EBIS Ions for RHIC Run 12

Setup of Booster and AGS for delivery of EBIS U, Au, and Cu to RHIC for physics

This was a difficult and challenging exercise which reached a successful conclusion only because of the extraordinary effort and talents of many…

The EBIS folks

The RF group

The Controls group

The Operations Coordinators and operators

The Tandem folks

and…

Keith Zeno Keith

Zeno Keith Zeno

Keith Zeno Keith

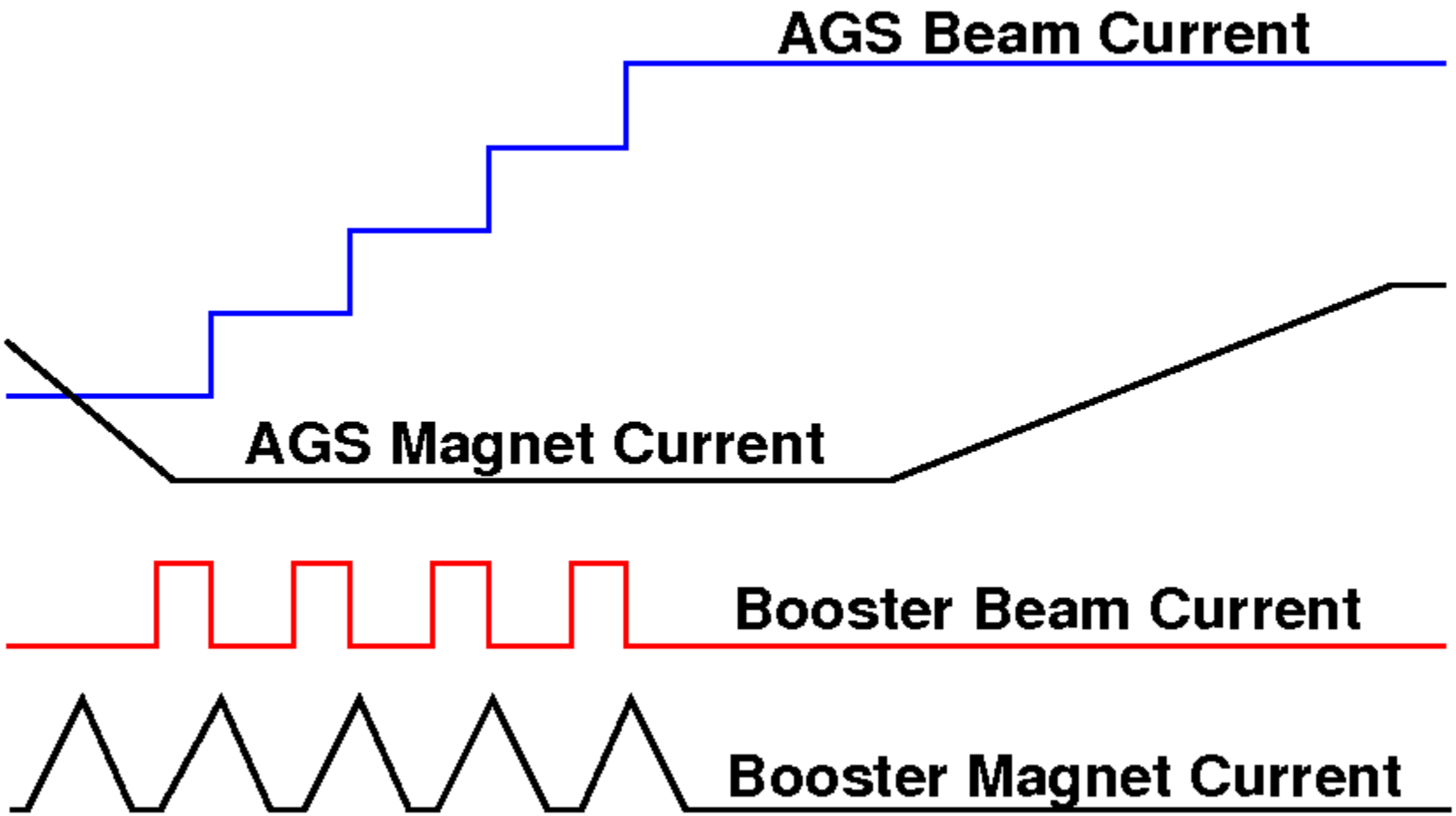
Zeno Keith Zeno

Review “standard setup” for delivery of ions to RHIC…

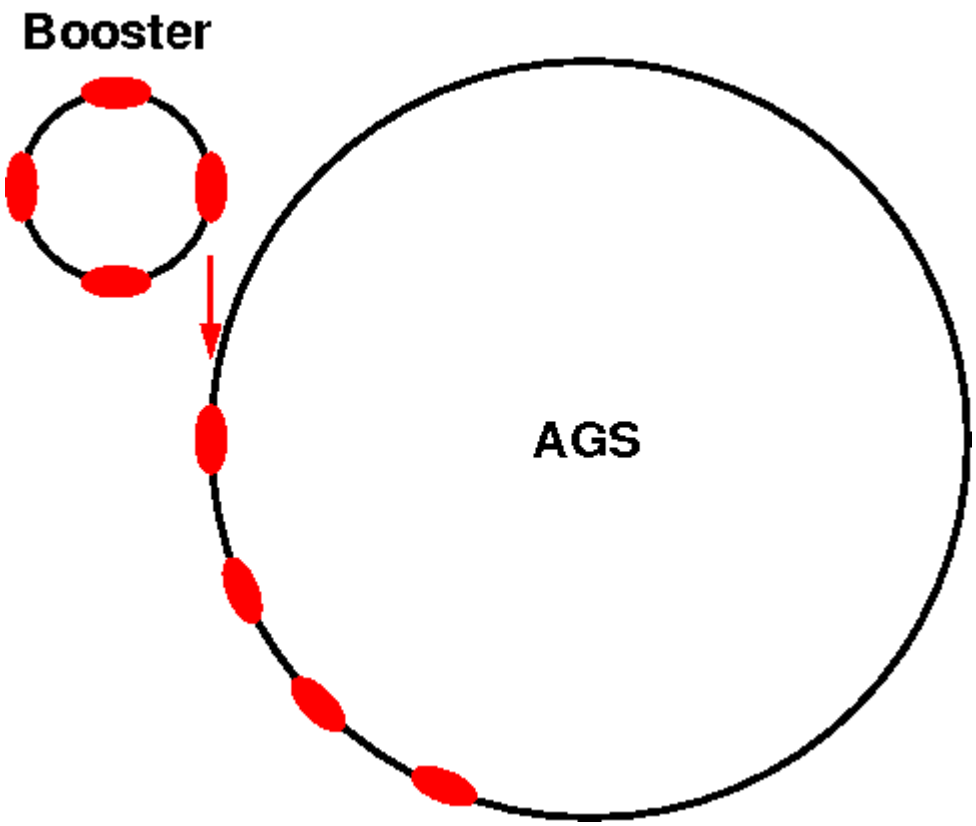
Standard setup…

- Transfer 4 Booster loads of 4 bunches to AGS per AGS cycle.
- Merge 16 to 8 to 4 bunches in AGS.
- Gives 1 Booster load per RHIC bunch.

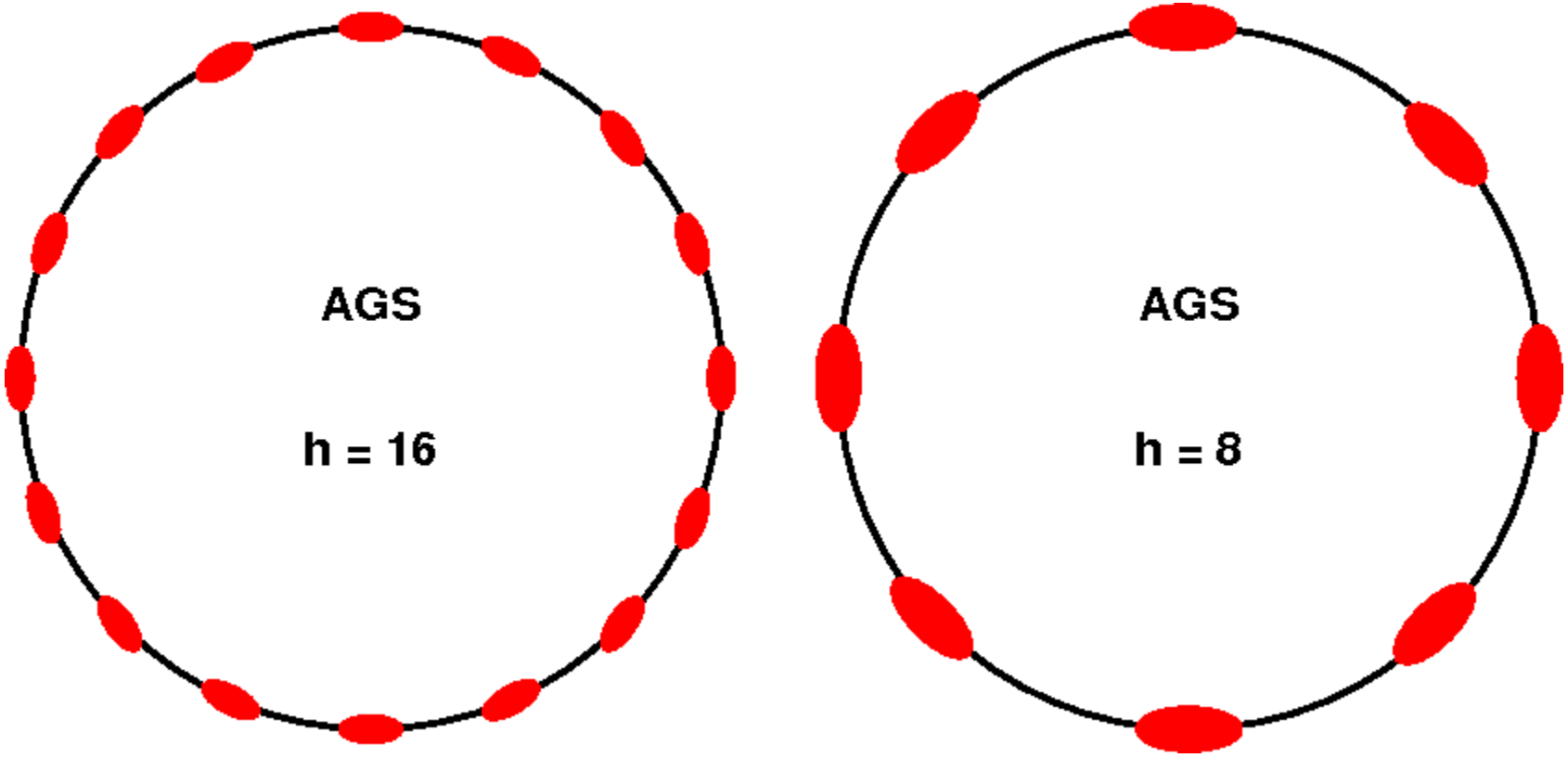
4 Booster loads per AGS cycle



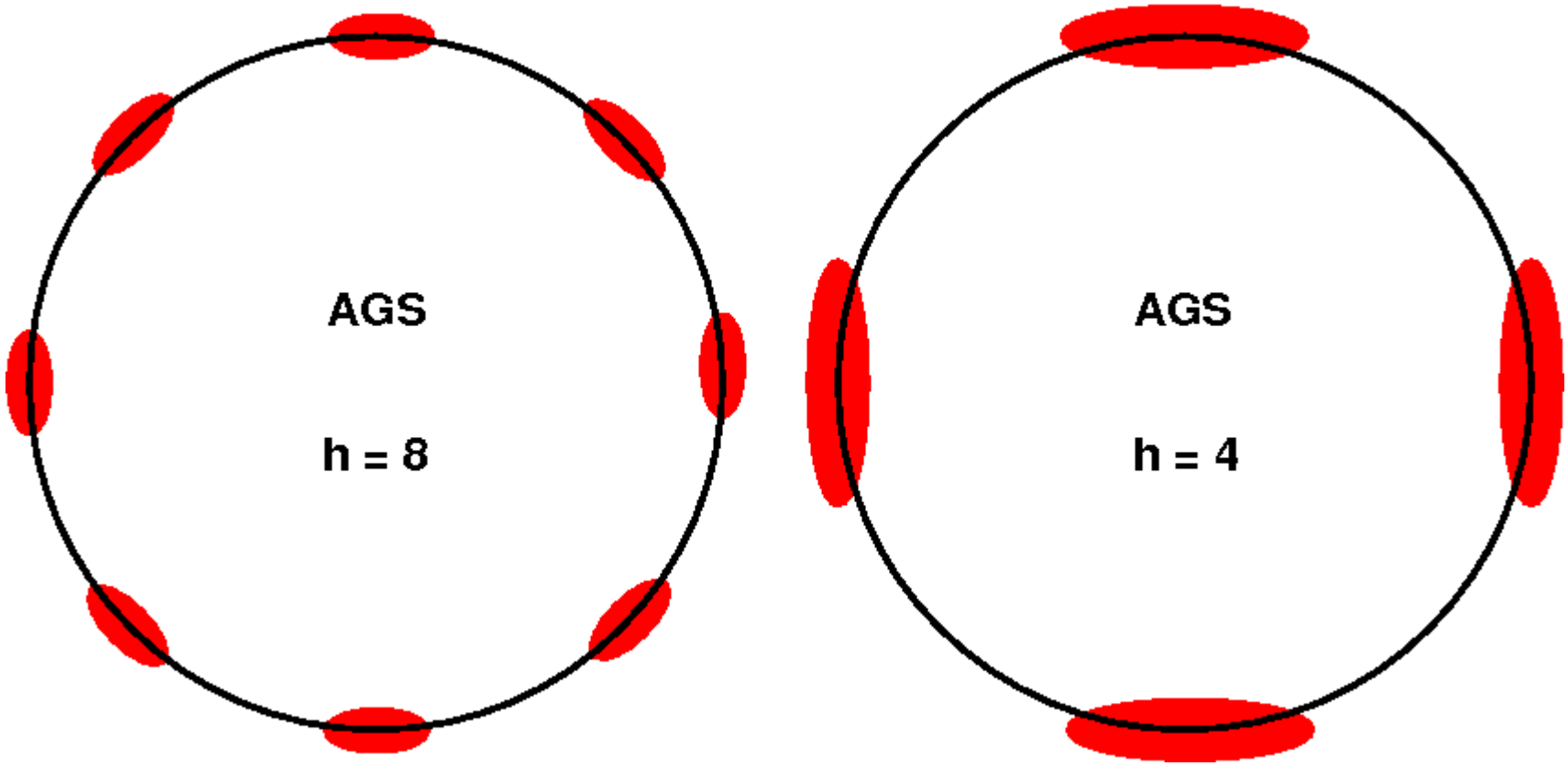
1 of 4 Booster load to AGS



Merge 16 bunches into 8



Merge 8 to 4



1 Booster load per bunch.

RHIC Run 7 Performance

- Our bench mark for several years
- 5.0e9 Au31+ ions per pulse from Tandem
- Booster output/input = 0.80 x 0.70 = 0.56
- (AGS output)/(Booster output) = 0.56
- 0.56 x 0.56 x 5.0e9 = 1.57e9 Au79+ ions per bunch at AGS extraction
- (PAC07 pp. 1862-1864)

EBIS has replaced Tandem as source of ions for RHIC

EBIS beam in Booster

- 1.3 to 1.6e9 Au32+ ions per EBIS pulse
- (5.0e9 Au31+ ions per Tandem pulse)
- Booster injection efficiency initially 60-70%
- (efficiency up to 80% for Tandem beam)
- Bstr capture and acceleration efficiency for EBIS beams somewhat better
- So per bunch intensity for RHIC down by factor of 1.6/5.0…

The challenge…

- Increase RHIC bunch intensity by a factor of 3 to 4
- And keep longitudinal emittance low enough for successful RHIC operation
- This was quite worrisome and stressful…

Even the Queen was concerned…

Things done or considered:

- Booster inflector aperture increased
- Booster “merge and squeeze” scheme used for deuterons during RHIC run 8
- Capture half-turn of EBIS beam in Booster with barrier bucket
- Debunch and rebunch beam in Booster
- 4 to 1 merge in Bstr; 16 to 8 to 4 in AGS

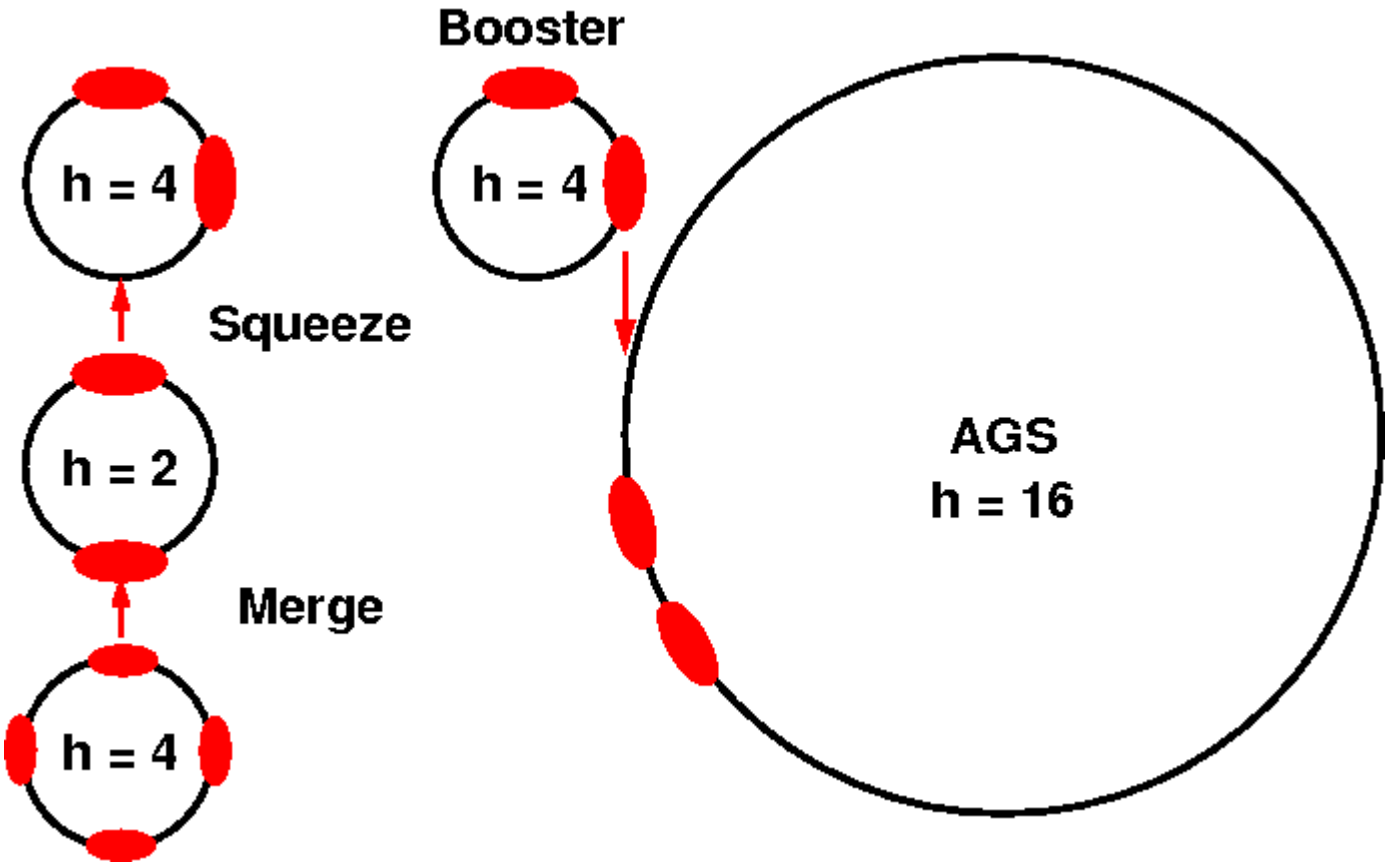
Inflector aperture increased:

- Booster inflector gap was increased from 17 to 21 mm in Nov-Dec 2011
- Injection efficiency increased from range of 60-70% to range of 80-95%
- Booster output/input now up to 77%
- (Had been 56% for Tandem beam with 17 mm inflector gap)

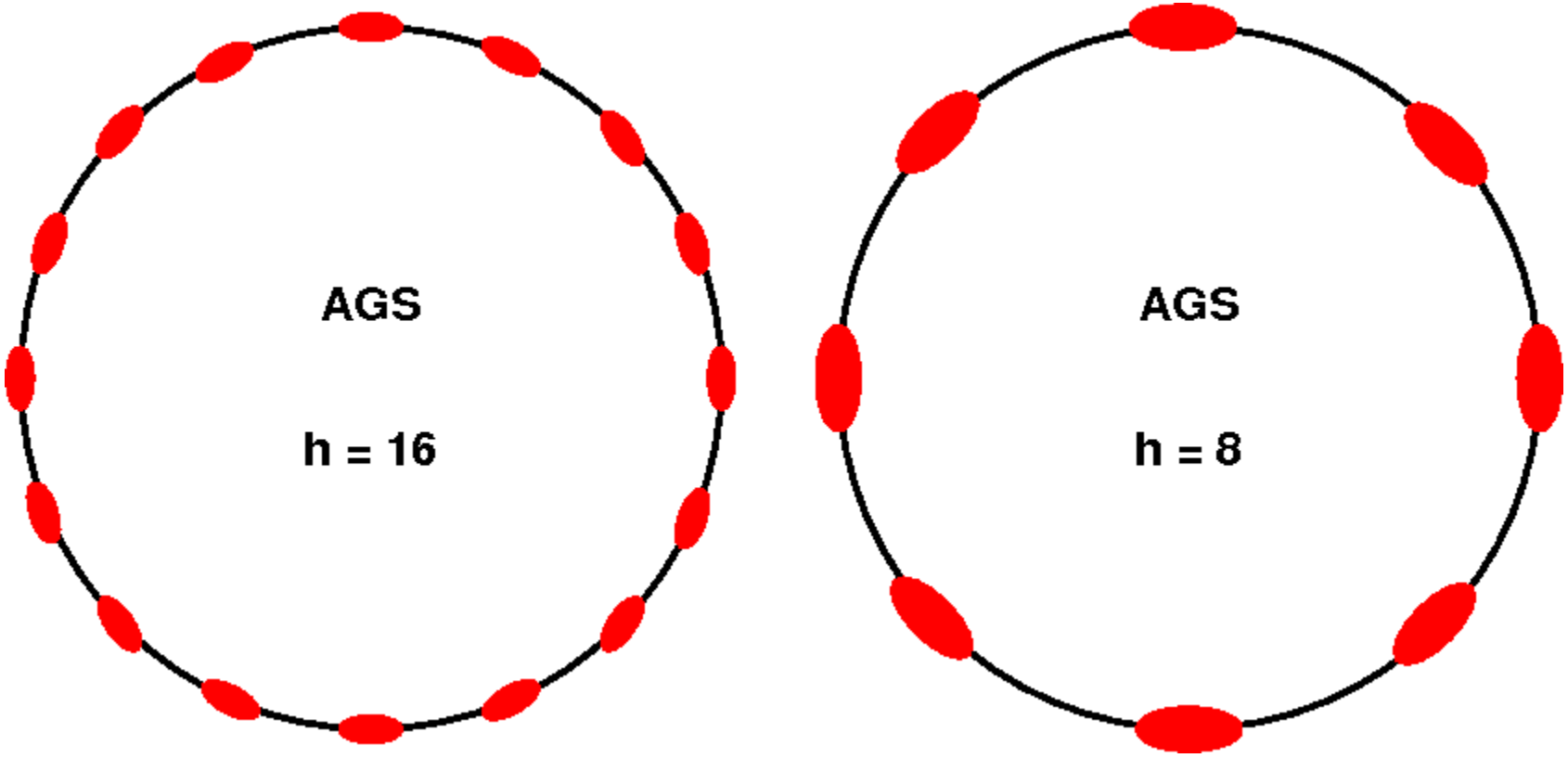
Merge and squeeze scheme:

- Merge 4 Booster bunches into 2. Squeeze into 2 adjacent h=4 buckets.
- Transfer 8 loads of 2 bunches to AGS per AGS cycle.
- Merge 16 to 8 to 4 bunches in AGS as before.
- <u>Gives 2 Booster loads per RHIC bunch.</u>

