

**A Proposed Interim Improvement  
to the Tevatron Beam Position  
Monitors with Narrow Band Crystal Filters**

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ABSTRACT: Since the start of Run II, we have found that we are unable to reliably and accurately measure the beam position with the present BPM system during high energy physics (HEP). This problem can be traced back to the analogue frontend called the AM/PM module which has trouble handling coalesced beam, but works well with uncoalesced beam. In this paper, we propose a simple fix to the AM/PM module so that we can measure the beam position during HEP. The idea is to use narrow band crystal filters which ring when pinged by coalesced beam so that the AM/PM module is tricked into thinking that it is measuring uncoalesced beam.

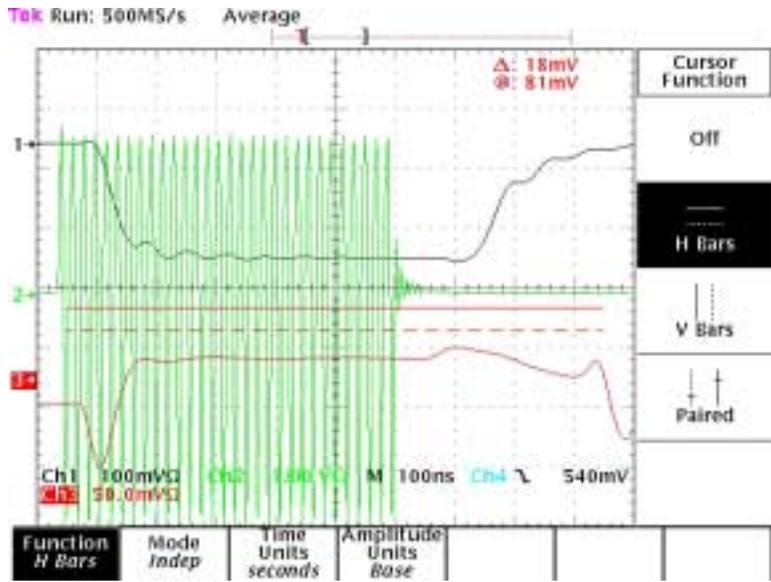
## INTRODUCTION

There is an ongoing problem with the beam position monitors (BPM) when they are used to measure the position of coalesced bunches in the Tevatron. The position that is returned by the BPMs in this mode has not been considered reliable or correct since the start of Run II operations. However, this failure of the BPMs should be contrasted for uncoalesced bunches where we do have reliable and accurate readings from the BPMs. The source of the difference in behaviour can be traced to the input beam structure into the analogue processing module called the AM/PM (amplitude modulation to phase modulation) module. (See also section *AM/PM Module*).

When we have uncoalesced beam in the Tevatron which consists of 30 bunches each with an intensity of  $\sim 5 \times 10^9$  protons/bunch and are spaced one bucket apart, we can see from the output of the AM/PM module shown in Figure 1 that there is a nice flat position signal (red trace) where the analogue to digital converter (ADC) can sample. Also the BPM ADC portion self triggers from the intensity signal (black trace) which means that any jitter of this trigger does not affect the position reading because of the flatness of the position signal.

Contrast this to the position and intensity signals from the AM/PM module for coalesced bunches which are high intensity bunches  $\sim 200 \times 10^9$  protons/bunch spaced at least 21 buckets apart shown in Figure 2. This figure is taken during high energy physics (HEP). We can immediately see the problem: the position signal (red) has a slope which for a self triggering system presents a problem. Furthermore, the shape of the position signal (black) depends on the bunch intensity although the slope seems to be independent of it. This is the source of the unreliability and inaccuracy of the BPMs for coalesced bunches.

To overcome this problem for coalesced bunches, we have to look at the input structure

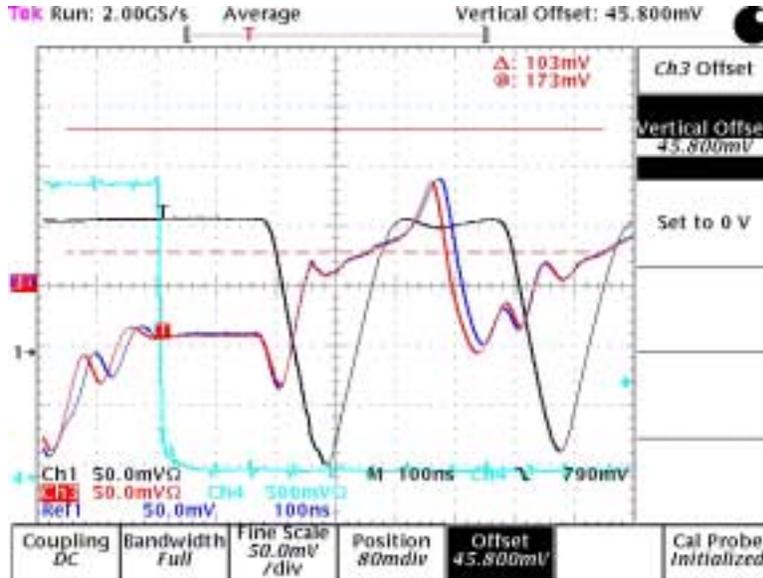


**Figure 1** When we have uncoalesced beam (green) as input to the AM/PM module, the output position signal (red) has a nice flat region for sampling. The output black trace is the intensity signal.

of the uncoalesced beam going into the AM/PM module. From Figure 1, we can see from the green trace that uncoalesced beam looks like a burst of sine waves which lasts for 30 RF cycles. And thus the motivation: if we can somehow make the input signal to the AM/PM module ring for coalesced bunches we can then mimic the uncoalesced bunch structure and get a nice position signal for the BPM ADC to sample. The solution is obvious, we need to preprocess the coalesced bunch signal with a narrow band, high  $Q$  filter, like a crystal filter, before the AM/PM module because the crystal can be thought of as a bell which rings when the coalesced bunches hit it.

