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RF Capture and Acceleration of Gold Ions in Booster - II

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1 Introduction

The very successful FY2000 RHIC run provided once again the opportunity to study the injection, capture and acceleration of gold ions (Au^{32+}) in the AGS Booster. The setup and the results and conclusions of the careful work of K. Zeno during this period are documented in Ref. [1]. One important revelation of this work is that extending the time allowed for “adiabatic” capture on the Booster injection porch from the 1–3 ms used in the past to approximately 6 ms does not adversely affect beam survival. This is contrary to the notion that spending more time at low energy generally produces more beam loss. Here the cross sections for electron capture interactions between gold and residual gas or ions in the vacuum chamber are relatively large. Clearly, if too much time is spent at low energy then these interactions will produce significant loss. On the other hand, if too little time is spent on capture, then there can be substantial capture loss. This will in turn generate more residual gas or ions in the vacuum chamber thereby increasing the rate of loss due to electron capture interactions. One therefore expects some sort of optimum setup in which the benefits of reducing capture loss outweigh the cost of spending more time at low energy. This is evidently what Zeno has found with the 6 ms capture setup.

As shown in Ref. [2], extending the time allowed for “adiabatic” capture results in less filamentation of the longitudinal emittance. This means that more of the beam ends up concentrated in the central region of the RF bucket and the “tails” of the distribution do not come as close to the bucket separatrix. This reduces beam loss in two ways. First, the momentum spread of the beam is reduced, thereby reducing (or eliminating) beam loss in areas of the ring with large dispersion. Second, because the "tails" of the distribution are further from the bucket separatrix, less (or no) beam is lost as the bucket area shrinks to its minimum value at the maximum Bdot (dB/dt).

In this note we use the simulation code developed in Ref. [2] to examine Zeno's long capture (6 ms) and acceleration setup. A setup with a shorter capture time and with chopped beam is also examined. For both setups, particular attention is paid to the programming of the gap voltage. For the simulations carried out in Ref. [2], the gap voltage after capture was simply programmed to be proportional to Bdot with the constant of proportionality left as an adjustable parameter. This parameter was adjusted so that the bucket area did not take too much of a dip just after capture (see Ref. [2] Figures 1 and 2). However, with the gap voltage programmed in this way, the bucket area increases to rather large values before settling down to a local minimum when the maximum Bdot is reached. This can produce a beam with a large momentum spread. For the simulations carried out here, the gap voltage is programmed as a fourth-order polynomial in time with coefficients adjusted to keep the bucket area and momentum spread at reasonable levels.

2 Magnetic Field and Gap-Volt Programs

The magnetic cycle set up by Zeno for the FY2000 run [1] had zero Bdot on the injection porch. In our simulations we therefore assume that the magnetic field B is held constant at value B_c during injection and capture. We assume that capture begins at time $t = 0$ and ends at time $t = T_c$ with the gap voltage $V_g(t)$ increasing parabolically from zero to V_c. Thus, for $0 \leq t \leq T_c$, we have

$$B(t) = B_c, \quad \dot{B}(t) = 0, \quad \ddot{B}(t) = 0, \tag{1}$$

$$V_g(t) = V_c\, t^2/T_c^2, \quad \dot{V}_g(t) = 2V_c\, t/T_c^2, \quad \ddot{V}_g(t) = 2V_c/T_c^2 \tag{2}$$

where

$$V_c = V_g(T_c), \quad \dot{V}_c = \dot{V}_g(T_c) = 2V_c/T_c \tag{3}$$

and the dots denote differentiation with respect to time. The parameters B_c, V_c and T_c are adjustable parameters of the simulation. Here B_c is given by the nominal rigidity $B\rho = 0.852334$ Tm for Au^{32+} ions at injection in Booster.

After capture, and until the maximum Bdot is reached at time T_m (i.e. for $T_c \le t \le T_m$), we shall assume that

$$B(t) = B_c + a(t - T_c)^3 + b(t - T_c)^4, \tag{4}$$

$$\dot{B}(t) = 3a(t - T_c)^2 + 4b(t - T_c)^3, \tag{5}$$

$$\ddot{B}(t) = 6a(t - T_c) + 12b(t - T_c)^2. \tag{6}$$

These functions and the ones defined by (1) are continuous at time T_c. The parameters a and b are determined by the requirement that

$$\dot{B}(T_m) = \dot{B}_m, \quad \ddot{B}(T_m) = 0 \tag{7}$$

where $\dot{B}_m$ and T_m are adjustable parameters to be specified. ($\dot{B}_m$ is the maximum Bdot.) Using (7) in (5) and (6), and solving for a and b, we obtain

$$a = \frac{\dot{B}_m}{(T_m - T_c)^2}, \quad b = -\frac{\dot{B}_m}{2(T_m - T_c)^3}. \tag{8}$$

