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Studies of Plan B

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Abstract

This note looks at test data for plan B for the Tevatron BPM upgrade, measurement of the Pbar position by gating the electronics to acquire data only when Pbars are present but protons are absent. The data from April 8 are discussed in detail, showing many fine structures at various phases of a shot. This work uncovered a problem with the Pbar resolution which was ultimately traced to a problem with the filters used on the Pbar cables. It is also shown that the problem can be solved by adding appropriate filters. The note concludes with a list of open questions, the most important of which is understanding and eliminating a large step in the proton position. The step is probably an artifact of the details of the timing used for this test and can be addressed in several ways.

Contents

1 Introduction

The data discussed in the main body of this document were taken on April 8, 2004 during the shot which started at about 0:45 AM. The data are VA14 BPM measurements data logged at 15 Hz in the so called "Plan B" mode, also known as the wide-band mode, in which the BPM electronics is gated to see only a few bunches of each species. The raw data from the data logger consist of 4 (I, Q) pairs, one each for the A and B cables of the proton and Pbar cables.

This note also discusses some VA14 BPM measurements taken on April 14 to study the effect of additional filters to reduce aliasing of high frequencies into the signal region.

2 Timing

Figure 1 shows a cartoon of the timing used for these measurements. The cartoon is a rough copy of a sketch which Bob Webber drew on the blackboard so don't take any of the edges of the timing windows as precise. Part a) shows the arrival times of the Proton and Pbar bunches at BPM VA14 when the accelerator cogging state is collision point cogging. The cartoon shows that two Pbar bunches arrive first, followed by ten nearly coincident P and Pbar bunches. Finally two isolated proton bunches arrive. The gates used for the proton and Pbar measurements are also shown. During the time marked "Proton Measurement Window", the signals from the proton cables are digitized, down-converted and so on. During the time marked "Pbar Measurement Window", the signals from the Pbar cables are digitized, down-converted and so on. Both gates are the same length, about 800 ns. During the Pbar measurement there is no significant proton signal but there is significant Pbar signal present during the proton gate.

The electronics are configured so that the timing windows do not change with changes to the cogging state of the accelerator. Part b) of the figure shows the same information as part a) but immediately after Pbar injection is complete and before the transition to collision point cogging. In this state, there are neither protons nor Pbars present during the Pbar gate. There are both proton and Pbar bunches present inside the proton gate. Finally, part c) shows the cogging timing immediately after the injection of Pbar bunches 5 to 8 and before the cogging which occurs between injection of Pbar bunches 8 and 9. Again, neither protons nor Pbars are present during the Pbar gate. In this case only protons are present during the proton gate.

3 Overview of the Signals

Figure 2 shows a summary of the raw A, raw B, sum and position signals for both protons and Pbars. No corrections were made to the A and B signals when computing the sum and position signals. The sum and position are defined as,

$$\text{Sum} = |\mathbf{A}| + |\mathbf{B}| \quad (1)$$

$$\text{Position} = 26\frac{|\mathbf{B}| - |\mathbf{A}|}{|\mathbf{B}| + |\mathbf{A}|} \quad (2)$$

where **A** and **B** are the complex numbers (I, Q) coming from the Echotek card. For reference the two raw data plots show the ACNET variables `T:IBEAM`, a measure of total current in the two beams, and `T:FBIANG`, a measure of the Pbar current. The axis units for these last two quantities are discussed in the figure caption. The distinctive pattern of a shot can be seen in both `T:IBEAM` and `T:FBIANG`. The Pbar position signal is drawn only for times at which a significant Pbar sum signal is present.

From this page we can see many features, some of which will be shown in more detail in the following sections:

- The proton signal from the BPM jumps from zero to full strength almost immediately after proton injection starts.
- The Pbar signal stays at zero throughout the Pbar injection and jumps to full strength shortly afterward, when the final cogging takes place.
- The proton and Pbar positions are reasonably stable as soon as their respective signals are present.
- The helix opening is clear.
- The increase in the sum signal during the ramp is clear.

4 Details of the Signals

4.1 Detail at Proton Injection

The top two plots in Figure 3 show a continuous time series of the proton sum signal with the ACNET variable `T:IBEAM` superimposed. Note the change in scale between the two plots. From these plots we see that the proton sum signal goes to full strength in one small step and two large steps, which coincide with the injection of the first three proton bunches. The final step is a little smaller than the middle step, although the corresponding steps in `T:IBEAM` are much closer to the same size. This pattern of step sizes can be explained by reference to Figure 1: the proton gate captures only the tail of ringing filter for the first proton bunch, all of the second proton bunch and most, but not all, of the third proton bunch. Subsequent bunches are outside of the gate and contribute nothing to the signal.

The middle plot in Figure 3 shows the proton position signal for the same time interval as used in the top right hand plot. There is an large change in position, of about 2.5 mm, between the first and second bunches and a smaller one, of about 500 μm, between the second and third bunches. After that the position becomes reasonably stable.

The large step between the first two bunches is worrisome and must be understood and corrected. This step can be explained if the gate captures only the tail end of the ringing filter for bunch 1 and the A and B filters are less well matched for the short time interval within the gate than they are for the full time interval. If this is indeed the case, the problem can be solved by using a narrower Echotek bandwidth (longer gate) when a single species is in the machine. If this is not desired, the problem can be addressed by adjusting gates or by using filters which ring out sooner. In any case, such a solution will require a lot of work to set the gates differently for each BPM and, possibly, to match filters in pairs. In the worst case, it would require separate calibrations depending on the pattern of bunches in the machine.

The smaller step, of 500 μm is less worrisome as it is on the same scale as many other effects. If we need to address it, the same tools are available as discussed for mitigating the larger step.

The bottom plot in Figure 3 shows the proton position starting from the injection of the third bunch until just before the helix opens. The superimposed green curve shows the ACNET variable `T:IBEAM`. I think that the large structures in the blue curve are bumps that are part of the injection process but I need to confirm this. Except for these structures, the position signal is stable with a sigma of about 10 microns.

4.2 Detail at Pbar Injection

Figure 4 shows details of the proton position and sum signals during Pbar injection. On both plots the yellow curve, provided for reference, shows the ACNET variable `T:FBIANG`. The main feature of the top plot is a shift in the measured proton position of about 200 μm when the Pbars are cogged to prepare for the final set of Pbar injections. That is, the step occurs when the Pbar bunches are cogged from the timing shown in Figure 1c) to that shown in Figure 1b). Most likely this is an instrumental effect which arises because the first Pbar bunch now contributes some signal within the proton gate. The proton sum signal also exhibits a step at the same time. There are also glitches in the proton position that are correlated in time with the Pbar injections. I don't yet know if these correspond to the planned beam motions, unexpected beam motion or an instrumental effect.