Goal

Therefore the goal of the exercise is to improve the current BPM system with crystal filters so that we can measure the beam position of coalesced bunches with confidence. Cost is a major driver of this project because it is only an interim solution until the new



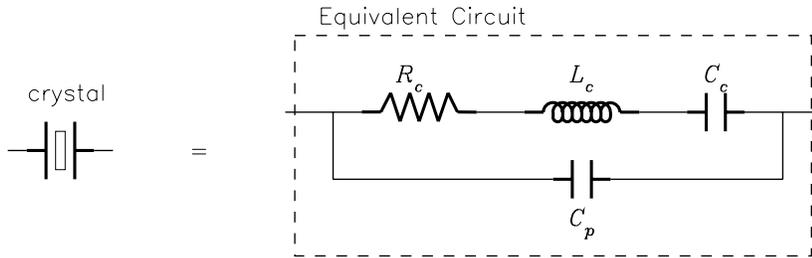
**Figure 2** This trace is taken from the output of the PM/AM module during HEP (store #2377). The magenta trace is the beam sync trigger used to trigger the scope (note: beam sync is not used in the BPM system). The black trace is the intensity signal. The red trace is taken at the start of HEP and the blue trace is taken at the end. Number of protons at the start is  $6000 \times 10^9$  and at the end is  $5700 \times 10^9$ .

BPM system comes online (which is about 2 years as of this writing). The proposed scope of this project is as follows:

- (i) Minimum cost. About \$25k-\$50k. This means that for the 250 BPMs in the Tevatron, the cost per channel is \$100-\$200.
- (ii) Little or no software rewrite.
- (iii) Must not change the BPM readings for uncoalesced beam.
- (iv) Only works during HEP because of the high  $Q$  crystal filters.

## QUARTZ CRYSTAL FILTER

Quartz crystals are crystalline forms of silicon dioxide which when mechanically distorted produces an electrical charge. Conversely, when we introduce an electric charge, we can mechanically distort the quartz crystal. And when the quartz crystal is thinly sliced, these mechanical distortions can vibrate at a very high  $Q \sim 50 \times 10^3$  [1]. This is exactly the property which makes them ideal for our purposes. When the charge of a coalesced bunch hits the crystal, it will distort and vibrate at its resonant frequency for a very long time. At 53 MHz and  $Q = 50 \times 10^3$ , the  $1/e$  time is about 0.3 ms  $\approx$  14 beam revolutions in the Tevatron.



**Figure 3** The crystal equivalent circuit.

For modelling purposes, the crystal can be thought of as a  $RLC$  circuit shown in Figure 3.  $C_p$  is a parasitic or parallel capacitance of the crystal which we will see later on degrades the performance of the filter but does not spoil its ringing characteristics.

All this discussion would be moot if we cannot procure crystals which vibrate at the Tevatron RF frequency. It turns out that custom made crystals are inexpensive  $\sim$ \$20 and can be made to order[2]. The custom crystals which we use is a round quartz disk with an electrode deposited on each flat surface. These electrodes provide an electrical path as

well as the mechanical mounting structure for the quartz crystal. The entire package is sealed hermetically in an aluminium housing. The mechanical and electrical parameters supplied by the manufacturer are shown in Table 1.

**Table 1. Electrical and Mechanical Parameters of Quartz Crystal**

Symbol	Description	Value
$f_c$	resonant frequency	53.104 MHz
–	3rd overtone mode of operation	–
$R_c$	equivalent series resistance	$< 40\Omega$
–	calibration tolerance at 25°C	$\pm 10$ ppm
–	temp. tol. rel. to 25°C from $-30^\circ\text{C}$ to $+60^\circ\text{C}$	$\pm 10$ ppm
–	package style	HC49U

The parameters which are not supplied or inadequately supplied by the manufacturer are measured and discussed in *Matching to 50Ω*. And for reference, the Tevatron RF frequency at HEP is 53.104705 MHz.

### Matching to 50Ω

In order to use the crystal in the world of RF, we have match the crystal impedance  $Z_c$  to  $50\Omega$  at its resonant frequency  $\omega_c$ . To do this, we have to use the well known condition that  $Z_c$  is purely resistive for an *RLC* circuit at resonance. This is easily demonstrated

$$Z_c(\omega) = R_c + i\omega L_c + \frac{1}{i\omega C_c} \quad (1)$$

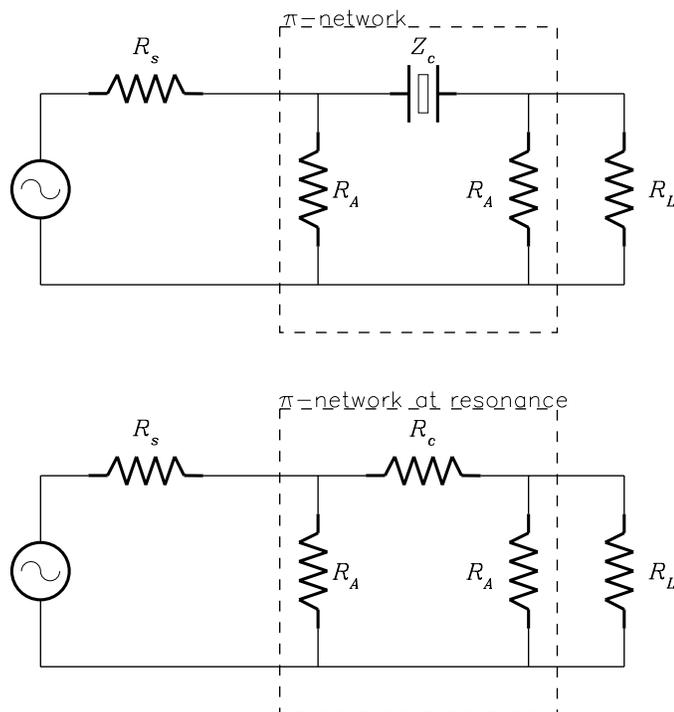
with resonant frequency  $\omega_c = 1/\sqrt{L_c C_c}$ . So  $Z_c(\omega_c)$

