not apparent.

Since the fwhm ε growth in the P bank case is small relative to the full ε growth in the P bank case, it must be that most of the full ε growth occurs outside the fwhm of the distribution when on the P bank. It might be possible to determine whether it's caused by the development of tails, growth closer to the center of the distribution than that, or both by measuring the bunch length differently. The scopes allow the rise time from 10% to 95% of peak to be measured, and that might be useful for learning more about this growth.

Checking the Conclusions

A main magnet function that doesn't switch to the P bank until after f_s drops below 720 Hz and then ramps rapidly to avoid spending more time than necessary on the ramp could be used to see if these conclusions are valid.

Figure 14 shows a possible 9.80 GeV main magnet function for a 6-3-1 merge that meets these criteria. The maximum dB/dt is about 22 g/ms compared to 17 g/ms on the standard function and 25 g/ms on the polarized proton function. Whether there will be enough accelerating voltage for a dB/dt this high remains to be seen, but dB/dt can be reduced if need be. If so, the flattop may need to be moved a little later, but it is unlikely that the cycle length would need to be increased. Note that with this cycle, although the rollover to the flattop is somewhat faster, the flattop timing is the same. The function was made with a maximum F bank voltage of 1800 V.

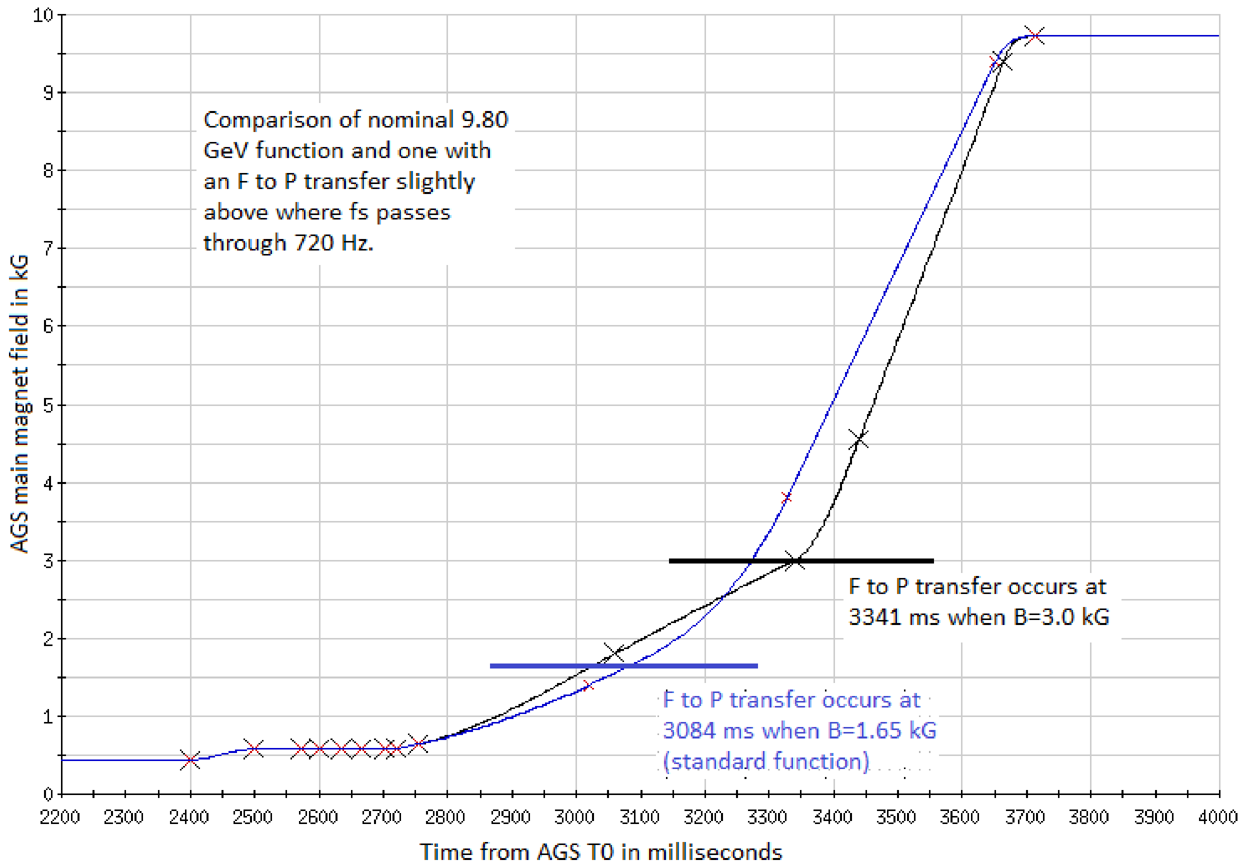


Figure 14: Comparison of standard 6-3-1 9.80 GeV AGS main magnet function (blue) and a function that has an F to P transfer slightly above where f_s is expected to cross through 720 Hz when the Rf voltage is high (black).

Appendix

This Appendix shows the main magnet functions that were used for the measurements.

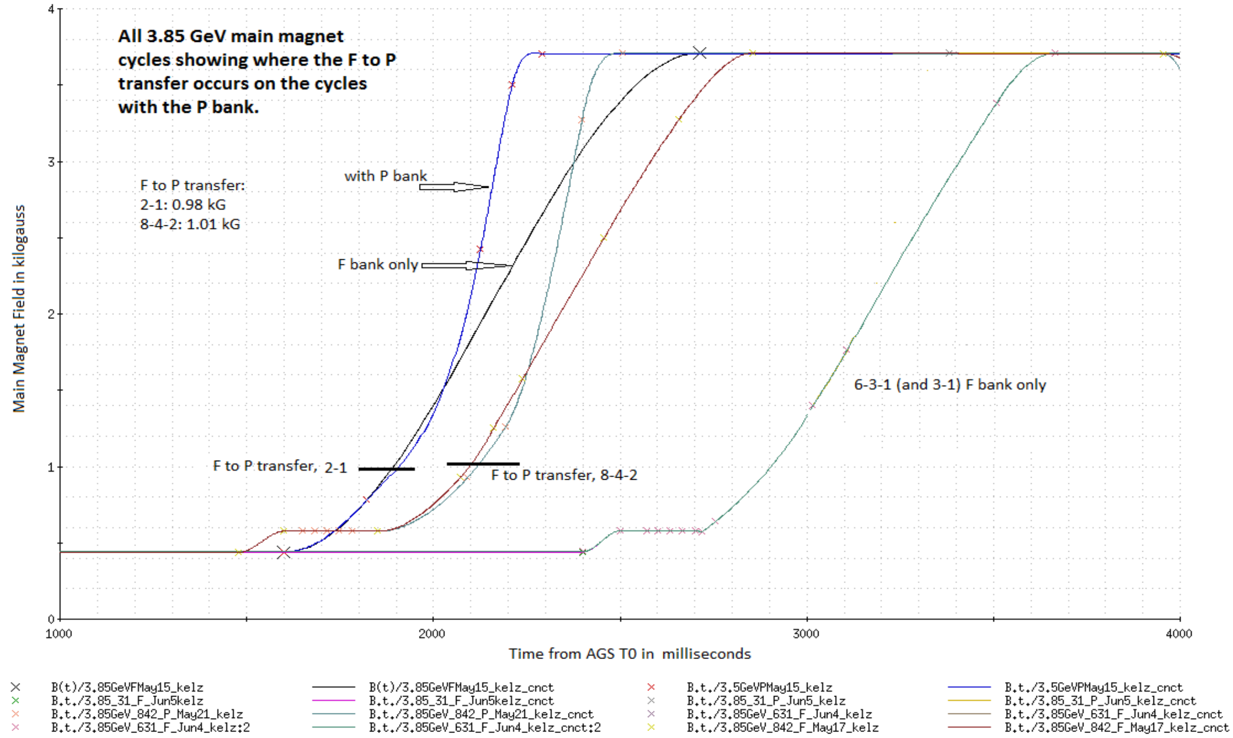


Figure 15: The 3.85 GeV AGS Main Magnet Cycles. For the 2-1 and 8-4-2 merges there is one that uses the P bank and one that stays on the F bank for the entire ramp. The 2-1 merge cycles do not have a merge porch. Only the 6-3-1 F bank only cycle was used. The 3-1 and 6-3-1 merge setups use the same cycle.

