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# A Detailed Look at Closed Orbit Data for the Upgraded MI BPMS

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**Abstract**

This note presents a measurement of the closed orbit position resolution of the upgraded MI BPM system, using the 53 MHz component of the signal. It also measures the repeatability of the orbit over 291 instances of MI state 21, NUMI multi-batch. The position resolution for the vertical BPMs is measured to be less than 3 $\mu$m (1 $\sigma$) and the cycle-to-cycle beam position repeatability for the vertical BPMs is measured to be less than about 10 $\mu$m (1 $\sigma$); close to extraction, the cycle-to-cycle repeatability is at the level of the resolution of the BPMs, about 3 $\mu$m. For the horizontal BPMs the MI state studied does not provide a time interval during which the beam position is stable enough to easily measure the position resolution. This note presents some numbers, of order 10 to 15 $\mu$m that should probably be interpretted as upper limits. A related problem inflates the measurements of the repeatability of the orbits in the horizontal plane. It was also observed that the system drops about half of the data, making the effective closed orbit sampling rate about 250 Hz, not 500 Hz. Steve Foulkes has fixed this problem while I have been writing this up; the updated code should be installed at MI40 soon if it is not already.

## Contents



## 1 Introduction

To read this note one must distinguish two related ideas, the intrinsic position resolution of the BPM system and the repeatability of the orbits. I will try to use language that keeps the two distinguished.

The data shown in this note are closed orbit data from 291 cycles of MI state 21, NUMI multi-batch, collected on February 7, 2006 between 4:00 and 4:30 PM. To acquire this data the front ends were put into state dependent mode with a special program:

- Wait for the start of a new state.
- Set the transition board gain to low and the Echotek configuration to 53 MHz narrow band.
- Clear the closed orbit buffer.
- Start taking closed orbit data.
- When the end of beam occurs, stop taking data and write the closed orbit buffer to disk.

This procedure will acquire data during one cycle, skip a few cycles while the front end is writing data, and then take data on the next available cycle. Data was written to disk for all 11 BPMs in MI40 that were instrumented with the new electronics.

The original dataset consisted of 302 cycles. Of these 291 cycles were selected for further study. In all of the 291 cycles selected, the first measurement with beam is at tick 29 and the last measurement with beam is at tick 307. For all of the 291 cycles selected the beam intensity, measured on the last measurement with beam, is stable within 2.5% of its mean value. A total of 11 cycles were excluded for the following reasons:

- 5 cycles were actually state 5, mixed mode, not state 21.
- On 4 cycles the beam arrived or departed at a different measurement number.
- 2 cycles had an anomalously low beam intensity.

# 2 The Data

Figures 1 through 3 show typical sum and position data for each BPM. The main features that can be seen in these plots are:

- The six injections and the single extraction.
- The decline in sum signal as cable length increases from V403 through V413.
- There is no evidence of saturation in the sum signal.
- There is only one time that the beam position is stable enough to allow a measurement of the position resolution on all BPMs: the last few measurements before extraction. Even this is marginal.

However the most important feature is more subtle. There are about 16 ticks of the 500 Hz clock between injections. The expected value is 33.3 ticks, the period corresponding to the 15 Hz Booster cycle. I spoke with Steve Foulkes about this and he discovered that the VME processor takes about 4 ms to read out all of the Echoteks in a fully populated crate. So the data shown are missing approximately every other data point. The conclusions reached by this study remain valid even with this error.

Figures 4 and 5 show a detail of the last 27 ticks before extraction for all BPMs in the data set. The upper left plot in figure 4 is an overlay of 291 histograms for BPM V403, one for each of the 291 cycles in the data sample. There are no entries outside of the displayed window. Similarly each of the other 10 plots is an overlay of 291 histograms. There are different vertical scales for the vertical BPMs, shown on the left with a full vertical scale of 100 $\mu$m, and for the horizontal BPMs, shown on the right with a full vertical scale of 700 $\mu$m. From these plots we can learn:

- Within a given time bin, the spread of points contains contributions from the resolution of the BPM and from the cycle to cycle variation of the beam position. It also contains a contribution from an artifact discussed in Section 5.
- For the vertical BPMs, the beam position is stable for about 8 to 15 ticks before extraction.
- For the horizontal BPMs, the beam position is never stable within the resolution of the BPMs. When the beam position has a steeper slope the spread of data points within a bin is larger. This is a consequence of the artifact discussed in Section 5.

The above data were processed to estimate of the resolution of the BPMs and the repeatability of the orbit.

## 3 Measuring the Position Resolution

Look at the plots in the left column (vertical BPMs) of Figures 4 and 5. In these plots the beam position is close to constant for the last eight ticks before injection. The plots in the right hand column, for horizontal BPMs, show a significant slope over the last 8 ticks with beam. In order to obtain an estimate for the resolution, the motion of the beam over the last 8 ticks was modeled as a straight line; clearly this will do a good job for the vertical BPMs but a poorer job for the horizontal BPMs. This issue will be revisited when full data sets, without missing points, are available.

For one cycle of V403, the last 8 points with beam were fitted using a straight line, using equal weights for all points. Then the RMS residual, $r_{\mathrm{RMS}}$, was computed,

$$r_{\mathrm{RMS}}^2 \quad = \quad \frac{N}{N-2} \sum_{i=0}^{N-1} \left[ p_i(\text{measured}) - p_i(\text{fit}) \right]^2 , \tag{1}$$

where $N = 8$ is the number of points used, $p_i$(measured) are the measured beam positions and where $p_i$(fit) are the beam positions predicted by the straight line model. The contributions to the RMS residual will be discussed in the next paragraph. The above exercise was done 291 times, once for each of the measured cycles of V403. The 291 measurements of the RMS residual are summarized as a histogram in the upper left plot of Figure 6. The data are tightly clustered with a mean value of $2.08 \pm 0.03$ $\mu$m, where the error is statistical only.[1] This mean value is recorded in Table 1. The remaining plots in Figures 6 and 7 show the results of the same exercise for the remaining BPMs. And mean values of these histograms are also recorded in Table 1.

The top plot in Figure 8 shows a summary of the data in Table 1, the RMS spread of the position plotted as a function of BPM name. In all cases the error on the point is smaller than the symbol size. The vertical BPMs all have small RMS spreads but most of the horizontal BPMs have much larger ones. Inspection of Figures 4 and 5 shows that a linear model is a good description for the beam motion over the last 8 ticks for the vertical BPMs but that it is a poor model for the horizontal BPMs. For the vertical BPMs, the RMS values have contributions from the intrinsic resolution of the BPMs plus unknown contributions from true beam motion. For purposes of this note, the unknown contribution will be ignored and the measured RMS values will be quoted as the nominal BPM resolutions; when a single nominal number is desired, the nominal resolution of the system will be quoted as less than 3 $\mu$m.