$$\left. \begin{aligned} Z_c(\omega_c) &= R_c + i\sqrt{\frac{L_c}{C_c}} - i\sqrt{\frac{L_c}{C_c}} \\ &\equiv R_c \end{aligned} \right\} \quad (2)$$

as required.

Therefore, to match the crystal at resonance to  $50\Omega$  we can use a  $\pi$ -network to accomplish this if we ignore the parasitic capacitor  $C_p$ . See Figure 4 for the circuit. By demanding that  $R_L = R_s$ , then at resonance, the  $\pi$ -network becomes purely resistive and thus the total resistance of the circuit  $R_{\text{tot}}$  shown in Figure 4 is

$$R_{\text{tot}} = \left( \frac{1}{R_A} + \frac{1}{R_s + \frac{R_A R_L}{R_A + R_L}} \right)^{-1} \quad (3)$$



**Figure 4** The  $\pi$ -network is used to match the crystal to  $R_s = R_L = 50\Omega$  at resonance.

Therefore, given any crystal, we can put it in the circuit shown in Figure 4 with an arbitrary value of  $R_A$ . We then do an  $s_{11}$  measurement with a network analyzer which measures  $R_{\text{tot}}$  from which we can determine  $R_c$  and  $R_A$ . Thus the method is:

- (i) Measure the impedance of the  $\pi$ -network with an arbitrarily selected  $R_A$ . Knowing

the resistive part of the impedance from the network analyzer, we can calculate  $R_c$  from (3).

(ii) Once we know  $R_c$  from (i), we can calculate  $R_A$  for the case when  $R_L = R_s = 50\Omega$ .

(iii) Check that  $s_{11}$  at resonance is about  $-30$  dB for a good match.

The results of doing this match is shown in Figure 5. The measured  $R_c = 13.4\Omega$  and with this value, we calculate that  $R_A = 380\Omega$  for  $R_s = R_L = 50\Omega$ . The closest resistor value that we can find for  $R_A = 382\Omega$  and with this value, we can see from Figure 5 that the measured impedance of the  $\pi$ -network and  $R_L = 50\Omega$  is  $53.6\Omega$  at resonance which is good enough. With these resistor values, the insertion loss  $K$  of the  $\pi$ -network is given by

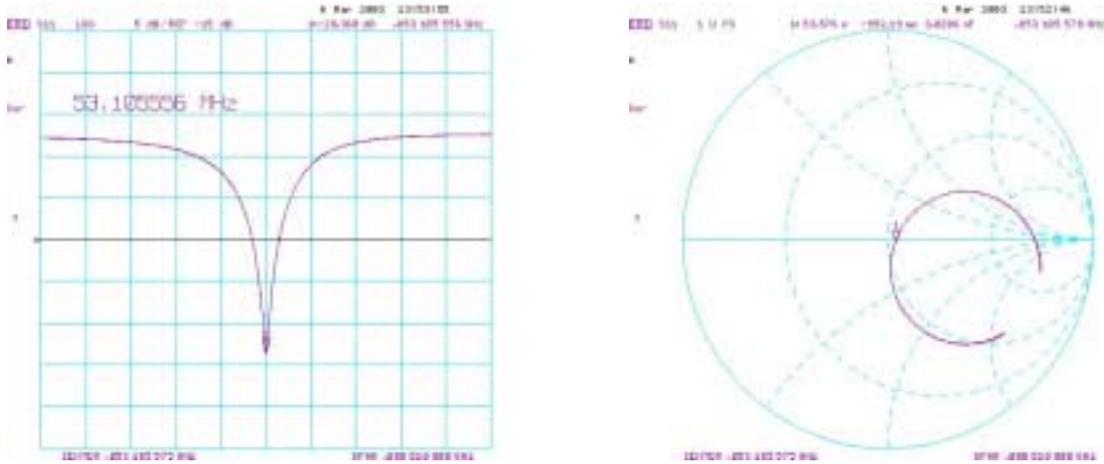
$$\left. \begin{aligned} K &= \frac{R_A + R_c - \sqrt{R_c(2R_A + R_c)}}{R_A} \\ &= 0.76 \\ &= 1.1 \text{ dB} \end{aligned} \right\} \quad (4)$$

which means that not much of the 53 MHz component is lost with the crystal filter in the circuit.

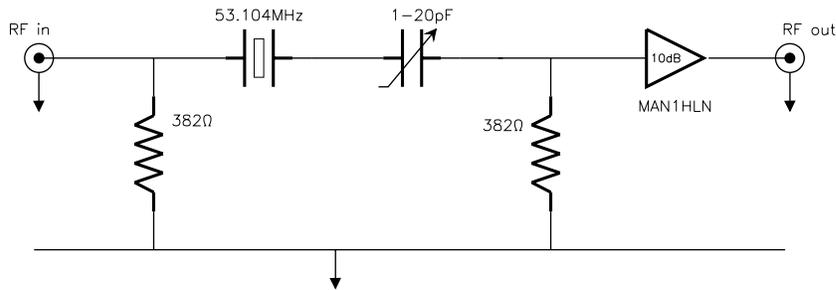
The resonant frequency is also not at the manufacturer's advertised frequency of 53.104 MHz because of the series load capacitance in the test circuit. This is rather irrelevant because we can tune the resonant frequency to where we want it. See section *The Filter Circuit*.