Similarly, after capture and until the maximum gap voltage is reached at time T_M (i.e. for $T_c \le t \le T_M$), we shall assume that

$$V_g(t) = V_c + \dot{V}_c(t - T_c) + c(t - T_c)^2 + d(t - T_c)^3 + e(t - T_c)^4 \tag{9}$$

$$\dot{V}_g(t) = \dot{V}_c + 2c(t - T_c) + 3d(t - T_c)^2 + 4e(t - T_c)^3 \tag{10}$$

$$\ddot{V}_g(t) = 2c + 6d(t - T_c) + 12e(t - T_c)^2. \tag{11}$$

Here the parameters c, d, and e are determined by the requirement that

$$\ddot{V}_g(T_c) = \ddot{V}_c, \quad V_g(T_M) = V_M, \quad \dot{V}_g(T_M) = 0 \tag{12}$$

where $\ddot{V}_c$, T_M, and V_M are adjustable parameters to be specified. Using (12) in (9–11) and solving for c, d, and e we obtain

$$2c = \ddot{V}_c, \quad d = \frac{1}{T^4}\left\{4DT - ET^2\right\}, \quad e = \frac{1}{T^4}\{-3D + ET\} \tag{13}$$

where $T = T_M - T_c$ and

$$D = V_M - V_c - \dot{V}_c T - cT^2, \quad E = -\dot{V}_c - 2cT. \tag{14}$$

Note that the functions $V_g(t)$ and $\dot{V}_g(t)$ defined by (9) and (10) and by (2) are continuous at time T_c. This is not the case for $\ddot{V}_g(t)$ unless $\ddot{V}_c$ is given the value $2V_c/T_c^2$. In general we will want to give $\ddot{V}_c$ a different value in order to keep the bucket area and momentum spread from becoming too large after capture.

After the maximum Bdot is reached, B continues to increase at constant Bdot. Thus, for $t \geq T_m$, we have

$$B(t) = B(T_m) + \dot{B}_m(t - T_m). \tag{15}$$

Similarly, for $t \geq T_M$, the gap voltage is held constant at V_M. Thus

$$V_g(t) = V_M. \tag{16}$$

3 Initial Particle Distribution

The initial particle distribution for the simulations is that of completely unbunched beam. This is the situation in Booster just after the beam pulse from tandem has been injected and before RF capture begins. As in Ref. [2], we assume a uniform distribution and consider a 50-by-50 rectangular array of points (particles) which cover the region occupied by one sixth of the beam. (This is the region of one RF bucket at harmonic $h = 6$.) The array has boundries at times $t = \pm\delta t$ and energies $e = \pm\delta e$. We shall take $\delta e = 0.091$ MeV. This corresponds to the momentum deviation δp given by $\delta p/p_s = \delta e/(E_s \beta_s^2) = 0.00025$ with p_s, E_s, and β_s evaluated at injection. At harmonic $h = 6$, the width of a single stationary bucket at injection is 2.518 μs, so we take $\delta t = 1.259$ μs. The longitudinal emittance of the array is $4(\delta t)(\delta e) = 0.46$ eV-s.

4 Simulation of the Long (6 ms) Capture Setup

4.1 Magnetic Field, Gap Voltage, and Bucket Parameters

Here we set

$$T_c = 6 \text{ ms}, \quad T_m - T_c = 23 \text{ ms}, \quad \dot{B}_m = 87 \text{ Gauss/ms} \tag{17}$$

which gives a magnetic field cycle close to the one set up by Zeno [1]. For the gap volt program we set

$$V_c = 0.5 \text{ kV}, \quad \ddot{V}_c = 0.4 \text{ kV/ms/ms}, \quad V_M = 30 \text{ kV} \tag{18}$$

and $T_M - T_c = 23$ ms. The resulting $\dot{B}(t)$ and $V_g(t)$ functions for acceleration to full energy (101 MeV/n) are shown in blue and red in **Figure 1**. The synchronous phase and bucket area are shown in black and green. The yellow curve is the fractional momentum half-height, $\Delta p/p_s$, of the bucket. Here, as shown in Ref. [2], the energy half-height of the bucket is

$$\Delta E = \left\{ \frac{2eQV_g\beta_s^2 E_s}{\pi h|\eta_s|} \right\}^{1/2} \left| \left(\frac{\pi}{2} - \phi_s\right) \sin\phi_s - \cos\phi_s \right|^{1/2} \tag{19}$$

which gives

$$\frac{\Delta p}{p_s} = \frac{\Delta E}{\beta_s^2 E_s} = \frac{1}{\beta_s} \left\{ \frac{2eQV_g}{\pi h|\eta_s|E_s} \right\}^{1/2} \left| \left(\frac{\pi}{2} - \phi_s\right) \sin\phi_s - \cos\phi_s \right|^{1/2}. \tag{20}$$

