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# Overview of the YEAR 2000 Au$^{+32}$ Booster Run

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# Introduction

This note summarizes work done in Booster during the FY' 2000 $Au^{+32}$ run. The following conclusions are drawn from the work:

## SLOWING Down Early Main Magnet Ramp Reduces Intensity Dependent Loss Rates.

The Booster intensity has been limited by losses that occur early in the cycle. As the injected intensity is increased these losses increase disproportionately, resulting in less and less output for a given amount injected. This 'intensity dependence' is thought to stem from beam loss at injection that deteriorates the vacuum through out-gassing. The extra particles in the vacuum chamber produced by beam loss cause further beam loss mainly through beam-gas interaction [1]. It has been shown that beam loss has an effect on subsequent loss rates [2]. The losses grow disproportionately as intensity is increased because of their cascading effect: Loss causes vacuum deterioration that, in turn, causes more loss…

The specific beam-gas interaction is probably electron capture since the cross-section for electron capture decreases rapidly as the beam's velocity increases [1]. The current transformer signal is consistent with this: Most loss is seen early in the cycle when the velocity of the Au ions is relatively low, and once the beam has accelerated to about twice its initial velocity losses become negligible.

The approach used to reduce the intensity dependence of these losses has been to increase the main magnet field relatively rapidly after injection. This reduces the time spent at low energy where the vacuum cross-sections are large. That is, less time at low energy should result in less loss. Work this year shows the opposite is true. It shows that other loss mechanisms, such as poor capture and momentum aperture, play a pivotal role in creating intensity dependent losses. Reducing the losses associated with these 'standard' loss mechanisms, even if it requires a *lower* dB/dt early in the cycle, can reduce the early loss rate even at the highest intensity. The overall efficiency at high intensity in the case where the dB/dt is lower early in the cycle was at least comparable to what it has been in previous years with a higher dB/dt. Since the time spent at low energy is greater with a lower dB/dt, and the efficiency is at least comparable, the loss *rate* is lower.

These observations and others suggest that a chopper may aid in reaching a higher maximum intensity by allowing less time to be spent at low energy.

## High Incoming Trajectory is not a Consequence of Coupled Injection

It was found that the fact that the position of the incoming beam needs to be about 1 cm. high on the last TTB multiwire for best injection efficiency is unrelated to the coupled injection scheme. The position still needs to be high when injection is uncoupled. The uncoupled setup was investigated further, using turn by turn measurements of a hole chopped in the Tandem pulse[3]. It was found that the injection bump must collapse faster as the vertical position is lowered in order for stacking to occur. Contrary to theory, it appears that the horizontal oscillations about the closed orbit are affected by the vertical trajectory when injection is uncoupled.

### Beam Size at Extraction is Consistent with a Vertical Aperture Restriction at Injection

If the beam enters the Booster 1 cm high, in order to inject optimally onto the closed orbit, the closed orbit should be 1 cm high. This would restrict the available vertical acceptance to 50 π mm mrad instead of the design acceptance of 90 π mm mrad. The vertical emittance, as measured on the first multiwire in BTA at extraction, is consistent with a 50 π mm mrad acceptance at injection. Since vertical acceptance limits the duration the Tandem pulse with coupled injection, correcting whatever problem requires the beam to be steered high vertically could allow for a significantly longer pulse to be injected. The problem seems to lie in the vicinity of the inflector. In 1995, it was necessary to raise the vertical position at the last multiwire to obtain reasonable injection efficiency. Previous to that, reasonable efficiency was obtainable with the beam centered vertically. At that time it was also possible to stack a Tandem pulse up to 1000 μs wide efficiently in the Booster. A couple of years ago it was found that part of the TTB vacuum system, a 'getter strip' in section 29, was left energized. It was thought that this explained why the beam had to be high. However, even when this was turned off, the optimal position remained the same. It still seems that something physically changed between Nov. 1994 and Sept. 1995 in TTB, or the Booster, and that the new condition requires the beam to be injected high vertically.

## Overview of the Run

### 1. The Charge State

- During this run, the harmonic number in the Booster was six, and there were usually four Booster cycles per AGS cycle. This year the Gold species from Tandem was changed from $Au^{+31}$, what it had been for the last few years, to $Au^{+32}$. With extraction from the Booster set to occur at the same rigidity, this allowed for a higher revolution frequency at extraction than with $Au^{+31}$. Consequently, all 6 Booster bunches were able to fit onto the A5 kicker pulse flattop and survive in AGS. This was not possible at this rigidity with $Au^{+31}$.

### 2. Real Time Injection Timing

- As last year, injection from Tandem was initiated by a real time (Pseudopeaker) rather than a Gauss time (Peaker) trigger. The use of a real time trigger allowed the tunes, which are derived from real time functions, to shift rapidly in and around injection without noticeable jitter with respect to injection.
- The magnetic field as a function of time was reproducible enough so that injection and acceleration efficiencies were not systematically different over the four Booster cycles. The hall probe measurement at BT0, a standard measure of magnet cycle reproducibility, typically showed less than a Gauss variation over the four cycles.
- Using real time at injection also allowed the main magnet field to be modified so that injection occurs

while the field is constant. When using Gauss timing the magnetic field needs to be changing near injection time so that an injection trigger is generated (Peaker). In previous years, and during much of this run, the field rose at 1 g/ms around injection. Real time triggers were also used for the beam control and radial loop start times. The only remaining gauss time (Peaker) dependence is the start time for the radial steering function.

## 3. Modifications to the Booster Magnet Cycle

- The Booster magnet cycle was modified so that it would cause less 'flicker' in the line voltage. The main change to the magnet function in this regard was to make the roll over at the peak field faster. With the faster rollover, some time in the cycle was freed up so that other parts of the function could also be modified. Consequently, the function was also modified so that capture and early acceleration would occur more slowly. Much of the tuning during the run involved optimizing the capture and early acceleration on three 'low flicker-type' magnet functions. The variations between the functions were mainly in the amount of time that was given to capture and early acceleration and the value of dB/dt during capture.

## 4. Double Pulsing

- A study, described in [2], was performed to look at the effect that dumping beam has on the loss rate of beam that is subsequently injected in the Booster. This was accomplished by injecting twice onto a flat magnet porch. The beam from the first injection was dumped at varying times before the injection of the second pulse, and the loss rate of the beam from the second pulse was measured. It showed that the first beam had an effect on the loss rate, and that the closer it was dumped to the second injection the larger the effect. The time structure was consistent with previous studies, i.e.- the supposed vacuum deterioration created by the dumped beam decays in 100 to 150 ms.

