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1 Introduction

In order to increase the intensity per Au77+ bunch at AGS extraction, a 6 to 3 to 1 merge scheme was developed and implemented by K. Zeno during the 2016 RHIC run [1]. For this scheme, 12 Booster loads, each consisting of a single bunch, are delivered to AGS per AGS magnetic cycle. The bunch from Booster is itself the result of a 4 to 2 to 1 merge which is carried out on a flat porch during the Booster magnetic cycle [2]. Each Booster bunch is injected into a harmonic 24 bucket on the AGS injection porch. In order to fit into the buckets and allow for the AGS injection kicker rise time, the bunch width must be reduced by exciting quadrupole oscillations just before extraction from Booster [1]. The bunches are injected into two groups of six adjacent harmonic 24 buckets. In each group the 6 bunches are merged into 3 by bringing on RF harmonic 12 while reducing harmonic 24. This is a straightforward 2 to 1 merge (in which two adjacent bunches are merged into one). One ends up with two groups of three adjacent bunches sitting in harmonic 12 buckets. These bunches are accelerated to an intermediate porch for further merging. Doing the merge on a porch that sits above injection energy helps reduce losses that are believed to be due to the space-charge force acting on the bunched particles [3]. (The 6 to 3 merge is done on the injection porch because the harmonic 24 frequency on the intermediate porch would be too high for the AGS RF cavities.) On the intermediate porch each group of 3 bunches is merged into one by bringing on RF harmonics 8 and 4 and then reducing harmonics 12 and 8. One ends up with 2 bunches, each the result of a 6 to 3 to 1 merge and each sitting in a harmonic 4 bucket. This puts 6 Booster loads into each bunch. Each merged bunch needs to be squeezed into a harmonic 12 bucket for subsequent acceleration. This is done by again bringing on harmonic 8 and then harmonic 12.

Results of simulations of the 6 to 3 to 1 merge and the subsequent squeeze into harmonic 12 buckets are presented in this note. These are meant to complement the observations made and knowledge gained during the implementation of the scheme in AGS. In particular they provide a benchmark for what can be achieved with the available RF voltages. The simulations are ultimately based on the work of Garoby [4, 5] at CERN and Blaskiewicz and Brennan [6, 7] at BNL.

2 Simulation Method

The simulation method is presented in detail in [8] and [9]. The 6 to 3 to 1 merge is treated (for the case of helion bunches) in sections 12 and 15 of [8]. The squeeze of the merged bunches into harmonic 12 buckets is treated in sections 13 and 14 of [9].

The present simulation acts on an initial 160-by-160 array of particles rather than the 80-by-80 array used in [8]. It also uses RF harmonics 24, 12, 8, and 4 rather than 12, 6, 4, and 2. The revolution frequency on the intermediate merging porch is taken to be $f = 195.75$ kHz, which is close to what is used in practice. The simulation differs from what is done in practice in that it does both the 6 to 3 and the 3 to 1 merges on the intermediate porch. In practice the 6 to 3 merge is done on the injection porch, as already mentioned. This difference does not affect the essential results and conclusions presented here.

It should be mentioned that the simulation treats only the longitudinal motion of the particles. Transverse motion and apertures are ignored. It is also assumed that the particles do not interact with one another.

The Fortran source code for the simulation is called Gold631mrgH12.f. It was compiled with the Intel Fortran Compiler (also known as ifort) resident on some of the accelerator operations computers. It includes new code that calculates the longitudinal emittance of the merged bunch and the squeezed bunch.

3 Results and Conclusions

The results of the simulation are illustrated in **Figures 1** through **37**. These are best viewed by setting the pdf viewer to advance one page at a time.

For the RF voltage programs and longitudinal emittances considered here, the 6 to 3 to 1 merge simulation shows that the six bunches can be merged into one bunch with just a small emittance growth of 2 percent or less. This is illustrated in **Figures 1** through **15**. The longitudinal emittance is defined to be the area inside the smallest matched bunch contour that encloses the merged bunch. This is illustrated in **Figure 14**.

During the squeeze, some particles may leak into harmonic 12 buckets on either side of the merged bunch. This is observed both in practice and in the simulation, and is illustrated in **Figures 16** through **25**. The amount of leakage depends on the emittance of the merged bunch and the available harmonic 4 voltage. This is illustrated in **Figures 26**, **31**, **34** and **36**. These figures show that if one wants to keep the leakage below, say 3.5%, then the total emittance of the 6 bunches to be merged must be less than 0.540, 0.563 and 0.587 eV-seconds per nucleon (eV*s/A) for harmonic 4 voltages 12, 15 and 18 kV respectively. In practice the measured harmonic 4 voltage is 15 kV [10] and the observed percentage of particles in satellite buckets is around 3.5% [1]. This implies an initial six-bunch emittance of 0.563 eV*s/A, which is consistent with the measured emittance 0.57 eV*s/A of the merged bunch [10].

Figures 27 and **28** illustrate how the longitudinal emittance of the squeezed bunch is determined. The squeezed bunch emittance versus the initial six-bunch emittance is shown in **Figures 29**, **32**, **35** and **37** for harmonic 4 voltages 12, 15 and 18 kV. In these figures one sees that as the initial six-bunch emittance increases, the squeezed bunch emittance eventually reaches a plateau. The average value attained on the plateau is taken to be the longitudinal acceptance of the squeeze. For harmonic 4 voltages 12, 15 and 18 kV, the longitudinal acceptances of the squeeze are 0.526, 0.550 and 0.574 eV*s/A respectively. The measured harmonic 4 voltage of 15 kV then implies a longitudinal acceptance of 0.55 eV*s/A. This is consistent with measurements made shortly after the squeeze [10].

References

[1] K.L. Zeno, Booster-AGS-EBIS-2016 elog

[2] C.J. Gardner, et al, "Operation of the RHIC Injector Chain with Ions from EBIS", Proceedings of IPAC2015, Richmond, Virginia, USA, pp. 3804–3807.

[3] This was proposed by K. Zeno shortly before the start of setup for RHIC Run 16.

[4] R. Garoby, "Bunch Merging and Splitting Techniques in the Injectors for High Energy Hadron Colliders", CERN/PS 98-048(RF), 1 October 1998.

[5] R. Garoby, S. Hancock, and J.L. Vallet, "Demonstration of Bunch Triple Splitting in the CERN PS", Proceedings of EPAC 2000, pp. 304–306.

[6] J.M. Brennan, "RF Issues in Booster/AGS/RHIC", Proceedings of the Third ICFA Mini-Workshop on High Intensity, High Brightness Hadron Accelerators, BNL-64754 (Informal Report), May 1997, pp. 3-23.

[7] C.J. Gardner, et al.,"Setup and Performance of the RHIC Injector Accelerators for the 2007 Run with Gold Ions", Proceedings of PAC07, pp.1862–1864.

[8] C.J. Gardner, "Simulations of Merging Helion Bunches on the AGS Injection Porch", C-A/AP/Note 527, August 2014.

[9] C.J. Gardner, "Simulations of Merging and Squeezing Bunches in Booster and AGS", C-A/AP/Note 460, July 2012.

[10] K.L. Zeno, Booster-AGS-EBIS-2016 elog, 12–14 April 2016

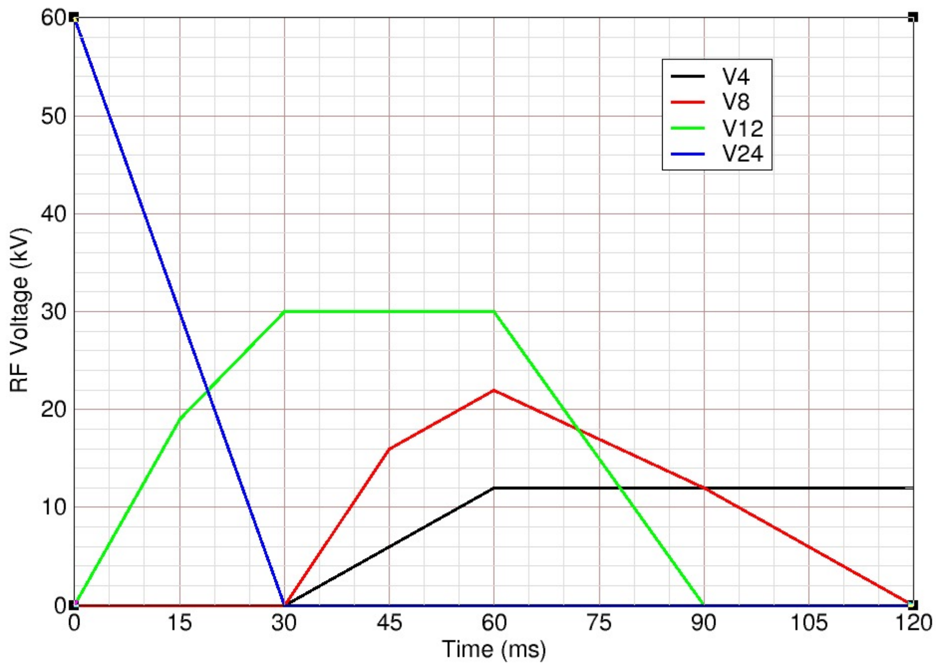


Figure 1: Voltage program for simulation of the complete 6 to 3 to 1 merge. The 6 to 3 and 3 to 1 merges are done over the periods from 0 to 30 ms and 30 to 120 ms, respectively. Note that the harmonic 12 voltage is held at its peak value until the harmonic 8 and 4 voltages reach their peaks. This is similar to what is done in practice, and gives a 3 to 1 merge in which there is only a small amount of emittance growth. In the following sequence of figures, the voltage program is shown below each figure so that the voltages at the indicated times can be seen.

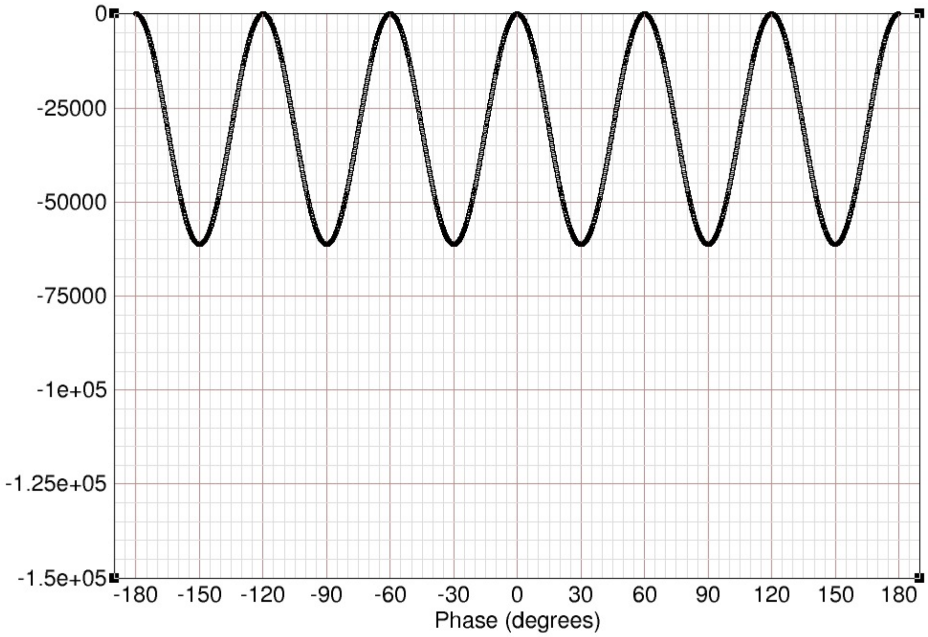
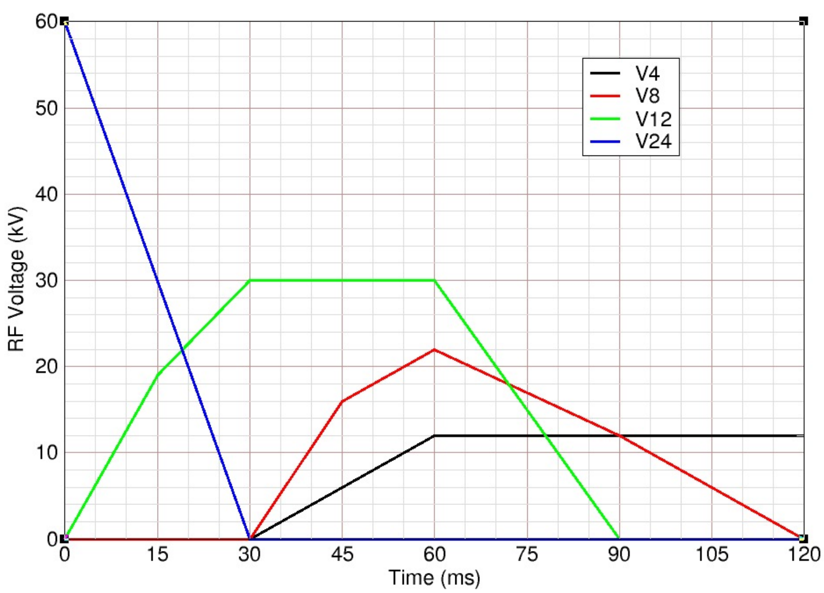


Figure 2: Six to three merge potential well at Time = 0 ms.