Figures 2 and 3 are details of Figure 1 showing the functions out to 11 and 35 ms respectively. (Note that, as indicated by the legends, what is actually plotted in the figures is Bdot/2, 10 times the bucket area, and 10000 times $\Delta p/p_s$.)

In Figures 1 and 3 we see that the bucket area increases linearly during the 6 ms capture, oscillates slightly over the next 23 ms, and then reaches a minimum of 2.1 eV-s as Bdot reaches its maximum of 87 Gauss/ms. The maximum $\Delta p/p_s = 0.0042$ occurs at approximately 14 ms. If the gap voltage parameter $\ddot{V}_c$ is increased from its setting of 0.4, then the maximum $\Delta p/p_s$ increases; if it is decreased, the bucket area takes too much of a dip just after capture. The setting of 0.4 is therefore a compromise between these two effects. Note that the maximum dispersion in Booster is $D_x = 2.9$ meters, which, with $\Delta p/p_s = 0.0042$, gives a closed orbit displacement of $\Delta x = (\Delta p/p_s)D_x = 12$ mm. Keeping $\Delta p/p_s$ under control after capture is therefore very important.

4.2 Evolution of Particle Distribution

Figure 4 shows the particle distribution in a single RF bucket at the end of the 6 ms capture period. Here the energy and time deviations are plotted for each particle and the rectangle outlines the region of the initial distribution. The final distribution shows a fair amount of filamentation of the initial emittance and we see that the tails of the distribution come close to the bucket separatrix. If the capture voltage V_c is decreased from its setting of 0.5 kV, then some of the particles in the tails will be lost as the bucket area decreases just after capture. If V_c is increased, there is