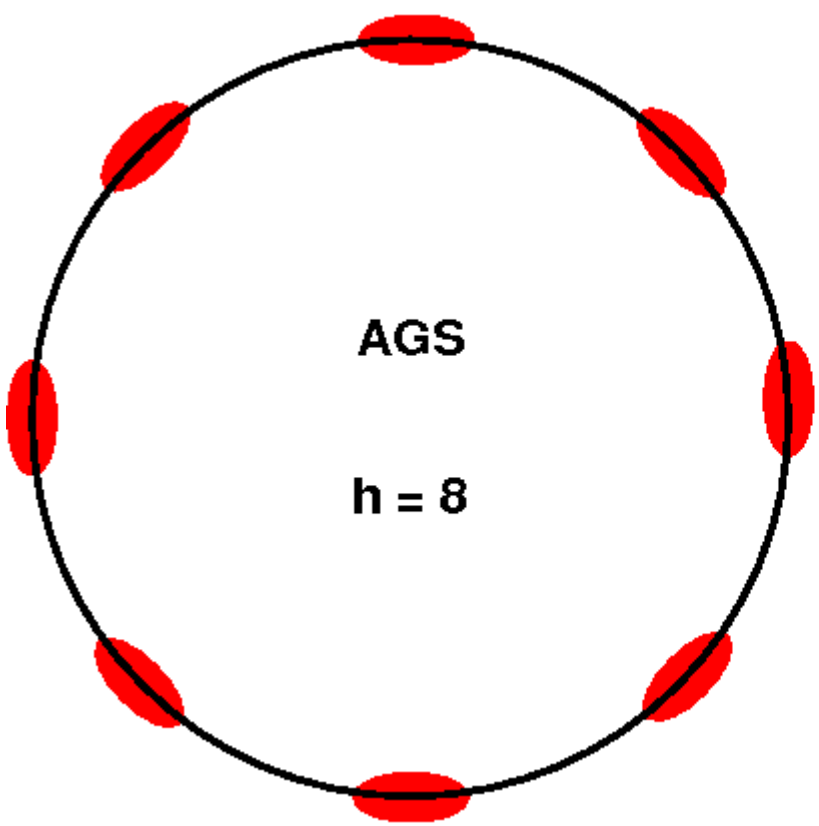
1 of 8 Booster loads to AGS

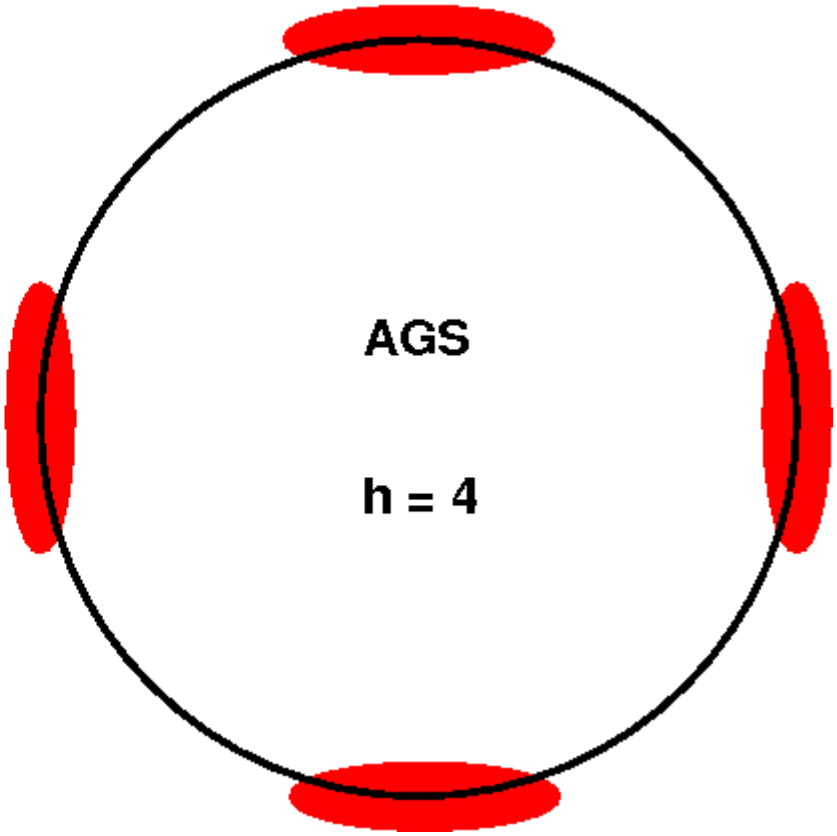


Merge 16 bunches into 8



Merge 8 to 4





2 Booster loads per bunch.

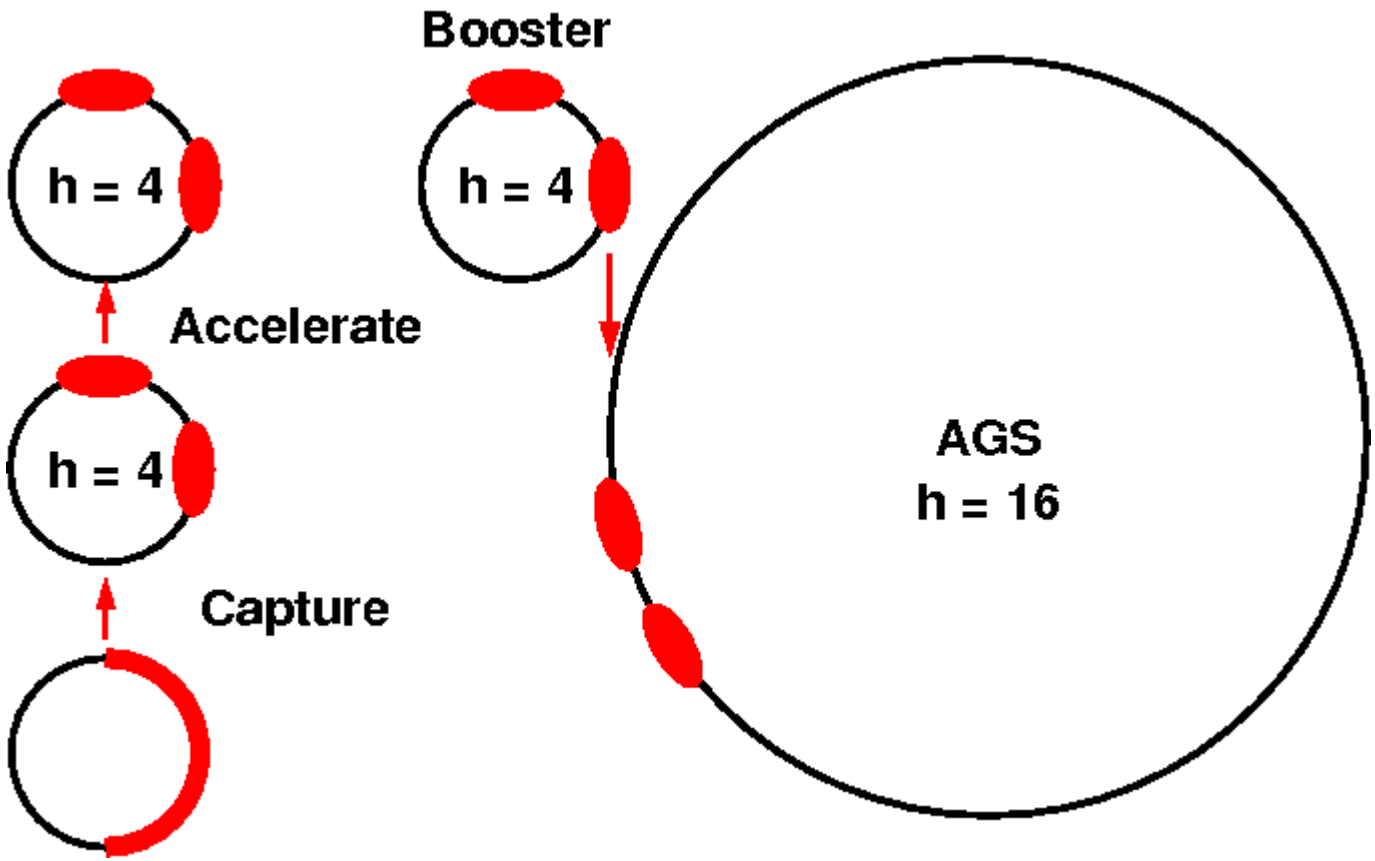
Issues…

- Needs 9 Booster cycles (8 plus “dummy”) with porch for merge-squeeze
- Perturbs local power grid with undesired harmonics. (Worked OK for run 8 deuteron cycle but perhaps not for desired run 12 Au cycle)
- Maybe not enough time to do a good merge and squeeze

Brennan and Blaskiewicz propose:

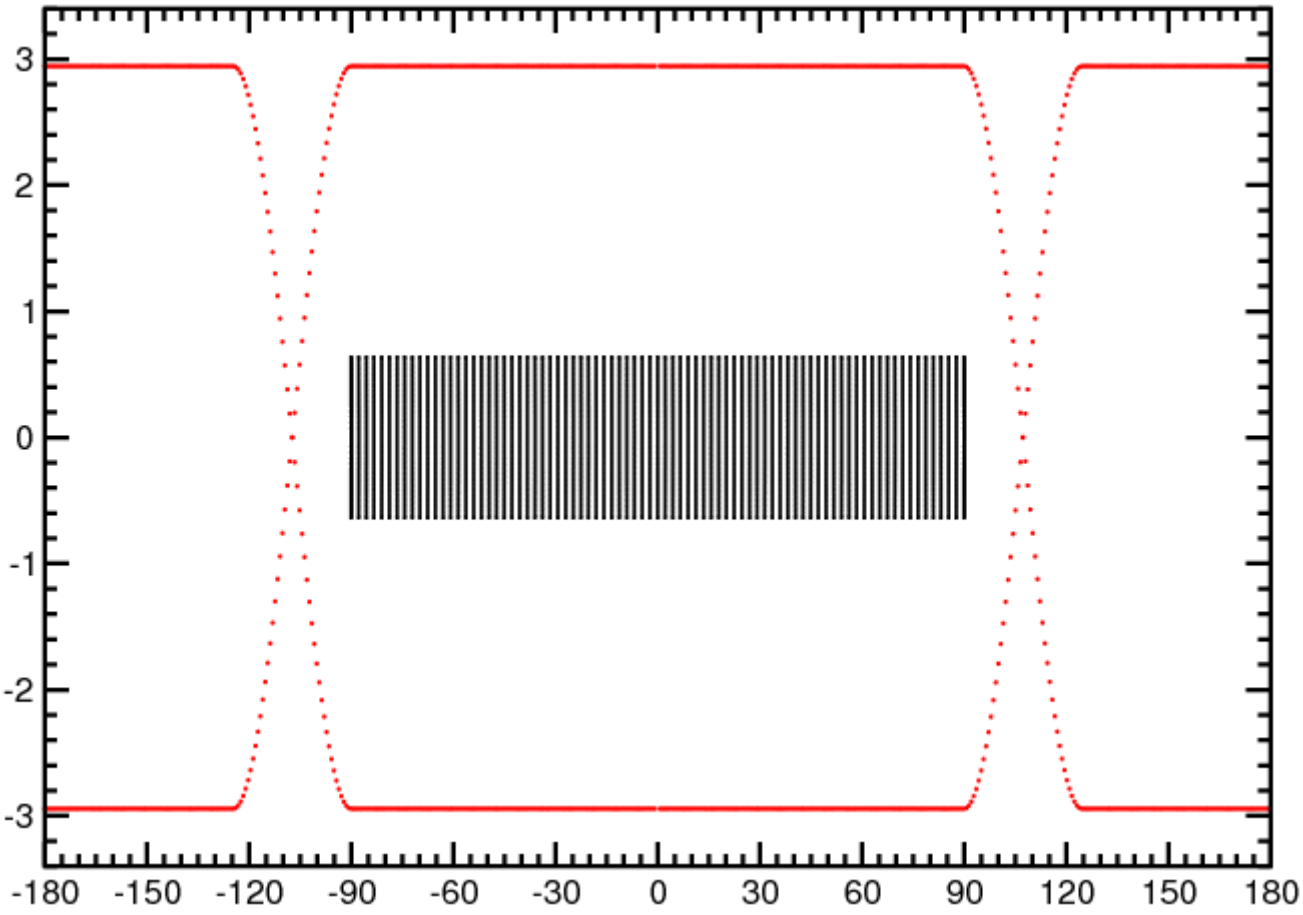
- Inject entire content of EBIS trap into a half-turn of Booster
- Hold in place with barrier bucket
- Capture into 2 of the harmonic 4 buckets
- Accelerate and transfer 8 loads of 2 bunches to AGS
- Doubles per bunch intensity but keeps longitudinal emittance the same

1 of 8 Booster loads to AGS

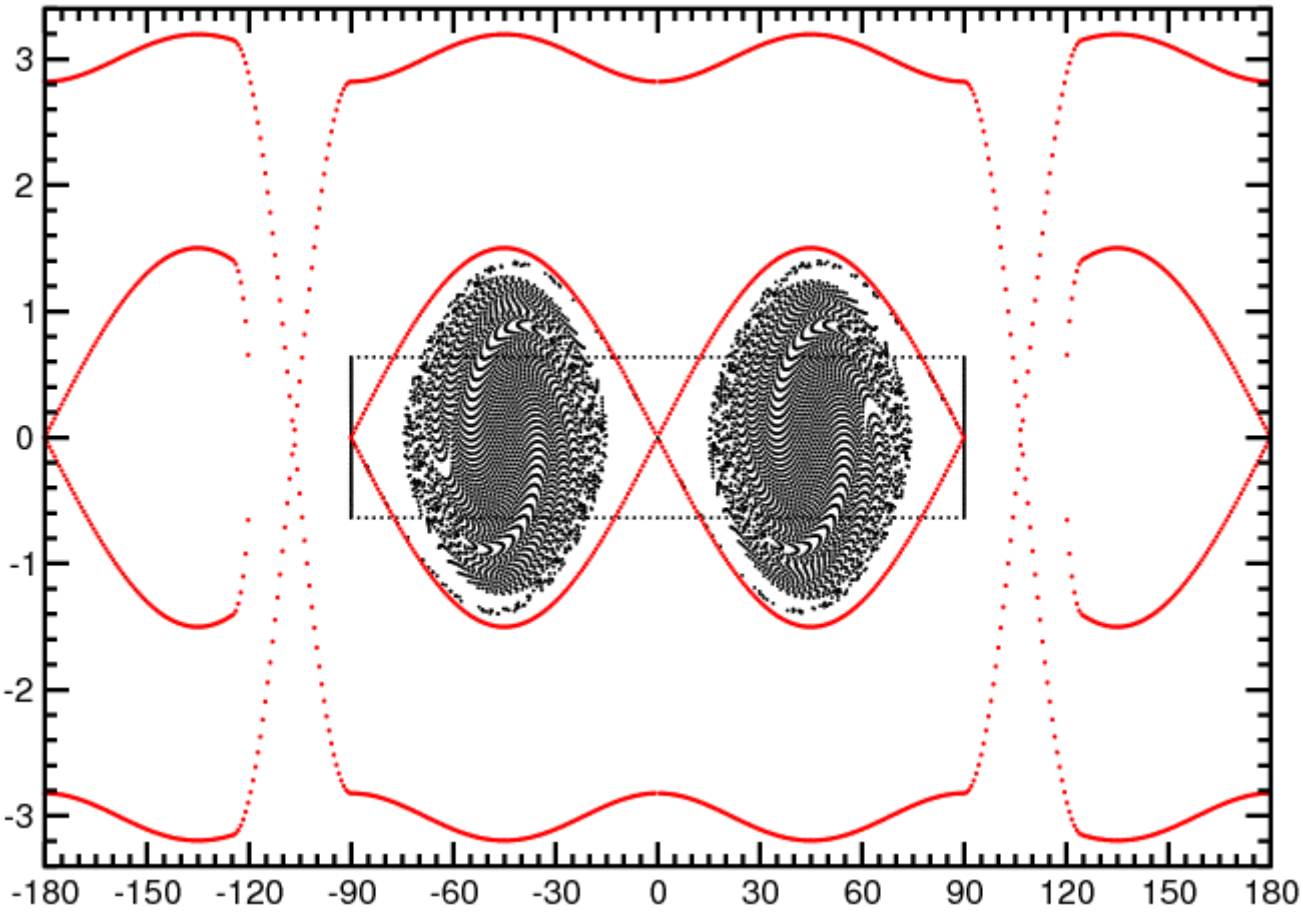


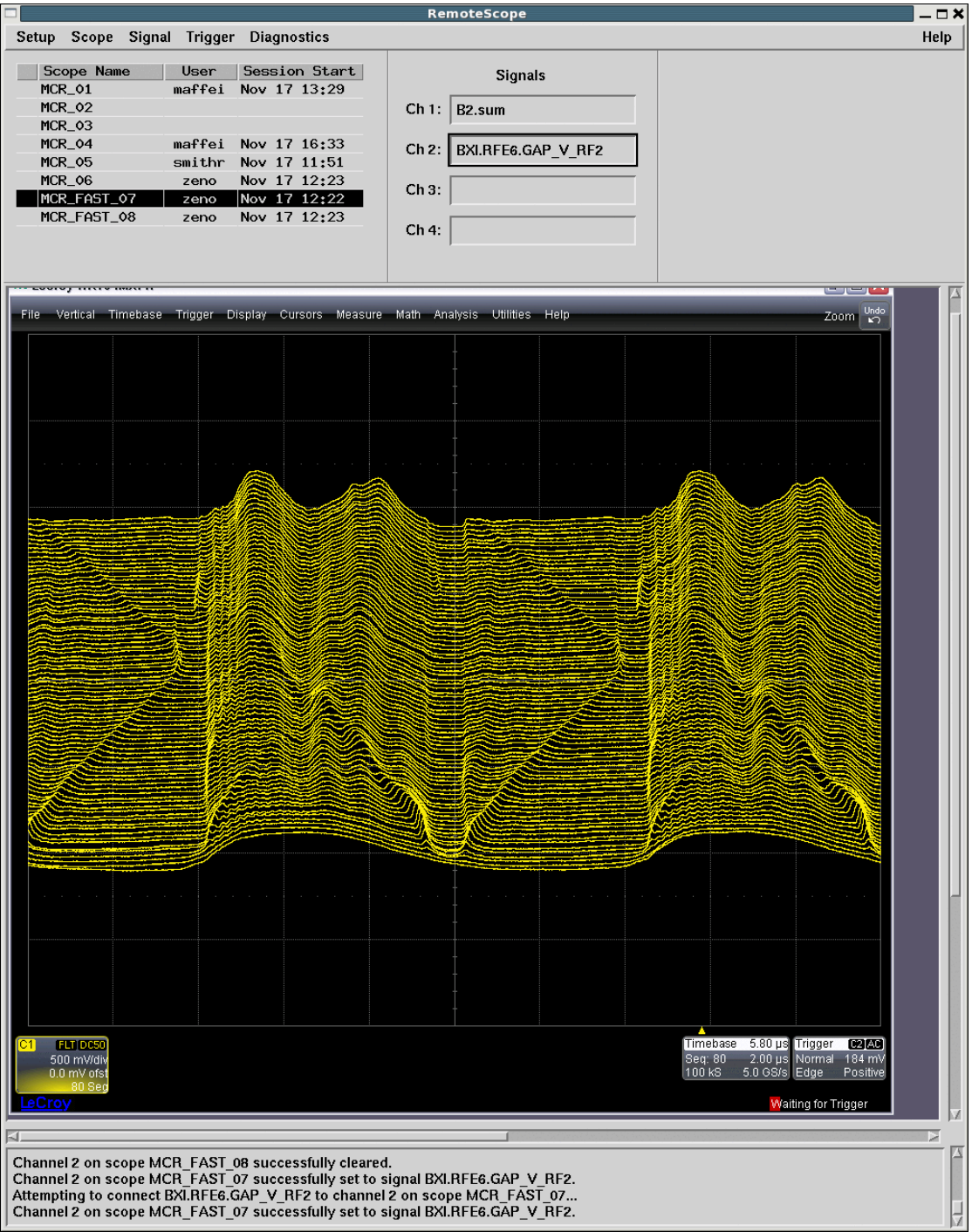
Merge 16 to 8 to 4 as before.
Gives 2 Booster loads per bunch.

Half-turn in barrier bucket



Captured into two h=4 buckets



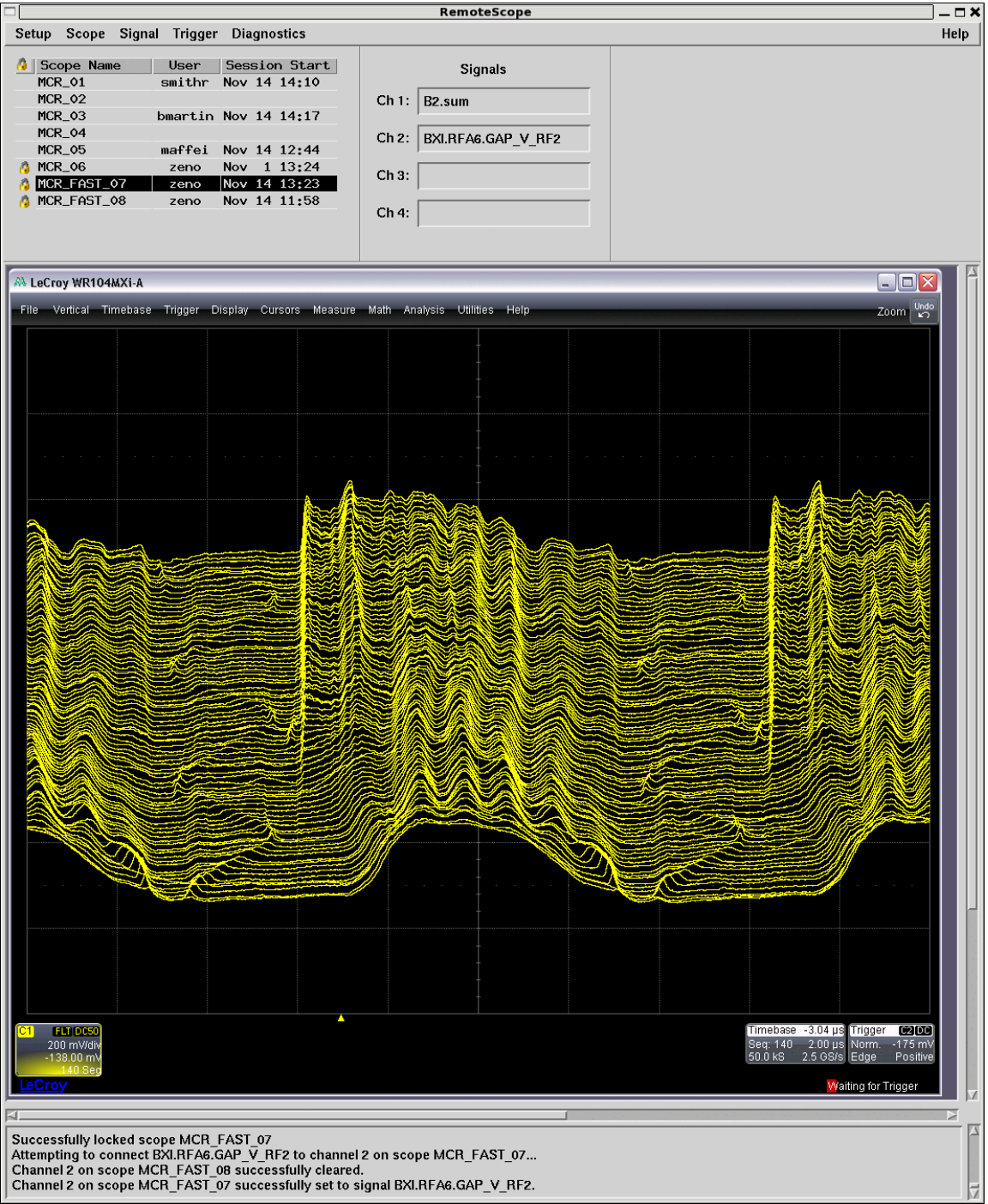


Here K. Zeno has captured beam in the barrier bucket.

The troughs on either side of the bunches show the location of the barriers.

Beam injected on the barriers gets a kick and bounces back and forth.

Note: beam pulse is chopped here, so not all beam in the trap is delivered to Booster



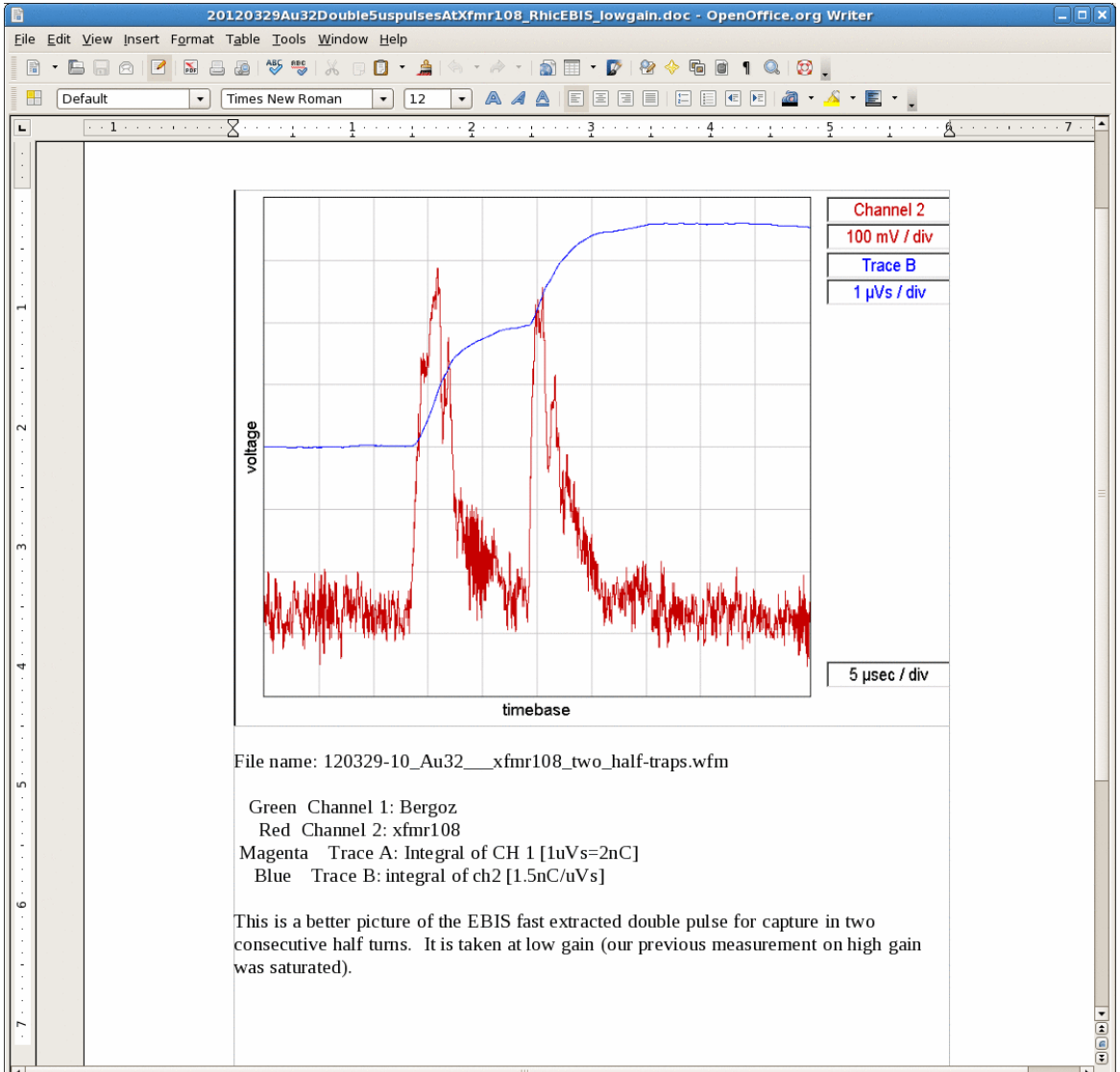
Here only the barrier cavities are excited. These perturb the beam with unwanted harmonics.

These could have been tuned out, but more pressing problems arose…

Issues…

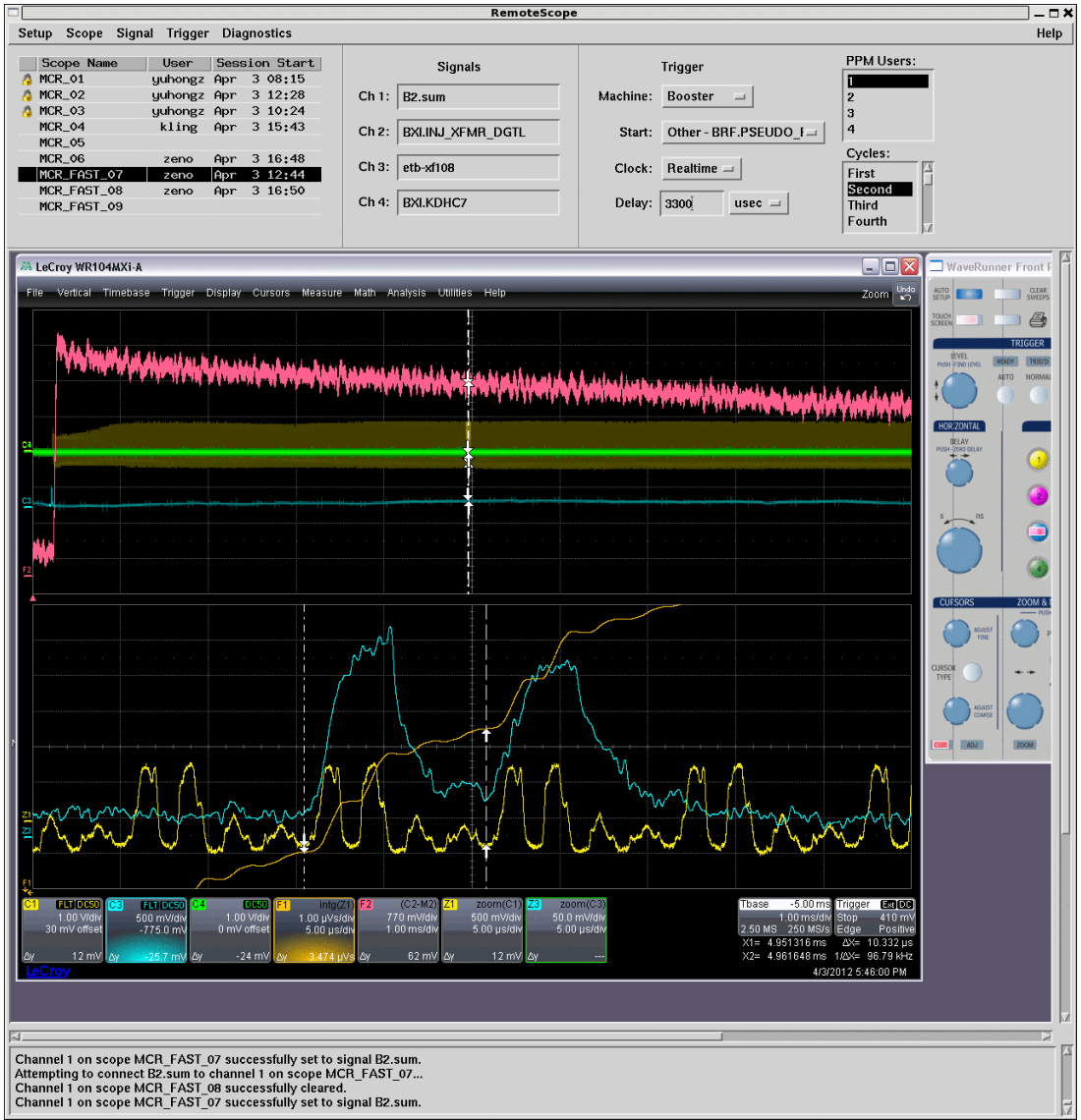
- Hard to empty EBIS trap in just 1 half turn (EBIS designed for 1 to 4 turn extraction)
- Go to “double pulse” mode with 2 half-turn extractions separated by 1 turn
- Get only 70-80% of beam into 2 bunches
- Beam distribution in barrier bucket not uniform; spreads out only very slowly. (In fact barrier bucket probably not needed.)