### The Filter Circuit

Finally, the basic crystal filter design is shown in Figure 6. A variable capacitor which can be used to tune the resonant frequency and a 10 dB amplifier is added to the basic circuit. It is necessary to have the variable capacitor because we have to phase match the pair of crystal filters used for each AM/PM module.



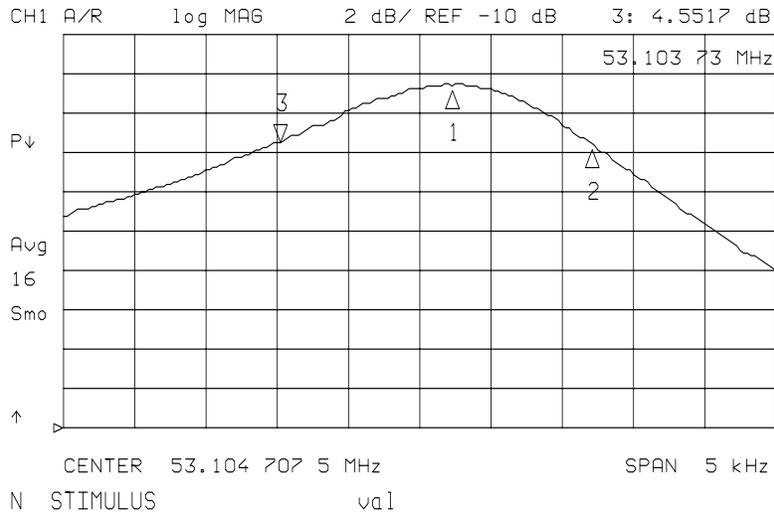
**Figure 5**  $s_{11}$  and Smith chart measurement when the  $\pi$ -network is matched at resonance to  $50\Omega$ .  $s_{11}$  is minimum when things are matched.



**Figure 6** This is the circuit diagram of the crystal filter circuit.

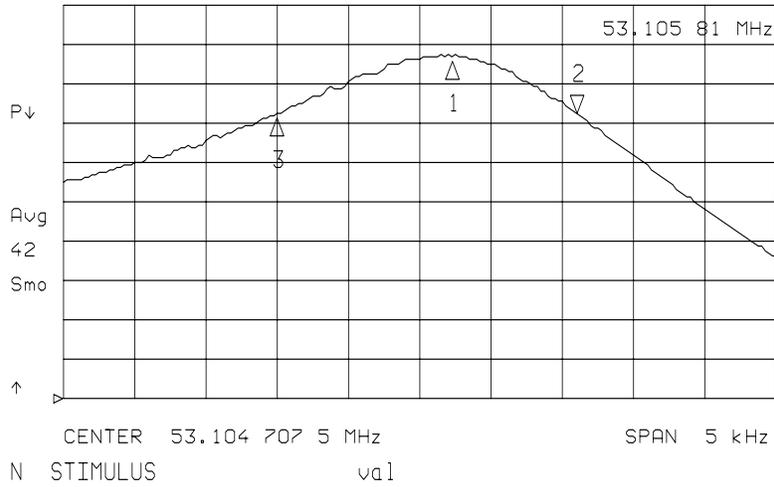
The frequency response of the two crystal filters when properly tuned so that their resonant frequencies are the same is shown in Figure 7.

From the 3 dB points, we can calculate that  $Q \approx 26 \times 10^3$ . In reality, this is a rather poor narrow band filter because of the parasitic capacitance  $C_p$  which acts like a high pass



1	53.104 932 5 MHz	7.4260 dB
2	53.105 917 5 MHz	4.4200 dB
3	53.103 73 MHz	4.5517 dB