4.3 Detail at Final Cogging

Final cogging takes the timing shown in Figure 2b) to that shown in Figure 2a).

Figure 5 shows details of the Pbar sum and position signals during the ramp and final cogging. It also shows the proton position signal during this time. The blue lines in the top two plots show a continuous time series of the Pbar sum signal, with a scale change at the time that the Pbar signal starts to appear within the Pbar measurement gate. The yellow line shows the value of the

ACNET variable `T:ERING`. The noise on the Pbar cables appears to drop during the energy ramp; this is not yet understood.

The top right plot is interpreted as the Pbar sum signal rising to full strength in two steps, as the two bunches are cogged into the Pbar gate. Reference to Figure 2 shows that the Pbar signal should start to appear within the Pbar gate when the cogging process is about 50% complete. If one assumes that the cogging takes place at a constant rate, the cogging started close to t=1.303 hours, which is just to the left of the left edge of the top right plot. I do not yet have an ACNET variable which can be used to confirm this interpretation.

The bottom right plot shows the Pbar signal for the same time interval as the upper right plot. The measured position wanders by about ± 200 μm during the cogging process. I don't understand this yet. Could it be due to energy changes, which are part of the cogging process, causing changes to the orbit radius?

The bottom left plot shows the proton signal during the final cogging. To be precise, the time interval from the green vertical line to the right edge of the plot corresponds to the same time interval as the Pbar position plot. The features of this plot are a burst of noise starting near t=1.303 hours and a position step of about 400 μm, comparing the times before and after the noise. Earlier I argued that the cogging process probably started at about t=1.303 hours. So the noise is likely due to the leading Pbar bunches being cogged through the proton gate. The step in proton position is probably an instrumental effect due to the difference in the amount of Pbar signal which appears on the proton cables within the proton gate.

4.4 Detail of Squeeze and Initiate Collisions

Figure 6 shows the proton and Pbar positions starting just after the final cogging. This includes the squeeze and the start of collisions. The purple curves show the ACNET variable `C:B1SHM`, the voltage on one of the horizontal separators.[1] The main feature of this plot is that the Pbar resolution is much poorer than the proton resolution. A second feature is that the beam motion during the squeeze is approximately mirror image but not truly equal and opposite this may reflect motion of the central orbit or a calibration problem.

4.5 Proton and Pbar Resolution

To study the resolution of the device, I selected proton and Pbar positions from the time interval between the green lines in Figure 6. The projection of these data on the position axis are shown as the left hand plots in Figure 7. The proton resolution is well described by a single gaussian but the Pbar resolution is described by the superposition of 5 gaussians, with different means but approximately equal widths.

The proton resolution was parameterized using a gaussian function with all three parameters free. The parameters of the function were determined using a

[1] This is a vertical BPM but I saved the information for only `C:B1SHM`.

binned maximum likelihood fit, the result of which is superimposed as the red curve in the upper left plot. The red curve is drawn only over those bins which were included in the fit. The fit yields a resolution of 11.1 μm.

The Pbar resolution was similarly determined by fitting the leftmost peak of the 5-peak pattern. The result of the fit is superimposed as the red curve on the lower left plot. The fit yields a resolution of 13.8 μm.

The instability in the Pbar resolution is explored in the bottom right plot, which shows a scatter plot of the phase of the Pbar A signal vs the Pbar position. The phase is defined as the phase of the complex number (I, Q) that is produced by the Echotek board. A further discussion of this problem, and its resolution, can be found in section 5.

For completeness, the top right plot shows the phase of the proton A signal plotted against the proton position. The proton positions are stable with respect to the phase of the proton A signal.

The right hand plots look similar regardless of which of the four cables, P or Pbar, A or B, is used for the phase of the vertical axis. That is, the phases of all 4 cables are fixed fixed relative to each other.

5 Understanding the Pbar Position Instability

The pattern of 5 allowed phases was explained in Beams-doc-1066. The bottom line in this explanation is that the digitization clock runs at 7/5 of the RF frequency but number of buckets in one turn of the Tevatron, 1113, is not evenly divisible by 5. So, on any measurement triggered by the turn marker, the digitization clock has one of 5 possible phases with respect to the turn marker. In the frequency domain, this shows up as a phase shift in the complex number (I, Q) produced by the Echotek board. In the time domain this effect appears as jitter of the gate — the gate is tied to the digitization clock but the timing of the bunches is tied to the RF clock.

Figure 7 showed that both the proton and Pbar positions can be sorted according to the phase of their A signal. For the protons, the position does not depend on this phase but, for the Pbars there is a strong dependence. The reason for this is that the band pass filters between the cables and the Echotek boards are different for the protons and the Pbars. Both sets of filters had center frequencies near 50 MHz. The proton filters had a width of about 9 MHz, while the Pbar filters had a width of about 3 MHz. Bob Webber says that he looked at the signals on a scope and that both the protons and Pbar signals had rung out well before the end of the gate. So the bandwidth of the filters is not the issue.

It is also believed that the Pbar filters had poorer attenuation at very high frequencies. Therefore these filters allowed more high frequency energy to reach the digitizers. Some of these frequencies can be aliased onto the 21.2 MHz down-conversion frequency. In this case the measured complex number, (I, Q) has contributions from the 2/5 RF frequency of interest plus other contributions from aliased frequencies.

One can think of the final (I, Q) as a the vector sum of several components, the component of interest plus aliased noise components. When the phase of the digitizing clock is changed, each component will pick up a different phase shift. Therefore the vector sum will also change both in phase and magnitude.

To test this hypothesis, Jim Steimel and Bob Webber installed a 70 MHz low pass filter on the Pbar cables, in series with the band pass filter. If the explanation is correct, then we expect the multiple peaks of the Pbar resolution to merge into a single peak. In this exercise, which was done on April 14, two measurements were made, one before the new filter was added, Figure 8, and one after the new filter was added, Figure 9. Both of these figures show the same information as was presented in Figure 7. In the new baseline, Figure 8, we see that the effect is still present although it has changed in detail. After the new filter was added, Figure 9, the effect has been greatly reduced.

More careful inspection of these figures shows that the resolutions of the Pbar signals have changed. In Figure 7 the Pbar resolution was measured to be about 13.8 μm while in Figure 9 it is about 21.1 μm. A small part of this broadening arises from the small phase dependent effect which remains; if the data is fitted in each phase separately (not shown), the mean resolution is about 20.5 μm. This is true both before and after the low pass filter was added so it cannot be the dominant effect.