EBIS double pulse mode



The two half-turn pulses occur 1 turn apart and end up on top of one another in Booster. Square pulses with uniform beam distribution to be bunched would be ideal.

80% in 2 main buckets



The blue trace shows the two half-turn pulses just before Injection.

The yellow trace shows the bunched beam after some acceleration. 80% of the bunched beam is in the 2 main bunches.

Moreover one gets less beam from trap than for long pulse mode.

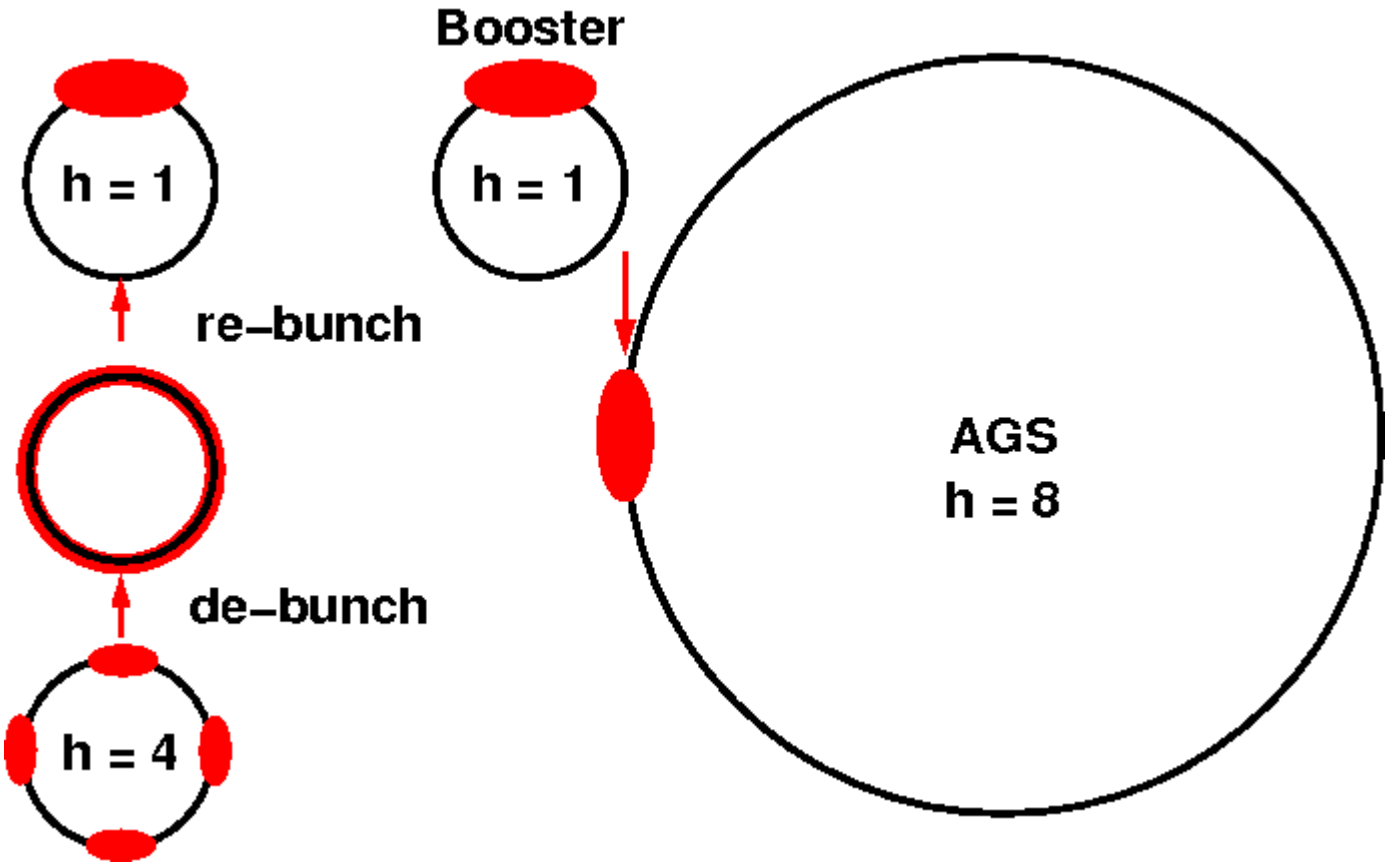
Double pulse and barrier bucket scheme exits stage left…

Booster debunch rebunch scheme enters stage right…

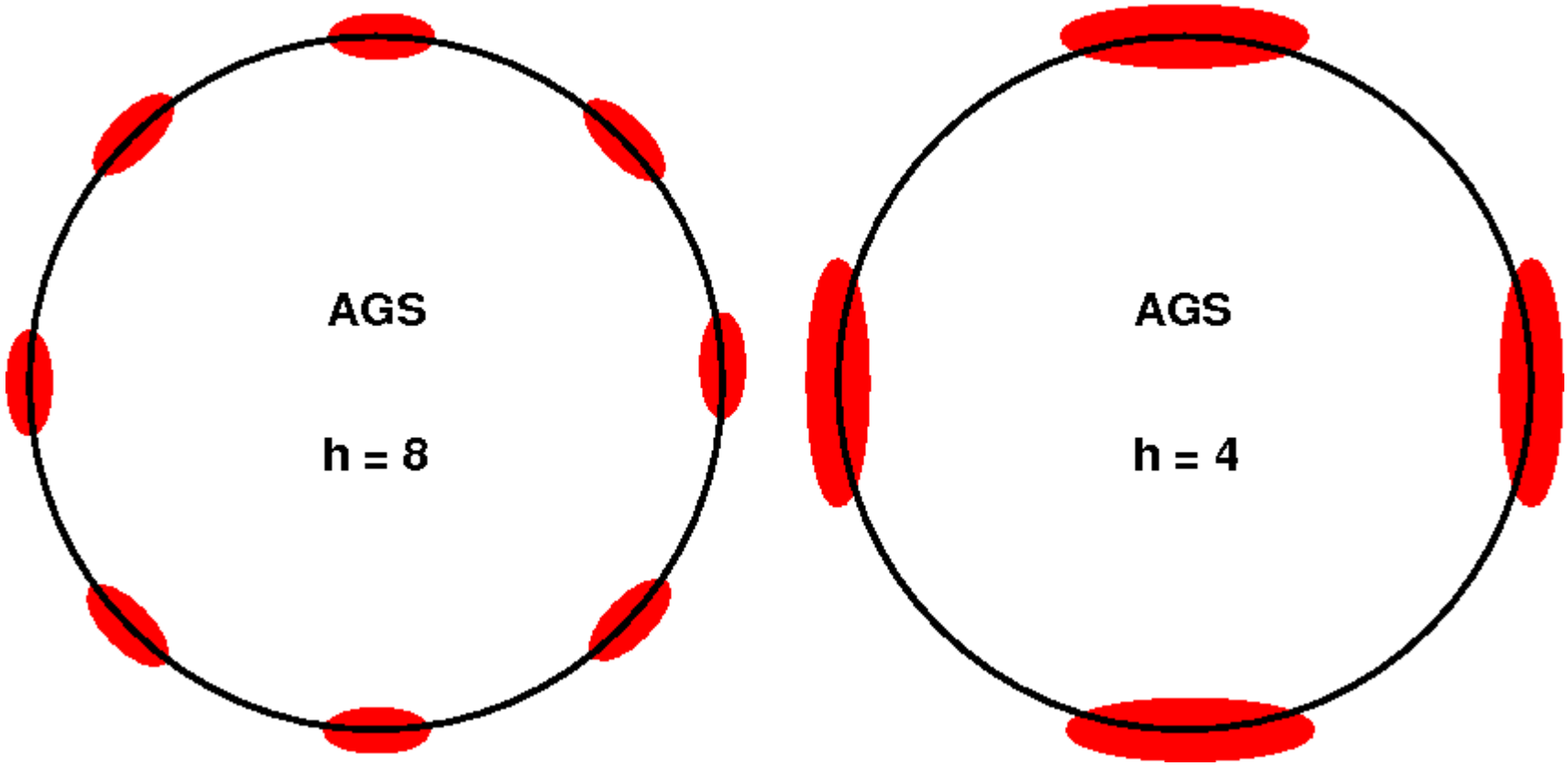
Booster debunch rebunch…

- Inject EBIS beam and capture and accelerate to an intermediate porch
- Debunch the 4 bunches and rebunch into one large bunch
- Accelerate, and transfer 8 loads of 1 bunch to AGS
- Merge 8 into 4 bunches on AGS porch

1 of 8 Booster loads to AGS

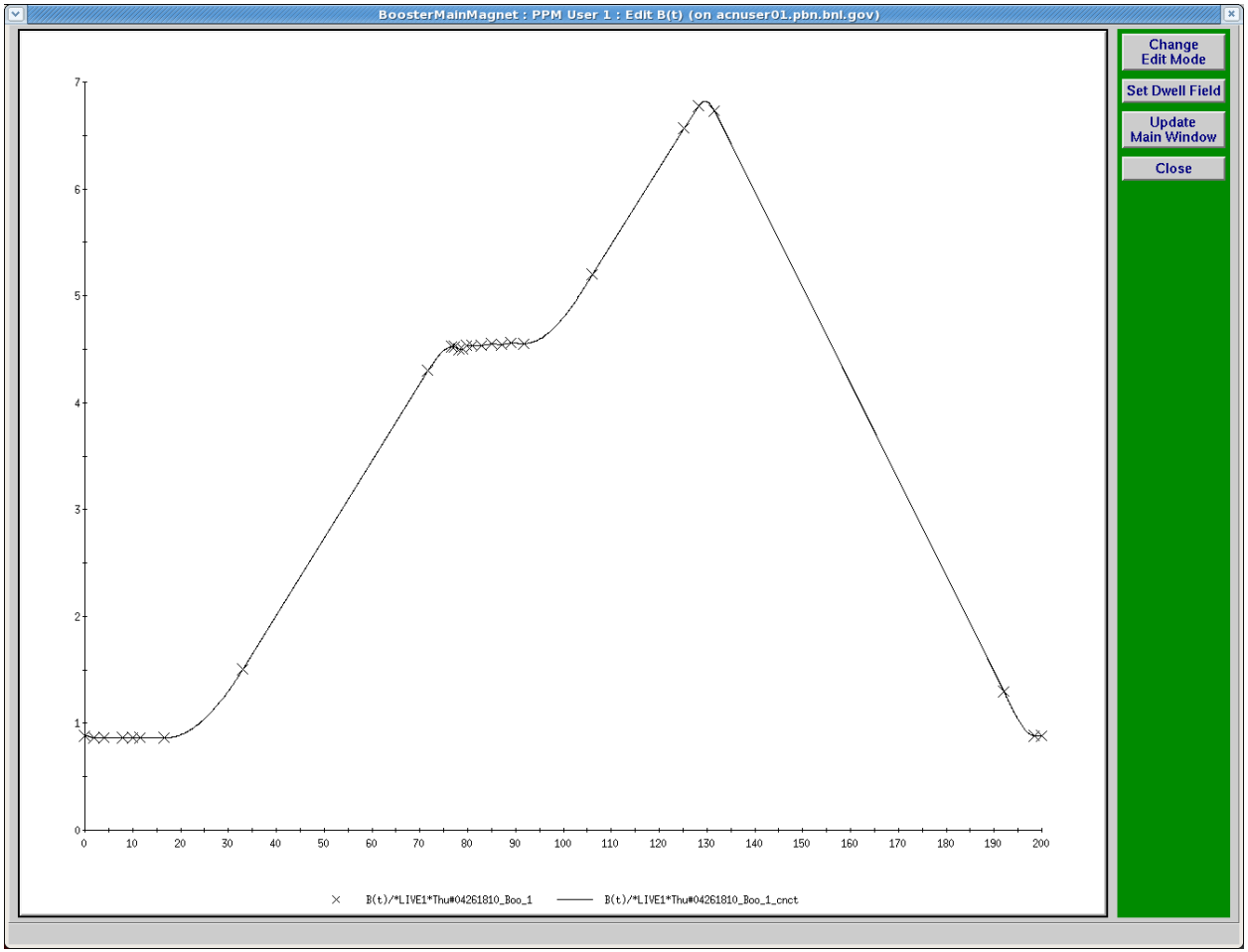


Merge 8 bunches into 4



2 Booster loads per bunch

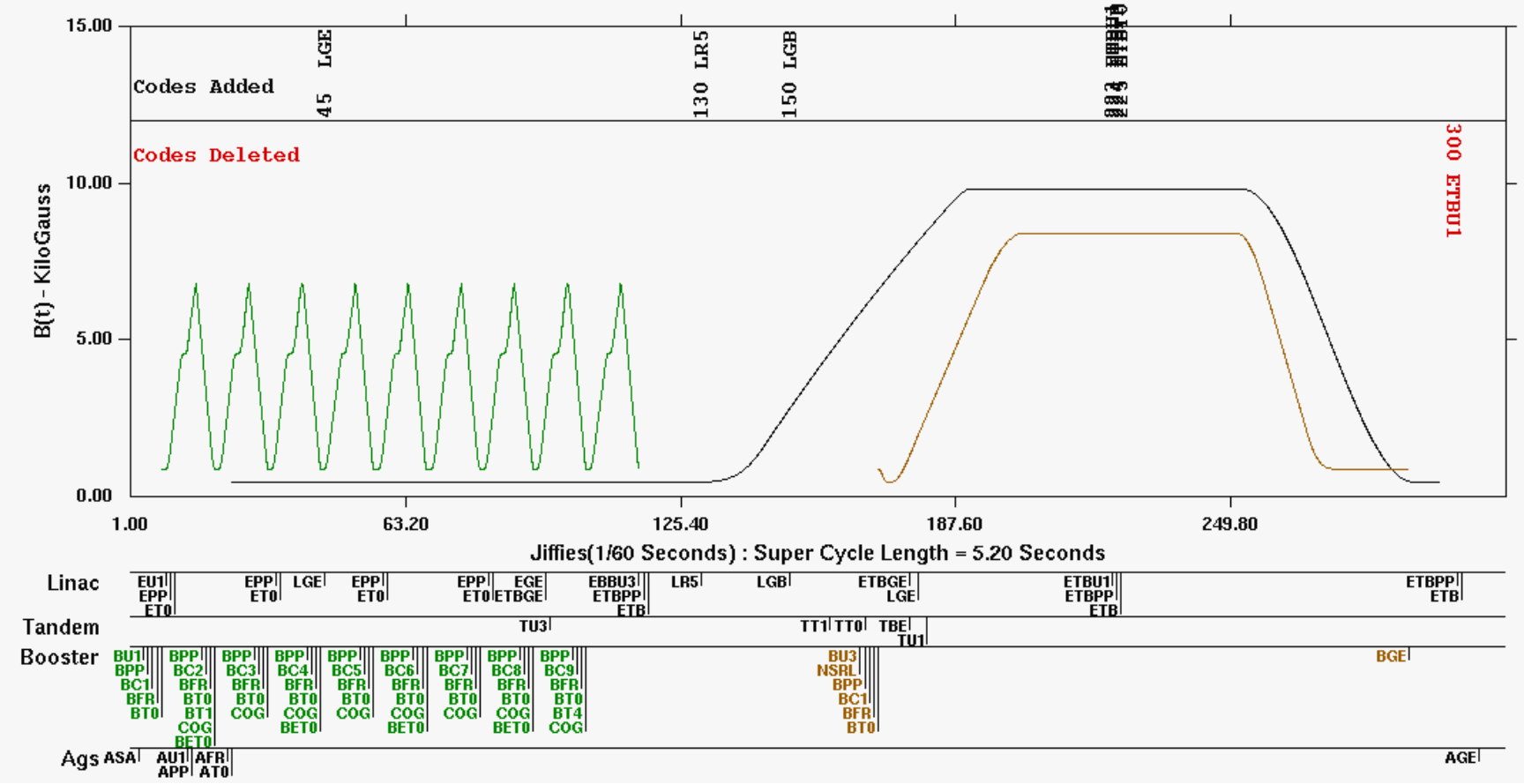
Booster magnetic cycle



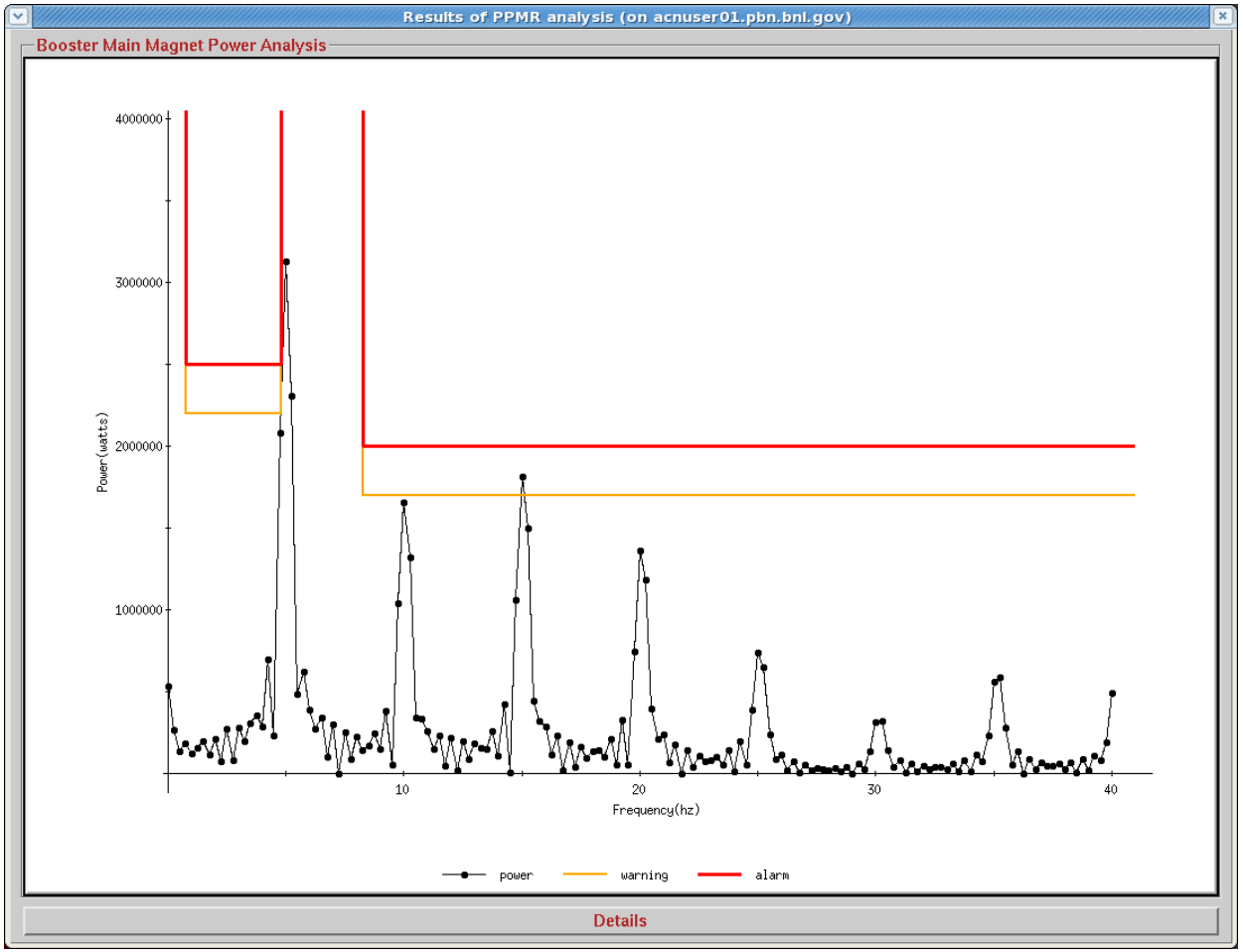
Debunch rebunch takes place on the porch.

Cycle length must be 200 ms or less in order to avoid harmful perturb-ations of the local power grid.

9 such per supercycle



Perturbation of local power grid



K. Zeno had to work hard to get a cycle with perturbations of the grid that stay below the red line limit.

The peak at 5 Hz just misses the red line.

Booster debunch rebunch setup used for part of U physics run

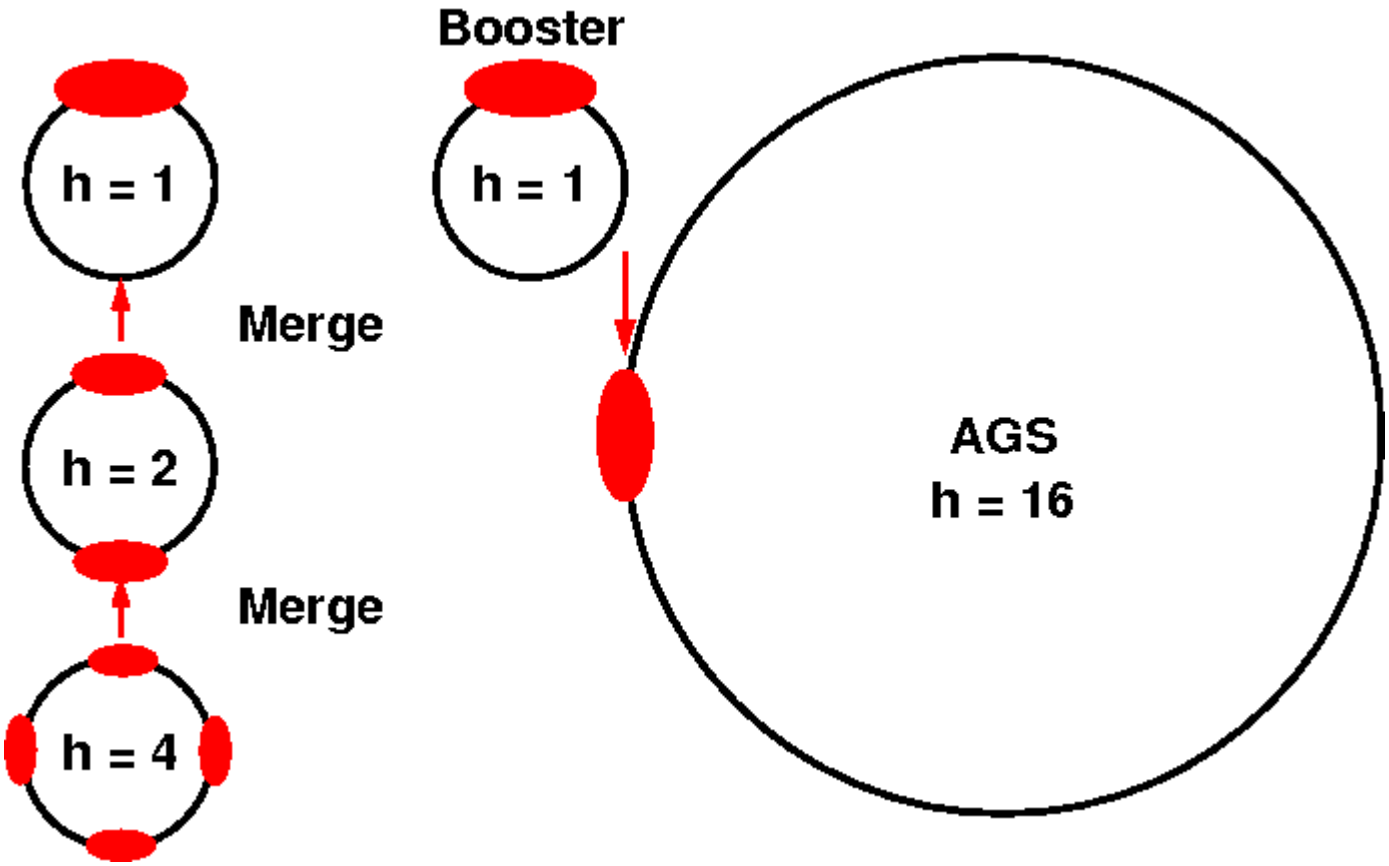
Then we switched to

something better…

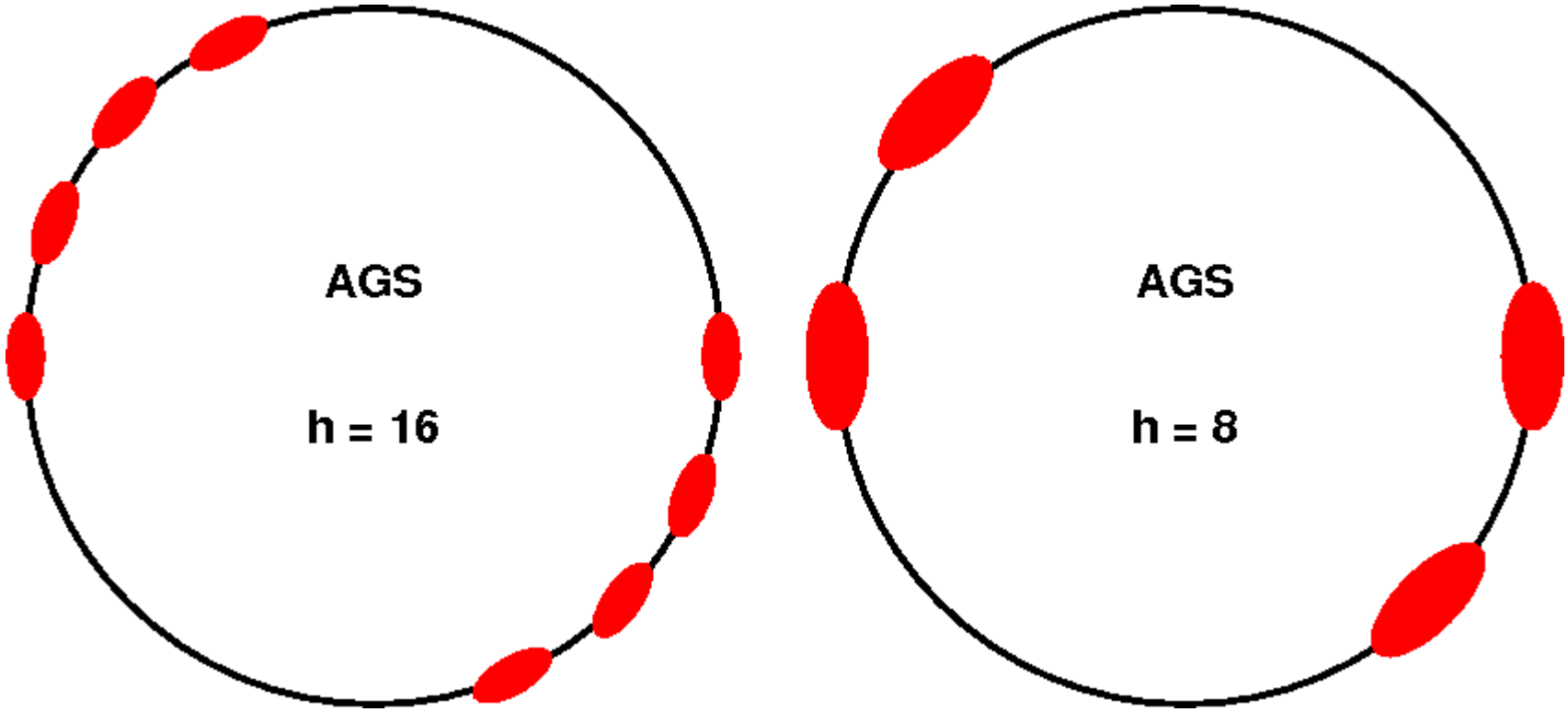
Booster double merge:

- Inject EBIS beam and capture and accelerate to porch as before
- Merge 4 bunches into 2, then the 2 into 1
- Accelerate, and transfer 8 loads of 1 bunch to AGS
- Find that Booster bunches now fit into harmonic 16 buckets in AGS. <u>This makes double merge in AGS possible.</u>

1 of 8 Booster loads to AGS

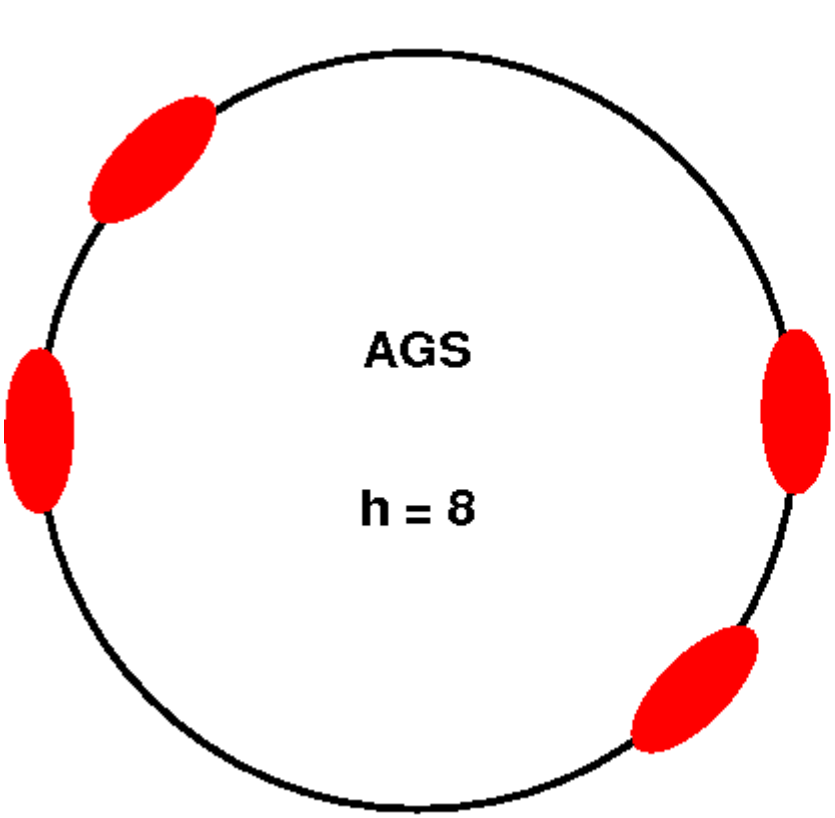


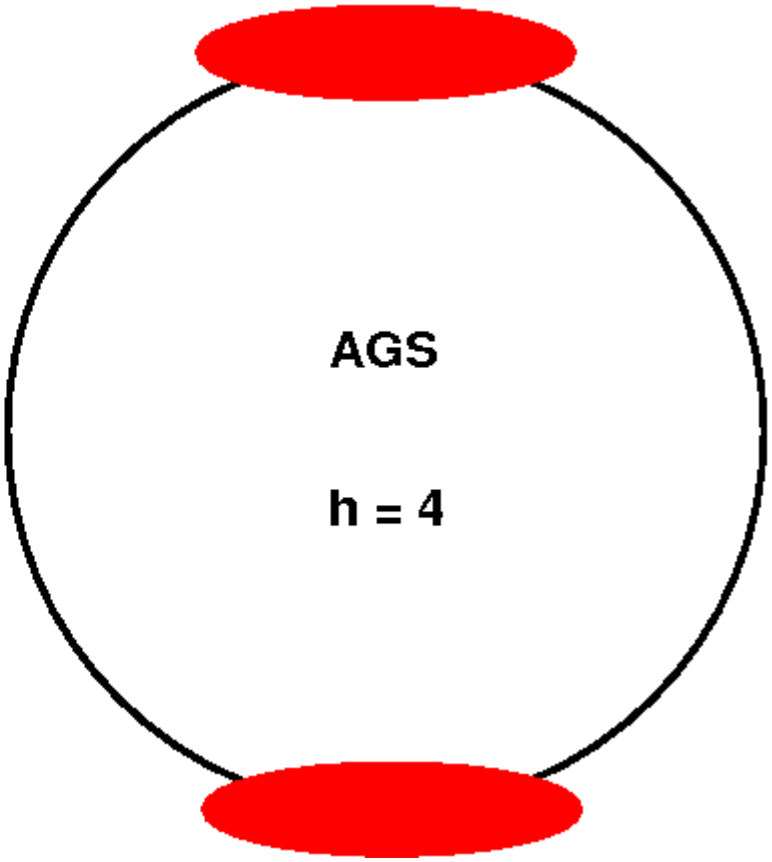
Merge 8 to 4



2 Booster loads per bunch

Merge 4 to 2





4 Booster loads per bunch

But, can the AGS merges be done with missing bunches?

(Here the Queen enters stage right…)

A 16 to 8 to 4 merge with missing bunches can’t be *that* difficult…

The difficulty was overcome and the scheme worked brilliantly

_____

Numbers achieved:

- 1.62e9 Au77+ ions per bunch at AGS ext
- 6.50e9 Cu29+ ions per bunch at AGS ext
- 3.8e8 U90+ ions per bunch at AGS ext
- 0.5 to 0.6 eV s per nucleon at AGS ext
- (Careful measurements by K. Zeno)
- These met the needs of the RHIC physics program…

And the Queen was delighted…

Issues…

“Baby” Bunches

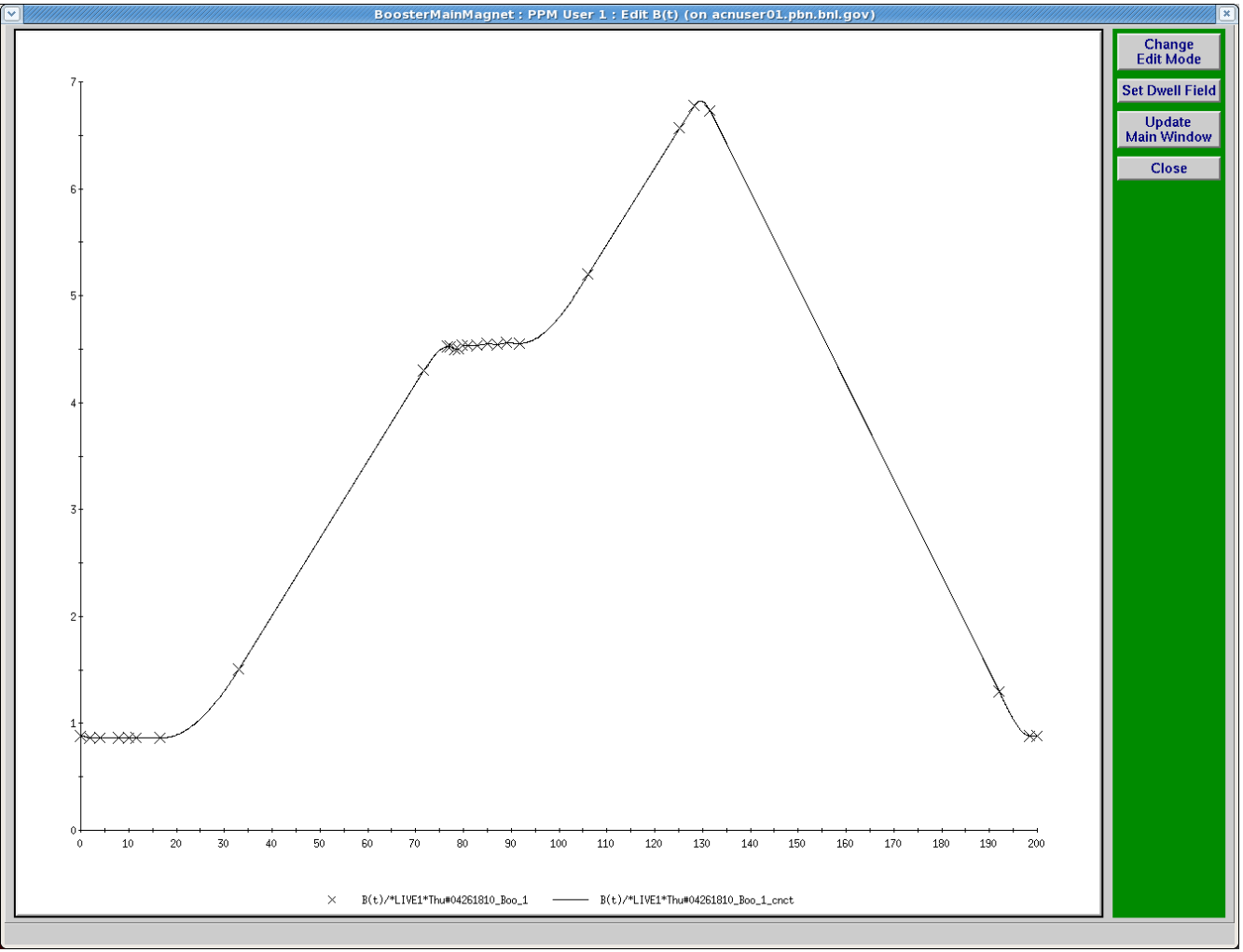
After merging, the bunches need to be squeezed into harmonic 12 buckets for subsequent acceleration. Some 8 to 12% (sometimes more) of the beam does not fit; these are the babies.

AGS capture loss

Beam is lost as as harmonic 12 voltage increases and the beam begins to accelerate. Most likely because longitudinal emittance is too big.

Another picture: Au Cap loss

Booster magnetic cycle

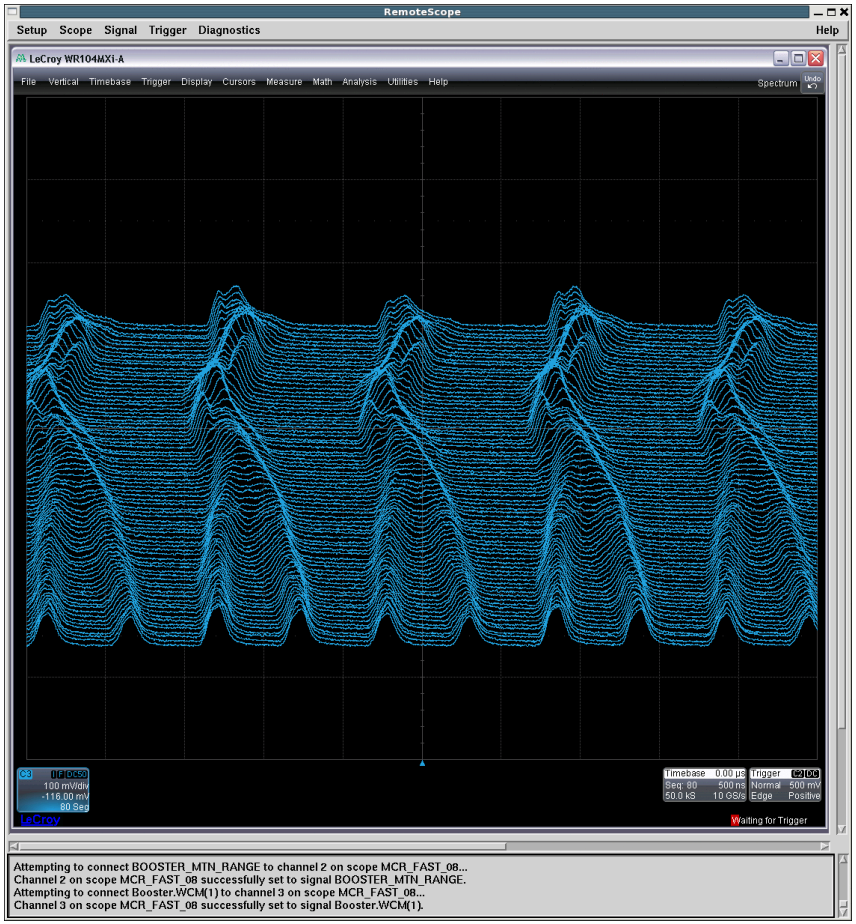


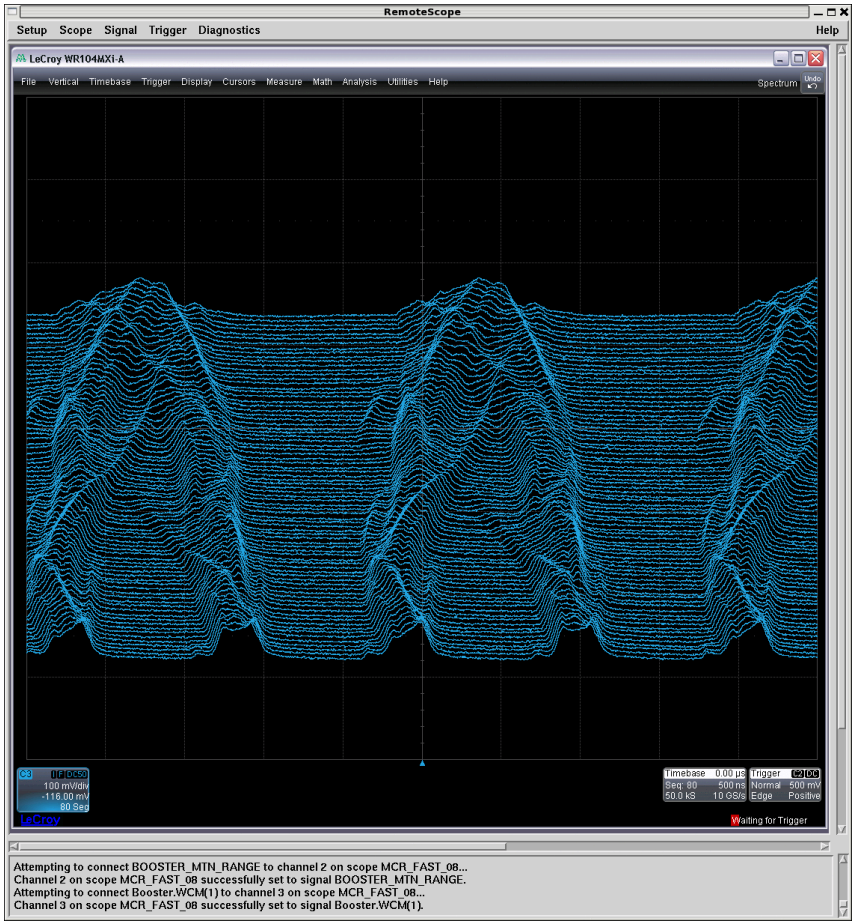
K. Zeno had to "tune" many points on the porch to get a flat field.

Can we get better BMM power supply regulation on the porch?

Can we somehow reduce coupling to local power grid so that we can have a longer porch?

Booster merges (why so ugly?)

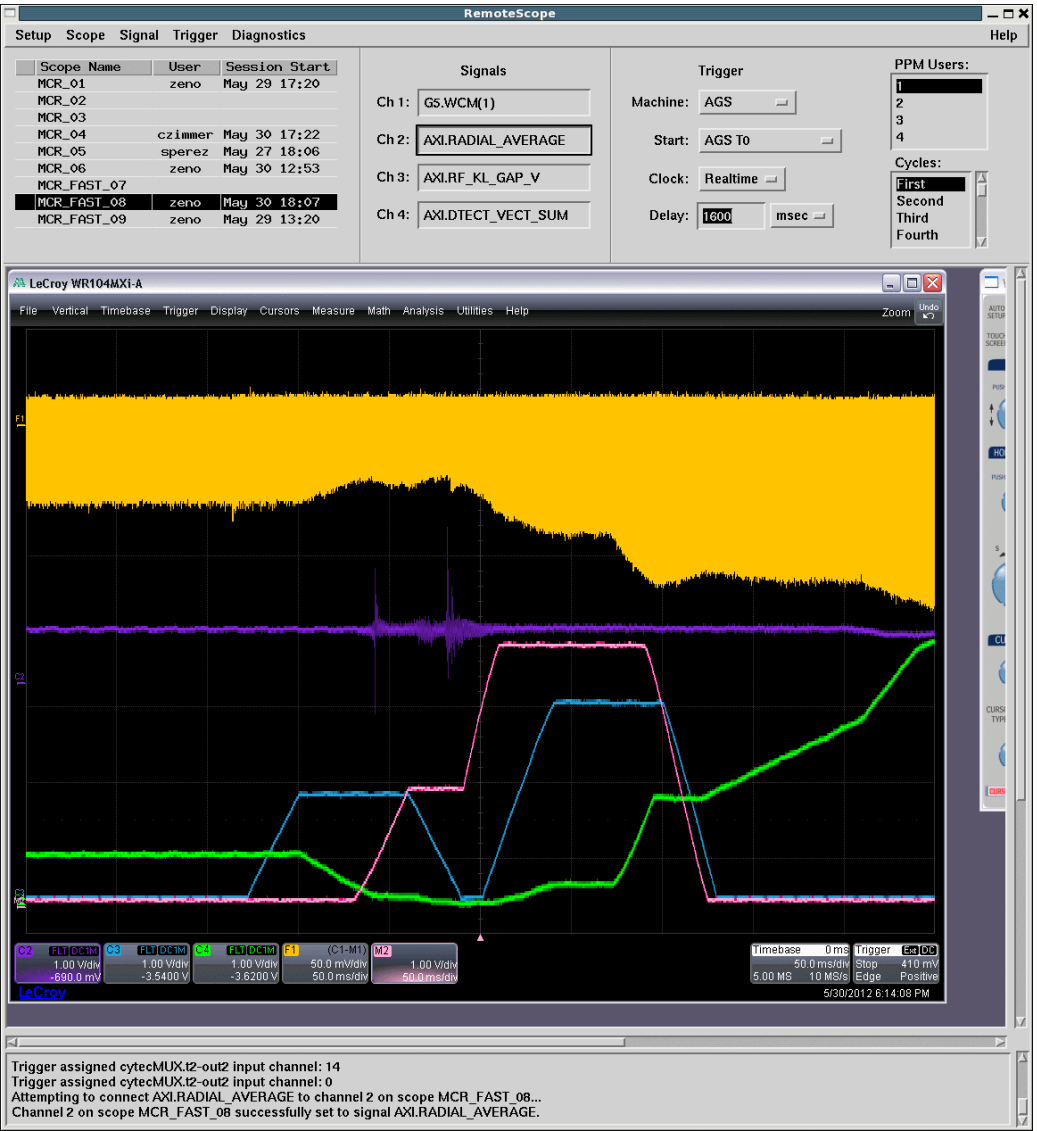




Backup slides…

Booster merge voltage program

AGS merge voltage program



K. Zeno’s U, Au, and Cu emittance measurements…

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U

	width	Synch freq	Matching Volts	Debunch time	dp/p	Emittance Ev-sec	
1st turn ags[a]	415 ns	1230 Hz h=12	20 kV (ags)			0.18	
1st turn Ags[b]	379 ns		28.4 kV (Booster)			0.15	
100 ms after inj[c]	424 ns	1161 Hz h=12	17.7 kV			0.17	
AGS inj[d]	400 ns			2.40 ms	1.51e-3	0.18	
1st turn ags[e]	372 ns		21.5 kV h=8			0.156	
100 ms after inj[f]	355 ns		21.5 kV h=8			0.144	
Ags inj[g]	290 ns		h=8 h=16	2.71 ms	1.36e-3	0.120 0.113	
100s of ms after inj[h]	337 ns	1124 Hz	24.5 kV h=8			0.140	

All these values are for 1 Booster bunch

a-with debunch rebunch, see Apr 26 elog
b-with debunch-rebunch, measuring emit late in Booster (before foil), see Apr 27 elog
c-with debunch rebunch, see Apr 27 elog
d-with Booster merge, see May 2 elog
e-with Booster merge, after foil, see May 7 elog
f-with Booster merge, see May 7 elog
g-with Booster merge, see May 7-8 elogs
h- with Booster merge, equilibrated bunch, see May 8 elog

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Au

	Width	Synch Freq	Volts	Debunch time	Dp/p	emittance	
Incoming ebis[a]	10.38 us			6.12 ms	0.3e-3	0.025	
1st turn in ags[b]	278 ns	1554 Hz h=16	23.1			0.111	
1st turn in ags[c]	278 ns		33 h=16	2.25 ms	1.65e-3	0.133	
1st turn in ags[d]	291 ns 298 ns	1554 Hz	22.4 h=16			0.117 0.120	
Flattop[e]	25.0 ns	86.7 Hz	145 kV			0.54	
900 ms after inj[f]	313 ns	1720 Hz	27.4 h=16			0.140	
Merge[g]	1025	557 Hz	11.4 kV h=4			0.560	

All these values are for 1 Booster bunch, except as noted
a-Nov 14 1914, emitance of an ebis pulse in Booster
b-jun 13 elog, this is after foil (1 Booster bunch)
c-jun 13 elog, get volts from bbat for 278 ns and 1.65e-3
d-jun 19 elog, after foil
e-jun 19, for a bunch made of beam from 4 Booster cycles
f-jun 19
g-jun 19, after merge, before squeeze, only h=4 is on. For a bunch made of beam from 4 Booster cycles.

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Width

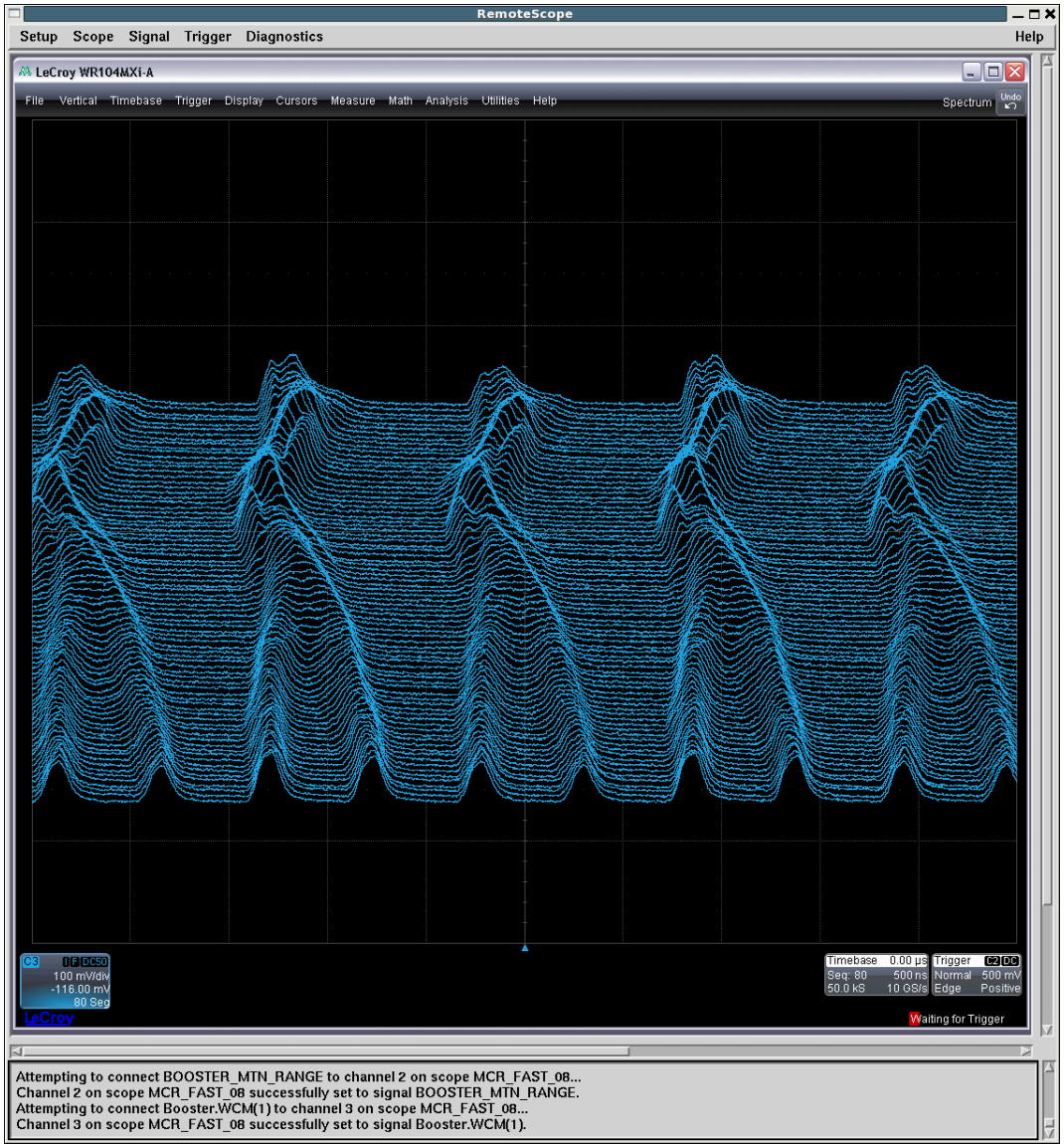
Cu

	Width	Synch freq	Volts	Debunch time	dp/p	emittance	
1st turn in ags[a]	318 ns		22.8 h=16	2.36 ms	1.57e-3	0.139	

