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Silicon Intensity Dependence of BTA Profile Shape

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Silicon Intensity Dependence of BTA Profile Shape

Study Period: November 19, 1999

Participants: L. Ahrens, C. Gardner, J. Wei, K. Zeno, S.Y. Zhang

Reported by: K. Zeno

Machine: Booster

Beam: Silicon

Tools: BTA Multiwire MW006, Beam Line Instrument program, TTB Multiwires, TTB Transformer, Injection Transformer, and Intensity Scalers

Aim: To study the dependence of the horizontal profile shape in BTA on the silicon charge density early in the cycle.

Introduction

Early in the Iron run it was noticed that the horizontal profile on MW006 (the first multiwire in the BTA line) was relatively flat on top rather than 'peaked'. The profile has not typically had such a 'square' shape during Gold and proton running, nor has it had this shape in at least some of the previous Iron runs. Although the case of protons is quite different, one might expect the horizontal profile for Gold to be similar to the one for Iron.

The Gold setup is rather similar to that for Iron although there are notable differences, which may or may not be relevant. In particular:

- In the case of Iron, the horizontal tune is above the vertical at injection and the vertical is shifted downward during the latter part of injection and shortly thereafter. In the case of Gold the vertical tune is above the horizontal at injection and the vertical is shifted upward during the latter part of injection and shortly thereafter.
- The 'relative sense' of the betatron tunes throughout the cycle is different. For Iron, the vertical tune is below the horizontal throughout the cycle. The Horizontal tune reference was about 4.80 and the vertical about 4.70 at extraction. In the previous Gold run, the reference for the vertical tune is above the horizontal throughout the cycle (the references were Q_H=4.75 and Q_V=4.79 at extraction). The tune references for Gold were also closer to each other through much of the cycle compared to during Iron running.

Ideally, the beam produced by multi-turn injection has a rather uniform phase space charge density in the horizontal plane. The projection of a uniform phase space charge density onto the horizontal axis would be less peaked than in the case of a Gaussian phase space distribution. Could it be that the charge distribution created during the injection process is preserved to some extent during acceleration and is visible at MW006?

Why then is this not apparent in the case of Gold? During the Iron run it was found that crossing the betatron tunes during mid to late acceleration resulted in a profile that was more 'peaked' and similar to those during Gold running (see figure 1). During the last Gold run, measurements of the horizontal and vertical profile widths at MW006 indicated that the vertical emittance was larger than the horizontal emittance.[1] Since the horizontal emittance created by the injection process is expected to be at least as large as the vertical it may be that the horizontal and vertical tunes were crossing during the cycle. When the tunes cross it is expected that the transverse charge distribution will be affected. So, one possibility is that the horizontal profile was not square for Gold because the tunes were crossing, or at least close enough to each other that significant interaction between the two planes occurred during the acceleration cycle.

In the midst of the NASA run, the particle species was changed from ${}_{56}Fe^{10+}$ to ${}_{28}Si^{5+}$. The rigidity of ${}_{28}Si^{5+}$ from the Tandem is the same as it is for ${}_{56}Fe^{10+}$ and the charge to mass ratio for both species is the same. Therefore, the Booster's setup was nearly identical. However, the horizontal profile at MW006 appeared more gaussian than square in the ${}_{28}Si^{5+}$ case. J. Wei speculated that this might be due to a space charge effect and could be intensity (charge density) dependent. Perhaps, in the case of normal iron running, the Booster operated below some charge density threshold where the distribution was preserved. Yet for Silicon, it operated

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[1] To calculate these emittances the values for the Beta functions at MW006 obtained from the Booster's MAD model were used (β_x=3.4 m, β_y=15.3 m). The uncertainty in whether the tunes crossed is due to the fact that the references were close to each other and the chromaticities were not zero.

above that limit and the distribution was no longer preserved. If this were the case, reducing the density of the Silicon beam, and nothing else, might cause the profile to become more square. With that in mind, the current (or charge density) of the beam entering the Booster was varied while observing MW006 profiles.

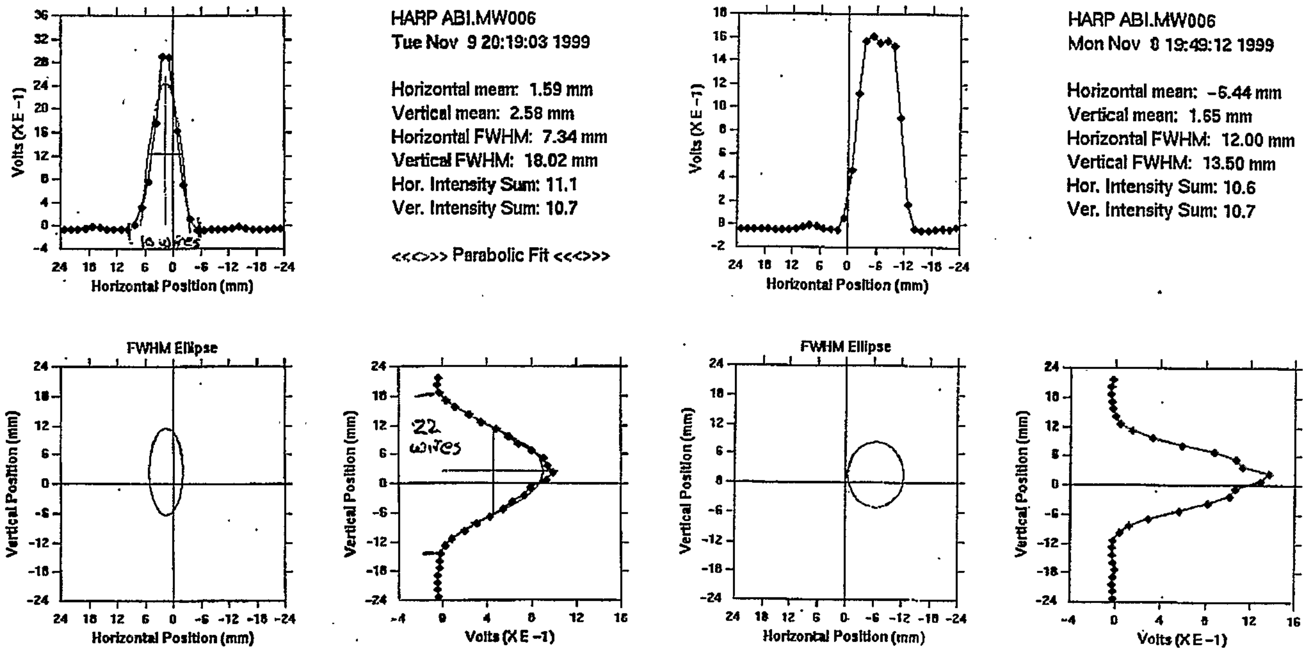

Figure 1: MW006 $_{56}Fe^{10+}$ profiles with tunes crossing (on left) and without tunes crossing (on right). Notice that without the tunes crossing the horizontal profile is squarer and wider, and with them crossed the vertical profile is wider. There also appears to be a sharp peak embedded in the vertical distribution without the tunes crossed that is not visible in the case where they are crossed.

Experimental Setup and Data

The injected current was varied in 14 roughly spaced steps from 83 μA to 13 μA by having a varied number of multiwires (harps) inserted in the TTB line while the beam was being injected. The more harps inserted, the lower the current reaching the Booster. It is thought that when a particle hits one of the wires of the multwire it is lost and therefore not injected. Alternately, if it doesn't hit a wire it is not affected by the fact that the multiwire was inserted. The wires are thin relative to the beam's width, hence each multiwire reduces the beam's current (charge density) by a 'small' amount. Ideally, a multiwire filters out some small percentage of the particles that make up the beam. The particles that are filtered out are roughly evenly distributed across both the horizontal and vertical extent of the beam since the multiwire is made up of both horizontally and vertically aligned wires.