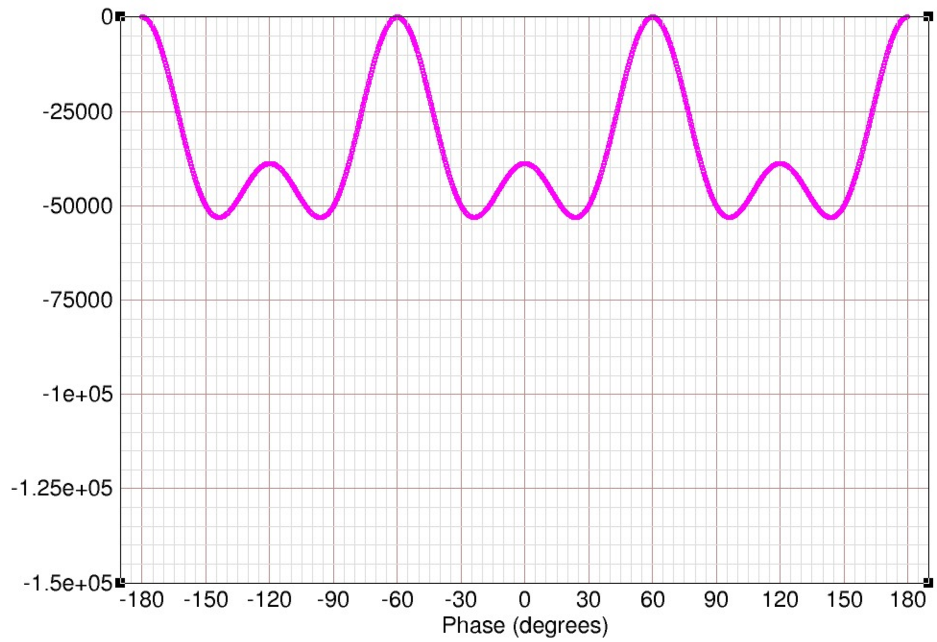
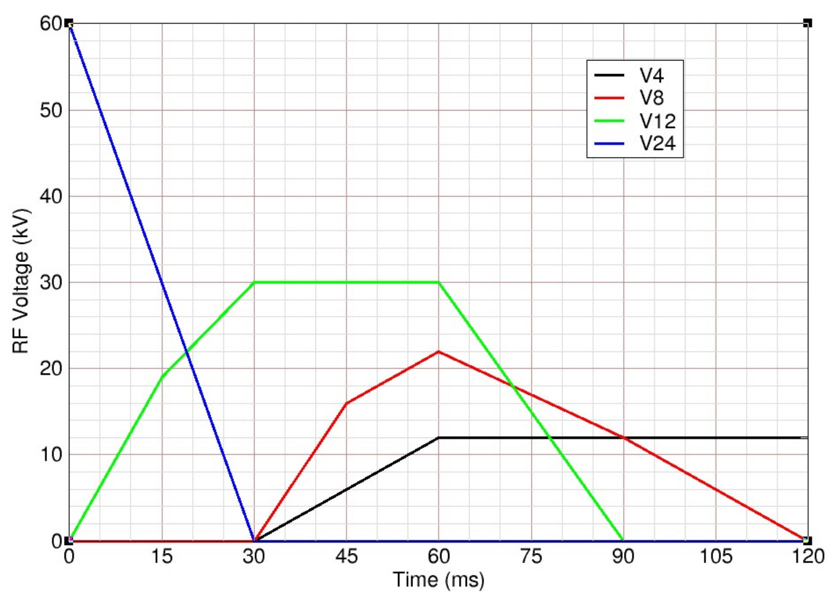


Figure 3: Six to three merge potential well at Time = 15 ms.



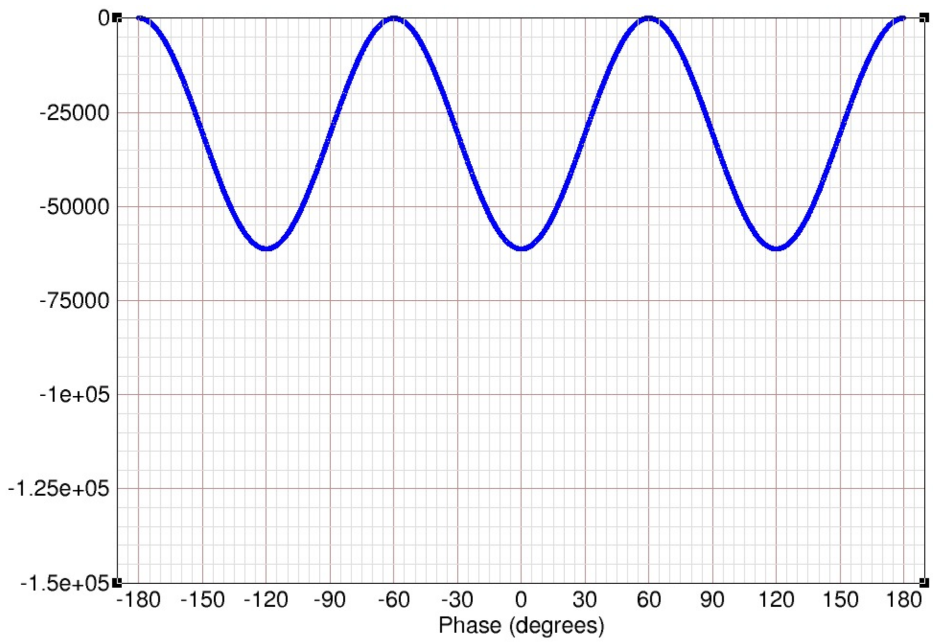
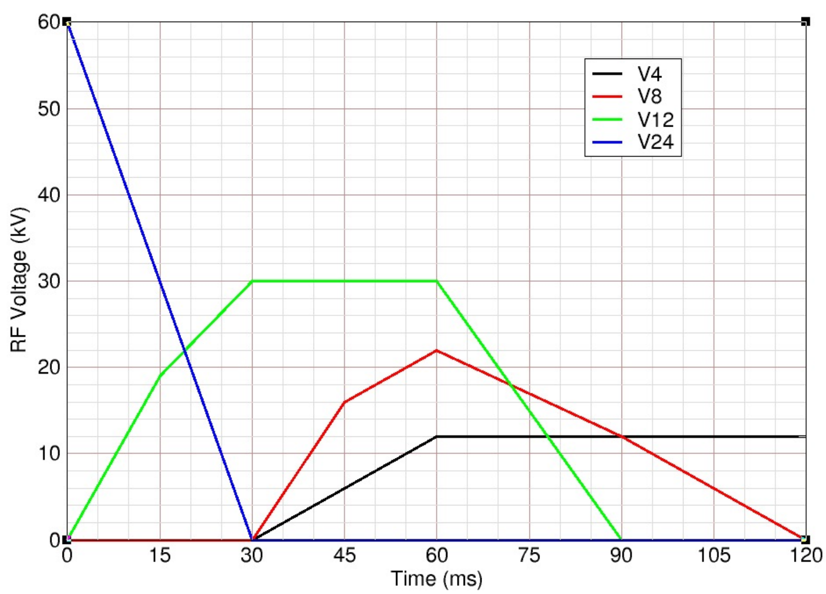


Figure 4: Six to three merge potential well at Time = 30 ms.



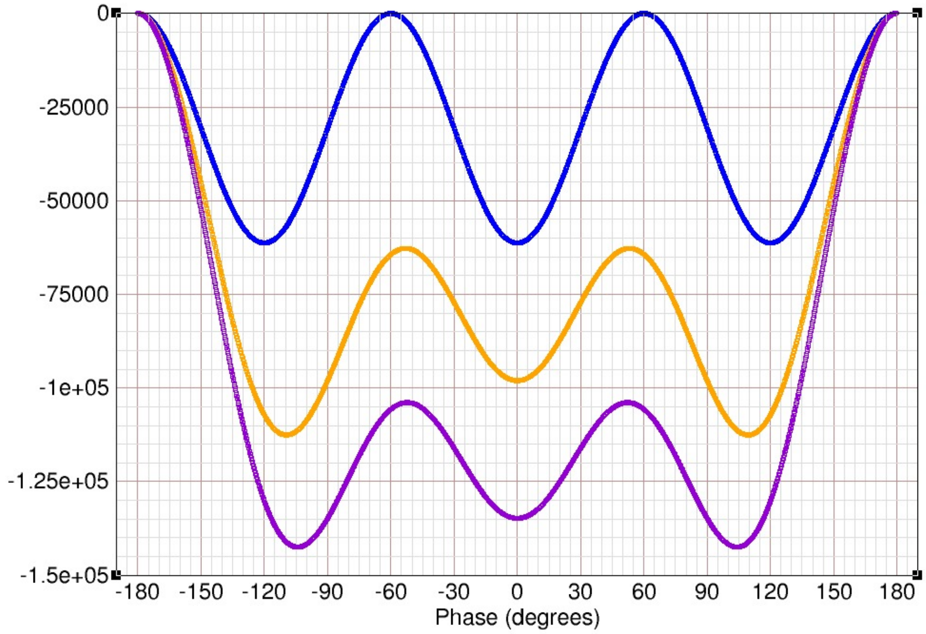
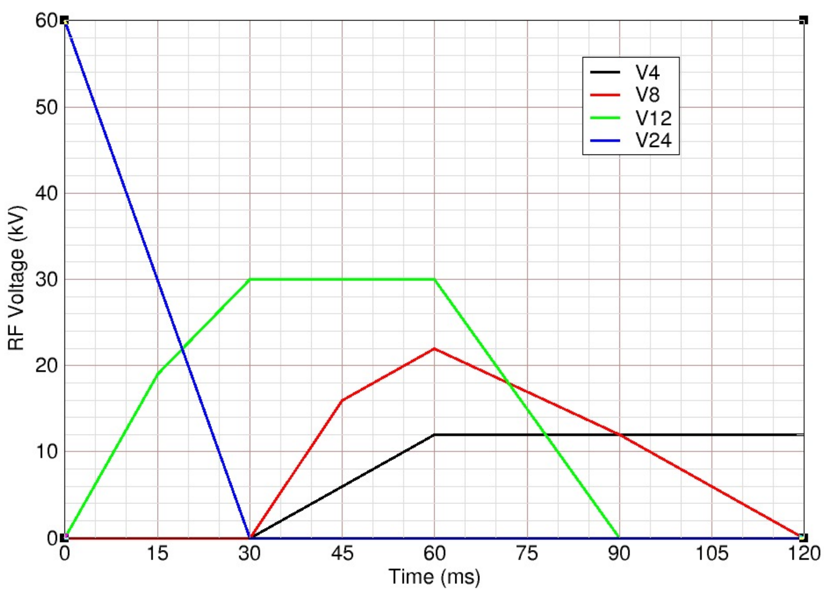


Figure 5: Three to one merge potential well at Times = 30, 45, 60 ms.



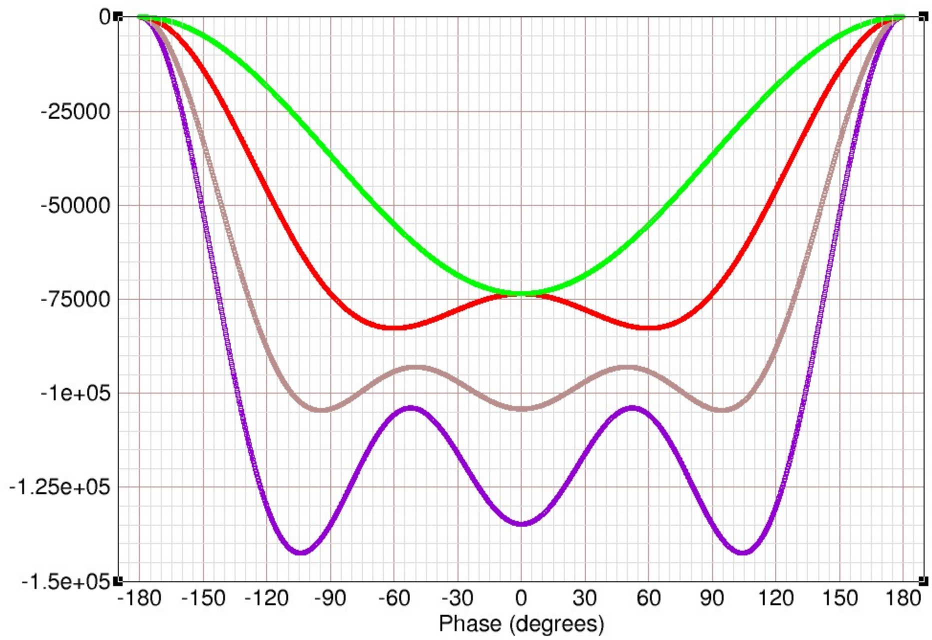
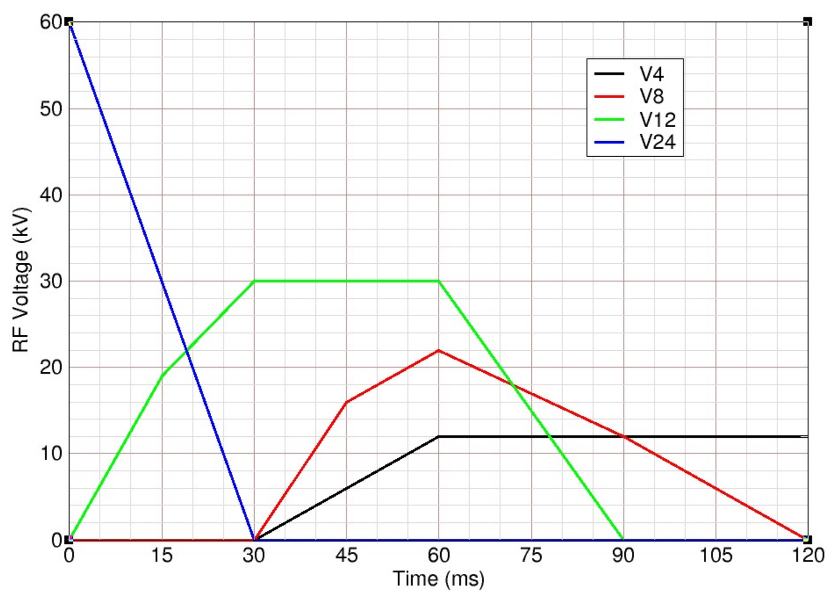


Figure 6: Three to one merge potential well at Times = 60, 75, 90, 120 ms.