## 5. Understanding why the Incoming Vertical Trajectory in High

- Contrary to the nominal setup, there was a period of about a week where, $Q_h$ was set to be greater than $Q_v$ at injection. This was motivated from modeling by C. Gardner that suggested that the improved efficiency with high vertical position (~10mm) at the last multiwire in TTB could be related to $Q_v$ being greater than $Q_h$ [4]. The modeling also showed that reversing the tunes would remove the need to make the beam high vertically, and thereby increase the available vertical acceptance in the Booster. Unfortunately, this setup did not appear to remove that dependence, and the injection efficiency was not as high as with $Q_v>Q_h$.
- The inability to remove the need to steer the beam high vertically at 29MW141 by making $Q_h>Q_v$ motivated us to look at coupled as well as uncoupled injection by chopping a hole out of the Tandem pulse so that turn by turn data could be obtained. The last time injection had been set up in an uncoupled mode (i.e.-without the skew quads) was about 7 years ago, and the uncoupled setup that we worked with was far from optimized. However, the data obtained indicates quite clearly that the beam still needs to be steered high vertically in the uncoupled injection case. In this much simpler case, it appeared that the dependence on a high vertical position was just as strong, perhaps even stronger than with coupled injection. In the uncoupled case, centering the beam vertically at

29MW141 caused the beam to be lost on the fifth turn around the accelerator. Increasing the rate at which the injection bump collapses restored the stacking. Subsequent turn by turn data showed that the amplitude of the horizontal oscillations of the hole in the Tandem pulse was increased when the beam was centered vertically.

## 6. Tandem Pulse Width was reduced on 'Low Flicker-Type' Functions

- On the 'low flicker-type' magnet cycles, and at least in the case of moderate intensities (~1e9 ions late) it was observed that reducing the tandem pulse width from 600 to 530 µs, for a fixed tandem current, did not reduce the Booster late intensity. This was true even though the entire 600 µs pulse stacked. Attempts were made to increase the pulse width past 530 µs while modifying various parameters, but no net benefit was apparent, so the pulse width was left at 530 µs. This suggests that the optimum pulse width depends on the time spent at low energy. Since chopped beam would require less time at low energy, the optimum pulse width might be longer with chopped beam.

## 7. High Intensity Running

- For various reasons, not the least of which was concern about the rate of foil consumption, the Tandem did not run at the highest possible current and intensity for much more than a shift at a time. There were only about 5 high intensity sessions during the course of the run. So, there was not much time spent tuning the machine at the highest intensities. For each significant variation of the magnet function, there was one of these "high intensity" tuning sessions. Not until near the end of the run did RHIC request intensities any higher than about 2e9 in AGS (1e9/cycle in Booster). Although many parameters changed during the course of the run, it seems that the second of the three variations of the low-flicker type magnet function had the best overall efficiency and highest peak intensity (for four cycles, 7.8e9 ions late in Booster). The differences between these magnet functions will be described in more detail below.

- The highest intensity reached early in the AGS cycle (AGSCBM) was 4.1e9 ions. This occurred when there was a total, summed over the four transfers, of 7.76e9 ions late in the Booster. The AGS A20 current transformer, which was used to measure intensities in the AGS, saturated during acceleration at about 2.5e9 ions. As a result, the peak intensity attained in AGS is not known. However, if the AGS late intensity scales with input intensity, the peak AGS late intensity would be about 50% of the peak late Booster intensity or 0.5*7.76e9 = 3.9e9 ions. 50% was a typical efficiency for intensities below where the A20 transformer begins to saturate. At these lower intensities, this ratio stayed nearly constant, or even increased slightly (possibly due to a negative offset in the AGS intensity scalers) as intensity increased. There are twelve buckets at extraction in AGS. Ideally, only four of these buckets contain beam. Assuming that the entire beam was in four of the twelve buckets, it follows that each bunch had (3.9e9 ions/4 bunches)=0.97e9 ions/bunch. This is very close to the RHIC design intensity of 1e9 ions/bunch.

- The setup for optimum efficiency at high intensity was markedly different than the optimal setup at moderate intensities. At high intensity the optimal injection bump falls faster than at lower intensity, especially towards the end of the Tandem pulse. The tunes at injection are somewhat higher (0.01-

0.02 in both planes), and the vertical tune during early acceleration is higher. Steering in TTB also had to be changed. Opening an aperture at Tandem increases the input intensity. The Tandem beam's emittance increases as this aperture is opened. Switching back to moderate intensity after the high intensity setup had been optimized resulted in relatively poor efficiency. The overall efficiency at the highest intensity was about 50% (B. late/B. input), at moderate intensity the overall efficiency was about 67%. At moderate intensity, but with a high intensity setup, the overall efficiency was about 50%. Note that this is similar to the high intensity efficiency, and highlights the fact that the late intensity did not show obvious signs of 'saturating' (i.e.- a diminishing increase in Booster late as Booster input is increased). Consequently, it is likely that higher Tandem current than we received this year would result in higher Booster late intensity than we had this year. Table I lists chronologically some of the highlights of the run.

## The Magnet Cycle

The Booster started up in Mid-March with a setup similar to that used in last summer's Gold run. There was one difference: the charge state was +32 instead of +31. Though the energy was the same, the different charge state required the injection rigidity to be lowered. The switch to $Au^{+32}$ from $Au^{+31}$ was made so that Booster extraction could occur at a higher revolution frequency with the same extraction field. This allows A5 to kick all 6 bunches into the AGS acceptance.

Last year's $Au^{+31}$ magnet function was modified to suit the slightly different injection rigidity. The magnet function that was initially used, call it "Cycle#1", is divided into three parts of interest.

1. An 8 ms long 1g/ms porch where injection and capture take place. This porch was just lowered several gauss to accommodate Au+32
2. An 18 ms long region where dB/dt increases quadratically from 1g/ms to 87g/ms which starts at the end of the porch and ends when the dB/dt reaches its maximum value. To match the B field at the end of this region the overall change in B is 20 gauss higher than it is for the $Au^{+31}$ function. The $Au^{+31}$ function changes 520 gauss during this period.
3. A region where the dB/dt is at its maximum value (87g/ms).

During the course of the run the BMMPS function had to be modified to reduce the 'flicker'. Consequently the opportunity arose to modify this 'low flicker' cycle in other ways as well. Slightly more than half way through the run this new magnet cycle became the running cycle.