No adjustments are made to the Booster injection setup when multiwires are inserted. One expects that the only significant parameter that does change is the overall charge density of the injected beam. Since the beam is expected to fill the same amount of space in the Booster regardless of the number of multiwires inserted, the resulting density of the stored beam is expected to decrease as the amount of beam injected decreases.

Initially, an Iris that the beam passes through at the Tandem was adjusted to vary the injected current. This would have changed the charge density as averaged over the initial transverse size of the Tandem beam.

However, when the aperture of this Iris was varied it was found that steering changes in TTB had to be made to restore the expected injection efficiency. So this method was abandoned.

Initially the Iris was set to the fully open position (position 8) at Tandem. The following parameters were recorded:

1) Booster Input, Booster Early, and Booster Late Intensity scalers.
2) The peak Booster current and the current 2.5 ms after this peak as measured on the Booster Injection transformer.
3) The vertical and horizontal full widths at half maximum (FWHMs) with profiles fit to parabolas on MW006.
4) The section 29 current and pulse width; and a printout of the MW006 multiwire profiles from BeamLineInstrument.

Subsequently, TTB multiwires were inserted. The insertion of each multiwire reduced the input intensity by about 10-20%. After each insertion the same data was taken. Table I contains the data. It was found that certain multiwires had more effect on the Booster intensity than others did. Different combinations of multiwires were used to increase the number of available intensity steps. A maximum of 7 multiwires was inserted at one time. Inserting more than seven multiwires reduced the intensity too much to accelerate the beam without changing the Booster setup. In fact acceleration with 7 inserted was marginal and unstable.

The profiles in the TTB line before the multiwires were inserted were very asymmetric and large horizontally. This may indicate that the beam was scraping upstream of section 27 (see figure 2). It was nevertheless decided to continue the study with TTB in this state.

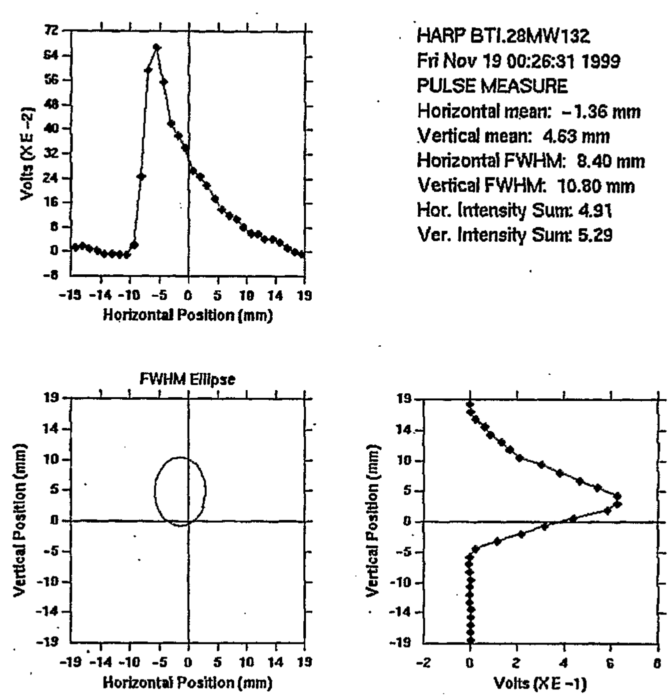

Figure 2: Multiwire 28MW132 in TTB showing the possible effect of scraping upstream of it. This multiwire is near the window frame mentioned below.

The 'window frame' in section 28 (28FC132 on spreadsheet) was also inserted without any TTB multiwires inserted and data taken for this condition as well. If the beam is centered passing through the window frame, then it will scrape off particles with relatively large horizontal excursions there. However, the profile there was very asymmetric (see figure 2).

Bunch widths and peak beam currents were measured at 14 times throughout the Booster cycle using the E6 wall current monitor in bldg.914. Table II contains this data. There was a large amount of structure in the longitudinal current profiles of the bunches. This was particularly true during early acceleration. This is reflected in the peak voltages measured. The late intensity was about 4e9 ions during these measurements.

Profile # (# of MWs)	Booster Input (10^9 ions)	Booster Early (10^9 ions)	Booster Late (10^9 ions)	Peak Intensity (10^9 ions)	Intensity @ 2.5 ms (10^9 ions)	Horiz. FWHM (in mm)	Vertical FWHM (in mm)	Horiz. Sum (in V)	Vert. Sum (in V)	Sec 29 Current (μA)
1 (0)	46***	15.8	11.2	23.7	15.5	8.3	11.2	11.9	11.7	83
2 (1)	43***	14.4	10.4	21.2	15.5	8.45	10.9	11.3	11.1	78
3 (2)	34***	12.6	8.8	17.5	12.5	8.4	10.8	10.1	9.97	62
4 (2)	30***	11.0	7.6	15.0	11.5	8.4	10	8.84	8.74	55
5 (3)	27.8	9.0	6.6	12.5	8.7	8.4	10.8	7.31	7.25	48
6 (3)	25.2	8.2	6.0	11.2	8.0	8.6	10.1	7.00	6.92	43.5
7 (3)	21.8	7.4	5.4	9.4	7.2	9.3	10.1	5.98	5.89	40
8 (4)	18.8	6.2	4.6	8.7	5.9	9.8	11.1	5.24	5.18	37
9 (5)	15.4	5.6	3.7	7.2	5.0	9.3	11.5	4.39	4.32	27
10 (5)	13.6	4.8	3.2	5.9	4.4	9.2	11.7	3.49	3.45	27
11 (6)	11.2	4.0	2.4	5.1	3.9	9.0	11.4	2.79	2.75	21
12 (6)	10.0	3.6	1.9	4.6	3.4	8.2	10.4	2.14	2.09	20
13 (7)	8.6	3.0	1.2	3.7	2.9	8.0	10.2	1.90	1.86	15
14 (7)	7.6	3.0	0.6	3.2	2.5	7.0	9.9	1.00	0.97	13
Window Frame	12.0	4.2	2.8	5.4	3.8	8.4	9.5	3.24	3.21	21

Table I: The data associated with the variation of the injected current. *** indicates that the Booster Input scaler was saturated. In these cases the input intensity was calculated directly from the section 29 transformer signal (100 μA/V). The Tandem pulse width was 440 μs. The values for the intensity scalers have been multiplied by two to give the correct values for $_{28}Si^{5+}$ (they were calibrated for $_{56}Fe^{10+}$). The numbers in parentheses in the first column indicate the number of TTB multiwires inserted.

Table III shows the horizontal and vertical full beam width at MW006 in terms of how many wires are in the beam. The wires are spaced 1.5 mm apart. For example, a beam 10 wires wide is 10 x 1.5 mm=15 mm wide. An example of this measurement is given in figure 1 for the profiles on the left.

Time from BT0 (in ms)	Full Width (in ns)	Peak Voltage (in mV)
15	624	64
20	505	125
25	363	137
30	363	137
35	215	212
40	200	274
45	180	320
50	130	450
55	130	450
65	121	450
75	107	670
85	85	700
95	75	780
102	80	640

Table II: Bunch data obtained from the E6 wall current monitor for $_{28}Si^{5+}$. Injection occurs at about 14 ms from BT0, extraction at about 103 ms. The wall current monitor was terminated with 50 Ω and had a 20 dB (x10) gain. The Booster late intensity is about 4e9 ions in 6 bunches.

Profile	1	2	3	4	5	6	7	8	9	10	11	12	13	14	WF
# of V. wires	18	18	18	18	18	17	16	16	17	16	16	17	16	16	15
# of H. wires	10	10	10	10	10	10	9	9	9	9	9	9	9	7	8

Table III: The horizontal and vertical beam full widths at MW006 for each Profile. The measurement units are the number of wires on which beam was visible. The wires are spaced 1.5 mm apart from each other

The MW006 profiles for the horizontal and vertical for all of the 14 cases are shown in figures 3 and 4, respectively. These have been compiled from the original multiwire plots. The BeamLineInstrument program uses autoscaling so that intensity changes are not immediately apparent. The profiles here have been modified so that they have the same intensity scales.

