BNL-104183-2014-TECH
AGS.SN310;BNL-104183-2014-IR

Measurements of Longitudinal Emittance of Au77 in the AGS

M. J. Brennan

October 1993

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC)

DISCLAIMER

AGS Complex Machine Studies (AGS Studies Report No. 310) Measurements of Longitudinal Emittance of Au^{77} in the AGS
Study Period: October 8, 14, 15, 1993; September 22, 1993
Participants: J.M. Brennan, D-P Deng, and J. Rose
Reported by: J.M. Brennan
Machine: AGS
Beam: Gold +77 Ions
Tools: LeCroy 7200 Scope, HP5372 Time Interval Analyzer, Gauss Clock, F20 and G5 Wall Current Monitors

Introduction

The AGS must supply heavy ion bunches to the RHIC with a longitudinal emittance of 0.2 eVs/nucleon. This specification follows from two considerations. First, in crossing the gamma transition in RHIC chromatic nonlinearites lead to beam loss if the momentum spread in the beam is too big. Second, the luminosity is inversely proportional to the bunch length and the bunches are kept short by storing them in buckets of the 200 MHz rf system. The emittance must be small in order to pass the bunches from the 26 MHz accelerating system to the storage system ("rebucketing") without spilling into adjacent buckets.

In the AGS for SEB the primary consideration is effective debunching, to eliminate rf and revolution frequency structure from the spill. This consideration favors large longitudinal emittance, limited by the bucket area the rf cavities can provide. For the fixed-target SEB run of FY93 with Au^{77} ions, the rf system was configured for 12 equally populated buckets with 0.4 eVs/nucleon bunches. (Note that this is equivalent to 1.6 eVs/nucleon/bunch if the beam were in three bunches, the canonical RHIC mode.)

This was accomplished by non-adiabatically debunching the beam injected from the Booster (one-quarter of the ring) to fill the AGS ring with coasting beam and then adiabatically capturing the beam into 12 bunches.

This study measured the emittance of the bunches throughout the acceleration cycle to look for emittance growth. In the standard operation mode at 2.5 x 10^7 ions per bunch, the only growth observed was at transition. However, the data showed a bottleneck in bucket area which explained some beam loss. The problem was corrected by modifying the main magnet cycle.

In order to make a more sensitive search for emittance growth, bunches of much lower emittance were accelerated by changing the rf mode of operation to eliminate the debunch/recapture process and to use bunch-to-bucket transfer between the Booster and the AGS. This low emittance beam, 0.02 eVs/nucleon, showed some emittance growth at low intensity 2 x 10^7 ions per bunch) and significant emittance growth at higher intensity (5 x 10^7 ions per bunch).

The required intensity for RHIC is 10^9 ions per bunch. Some possibilities to reduce emittance at high intensity are discussed.

Experimental Technique

The longitudinal emittance was deduced from measurements of the bunch length, magnetic field rate of rise (B-dot), rf voltage, and beam momentum (inferred from either rf frequency or magnetic field). The basic assumption of the technique is that the bunch is matched to bucket. The assumption is not always valid, for example, after transition at the higher intensities.

The bunch length was measured with a LeCroy 7200 digital oscilloscope at one nanosecond per point. The beam pick-up was the wall current monitor at F20 for data taken in building 929 mezzanine, and at G5 for data taken in the MCR. Bunch length measurements were taken in 10 ms intervals throughout the cycle. One measurement was made per machine cycle by manually moving the scope trigger between measurements.

B-dot was determined by measuring the Gauss clock frequency with the Frequency and Time Interval Analyzer, HP5372A. The rf frequency was measured with the same instrument. The magnetic field was determined by integrating the analog signal from the backleg winding of the reference magnet with the LeCroy 9424 digital oscilloscope.

The rf voltage was taken from the magnitude of the rf vector sum signal. The vector sum signal was calibrated by measuring the size of the phase jump at transition (HP5372A). Since the phase at transition jumps from φ_s to $\pi - \varphi_s$, φ_s is given by

$$\varphi_s = 1/2\ (\pi - \varphi_{jump}).$$

Knowing φ_s and B-dot one can determine the rf voltage from,

$$V_{rf} \sin(\varphi_s) = 2\pi R \rho \text{ B-dot}$$

Where: R is the average radius of the orbit
ρ is the magnet bending radius

The perimeter of the bunch in phase space is given by

$$E(\varphi) = \sqrt{[\cos\varphi - \cos\varphi_1 - (\varphi - \varphi_1)\sin(\varphi_s)]/2}$$

where φ_1 is one of the angles where the perimeter intercepts the phase axis, $E(\varphi_1)=0$. The other angle is φ_2, $E(\varphi_2)=0$. Figure 1 illustrates these definitions. The bunch length is the difference between φ_1 and φ_2,

$$\Delta\varphi = \varphi_1 - \varphi_2$$

$$\Delta\varphi = \tau_{\text{bunch}}\,\omega_{\text{rf}}$$

See Figure 2 for a typical bunch pick-up signal from which τ_{bunch} was determined. φ_1 is found by solving the equation,

$$\cos(\varphi_1)-\cos(\Delta\varphi-\varphi_1)-\Delta\varphi\sin(\varphi_s) = 0$$

$$\varphi_1 = 1/2\,\Delta\varphi - \arcsin\left(\frac{\Delta\varphi}{2}\cdot\frac{\sin\varphi_s}{\sin\frac{\Delta\varphi}{2}}\right)$$

The bunch area, or emittance, is then

$$emittance = 2\sqrt{\frac{2eV_{rf}E_s\beta^2}{\pi h\eta\,\omega_{rf}^2}}\int_{\varphi_2}^{\varphi_1} E(\varphi)\,d\varphi$$

where: E_s is the beam energy
V_{rf} is the rf voltage
ω_{rf} is the rf angular frequency
η is the frequency slip factor
h is the rf harmonic number
β is the ratio of speed of beam to that of light

Results

SEB Mode (debunch/rebunch)

Figure 3 shows the emittance and bucket area throughout the cycle, measured on 9/22/93. One see that the recapture process results in an emittance of about 0.45 eVs/nucleon, whereas the bucket area dips to 0.40 eVs/nucleon. This bottleneck caused beam loss, which can be seen in the current transformer signal shown in Figure 4. The cause of the bottleneck was a B-dot program that rose too fast for the available rf voltage, 200 kV/turn (only eight cavities installed and power amplifiers somewhat past their prime). B-dot is shown in Figure 5, which is the voltage on a backleg winding on the reference magnet. It rises to 1 T/s in 100 ms. This out paces the natural rise in bucket area (adiabatic damping) due increasing beam energy (falling of eta).

The B-dot program was changed to that shown in Figure 6, which gives a bucket area shown in Figure 7, together with a remeasurement of the bunch emittance. There is no bottleneck. However, from Figure 5 one see the onset of large fluctuations in B-dot when the Siemens power supply switches from F-bank to P-bank. If one uses the maximum value of B-dot to calculate the bucket area then the curve of Figure 8 is obtained. The bottleneck reappears but the beam emittance now at least fits through the bottleneck.

One might ask if the backleg winding voltage of Figure 5 truly reflects the magnetic field that the beam sees. Eddy currents in the vacuum chamber could shield the beam from fast fluctuations in field. However, the Gauss clock is driven by a pick-up coil inside a vacuum chamber in the reference magnet. Figure 9 is a measurement of the Gauss clock frequency in a 20 ms interval around the time the power supply switches to P-bank. The fluctuations are also seen here. A spectrum of the voltage from the backleg winding is shown in Figure 10, displayed with log and linear ordinate. The strongest line is at 730 Hz, followed by 1440, 360, 1080, 1800 Hz respectively.