Another candidate for the dominant effect is that the beam intensity for the measurements on April 14 was about half that of those those made on April 8. It is possible that, at the lower intensities, we are starting to see the dominance of the digitization granularity over other contributions to the resolution. This hypothesis needs to be checked. That hypothesis must also be checked against the much smaller change in the proton resolution. According to Figure 2 the proton sum signal is about four times the Pbar sum signal — so it is possible that these signals are large enough that the digitization granularity is not dominant.

There is an apparent drop in the proton resolution from Figures 8 to 9, even though the the filters are unchanged and the beam current has decreased. This occurs because there is a small step, of a few microns, in the data used for Figure 8. There is no such step for the data used in Figure 9.

6 Open Questions

There is one major problem which remains:

1. Figure 3, middle plot. Do I correctly understand the two steps in the position as the second and third bunches are injected? Is there a satisfactory strategy to reduce these effects to an acceptable level.?

There are also some smaller issues:

1. Figure 3, bottom. Confirm that the big structures are “injection bumps”.

2. Figure 4. Are the glitches the position programmed beam motion or something else?

3. Figure 4. What are the glitches in the sum signal?
4. Figure 5. Why does the Pbar noise level drop during the ramp?
5. Figure 5. Why does the measured Pbar position oscillate during the cogging. Energy changes causing radius changes? An instrumental effect?
6. Figure 5. Do I correctly understand the noise burst and the step in the proton position?
7. Figure 6. The motion is not equal and opposite. Is this a calibration issue or does it indicate that the central orbit changed? Or both? How can we tell?
8. Figure 7 to 9. Does change in beam current explain the change in resolution for the Pbar? Is that model consistent with the smaller change for the protons?

7 Summary and Conclusions

The technique appears fundamentally sound but two major problems have been identified. The problem with the poor Pbar resolution has been understood and can be solved by careful specification of the filters. The problem with the step in proton position can be solved by using a narrow band solution when there is only one species in the machine. Other solutions to the latter problem appear to require significant fiddling of timing and filters for each BPM independently.

There also remain a number of smaller problems which need to be understood. In many cases we can live with no mitigation of these problems since they produces biases on the order of a few hundred microns, on the scale of many other effects.

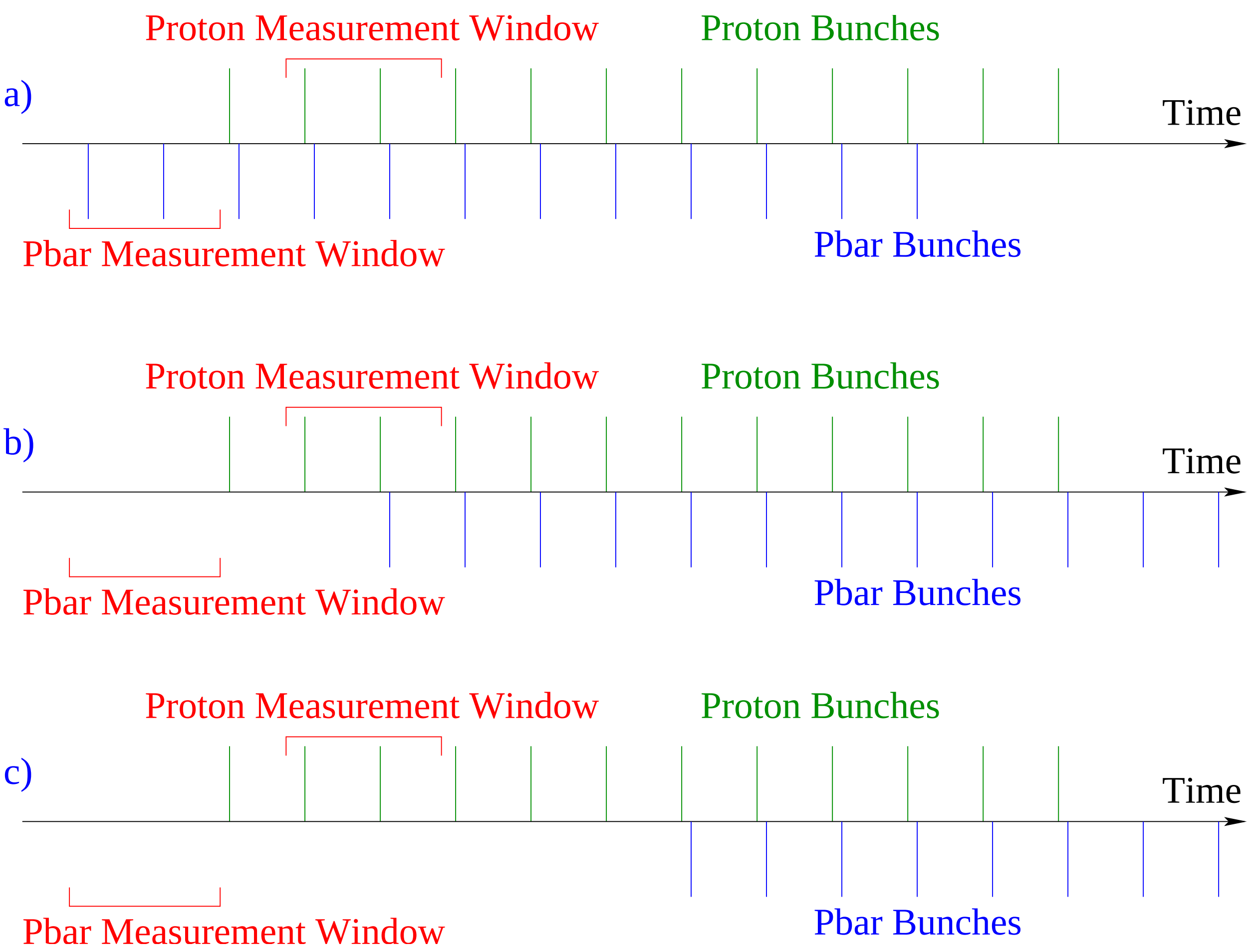

Figure 1: Cartoon of the arrival times of the P and Pbar bunches at VA14 for a) collision point cogging, b) the time after the injection of the last 4 Pbar bunches in each train but before the transition to collision point cogging, and c) the time after the injection of Pbar bunches 5 to 8 and before the cogging between bunches 8 and 9. The gates for the position measurement are also shown. The figures are further described in the text.