Figure 5 shows injection as seen on the Booster injection transformer for the case of full intensity (iris setting @ 8 and no multiwires inserted) as well as the case where the window frame was inserted.

Figure 6 contrasts the MW006 profiles in two cases: 1) when the window frame is inserted, and 2) when the multiwires sums are reduced to about the same intensity as in case 1) using TTB multiwires.

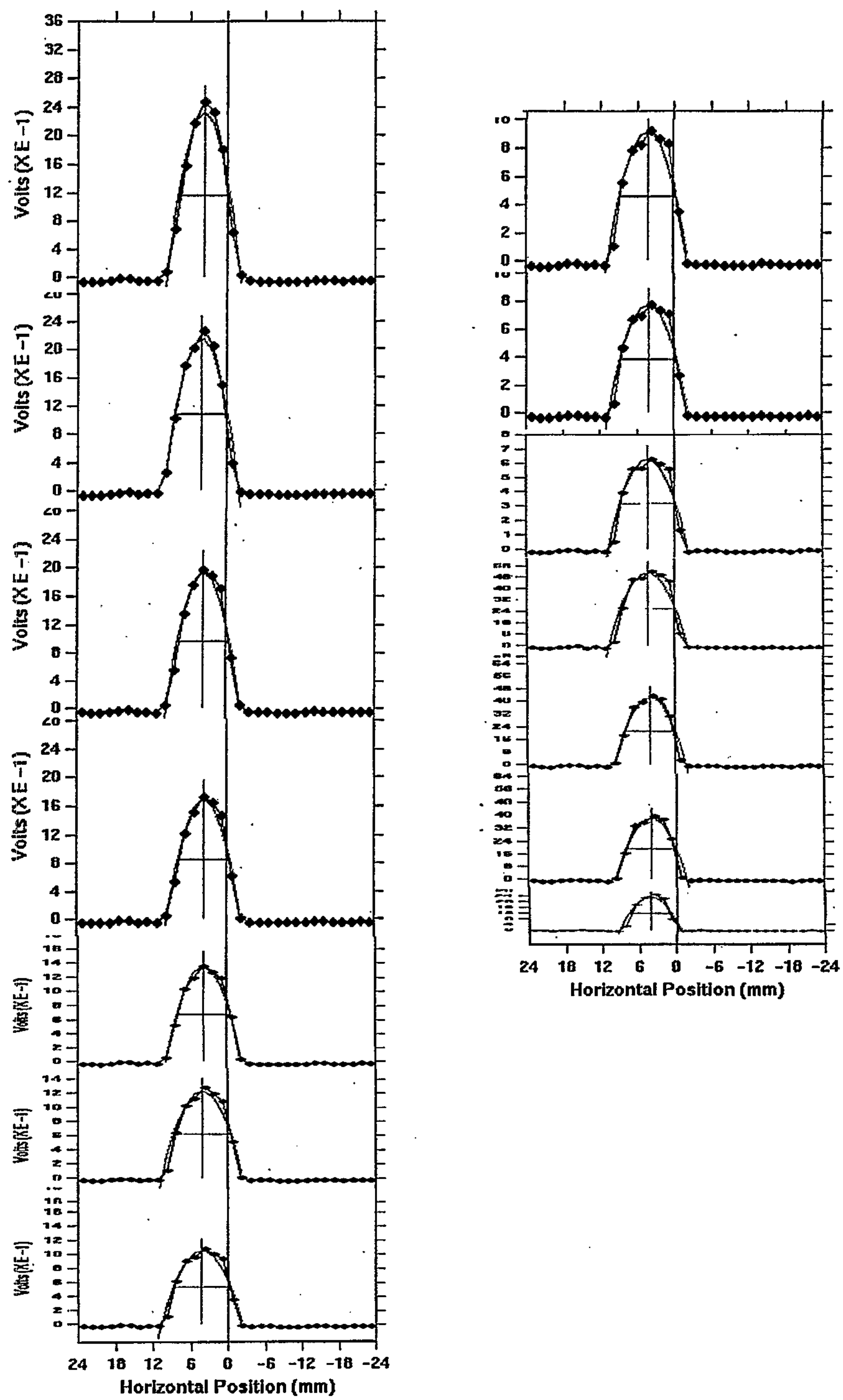

Figure 3: The Horizontal profiles from MW006 for all 14 cases. Profiles 1 through 7 are on the left (profile 1 at the top) and have the same intensity or wire voltage scale (the vertical axis). Profiles 8 through 14 are on the right and all have the same intensity scale, which is twice as sensitive as the scale on the left.

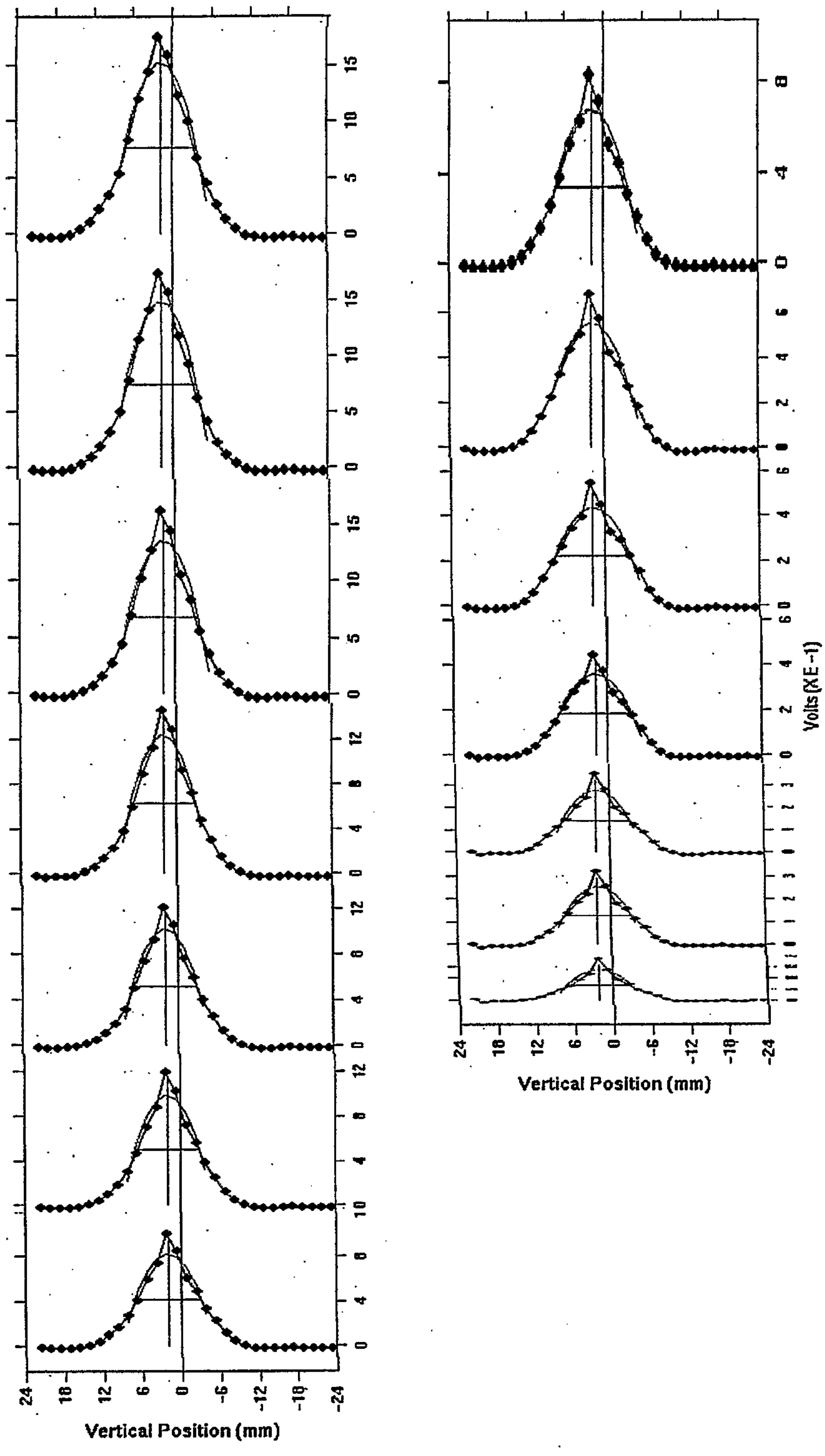

Figure 4: The vertical profiles from MW006 for all 14 cases. Profiles 1 through 7 are on the left (profile 1 at the top) and have the same intensity or wire voltage scale (the vertical axis). Profiles 8 through 14 are on the right and all have the same intensity scale, which is twice as sensitive as the scale on the left.