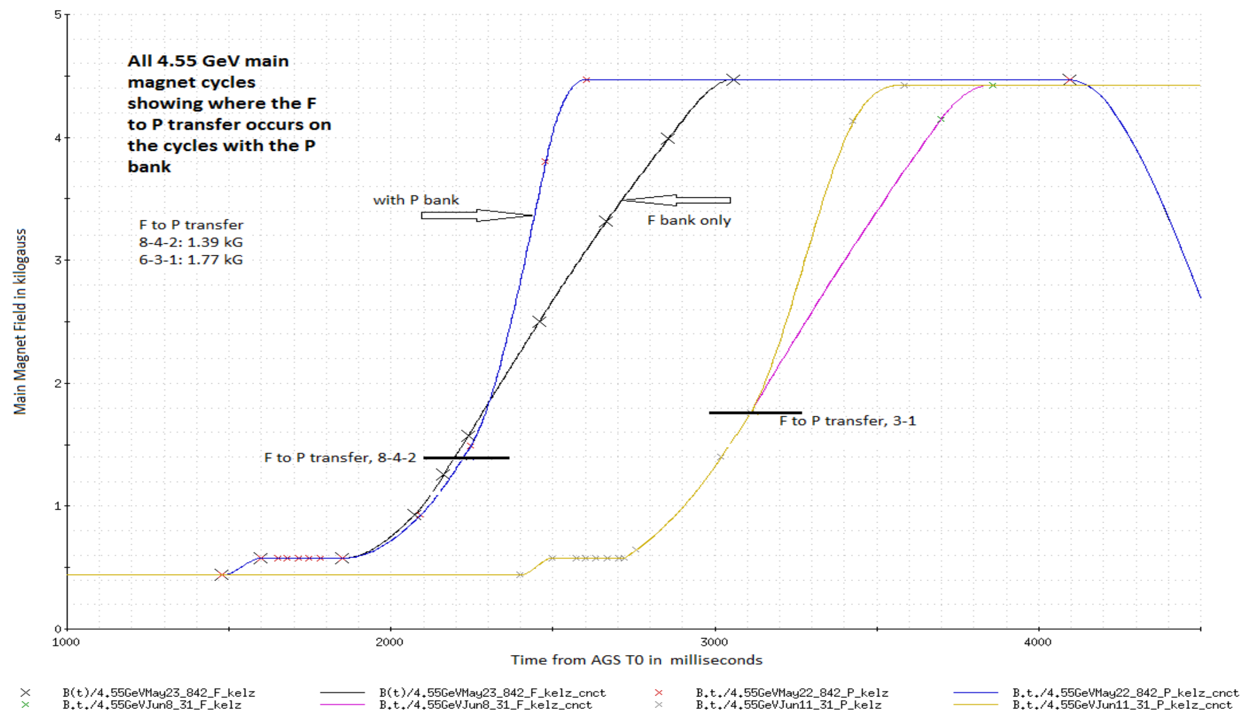


Figure 16: The 4.55 GeV AGS Main Magnet Cycles. The F bank only 6-3-1 and 3-1 cycles are the same.