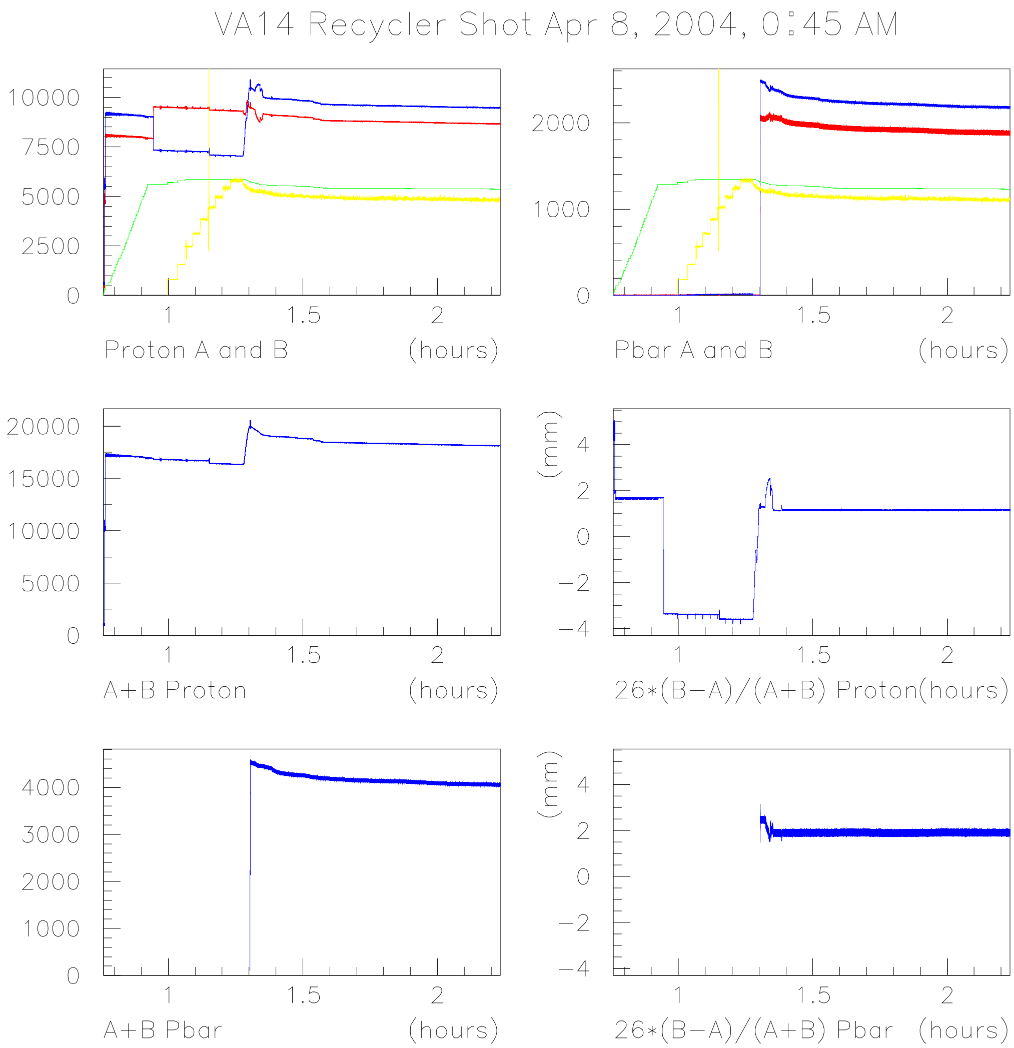

Figure 2: In the top two plots the red and blue curves show, respectively the A and B signals from the proton and Pbar cables. For all plots on this page the horizontal axis is hours from midnight on April 8, 2004. The vertical scale is for the red and blue curves and is in units of magnitude of Echotek output. The green curve shows the ACNET variable T:IBEAM (full scale 0 to 20), which measures the sum of the proton and Pbar beam currents. The yellow curve shows T:FBIANG (full scale 0 to 2500), which measures the Pbar current. The next four plots show the position and sum signals derived from the raw proton and Pbar, A and B measurements.