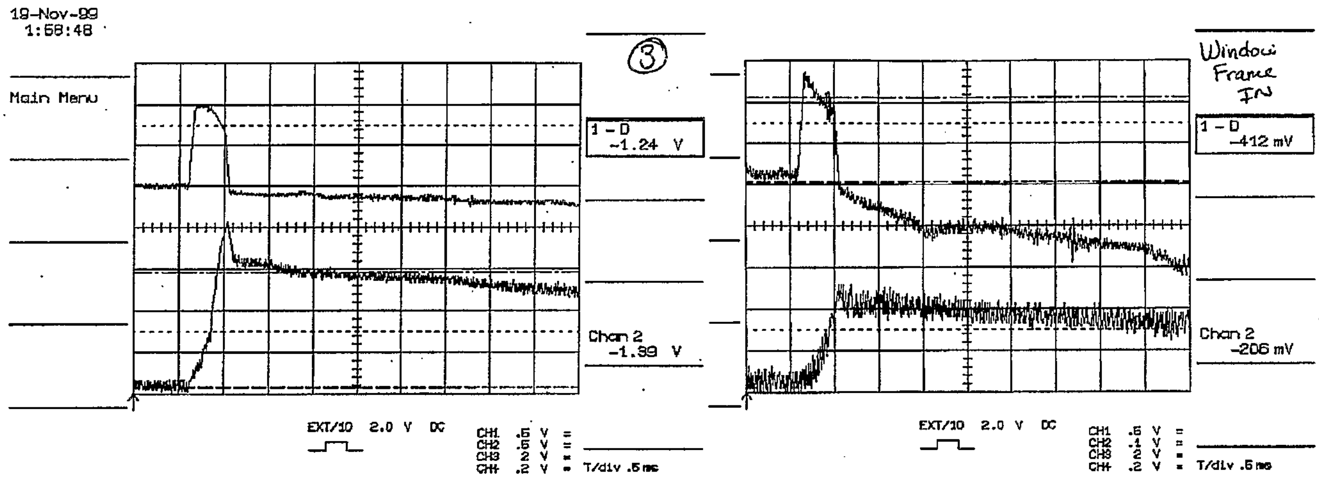

Figure 5: The TTB section 29 current transformer and Booster injection transformer for the full intensity case (left, profile #1) and the case where the window frame is inserted (right).

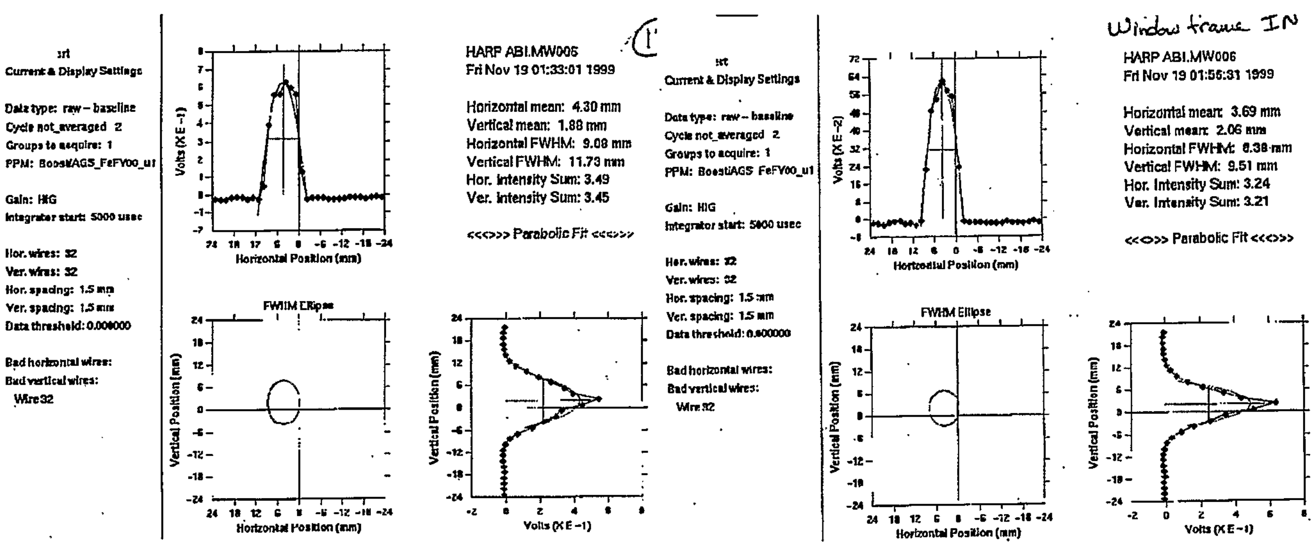

Figure 6: BTA MW006 in a 'multiwire inserted' case and close to 'window frame inserted' case intensity (left, profile #10) and the case where the window frame is inserted (right).

Analysis:

The principle reason for taking this data was to see if the shape of the profiles, particularly the horizontal, was affected by changes in the charge density at injection. From looking at figure 3 one can see a fairly obvious flattening of the horizontal profile as the intensity (charge density) decreases. However, the profiles for the lowest intensities once again take on a more peaked appearance. This is particularly true of profile #14, the lowest intensity, which is also significantly narrower than the others. It is tempting to disregard this profile because acceleration was unstable at this intensity and the beam may have been scraping.

On the other hand, the vertical profiles do not show any tendency to flatten out with decreasing intensity. A sharp peak like the one visible in figure 1's 'uncrossed' case is also somewhat apparent. However, the top half of the multiwire often has a slightly different gain than the bottom half. This can lead to some misinterpretation of the profile shape. From looking at the profiles it appears that the gain of the lower half (negative position) may be slightly lower than the upper half.

In order to quantify the flattening seen in the horizontal, the voltages of the five wires closest to the center of the distribution were considered in both the horizontal and the vertical. The maximum difference between the voltages of any of these five wires was measured by eye for each case. For a given intensity this gives some indication of the flatness of the profile. That is, less variation should be correlated with flatter profiles. The intensity at MW006 ranges from 11.2e9 ions on profile 1 to 0.6e9 ions on profile 14. In order to compensate for this, the voltage variation was divided by the multiwire sum for each case. Figure 7 shows the results.