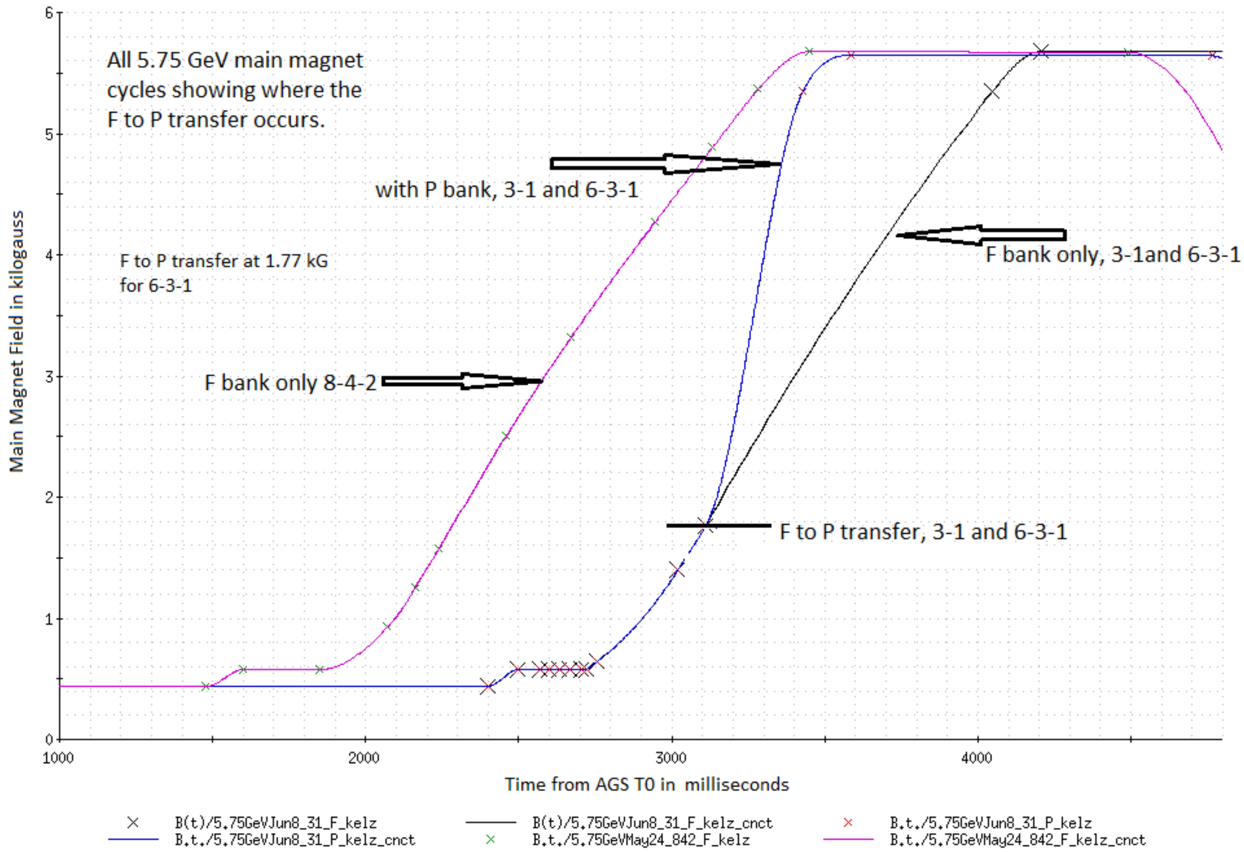


Figure 17: The 5.75 GeV magnet cycles. There is one 8-4-2 F bank only cycle and a 6-3-1 F bank only and P bank cycle that are also used for 3-1 merge measurements.