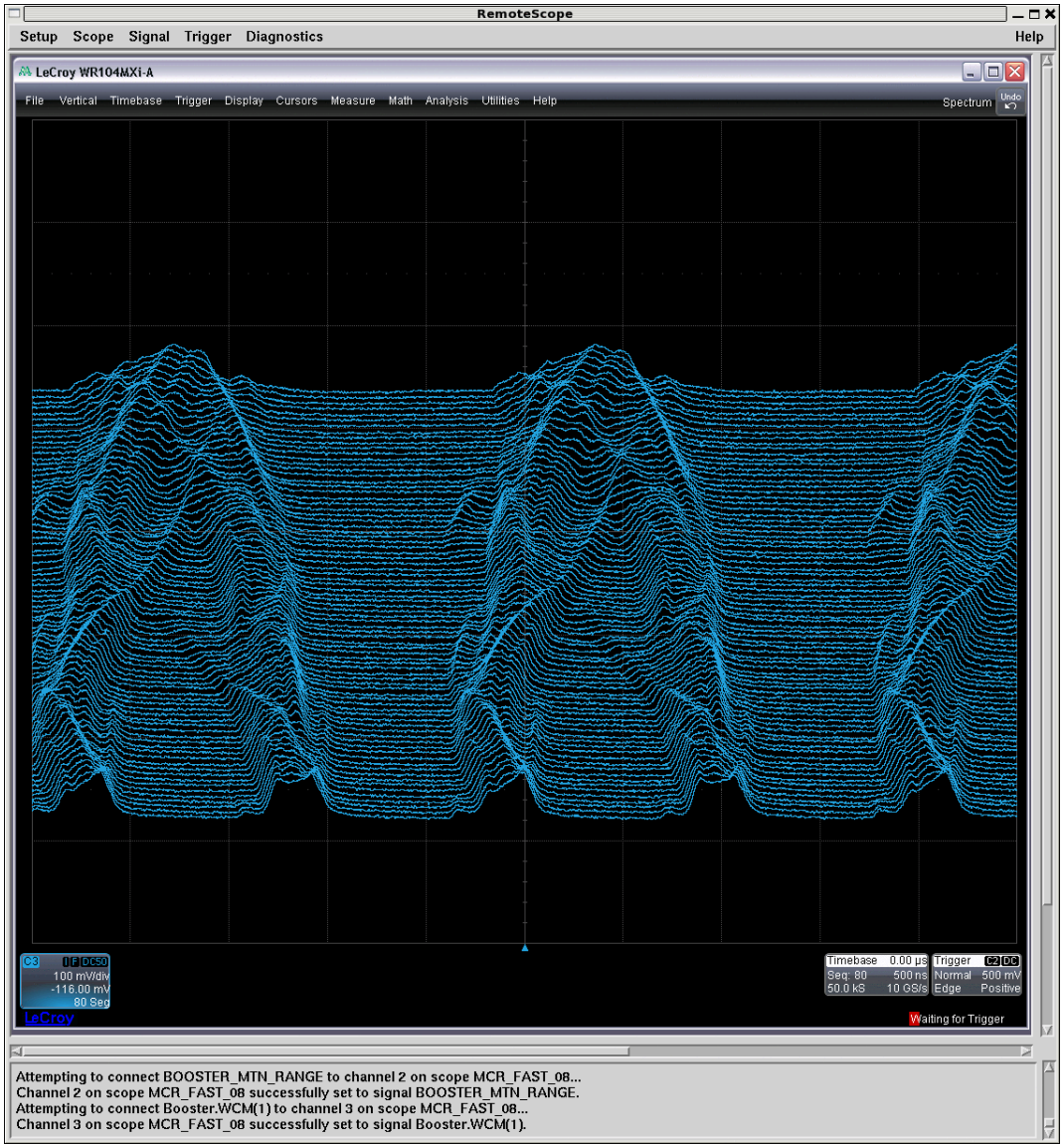
a-volts from bbat, jun18 elog

Mountain range pictures of merges…

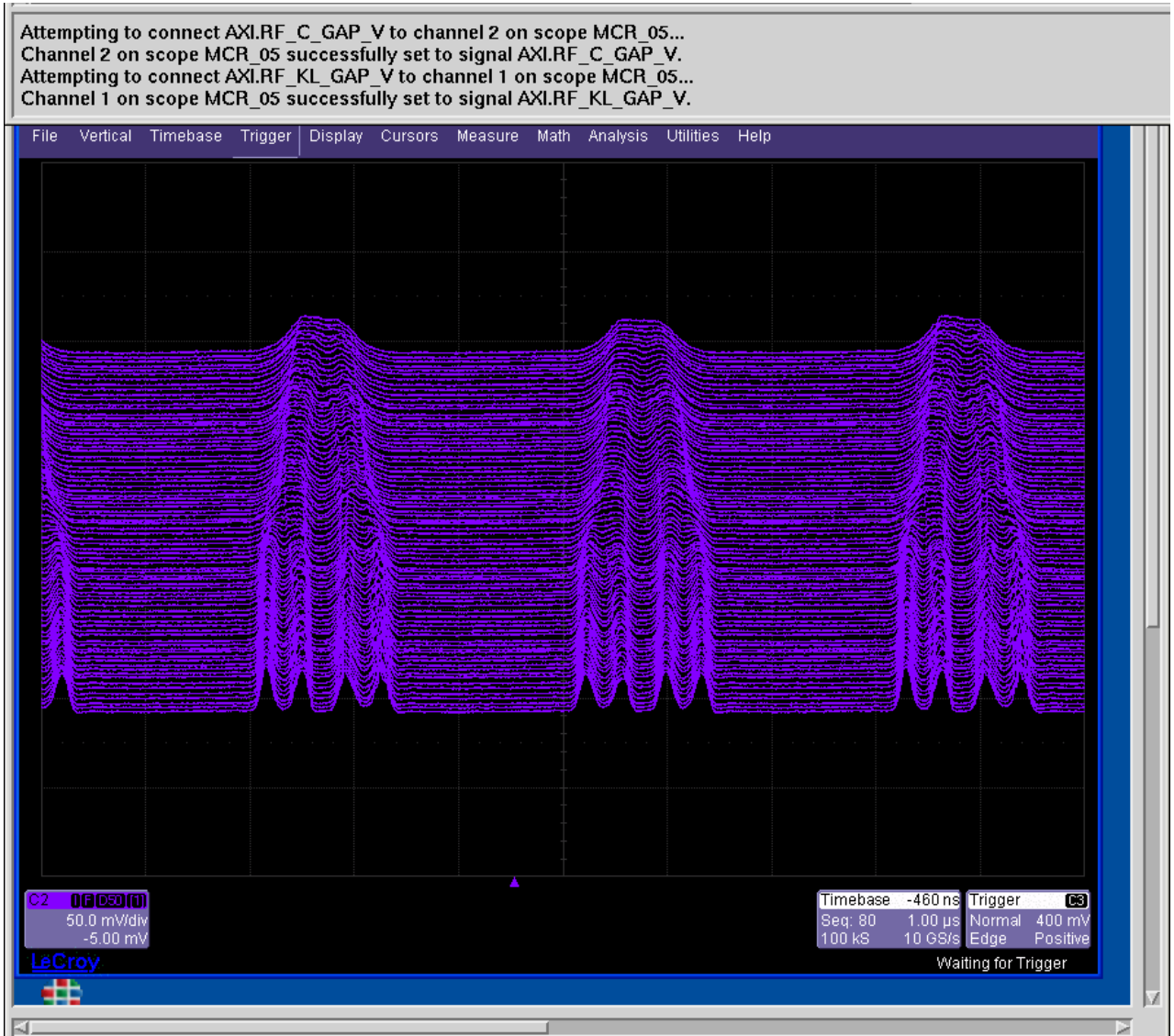
Booster 4 to 2 merge:



Booster 2 to 1 merge:



AGS 4 to 2 to 1 merge:



Merge simulation pictures…

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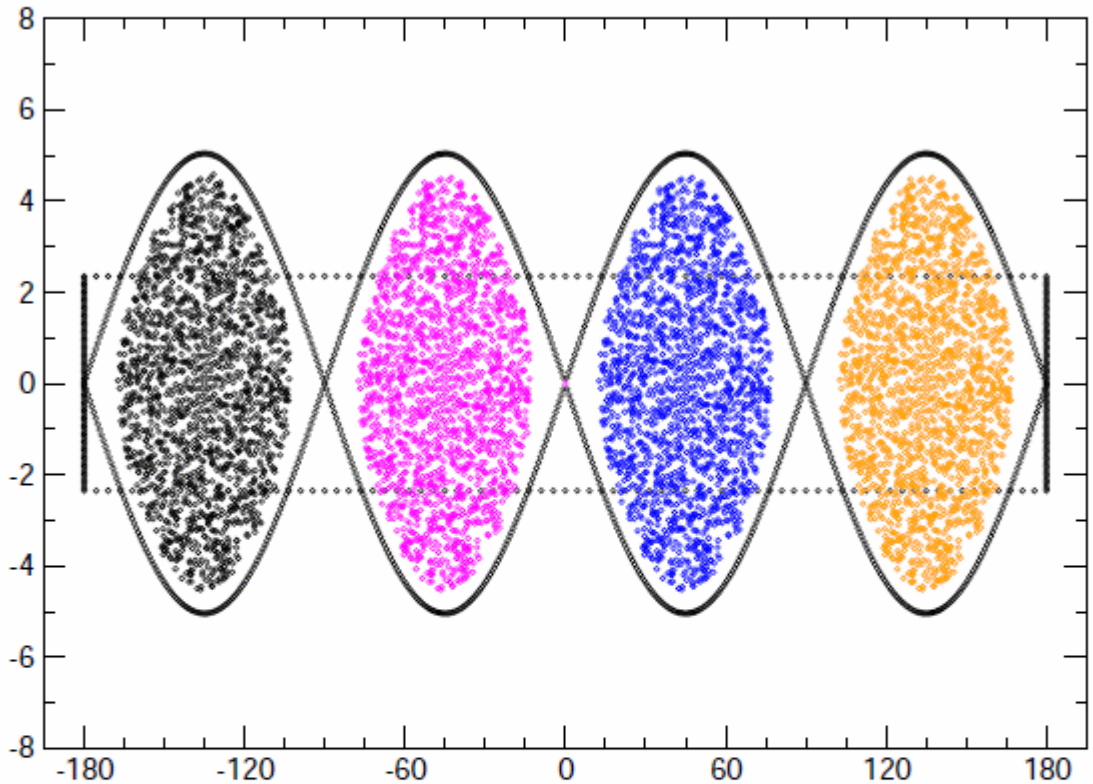

Figure 1: Four bunches of Au32+ ions in harmonic 4 buckets on the Booster merging porch. The harmonic 4 frequency is $4f_s = 1.860$ MHz. The voltage is $V_C = 2.0$ kV. The black rectangle is the border of the uniform distribution used to make the bunches. The longitudinal emittance of the distribution is 0.15 eV s per nucleon. One can see by inspection that the emittance of the 4 bunches is close to that of the initial distribution. The horizontal axis is the phase ϕ in degrees. The vertical axis is W in units of eV s.

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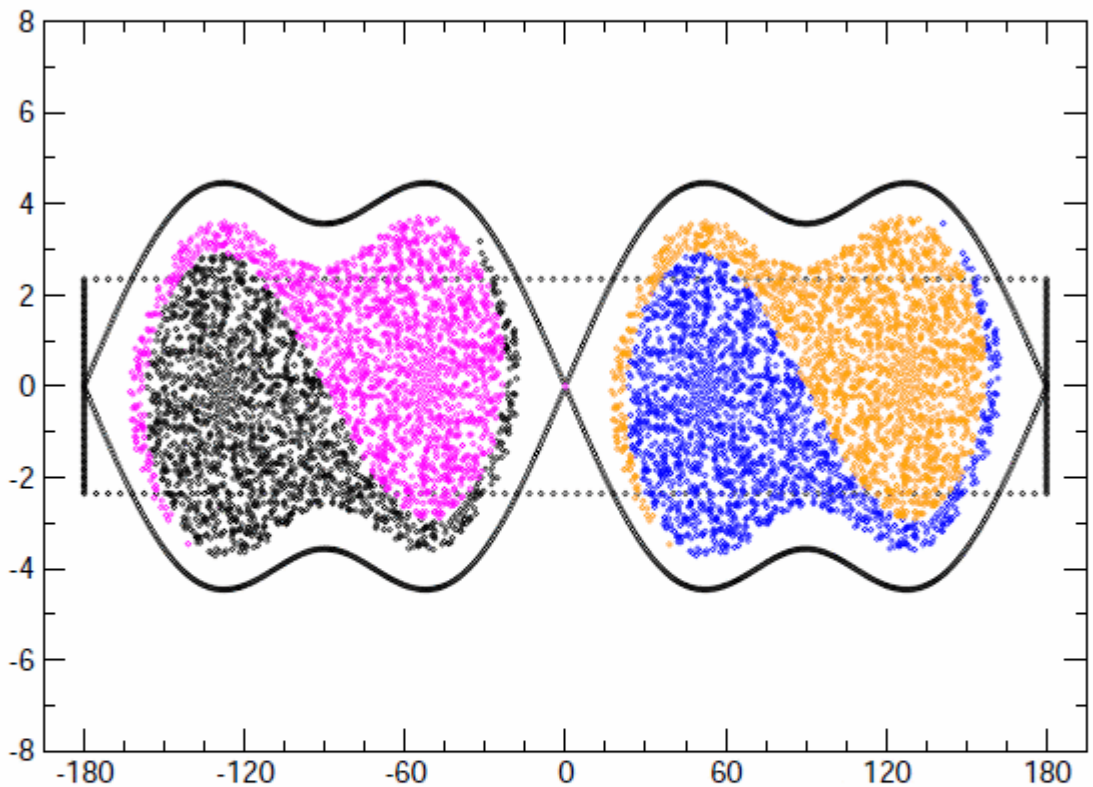

Figure 2: Halfway through the 4-to-2 merge of the bunches in **Figure 1**. Here the harmonic 4 voltage is $V_C/2 = 1.0$ kV. The harmonic 2 voltage is $V_K/2 = 0.5$ kV. The time from the start of the merge is $T_K/2 = 7.5/2$ ms.

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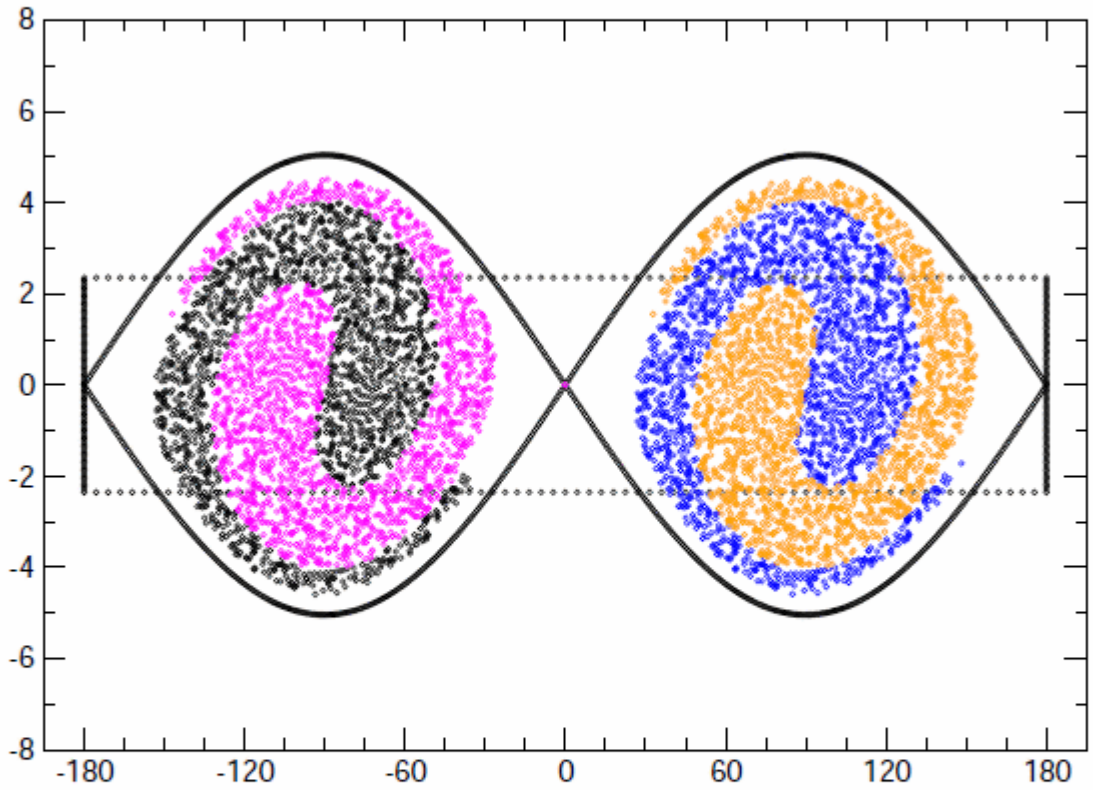

Figure 3: Completion of the 4-to-2 merge. Here the harmonic 2 voltage is $V_K = 1.0$ kV. The total time for the merge is $T_K = 7.5$ ms.

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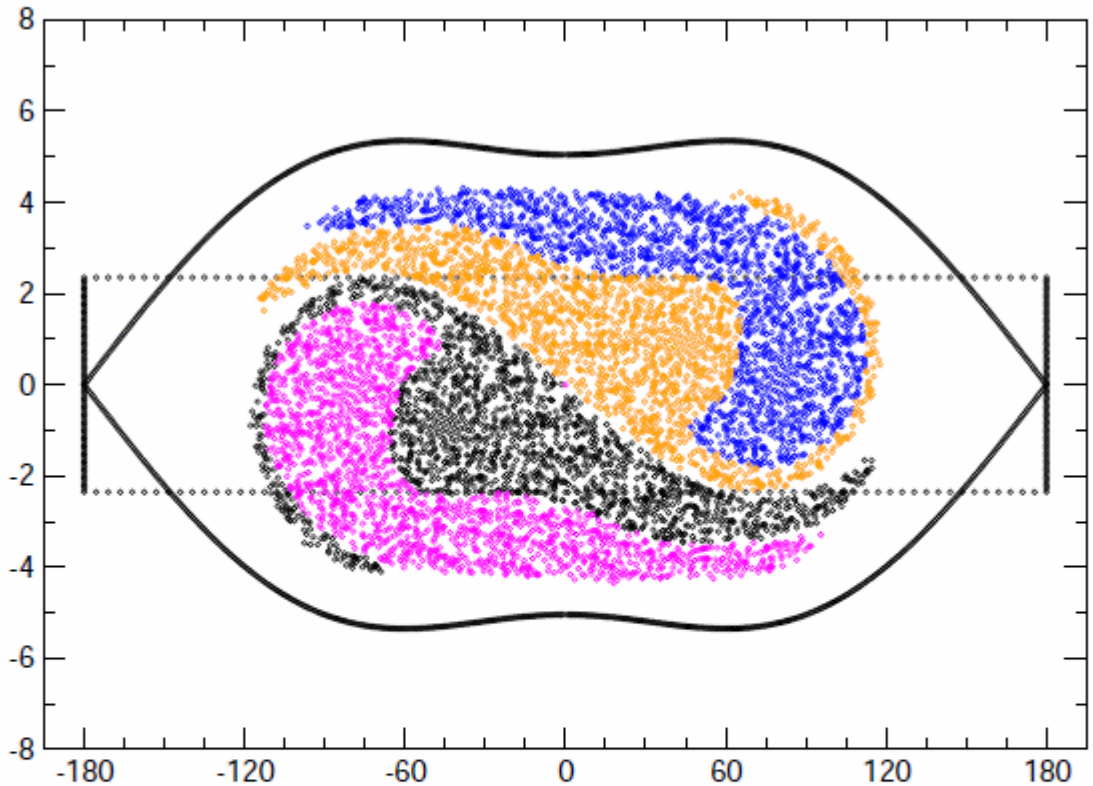

Figure 4: Halfway through the 2-to-1 merge of the bunches in **Figure 3**. Here the harmonic 2 voltage is $V_K/2 = 0.5$ kV. The harmonic 1 voltage is $V_L/2 = 0.5$ kV. The time from the start of the 2-to-1 merge is $(T_L - T_K)/2 = 7.5/2$ ms.

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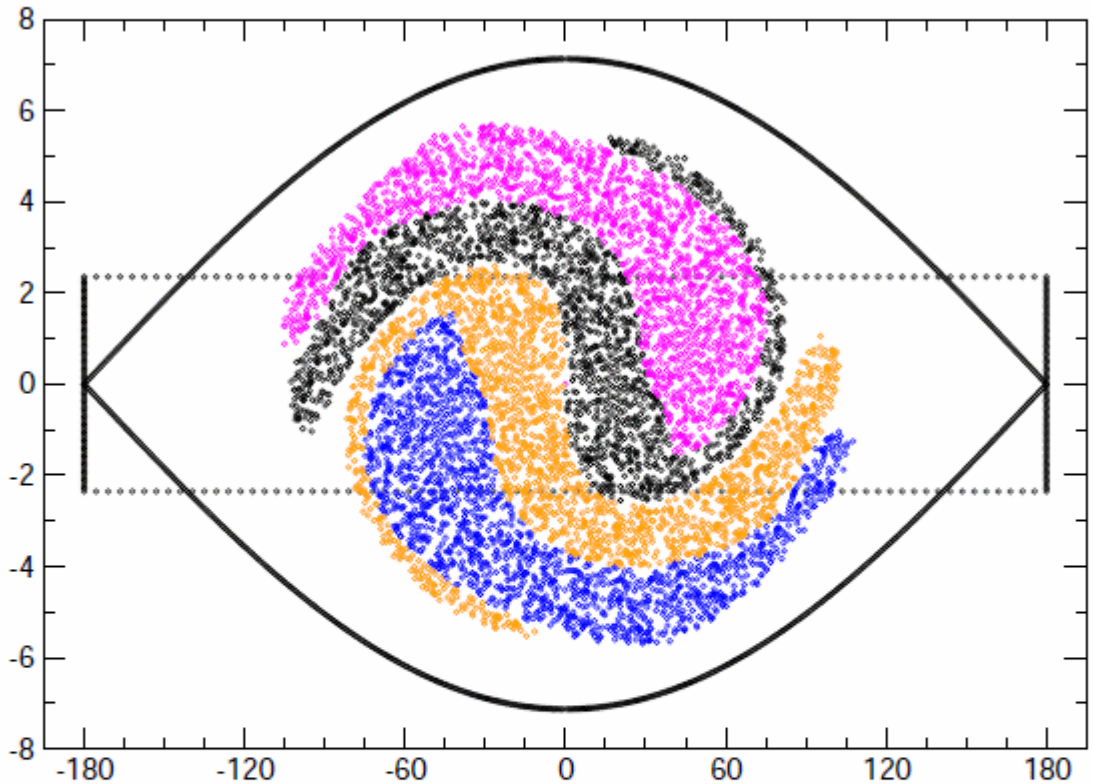

Figure 5: Completion of the 2-to-1 merge. The harmonic 1 voltage is $V_L = 1.0$ kV. The total 2-to-1 merge time is $T_L - T_K = 7.5$ ms. The total 4-to-1 merge time is $T_L = 15$ ms. The fractional momentum spread of the bunch is $\Delta p/p = \pm 0.00088$. The tails seen here make the effective emittance of the bunch larger than that of the initial 4 bunches. This is a result of the short total merging time of 15 ms. In practice we are limited to this time in order to avoid introducing potentially harmful harmonics on the local power grid. **Figure 6** shows the final bunch for the case in which the two merge times are doubled. The effective emittance in this case is noticeably reduced.

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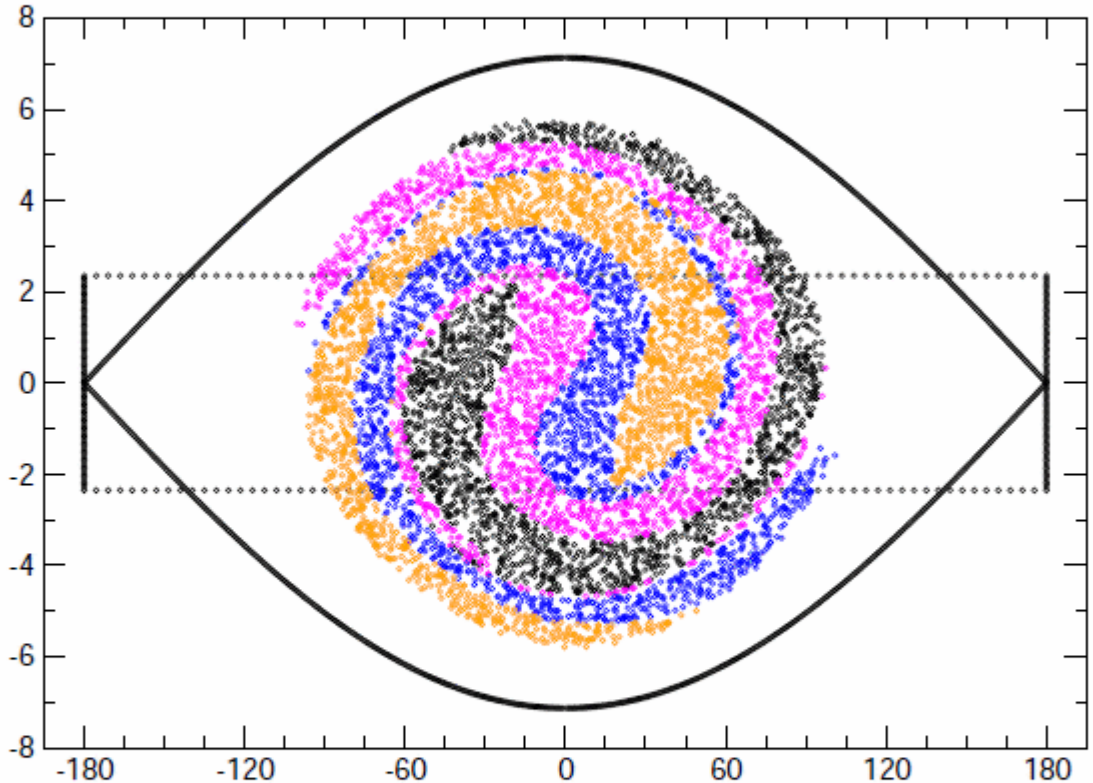

Figure 6: Same as **Figure 5** but with merge times doubled. The effective emittance of the bunch is noticeably reduced.

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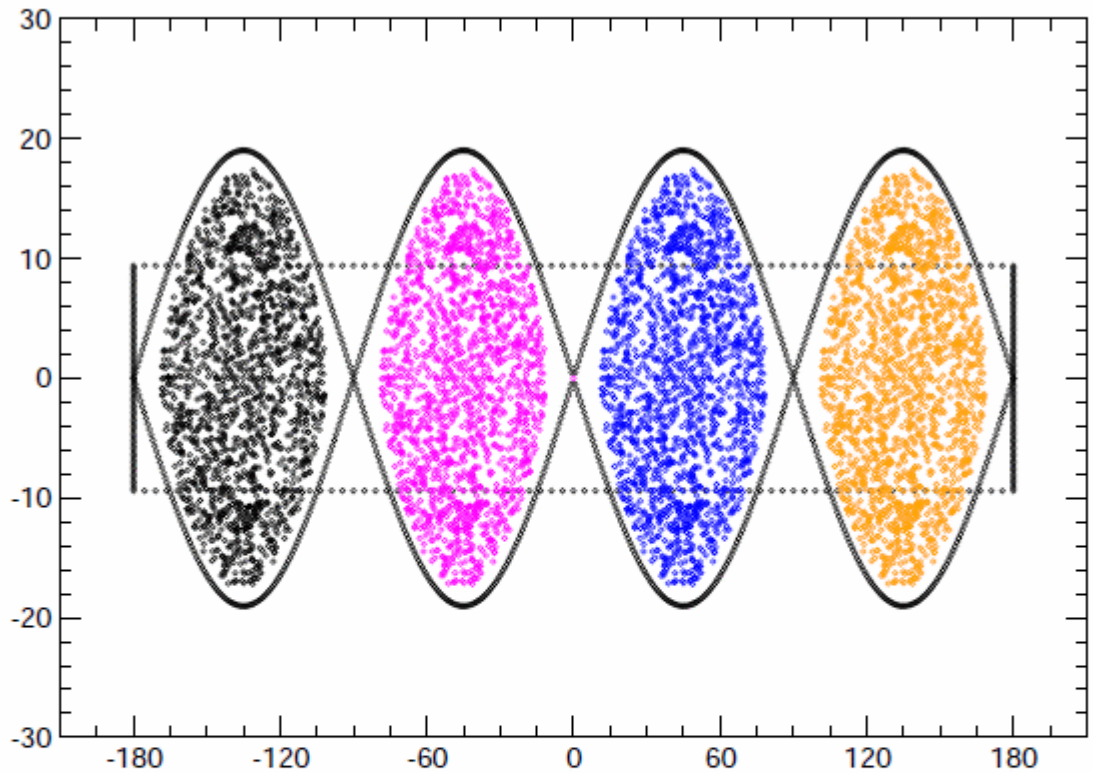

Figure 7: Four bunches of Au77+ ions in harmonic 16 buckets on the AGS injection porch. The harmonic 16 frequency is $16 f_s = 2.61$ MHz. The voltage is $V_C = 40$ kV. The black rectangle is the border of the uniform distribution used to make the bunches. The longitudinal emittance of the distribution is 0.60 eV s per nucleon. One can see by inspection that the emittance of the 4 bunches is close to that of the initial distribution. The horizontal axis is the phase ϕ in degrees. The vertical axis is W in units of eV s.