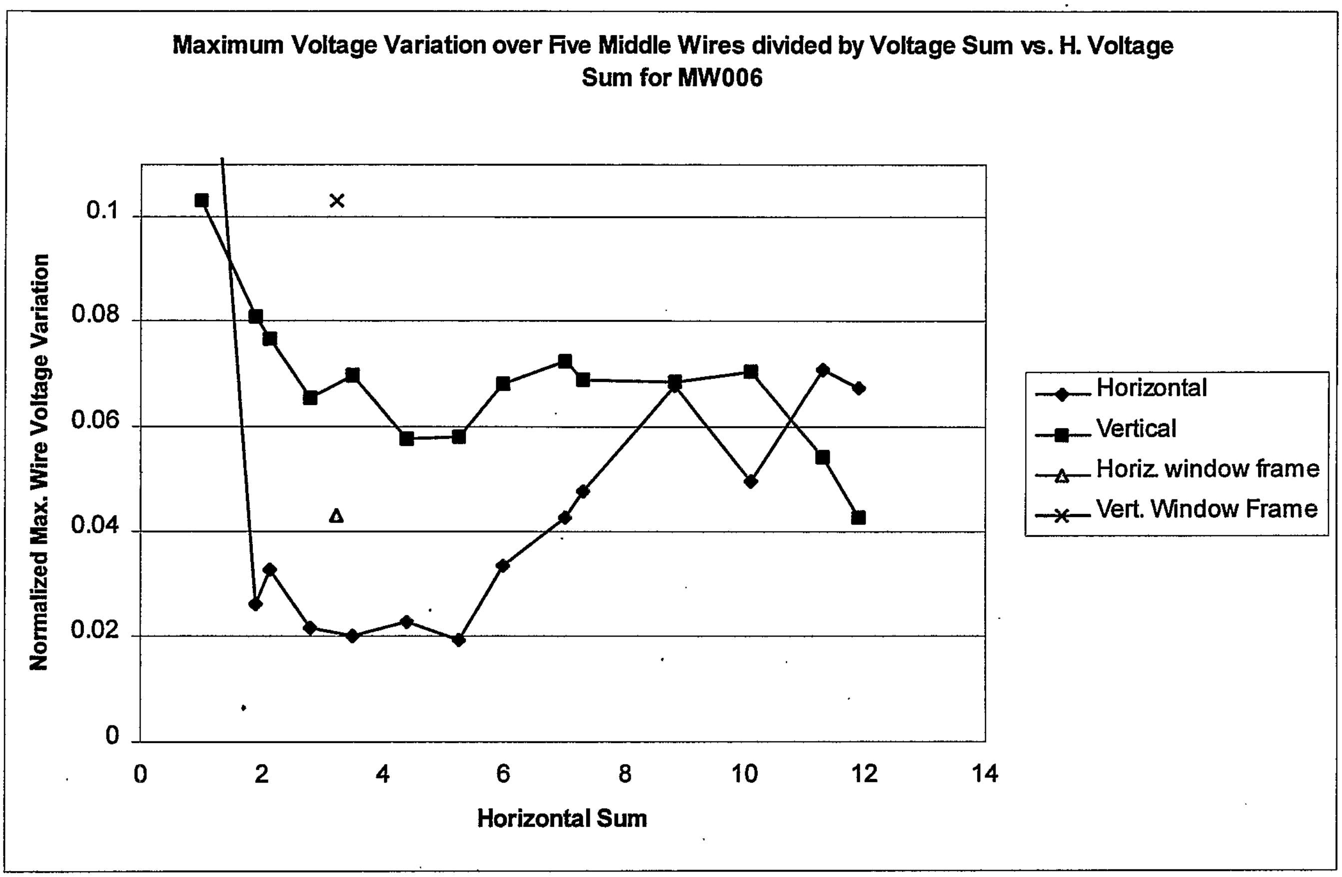

Figure 7: The maximum variation in the voltage of the 5 central wires normalized to the beam's intensity vs. the horizontal sum for both the horizontal and vertical profiles. Smaller variation indicates a 'squarer' profile. The horizontal profile at the lowest intensity has a larger 'intensity normalized' variation than any other profile (0.18, off the chart). One reason the variation is so large is because the profile is narrower. The acceleration was erratic in this case and the beam may have been scraping during acceleration. This data is also shown for the case of the window frame.

From Table III and figures 3 and 4 it appears that the beam width in either dimension only went down by perhaps 10% as the input intensity was reduced (neglecting profile#14). However, the FWHMs (table I) and the # of wires encompassing the beam (table III) for the horizontal and vertical beam widths are significantly smaller when the window frame is inserted.

Since the change in the horizontal profile shape is hypothesized to be due to space charge it is natural to look for other effects that might be space charge related. Figure 8 is a graph of the peak intensity vs. the intensity at 2.5 ms after the peak.[2] The peak usually occurs near the end of the injected pulse. After the peak there is often a sharp drop within a hundred microseconds followed by slower losses. If the beam were affected by space charge during this time, one might expect the size of the fast loss, as well as the relatively slow losses thereafter, to increase disproportionately as the peak intensity increases. However, figure 8 shows a basically linear relationship between the peak intensity and the intensity at 2.5 ms afterwards (i.e.- the losses are not disproportionate). This is true except for the highest peak intensity (2.37e10 ions). Since this is only one data point, it is hard to justify making any conclusions from it.

Space charge effects might also show up as a non-linear relationship between the Booster input intensity and the peak Booster intensity. Figure 9 shows a plot of this data. The relationship is linear over the entire range of intensities.

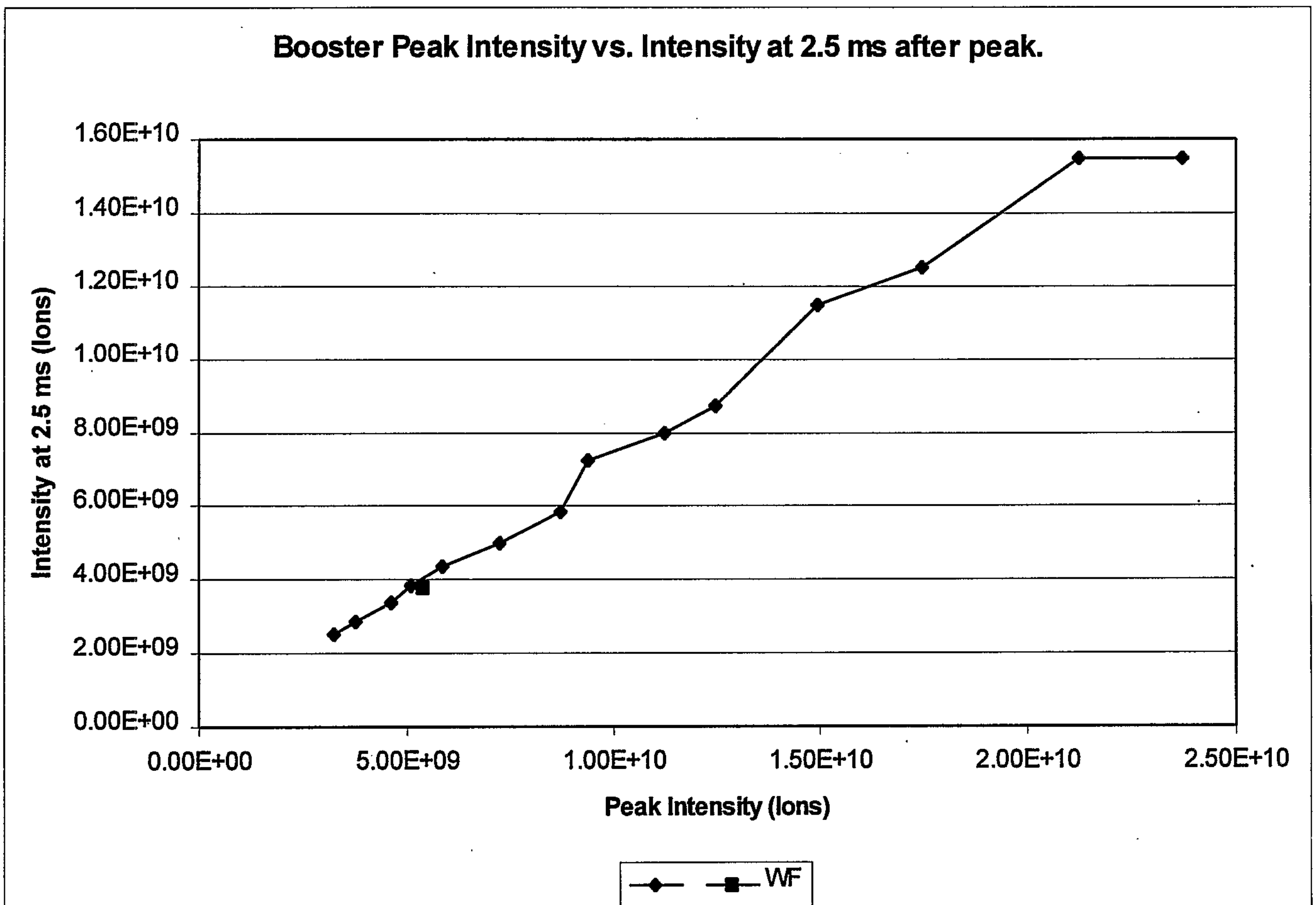

Figure 8: Booster Peak Intensity vs. the intensity at 2.5 ms afterwards. The intensity is measured using the Booster injection transformer (4.8 V=500 μA; revolution period= 9.7 μs). The data is from table I. The window frame data point is also included (denoted 'WF').