For the horizontal BPMs the true resolutions are presumably close to those for the vertical BPMs. However that cannot be proven with this data set. The best that can be said is that the resolutions are less than the quoted RMS spreads, which are presumably dominated by the poor quality of the linear model of the beam motion. But other explanations are possible. In the Tevatron, for example, there is persistent coherent motion that affects the horizontal BPMs, but not the vertical BPMs; this data set cannot exclude such an effect in the MI. This will be addressed in a later note.

The bottom plot in Figure 8 shows, for the vertical BPMs, the RMS position spread plotted as a function of the sum signal for that BPM. The sum signal was taken as the mean over the 291 cycles of the sum signal for the last tick before extraction. There is an indication that the resolution is poorer at smaller sum signal; the statistical significance is large but I have not seriously looked at other sources of error. I will look at the position resolution after each injection in order to extend this plot to lower values of the sum signal.

[1] The statistical error on the mean was computed as the RMS width of the histogram divided by $\sqrt{(N-1)}$.

| BPM | RMS Residual ($\mu$m) |
|---|---|
| v403 | $2.08 \pm 0.03$ |
| h404 | $4.07 \pm 0.04$ |
| v405 | $2.27 \pm 0.05$ |
| h406 | $8.08 \pm 0.22$ |
| v407 | $2.25 \pm 0.06$ |
| h408 | $12.56 \pm 0.42$ |
| v409 | $2.24 \pm 0.04$ |
| h410 | $13.63 \pm 0.38$ |
| v411 | $2.44 \pm 0.05$ |
| h412 | $14.48 \pm 0.36$ |
| v413 | $2.81 \pm 0.05$ |

Table 1: Summary of the study of the closed orbit position resolution. The right column contains the RMS residual from a linear model of the beam position over the last 8 ticks before extraction. The number quoted is the mean of 291 measurements of this quantity and the quoted error is the error on this mean. For the vertical BPMs the RMS residual is the best available estimate of the position resolution of the BPM system; for horizontal BPMs it probably measures the quality of the model of the beam motion.

# 4 Repeatability of the Orbits

Consider the upper left plot in Figure 4. For each bin in this plot I computed the mean and RMS of the 291 measurements. The upper row of plots in Figure 9 shows, for BPM V403, the mean value of the position within each time bin and the RMS spread of the position within each time bin; in this figure the data is shown for all time bins with data above threshold, not just for the last 27 bins. Except for a handful of time bins, the RMS spread of the data points is less than 10 $\mu$m. This represents the sum of the BPM resolution plus the cycle to cycle variation of the orbit. At times close to extraction the cycle-to-cycle variation is indistinguishable from the position resolution. At other times the repeatability is definitely much larger than the position resolution. The remaining plots in Figures 9 through 11 repeat the exercise for the remaining BPMs.

Inspection of Figures 9 through 11 shows several features:

- Many of the vertical BPMs show a sharp drop in the RMS after about 16 ticks. This is when the second batch is injected. At a few BPMs a sharp drop can be seen as other batches are injected. Is this a measure of the dependence of the resolution on the granularity of the digitizer? Is it some other intensity dependent effect? Or something else? This is not yet understood.

- The horizontal BPMs show an exponential-like drop of the RMS position right after injection. This is presumably the damping out of synchrotron oscillations of the bunch center.

- For many BPMs, at 166 ticks there is a sharp spike in the RMS. On these BPMs there is also sharp change in beam position at that time. This is another result of the artifact discussed in Section 5.
- For the vertical BPMs, almost all of the time bins have an RMS less than about 20 $\mu$m.
- For the horizontal BPMs, excluding the synchrotron oscillations and the spike at 166 ticks, most of the bins have an RMS of less than about 50 $\mu$m.

# 5 A Timing Artifact Masquerading as Bad Position Resolution

The RMS position spreads presented in the middle and right columns of Figures 9 through 11 contain contributions from three sources:

- The resolution of the BPM.
- Cycle-to-cycle variation in the beam position.
- An instrumental artifact that arises because the closed orbit sampling clock is not synchronized with the beam; it is described below.

According to Bill Haynes and Steve Foulkes, the "time zero" for the closed orbit 500 Hz clock is established when the VME processor writes to the appropriate registers in the timing board. This time is not synchronized with any of the detailed beam timing information. The "time zero" has some jitter arising from variable delays that depend on what the VME processor is doing when the timing board receives the master reset. On successive MI cycles, therefore, each closed orbit "tick" samples a slightly different part of the MI cycle. Now compare bins 300 to 307, the last eight ticks with beam, in right hand plots in Figure 4; all of these plots are on the same vertical scale. When the beam position is stable, as in the upper right plot, the detailed timing of the 500 Hz closed orbit sampling clock is irrelevant. When the beam position is changing rapidly enough, as in the other two right hand plots, a small change in timing causes the BPM to sample a different part of the cycle, when the beam is actually at another position. This causes the observed spread of the data points within each time bin.

The size of the effect should increase when the rate of beam motion increases. This can be seen in the plots for the horizontal BPMs in Figures 4 and 5. This is also the explanation for the large spikes in the RMS repeatability near 166 ticks that is seen in Figures 9 through 11.

This explanation raises a question: if the time jitter causes this artifact in the repeatability measurement why does the beam always appear at tick 29 and disappear after tick 307? First, there are a four cycles in which this does happen; I suppressed them in order to simplify coding. Second, we are systematically throwing out about half of the data points; it's possible, but not yet proven, that we almost always throw out the bin which sometimes contains beam and sometimes does not. This will be investigated further when a full data set, not skipping any turns, is available.

Should this time jitter effect inflate the resolutions presented in Table 1 and in figure 8? No. The resolutions were determined by fitting a straight line to the last 8 position measurements before extraction. This uses a single MI cycle; so it cannot be affected by by cycle-to-cycle variations in timing.

## 6 Summary and Conclusions

The data shown here demonstrate the the closed orbit position resolution for the vertical BPMs is less than 3 $\mu$m, with a best value of about 2 $\mu$m. The corresponding numbers for the horizontal BPMs are much larger but these are certainly contaminated by a poor model of the beam motion during the time that the resolution was determined. An improved model will follow in a later note.