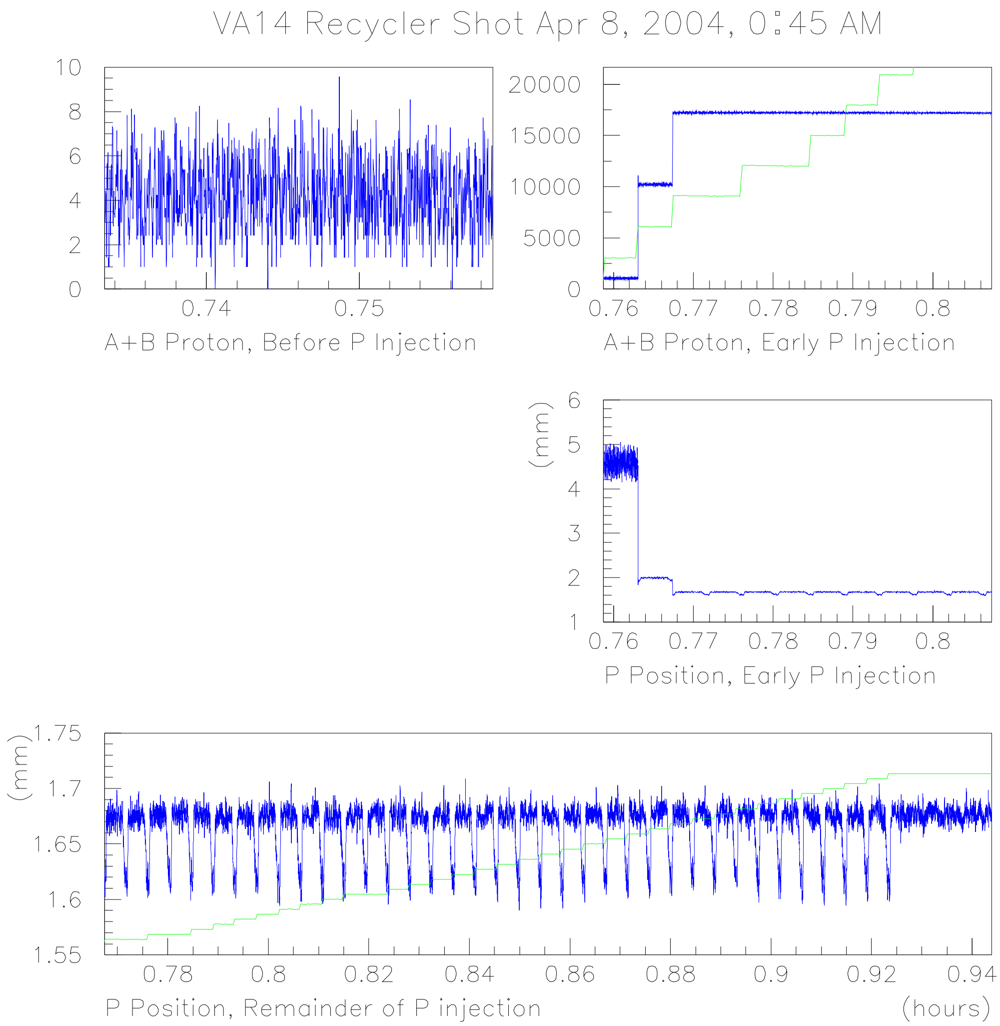

Figure 3: The top two plots show a continuous time series of the proton sum signal — the first bin in the right hand plot occurs 1/15 of a second after the last bin in the left hand plot. Note the change in vertical scale. The green curve in the right hand plot shows the ACNET variable `T:IBEAM` (full scale 0 to 2). For all plots on this page the horizontal axis is time, in units of hour of the day. The middle plot shows the proton position for same time interval as the sum plot above it. The bottom plot shows the proton position from the injection of the third proton bunch to just before the helix opens. The superimposed green curve shows `T:IBEAM` (full scale 0 to 12). Note the change in vertical scale between the middle and bottom plots.

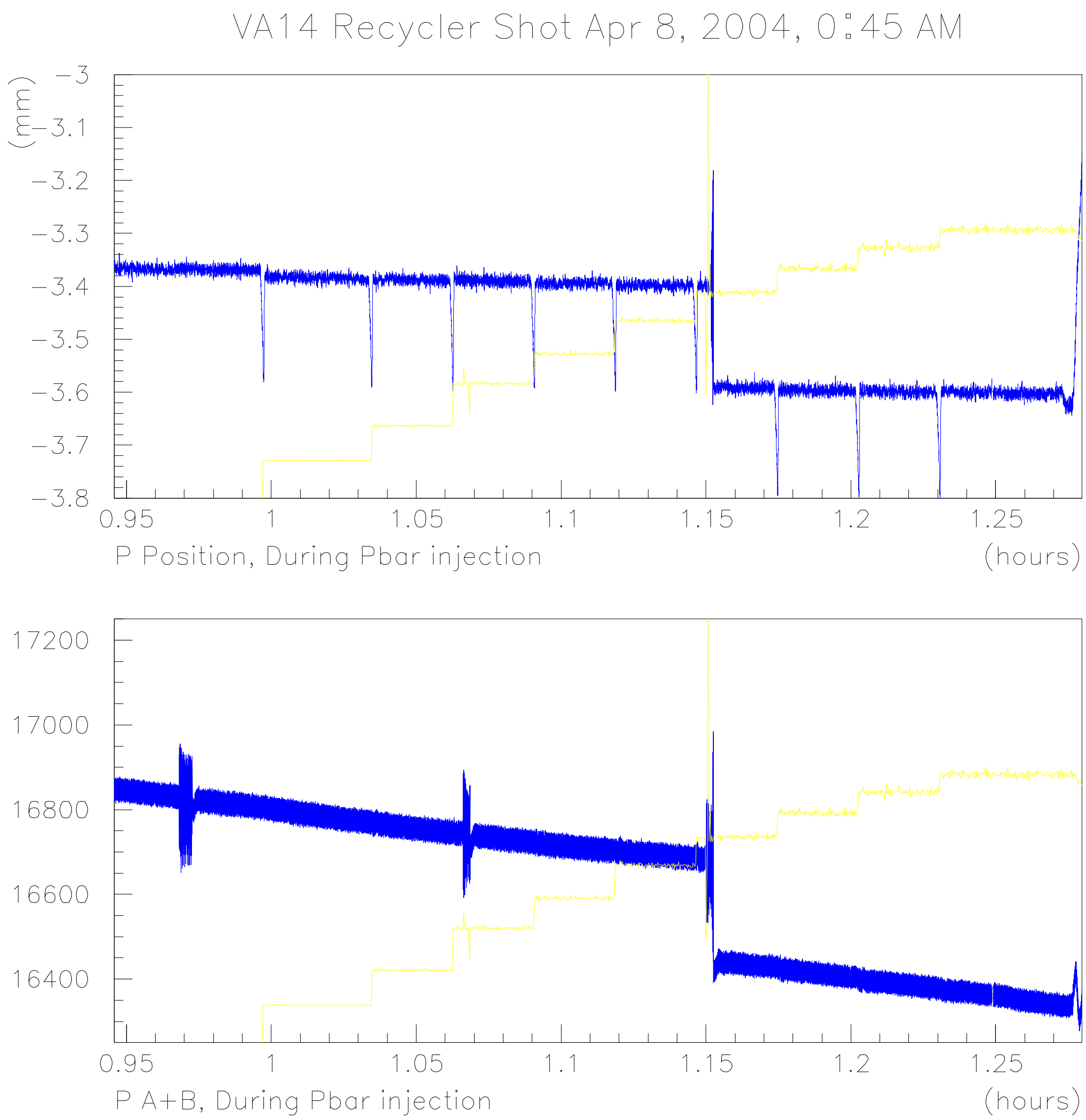

Figure 4: The top plot the blue line shows the proton position during the Pbar injection. For reference, the yellow line shows the ACNET variable `T:FBIANG`, a measure of the Pbar current. The bottom plot shows the proton sum signal for this same time, along with the same yellow reference curve. On both plots the vertical scales of the positions are highly zoomed and the vertical scale of `T:FBIANG` is 0 to 2000.