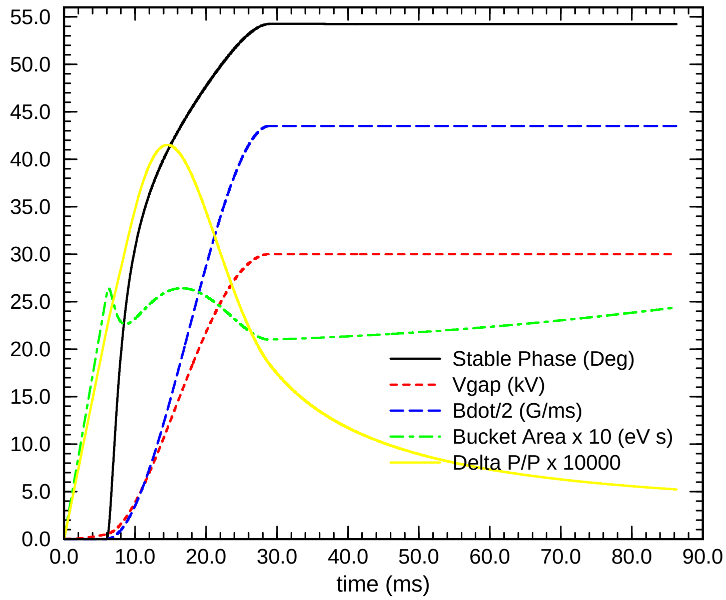

Figure 1: Long Capture and Acceleration Functions

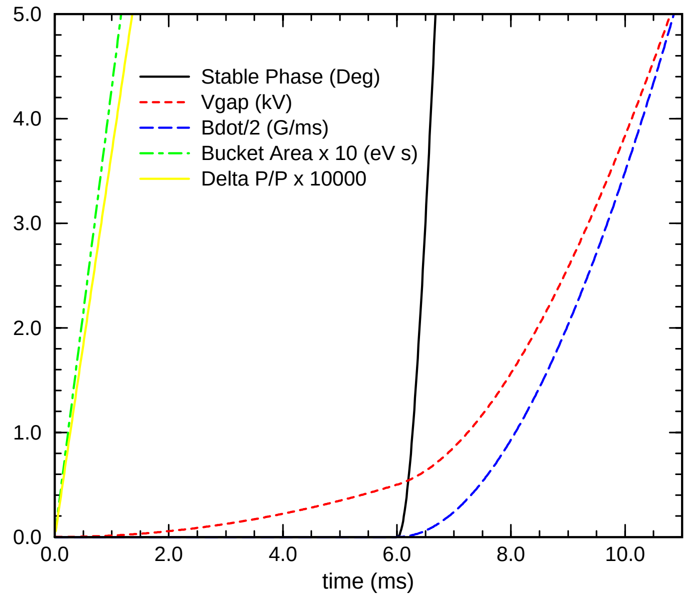

Figure 2: Detail of Figure 1

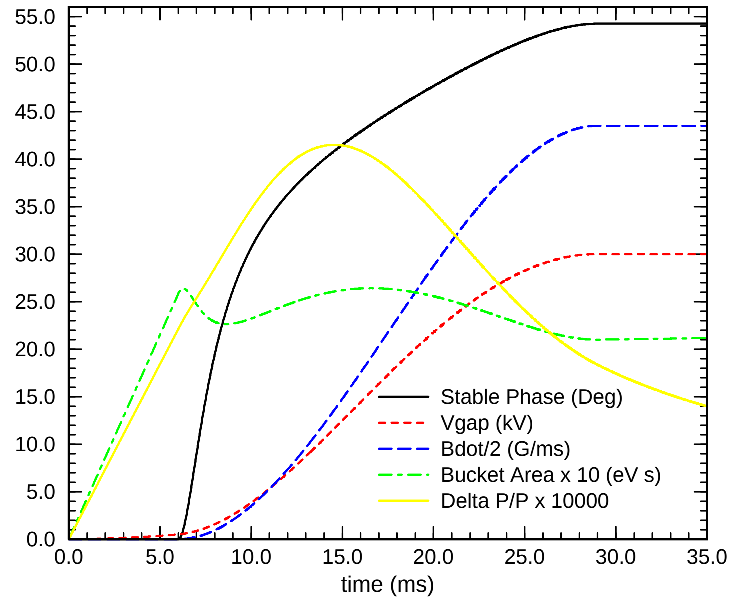

Figure 3: Detail of Figure 1

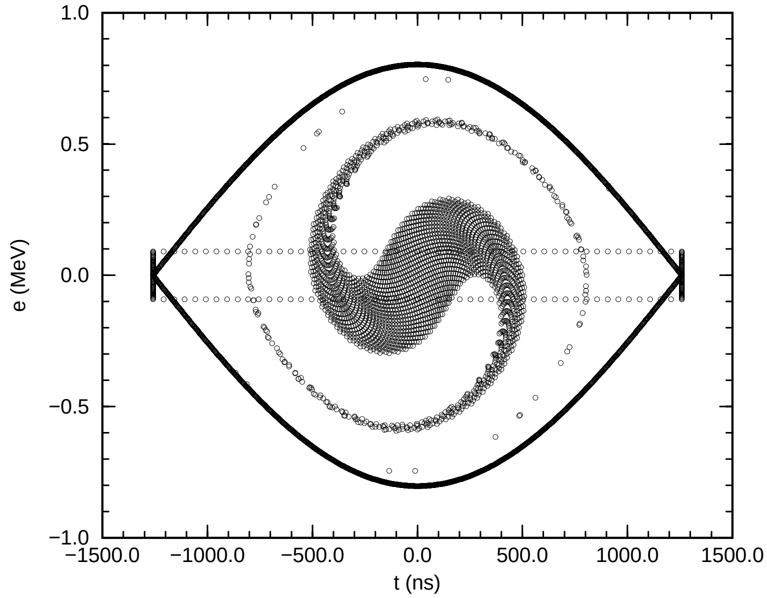

Figure 4: Particle Distribution at End of Capture

greater filamentation of the emittance and this results in more loss as the bucket area reaches its minimum at maximum Bdot. In this way $V_c = 0.5$ was found to be the optimum setting for the 6 ms capture setup.

Figure 5 shows the momentum distribution of the particles at the end of capture. Here the time and fractional momentum deviations $\Delta p/p_s$ are plotted for each particle. The maximum $\Delta p/p_s$ is 0.0021 which gives a closed orbit displacement of $\Delta x = (\Delta p/p_s)D_x = 6$ mm at points of maximum dispersion ($D_x = 2.9$ meters) in Booster.

Figure 6 shows the momentum distribution at the point where the fractional momentum height of the bucket reaches its maximum (see Figure 3). The maximum $\Delta p/p_s$ of the distribution is 0.0035 which gives a closed orbit displacement of 10 mm at points of maximum dispersion in Booster. This may account for the some of the early acceleration loss seen by Zeno [1].