Collider Mode (low emittance, bunch-to-bucket)

To provide the lowest possible emittance for RHIC the low emittance obtained in the Booster must be maintained. This requires bunch-to-bucket transfer between the Booster and AGS. In this run the Booster cycle finished with six bunches at 5.0 MHz. The AGS must use harmonic 12 which makes the rf frequency 2.5 MHz and so bunch-to-bucket transfer of all six bunches is not possible. On the other hand, one bunch is sufficient for the study. To get one bunch in the AGS the A5 fast kicker was mistimed for all but one of the six bunches coming from the Booster. This single bunch has the correct velocity for a twelfth harmonic bucket in the AGS.

No attempt was made to synchronize the Booster to the AGS. This means that the bunch arrived in the AGS bucket at an arbitrary phase. The phase loop in the AGS was invoked to quickly (100 microseconds) move the bucket to the bunch. This turned out to be not completely satisfactory. The bunch always experienced some bunch shape oscillations at injection in the AGS for all values of AGS rf voltage. Furthermore, there was a correlation between the magnitude of the bunch shape oscillations and the initial phase at injection, with the largest oscillation occurring for the largest phase offset.

Nevertheless, even with some dilution due to shape oscillations the single bunch emittance was much smaller than the emittance with the debunch/rebunch mode. Figure 11 shows the results of emittance measurements in the one bunch case. Compare this to Figure 8. The emittance is down by a factor of 10. It is replotted in Figure 12 with 1/10 vertical full scale.

The data of Figure 12 correspond to a beam intensity of approximately 2 x 10^7 ions per bunch. In the course of the study the Tandem changed to fresh terminal stripper foil and the beam intensity increased to 5 x 10^7 ions per bunch. The beam behavior became dramatically different. Strong bunch shape oscillations began at transition, and the bunch length at full energy went from 15 ns to as much as 65 ns. Since the strong bunch shape oscillations that began at transition persisted to full energy it was not possible to estimate the emittance in this case. Figures 13 and 14 show the bunch profiles in the low and high intensity cases respectively.

Turning the beam intensity up and down between the two levels, via the variable iris before the Tandem, caused the bunch shape oscillation effect to come and go reproducibly.

Discussion

A wide range of longitudinal emittance for heavy ions can be provided by the AGS. The energy spread in the tandem beam is very small allowing the Booster to capture low emittance bunches. If bunch-to-bucket transfer is used between the Booster and AGS then these low emittance bunches can be preserved during acceleration in the AGS.

From Figure 12 we see that in the low emittance case some emittance growth occurs between injection and transition, resulting in about 0.06 eVs/nucleon bunches before transition. One of the goals of the study was to see if the ripple in B-dot, shown in Figure 5 caused emittance growth. The data are inconclusive. Even though there is continual emittance growth, there is no sign of the onset of growth coinciding with the onset of B-dot ripple.

Upon crossing transition (at 2 Tesla/s) there is significant growth. Some bunch shape oscillations after transition were observed and account for the large scatter in the calculated emittances after transition. Presumably these shape oscillations are stimulated by the space charge of the bunch[1]. At first thought it may seem unlikely that this low intensity beam is affected by space charge. However, the intensity is not negligibly low. The space charge voltage is proportional to the derivative of the line charge density. If we approximate the line density with a parabolic distribution then the derivative scales as the inverse square of the bunch length. We can compare the gold beam with protons. The proton intensity (per pulse) that would have the same derivative of line charge density is given by (12 bunches) x (77 charges) x $(115\ \mathrm{ns}/15\ \mathrm{ns})^2$ x number of Au^{77} ions per bunch. The 115 ns proton bunch length is typical for high intensity SEB operation.

This scaling leads to significant protons intensities. The gold beams of 2 and 5 x 10^7 ions compare to 1 and 3 x 10^{12} ppp. One would not expect to see particle loss at these proton intensities but it would not seem unlikely to find emittance growth at transition.

Recalling that the RHIC requirement for heavy ion intensity is 10^9 ions per bunch we see that something new will be required in the AGS. The gamma transition jump facility, to be commissioned in FY94, is certainly the most important new capability for reducing emittance growth at transition. It remains an open question as to whether or not it will be sufficient for intensities 50 times higher than measured here.

There are other techniques that may be effective. A radial jump from inside to outside at transition takes advantage of the dependence of transition radius[2]. How, or whether this would work in conjunction with the transition jump is another open question.

The technique of "focus-free" transition crossing[3] by use of a third harmonic component of the rf voltage may be applicable. The cavity for the longitudinal damper will work at the third harmonic of the rf and might be useful in a "focus-free" transition scheme.

Acknowledgement

We thank Keith Zeno for taking the set of bunch width measurements of 9/22/93.

References

1. A Sorenssen, Particle Accelerators 6,141 (1975).
2. E Raka et al, AGS Studies Report Number 192, 1985.
3. J.E. Griffin Fermilab internal note TM-1734 (March 1991).

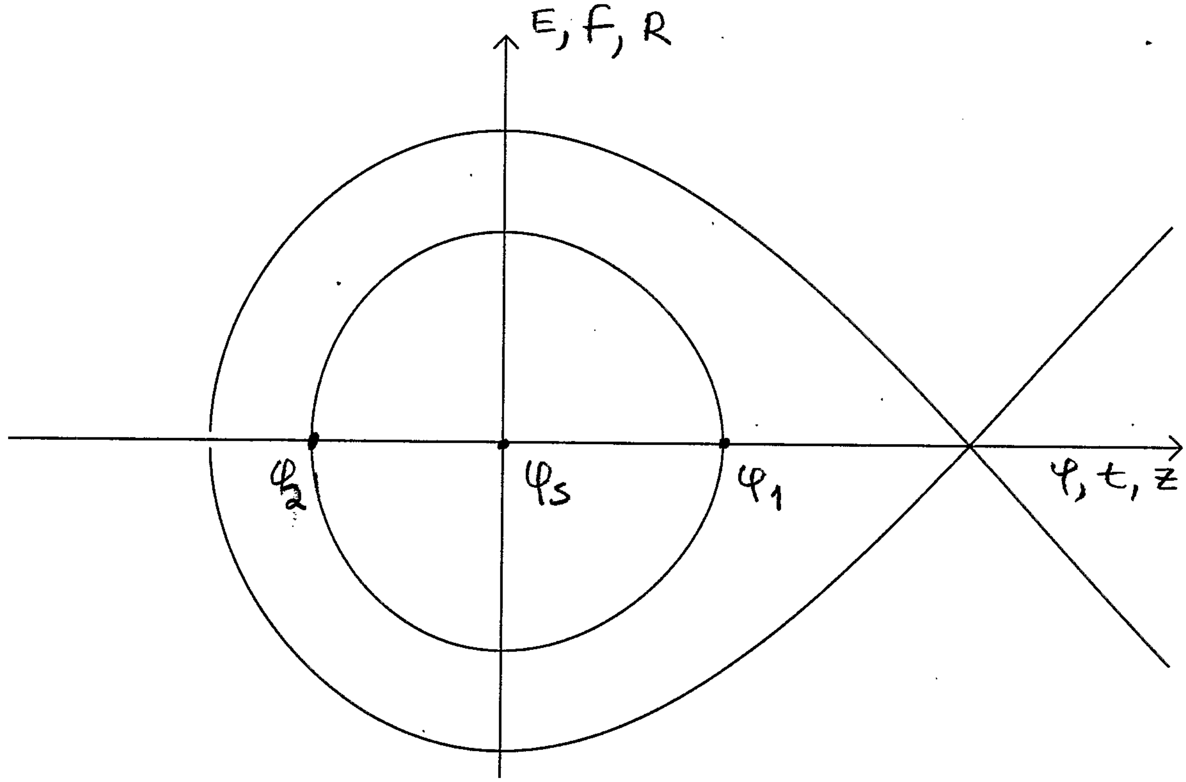

Figure 1. Illustration of moving bucket in longitudinal phase spase. Angles φ_1 and φ_2 are defined in the figure.