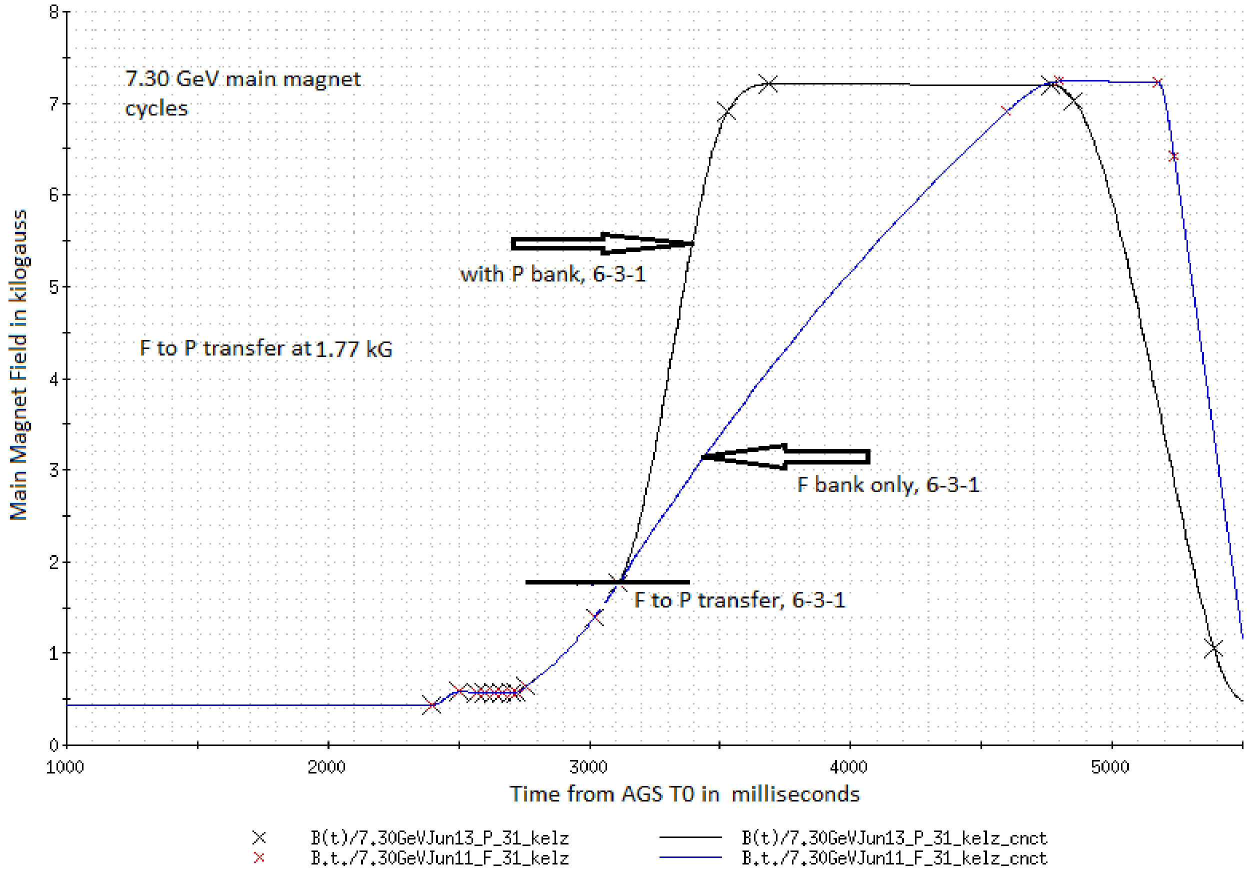


Figure 18: The 7.30 GeV magnet cycles which are an F bank only and a P bank 6-3-1 cycle.