Figure 7 shows the particle distribution in the RF bucket at 35 ms, near the point of minimum bucket area. Here the bucket area is 2.1 eV-s and the kinetic energy is 11 MeV/n. (Note that actual measurements late in the acceleration cycle give a longitudinal emittance of 1.3 eV-s.)

Figure 8 shows the points (particles) of the initial distribution that survive acceleration to full energy. The "missing" points indicate which particles are lost. Here 17 of the initial 2500 particles are lost with 3 lost just after capture and the rest lost as the bucket reaches its minimum at maximum Bdot.

These figures show that with a magnetic cycle close to the one set up by Zeno [1], the gap voltage can be programmed so that there is very little capture and acceleration loss. In practice, there is always some early acceleration loss. This may be due to the momentum spread of the beam in the RF bucket.

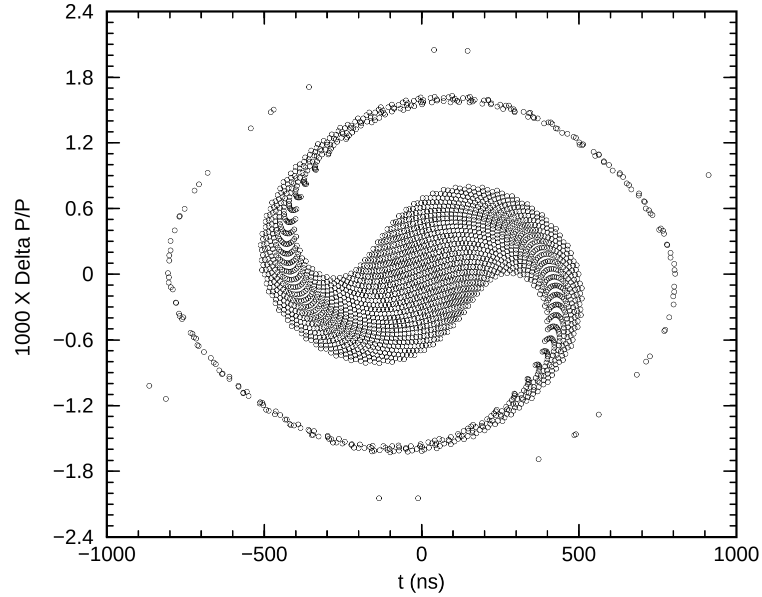

Figure 5: Momentun Distribution at End of Capture

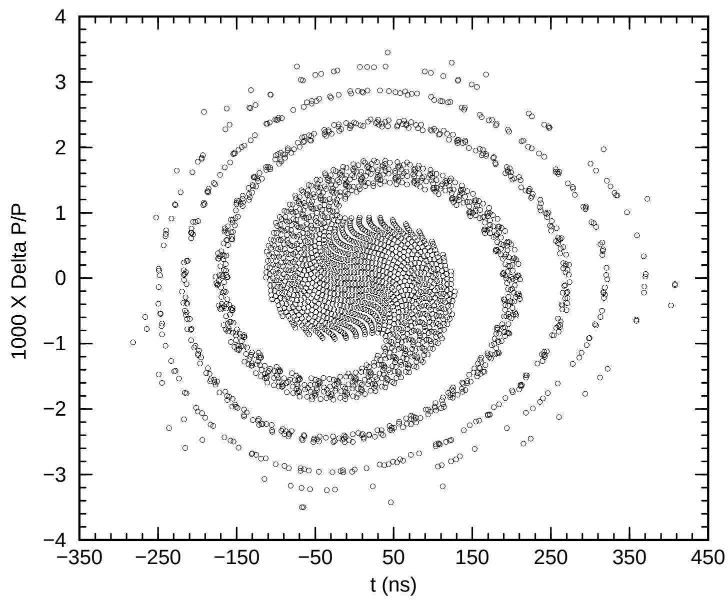

Figure 6: Momentum Distribution at Maximum Bucket $\Delta p/p$

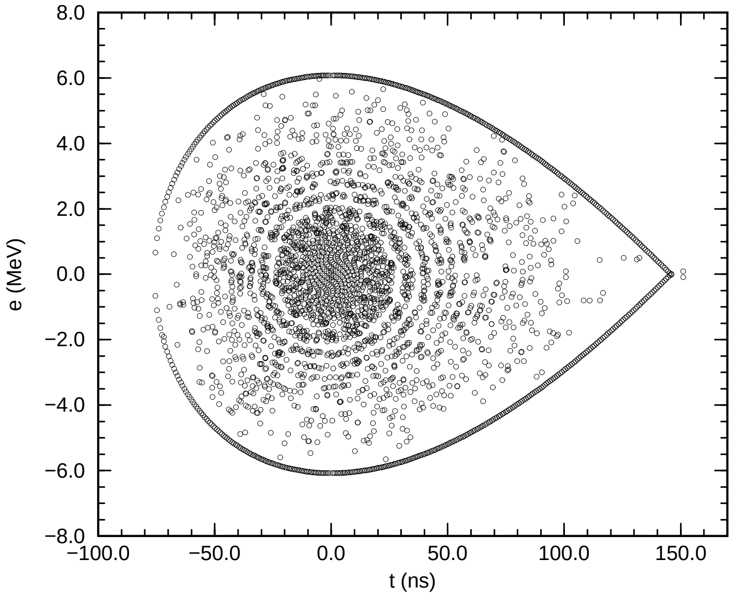

Figure 7: Distribution at 35 ms (11 MeV/n)

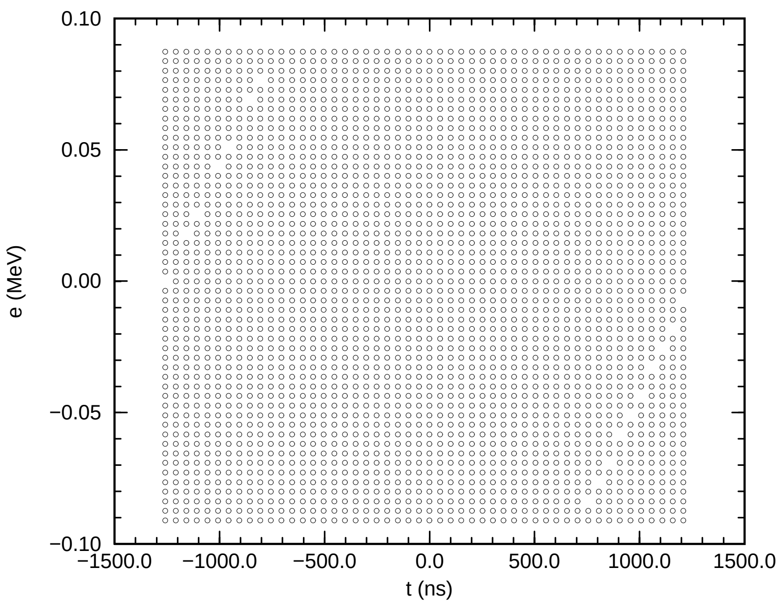

Figure 8: Surviving Particles of the Initial Distribution

5 Simulation with Faster Capture and Acceleration

5.1 Magnetic Field, Gap Voltage, and Bucket Parameters

Here we set

$$T_c = 1 \text{ ms}, \quad T_m - T_c = 15 \text{ ms}, \quad \dot{B}_m = 87 \text{ Gauss/ms} \tag{21}$$