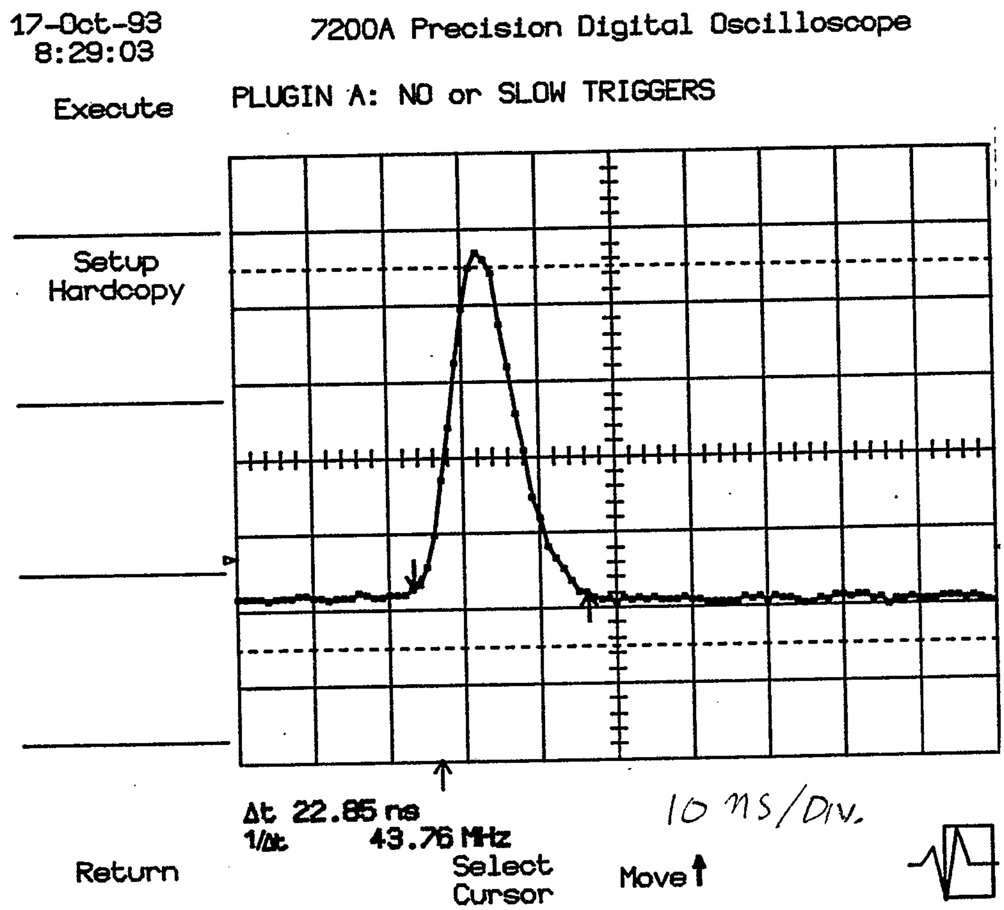

Figure 2. Typical bunch profile form F20 wall current monitor for Au^{77} ions. Arrow indicate bunch length for this typical case. Time axis is 10 ns/division.

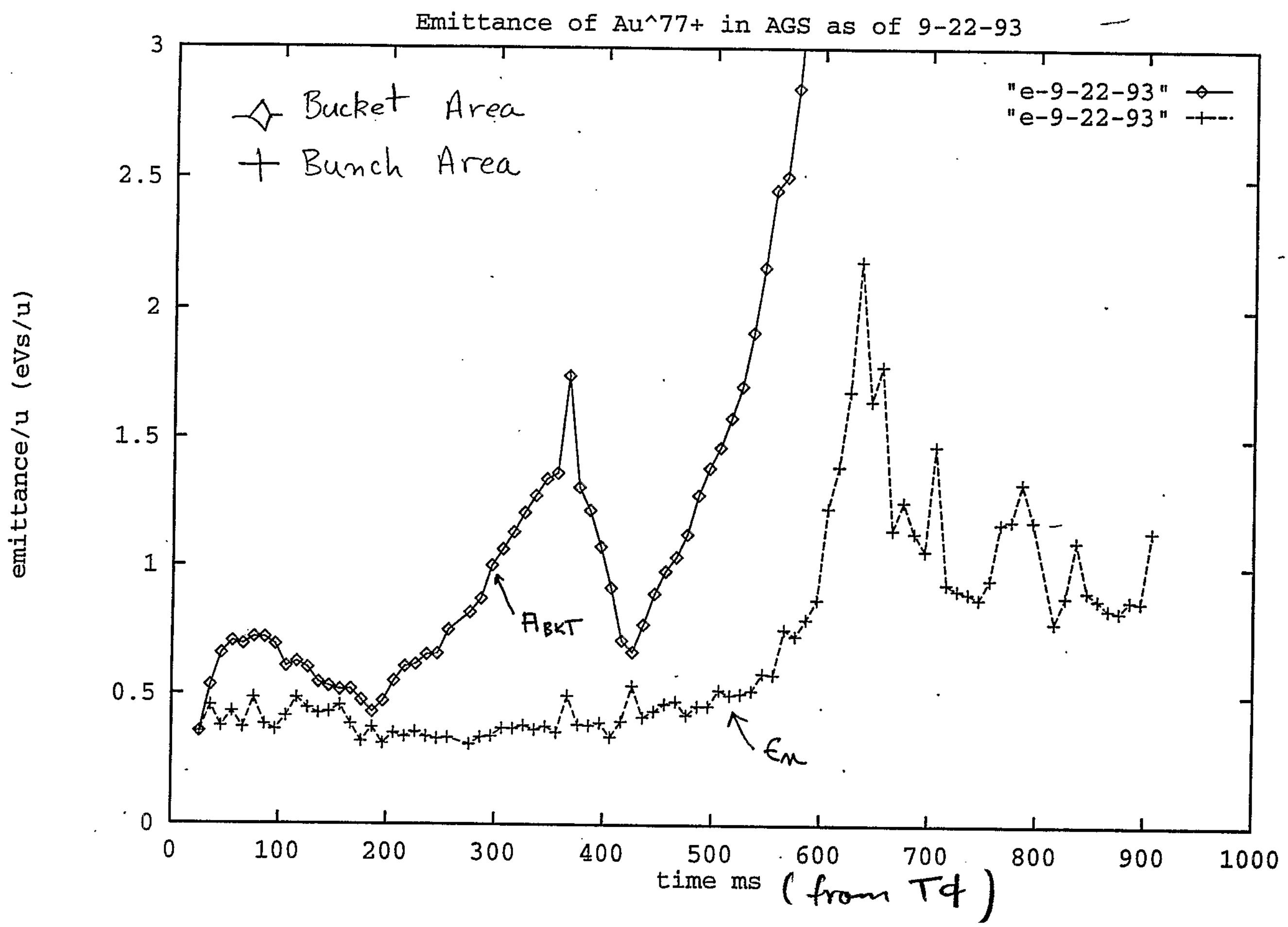

Figure 3. Results of calculation of bunch longitudinal emittance and bucket areas per nucleon from Vrf, B-dot, and bunch length. A bottleneck appears in the bucket area at about 170 ms. The reduction in bunch emittance corresponds to beam loss. Transition is at about 625 ms.