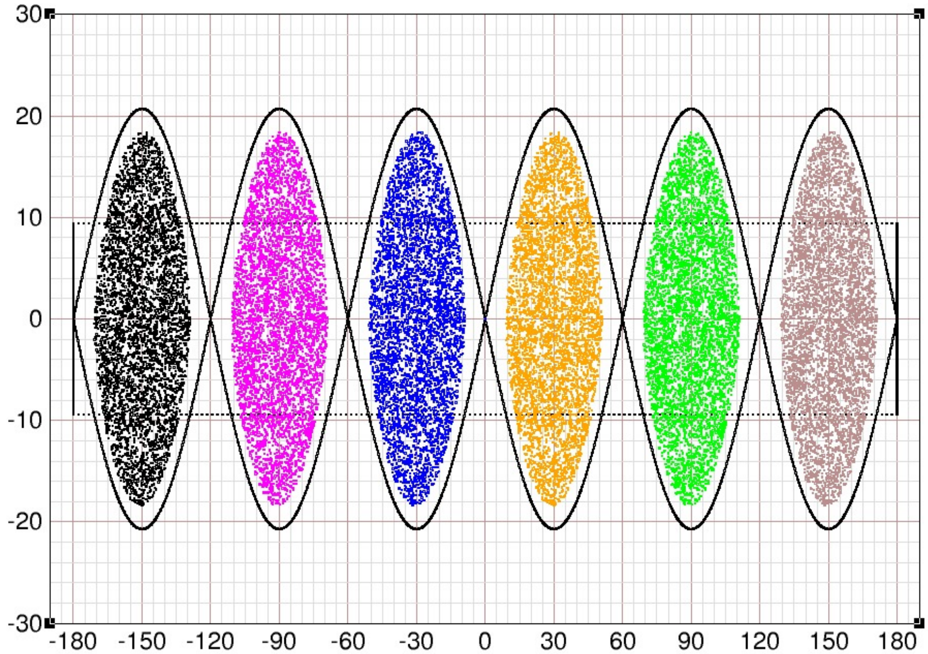
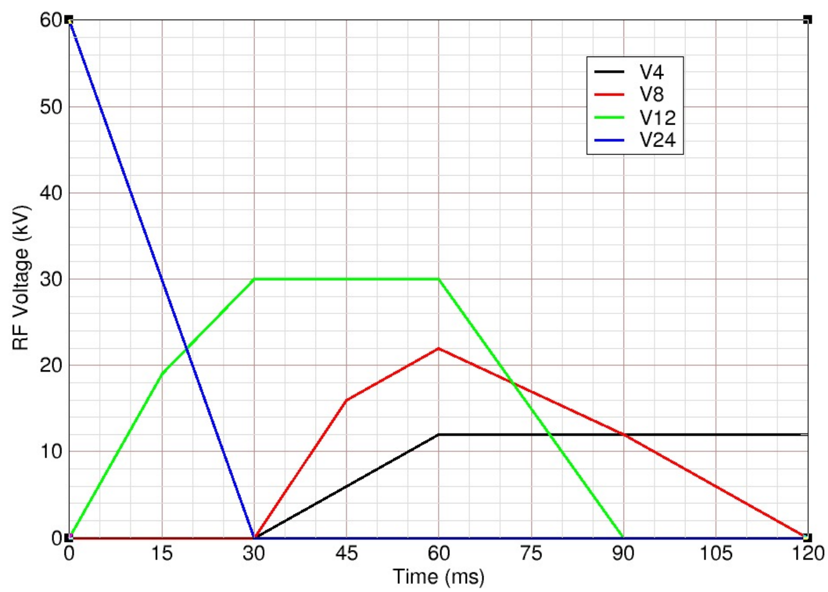


Figure 7: Six Au77+ bunches to be merged. Time = 0 ms. The total emittance of the 6 bunches is 0.60 eV*s/A.



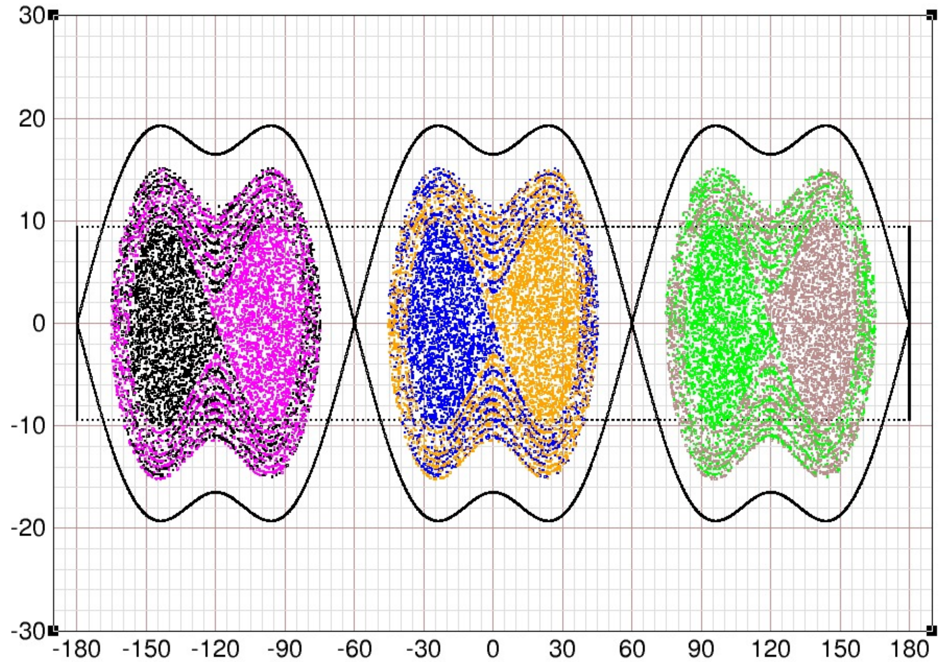
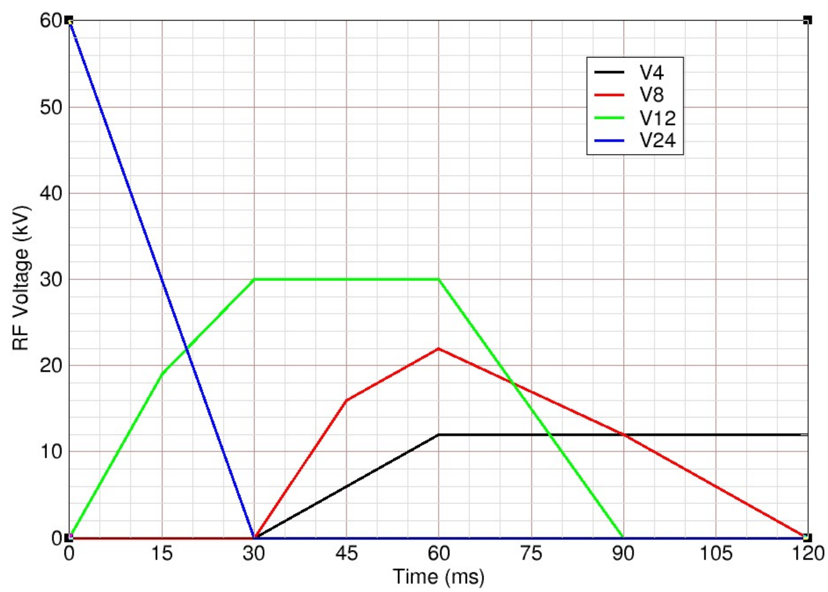


Figure 8: Halfway through 6 to 3 merge. Time = 15 ms.



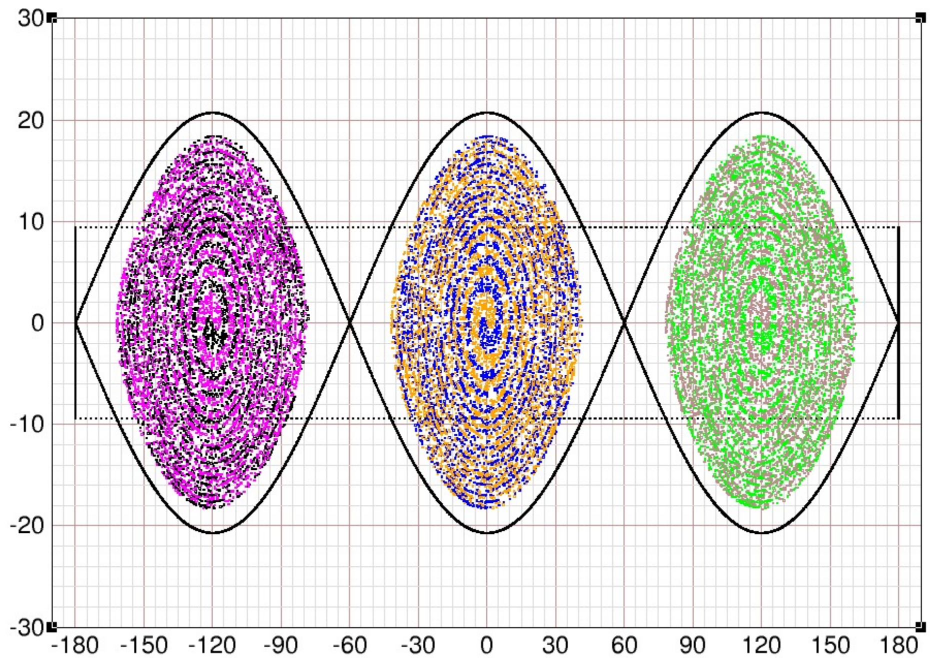
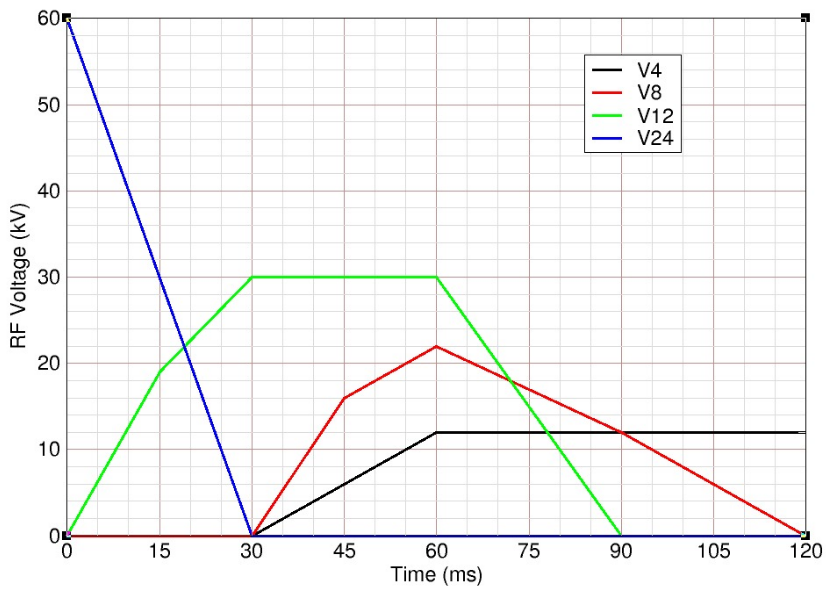


Figure 9: Completion of 6 to 3 merge. Time = 30 ms.



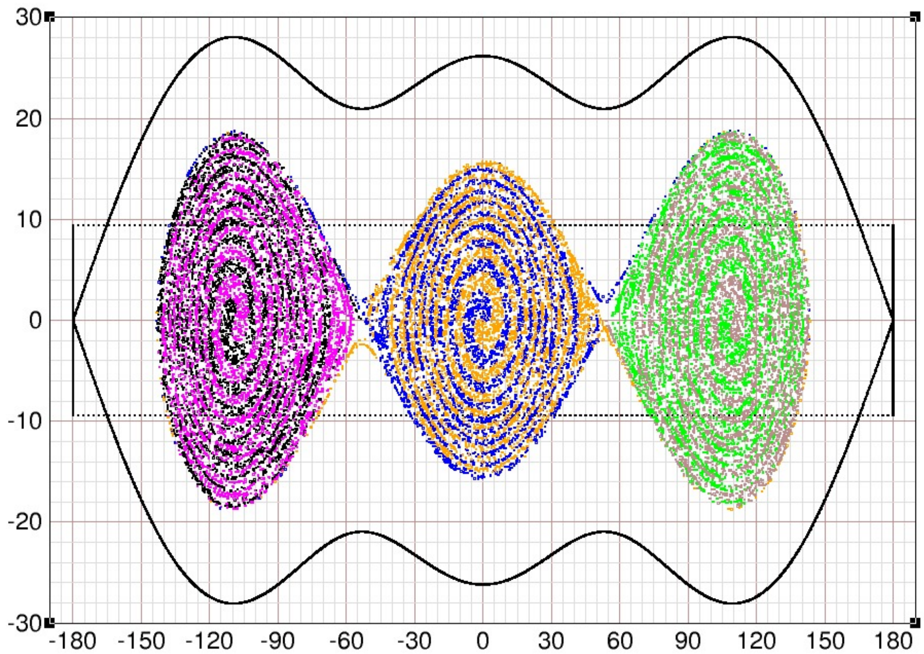
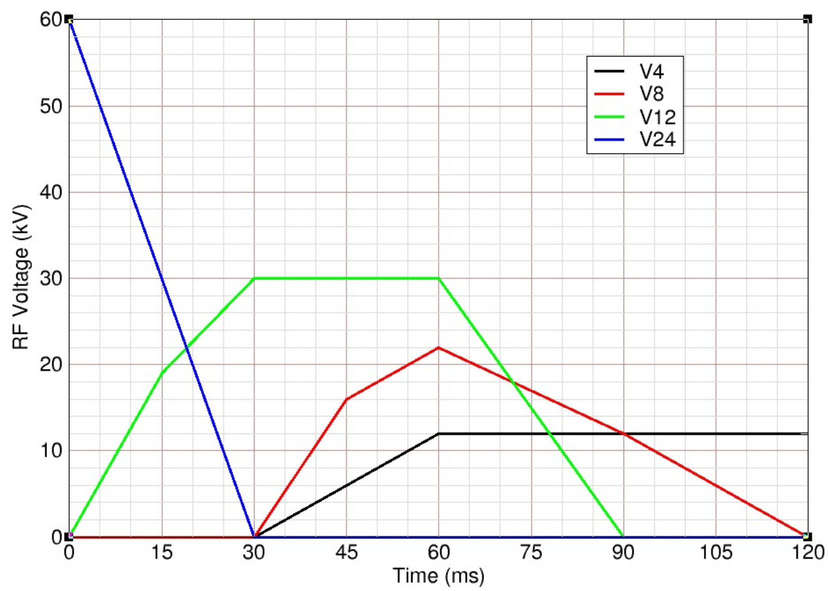


Figure 10: Three to one merge. Time = 45 ms.