| **Date** | **Stacked** | **Stored @ 2.5ms** | **Booster Input (1 xfer)** | **Booster Late (1 xfer)** | **Booster Input (4 xfer)** | **Booster Late (4 xfer)** | **Comments** |
|---|---|---|---|---|---|---|---|
| **3/16** | | | | | | | Start of Run |
| **3/17** | 49%* | 29%* | 2.3e9 | 0.3e9 | | | 1st acceleration, 600 μs Tandem Pulse |
| **3/21** | 57%* | 39%* | 2.0e9 | | | | |
| **3/25** | 56%* | 41%* | 2.5e9 | | | | |
| **3/27** | | | 1.2e9 | 0.44e9 | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **3/30** | | | 4.4e9 | 1.4e9 | | | Harmonics, particularly vertical, reduced large early acceleration loss. Peak late=1.48e9 ions |
| **4/5** | | | | 1.58e9 (peak) | 14.3e9 (peak) | 5.2e9 (peak) | High intensity work, AGS CBM=2.78e9; avg. per cycle late=1.3e9. |
| **4/26-4/29** | | | 3.8e9 (peak) | 1.25e9 (peak) | | | $Q_x>Q_y$ @ injection. Overall efficiency was not as high, return to $Q_y>Q_x$ |
| **4/29** | | | | | | | Turn by turn work looking at Vertical steering coming into Booster with coupled and Uncoupled injection. |
| **6/5** | 67% | 57% | 1.02e9 | | | | |
| **6/20** | | | | | 4.62e9 | 1.96e9 | Low-moderate intensity efficiency |
| | | | | | 9.54e9 | 3.88e9 | Moderate-high intensity efficiency |
| **6/23** | | | | | | | Switch to initial low flicker cycle, overall Efficiency is comparable to original cycle. |
| **6/26** | | | | | | | BTA MW006 vertical profile is still gaussian. |
| **6/27** | 74%* | 63%* | 1.3e9 | | 5.2e9 | 2.8e9 | BTA MW006 vert. Profile is no longer gaussian. Profile shape changed around the time that steering work in TTB was done. Beam was centered at the "window frame" (28FC132), and efficiency improved. |
| **6/28** | | | | | | | BTA MW006 profile is sensitve to tunes at injection. When Qy=4.8, Qx=4.743 profile is Gaussian. When Qy is very close to Qx (normal situation) profile is not gaussian. |
| **6/29** | 78% | 65% | 1.7e9 | 0.9e9 | 7.3e9 | 3.8e9 | B input=1.08e9 for injection measurement. |
| **6/30** | | | | | 16e9 (peak) | 6.9e9 (peak) | High intensity, peak AGSCBM=3.75e9 |
| **7/25** | | | | | | | Tandem pulse width reduced from 600 µs to 500 µs since late intensity is unaffected. |
| **7/28** | | | | | 5.4e9 | 3.3e9 | |
| **7/28** | 86% | 74% | 1.35e9 | | 5.4e9 | 3.6e9 | Pulse width=530 µs, second low flicker type BMMPS cycle loaded. 1g/ms ramp of capture Porch removed and dB/dt increases at a higher rate after porch. The dB/dt when bucket area minimum occurs is reduced. |
| **8/4** | | | | | 16e9 (peak) | 7.76e9 (peak) | High intensity work, peak AGSCBM=4.1e9, Peak 10 pulse average AGSCBM=3.96e9 ions |
| **8/21** | | | | | | | Modify BMMPS function again. Injection Is now 2 ms earlier and the capture Porch is 2 ms longer. |
| **8/24** | | | | | 16e9 (peak) | 7.2e9 (peak) | High intensity work, typical #s at lower intensity: |
| **8/27** | | | | | 7.6e9** | 4.6e9 | |

**Table I**

**Table I**: Summary of Booster 'highlights' during FY'2000 $Au^{+32}$ run. The first 2 columns, 'Stacked' and'Stored' refer to the standard injection measurement. "Stacked" is the ratio of the peak Booster beam current (the current at the top of the 'stack') to the injected beam. "Stored" is the ratio of the beam 2.5 ms after the stack to the injected beam. The next column, Booster Input, is the intensity measured with the TTB section 29 transformer. Booster Late is the intensity measured just before extraction with the Booster circulating transformer. The next two columns are the same as the previous two except that they refer to intensities summed over the four Booster cycles.

*- These efficiencies were initially found using the TTB sec. 29 transformer signal using a 10 μA/V calibration. The B. input scaler calibration is more accurate, and shows that the sec 29 intensity is about 15% higher than the signal indicates. These numbers have been lowered by that amount to reflect this.
**-With this magnet cycle Booster Input had an offset so that the scaler would read 5.5e8 without beam. 5.5e8 has was subtracted from B. input here.

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The cycle, call it "cycle #2" was different from the initial $Au^{+32}$ function in the following ways:

1. The capture porch is extended by 3 ms yet the field changes by the same amount (about 3 g) it did with the previous function.
2. The dB/dt ramp is 20 ms long instead of 18 yet rises about 30 g higher. Overall, the dB/dt ramp is slower. At BT0+38ms, the end of the dB/dt ramp, the field is 32 g higher than it was at 33ms (the initial end of B dot ramp). Basically, about 4.5 ms have been added onto the capture/early acceleration part of the magnet cycle.
3. The injection field is lower in the low flicker cycle by several gauss, but injection time is not changed.

About a month later this magnet cycle was modified further, call the resulting cycle "cycle#3":

1. The capture porch was made flat for the first 3-5 ms after injection.
2. The field increases at a slightly faster rate after that, still much slower than the initial high flicker cycle.
3. dB/dt was lowered around the bucket minimum that occurs near where dB/dt reaches its maximum.

About a month after that, the magnet cycle was modified again, call it "cycle#4". The function was adjusted so that the capture porch was 2 ms longer, beginning 2 ms earlier than previously. Injection time was moved earlier by 2 ms.

Figure 1 compares the 4 magnet cycles over the first 50 ms from BT0. Note that the field starts to rise earlier on cycle 1 than on any of the others. The differences between cycles 2-4 during the capture porch are too small to make out on this graph. What can be seen is that they all come up slower than cycle 1, cycle 2 comes up slower than cycles 3 and 4, and cycles 3 and 4 have an extra point at about 47 ms. The actual field differs somewhat from that in the functions. In particular, on cycles 3 and 4, lowering the function dB/dt between the points at 37 ms and 47 ms has the effect of reducing an overshoot in dB/dt at about BT0+40ms (where the bucket minimum occurs).

Significant loss was not occurring at this 'bucket minimum' on cycle 2, but was occurring on the 'initial' cycle 3 that did *not* have the extra point at 47 ms to reduce the overshoot. The peak dB/dt near the bucket minimum was measured with the gauss clock to be 95g/ms for both cycles 1 and 2. It was reduced to 88 g/ms on cycles 3 and 4. The dB/dt for the remainder of acceleration is similar for all of the four magnet cycles.

The Rf voltage during the remainder of acceleration is always at the maximum value. Lowering it from its maximum value by as little as 5% causes sharp losses to occur during acceleration. These losses can occur even with the Rf voltage at its maximum value, and seem more pronounced at higher intensities. It is likely that lowering the acceleration dB/dt would reduce this kind of loss. Because of constraints with cycle length and extraction this was not done this year.