which gives a magnetic field cycle with faster capture and acceleration. Capture and acceleration to maximum Bdot require $1 + 15 = 16$ ms in this case compared to $6 + 23 = 29$ ms for the longer capture cycle. For the gap volt program we set

$$V_c = 0.4 \text{ kV}, \quad \ddot{V}_c = 0.55 \text{ kV/ms/ms}, \quad V_M = 30 \text{ kV} \tag{22}$$

and $T_M - T_c = 15$ ms. The resulting $\dot{B}(t)$ and $V_g(t)$ functions are shown in blue and red in **Figure 9**. Here the plot goes out to approximately 26 ms where the kinetic energy gained by the gold ions is the same as it is at 35 ms for the longer capture cycle (see Figure 3). As before, the synchronous phase and bucket area are shown in black and green, and the yellow curve is the fractional momentum half-height, $\Delta p/p_s$, of the bucket. The bucket area reaches a maximum of 2.9 eV-s at 2 ms and decreases to a minimum of 2.1 eV-s at 16 ms. $\Delta p/p_s$ reaches a maximum of 0.0041 at 6 ms. The maximum and minimum bucket area and the maximum $\Delta p/p_s$ are comparable to those for the longer capture cycle.

5.2 Evolution of Particle Distribution

Figure 10 shows the points (particles) of the initial distribution. The particles that survive acceleration to full energy are indicated by open circles; those that are lost are indicated by the red filled circles. Here 516 of the initial 2500 particles are lost as the bucket area decreases from 2.9 to 2.1 eV-s. The pattern of lost particles clearly shows that if the initial distribution is chopped so that only particles between $t = \pm 800$ ns are injected, then no particles will be lost during capture and acceleration.