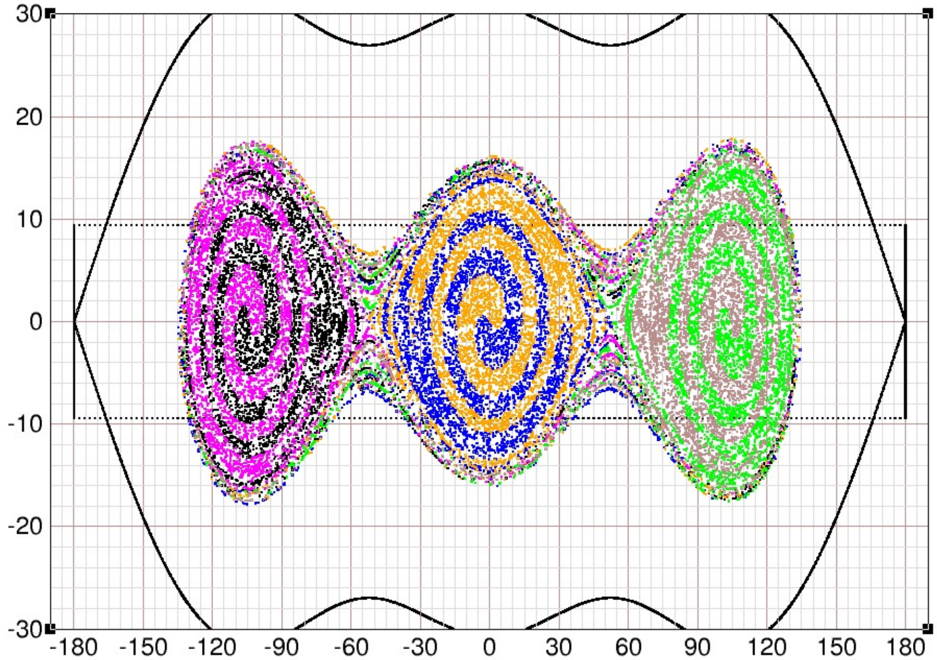
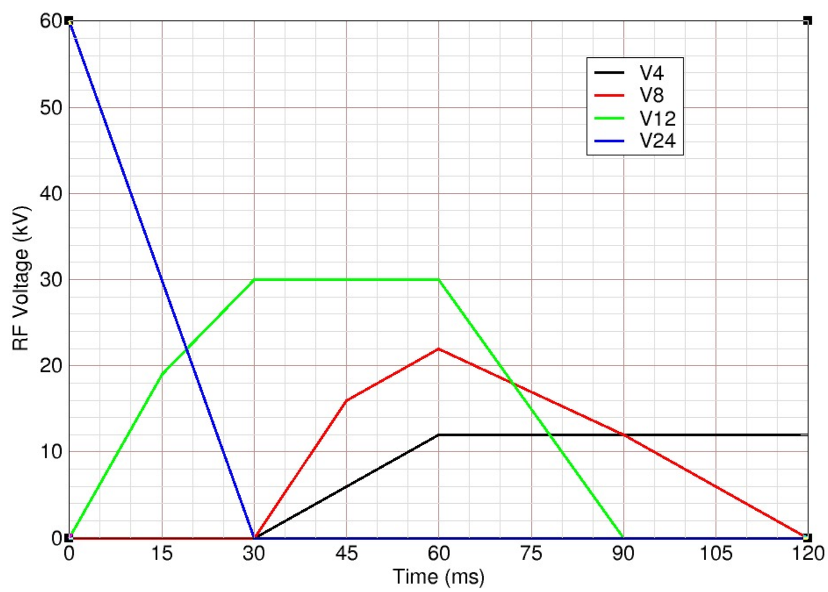


Figure 11: Three to one merge. Time = 60 ms.



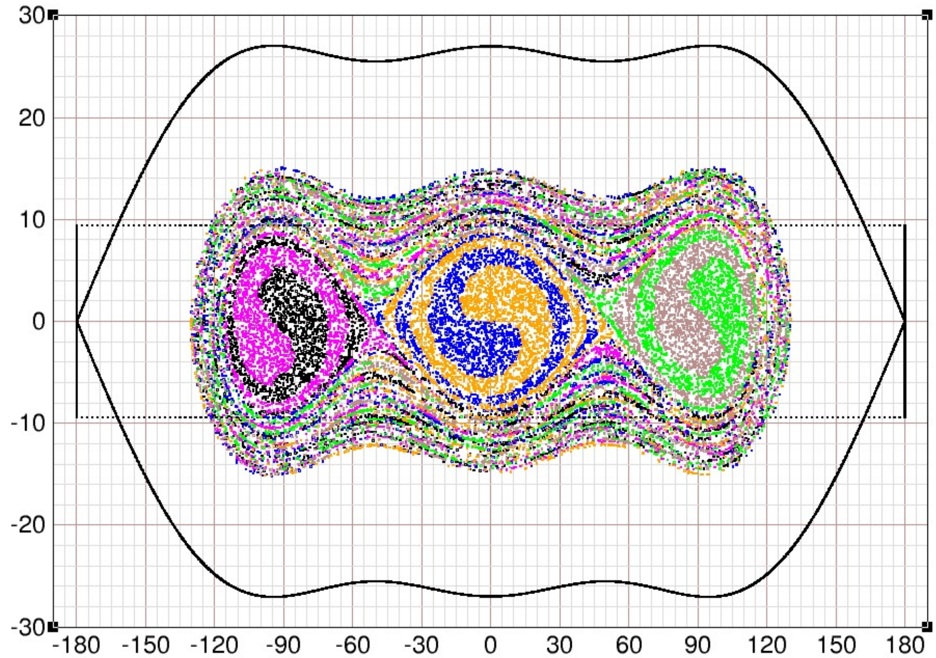
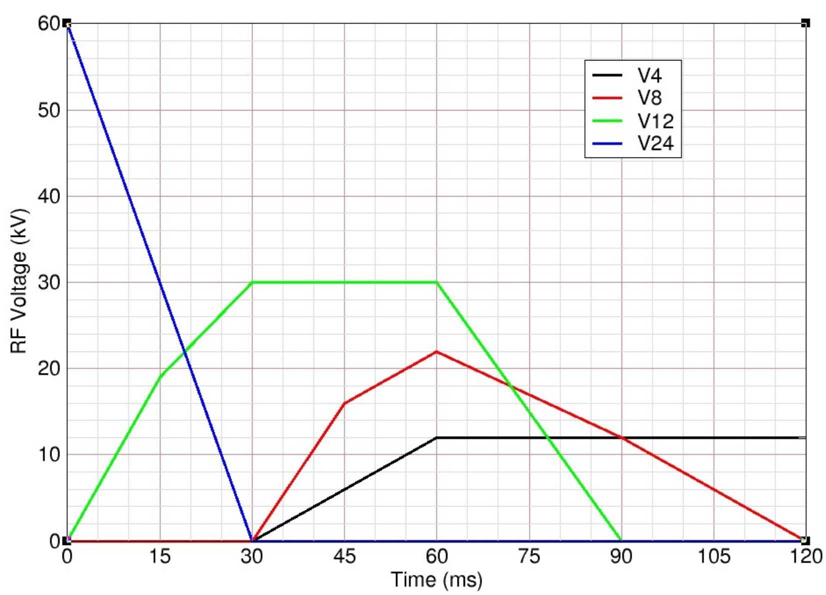


Figure 12: Three to one merge. Time = 75 ms.



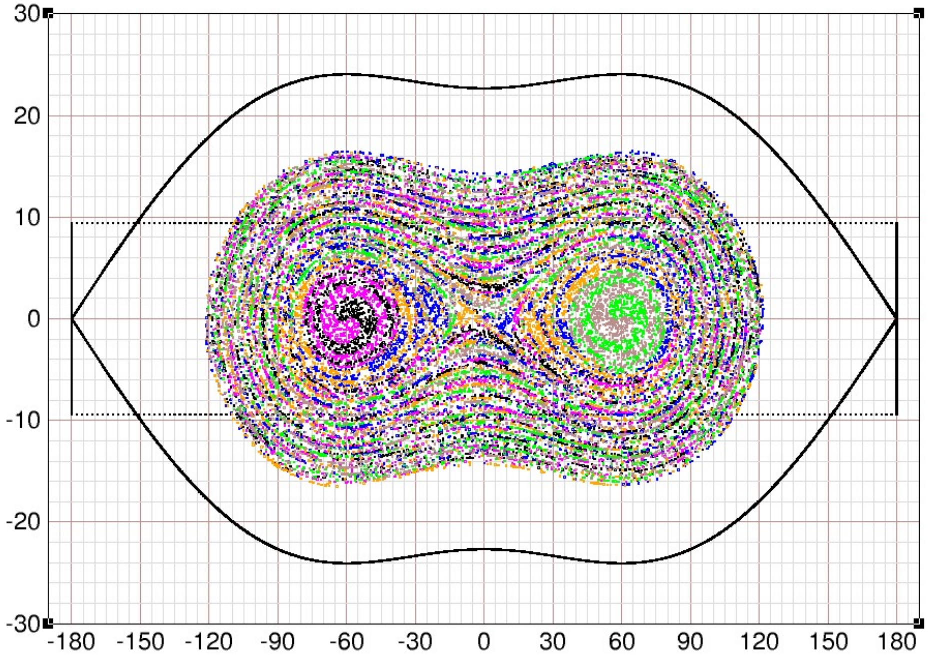
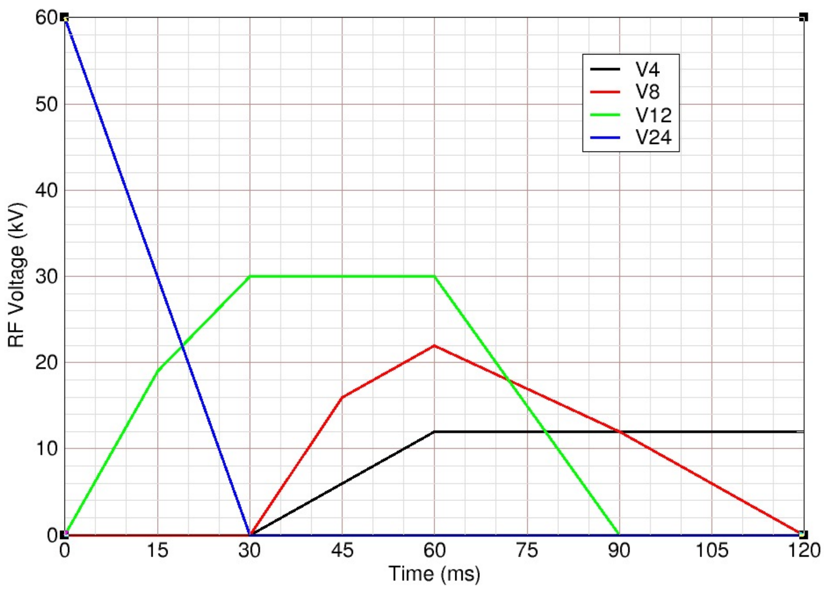


Figure 13: Three to one merge. Time = 90 ms.



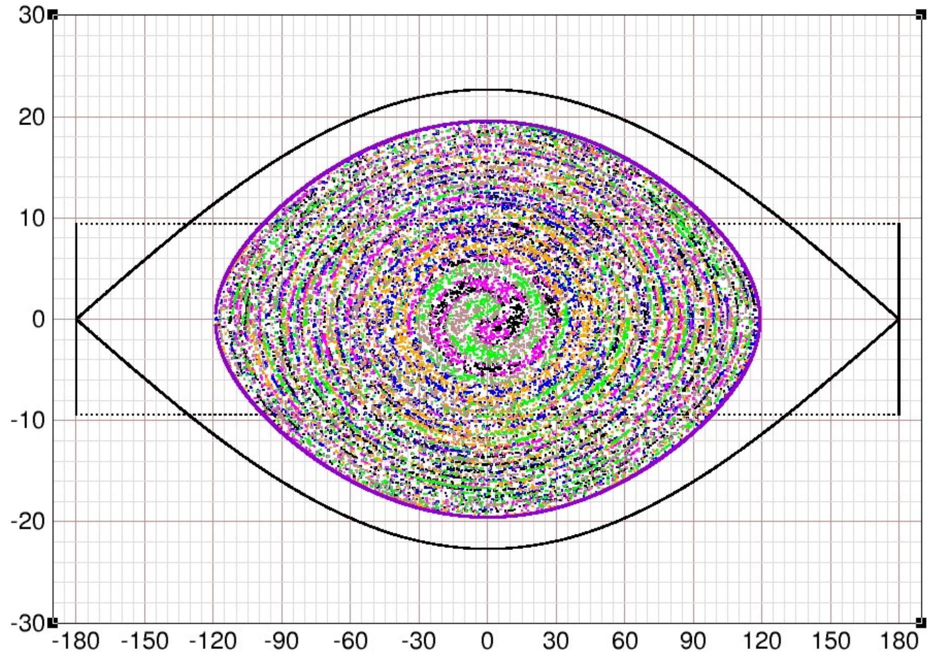
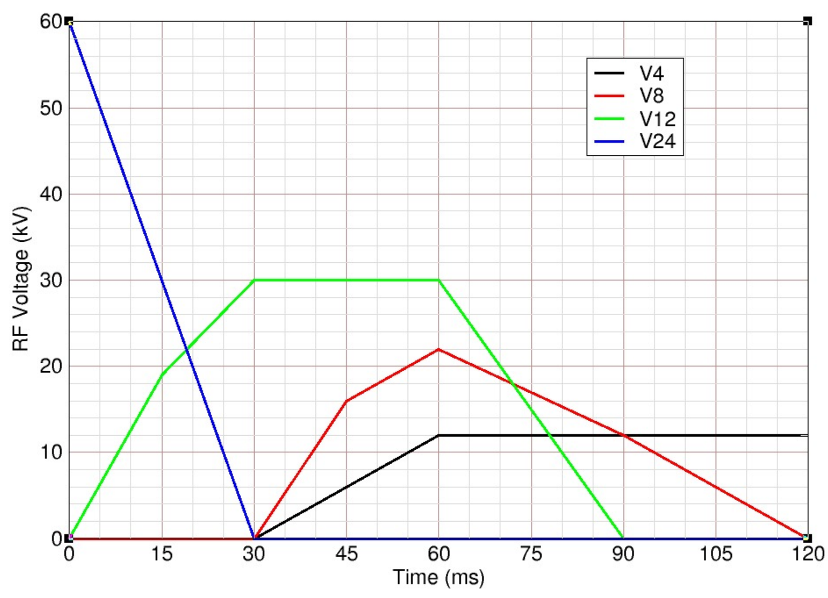


Figure 14: Completion of 3 to 1 merge. Time = 120 ms. The violet border enclosing the bunch is matched to the bucket. The area inside the border is 0.612 eV*s/A. This gives a growth factor of 0.612/0.60 = 1.02.



