Analysis of an Electrostatic Beam Position Monitor

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26th August 2013

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1 Aim

In this report we investigate the operation of a beam position monitor (BPM). Firstly, we compare the output of a BPM to a simulated single bunch of particles and then we test to see whether the potential difference between the electrodes in the BPM is linearly proportional to the beam's position.

2 Introduction

2.1 Beam Position Monitors

A BPM is a device used in particle accelerators to track the position of the beam within the machine. This crucial function ensures that the beam is well controlled and accurately collides with its target whilst also protecting the machine from damage caused by the spray of high energy particles. Other systems can use information provided by BPMs to trigger a beam dump if the beam's position becomes unsafe.

2.2 The BPM under investigation

There are various types of BPM but here we shall consider and test an electrostatic BPM which uses 'buttons' for monitoring beam position. The buttons consist of a pair electrodes located on opposite sides of a wire which is placed in the middle of the BPM to simulate the beam. The position of the electrodes around the wire can be adjusted in planes parallel and perpendicular to the wire using Vernier-calibrated knobs.

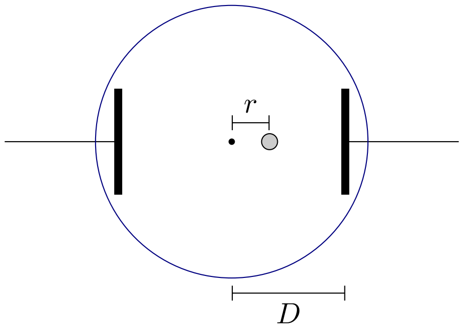
As charged current flows through the wire and between the electrodes, the accompanying electric field causes charges to build up on the electrodes. The strength of the electric field decreases as the distance between the wire and electrode increases. Therefore, the amount of charge which accumulates on each electrode is dependent on the relative position of the wire.

2.3 Theory

According to theory[1], the strength of the electric field at a point is inversely proportional to distance r from the electrode, i.e. $E \propto 1/r$. If the electrodes are at $\pm D$ and the beam is at r, as shown below, and assuming that $r \ll D$, then there is a linear relationship between the difference in electric fields and the beam's position.

[1] Vismara "Signals processing for Beam Position Monitors", 2000

$$E_1 \propto \frac{1}{D-r}$$
$$E_2 \propto \frac{1}{D+r}$$
$$E_1 - E_2 \propto \frac{2r}{D^2-r^2} \approx \frac{2r}{D^2}$$
If $r \ll D$



Thus, electrostatic BPMs provide a simple way of determining beam position as the charge accumulating on the electrodes, and therefore the potential difference across the electrodes, is linearly dependent on the electric field.

3 Method

3.1 Response of the BPM to a pulse

Firstly, we set each of the BPM's buttons to their zero point so that the wire was equidistant from the electrodes.

We connected the wire running through the BPM to a picosecond pulse generator[2] and oscilloscope[3] and recorded its response to 500 pulses per kHz with a 4 V peak height. The output of one of the buttons was connected to the oscilloscope and the time-average reading of the output was recorded.

As the picosecond pulses ought to be a fair approximation to the Dirac delta function, we also computed the Fourier transform of the time-average reading in order to obtain the frequency response of the BPMs.

While the oscilloscope is able to take the Fourier transform of a signal, it is not optimised to perform this task. On the other hand, a network analyser is specially designed for this purpose. As such, we connected the wire and one BPM button to a network analyser[4] to measure the S-parameters of the BPM.

3.2 Beam Position Response

We connected the wire to the picosecond pulse generator and the two outputs to the oscilloscope in order to test how the output of each button varies with

[2]Picosecond Pulse Labs 4015C
[3]LeCroy WavePro 7300A
[4]Agilent Technologies N5230A

the distance of the electrodes to the wire. The time average of the peak size was also recorded to improve accuracy and we then systematically swept through a range of positions.

The BPM may be moved parallel and perpendicular to the buttons' alignment. In the parallel direction, we varied from 23 to 56 mm in 3 mm steps. In the perpendicular direction varied from 20 to 60 mm in jumps of 4mm.