Another part of the cycle that has not been checked for an intensity dependent loss rate is the section between the early part of the cycle to extraction. This part of the cycle is more prone to show an intensity dependent loss rate for mundane reasons than are the previous parts. In particular, the efficiency during this part of the

[2] Figure 5 shows the beam as it appears around injection on the Booster transformer.

cycle is dependent on how the Rf system responds to intensity variations. The radial and phase loops only have a finite range over which their response is linear. If the intensity is too high they will saturate, if it is too low they will be dominated by noise. For example, for the lowest intensity (profile 14) the beam would only accelerate to extraction energy about one out of 5 times. This was unrelated to any effect of interest here; it was probably related to some intensity dependence of the phase and/or radial loops.

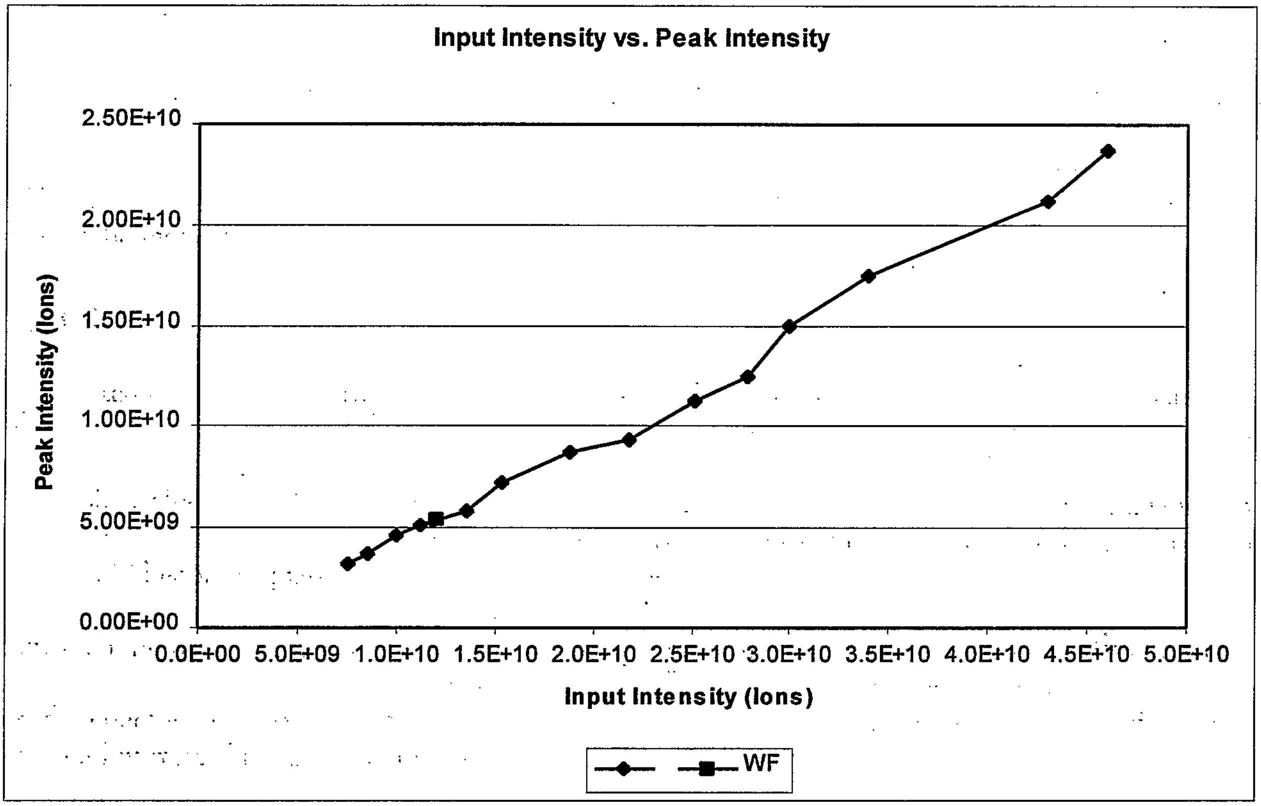

Figure 9: Booster input intensity scaler vs. peak intensity as measured on Booster injection transformer. The data is from table I. The window frame data point is denoted by 'WF'.

Figure 10 shows data from this part of the cycle. Both the Booster early scaler and the intensity at 2.5 ms after the peak have been plotted against the Booster Late scaler (intensity just before extraction). It appears that both the early measurements give similar results across the range of intensities. Unlike the previous figures this one does appear to show a possible nonlinear relationship. It looks as if Booster late may increase at a faster rate at low intensity than when it is high. This non-linearity is also the kind one would expect from a space charge related loss mechanism. That is, as the early intensity is increased by a given amount, the late intensity does not increase proportionately, but trails off. However, a more plausible explanation for this is that Booster acceleration is intensity dependent, and was optimized for the nominal running intensity (say 4e9 ions late). At this intensity, the ratio (Booster late/Booster early) is maximized. By approaching that nominal intensity from below, the rate at which Booster late would increase could be disproportionately high. Similarly, increasing the intensity beyond the optimized level could cause Booster late to increase at a disproportionately slow rate.