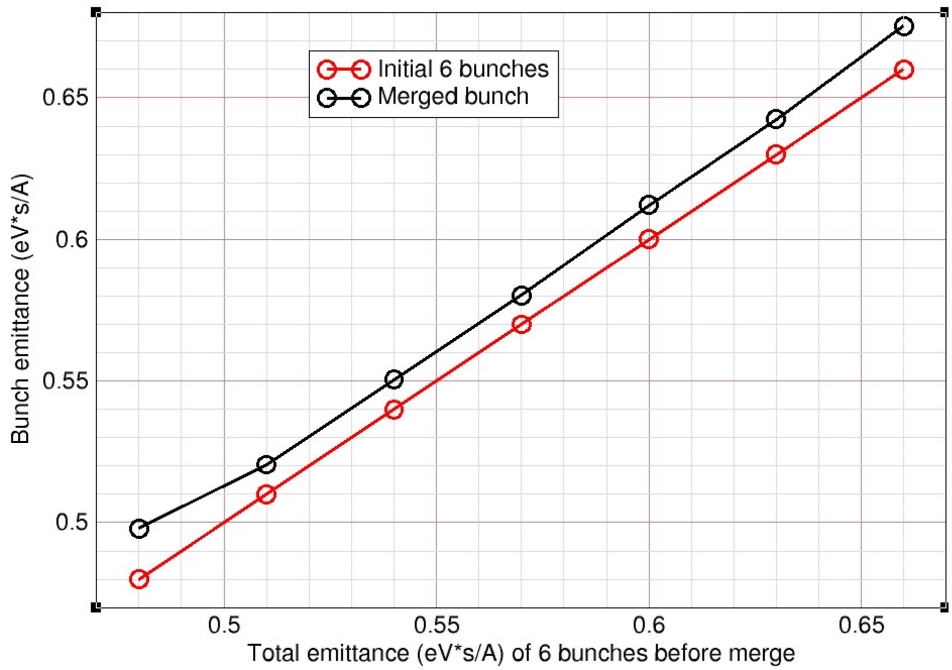


Figure 15: Merged bunch emittance versus initial six-bunch emittance. Here the merge simulation has been carried out with the same voltage program of the previous figures, but with various total emittances of the 6 bunches to be merged. The red circles mark those emittances. The black circles give the area enclosed by the matched border that surrounds the merged bunch. The ratio of the black circle value to that of the red circle below it gives the emittance growth factor. These are 1.037, 1.021, 1.019, 1.018, 1.020, 1.020, and 1.023 for initial emittances 0.48, 0.51, 0.54, 0.57, 0.60, 0.63, and 0.66 eV*s/A, respectively. The emittance growth therefore ranges from 1.8 to 2.3 percent for all except the initial emittance of 0.48 eV*s/A. Note also that for initial emittance 0.57 eV*s/A, the harmonic 8 voltage setting at 45 ms was reduced from 16 to 14 kV to give a tighter merge.

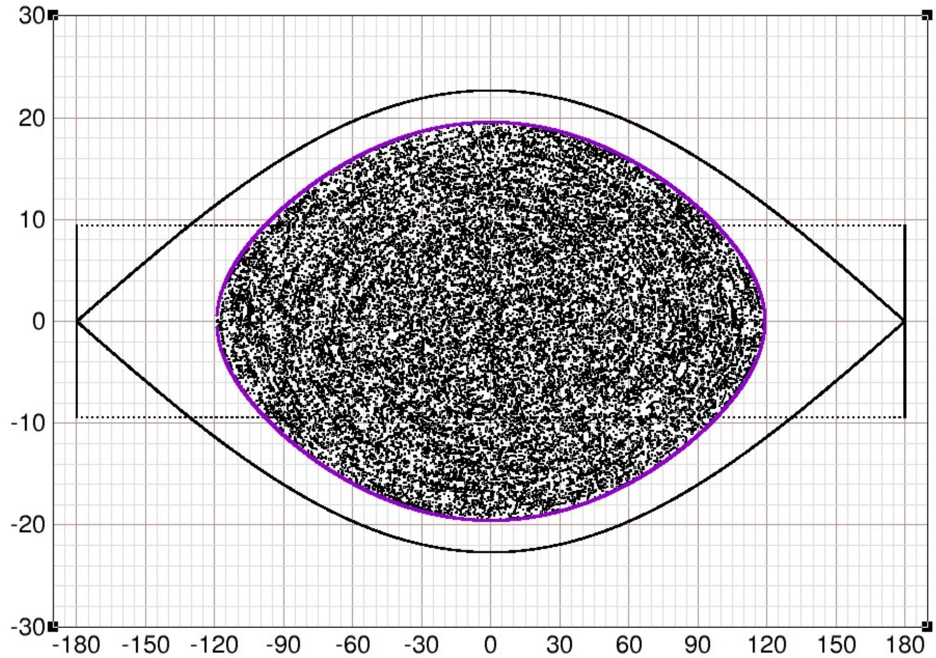


Figure 16: Merged bunch of Figure 14 with color suppressed. This is the **start of harmonic 8 squeeze**. As already mentioned, the total emittance of the 6 bunches that were merged to make this bunch is 0.60 eV*s/A. The violet border enclosing the bunch is matched to the bucket. The area inside the border is 0.612 eV*s/A, which gives a growth factor of 0.612/0.60 = 1.02. Note also that the fractional momentum spread of the bunch is $\Delta p/p = \pm 0.0016$.

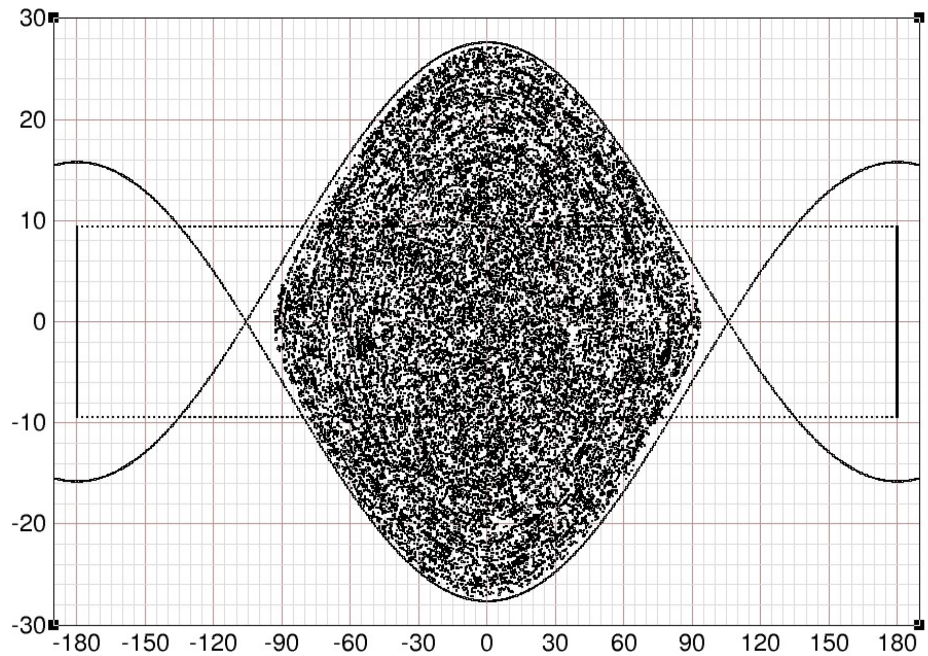


Figure 17: Merged bunch of Figure 16 at **end of harmonic 8 squeeze**. The squeeze is done by raising the harmonic 8 voltage linearly from 0 to 22 kV over a period of 20 ms. The harmonic 4 voltage is held constant at 12 kV during this time. The central bucket is just large enough to contain the bunch. If the total emittance of the 6 bunches to be merged is larger than 0.60 eV*s/A, particles leak out of the central bucket and into the satellite buckets on either side. There also may be leakage during the harmonic 12 squeeze as illustrated in the next figure.

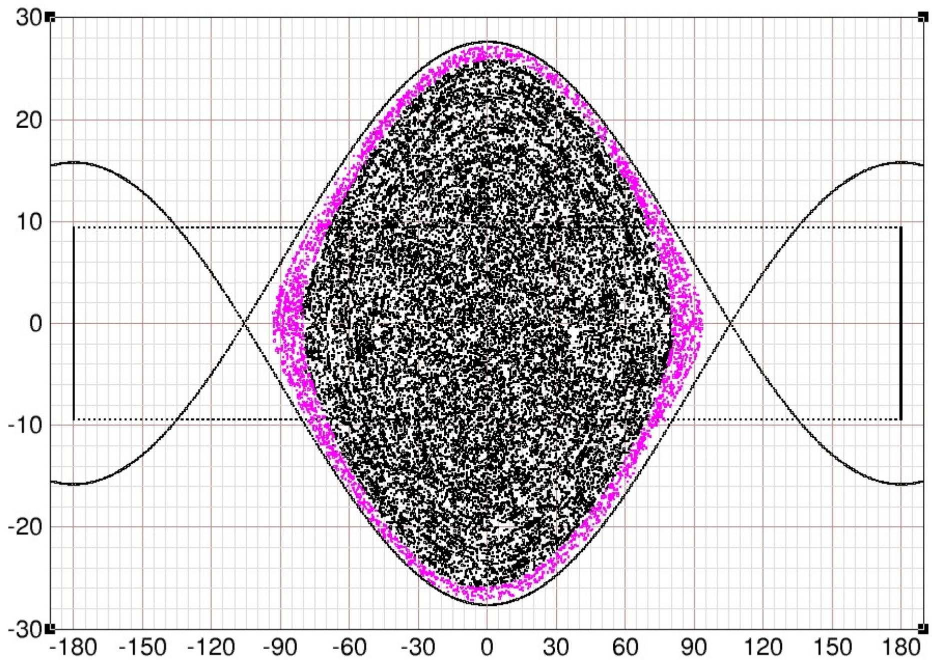


Figure 18: The magenta points show which particles in the previous figure end up in satellite buckets during the harmonic 12 squeeze. The harmonic 12 squeeze is done by raising the harmonic 12 voltage linearly from 0 to 180 kV over a period of 10 ms. The harmonic 4 and 8 voltages are held constant at 12 and 22 kV, respectively, during this time.

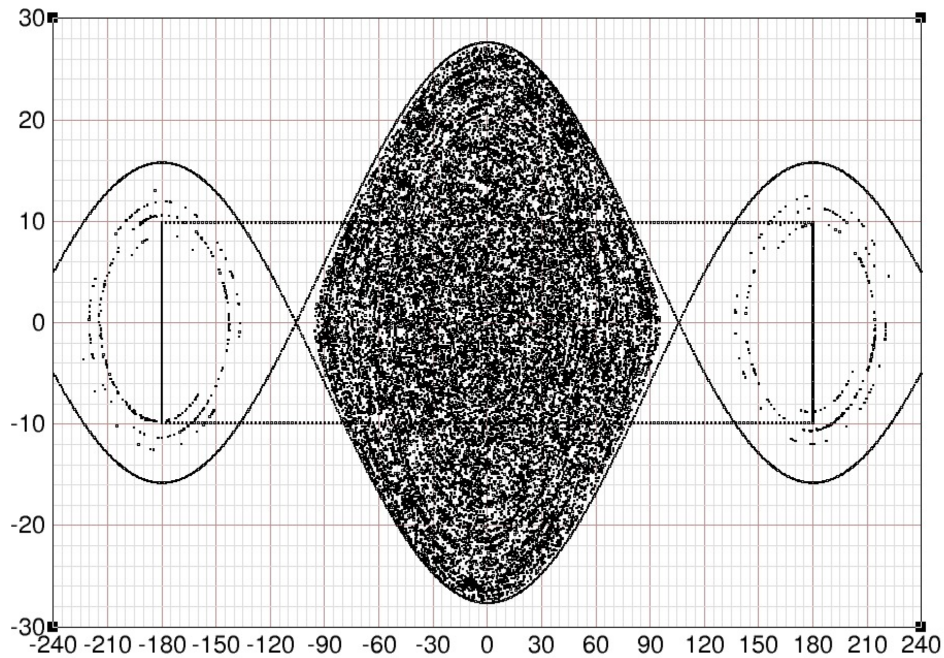


Figure 19: Here the merged bunch at the **end of harmonic 8 squeeze** is shown for the case in which the total emittance of the 6 bunches to be merged is 0.63 eV*s/A. The squeeze is again done by raising the harmonic 8 voltage linearly from 0 to 22 kV over a period of 20 ms. The harmonic 4 voltage is again held constant at 12 kV during this time. The central bucket is no longer large enough to contain the bunch and particles leak into the satellite buckets on either side.

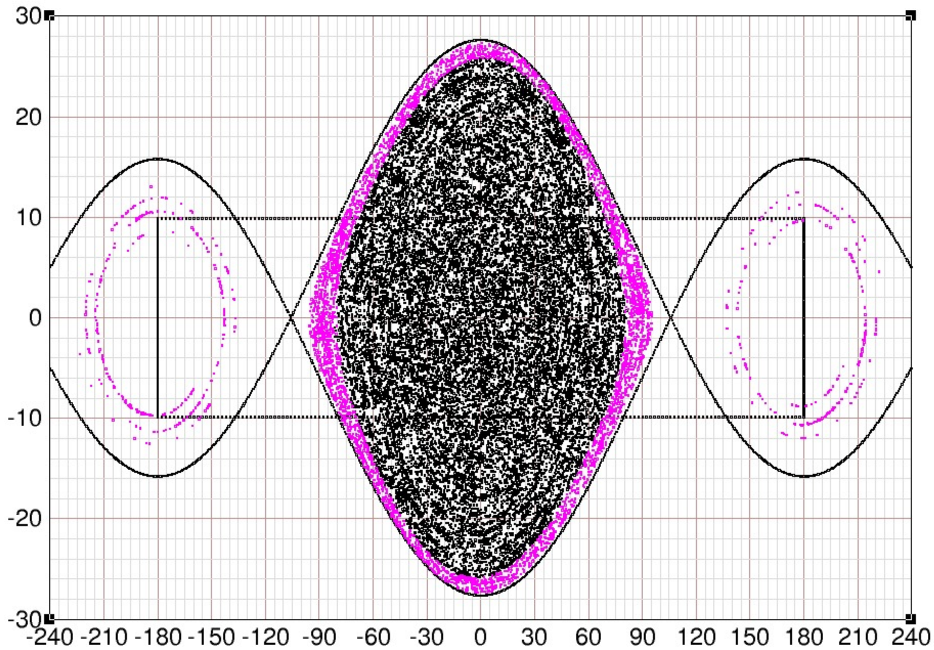


Figure 20: The magenta points show which particles in the previous figure end up in satellite buckets during the harmonic 12 squeeze.