For each set of coordinates we waited for the time average to be stable to four significant figures before recording the peak-to-peak height of the response for both buttons.

4 Results

4.1 Response of the BPM to a pulse

The BPM's response to a single pulse as measured by the oscilloscope is displayed in red in Figure 1, with the pulse sent directly into the oscilloscope displayed in blue. Taking the derivative and then the Fourier transform of the signal in Figure 1 produces the frequency response of the pulse across all frequencies since the derivative of a step is a Dirac delta, and its Fourier transform is a flat power spectrum. This is displayed in Figure 2.

In practice, the accuracy of the data collected and the frequencies tested is limited by one's experimental apparatus as instruments have their own intrinsic effects. For example, the length of the cabling between the beam position monitor and instrument can appear in the frequency response if a resonance forms within it. For this reason we took measurements on both the oscilloscope and network analyser so that such effects could be compared. We also performed direct measurements of the set-up and cabling without the beam position monitor.

The pulse put through the BPM was 4 V but the oscilloscope detected only a peak-to-peak pulse of 70 mV (Figure 1). The signal is therefore heavily attenuated as it passes through the BPM. Figure 2 shows Fourier transforms of the derivatives of the two pulses. By subtracting the instrument-only frequency response from the intrument+BPM response, the BPM-only frequency response can be found.

The BPM heavily attenuates very low frequencies which is as expected as it is essentially a capacitor. There is also a dip in the gain at 1.3 GHz which corresponds to a wavelength of 21 cm; this is approximately the length of the BPM's tube, so this feature is probably a resonance. Overall, the BPM has a gain of about −40 dB, which is consistent with the heavily damped time signals.

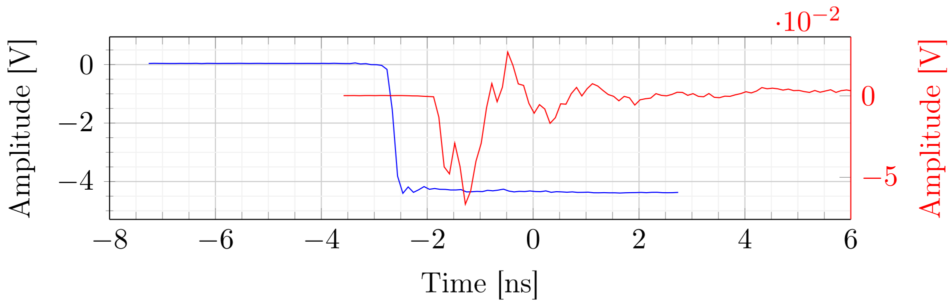


Figure 1: The BPM response to the pulse in red, compared to the pulse through the same wires in blue.

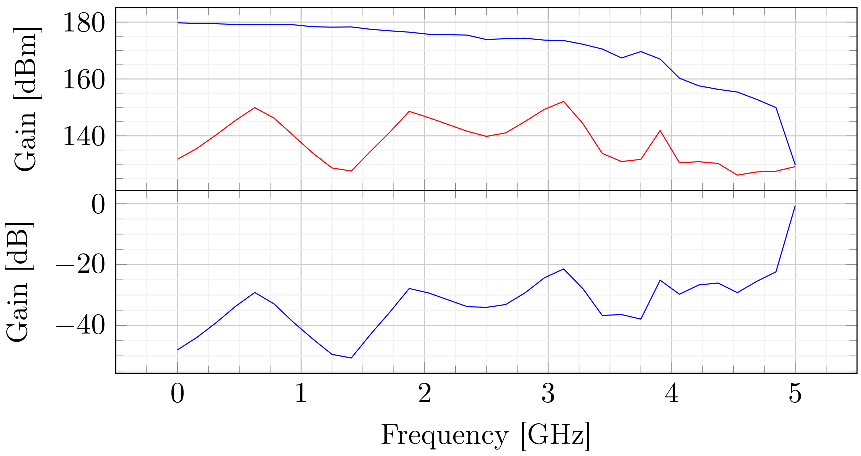


Figure 2: Top: In red, the BPM frequency, response to the step seen in Figure 1. In blue, the frequency response of the equipment without BPM. Bottom: The difference in the frequency responses, showing the actual frequency response of the BPM without the effect of the equipment.