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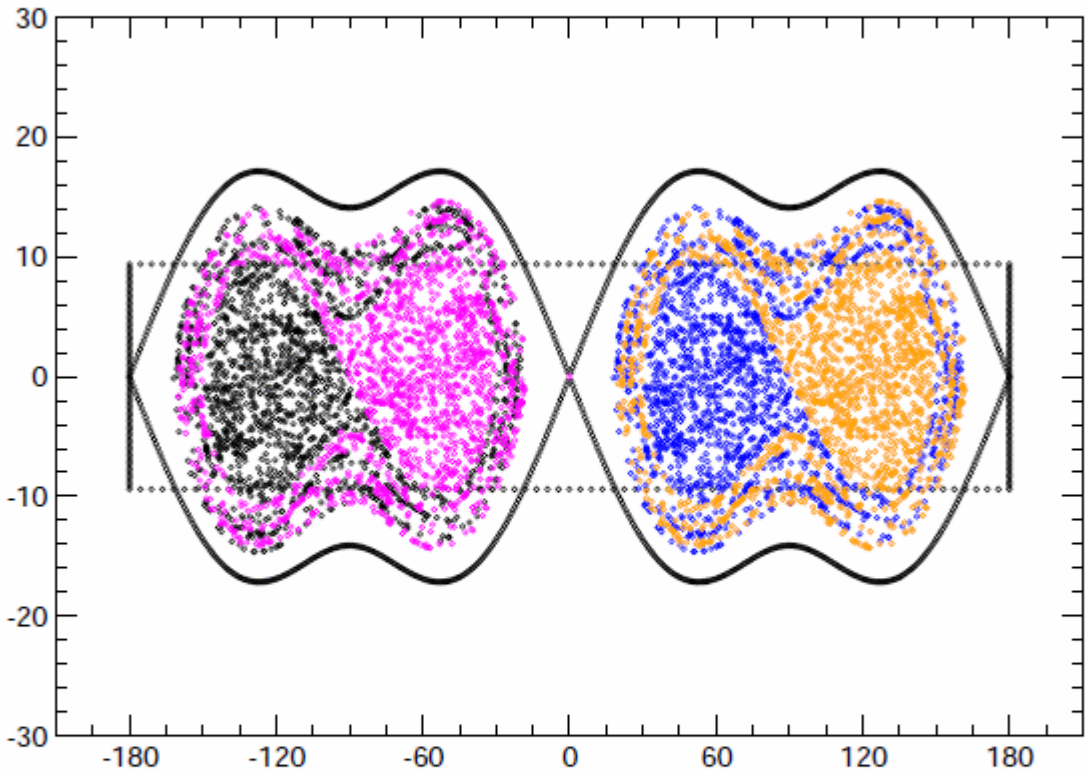

Figure 8: Halfway through the 4-to-2 merge of the bunches in **Figure 7**. Here the harmonic 16 voltage is $V_C/2 = 20$ kV. The harmonic 8 voltage is $V_K/2 = 11$ kV. The time from the start of the merge is $T_K/2 = 15/2$ ms.

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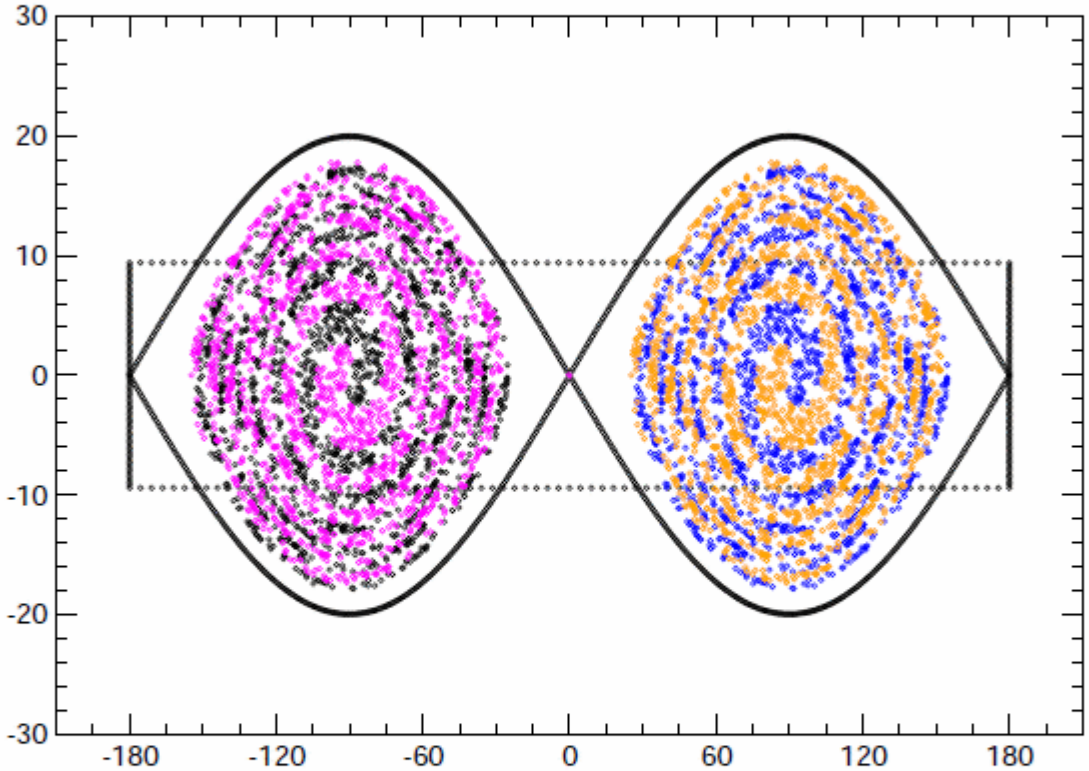

Figure 9: Completion of the 4-to-2 merge. Here the harmonic 8 voltage is $V_K = 22$ kV. The total time for the merge is $T_K = 15$ ms.

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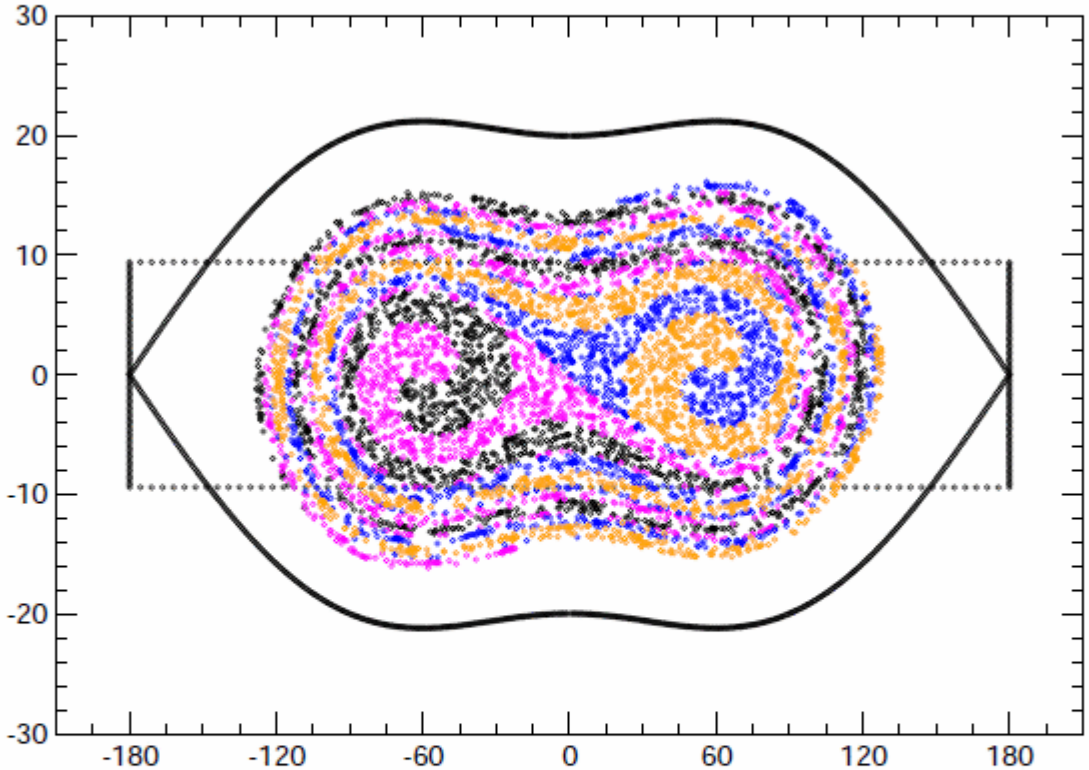

Figure 10: Halfway through the 2-to-1 merge of the bunches in **Figure 9**. Here the harmonic 8 voltage is $V_K/2 = 11$ kV. The harmonic 4 voltage is $V_L/2 = 11$ kV. The time from the start of the 2-to-1 merge is $(T_L - T_K)/2 = 15/2$ ms.

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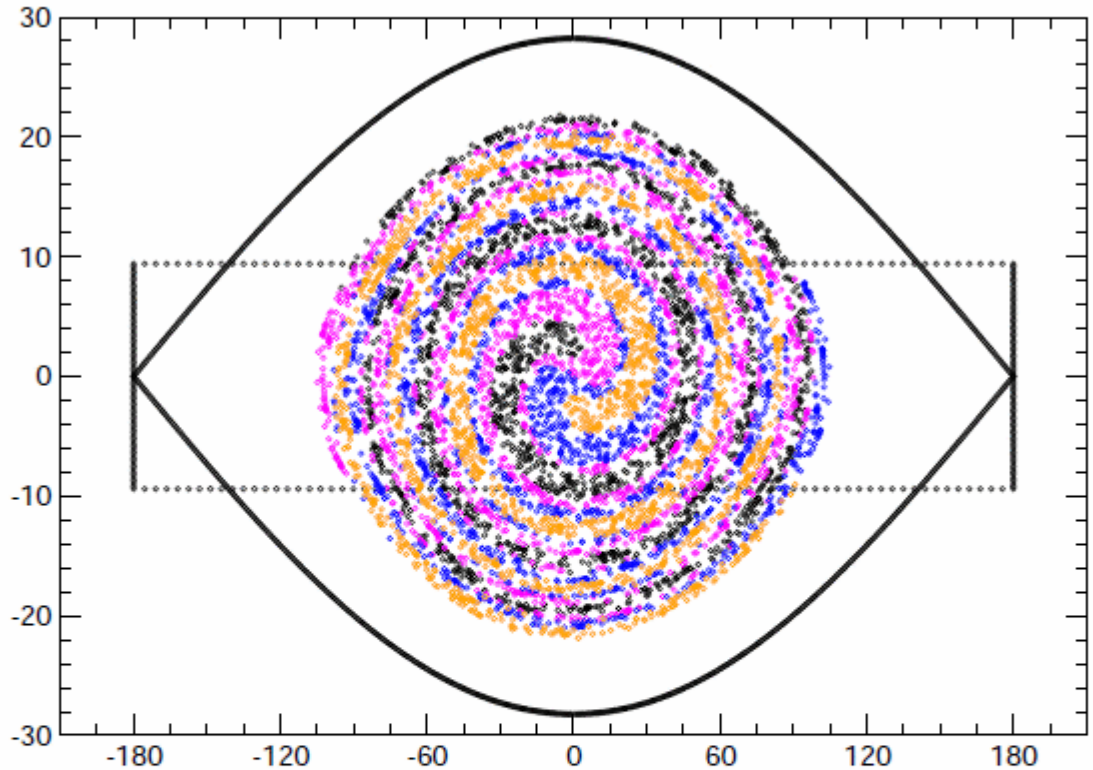

Figure 11: Completion of the 2-to-1 merge. The harmonic 4 voltage is $V_L = 22$ kV. The total 2-to-1 merge time is $T_L - T_K = 15$ ms. The total 4-to-1 merge time is $T_L = 30$ ms. The fractional momentum spread of the bunch is $\Delta p/p = \pm 0.0023$. One can see by inspection that the emittance of the bunch is close to that (0.60 eV s per nucleon) of the initial distribution of unbunched beam. It is easily held in the harmonic 4 bucket.

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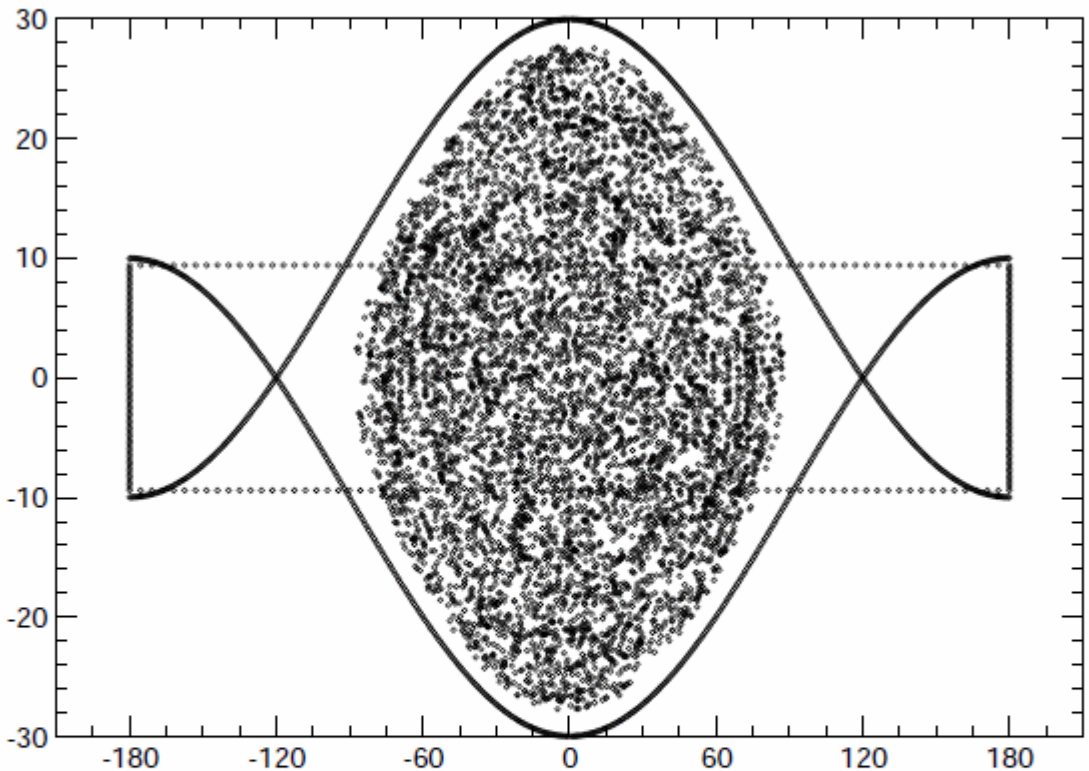

Figure 12: Here the merged bunch of **Figure 11** has been squeezed by bringing on the harmonic 8 voltage. The voltage is raised from zero to $V_K = 22$ kV in 20 ms. The harmonic 4 voltage is held constant at $V_L = 22$ kV. The unstable fixed point phases are $\phi_u = \pm 120$ degrees.

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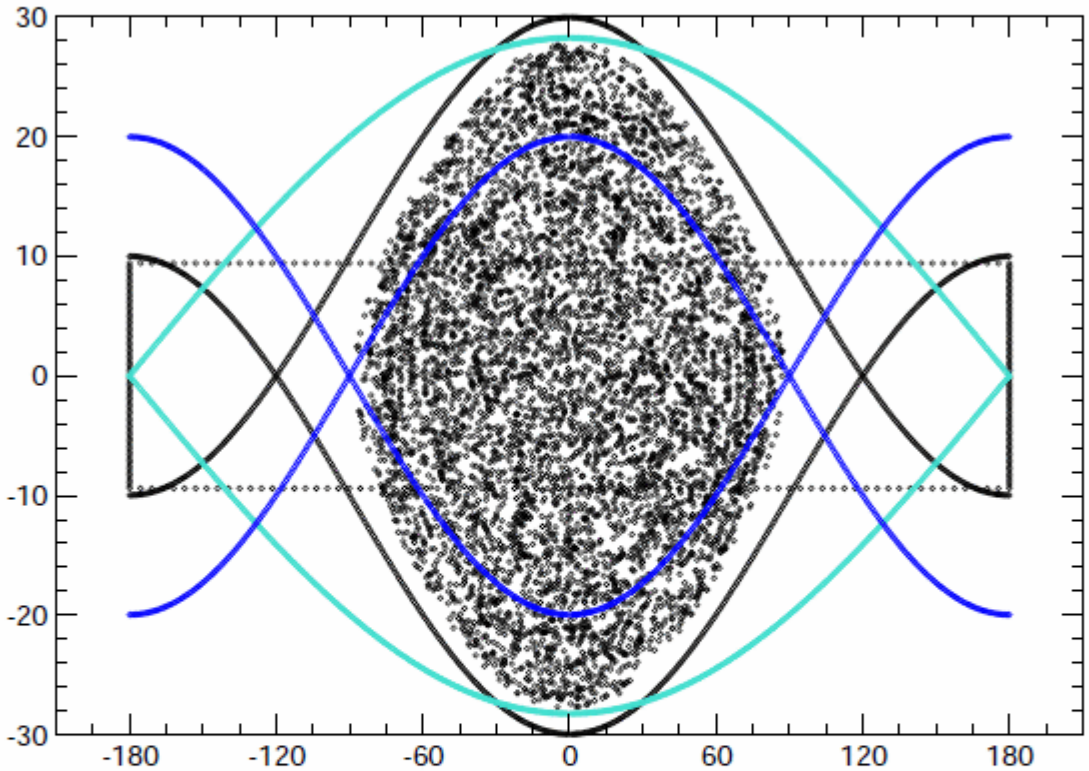

Figure 13: Same as **Figure 12** but with the harmonic 4 and 8 buckets superimposed. These act together with voltages $V_L = 22$ kV and $V_K = 22$ kV to make the black separatrix. The harmonic 8 bucket acting by itself is not large enough to contain the bunch.

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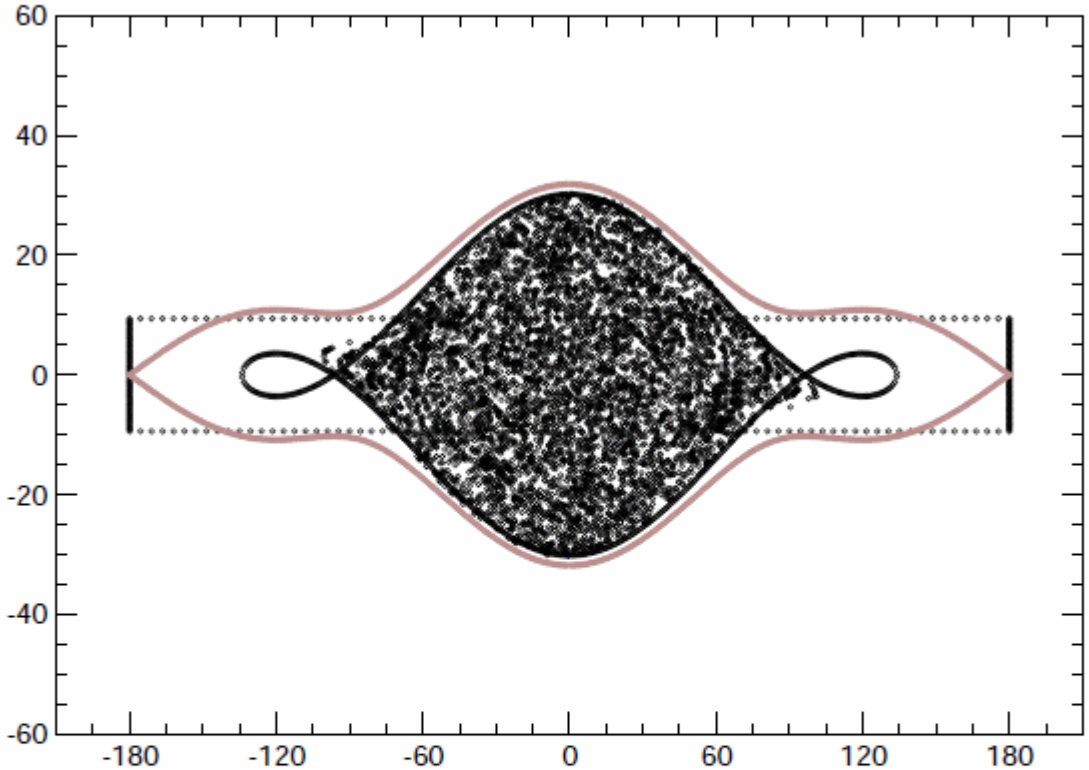

Figure 14: Here the bunch of **Figure 12** has been squeezed by bringing on the harmonic 12 voltage. The voltage is raised from zero to $V_A = 18$ kV in 1 ms. The harmonic 4 and 8 voltages are held constant at $V_L = 22$ kV and $V_K = 22$ kV respectively. The unstable fixed point phases are $\phi_u = \pm 96.4$ and $\phi_u = \pm 180$ degrees.

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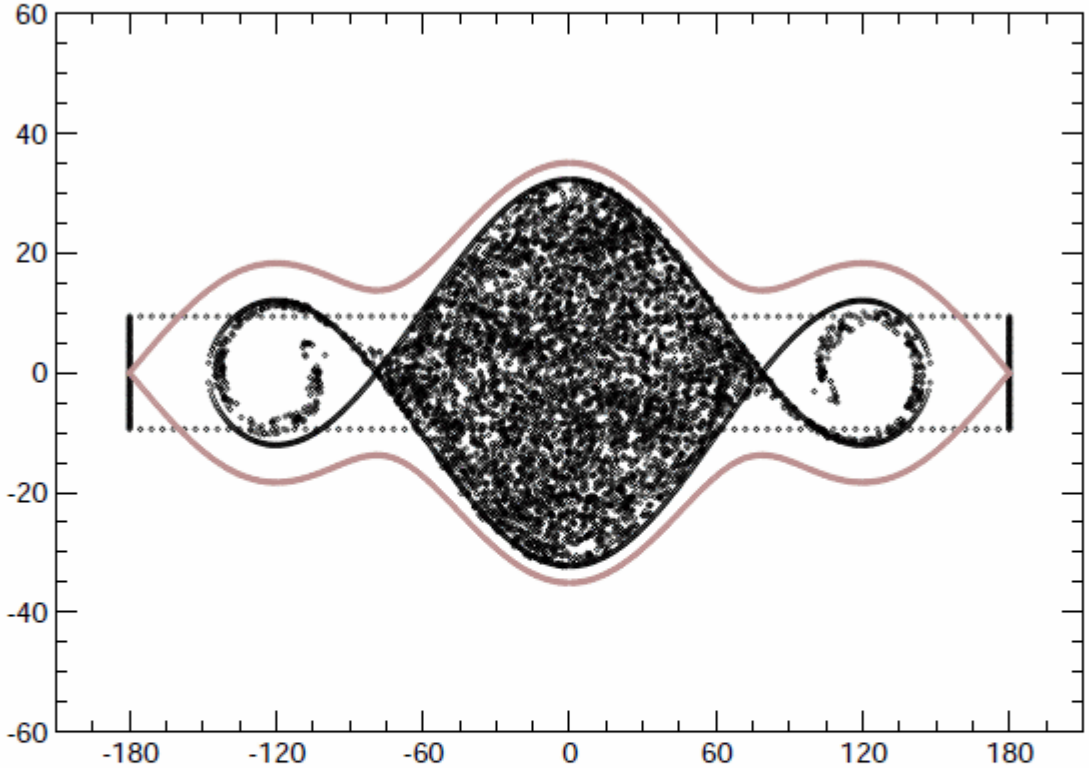

Figure 15: Here, with the harmonic 4 and 8 voltages held at $V_L = 22$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 36$ kV in 2 ms. The unstable fixed point phases are $\phi_u = \pm 78.8$ and $\phi_u = \pm 180$ degrees.

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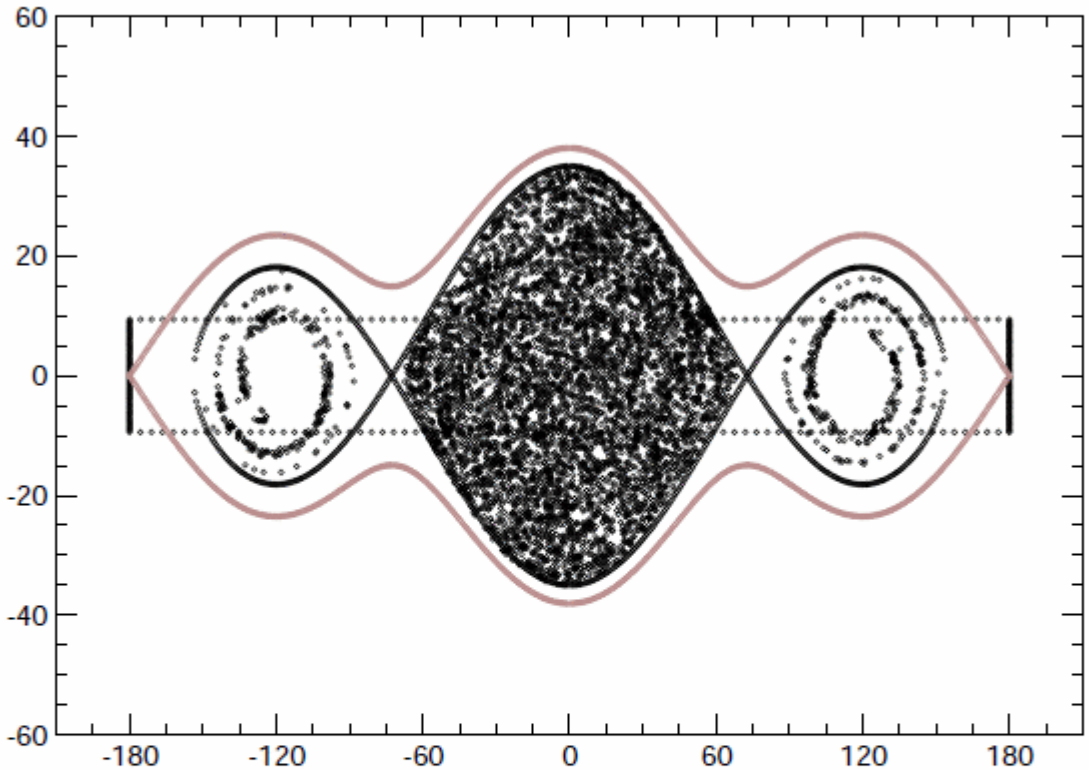

Figure 16: Here, with the harmonic 4 and 8 voltages held at $V_L = 22$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 54$ kV in 3 ms. The unstable fixed point phases are $\phi_u = \pm 72.8$ and $\phi_u = \pm 180$ degrees.