Over most of MI cycle 21, the vertical positions have a cycle-to-cycle repeatability of less than 10 $\mu$m; close to extraction, the vertical positions have a cycle-to-cycle repeatability that is indistinguishable from the position resolution. The corresponding numbers for the horizontal position repeatability is not very meaningful because they are inflated by an artifact of the timing system.

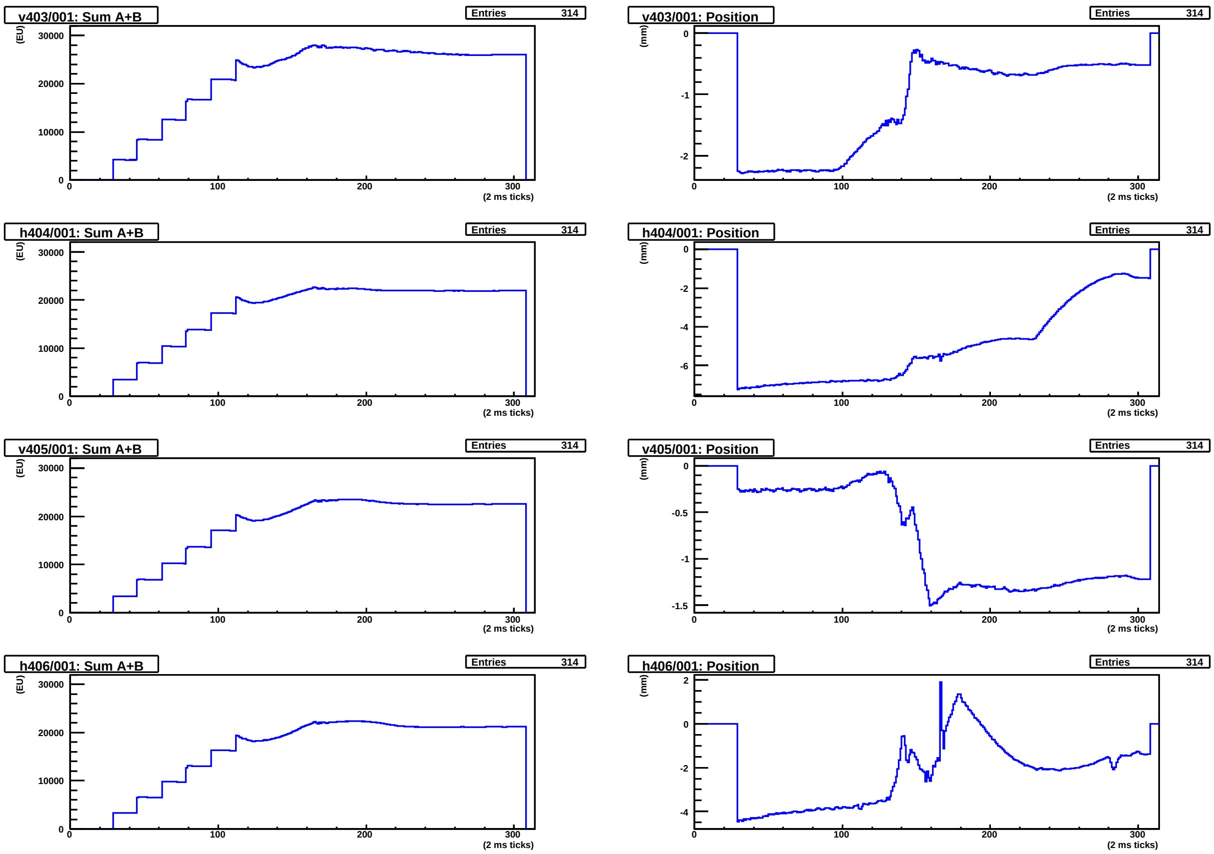



Figure 1: The top row shows closed orbit sum and position data for BPM V403 for one cycle of MI state 21 (NUMI multi-batch). The remaining three rows show the same information for three more BPMs. In all plots the horizontal axis is time measured in ticks of the 500 Hz closed orbit clocked. The vertical axis for the sum signal is in Echotek Units (EU) and has the same full scale for all BPMs. The vertical axis for the position is in mm but the scales vary from BPM to BPM. The position is computed to fifth order but the offsets are not included. The plots are discussed in the text.