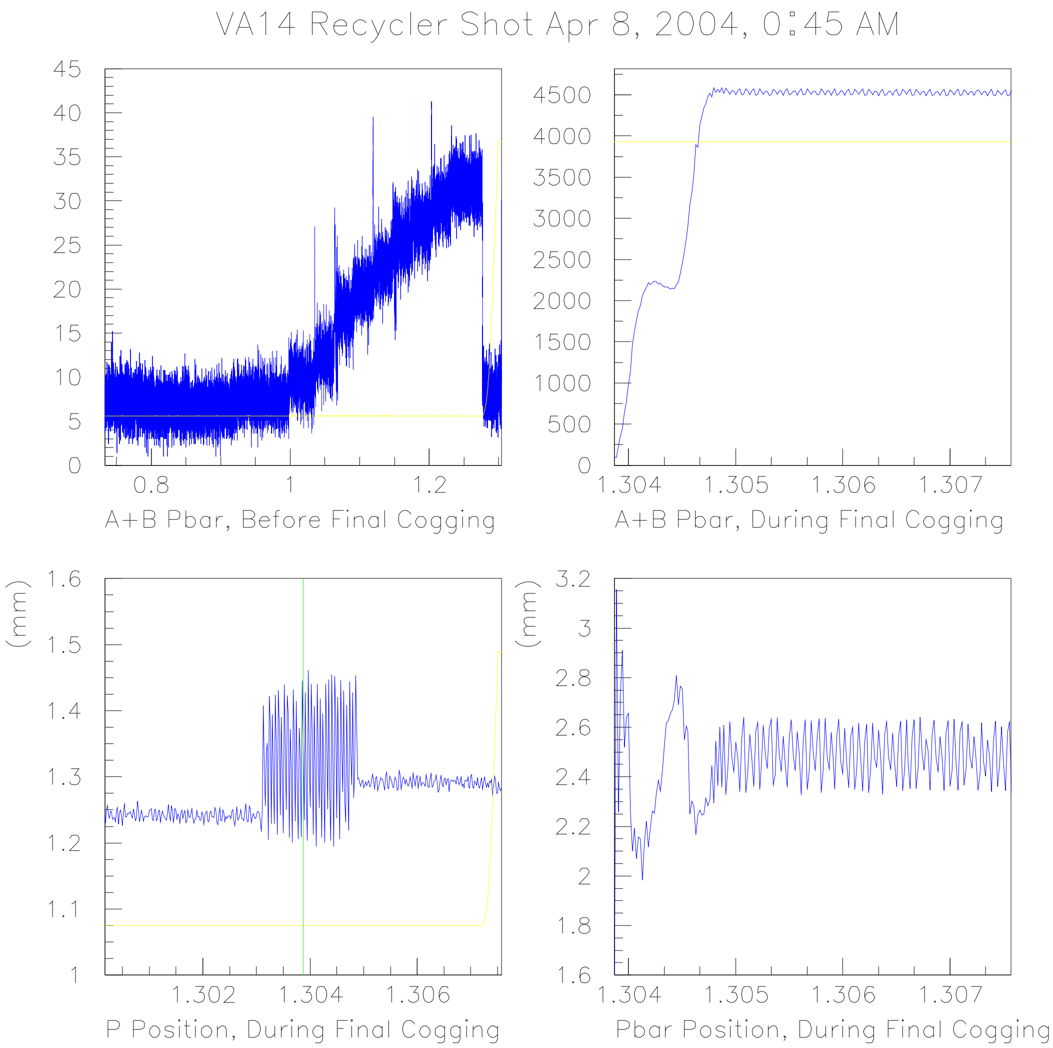

Figure 5: The blue line in the top two plots shows a continuous time series of the Pbar sum signal — the first bin in the right hand plot occurs 1/15 of a second after the last bin in the left hand plot. Note the change in vertical scale. The yellow line on both plots shows the ACNET variable `T:ERING`. The bottom right plot shows the Pbar position for the same time interval as shown on the top right plot. The bottom left plot shows the proton position for a slightly longer time interval; vertical green line marks the time corresponding to the left edge of the previous plot. The yellow curve shows the ACNET variable `T:ERING`. For all plots the vertical scale for `T:ERING` is 0 to 1200 GeV.