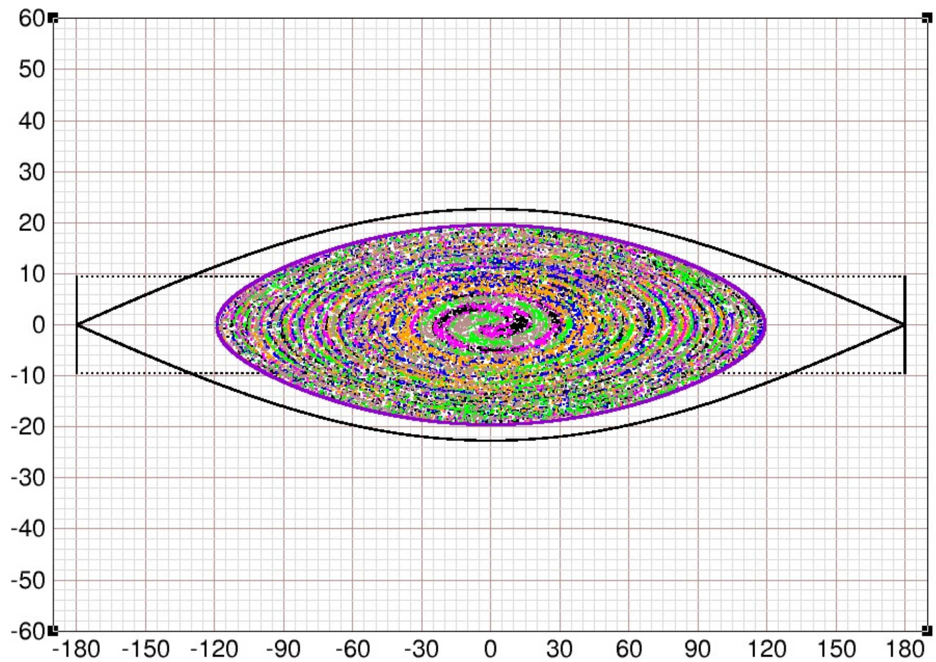


Figure 21: To illustrate the harmonic 12 squeeze, we return to the initial merged bunch and increase the vertical scale. As already mentioned, this bunch is the result of merging 6 bunches that have a total emittance of 0.60 eV*s/A. The violet border enclosing the bunch is matched to the bucket. The area inside the border is 0.612 eV*s/A.

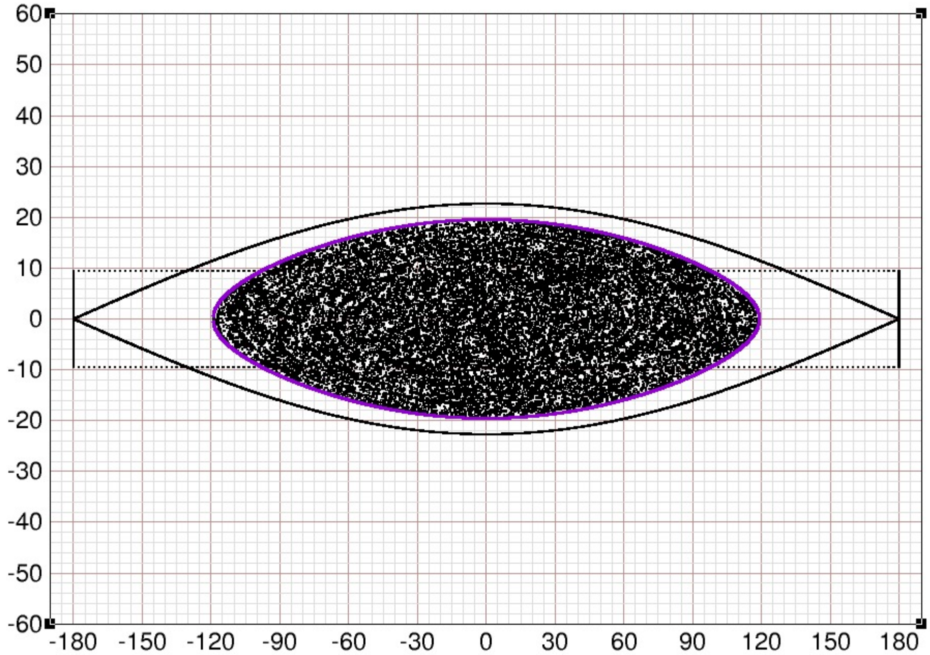


Figure 22: Merged bunch of previous figure with color suppressed.

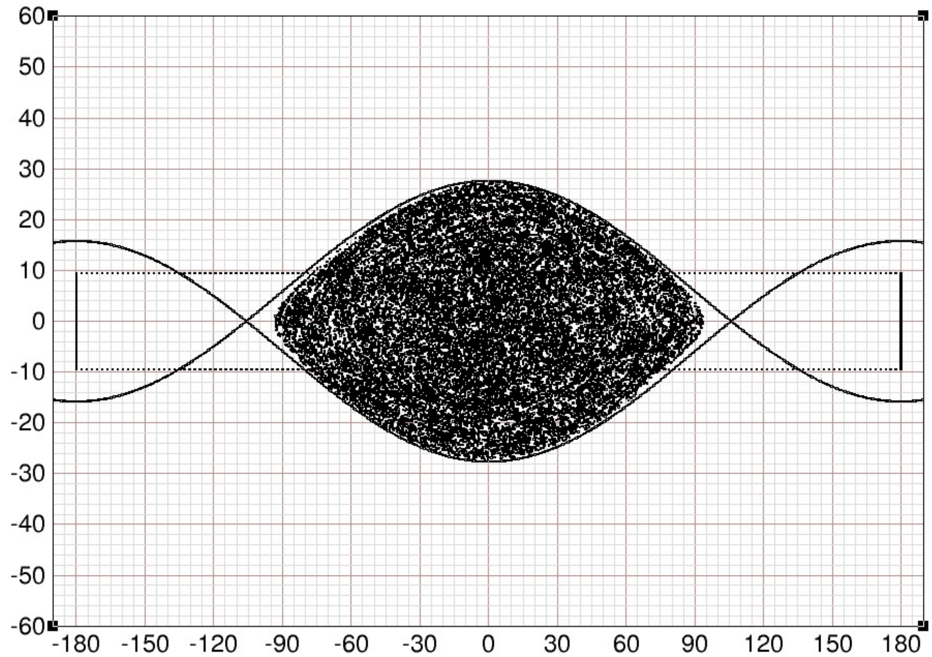


Figure 23: Merged bunch of previous figure at the end of the harmonic 8 squeeze. This is the **start of the harmonic 12 squeeze**.

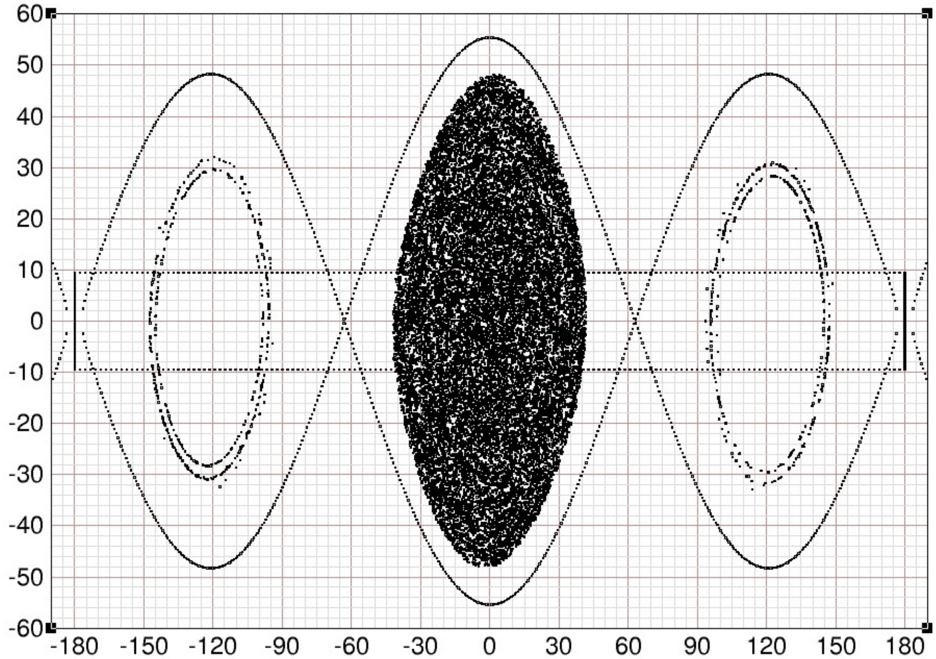


Figure 24: **End of harmonic 12 squeeze**. As already mentioned, the squeeze is done by raising the harmonic 12 voltage linearly from 0 to 180 kV over a period of 10 ms. The harmonic 4 and 8 voltages are held constant at 12 and 22 kV, respectively, during this time. Two of the four satellite bunches formed during the squeeze are shown.

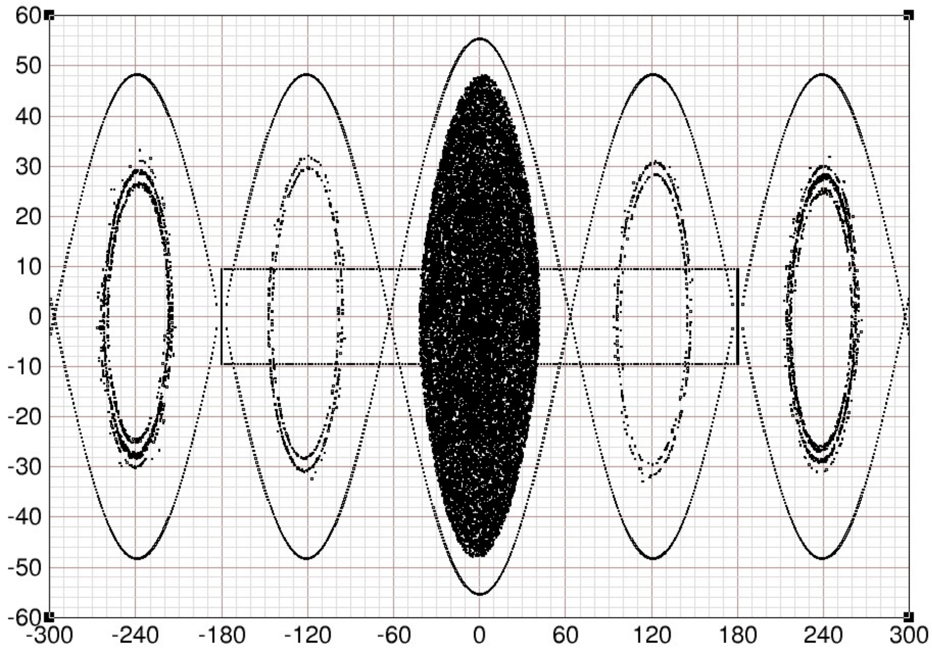


Figure 25: **End of harmonic 12 squeeze** showing all satellite bunches. A total of 12.95 percent of the particles in the initial merged bunch end up in satellite buckets with 3.42 percent in the two inner satellite and 9.53 percent in the two outer satellite buckets. The fractional momentum spread of the central bunch is $\Delta p/p = \pm 0.0039$.

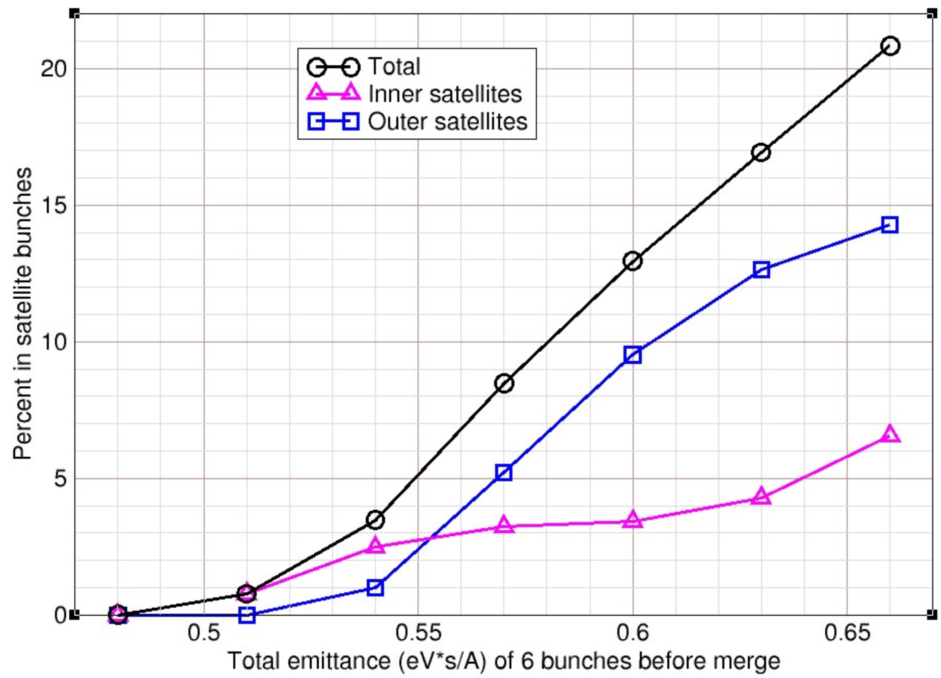


Figure 26: Percentage of particles in harmonic 12 satellite buckets versus initial six-bunch emittance. Here the merge and squeeze simulation has been carried out with the same voltage program of the previous figures, but with various total emittances of the 6 bunches to be merged. The black circles give the total percentage in the satellite buckets. The magenta triangles and blue squares give the percentage in the inner and outer satellites, respectively. For initial six-bunch emittances of 0.51 eV*s/A or less, the percentage of particles that end up in satellite buckets is zero or at most one percent. As already mentioned, the squeeze takes place with the harmonic 4 voltage held at 12 kV.