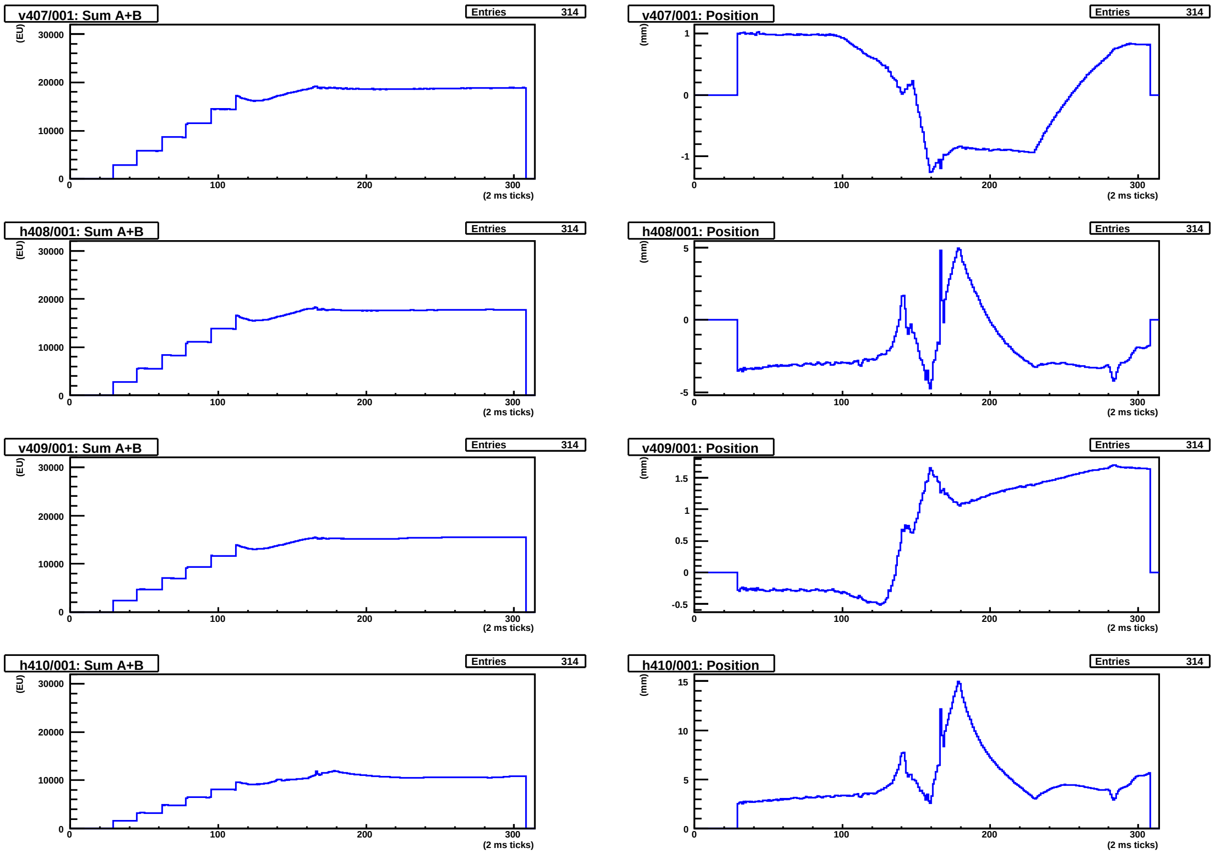



Figure 2: Continuation of Figure 1, showing data for four more BPMs. The plots are discussed in the text.

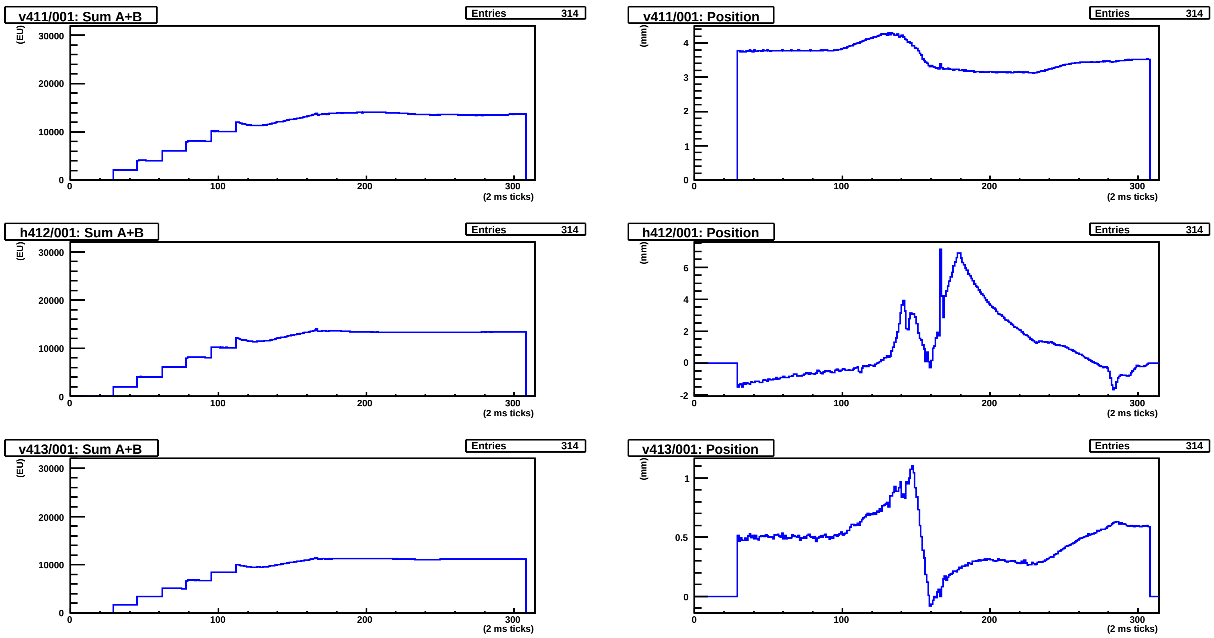



Figure 3: Continuation of Figure 1, showing data for three more BPMs. The plots are discussed in the text.