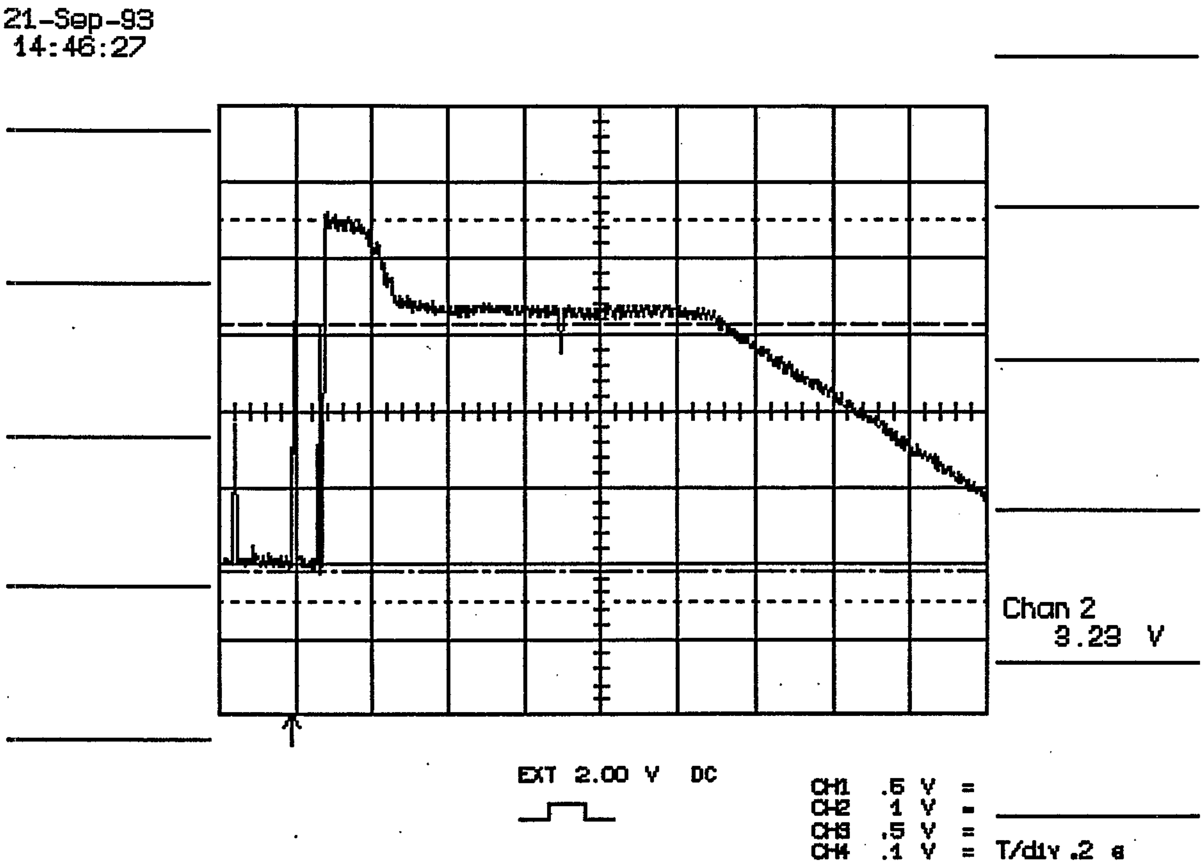

Figure 4. F15 beam current transformer, normalized of changing revolution frequency. step loss at 175 ms corresponds to bottleneck in bucket area. Time axis is 200 ms/division.

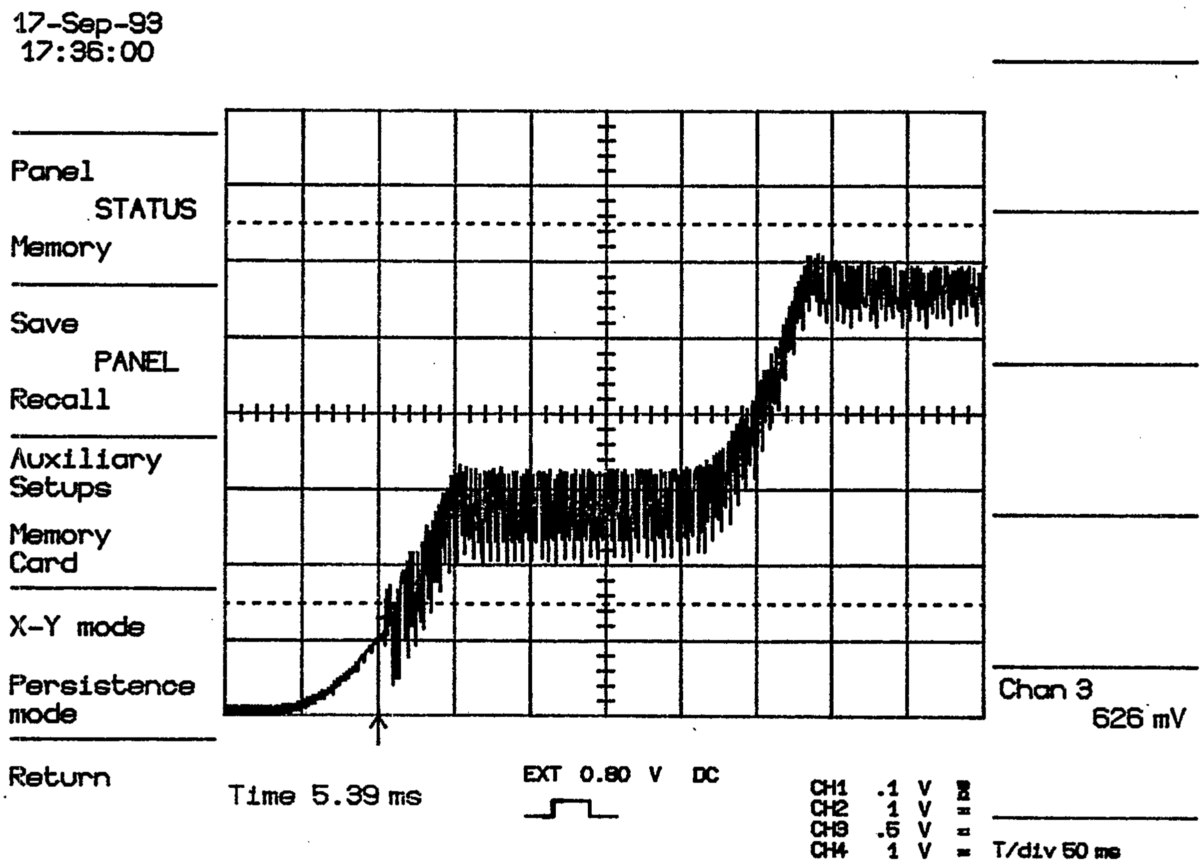

Figure 5. B-dot from backleg winding in reference magnet. Note the onset of ripple in B-dot at about 70 ms after B-dot begins to rise. This corresponds to the Siemens power supply changing from F-bank to P-bank.

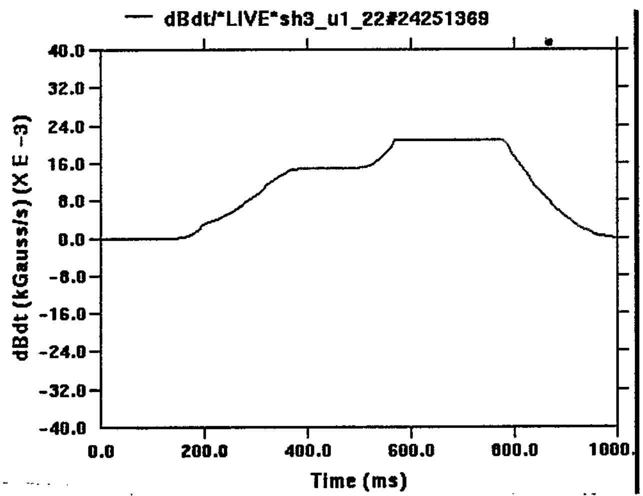

Figure 6. B-dot after change to eliminate bottleneck in bucket area.