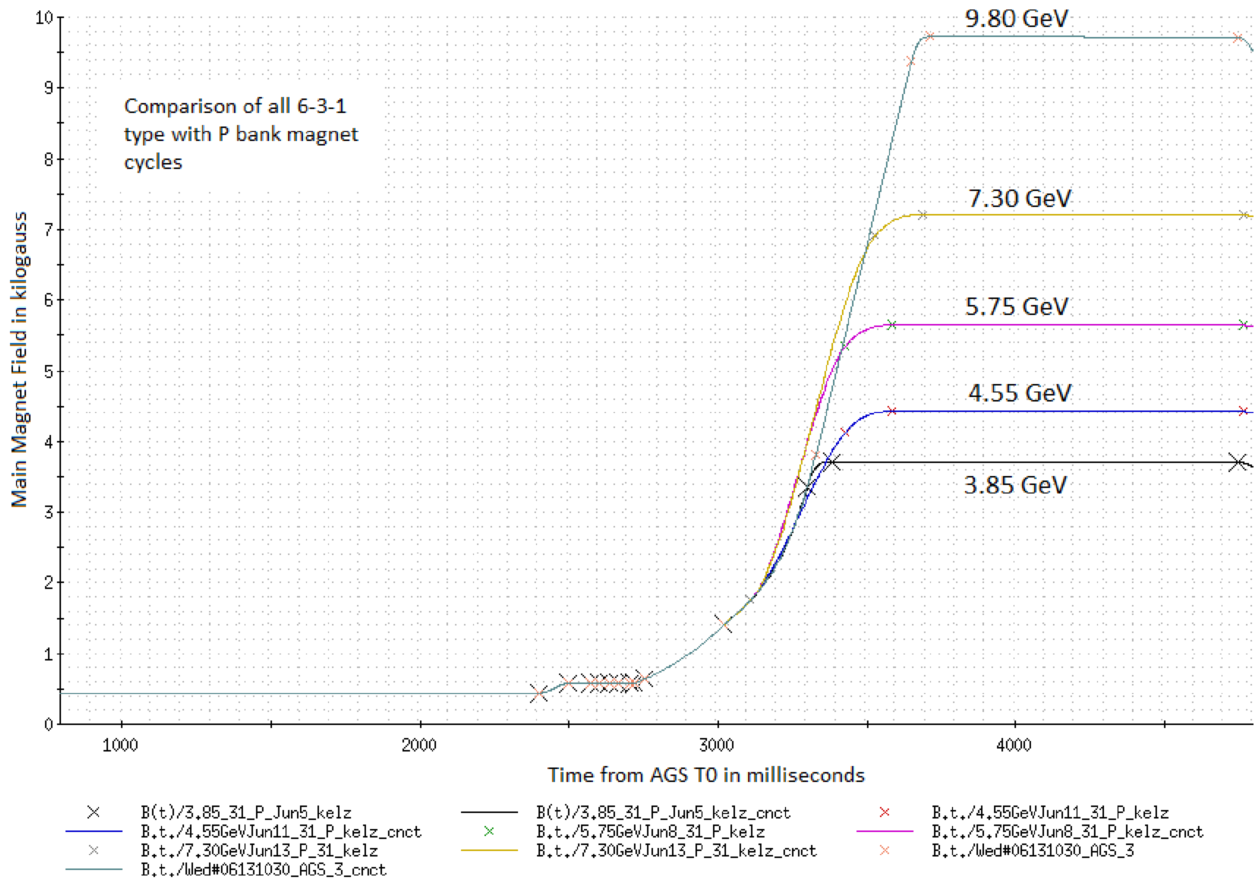


Figure 19: Comparison of all the 6-3-1 type P bank magnet cycles.