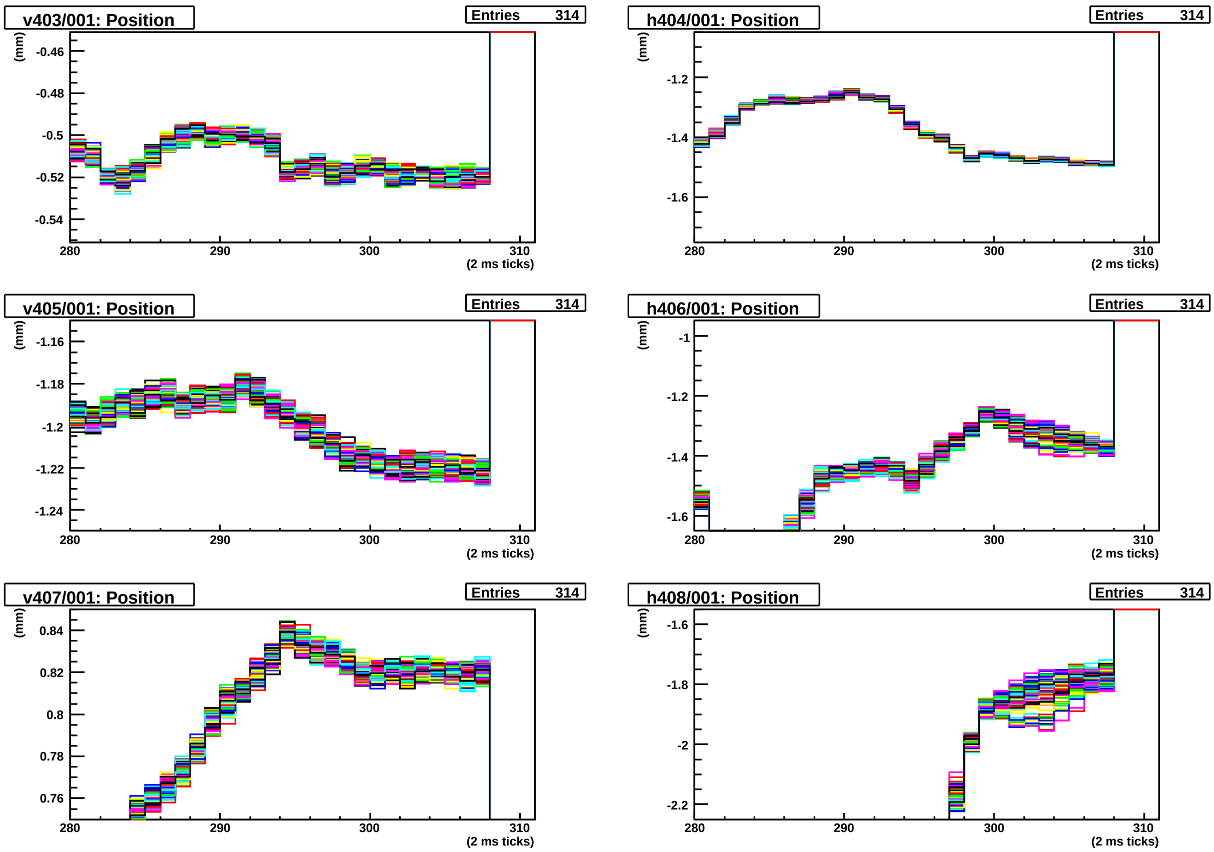



Figure 4: The upper left plot shows a detail of the position data for V403; the detail shows the last last 27 measurements before extraction plus a few after extraction. The plot shows all 291 measured cycles overlayed on top of each other. The position is highly repeatable. The remaining plots on the page show the same information for five other BPMS. All plots in the left column are for vertical BPMs and all have the same full vertical scale of 100 $\mu$m; all plots in the right column are for horizontal BPMs and all have a full vertical scale of 700 $\mu$m, The plots are discussed in the text.

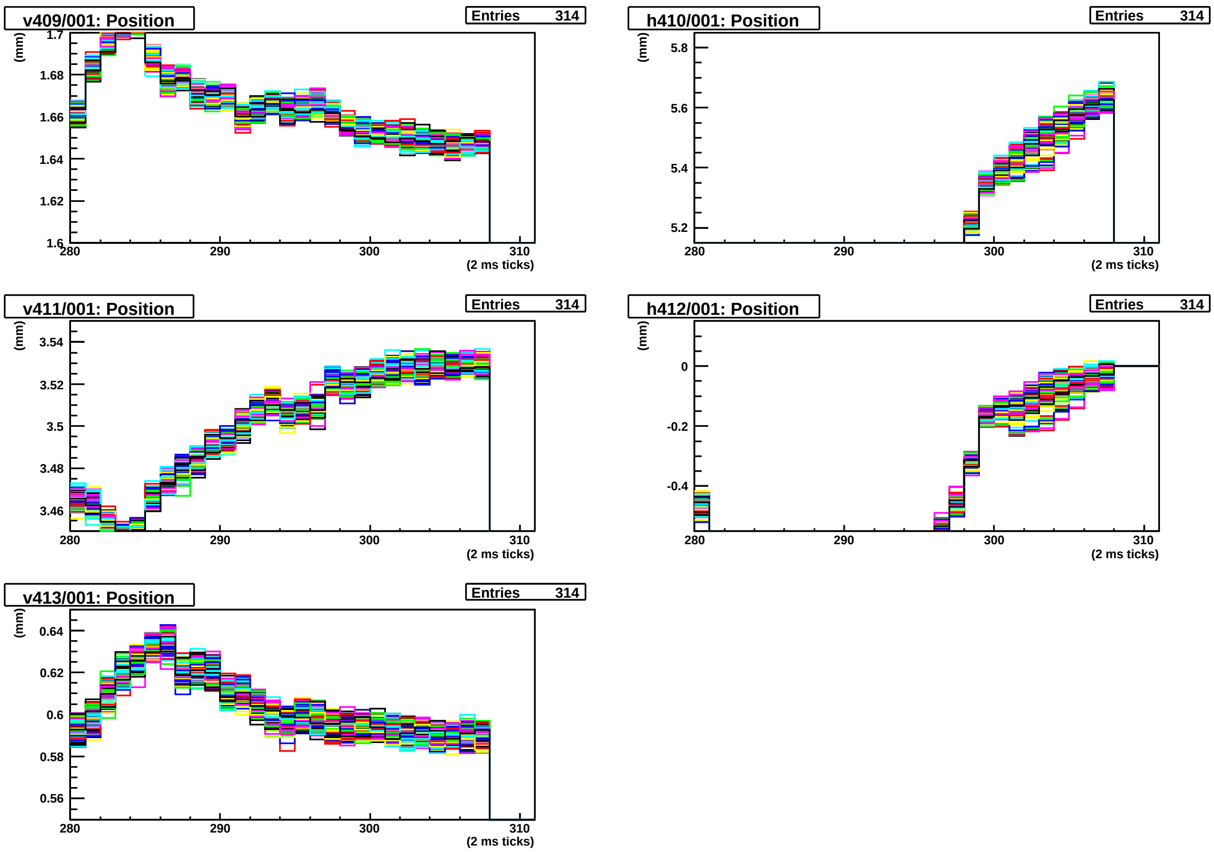



Figure 5: Continuation of Figure 4, showing data for five more BPMs. The plots are discussed in the text.