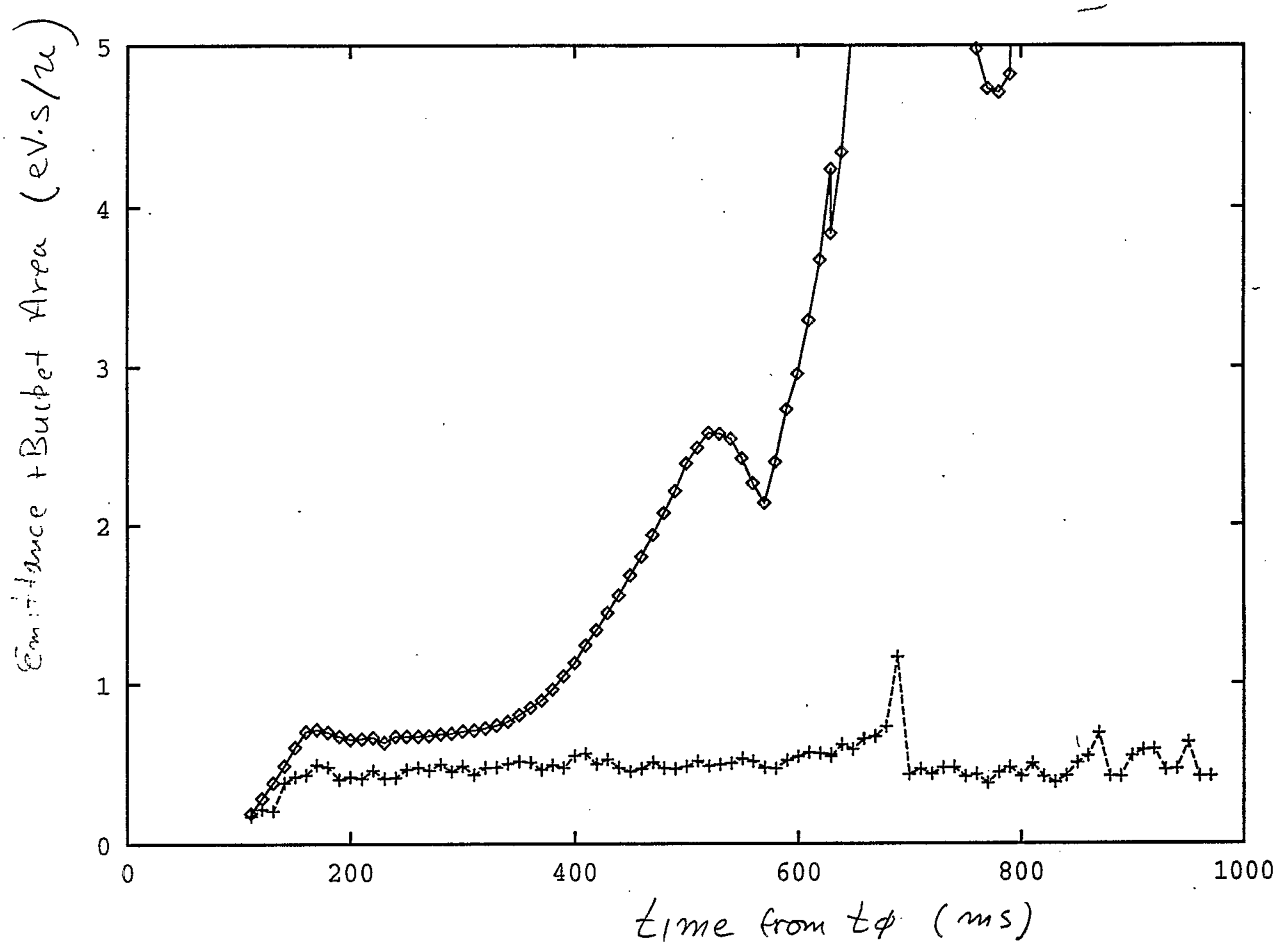

Figure 7. Measurements of bucket area and bunch emittance after change in B-dot to eliminate bottleneck in bucket area. There is essentially no emittance growth after the capture process is complete.

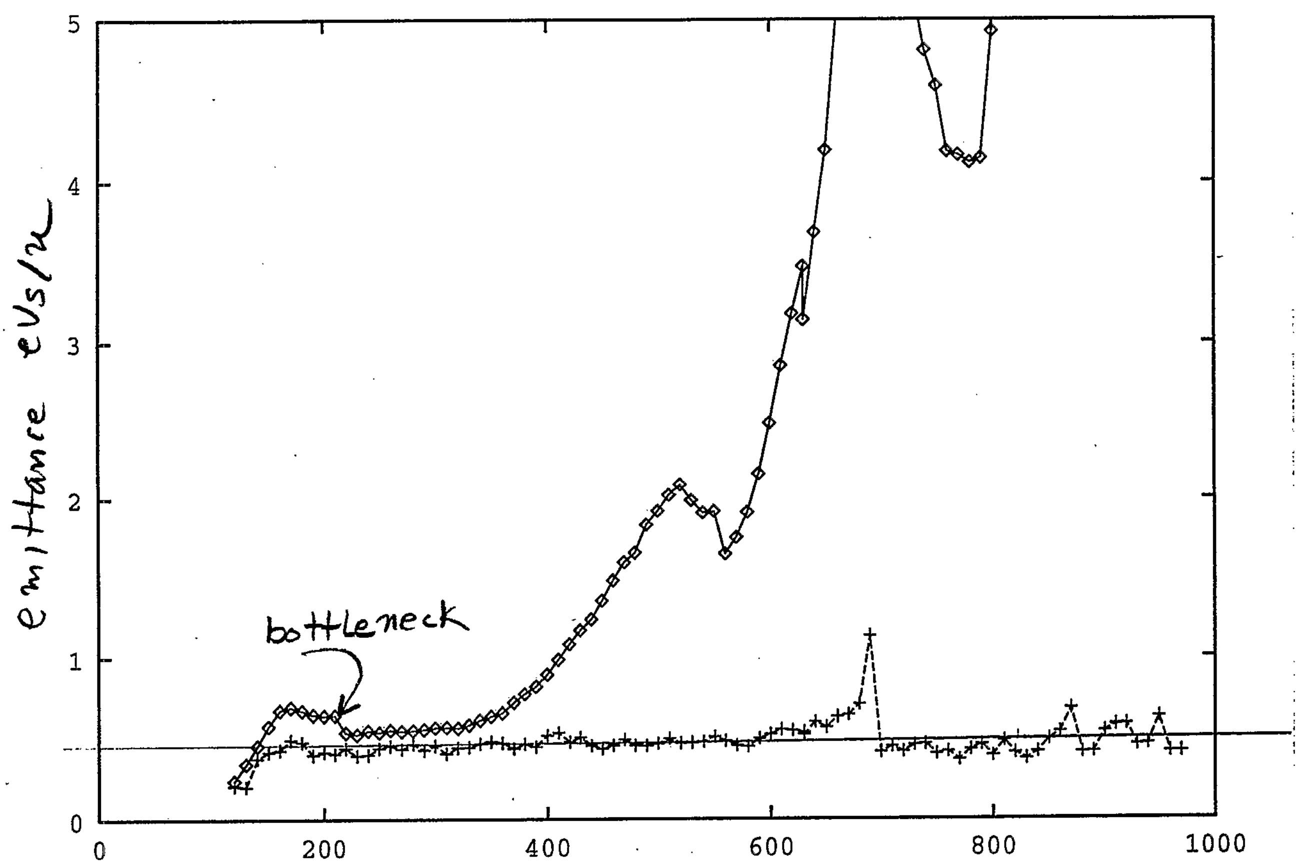

Figure 8. Measurement of bucket area based on the local (1 ms interval) maximum value of B-dot. The bottleneck reappears when the ripple begins but the bunch emittance is still less than the minimum bucket area.