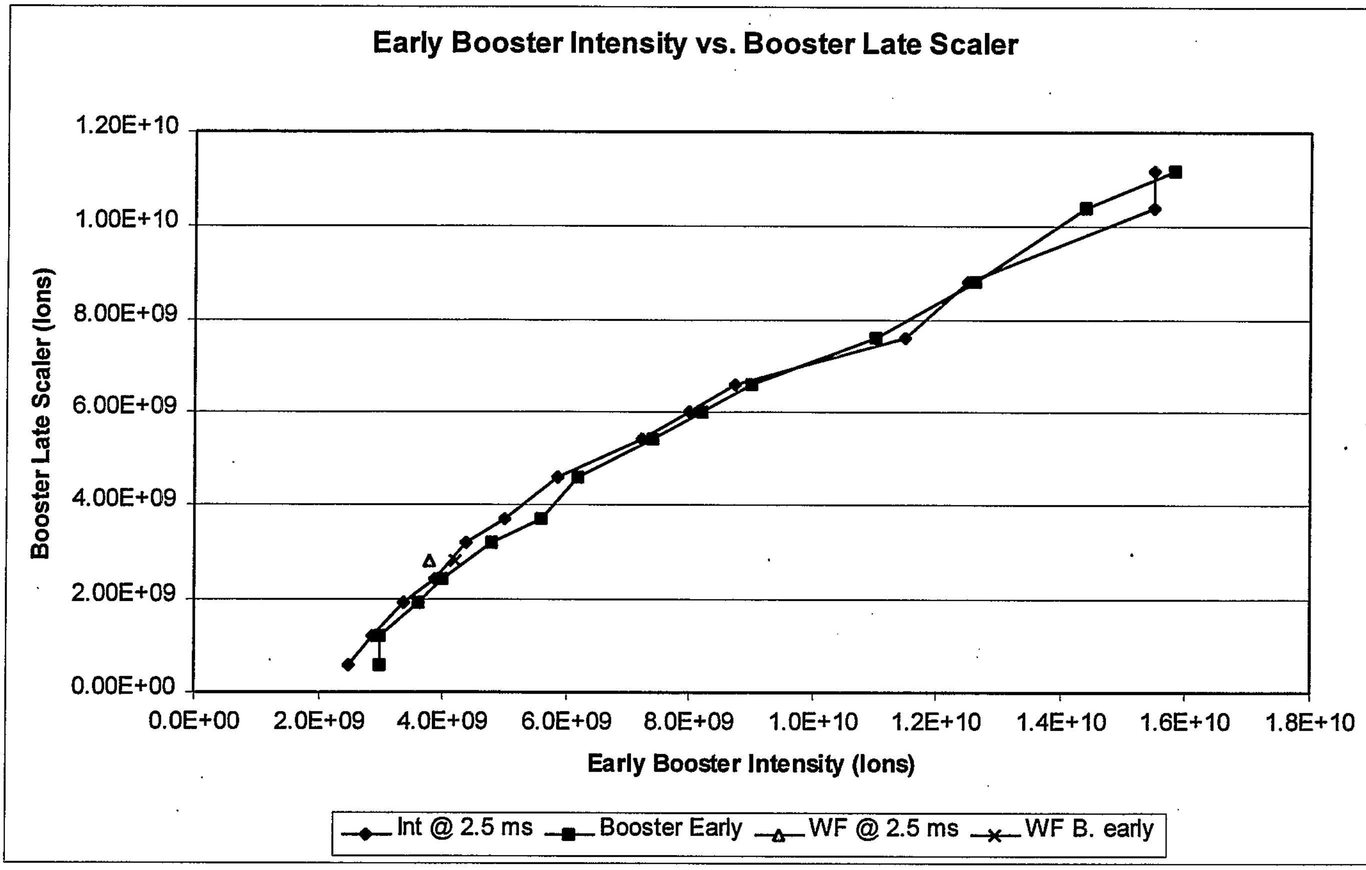

Figure 10: Early Booster intensity vs. the Booster late scaler. Both the intensity at 2.5 ms from peak and the Booster early scaler are shown. Window frame (WF) points are also included. The data is from table I.

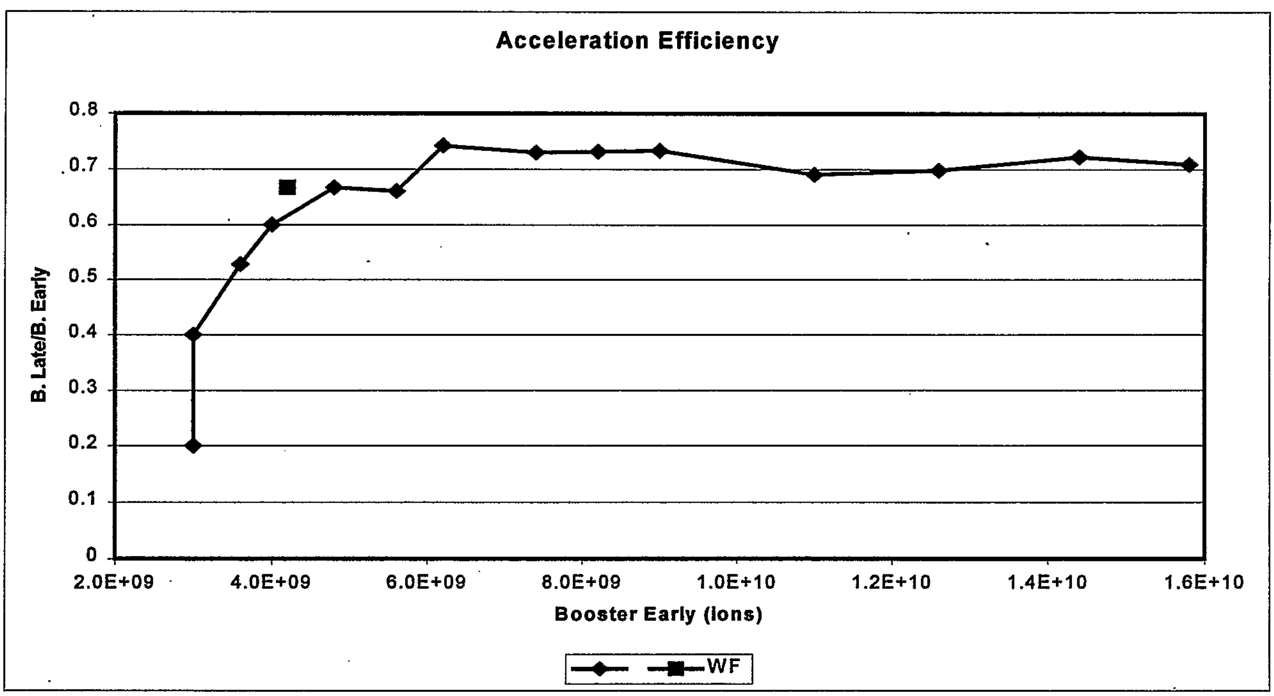

Figure 11: Acceleration efficiency (Booster Late/Booster Early) as a function of Booster Early intensity. Window frame (WF) point is included.

Figure 11 shows that Booster Late/Booster early (acceleration efficiency) does deteriorate as the intensity is reduced below about 3-4e9 late. Notably, there is not the degradation in the efficiency at higher intensities that one might expect from a space charge related effect.

Alternately, a non-linearity might be due to an intensity dependence of the instrumentation. However, the Booster early scaler uses the circulating transformer and the '2.5 ms from peak' measurement uses the injection transformer. So, two instruments seem to agree about the early intensity. Also, the voltage sums for MW006 could also be used as a relative measure of the late Booster intensity. However, the MW006 data may also include any intensity dependent extraction losses, which may or may not be relevant. Figure 12 shows the MW006 horizontal and vertical sums plotted against the Booster late scaler. The relationship between them is quite linear.

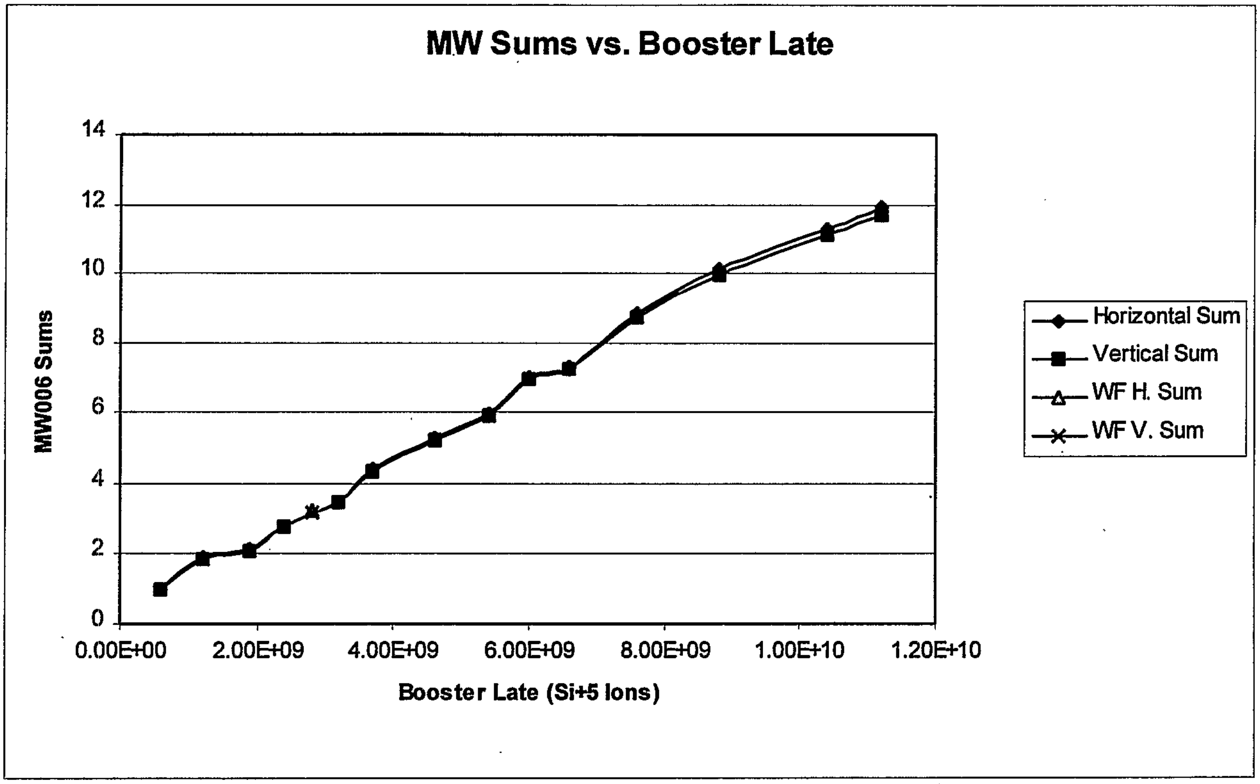

Figure 11: BTA MW006 Voltage Sums vs. Booster Late. Data is from table I. Window Frame (WF) points included.