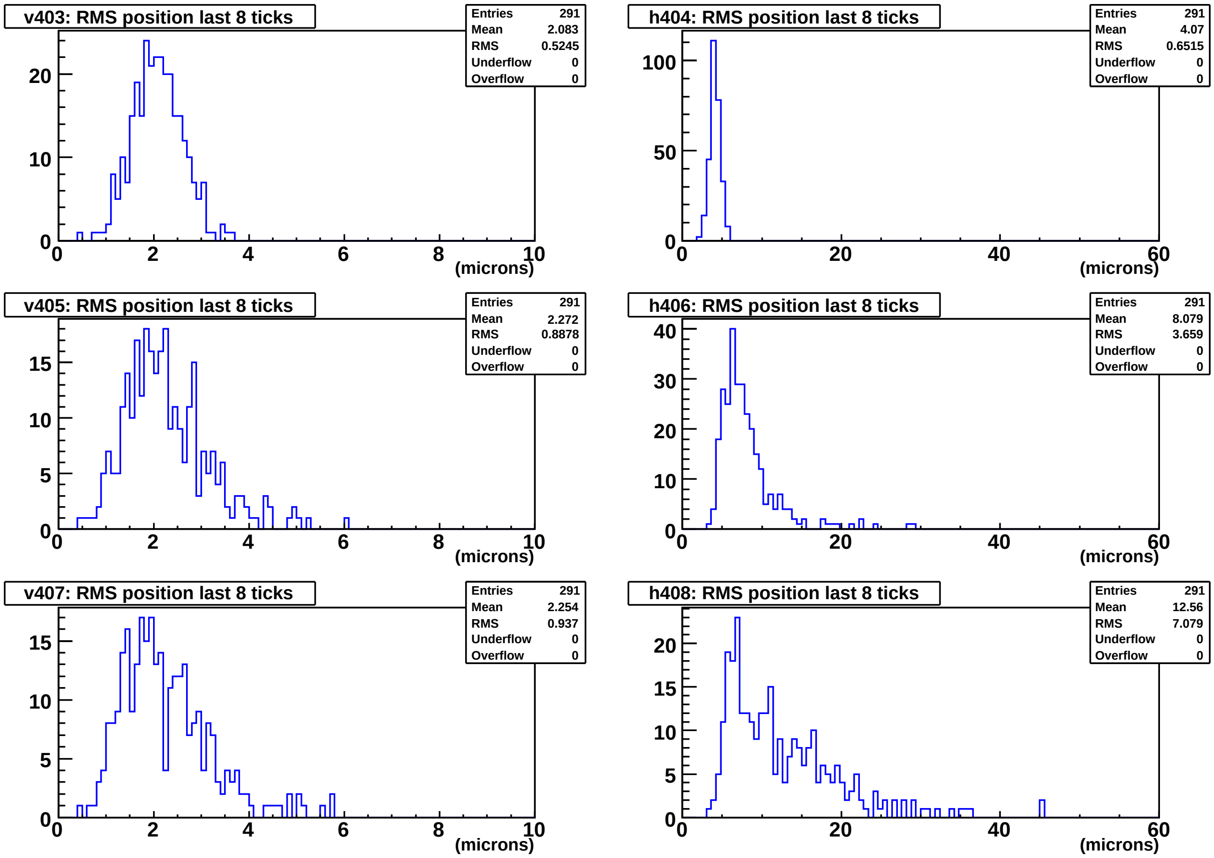



Figure 6: The upper left plot shows a histogram of the closed orbit position resolution measured using the last eight points at BPM V403. Each entry in the histogram corresponds to one cycle of the MI. The mean value of this histogram was used as the data point for V403 in Figure 8. The remaining plots show the same information for five other BPMs. All of the left hand plots are for vertical BPMs and have the same horizontal scale; all of the right hand plots are for horizontal BPMs and have the same horizontal scale. The plots are discussed in the text.

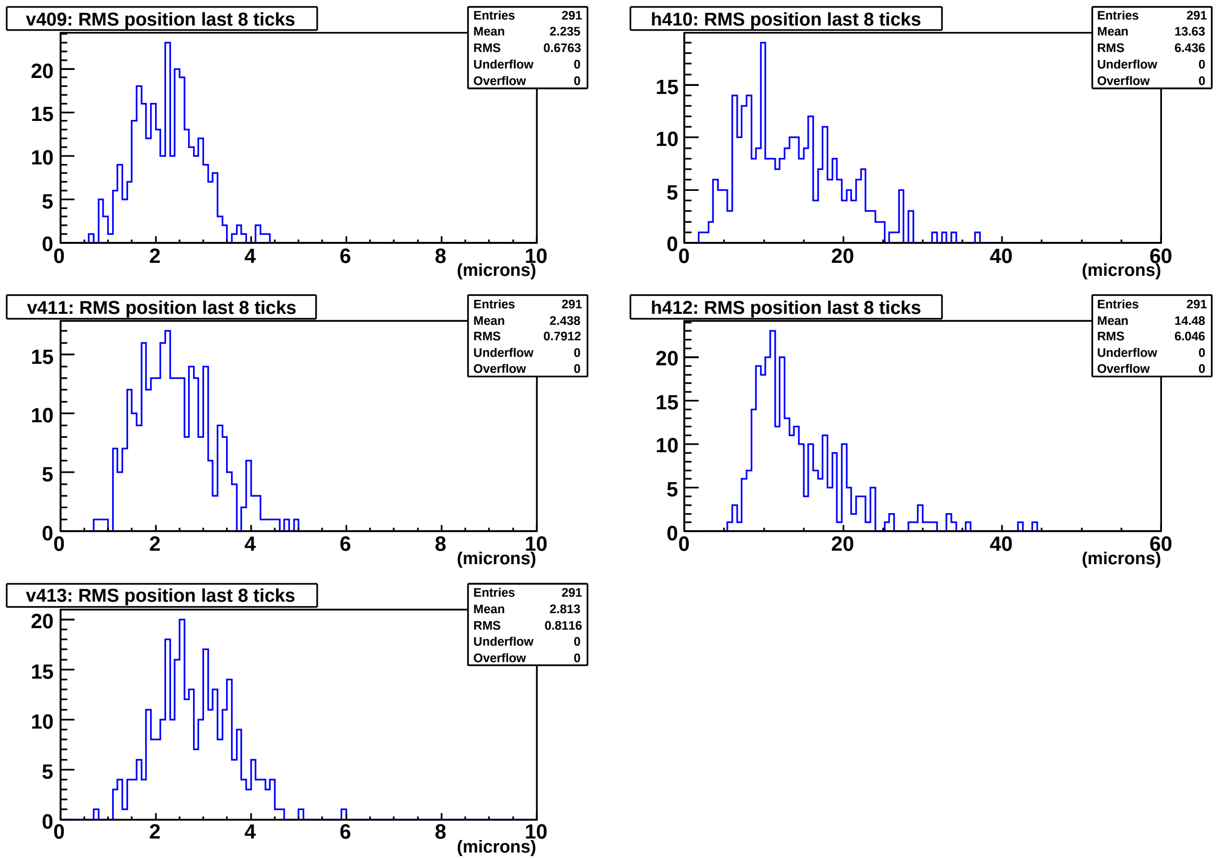
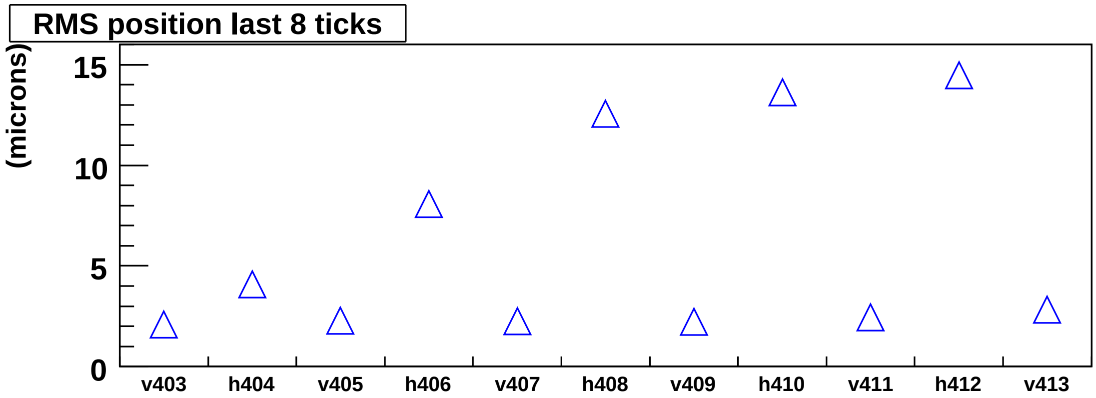



Figure 7: Continuation of Figure 6, showing data for five more BPMs. The plots are discussed in the text.