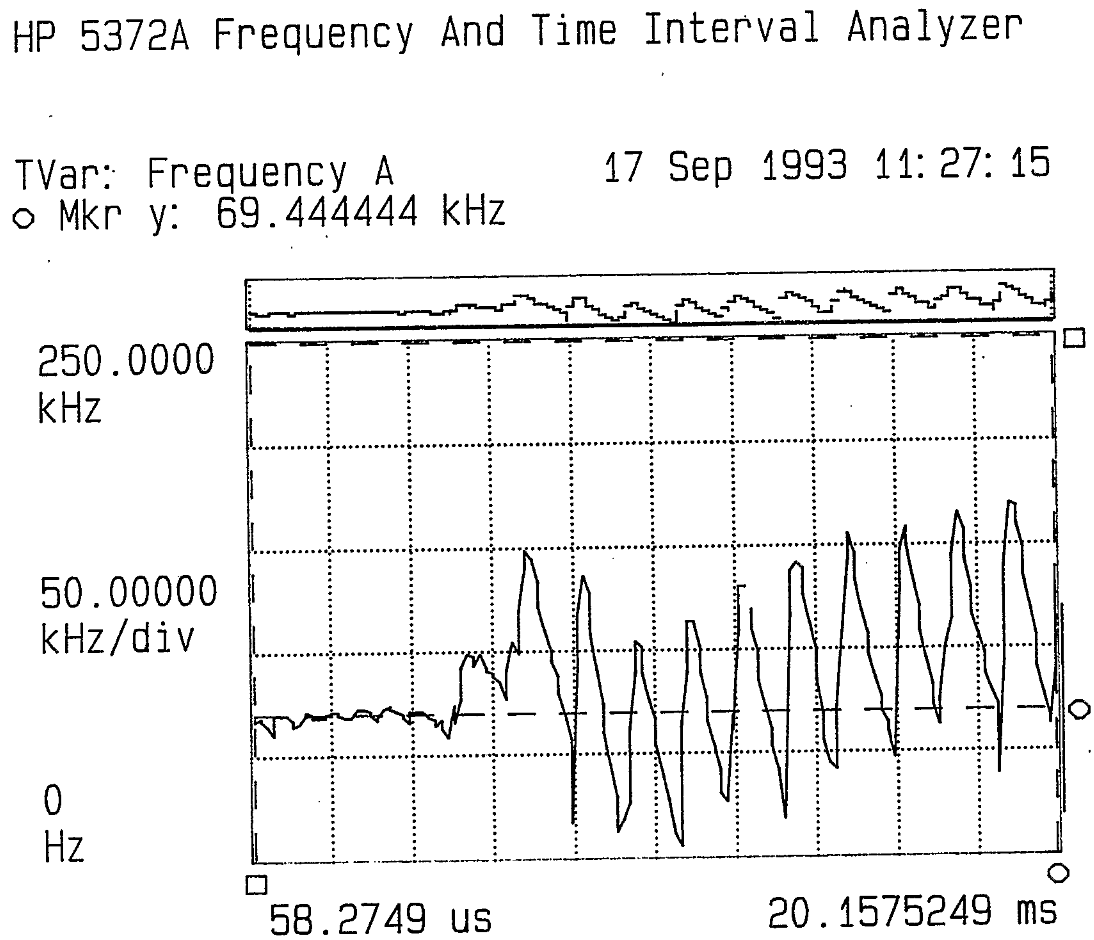

Figure 9. Gauss clock frequency in a 20 ms interval around the time the B-dot ripple begins. Vertical scale is zero to 250 kHz. Gauss clock calibration is 0.05 Gauss per clock tick. This shows that the pick-up coil for the Gauss clock which is inside the vacuum chamber of the reference magnet detects the same ripple as the backleg winding signal of figure 5.

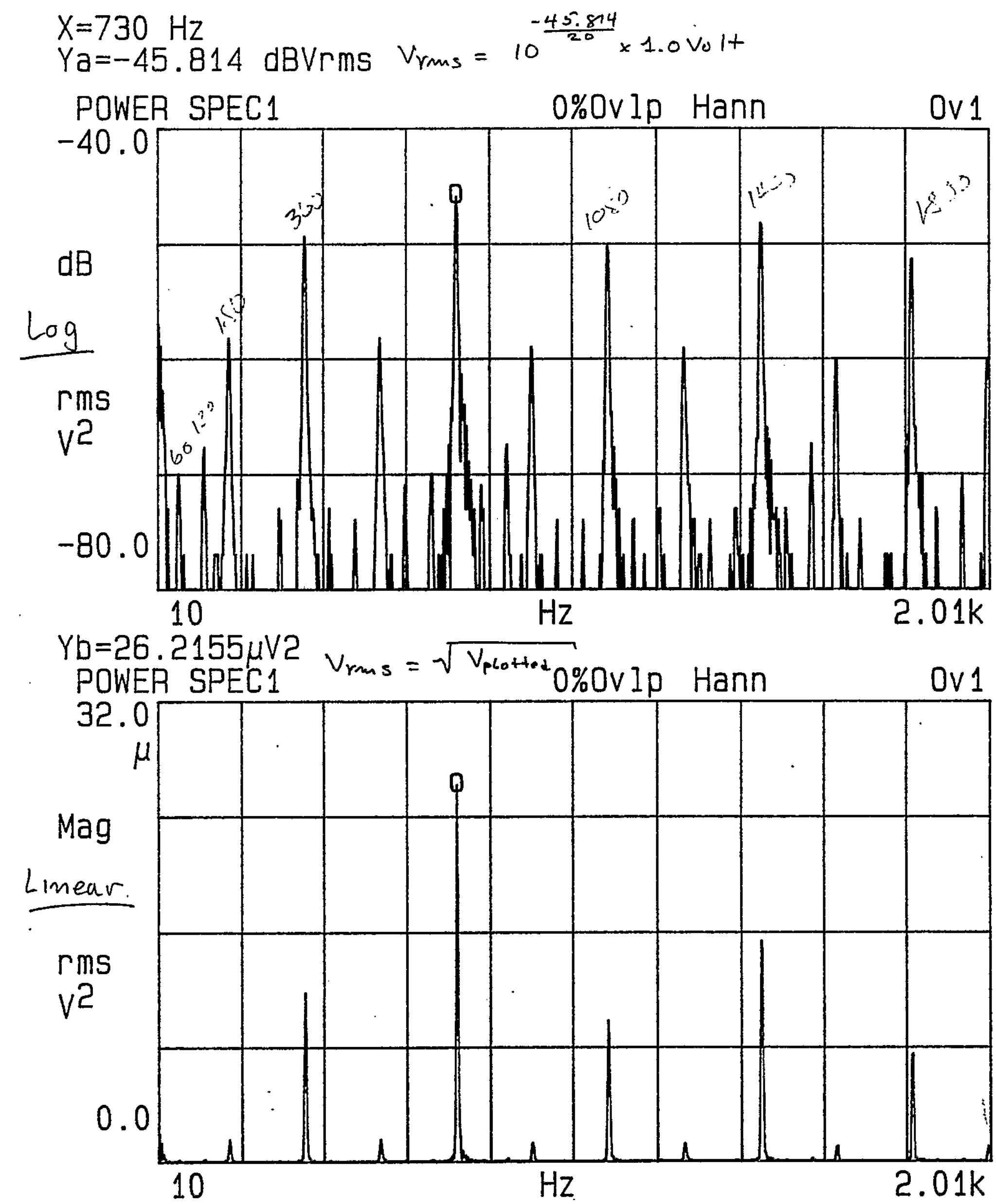

Figure 10. Spectrum of backleg winding signal of figure 5, taken with HP3562 Dynamic Signal Analyzer (FFT box). Top is log scale, bottom is linear scale of same data as top. Strong lines appear near 720, 1440, 360, and 1800 Hz.