Comparing the oscilloscope and network analyser allows us to compare how both devices function, and identifies possible instrumental artefacts in the data.

The network analyser carried out a frequency sweep in order to obtain a frequency response, whereas the oscilloscope relied on the pulse generator to send a single step function pulse. The network analyser also differs in that it measured the frequency response in both direction through the BPM as well as the reflection. We are mostly interested in how a signal sent through the wire is picked up by the button which is labelled S_{21} as shown in Figure 3 and Figure 4.

If the BPM was a perfect pick-up then the S_{21} coefficient would be 1, however it is mostly zero as can be seen in Figure 4. This is consistent with the greatly reduced peak amplitude seen in the oscilloscope and is expected as the wire and button never come into contact, therefore the signal cannot be easily transmitted.

A direct comparison of S_{21} with the oscilloscope is shown in Figure 3. They closely correspond, though it is clear that the network analyser is optimised for this task and provides a much higher frequency resolution. Additionally, the network analyser is able to probe frequencies up to 13.5 GHz (Figure 4), whereas the oscilloscope could only go up to about 5 GHz.

Up to 3 GHz, the network analyser and oscilloscope show essentially identical responses. Beyond 3 GHz, the network analyser found more features — most notably a number of peaks. These peaks could be due to resonances

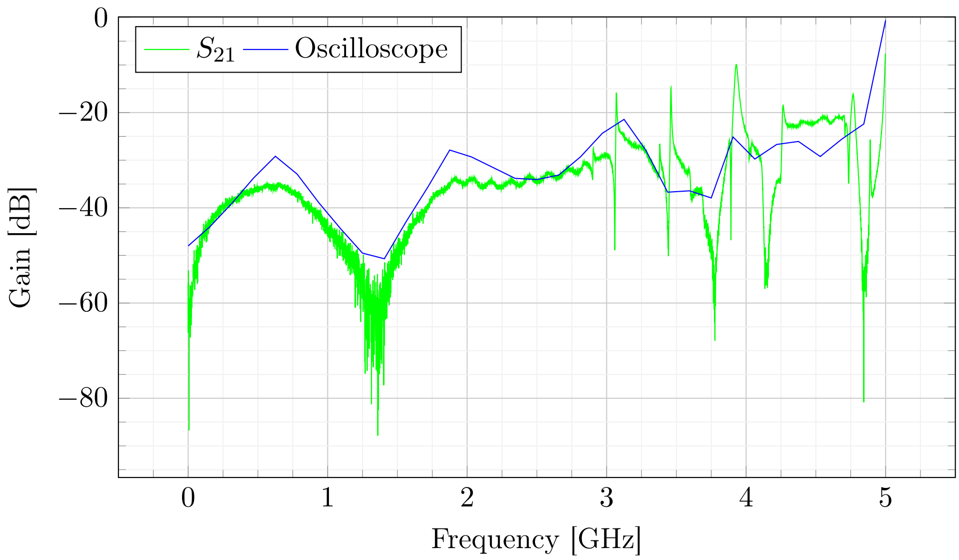


Figure 3: Comparison of the frequency responses as determined by the spectrum analyser (blue) to the network analyser (green).

transverse to the BPM tube as they correspond to wavelengths of $\sim$ 60 mm and the beam diameter is $\sim$ 80 mm.

Using Figure 4, we can compare the frequency response of sending a signal through the wire which is picked up by the button (S_{21}), to the reverse process (S_{12}). There are no observable differences between these two responses. This is expected as the BPM is a simple electrode, has no biases, and thus follows the reciprocity theorem. On the other hand, the reflected signals do differ since the wire in S_{11} ought to reflect different signals to the electrode of S_{22}.