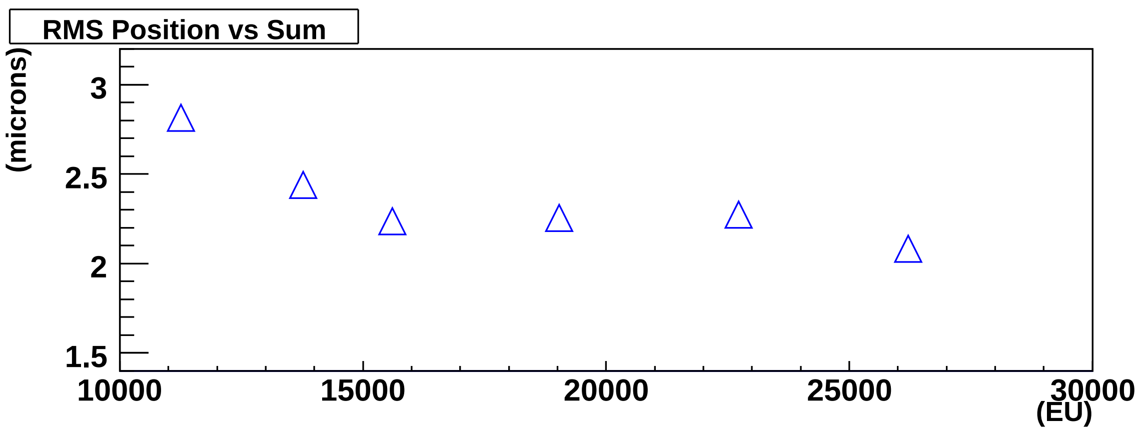




Figure 8: The top plot shows the RMS spread of the position, measured over the last eight points before extraction, for each BPM. The data points are taken from 1 and the statistical errors are smaller than the symbol size. For the vertical BPMs, the RMS spreads are our current best estimate of the closed orbit position resolution of the upgraded BPM system; the horizontal BPMs contain a significant contribution from beam motion, as discussed in the text. The bottom plot shows the RMS spread of the position plotted against the sum signal for that BPM. The plots are discussed in the test.

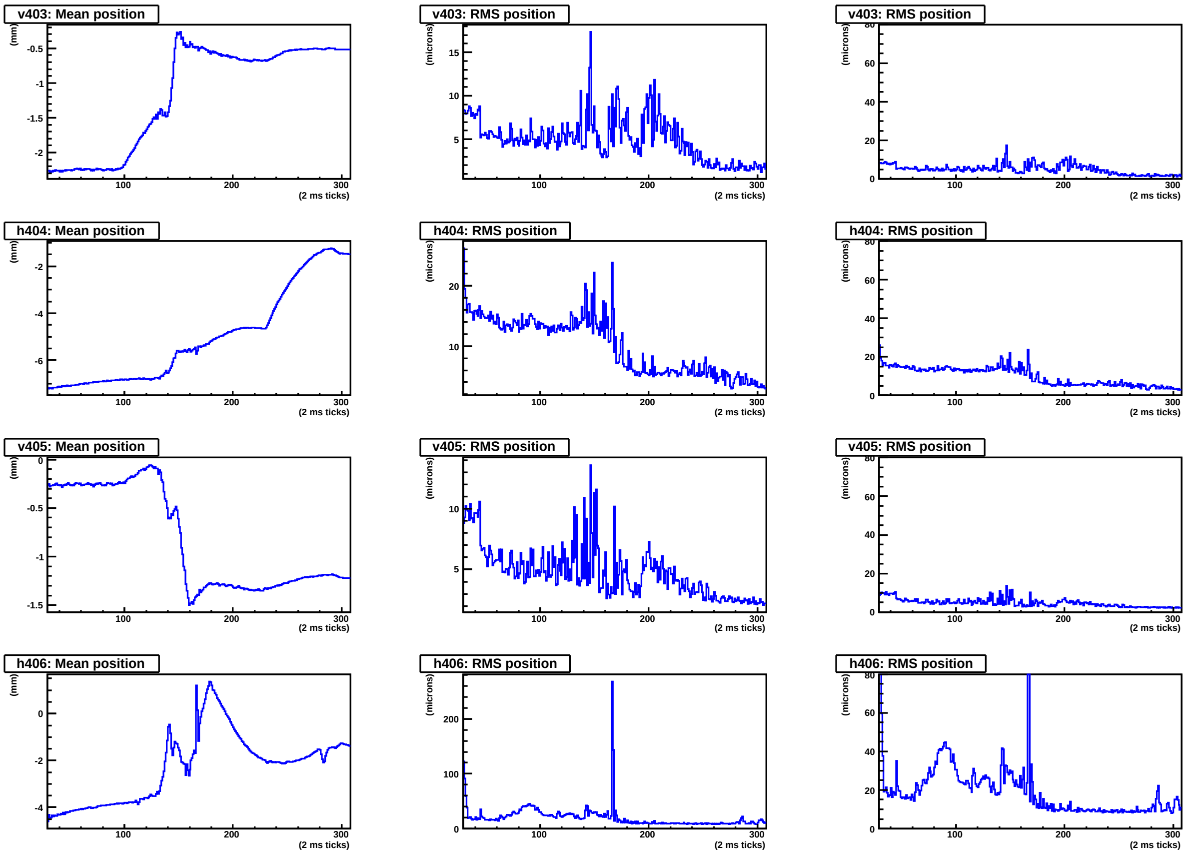



Figure 9: The top left plot shows the mean position from V403, averaged over all 291 cycles in the data sample. This can be compared to the upper right plot in Figure 1, which shows the same data for a single cycle. The top middle plot on this page shows the RMS spread of the beam position. The top right plot is a repeat of the middle plot with a different vertical scale; all plots in the right hand column have the same vertical scale but the plots in the left and middle column have scales that float with the data. For all plots the horizontal axis is time measured in ticks of the 500 Hz closed orbit clock. The remaining three rows show the same information for three other BPMs. The plots are discussed in the text.