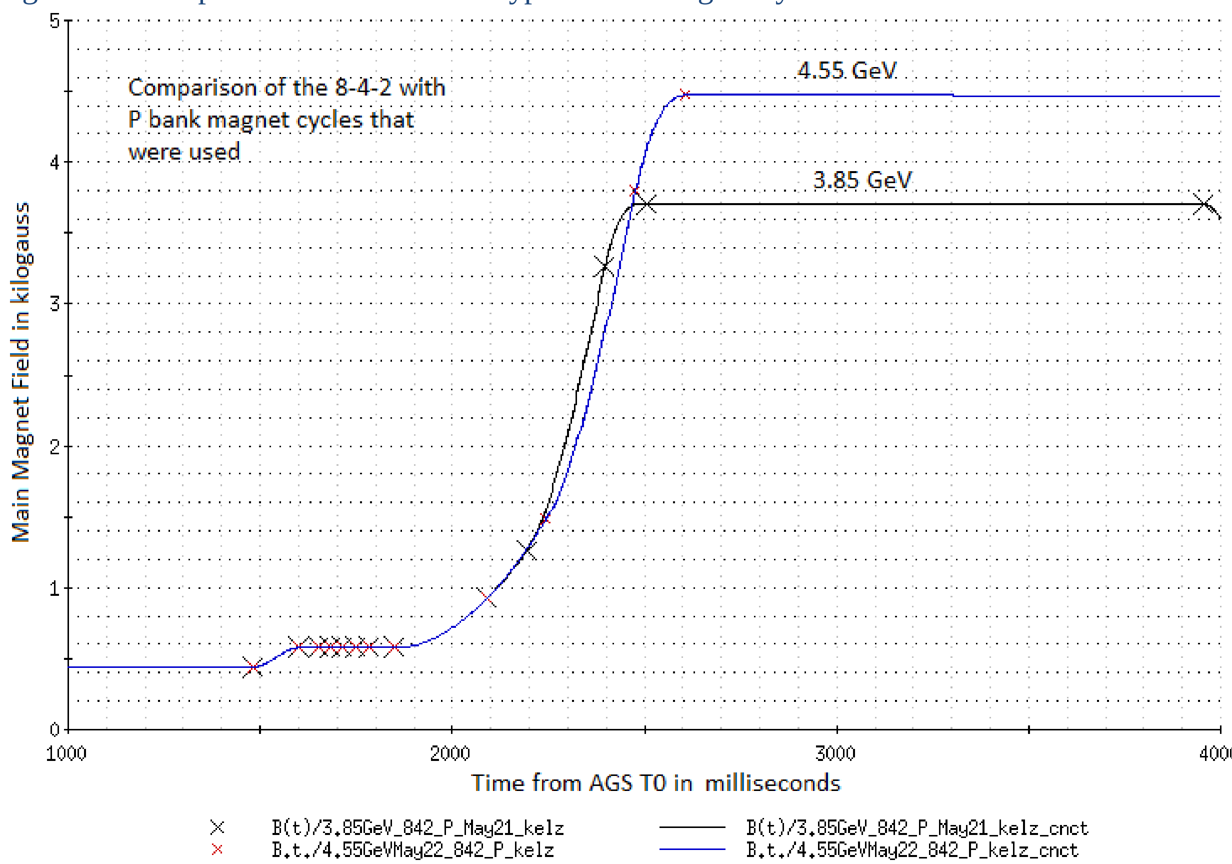


Figure 20: Comparison of the 8-4-2 type with P bank magnet cycles.

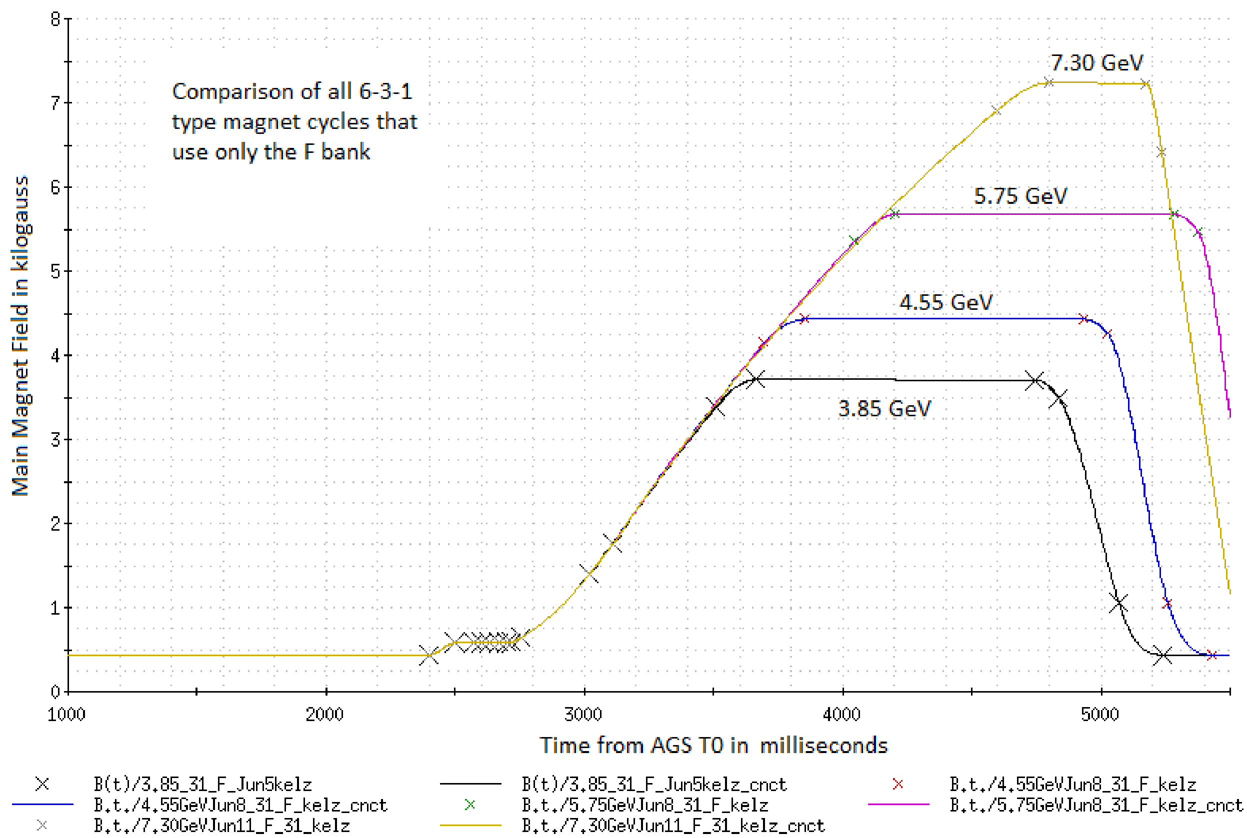


Figure 21: Comparison of all 6-3-1 type F bank only magnet cycles.