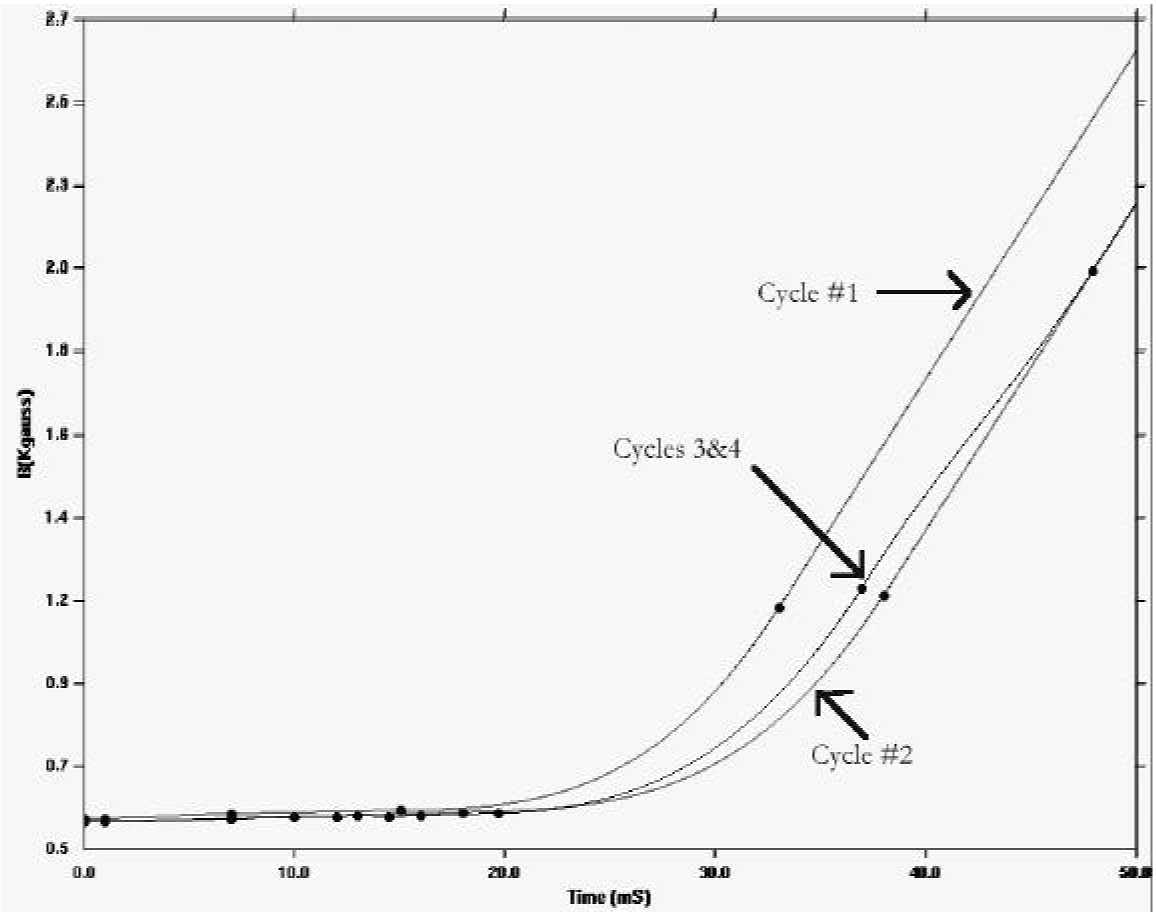

**Figure 1:** Overlay of all 4 magnet functions from BT0 to BT0+50 ms. Injection occurs at about BT0+12.5 ms except for cycle 4 where it occurs at 10.5 ms.

After several days with cycle 2 as the running cycle, the overall efficiency was better than it had been on cycle 1 (both using a pulse width of 600 µs). Cycle 1 had already been running for several months, and was quite optimized, at least at moderate intensities, so the improvement going to cycle 2 is significant. After about a month running on cycle 2 the pulse width was reduced to 500-530 µs with no reduction in late intensity for the same Tandem current. Shortly thereafter the function was modified into cycle 3. After very little tuning cycle 3's overall efficiency was better than cycle 2's had been. About a month later cycle 4 was introduced. The efficiency on cycle 4 after running with it for another week and a half, was not as good as it had been on cycle 3.

Figure 2 is an overlay of the capture porch for each of the cycles. These graphs were obtained from gauss clock measurements.

The highest late intensity and the highest efficiencies were obtained with cycle #3. It had a flat capture porch, lower dB/dt at the bucket minimum, and did not have the extended porch of cycle#4.

Previous to this run, the highest intensity was obtained during the 1998 $Au^{+31}$ run using a cycle similar to cycle#1. With a 680 µs long pulse, a peak of 20.6e8 ions/pulse was obtained. Typical numbers at high intensity from that run were Booster Input=53e8 ions, B. late=20e8 ions. Assuming that the beam injected from 530 µs to 680 µs did not contribute at all to the intensity late in the cycle, this gives an 'adjusted' input of 41e8 ions (i.e.-[530/680]*53e8=41e8).

The highest intensity this run was B input= 160e8 ions, B. late= 77.6e8 ions. This run work was done primarily with four transfers instead of one. Given the cycle to cycle intensity variations it is likely that the highest per cycle intensity was at least as high as in 1998, but this cannot be confirmed. What is clear was that the efficiency, even with the 'adjusted' B. input in 1998, and with less time spent optimizing the high intensity setup this year, was at least comparable.

## Accounting for Losses during the Cycle

It is often difficult to determine what the actual loss pattern looks like throughout the Booster cycle. Consequently, it is difficult to discern what process is responsible for what loss. The injection transformer has a relatively fast response time (good resolution on the order of 100 µs), and it gives a good picture of what is going on during the first 8 milliseconds or so. The circulating transformer has a relatively slow time response (good resolution on the order of a few milliseconds). It gives a good picture of what's occurring on the time scale of the entire cycle. The loss pattern during early acceleration is the hardest to resolve. The injection transformer signal is not reliable there because of its fast "AC-like" time response. The circulating transformer has a considerable amount of noise on it at that time which is not easy to filter, and its time response is slow compared to the time scale of the 'events'.

From either transformer it's evident that there is a slow loss that occurs at injection energy with a flat field, with or without Rf voltage. With the magnet cycle that has zero dB/dt for the first 5 ms or so, a measure of the loss rate during this slow loss can be obtained using the Circulating transformer. During standard running the machine was tuned in such a way that the loss rate was the same on this 'capture porch' whether the Rf was on or off.