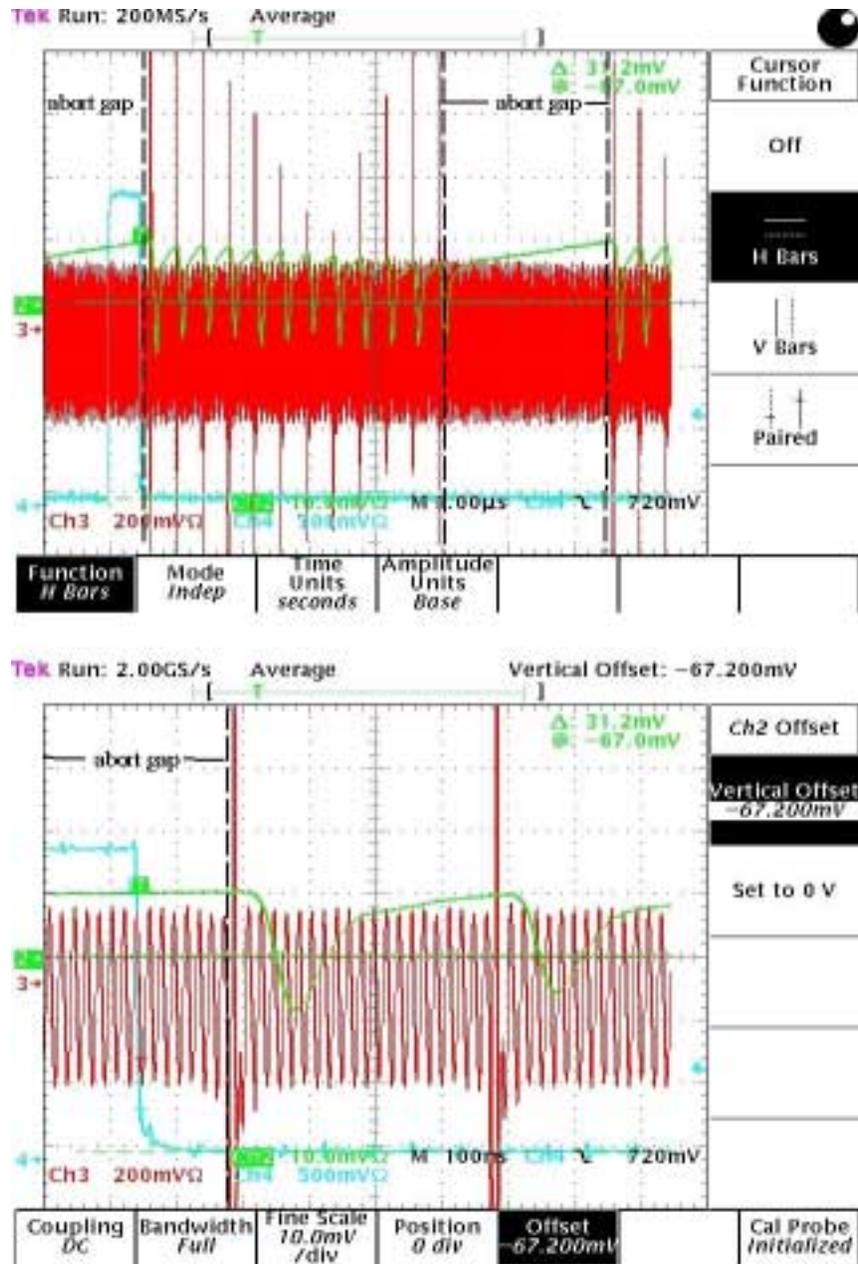
CH1 A/R log MAG 2 dB/ REF -10 dB 2: 4.4492 dB



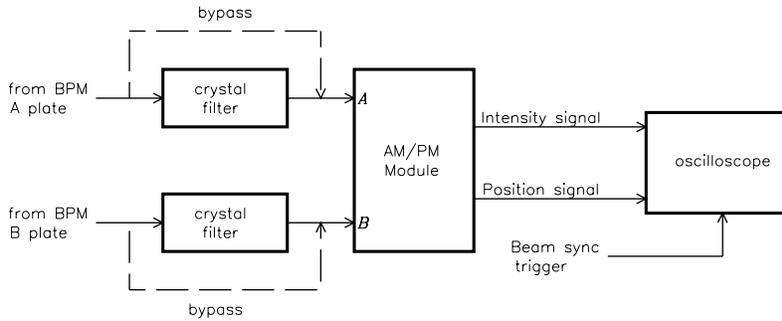
1	53.104 932 5 MHz	7.4026 dB
2	53.105 81 MHz	4.4492 dB
3	53.103 702 5 MHz	4.5084 dB

**Figure 7** These two graphs show the frequency response of two crystal filters. We can tune their resonance frequency so that they are the same by varying the variable capacitor in the circuit.

filter allowing high frequency components of the beam to go through. This is manifested by the amplitude response not going down more outside markers 2 and 3. However, as we can see from Figure 8, the ringing property is not hurt by this at all. This figure shows the effect of the crystal filter being rung by 36 proton bunches during HEP. The sharp spikes come from beam signal bypassing the crystal and going through the parasitic capacitor.



**Figure 8** The beam signal from the stripline going through the crystal filter. The top figure is a zoomed out signal showing the ringing in the abort gap and between bunches (red trace). The bottom figure is a zoomed in picture which shows ringing between bunches. Green trace is the intensity signal from the AM/PM module.



**Figure 9** This is the setup used for beam measurement. Not shown are the relays which can be energized to bypass the crystals and feed the stripline signals directly into the AM/PM module.