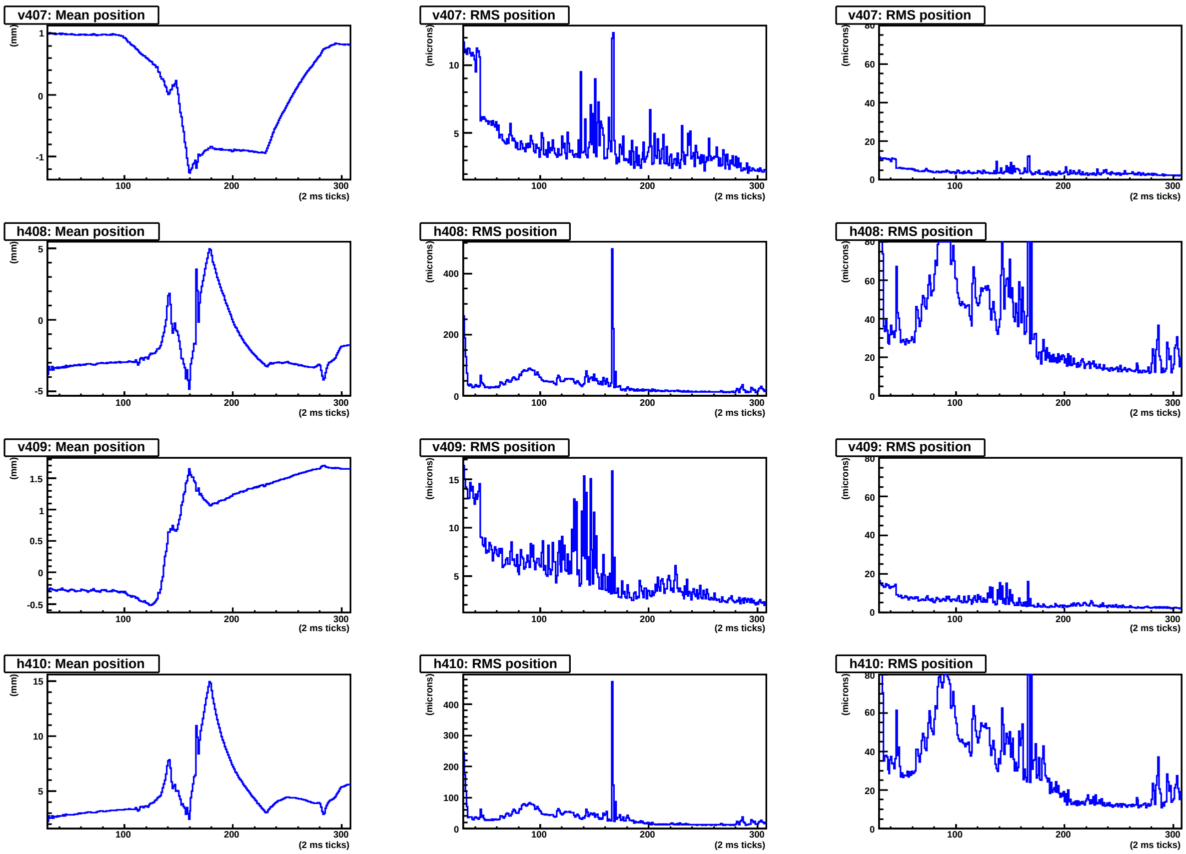



Figure 10: Continuation of Figure 9, showing data for four more BPMs. The plots are discussed in the text.

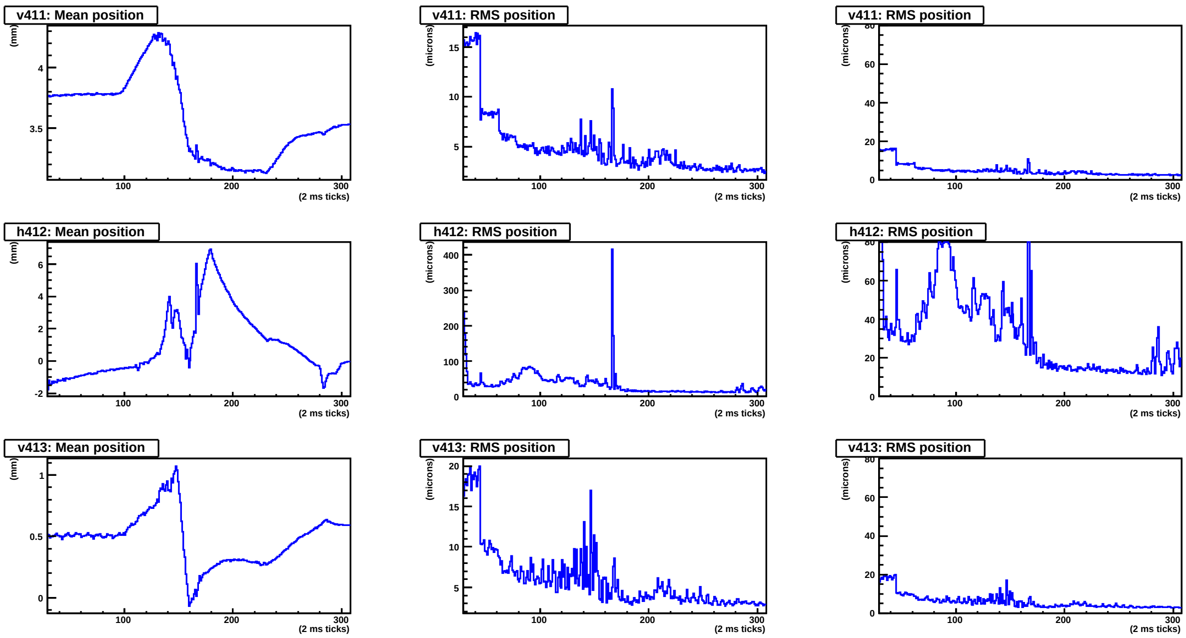



Figure 11: Continuation of Figure 9, showing data for three more BPMs. The plots are discussed in the text.