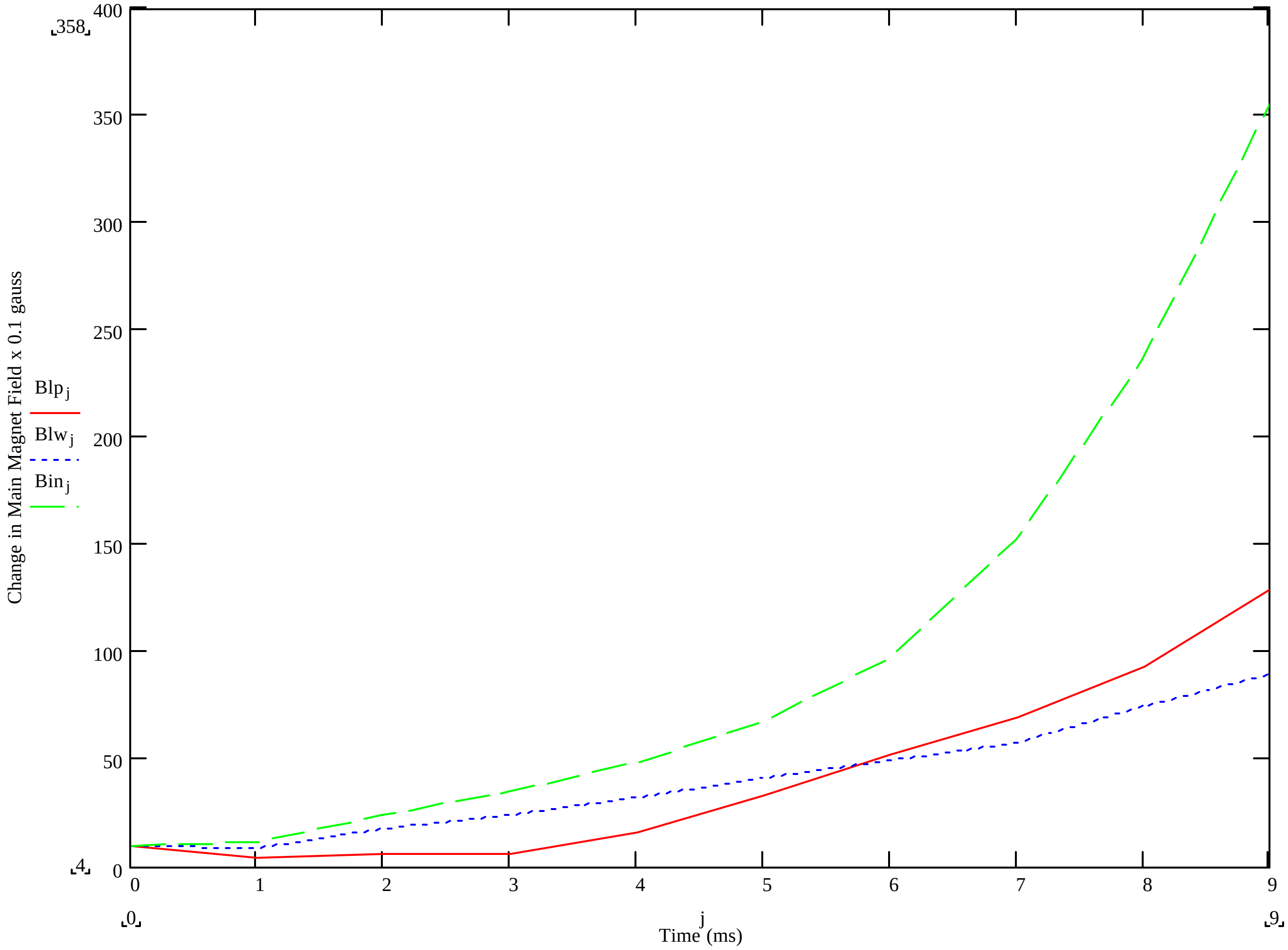

**Figure 2:** Comparison of Magnet cycles in and around the capture porch. Dashed line is cycle#1, dotted line is cycle#2, and solid line is cycle#3. Injection occurs between 0.5 and 1 ms. Cycle #4 is essentially the same as cycle#3 except that the 'capture porch' is 2 ms longer, starting 2 ms earlier. On cycle#4 injection happens between –1.5 and –1 ms.

Figure 3 shows the Circulating transformer signal with the zero dB/dt magnet cycle and moderate intensity (13.3e8 ions injected, 9e8 ions late). The trace agrees well with the injection efficiency measurements made with the injection transformer. That is, the measured peak intensity is 11.4e8 ions using the injection transformer, and 11.3e8 ions using the circulating transformer. Using the circulating transformer the loss rate over the first 10 ms appears constant (7.2e8ions/100ms or 0.072e8/ms -> (.072e8/11.3e8) x 100=0.7%/ms). This will be identified with the loss caused by vacuum deterioration from beam loss at injection. In the next 10 ms or so, while dB/dt ramps to its maximum value, about 8% of the beam is lost. The first half of this interval contributes the vast majority of the loss. Once dB/dt has reached its maximum value the loss rate is almost negligible. Losses from this point to extraction are about 3% of the beam that remains (0.3e8). So, a total of 18% of the stacked beam as it appears on this transformer, or 0.18*11.3e8=2.1e8 ions, is lost during the cycle.

Viewed on the faster time scale of the injection transformer (figure 4) the loss rate no longer appears constant, and the loss rate appears higher (>1.5%/ms) over the first 3 ms or so. So, the loss rate is most likely decreasing over the length of the capture porch and the 0.7%/ms measured using the circulating transformer is an average rate. In the case of higher intensity (about 24e8 injected) the loss rate is >2.6%/ms as viewed on the injection transformer (see figure 5).

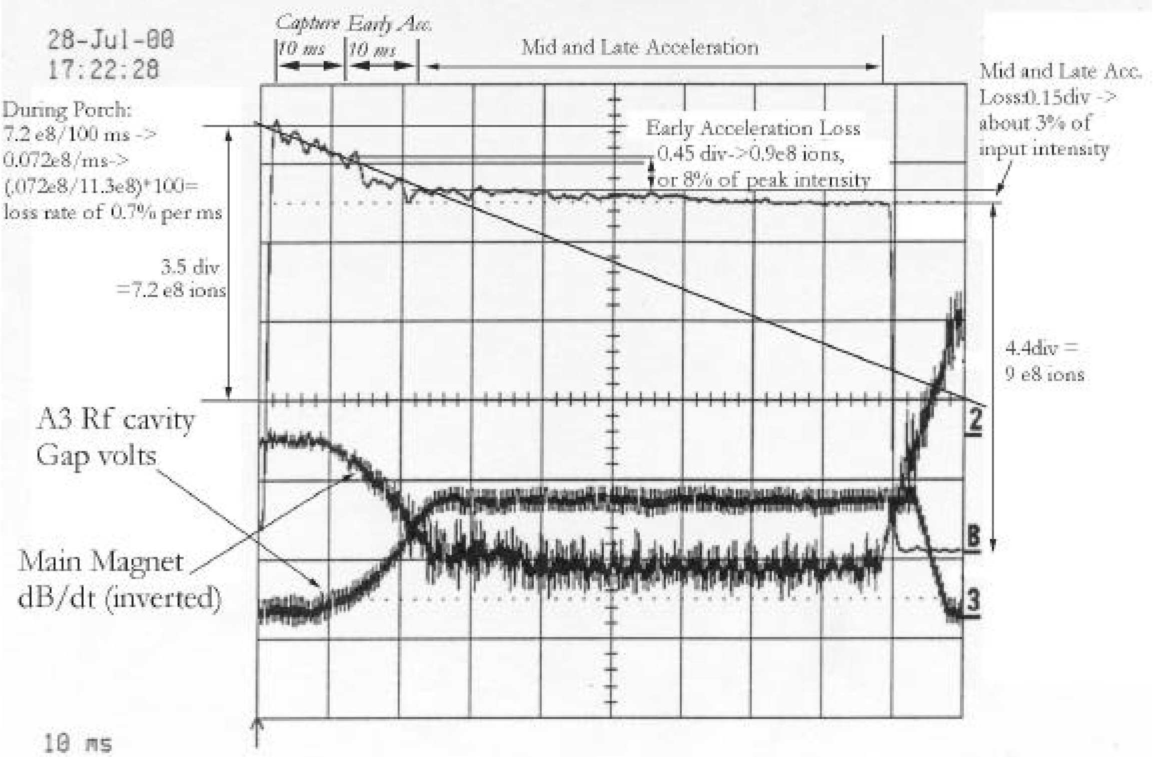

**Figure 3:** Normalized Circulating Transformer with cycle 3. An Rf voltage and Main Magnet dB/dt signal are also shown. Booster Input=13.3e8, B. late is 9e8 ions.