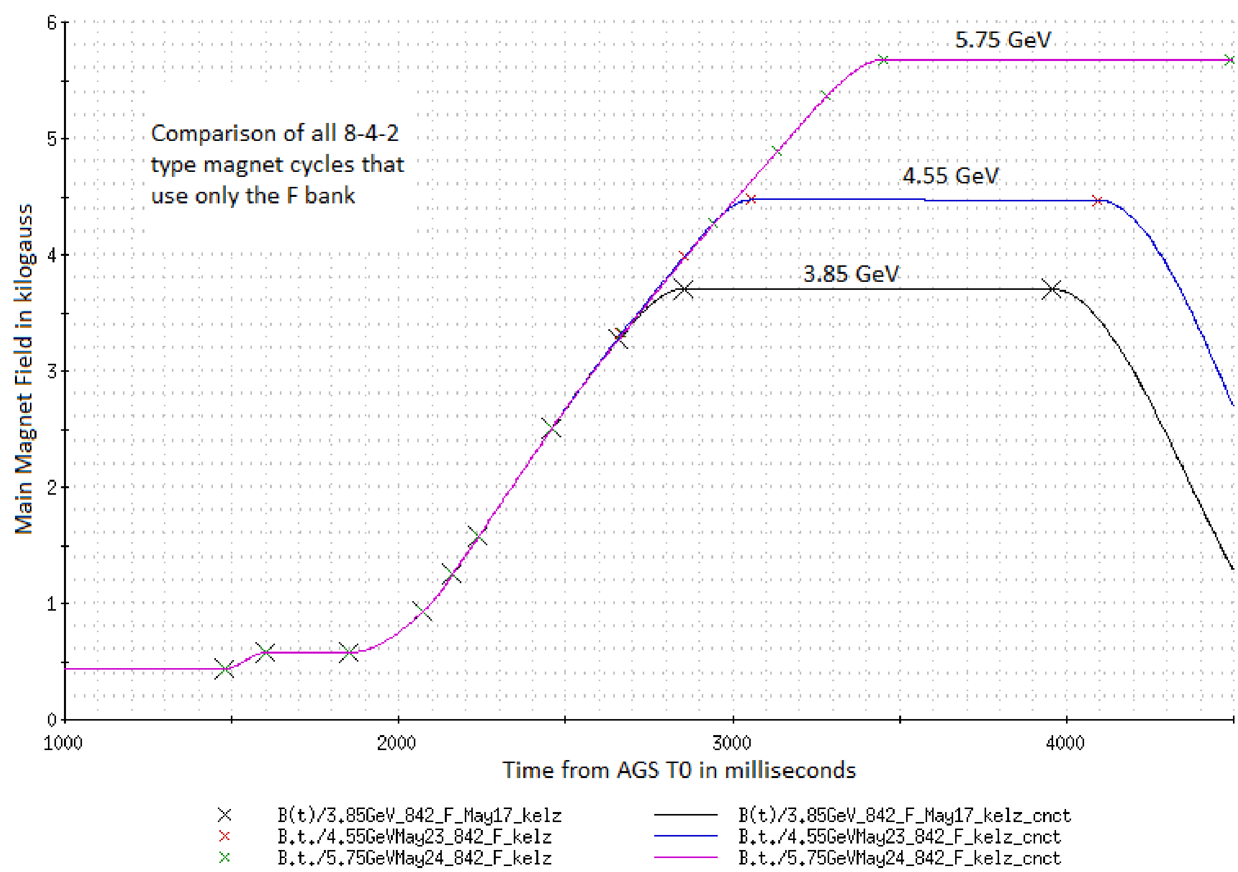


Figure 22: Comparison of all 8-4-2 type F bank only magnet cycles.