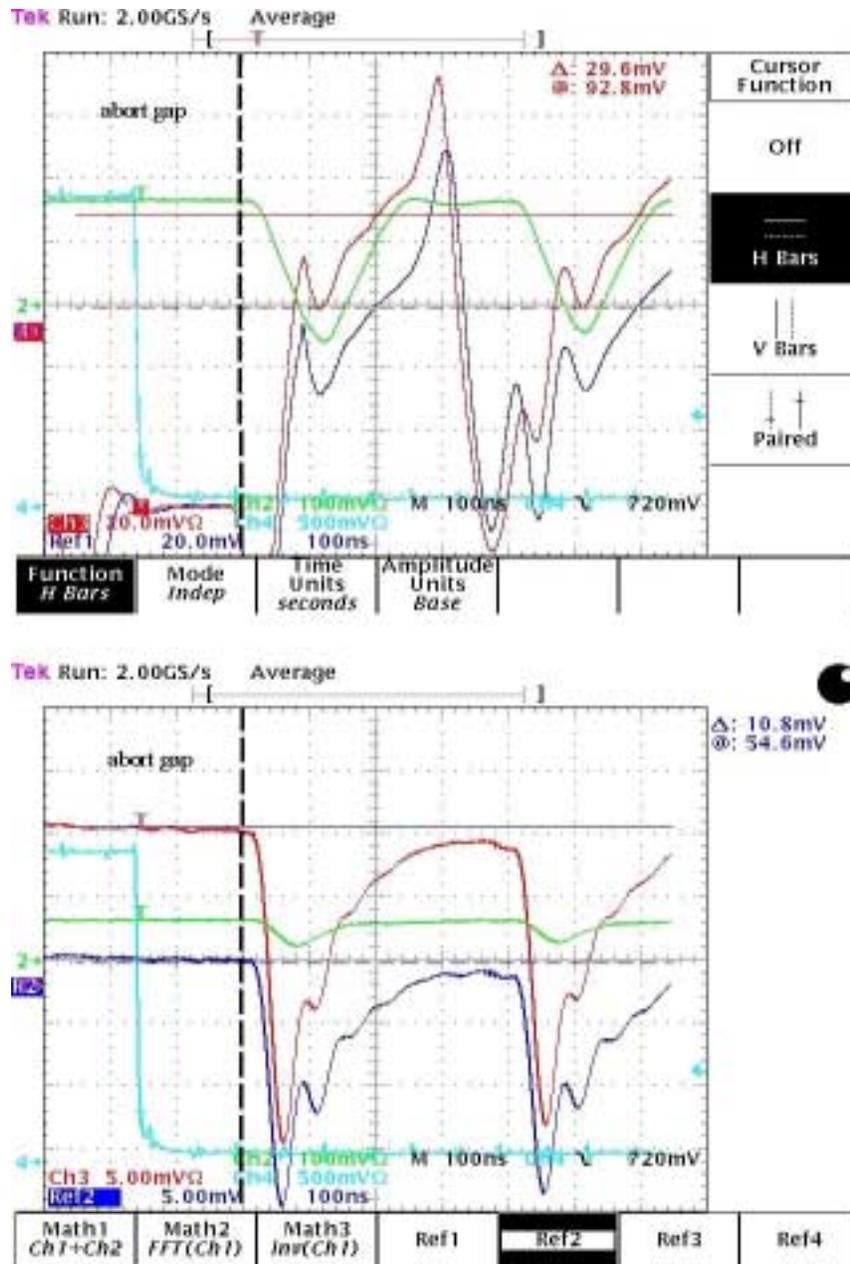
## RESULTS

The setup for all the BPM measurements using beam are shown in Figure 9. Two crystal filters are needed for each AM/PM module. A scope is connected to the two outputs of the AM/PM which gives both intensity and position signals. The trigger for the scope comes from beam sync which is not used by the BPM electronics. The BPM used here is T:VA16.

Figure 10 shows how the AM/PM output signals look like with and without the crystal filters during HEP. We can immediately see that the signal with the crystal filter is significantly improved. In fact the position slope without the filters is gone. Looking at the bottom figure of Figure 10, we can see that the best place to sample the position signal is in the abort gap. This is where we will place the scope markers to measure the position signal as a function of 3 bump size at T:VA16.

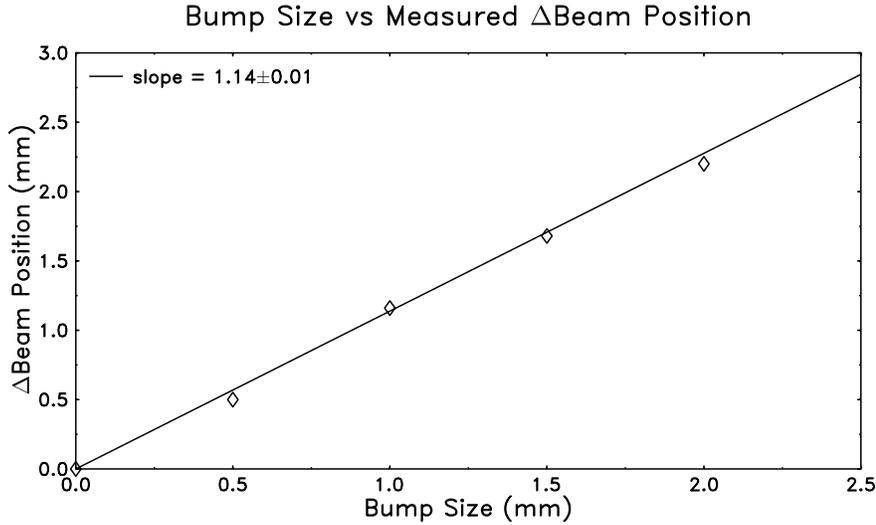
## Calibration

To start off, we will will check the T:VA16 3 bump with the difference orbit read by



**Figure 10** This shows how the AM/PM output signals without (top) and with the crystal filter in the circuit. When the beam is displaced we see that there is a nice flat portion in the abort gap where we can sample and hold compared to the signal without the crystal filter.

T39 (the Tevatron BPM programme) without the crystal filters during HEP. The results are shown in Figure 11. We can see from the fit that there is a 14% error between the



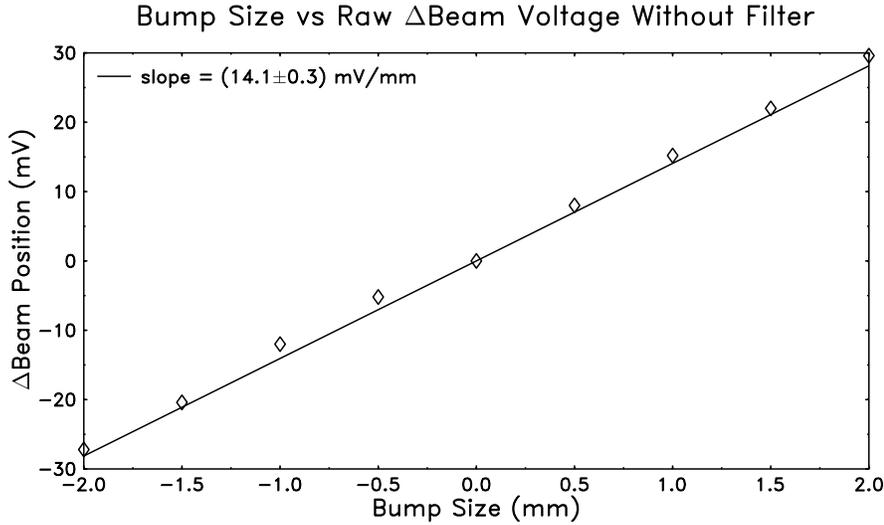
**Figure 11** With the present system, using T:VA16, we calibrated the  $\Delta$  beam position versus bump size and found that the slope is not 1.0 but has an error of 14%. Of course, we cannot tell whether it is the bump that is in error or the BPM.