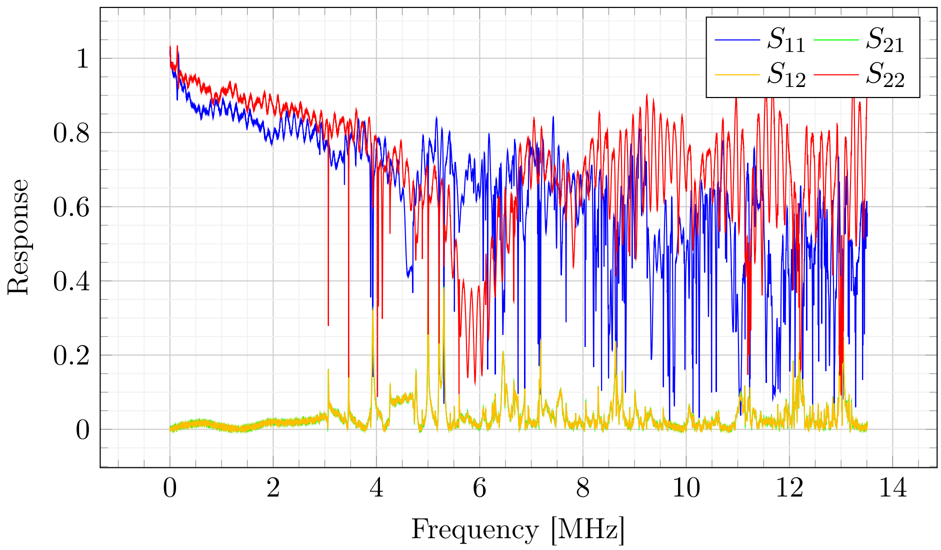


Figure 4: Frequency response. S_{11}: beam → beam; S_{21} beam → button; S_{12}: button → beam; S_{22} button → button.

4.2 Beam Position Response

Figures 5a and 5b illustrate the strength of the output signal from Buttons 1 and 2 respectively as the distance of the wire relative to the electrodes is varied.

As expected the closer the wire is to either electrode the larger the output signal from the relevant button. From Figures 5a and 5b we can see that the maximum output for both buttons is centred on 40 mm along the perpendicular axis This corresponds to the central point of the electrodes. The response through both buttons appear to be mirror images of each other, which is a desirable feature when we want to compare their voltages.

Figure 6a represents the difference between Figures 5a and 5b normalised by their sum. This plot allows us to make a more qualitative analysis of the relationship identified from Figures 5a and 5b.

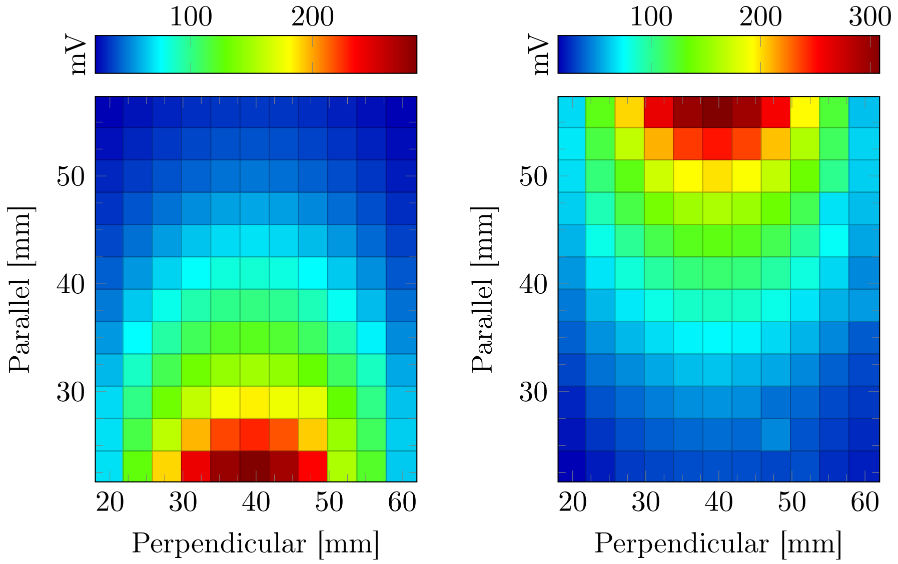
We see a high dependence of the normalised response to the positioning of the wire parallel to the buttons' orientation. We also see minimal dependence to the perpendicular positioning. Thus, if the beam is perpendicularly displaced, the position measurement is still accurate along the parallel plane.