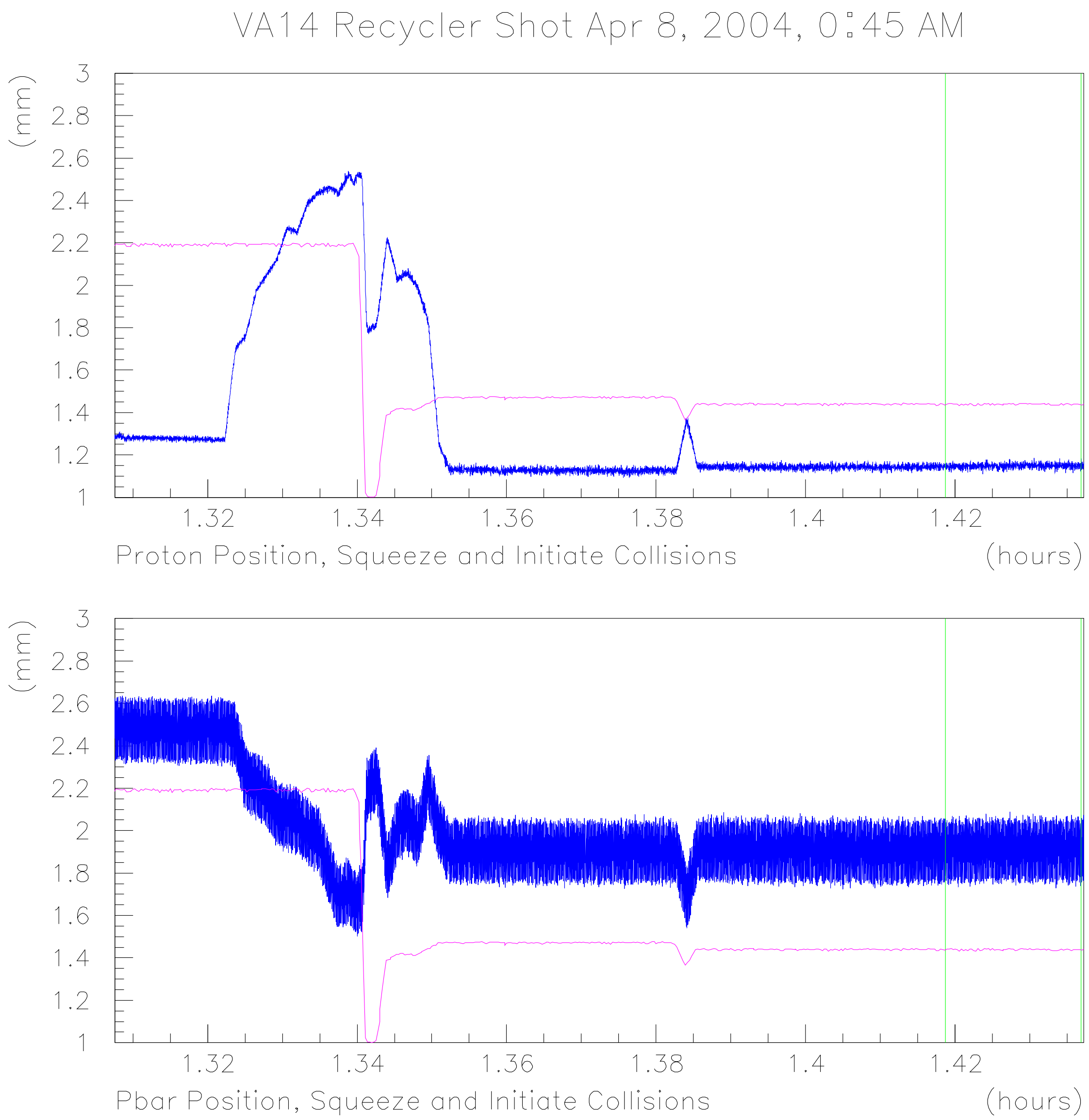

Figure 6: The blue lines show the proton and Pbar positions as a function of time, starting just after the final cogging, through the squeeze and the start of collisions. The purple lines show ACNET variable `C:B1SHM`, the voltage on one of the horizontal separators. The vertical scale for `C:B1SHM` is 0 to 200. The green lines indicate the range of data selected to measure the resolution of each beam species.

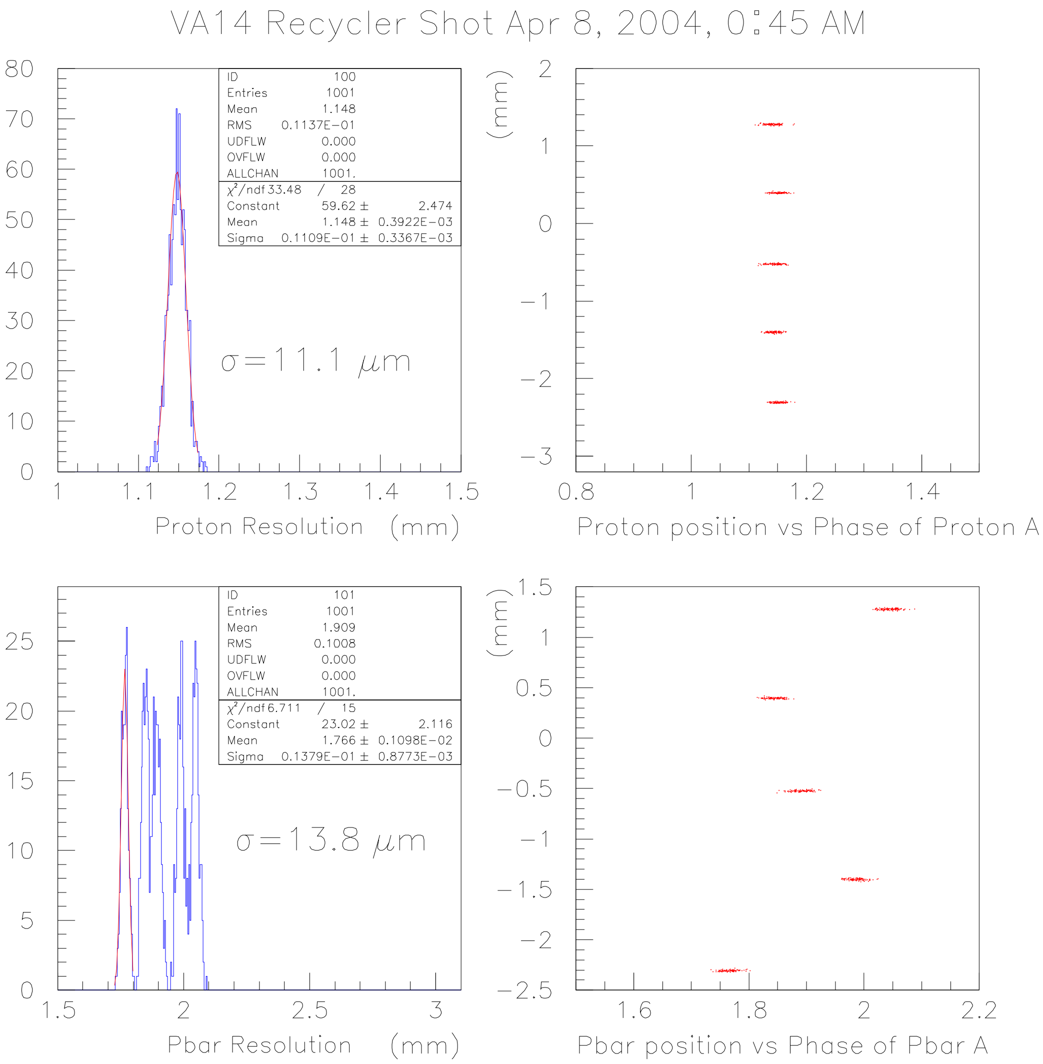

Figure 7: The top left plot shows the proton resolution. The histogram was obtained by taking data from between the green lines on the previous figure and projecting it onto the position axis. The superimposed red curve shows the result of a fit described in the text. The upper right hand plot is a scatter plot of the phase of the proton A signal vs the proton position. The lower plots show the same information for the Pbar signal; for the lower right plot the vertical axis is the phase of the Pbar A signal.