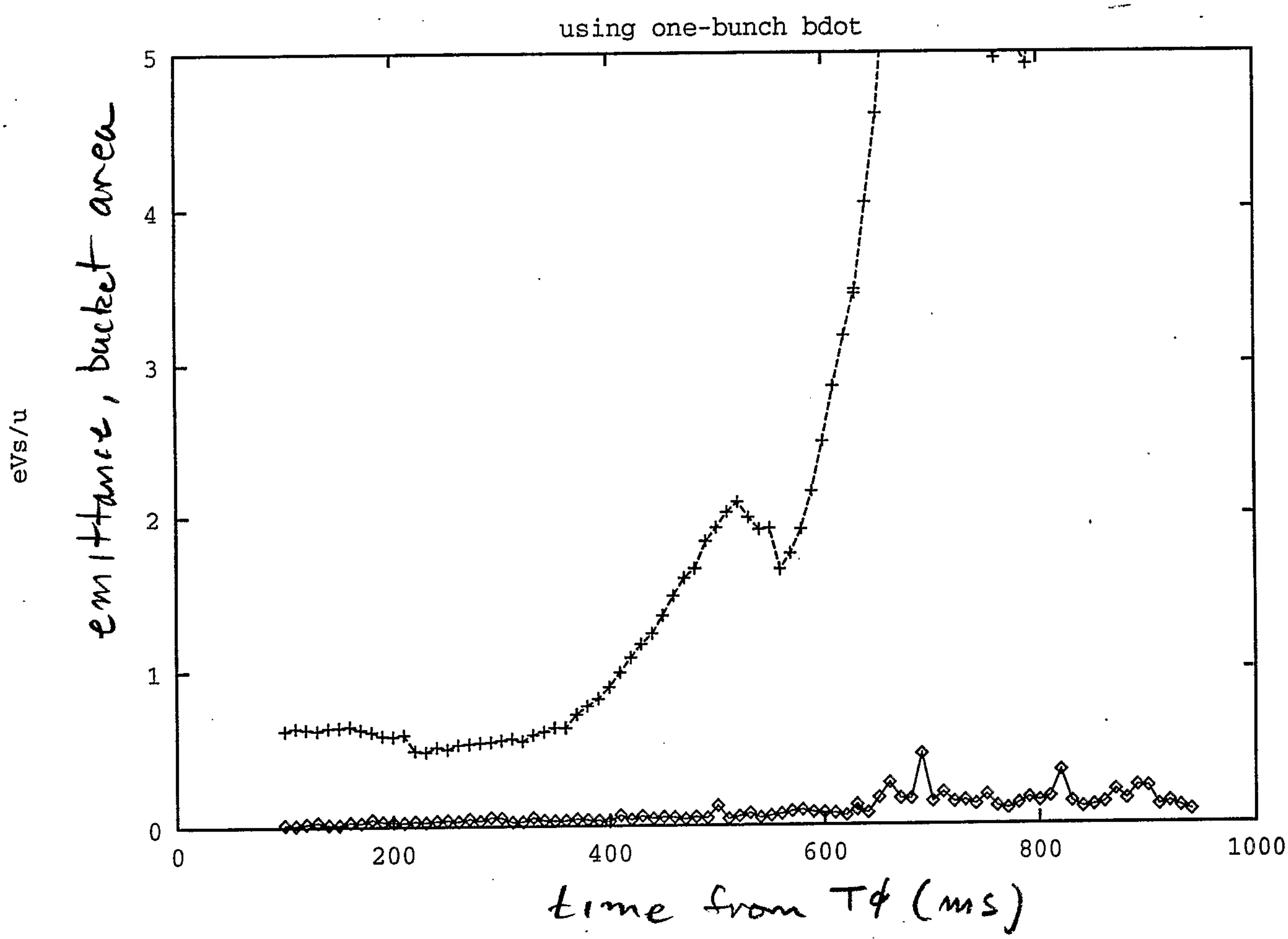

Figure 11. Results of emittance measurements when bunch-to-bucket transfer between Booster and AGS was used to get small longitudinal emittance (0.025 eVs/nucleon). The beam intensity was about 2 x 10^7 ions per bunch. This beam was used as a sensitive probe of emittance growth. See figure 12 for a more appropriate vertical scale.

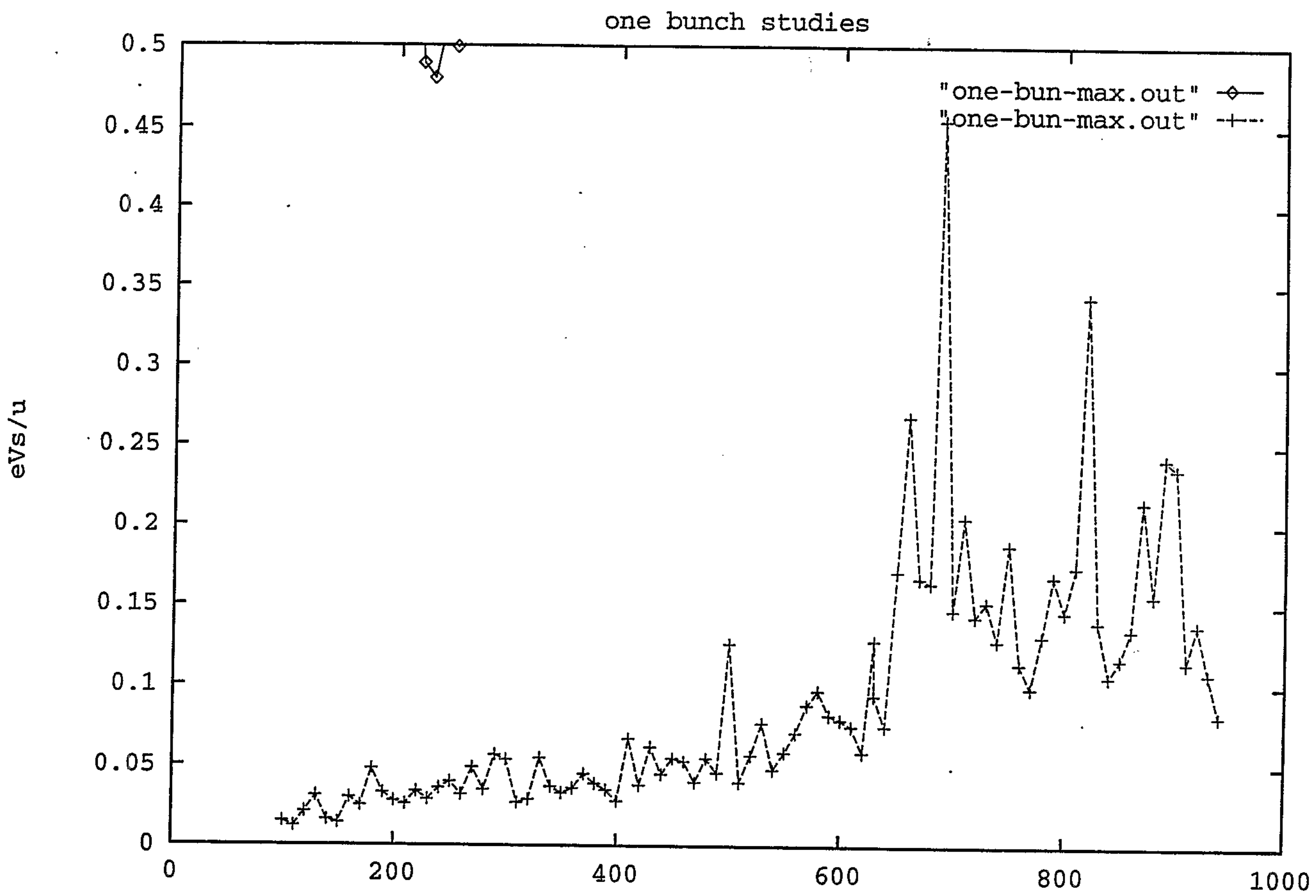

Figure 12. Replot of data shown in figure 11 with 1/10 vertical full scale. Some emittance growth can be seen (0.05 eVs/nucleon) between injection and transition. Significant emittance growth occurs at transition. At higher intensity, 5 x 10^7 ions per bunch, very large emittance growth was seen.