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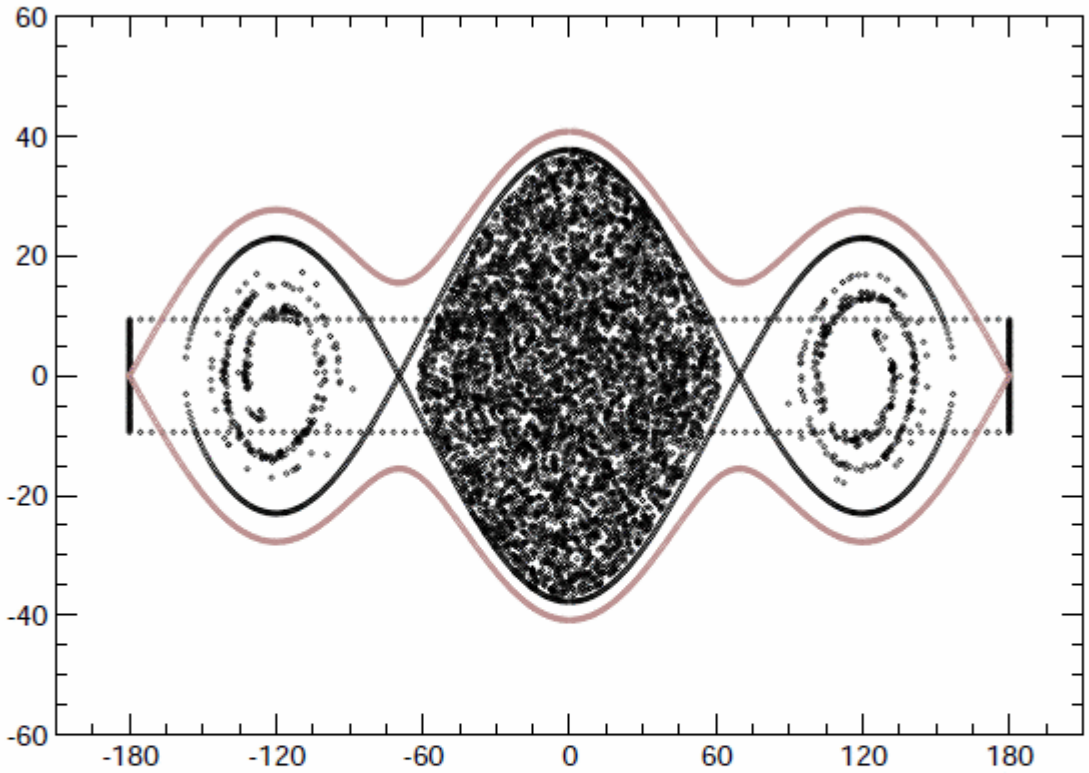

Figure 17: Here, with the harmonic 4 and 8 voltages held at $V_L = 22$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 72$ kV in 4 ms. The unstable fixed point phases are $\phi_u = \pm 69.7$ and $\phi_u = \pm 180$ degrees.

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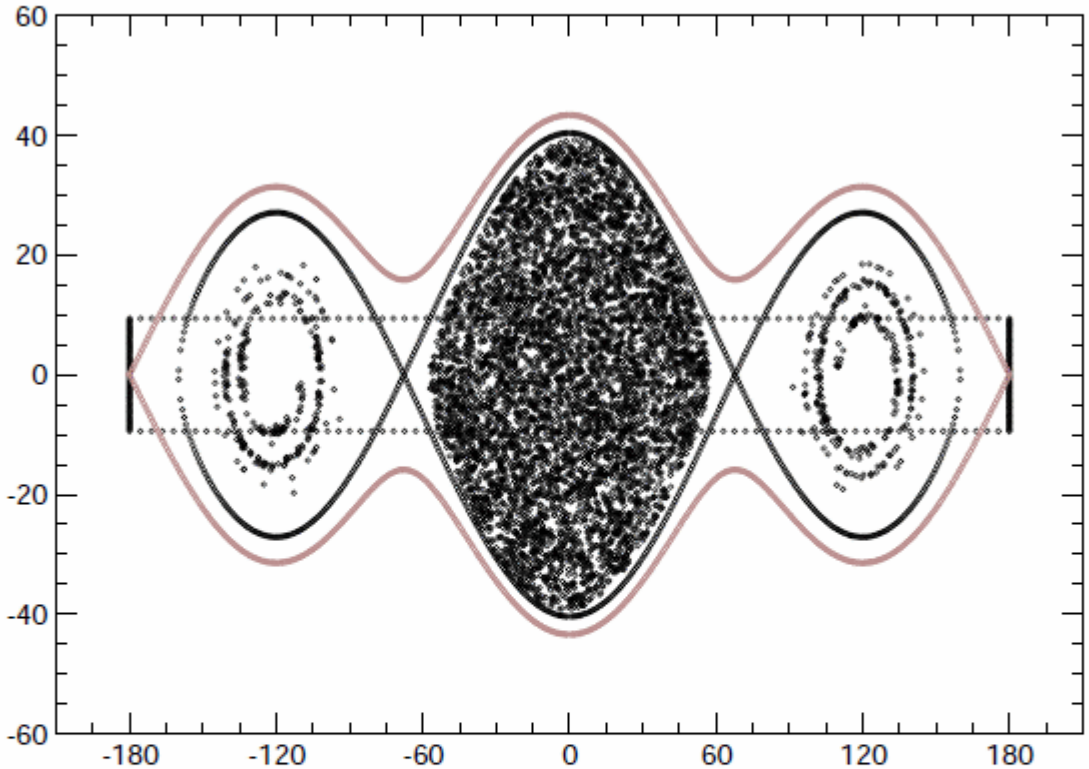

Figure 18: Here, with the harmonic 4 and 8 voltages held at $V_L = 22$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 90$ kV in 5 ms. The unstable fixed point phases are $\phi_u = \pm 67.8$ and $\phi_u = \pm 180$ degrees.

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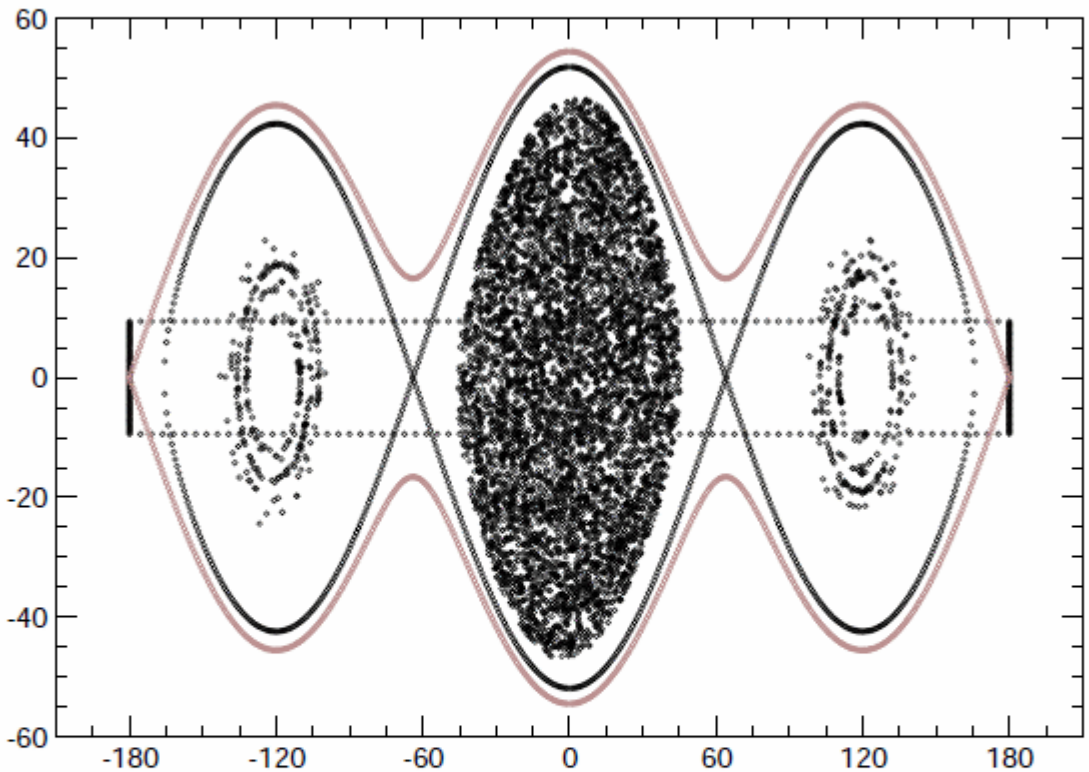

Figure 19: Here, with the harmonic 4 and 8 voltages held at $V_L = 22$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 180$ kV in 10 ms. The unstable fixed point phases are $\phi_u = \pm 64.0$ and $\phi_u = \pm 180$ degrees. The fractional momentum spread of the central bunch is $\Delta p/p = \pm 0.00484$. The fraction of Au77+ ions in the outer buckets is 0.089.

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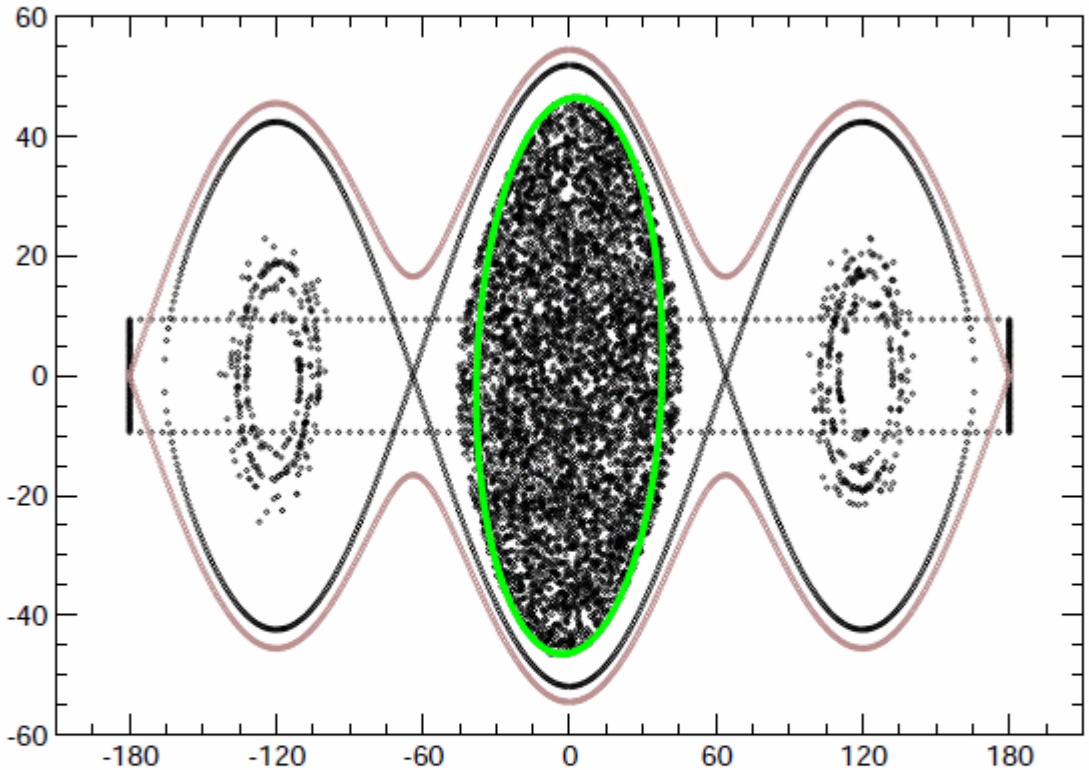

Figure 20: Same as **Figure 19** but with green ellipse added. The bunch and ellipse are rotated slightly clockwise with respect to the vertical axis. This is a feature of the motion generated by (38) and (39) and is discussed in the Appendix.

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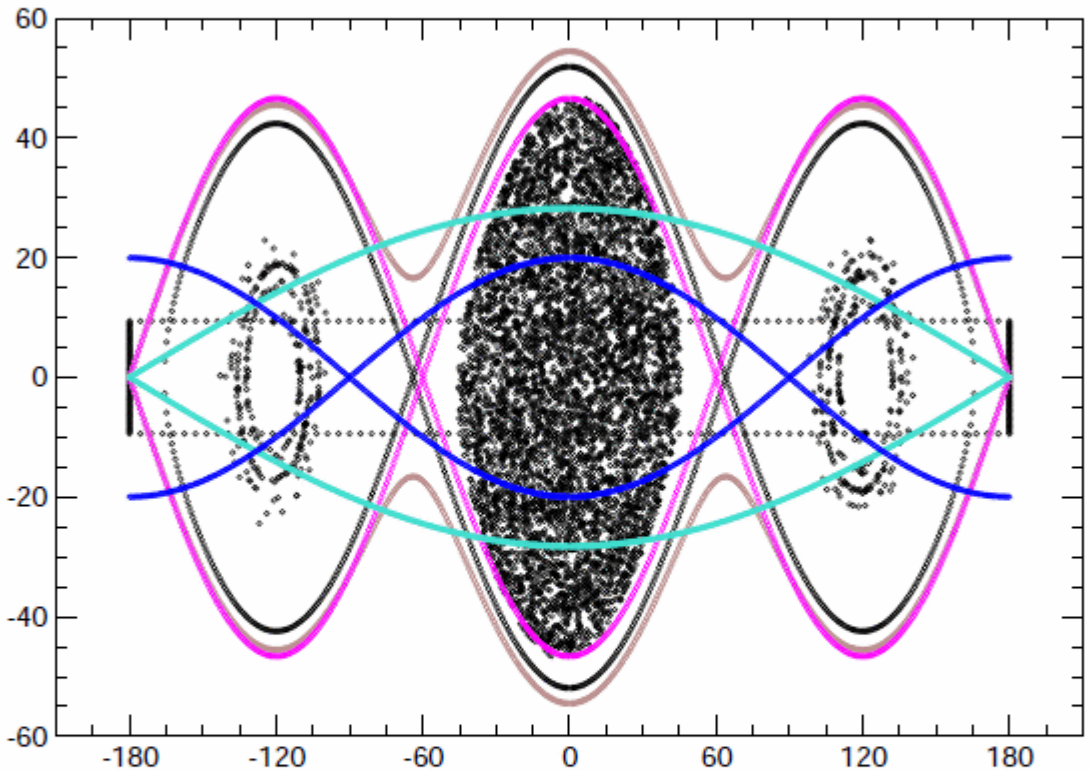

Figure 21: Same as **Figure 19** but with the harmonic 4, 8, and 12 buckets superimposed. These act together with voltages $V_L = 22$ kV, $V_K = 22$ kV, and $V_A = 180$ kV to make the black and brown separatrices.

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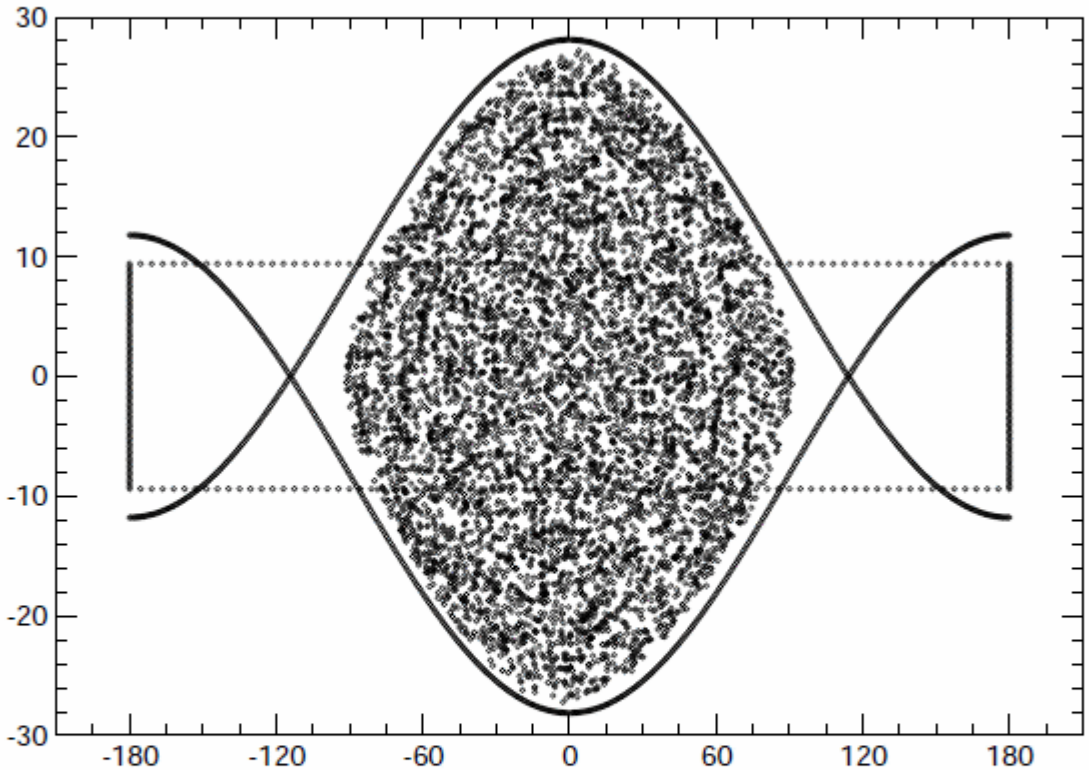

Figure 22: Here the simulation that produced **Figures 7** through **19** has been carried out with the maximum harmonic 4 voltage reduced to $V_L = 18$ kV. The unstable fixed point phases are $\phi_u = \pm 114$ degrees.

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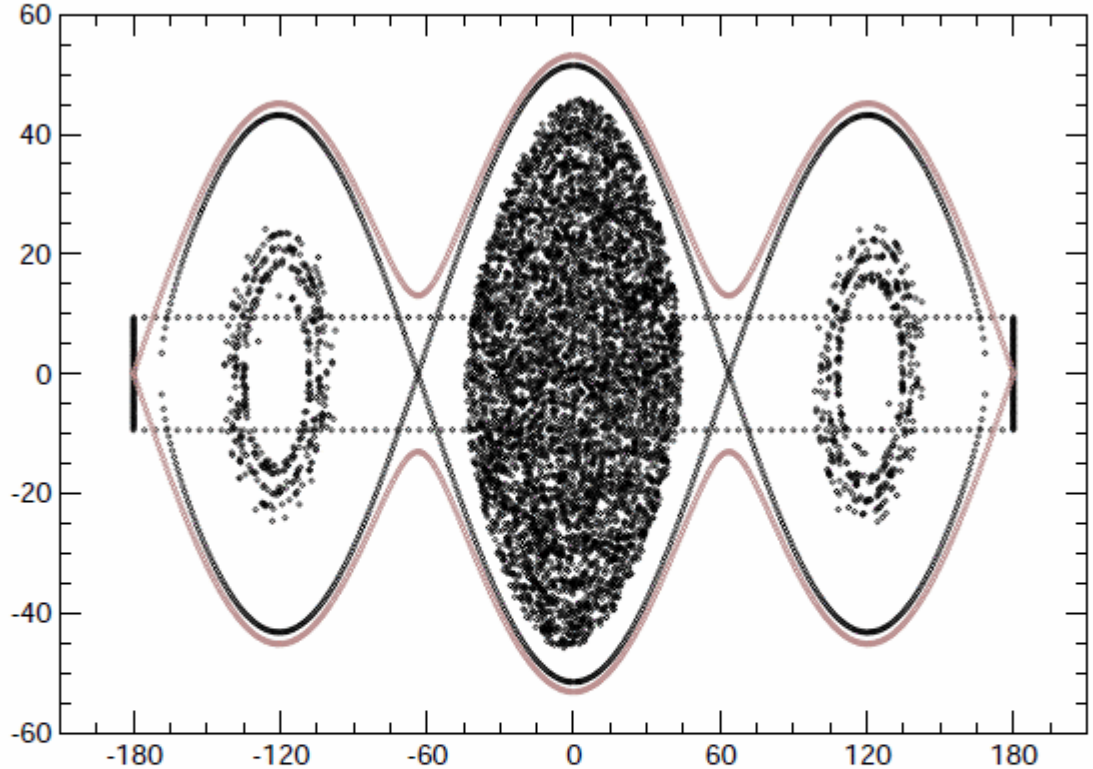

Figure 23: Here as in **Figure 22** the simulation has been carried out with the maximum harmonic 4 voltage reduced to $V_L = 18$ kV. The unstable fixed point phases are $\phi_u = \pm 63.6$ and $\phi_u = \pm 180$ degrees. The fractional momentum spread of the central bunch is $\Delta p/p = \pm 0.00477$. The fraction of Au77+ ions in the outer buckets has increased to 0.138.

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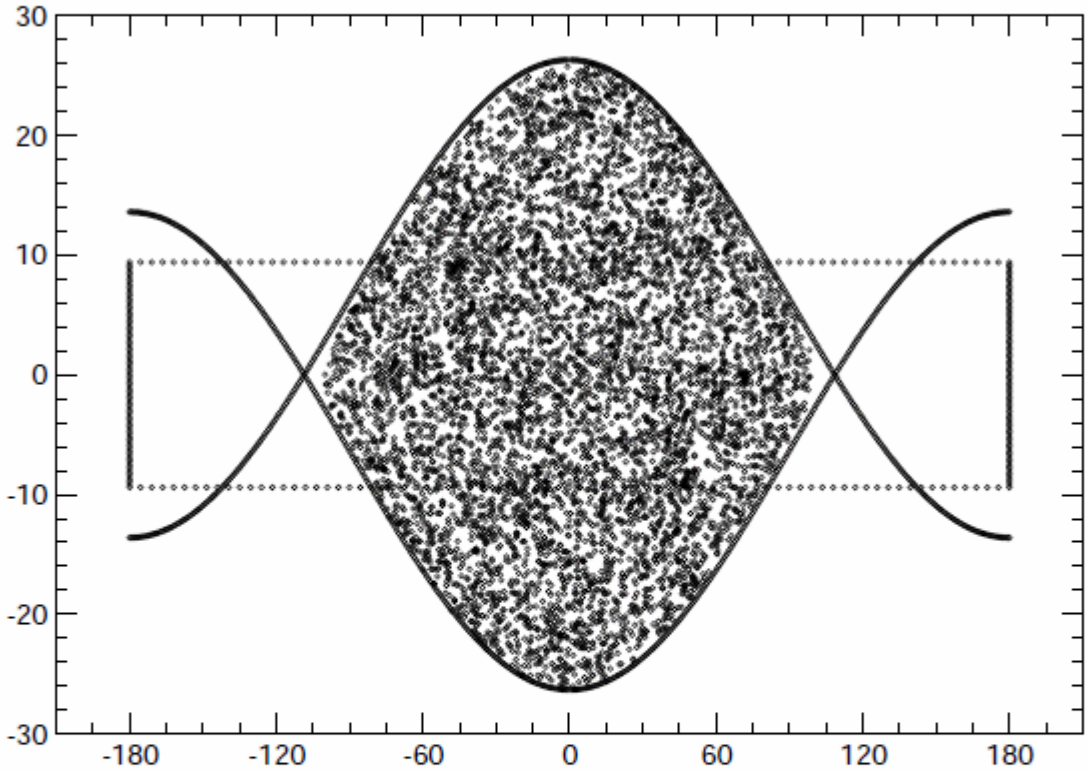

Figure 24: Here the simulation that produced **Figures 7** through **19** has been carried out with the maximum harmonic 4 voltage reduced further to $V_L = 14$ kV. The bucket is now just large enough to contain the bunch. The unstable fixed point phases are $\phi_u = \pm 109$ degrees.

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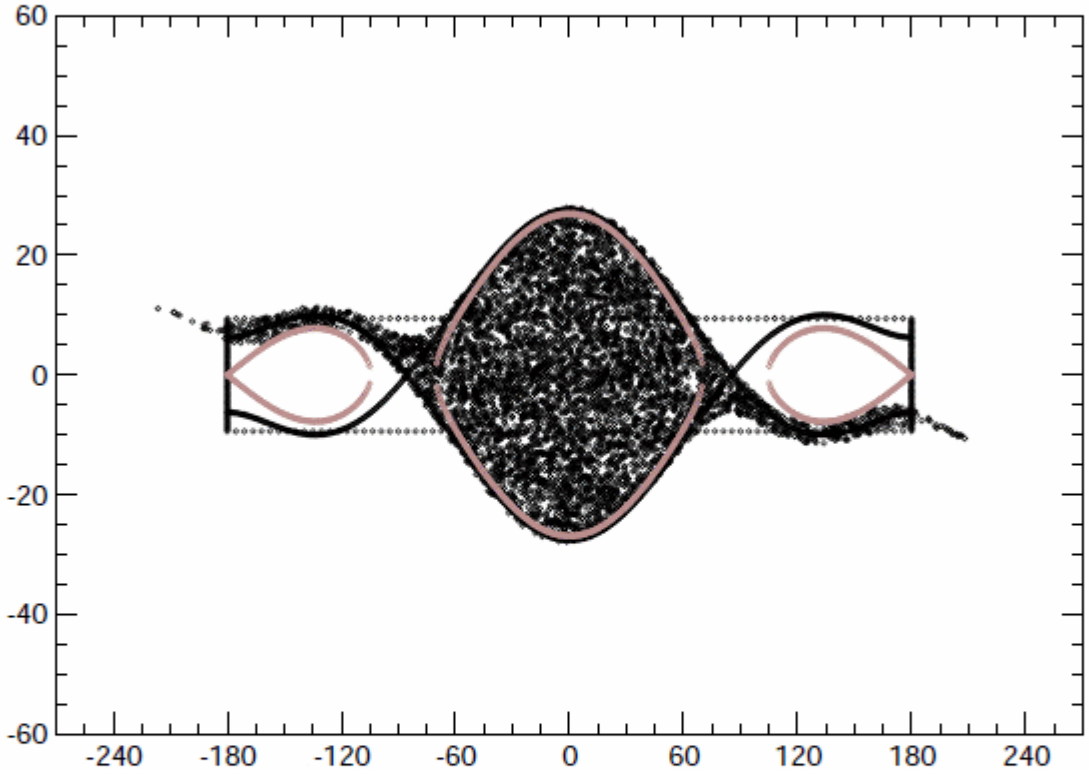

Figure 25: Here the bunch of **Figure 24** has been squeezed by bringing on the harmonic 12 voltage. The voltage is raised from zero to $V_A = 18$ kV in 1 ms. The harmonic 4 and 8 voltages are held constant at $V_L = 14$ kV and $V_K = 22$ kV respectively. The unstable fixed point phases are $\phi_u = \pm 85.4$ and $\phi_u = \pm 180$ degrees.

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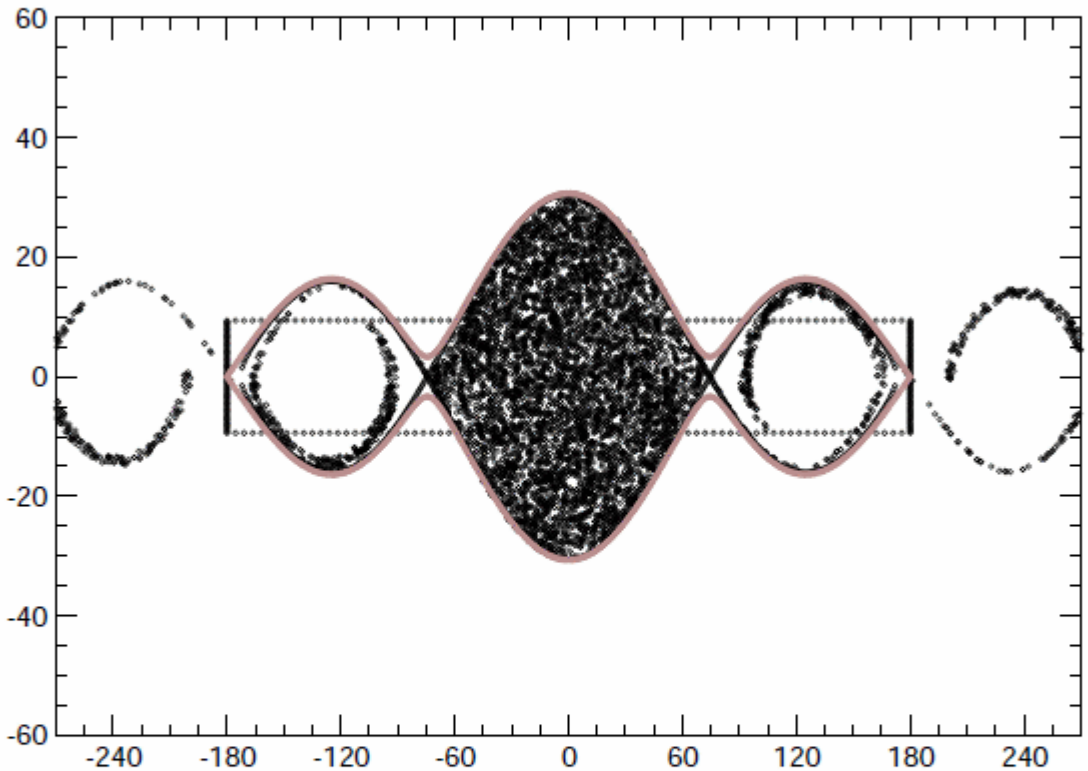

Figure 26: Here, with the harmonic 4 and 8 voltages held at $V_L = 14$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 36$ kV in 2 ms. The unstable fixed point phases are $\phi_u = \pm 74.5$ and $\phi_u = \pm 180$ degrees.