If the injection efficiency in the case of moderate (13.3 e8 injected) and higher (24.4 e8 injected) intensities is similar, the amount of beam lost at injection at moderate intensity is 0.14*13.3e8=1.9e8 ions, and at the higher intensity it is 0.14*24.4e8=3.4e8 ions. The ratio of the amounts of beam lost at injection (1.9e8/3.4e8) roughly scales with the ratio of the loss rates as measured on the injection transformer (1.5%/2.6%).

The beam loss at low energy appears to be one of the primary reasons the efficiency deteriorates as the intensity is increased. Why then has it been observed that increasing the time spent at low energy does not deteriorate the overall efficiency, even at the highest intensities? The best high intensity efficiency obtained this year was with a magnet cycle that spends more time at low energy than in previous years. This was at least comparable to the highest high intensity efficiency prior to this year.

It's natural to expect that reducing losses associated with any mechanism at low energy, not only injection itself will reduce the cascading beam loss. Modeling by C. Gardner has shown that more time spent capturing reduces the longitudinal emittance by reducing the amount of filamentation [3]. When there is filamentation there are particles that make large excursions in momentum relative to the 'core' of the beam. It is these particles that may be responsible for much of the capture related beam loss.

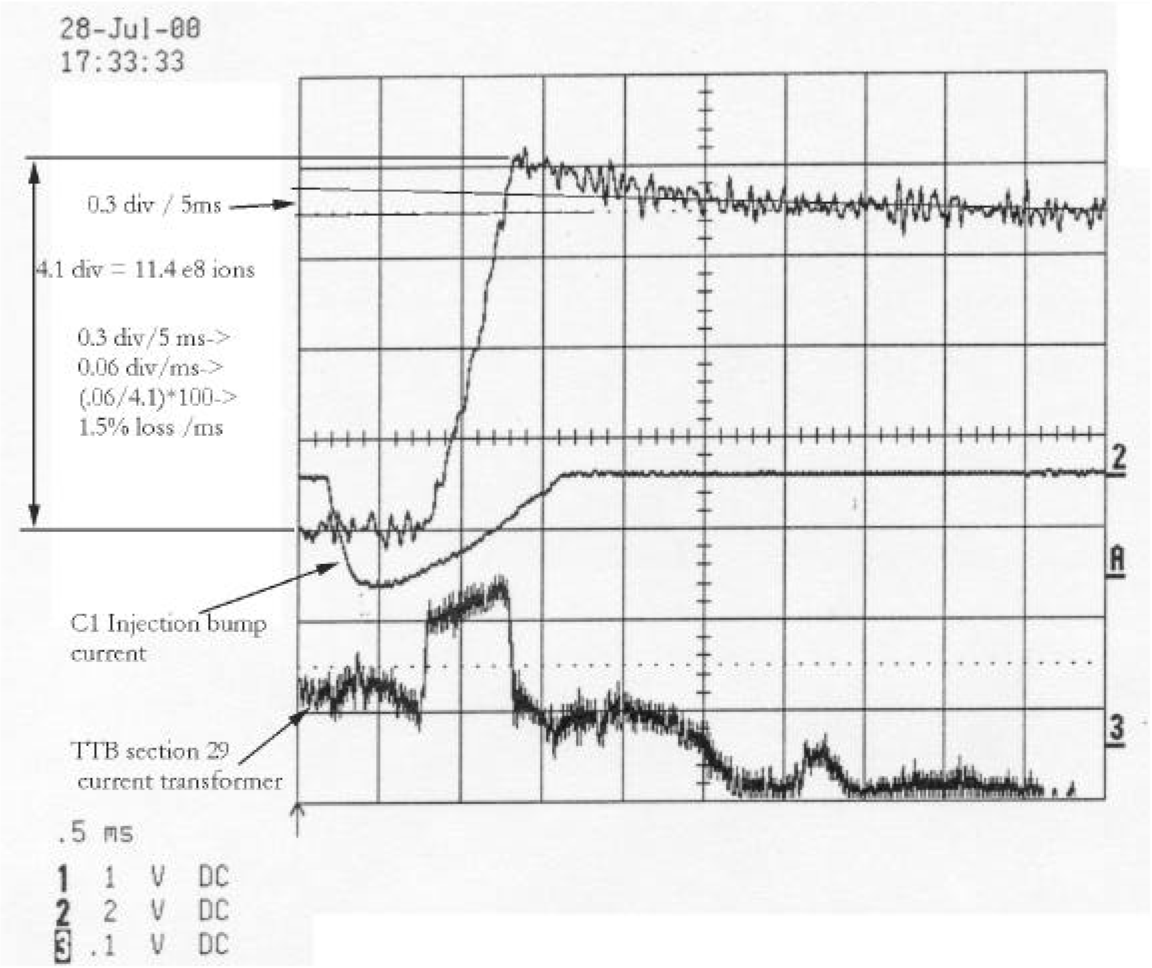

**Figure 4:** The Injection Transformer showing the first 4 ms of the cycle (with cycle 3). The injected intensity, setup, and efficiencies are similar to in figure 3. Note that the loss rate is not constant over the interval, but decreases. Measurement for a loss rate of 1.5%/ms is shown. Clearly the loss rate is higher than this < 1 ms after the end of the Tandem pulse.

It is not so clear what 'time spent capturing' means. Perhaps the best measure of it is the length of time the counterphasing function takes to shift from nearly completely counterphased to completely uncounterphased (it begins to shift at injection time). The Rf voltage is raised from <<1 kV to about 3 kV over this interval by moving the two Rf cavity waves into phase. Each of the 4 magnet cycles run this year have this shift occurring over an interval which best optimizes the overall efficiency. For magnet cycle 1 the interval is 1.5 ms, cycle 2 it is 3.8 ms, cycle 3 it is 5.6 ms, and cycle 4 it is 8 ms. So, each of these magnet cycles differs significantly in the time given to 'capture'. Note that, although the fields change by about the same amount over the first 5-6 ms after injection for cycles 2 and 3 (see figure 2), the capture time is about 2 ms longer for cycle 3. Could this have to do with the fact that the field is flatter during the first few ms of cycle 3? C. Gardner's modeling shows that these differences in capture time are significant in terms of the amount of filamentation that occurs in each case [3].

A larger longitudinal emittance will be reflected in a larger transverse beam size, and if there are aperture constraints this could result in beam loss. Additionally, all of the beam may not be captured in an optimal setup where not enough time is given for capture. Beam will then be lost as the field increases again resulting in cascading beam loss.