In Figure 6b, a slice is taken through the centre of the normalised response. We fit linear and cubic polynomial to check which fit best matches the data. The linear fit was done in over the range of 32–47 mm (ignoring the 3 outermost points) so as to fit where the beam is most likely going to be, and ignore the outer effects. The cubic fit was over all of the data.

The straight line approximates BPM response very well for small to medium oscillations but fails for large oscillations. If the beam is expected to only have very small oscillations, then the linear fit should be sufficient.

On the other hand, the cubic polynomial offers a better overall fit with much smaller errors. Looking at how the data points deviate from the cubic curve, we see no clear pattern which suggests the higher order terms will most likely not provide a better fit.

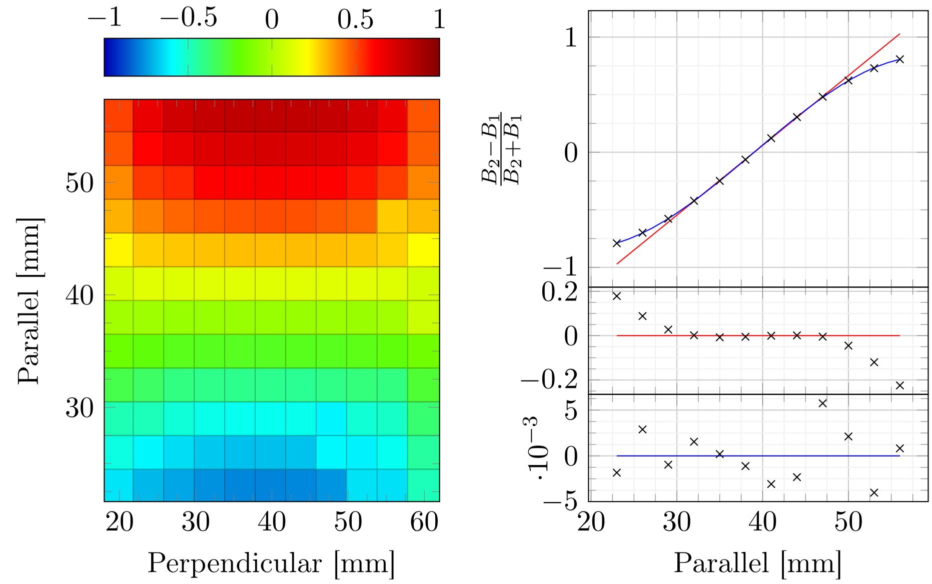
We were expecting to see a linear relationship between the wire's distance from the electrodes and signal strength for small oscillations which we have observed. However, at larger oscillations other effects become more significant and the approximation no longer holds. Such effects could be due to the shape of the electrodes and the way the electric field interacts with the wall and the buttons.



(a) Button 1 response.

(b) Button 2 response.

Figure 5: Indivudal button responses.



(a) Difference of the buttons normalised by their sum: $(B_2 - B_1)/(B_2 + B_1)$.

(b) Slice through the center (40 mm) of the normalised response with a linear fit (red) and cubic fit (blue).

Figure 6: Indivudal button responses.

5 Conclusion

In the report, we have considered the operation of an electrostatic BPM.

We observed that the BPM's response to a single bunch is greatly attenuated. The response through both buttons appear to be mirror images of each other.

The difference of the buttons' responses about the central position follows a nearly linear relationship to the beam's positioning parallel to the buttons. We also found a very small dependence on the positioning perpendicular to the buttons so that even if the beam is displaced perpendicularly, the parallel position measurement will remain accurate.

Our results show a linear relationship between the normalised response and the beam's position for small deviations about the BPM's centre. For larger deviations the linear approximation no longer holds and a more complex behaviour is seen. This behaviour can still be well approximated by a cubic polynomial.