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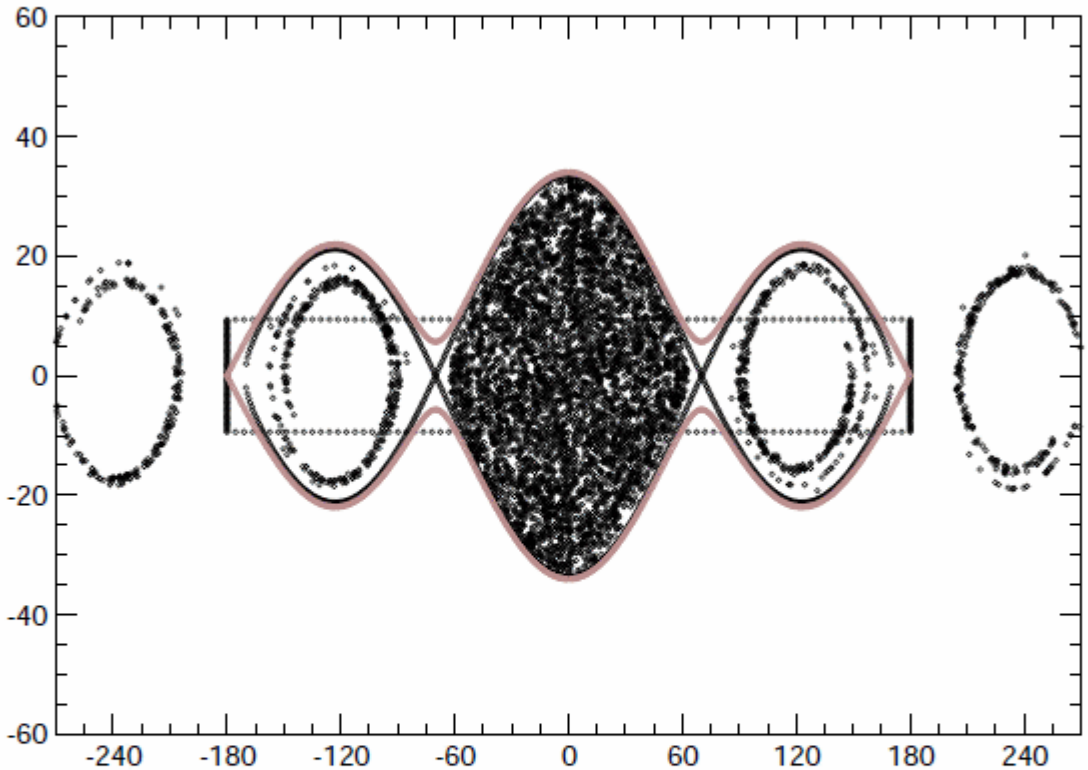

Figure 27: Here, with the harmonic 4 and 8 voltages held at $V_L = 14$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 54$ kV in 3 ms. The unstable fixed point phases are $\phi_u = \pm 70.1$ and $\phi_u = \pm 180$ degrees.

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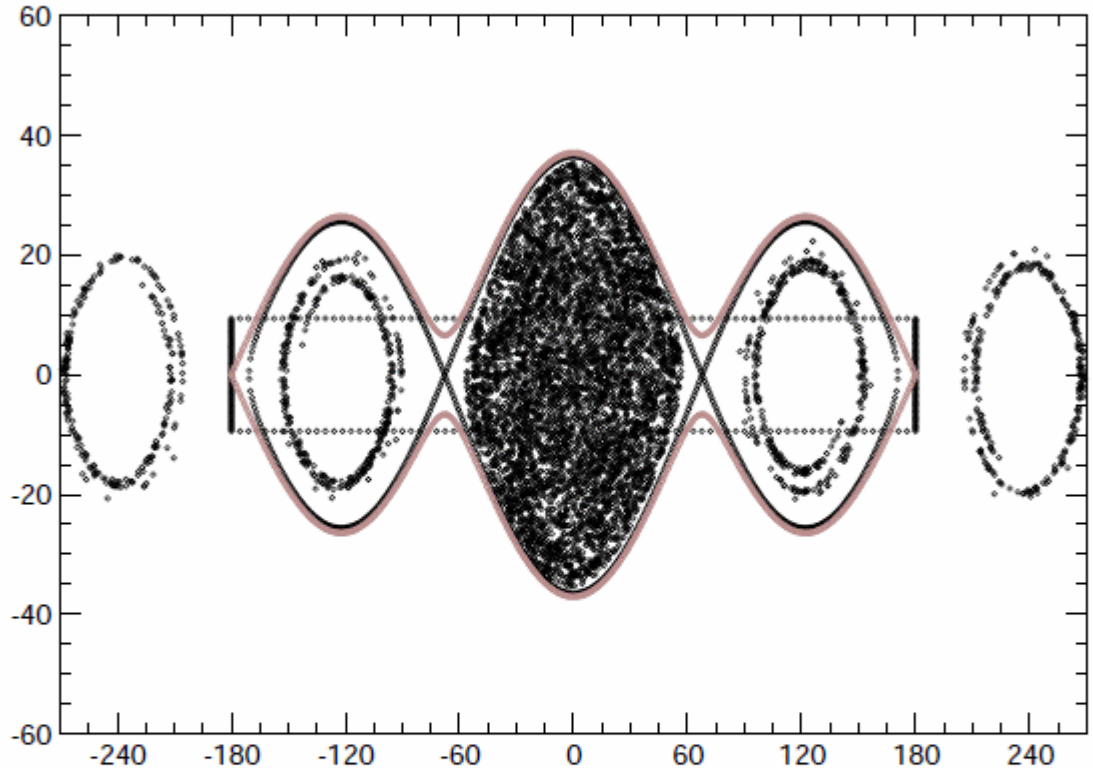

Figure 28: Here, with the harmonic 4 and 8 voltages held at $V_L = 14$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 72$ kV in 4 ms. The unstable fixed point phases are $\phi_u = \pm 67.7$ and $\phi_u = \pm 180$ degrees.

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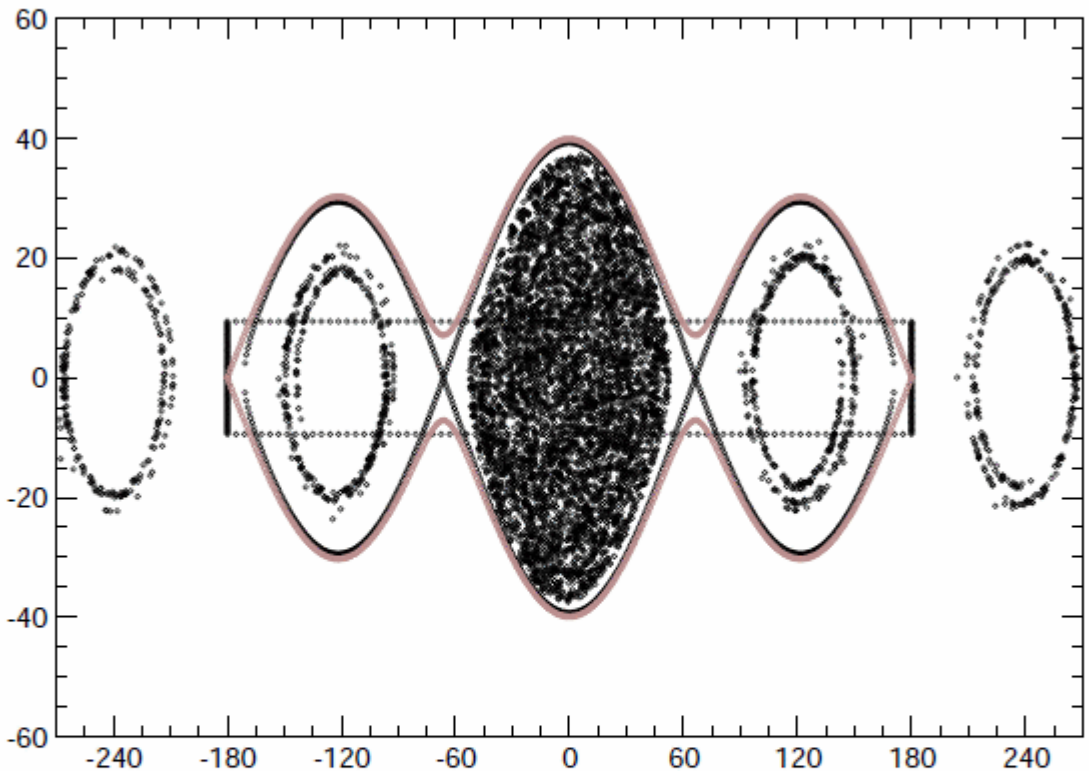

Figure 29: Here, with the harmonic 4 and 8 voltages held at $V_L = 14$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 90$ kV in 5 ms. The unstable fixed point phases are $\phi_u = \pm 66.3$ and $\phi_u = \pm 180$ degrees.

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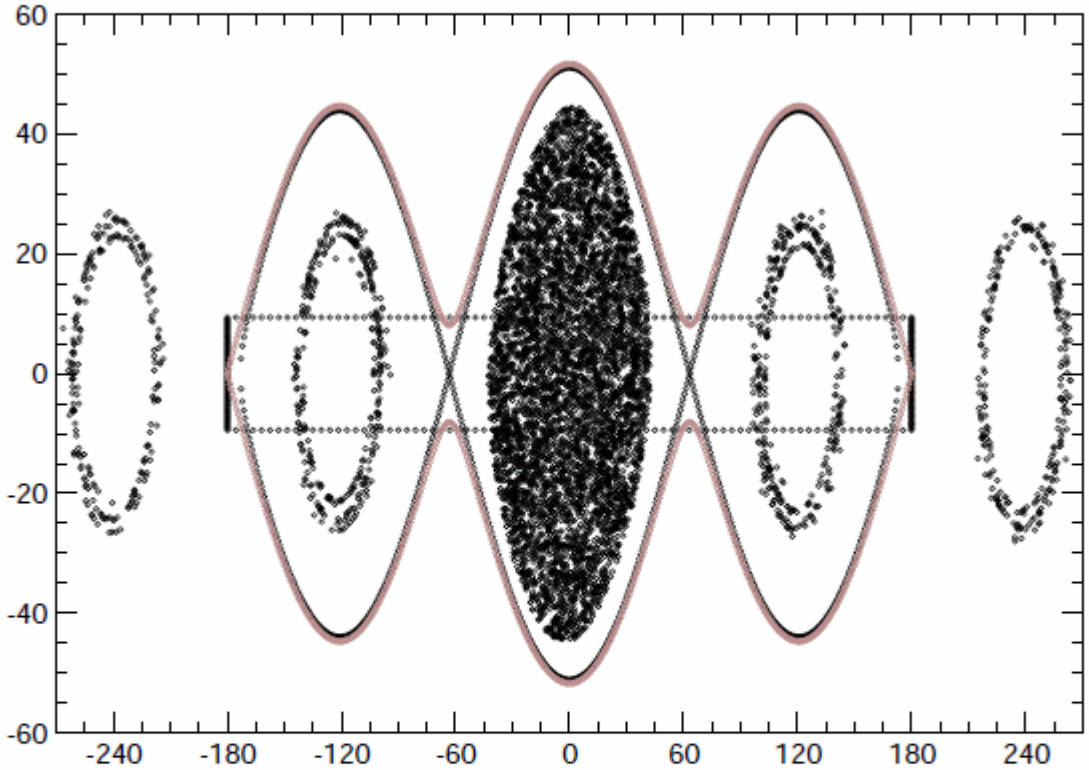

Figure 30: Here, with the harmonic 4 and 8 voltages held at $V_L = 14$ kV and $V_K = 22$ kV respectively, the harmonic 12 voltage has been raised from zero to $V_A = 180$ kV in 10 ms. The unstable fixed point phases are $\phi_u = \pm 63.2$ and $\phi_u = \pm 180$ degrees. The fractional momentum spread of the central bunch is $\Delta p/p = \pm 0.00462$. The fraction of Au77+ ions outside the central bucket is 0.180. The fraction in the outermost buckets is 0.075.

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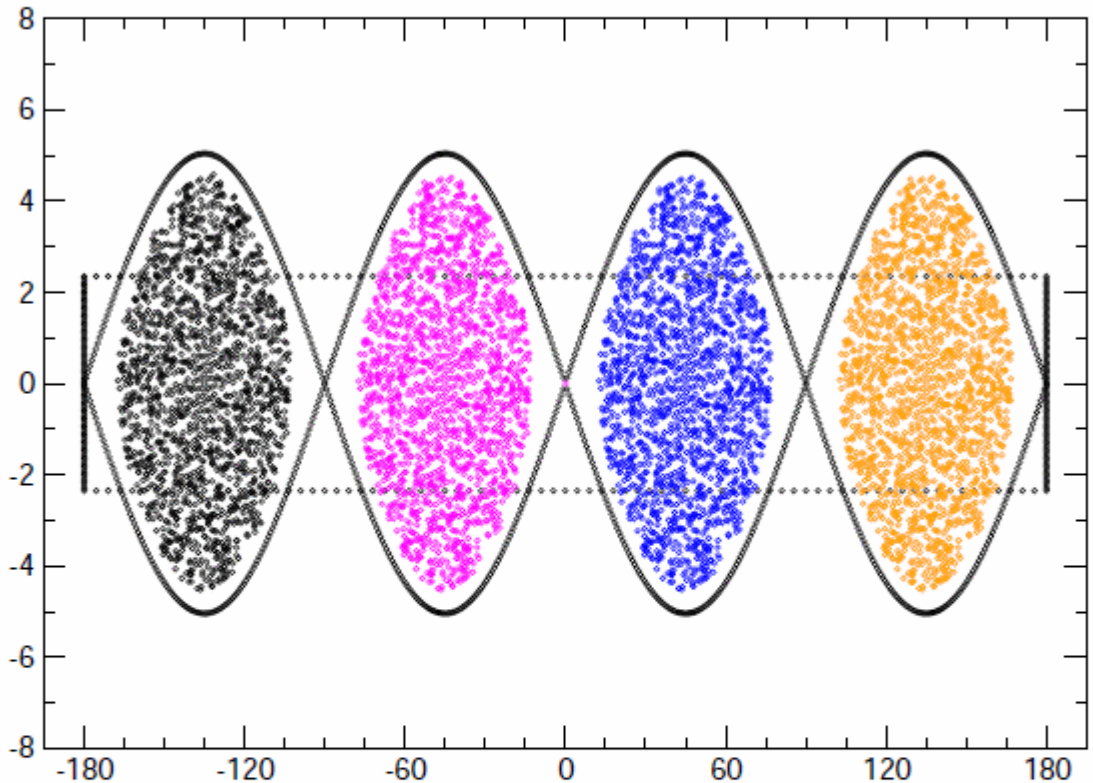

Figure 31: Four bunches of Au32+ ions in harmonic 4 buckets on the Booster merging porch. The harmonic 4 frequency is $4f_s = 1.860$ MHz. The voltage is $V_D = 2.0$ kV. The black rectangle is the border of the uniform distribution used to make the bunches. The longitudinal emittance of the distribution is 0.15 eV s per nucleon. One can see by inspection that the emittance of the 4 bunches is close to that of the initial distribution. The horizontal axis is the phase ϕ in degrees. The vertical axis is W in units of eV s.

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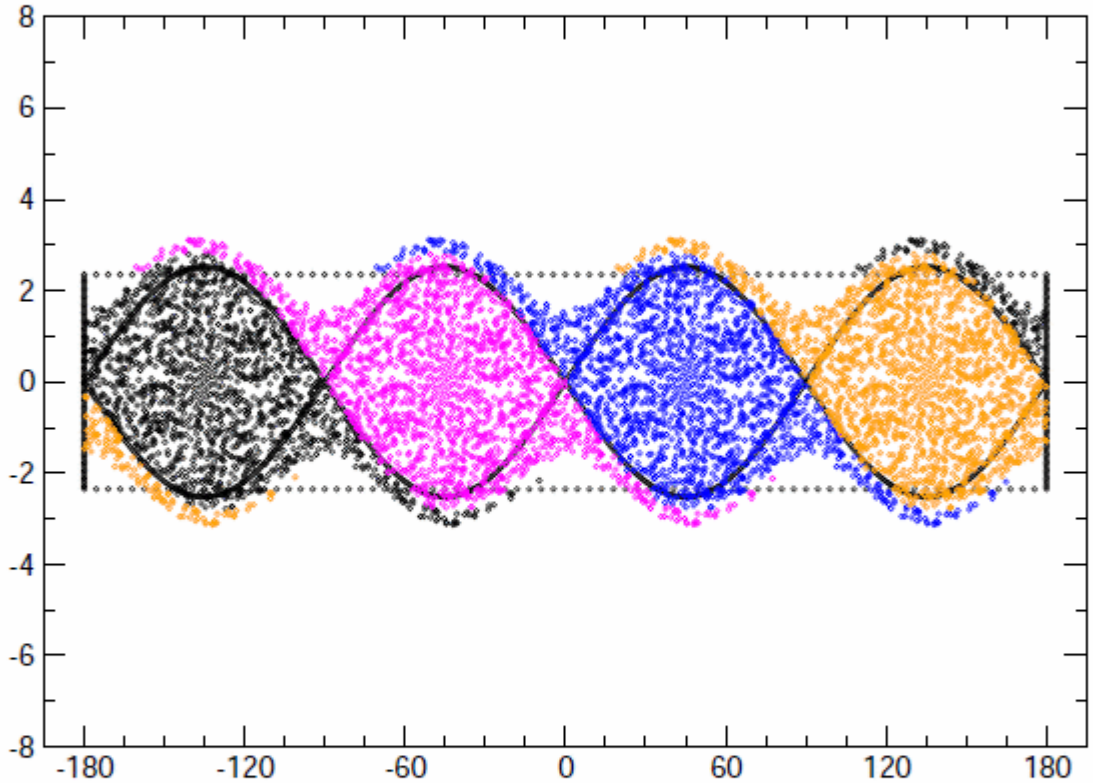

Figure 32: Halfway through the debunching of the bunches in **Figure 31**.

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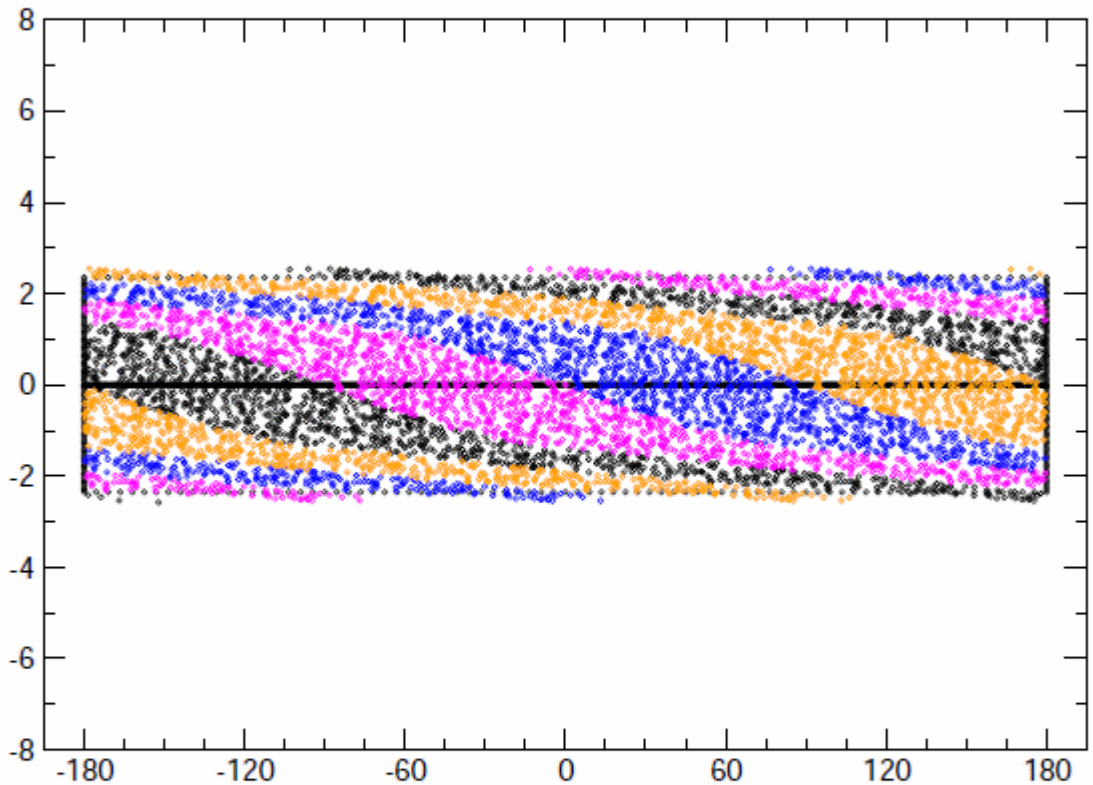

Figure 33: Completion of the debunching in 7.5 ms.

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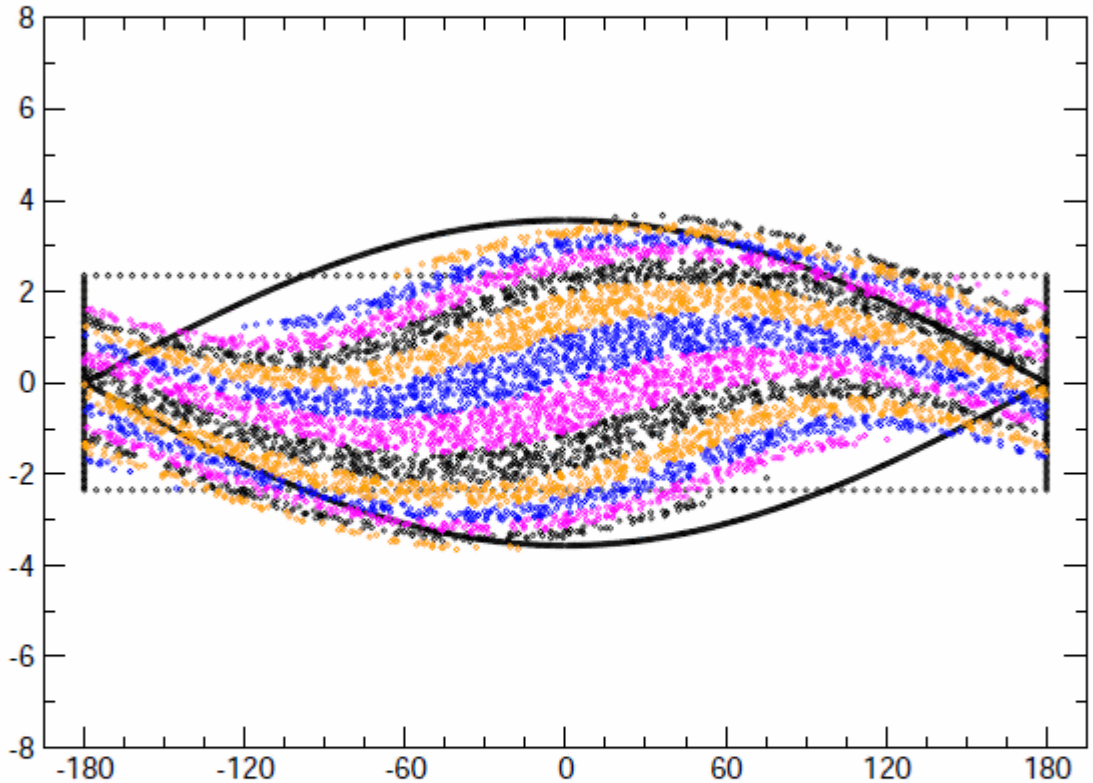

Figure 34: Halfway through the rebunching of the beam in **Figure 33**.

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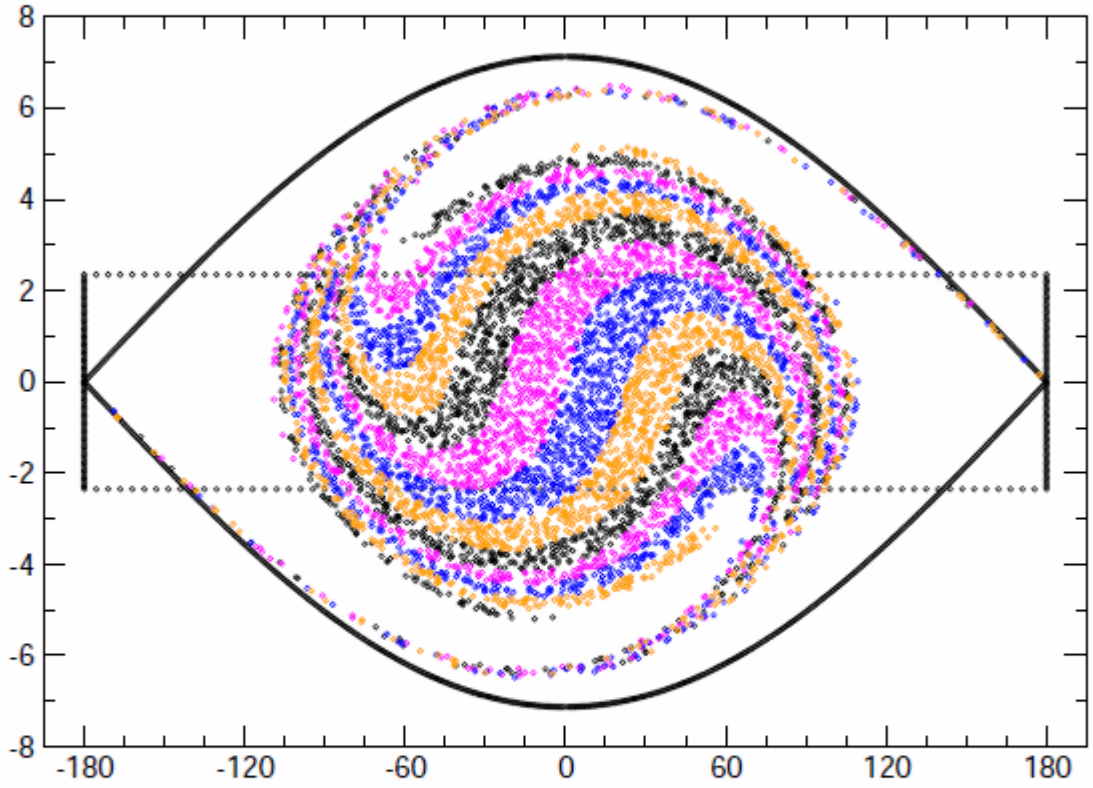

Figure 35: Completion of the rebunching in 7.5 ms.

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