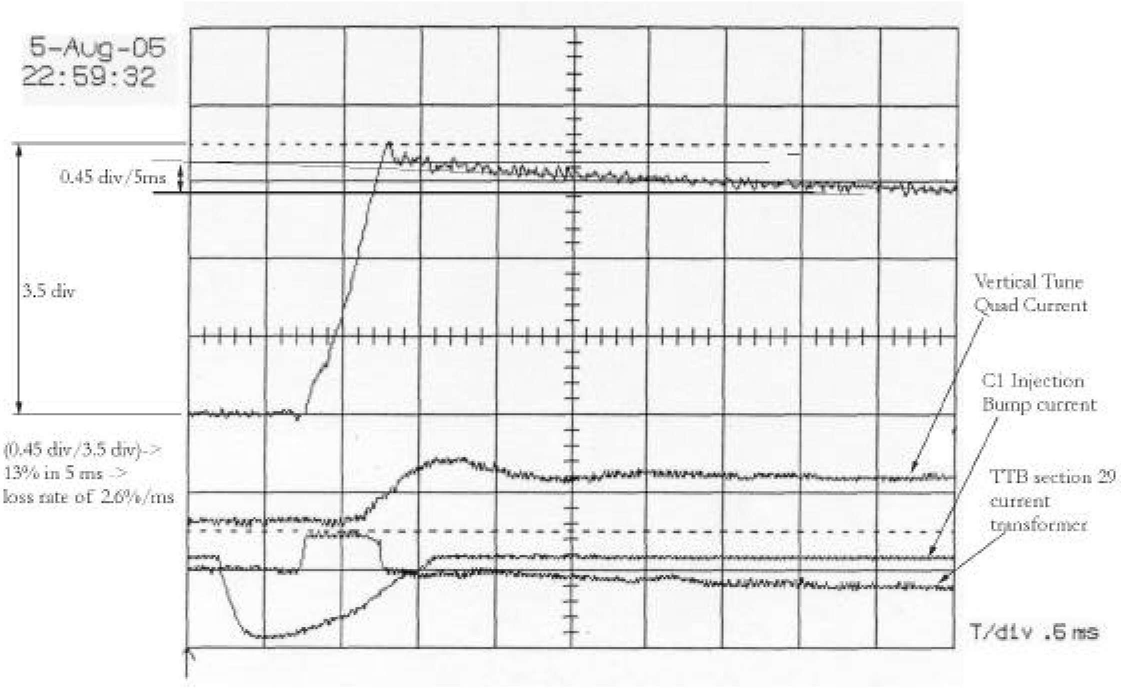

**Figure 5:** The Injection transformer showing the first 4 ms of the cycle (with cycle 3). The injected intensity is higher than in figures 2 and 3, 24.4e8 injected vs. 13.3e8 injected. The injection efficiency is assumed to be the same. Measurement for a loss rate of 2.6% per ms is shown. Note that the loss rate within 1 ms of injection is higher than this.

Although the resolution of the circulating transformer is less than ideal, figure 3 and the earlier analysis suggest significant beam loss, at a rate higher than on the capture porch, occurs during early acceleration, a time when vacuum cross sections are thought to be decreasing. It is natural to suspect that these losses are at least initiated by aperture constraints associated with the increasing momentum spread that goes along with increasing Rf voltage, as well as the loss of uncaptured beam. It was observed during the run that losses here are quite sensitive to orbit corrections in either plane and how fast the gap volts rise after the capture porch.

A simple explanation for why efficiency does not decrease when more time is spent near injection energy is that the time there can be spent to capture better, thereby reducing related losses. Also, with a slower dB/dt ramp during early acceleration, the Rf voltage can be raised more slowly there, keeping the momentum spread related increase in beam size smaller. Consequently, there is a reduced rate of ‘cascading’ beam loss. This reduction in beam loss rate offsets the increased loss associated with spending more time at low energy. Note that cycle 4 had lower overall efficiency than cycle 3 even though the capture time was longer. Perhaps this is because too much time was spent at low energy on cycle 4.

All this points to the need for a chopper for the Tandem beam. With a chopper, beam could be injected directly into buckets, and time would not be required for adiabatic capture. The resulting bunch might have lower longitudinal emittance, and therefore momentum aperture constraints would be reduced. The need for spending time near injection energy would be reduced. The downside is the amount of beam that could be injected per unit time would be less.  It remains to be seen where the optimal condition lies, but the behavior of the beam with different magnet cycles shows the importance of the longitudinal dimension in reducing the intensity dependence of losses.

One could argue that the reason why the efficiency did not decrease with the extended capture porch and slower dB/dt ramp was because the pulse width was reduced for those magnet cycles. However, from Table I it can be seen that the reduction in pulse width from 600 to 500μs occurred on 7/25, well after the switch to the initial low flicker cycle on 6/23 and significant improvements in efficiency (compare 6/20 to 6/27 and 6/29).  It could still be argued that other changes, unrelated to the increased time for capture were responsible.  For example, the injection field, which was changed in going from cycle 1 to cycle 2, could be at a more optimum value. This possibility is hard to discount completely.

One might also argue that the reduced pulse width is solely responsible for the improved high intensity efficiency with cycle 3 over that of the '98 run, and that capture was not a significant factor. That is, decreasing the pulse width using a '98 setup from 680 μs to 530 μs would yield the same efficiency as seen with cycle 3.[1]  It is true that the injection efficiency was much better in the latter part of the run when the pulse width was shorter. Presumably, this had a positive effect on intensity dependent losses. Using this reasoning, the loss rate at low energy in '98 with a reduced pulse width would be the same as it was this year.  But, this year the time spent at low energy was longer, therefore there would be more accumulated loss this year, and the overall efficiency would be lower. The 'adjusted' efficiency from '98 and this year's efficiency are about the same.[2]

It's likely that the optimum pulse width, the one that yields the highest late intensity with the highest efficiency (B. late/B. input), decreases as the time spent at low energy increases. Since, as the time spent there increases, the loss rate from injection integrates for a longer time. It has also been shown that the last part of the beam injected contributes disproportionately to the loss rate [5]. This makes the pulse width an even more sensitive parameter. Note that the Tandem pulse width was not reduced until we had gone to cycle 2.  It is possible that the wider pulse (600 μs for cycle 1, or 680 μs of '98) gave a net benefit with the faster magnet ramp, but not with the latter cycles. The case for a chopper is strengthened by this: If it is the case that longer time at low energy translates into a shorter optimum pulse width, then chopped beam would have a longer optimum pulse width because the time spent near injection energy would be less.

## The Vertical Aperture at Injection

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[1] In '98: B. input=53e8 (adjusted to 41e8 for a 530 μs pulse), B. late=20e8, 680 μs pulse: This year: B. input=40e8, B late=19.6e8, 530 μs pulse. This year's numbers are the quoted high intensity numbers for 4 transfers divided by four.

[2] There is another possibility, though a very unlikely one. If the part of the pulse that was cut out was actually responsible for reducing the late intensity in '98 this could explain the observation.  For example, for an adjusted input of 41e8 the late intensity might be 25e8 instead of 20e8.  Then the fact that more time at low energy would have resulted in a lower efficiency this year would be consistent with the '98 run.

AGS Studies report No. 377 [4] describes much of the work that was done investigating the vertical steering in TTB.