3 bump and the BPM position reading. Of course, we cannot tell whether it is the 3 bump or the BPM is in error, but we will use the 3 bump as the reference.

So continuing on with the crystal filters still not in the setup, we look directly at the position signal output from the AM/PM module. We see from Figure 12, that the calibration factor is  $(14.1 \pm 0.3)$  mV/mm.

Finally, with the crystal filters in the setup, we find that the calibration is  $(12.4 \pm 0.1)$  mV/mm from the slope in Figure 13. This value is quite close to the canonical calibration factor of 12 mV/mm obtained from bench measurements. Comparing Figures 12 and 13, we can see that the scatter of the data points is worse when there are no crystal filters in the setup because the slope of the position signal makes it difficult to get a consistent reading.

If we believe the canonical calibration factor of 12 mm/mV, we can see that the error

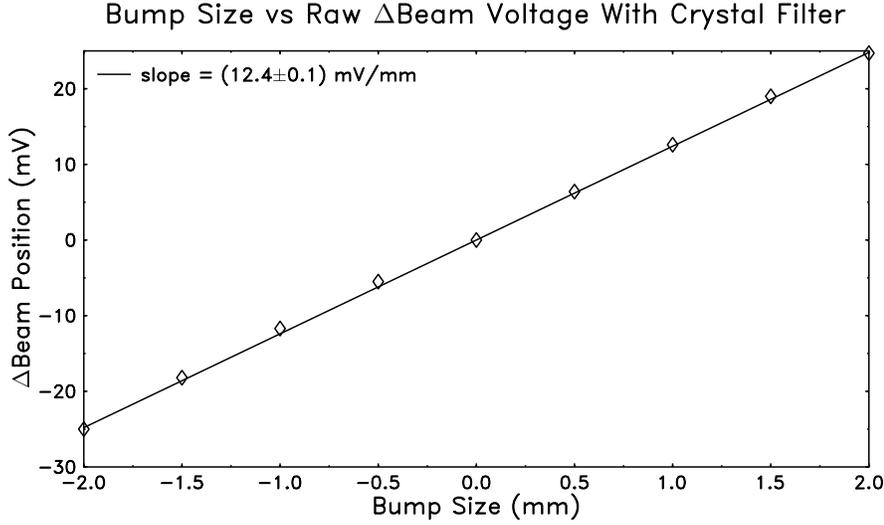


**Figure 12** With the present system, just using the raw position voltage sign, we find that the calibration is  $(14.1 \pm 0.3)$  mV/mm. There is also a lot more scatter in the data points compared to Figure 13 because of the slope in the voltage.

of 14% from the 3 bump versus T39 data of Figure 11, comes mainly from the calibration factor error of  $(14.1 - 12)/12 = 17\%$ .

### Up the Ramp

In order to see how a crystal filtered BPM works up the ramp, we split the BPM *A* and *B* plate signals at HA17 (not VA16) so that one pair of these signals goes to an Echotek and the other goes to the crystal filters. The Echotek is a proprietary digital signal processing system which takes in raw BPM signals to produce a position signal[4]. To compare the Echotek data in mm to the crystal filtered BPM data which is in volts, we use the Echotek position data at collisions only to fit the crystal filtered BPM data to get a conversion formula from volts to mm (the reasons for not using the calibration from



**Figure 13** By adding the crystal filter, we find that the calibration is  $(12.4 \pm 0.1)$  mV/mm which is much closer to the canonical calibration value of 12 mV/mm.

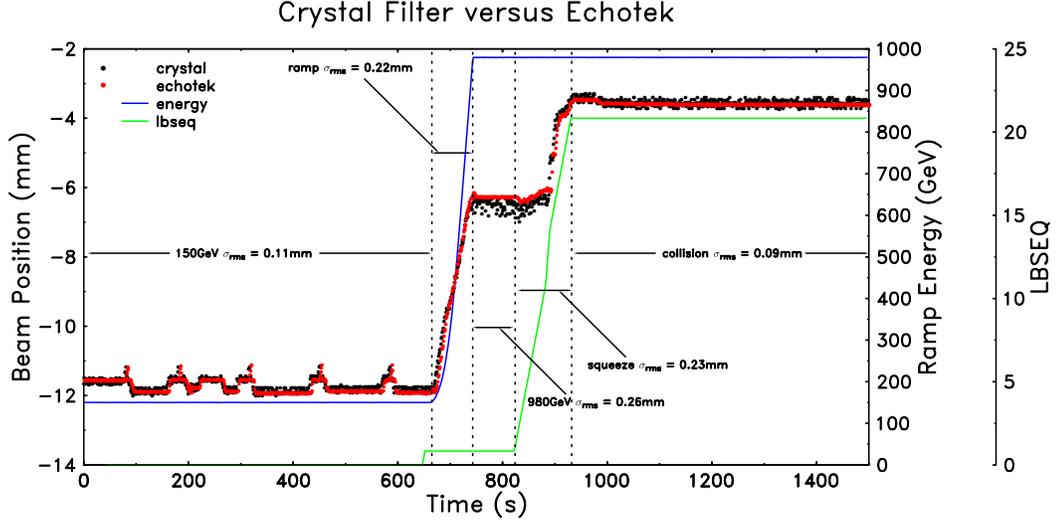
3 bump data for the crystal filtered BPM is discussed below)

$$x_{\text{crystal}} = 8.73 \times V_{\text{crystal}} - 0.66 \quad (5)$$

where  $x_{\text{crystal}}$  is the beam position in mm and  $V_{\text{crystal}}$  is the beam position in volts from the crystal filtered BPM. This means that the rms error between the Echotek and crystal filtered BPM data is minimum at collisions. With this formula, we can plot the behaviour of the positions measured by the Echotek and the crystal filtered BPM for different parts of the ramp. This is shown in Figure 14.