Figure 11 shows the chopped distribution at the end of the 1 ms capture period.

Figure 12 shows the momentum distribution at 6 ms, where the fractional momentum height of the bucket reaches its maximum. The maximum

$\Delta p/p_s$ of the distribution is 0.0035, the same as in Figure 6. This gives a closed orbit displacement of 10 mm at points of maximum dispersion in Booster.

Figure 13 shows the particle distribution in the RF bucket at 26 ms (where the kinetic energy gained by the gold ions is the same as it is at 35 ms for the longer capture cycle). Comparing with Figure 7 we see a distribution with similar filamentation but with a smaller central core.

These figures show that by chopping the beam before injection, one can capture and accelerate the beam over a shorter period of time with no beam loss. The price paid for this, of course, is that less beam is injected than with the long capture setup. Whether or not the benefits of spending less time at low energy outweigh the cost of chopping the beam, is something that needs to be determined experimentally.

References

[1] K.L. Zeno, "Overview of the Year 2000 Au^{32+} Booster Run", C-A Department Accelerator Physics Note C-A/AP/26, October, 2000.

[2] C.J. Gardner, "RF Capture and Acceleration of Gold Ions in Booster", C-A Department Accelerator Physics Note C-A/AP/7, November, 1999.

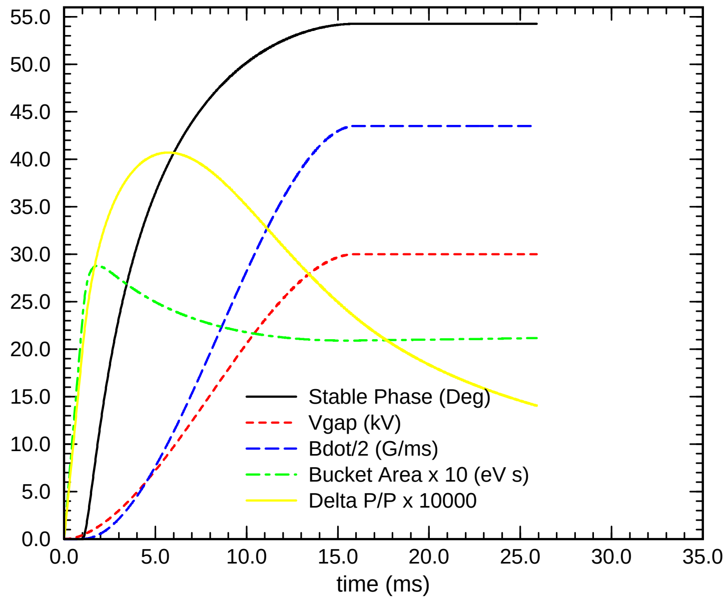

Figure 9: Fast Capture and Acceleration Functions

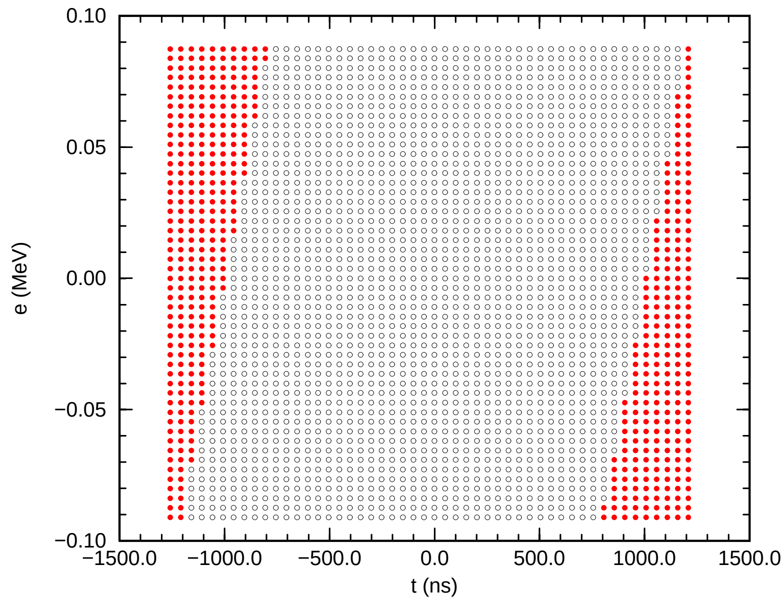

Figure 10: Initial Unchopped Distribution

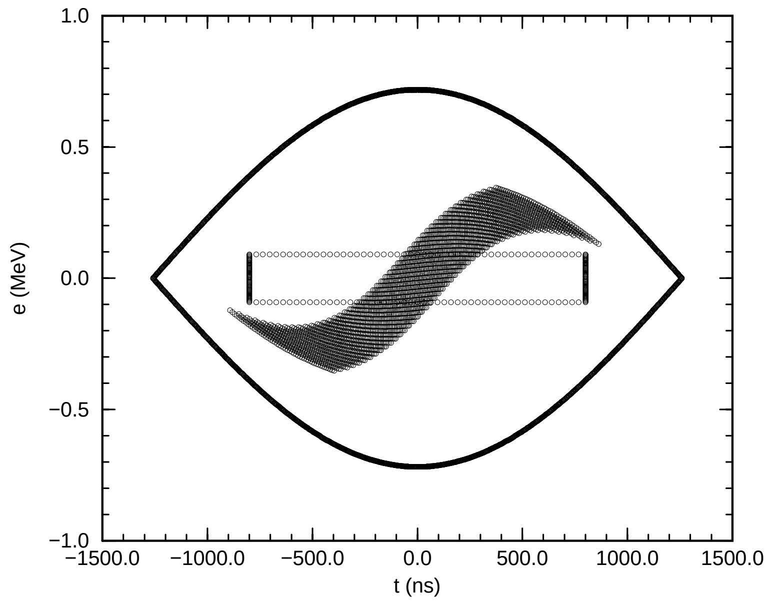

Figure 11: Capture of Chopped Beam

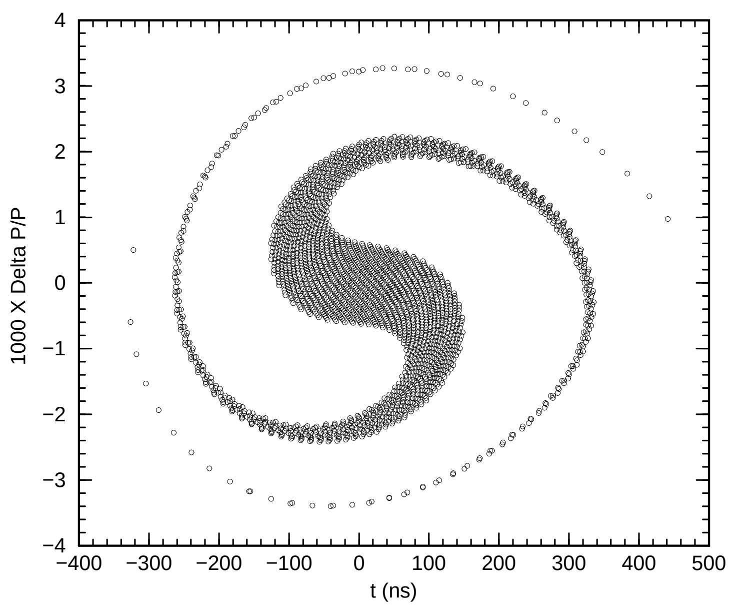

Figure 12: Momentum Distribution at Maximum Bucket $\Delta p/p$

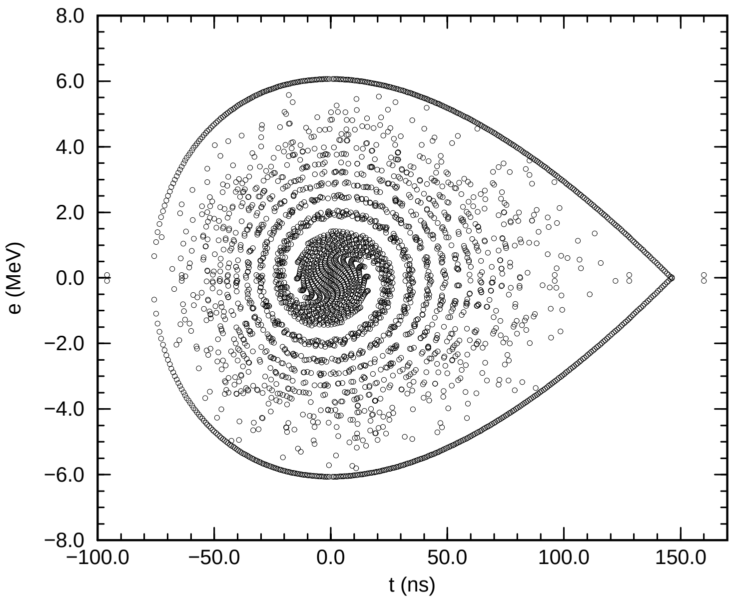

Figure 13: Distribution at 26 ms (11 MeV/n)