The Window Frame:

Figure 5 (right) shows injection in the window frame case. In this case there is no discernable fast loss after the peak intensity is reached as opposed to the high intensity case (fig. 5 left). From this one might expect the intensity at 2.5 ms after the peak to be closer to the peak intensity than it is in the 'multiwire' case with similar peak intensity. However, figure 8 (peak intensity vs. intensity @ 2.5 ms after peak) shows no evidence of this. This would be consistent if the fast loss did not occur in the 'multiwire' case at this peak intensity. On the other hand, if the amount of fast loss was dependent on the input intensity one would naively expect the data in figure 8 to be non-linear. The dependence of the fast loss on input (or peak) intensity was not investigated in this study.

The shape of the TTB current pulse downstream of the window frame changes when the window frame is inserted (figure 5). Could this be a consequence of the asymmetric shape of the profile at the window frame (figure 2)?

Figure 13 shows the TTB section 29 multiwires before the study began (iris @ 4.3, no multiwires inserted) and with the window frame inserted (iris @ 8, fully opened). The differences in position at 29MW090 in the two cases are most likely due to steering changes made after the iris was fully opened to optimize the injection efficiency.

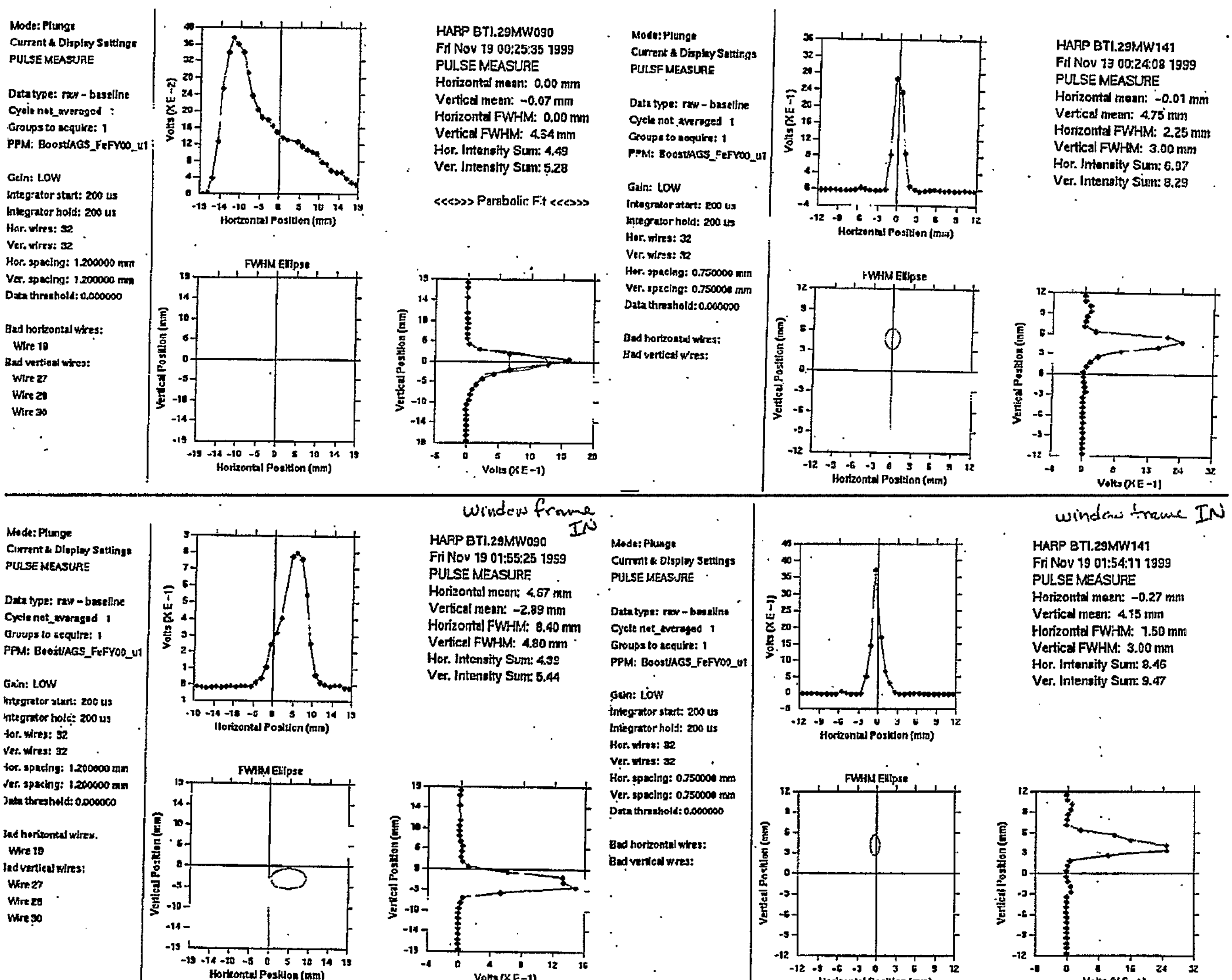

Figure 13: TTB section 29 multiwires before the study began (top) and after the window frame was inserted towards the end of the study (bottom).

The shape at 29MW090 is also different in the two cases. Most notably, the peculiar shape that may be associated with scraping upstream is not there. The vertical profile appears generally wider in the window frame case, though its base is slightly narrower (7-8 wires vs. 9 wires). One expects that a larger iris setting (8 vs. 4.3) would tend to make the profile wider, and that the window frame would shave off the particles with larger oscillations in both the H. and V. dimensions, thereby reducing the base's width. These profiles are not obviously inconsistent with these expectations.

As for the 29MW141 profiles:

1) The horizontal profile at 29MW141 is generally much narrower in the window frame case, but its base is actually wider (7 wires vs. 5 wires).
2) The vertical profile at 29MW141 appears slightly wider for the window frame, but is actually slightly narrower at its base (7 wires vs. 8 wires).

The vertical profile is not inconsistent with expectations. It is not clear what to conclude about the horizontal.

In figures 8-12 the window frame data fits pretty closely with the data for the multiwire cases. However, figures 6 and 7 indicate that the horizontal profile is not as square in the window frame case. This may in part be caused by the fact that the profile is narrower (the vertical profile is narrower as well).

Summary

It's speculated that the reason the horizontal profile at MW006 for Fe^{10+} is 'square' is that the charge distribution which arises from the injection process is preserved through acceleration. It's also thought that above some space charge related threshold it will not be preserved. It was observed that the Si^{5+} beam was not 'square'. Since the Si^{5+} and Fe^{10+} setups were nearly identical, this observation lead to the speculation that the Silicon beam was above this space charge related threshold. If this is true, the shape of the Si^{5+} horizontal profile should become squarer as the injected intensity is lowered.

The injected intensity was adjusted by inserting multiple harps in TTB and the profiles at MW006 were examined for any changes in shape. The horizontal profile did appear to become squarer as the intensity was reduced. There were no other effects found associated with these intensity changes which lend themselves to an explanation related to space charge forces.

Reference

FY '99 HIP Setup Booster/AGS/RHIC Book II, pgs. 53, 57-58, 93-103