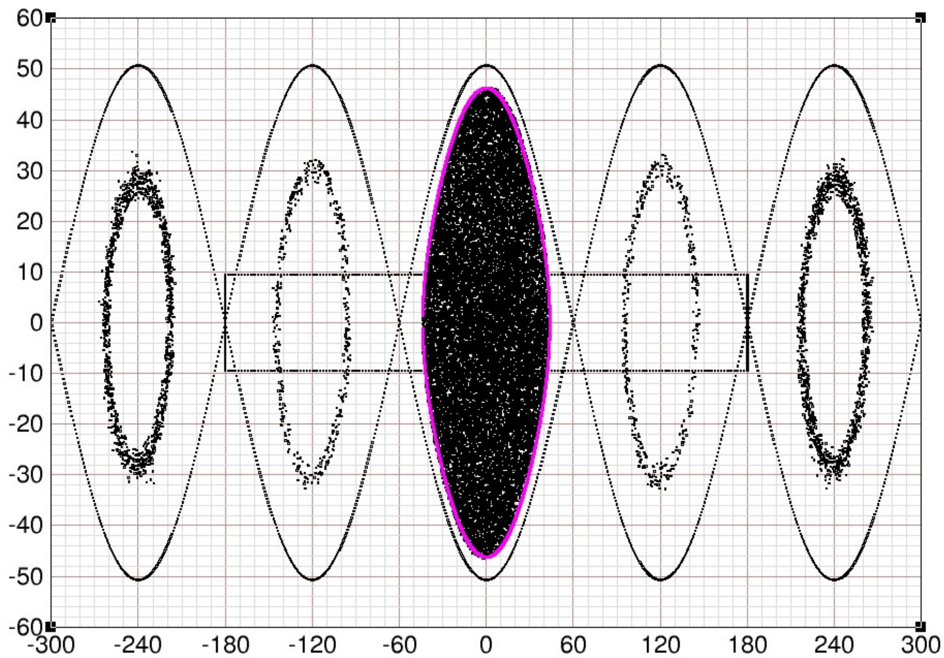


Figure 27: To obtain the emittance of the bunch at the end of the harmonic 12 squeeze, the harmonic 12 voltage is held constant and the harmonic 4 and 8 voltages are lowered linearly to zero over a period of 20 ms. The bunches are then allowed to evolve for an additional 10 ms to ensure that they reach equilibrium in the harmonic 12 buckets. Applying this technique to the bunches in **Figure 25**, we obtain the result shown above. The magenta border enclosing the central bunch is matched to the bucket. The area inside the border is 0.5238 eV*s/A. This is the longitudinal emittance of the squeezed bunch.

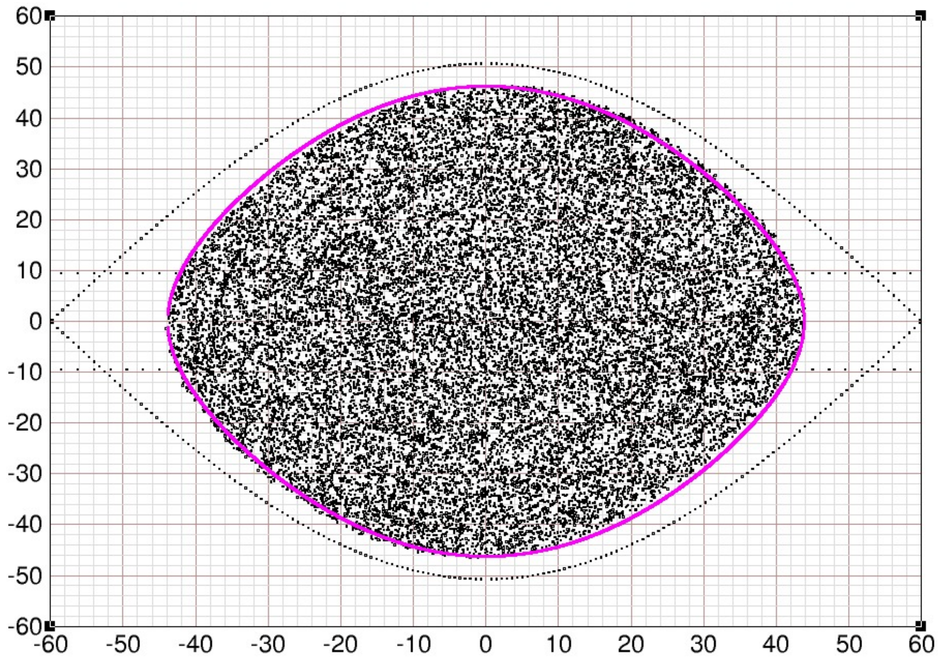


Figure 28: Magnified view of central bunch in previous figure. The magenta border enclosing the bunch is matched to the bucket. The area inside the border is 0.5238 eV*s/A. This is the longitudinal emittance of the squeezed bunch.

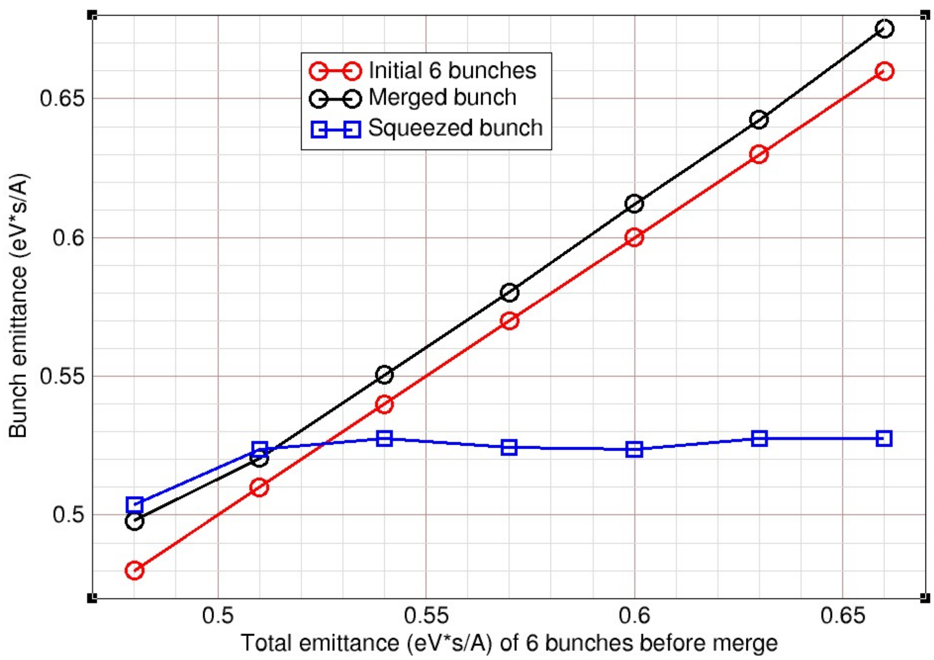


Figure 29: Merged and squeezed bunch emittances versus initial six-bunch emittance. Here the merge and squeeze simulation has been carried out with various total emittances of the 6 bunches to be merged. The red circles mark those emittances. The black circles and blue squares give the resulting emittances of the merged and squeezed bunches, respectively. As already mentioned, the squeeze takes place with the harmonic 4 voltage held at 12 kV. The emittance of the squeezed bunch is obtained by applying the technique described in Figure 27. Note that initially the squeezed bunch emittance increases as the initial six-bunch emittance is raised above 0.48 eV*s/A. However, for initial emittances above 0.51 eV*s/A, the squeezed bunch emittance remains essentially constant. This is consistent with **Figure 26** which shows that particles start leaking into satellite buckets near an initial emittance of 0.51 eV*s/A. As the initial emittance is raised beyond this value, the leakage increases and this keeps the squeezed bunch emittance from increasing any further. One can conclude that the plateau reached by the squeezed bunch emittance is the longitudinal acceptance of the squeeze. Taking the average of the squeezed bunch emittances (blue squares) on the plateau, we obtain a longitudinal acceptance of 0.526 eV*s/A.

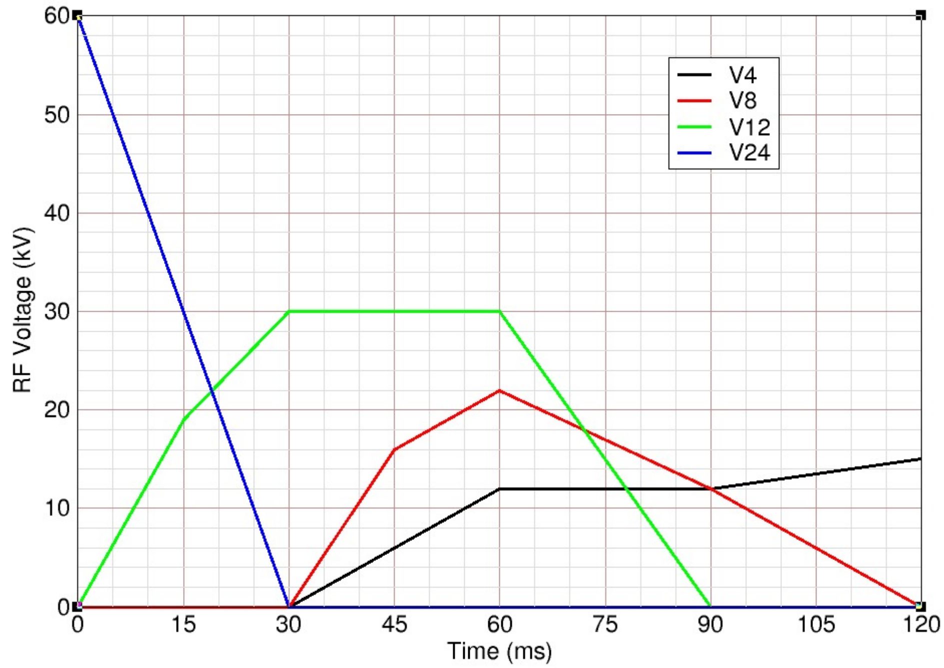


Figure 30: The longitudinal acceptance of the squeeze is sensitive to the harmonic 4 voltage. This has been 12 kV for all of the simulations done so far. Consider now the voltage program shown above. Here, during the interval from 90 to 120 ms, the harmonic 4 voltage is raised from 12 to 15 kV. The voltage is held at this value during the squeeze of the merged bunch. The resulting plots of satellite bunch percentage and squeezed bunch emittance are given in the next two figures.

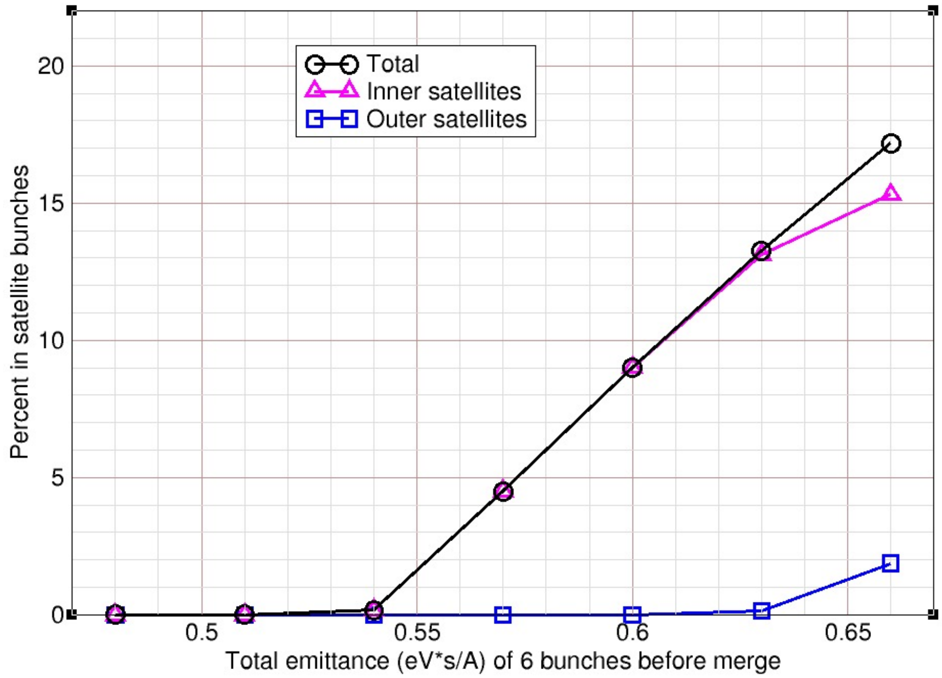


Figure 31: Percentage of particles in harmonic 12 satellite buckets versus initial emittance. The merge and squeeze simulations have been carried out with the voltage program of Figure 30. The squeeze takes place with the harmonic 4 voltage held at 15 kV. As before, the black circles give the total percentage in the satellite buckets. The magenta triangles and blue squares give the percentage in the inner and outer satellites, respectively. For initial six-bunch emittances of 0.54 eV*s/A or less, the percentage of particles that end up in satellite buckets is zero or at most a small fraction of one percent.

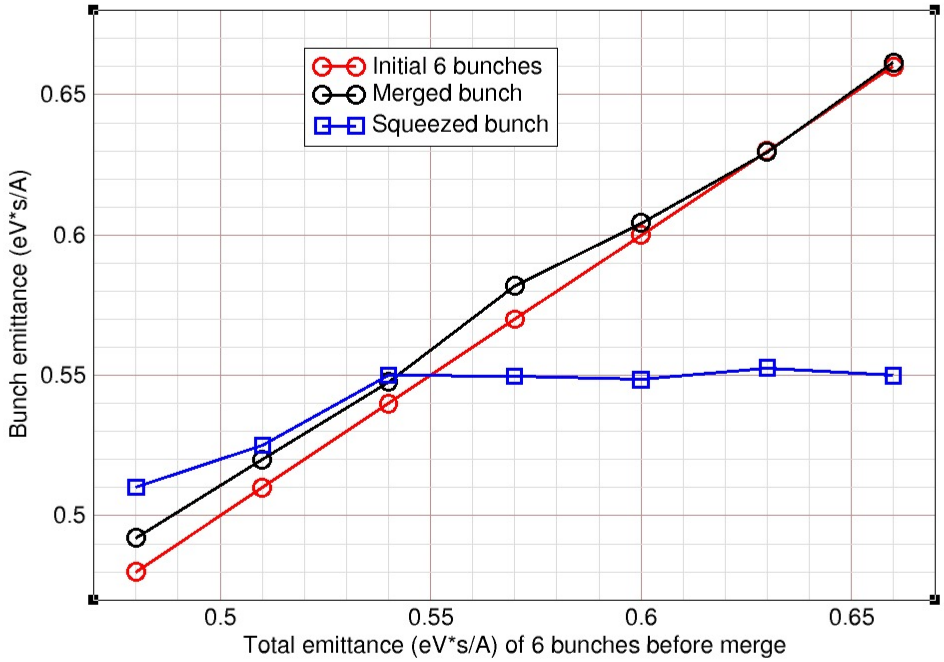


Figure 32: Merged and squeezed bunch emittances versus initial six-bunch emittance. The merge and squeeze simulations have been carried out with the voltage program of Figure 30. The squeeze takes place with the harmonic 4 voltage held at 15 kV. As before, the red circles mark the initial six-bunch emittances. The black circles and blue squares give the resulting emittances of the merged and squeezed bunches, respectively. Here we see that for initial emittances of 0.54 eV*s/A or greater, the squeezed bunch emittance remains essentially constant. Taking the average of the squeezed bunch emittances (blue squares) on the plateau, we obtain a longitudinal acceptance of 0.550 eV*s/A.