A vertical 3-bump at C3, the exit of the inflector, was varied, and vertical oscillations, using a hole chopped in the tandem pulse, were observed with an uncoupled injection setup. The initial amplitude of oscillations was +/-4 mm, with a –3 mm bump the oscillations were +/- 6 mm, and with a +6 mm bump the oscillations were +/- 2 mm, but of opposite phase. The opposite phase indicates that the oscillations had moved through zero in going from no bump to a +6 mm bump. Amplitudes more negative than –3 mm or greater than +6 mm resulted in significant beam loss. The oscillation amplitude serves only as a relative measurement, the D1 PUE that was used was not calibrated.

These observations are consistent with the beam coming in high. If the beam were centered coming in, the maximum oscillation amplitude should be similar for both the maximum positive and negative bumps. But it was found that the oscillation amplitude was larger, just before beam loss occurs, in the case of a negative bump. One expects that larger amplitude oscillations will be possible when the closed orbit is low at C3 than when it is high if the incoming beam is high. Raising the closed orbit above the high incoming beam would reduce the aperture available for oscillations whereas lowering it below it would increase it. So, there is some consistency between these observations and the position on the 29MW141 multiwire.

As noted in [4], the reason the vertical position is high appears to be associated with the horizontal trajectory’s match to the Booster’s closed orbit. A higher vertical position allows smaller horizontal oscillations about the closed orbit and better stacking. The reason for this is not understood. Previous to 1995 it appeared that the beam was generally centered vertically for the best efficiency. It also appears that the maximum Tandem pulse width that could be stacked was longer. There was no obvious change to the optimal horizontal position between ’94 and ’95. However, since then it has drifted from a few mm positive to a few mm negative.

When coupled injection is used, the maximum pulse width that can be stacked efficiently is limited by the vertical acceptance. In recent years, coupling has been shut off during the latter part of the injection process so that a wider pulse can be stacked. This is probably because the vertical acceptance has been filled. This limits the length of the pulse that can be injected, and therefore the amount of beam that can be injected. Having a larger vertical acceptance would most likely allow the Booster to run at higher intensity.

Prior to 1998, a standard coupling setup (where the tunes are set close to each other) was not used, presumably because of vertical aperture problems. The ability to shut off the coupling by shifting the vertical tune rapidly in the latter part of injection made the use of a standard coupling scheme during the early part of injection practical. Previous to that, the skew quads were powered during injection, but the tunes were relatively far apart (>0.1). The effect of the skew quads in that kind of setup is not well understood.

It remains true that the highest Booster intensities did not occur prior to 1995, but have occurred recently. It is hoped, perhaps optimistically, that these high intensities have to do with improvements to the Booster and Tandem setups, and that thay have occurred despite a real problem involving the vertical acceptance.

Figure 6A shows a MW006 profile made while the Booster was running most efficiently. The normalized vertical emittance measured from the vertical profile is 4.5 $\pi$ mm mrad (using $\beta_y$=17.86m). At injection energy this corresponds to an unnormalized emittance of 47 $\pi$ mm mrad. If the incoming beam is 1 cm high, and injected onto the vertical closed orbit, this would reduce the Booster's acceptance. In order to keep the beam small, and thereby reduce losses, it would make sense to inject onto the closed orbit. The minimum vertical aperture in the Booster is 70 mm and occurs inside the main dipoles where the Beta function attains a maximum value of about 14 m. This gives a vertical acceptance of about 90 $\pi$ mm mrad. If the closed orbit were 1 cm high in one of these dipoles, say at C2, that would reduce this acceptance to 50 $\pi$ mm mrad.

The shape of the profile at MW006 is dependent on the proximity of the injection tunes to each other. When they are close ($Q_x$=4.743, $Q_y$=4.745 in BoosterTuneControl) the profile has flat appearance except for a peak on either side of the center (figure 6A ). If $Q_y$=4.80 and $Q_x$=4.74, the profile appears gaussian (figure 6B). The tunes just after injection remain unchanged. Consequently, the initial beam distribution may be preserved to extraction, suggesting that using the profile for an injection emittance measurement is reasonable. Additionally, the non-gaussian shape appears to be correlated with coupled injection. Although the full width does not change that much in the case where $Q_y$=4.80 versus 4.76, the average width does increase. This is consistent with energy being transferred into the vertical plane during injection from the coupling. The horizontal width also decreases when the tunes are moved closer together, also indicating an energy transfer.

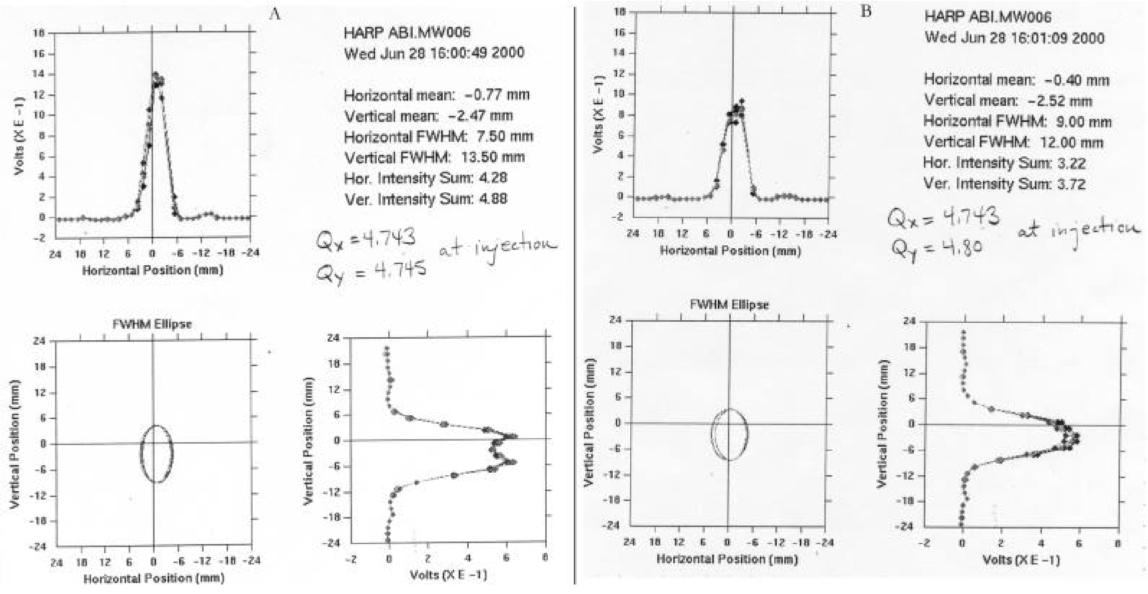

**Figure 6:** BTA MW006 A) $Q_y$ is set close to $Q_x$ at injection (standard setup). B) $Q_y$ is set much higher than $Q_x$ (non-standard setup).

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[1]- Calvani, H.M. and Ahrens, L.A., Booster Tech. Note No. 288, "Au$^{32+}$ Beam Intensity Losses in the AGS Booster due to Charge Exchange Processes", Oct. 1, 1998.

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