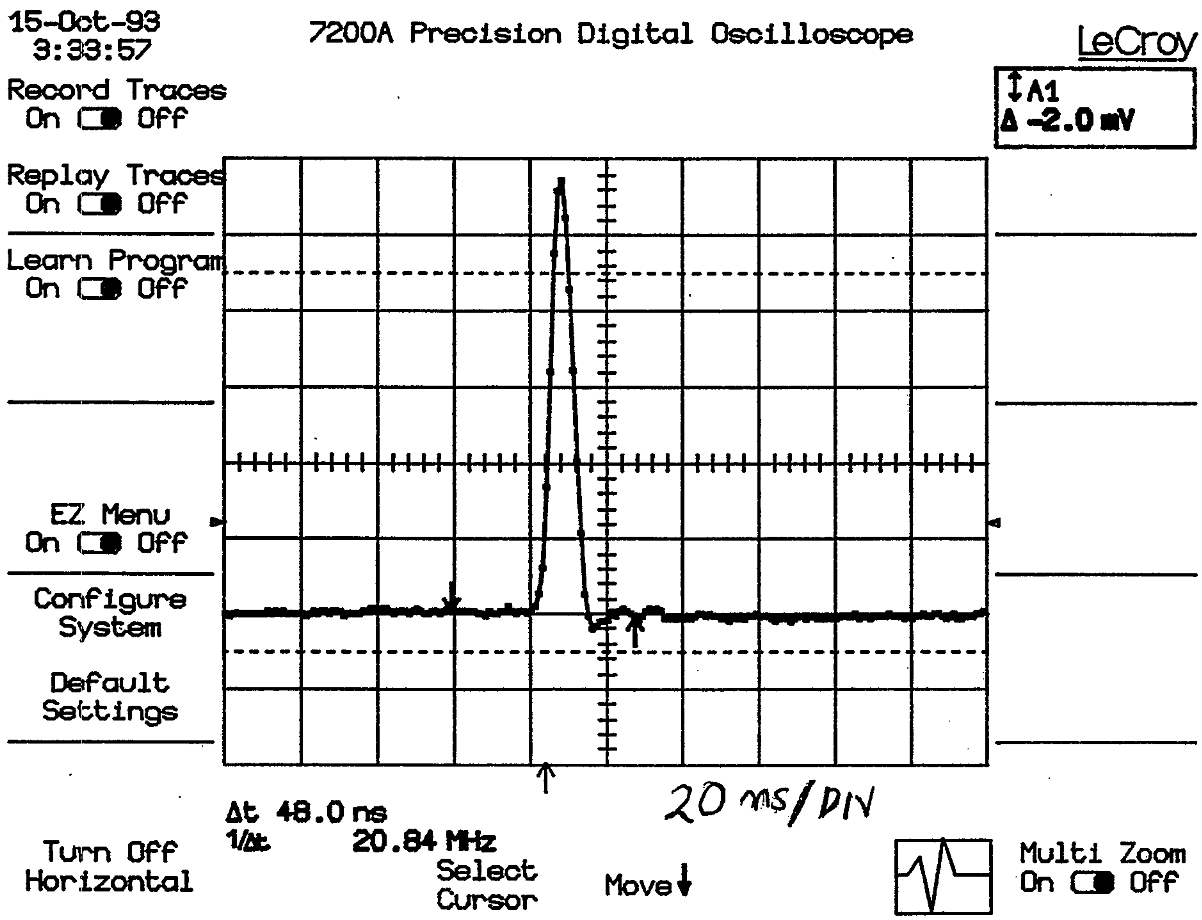

Figure 13. Typical bunch profile at full energy, zero B-dot, Vrf=200kV/turn. Intensity is about 2 x 10^7 ions per bunch. Time axis is 20 ns/division. For higher intensity bunch see figure 14.

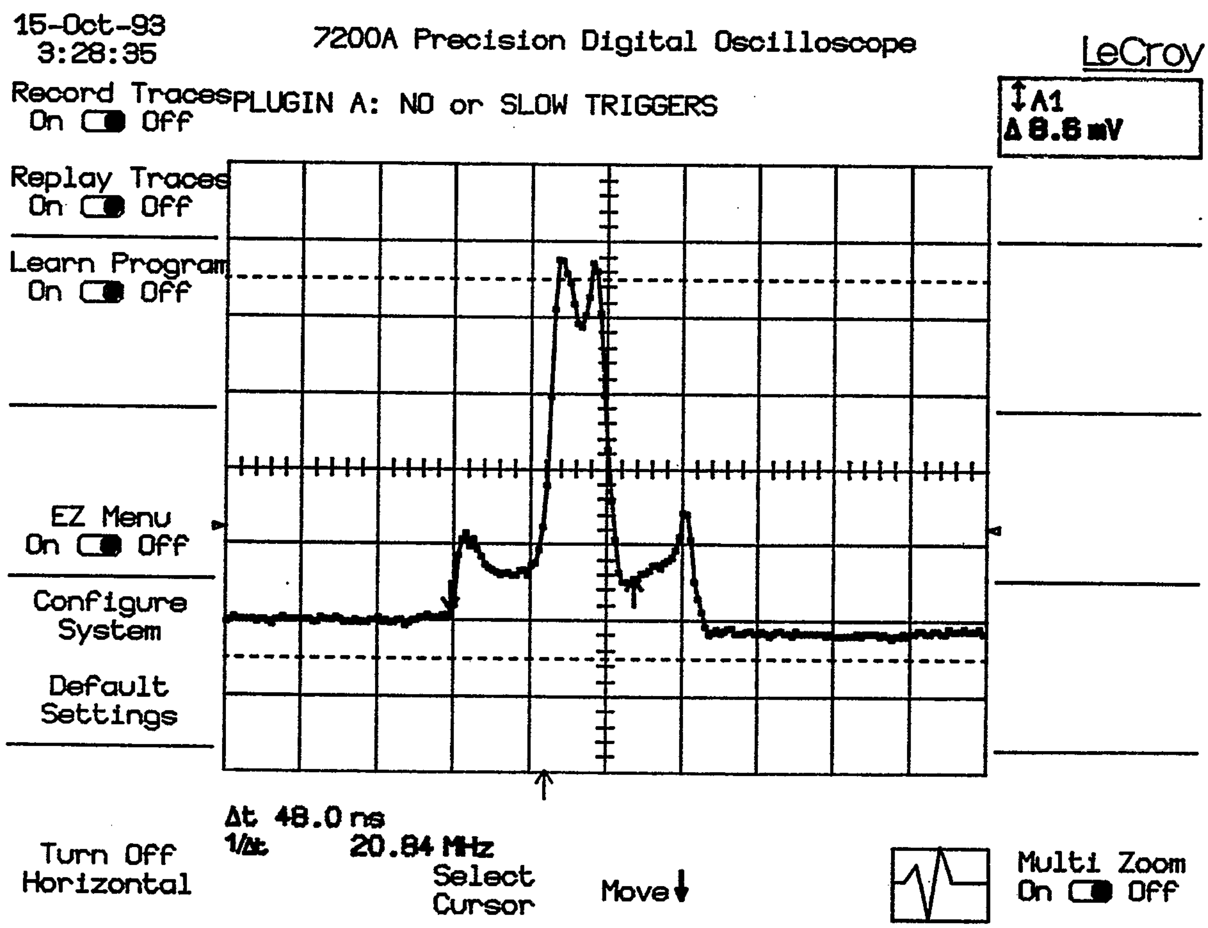

Figure 14. Bunch profile under same conditions as figure 13 but intensity is higher, 5 x 10^7 ions per bunch. Strong bunch shape oscillations began at transition and continued to full energy.