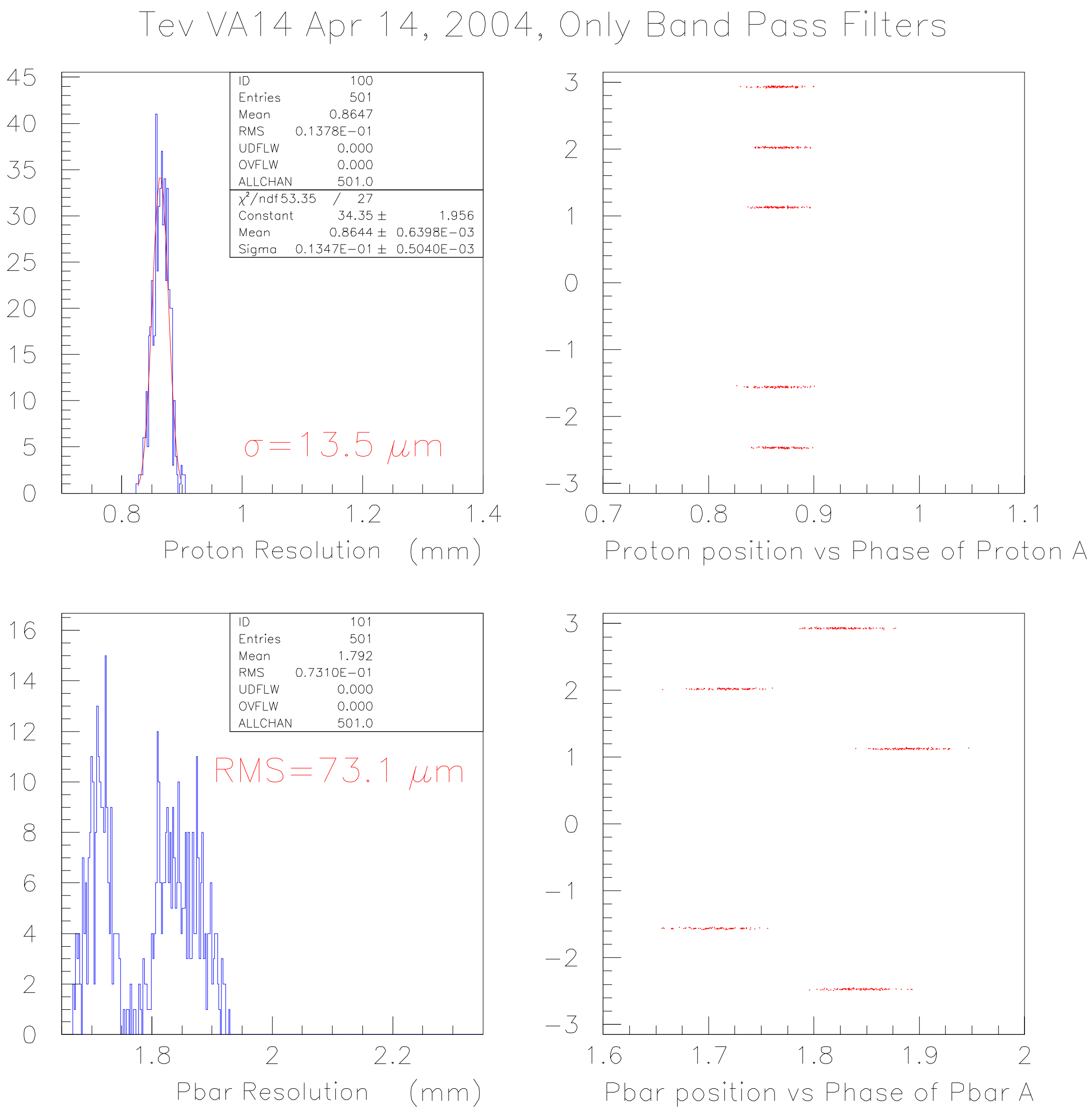

Figure 8: Same information as Figure 7 but for data from April 14, 2004 before the low pass filter was added.

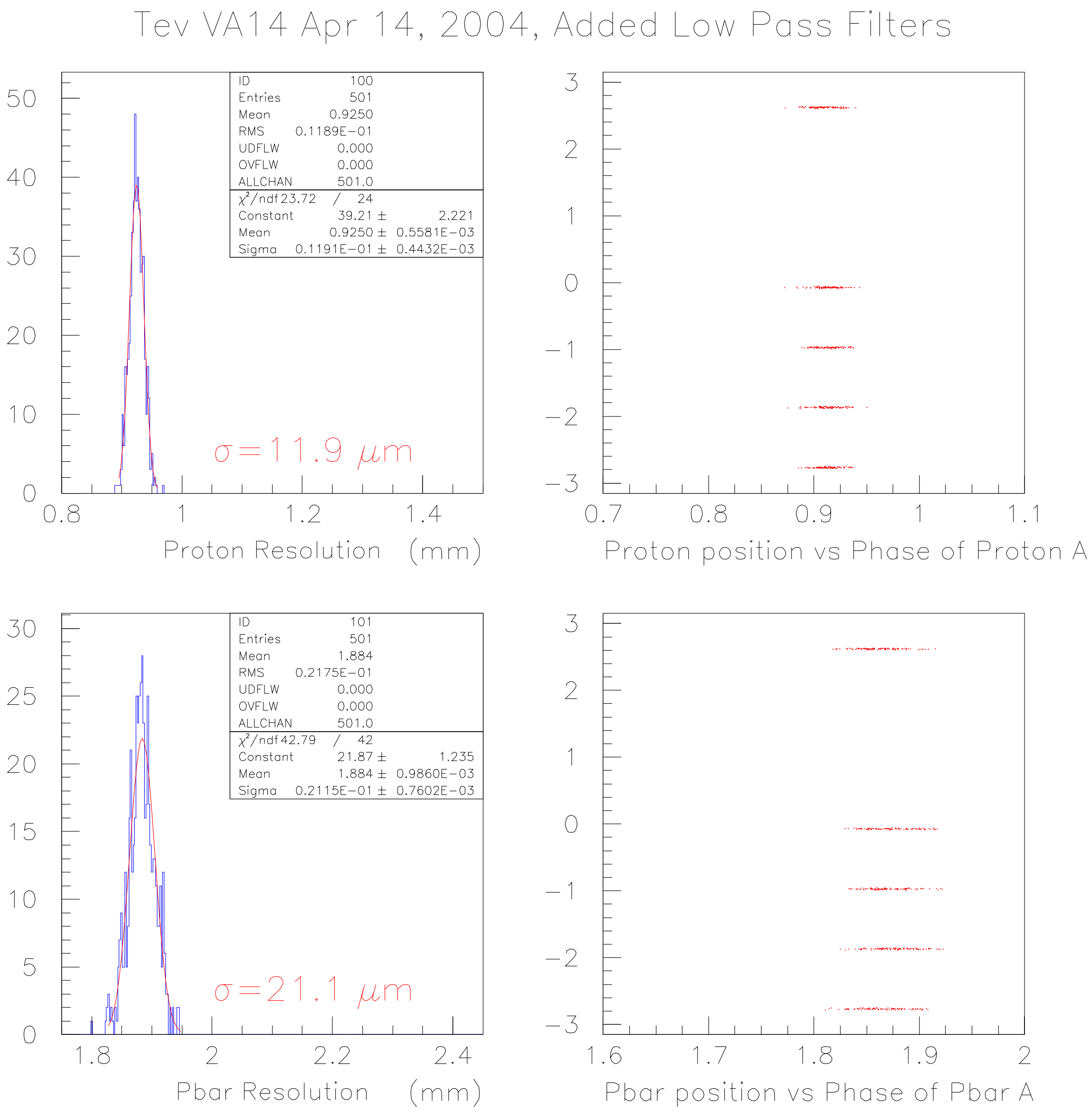

Figure 9: Same information as Figure 8 but for the data from April 14, 2004 after a 70 MHz low pass filter was added in series with the band pass filter.