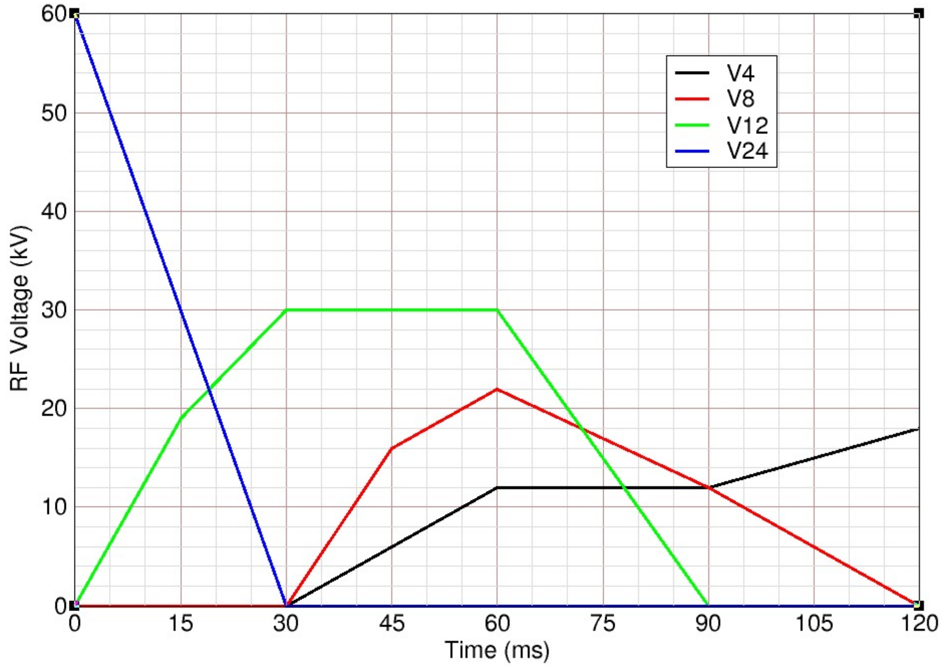


Figure 33: Consider now the voltage program shown above. Here, during the interval from 90 to 120 ms, the harmonic 4 voltage is raised from 12 to 18 kV. The voltage is held at this value during the squeeze of the merged bunch. The resulting plots of satellite bunch percentage and squeezed bunch emittance are given in the next two figures.

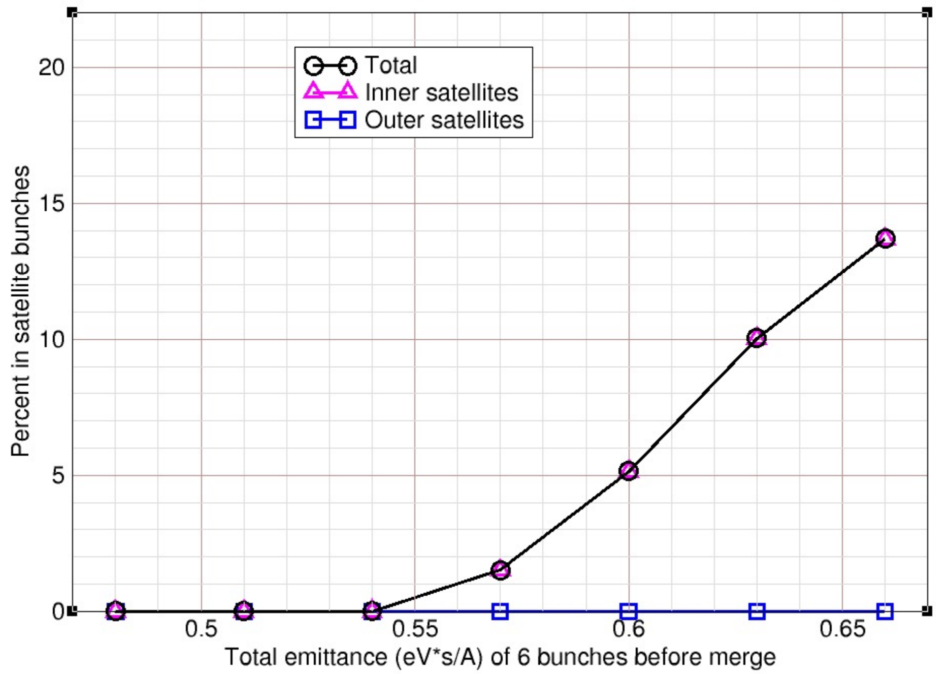


Figure 34: Percentage of particles in harmonic 12 satellite buckets versus initial emittance. The merge and squeeze simulations have been carried out with the voltage program of Figure 33. The squeeze takes place with the harmonic 4 voltage held at 18 kV. As before, the black circles give the total percentage in the satellite buckets. The magenta triangles and blue squares give the percentage in the inner and outer satellites, respectively. For initial six-bunch emittances of 0.57 eV*s/A or less, the percentage of particles that end up in satellite buckets is zero or at most 1.5 percent.

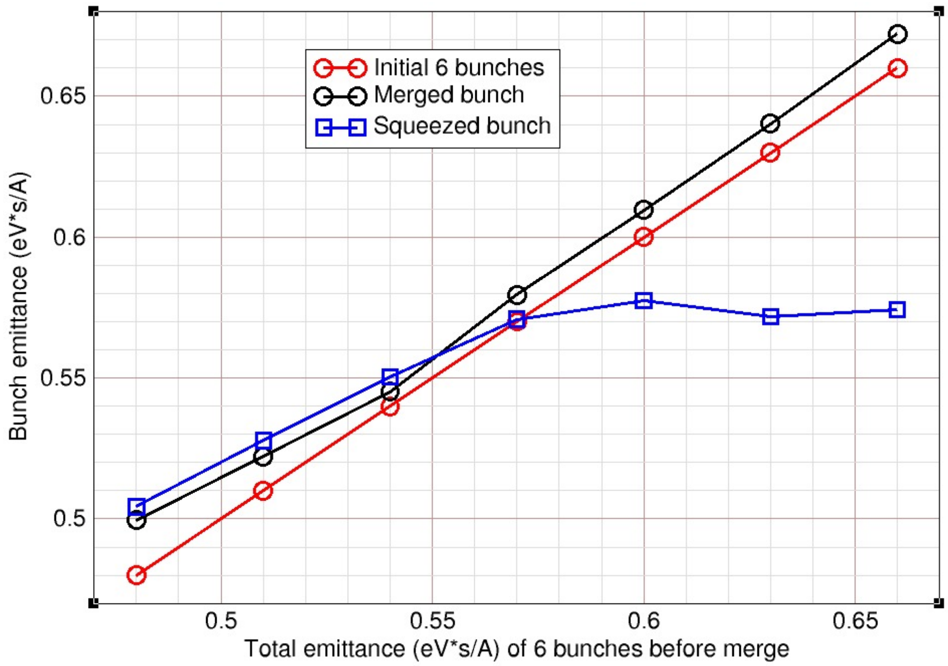


Figure 35: Merged and squeezed bunch emittances versus initial six-bunch emittance. The merge and squeeze simulations have been carried out with the voltage program of Figure 33. The squeeze takes place with the harmonic 4 voltage held at 18 kV. As before, the red circles mark the initial six-bunch emittances. The black circles and blue squares give the resulting emittances of the merged and squeezed bunches, respectively. Here we see that for initial emittances of 0.57 eV*s/A or greater, the squeezed bunch emittance remains essentially constant. Taking the average of the squeezed bunch emittances (blue squares) on the plateau, we obtain a longitudinal acceptance of 0.574 eV*s/A

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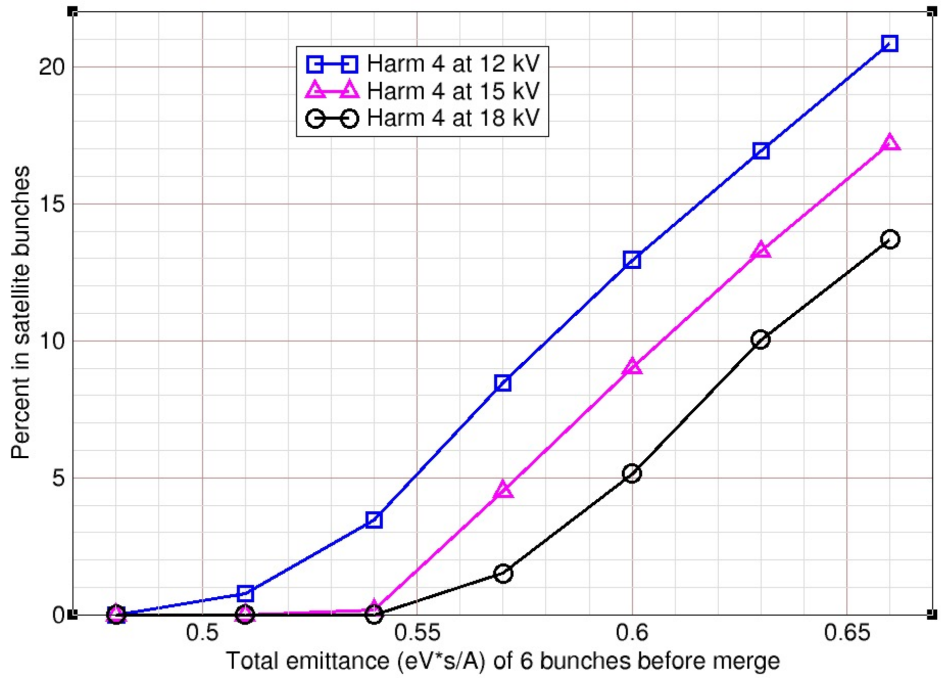

Figure 36: Summary of total percentage of particles in harmonic 12 satellite buckets versus initial six-bunch emittance. Here the blue squares, magenta triangles, and black circles give the total percentages obtained for harmonic 4 voltages 12, 15 and 18 kV, respectively. These totals are taken from Figures 26, 31 and 34, respectively. The curves show that if one wants to keep percentage of particles in satellite buckets below, say 3.5%, then the total emittance of the 6 bunches to be merged must be less than 0.540, 0.563 and 0.587 eV*s/A for harmonic 4 voltages 12, 15 and 18 kV respectively. In practice the measured harmonic 4 voltage is 15 kV [10] and the observed total percentage of particles in satellite buckets is around 3.5% [1]. This implies an initial six-bunch emittance of 0.563 eV*s/A, which is consistent with the measured emittance 0.57 eV*s/A of the merged bunch [10].

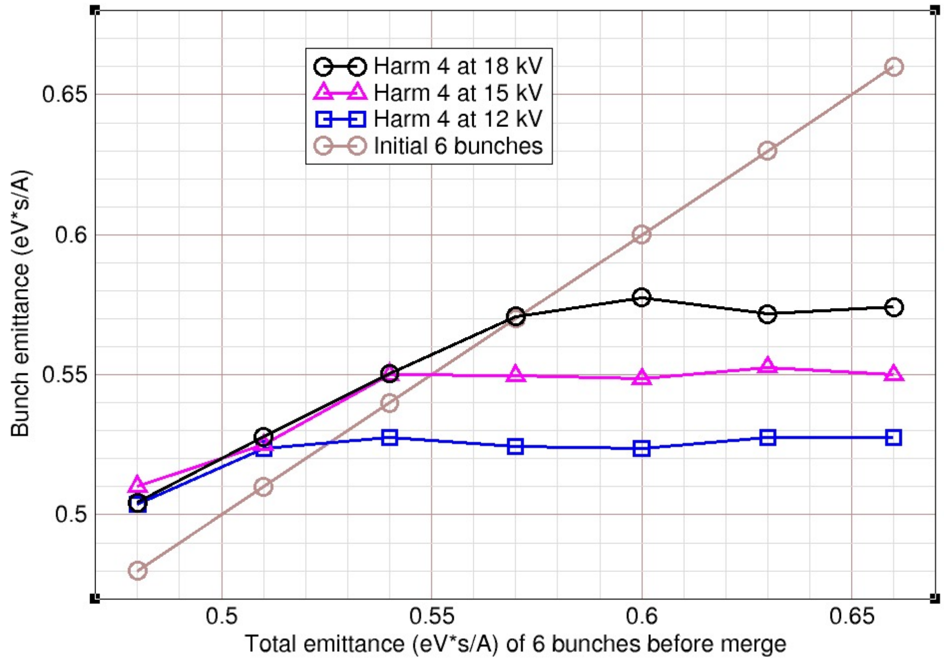

Figure 37: Summary of squeezed bunch emittances versus initial six-bunch emittance. Here the blue squares, magenta triangles, and black circles give the squeezed bunch emittances obtained for harmonic 4 voltages of 12, 15 and 18 kV, respectively. These are taken from Figures 29, 32 and 35, respectively. As already noted, one sees that as the initial six-bunch emittance increases, the squeezed bunch emittance eventually reaches a plateau. The average value attained on the plateau is taken to be the longitudinal acceptance of the squeeze. For harmonic 4 voltages 12, 15 and 18 kV, the longitudinal acceptances are 0.526, 0.550 and 0.574 eV*s/A respectively. The measured harmonic 4 voltage of 15 kV then implies a longitudinal acceptance of 0.55 eV*s/A for the squeeze. This is consistent with measurements made shortly after the squeeze [10].