There are three reasons why the Echotek signal looks better than the crystal filtered signal in Figure 14:

- (i) The MADC channel is a free running ADC which not only samples the abort gap it also samples everywhere else.
- (ii) The MADC channel is 8 bits and when we zoom in, we can clearly see the quanti-



**Figure 14** This is a comparison between the Echotek and the crystal filtered signal looking at HA17 at the same time.

zation effect. See Figure 15. After averaging with 16 consecutive data points, the crystal filtered BPM data looks much smoother.

- (iii) The input impedance of the MADC channel is high impedance while the impedance of the AM/PM module position output is  $50 \Omega$  and thus there are unwanted reflections. The reason for not matching the impedance for this quick setup is because the voltage seen by the MADC will be 20 times smaller when matched. This also means that our previous calibration with 3 bumps of the crystal filtered BPM is invalid.

- (iv) The Echotek averages the position data before reporting it to the user.

The rms error between the crystal filtered BPM data for different parts of the shot sequence are shown in Table 1 and Figure 14. As expected, the rms error is minimum at collisions because this is where we calibrated the Echotek and the crystal filtered BPM. Interestingly, the rms error is also less than 0.15 mm (one least significant bit of the present

BPM system) at 150 GeV. We are surprised because the RF frequency at 150 GeV is  $f_{150} = 53.103639$  MHz compared to the RF frequency at 980 GeV which is  $f_{980} = 53.104705$  MHz and we have tuned the filters to resonate near  $f_{980}$ . The high  $Q$  of the crystal filters makes a frequency shift  $f_{980} - f_{150} \approx 1$  kHz significant enough to reduce the magnitude of the response by 3 dB with a corresponding phase shift (See Figure 7). This means that if the system is calibrated at 980 GeV, technically, we do not know whether the calibration is the same at 150 GeV.

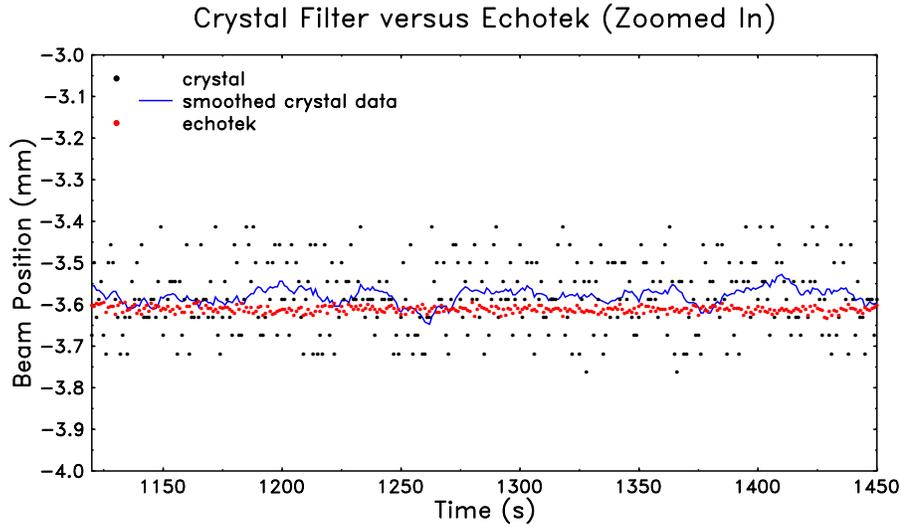
The calibration between the Echotek and the crystal filtered BPM is obviously different up the ramp, even at 980 GeV before the start of the squeeze and during most of the squeeze. We do not know whether the Echotek or the crystal filtered BPM is lying since both are experimental systems.

**Table 1. RMS errors between Echotek and Crystal Filtered BPM**

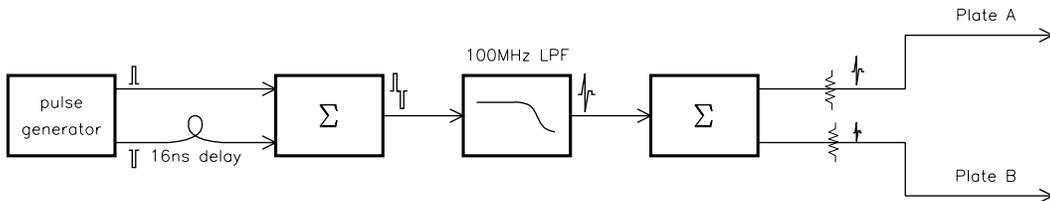
<b>Sequence</b>	<b>RMS error (mm)</b>
at 150 GeV on helix	0.11
up the ramp	0.22
at 980 GeV	0.26
through squeeze	0.23
at collisions	0.09

### Bench Measurements

In order to measure other effects of the crystal filter, we made a fake beam signal using a pulse generator. The block diagram of this circuit is shown in Figure 16. The reason for doing this rather than with real beam is because of the scarcity of studies time. Our setup allows us to produce any bunch pattern we want. In particular for these measurements, we can fake 36 bunches in their usual HEP pattern.



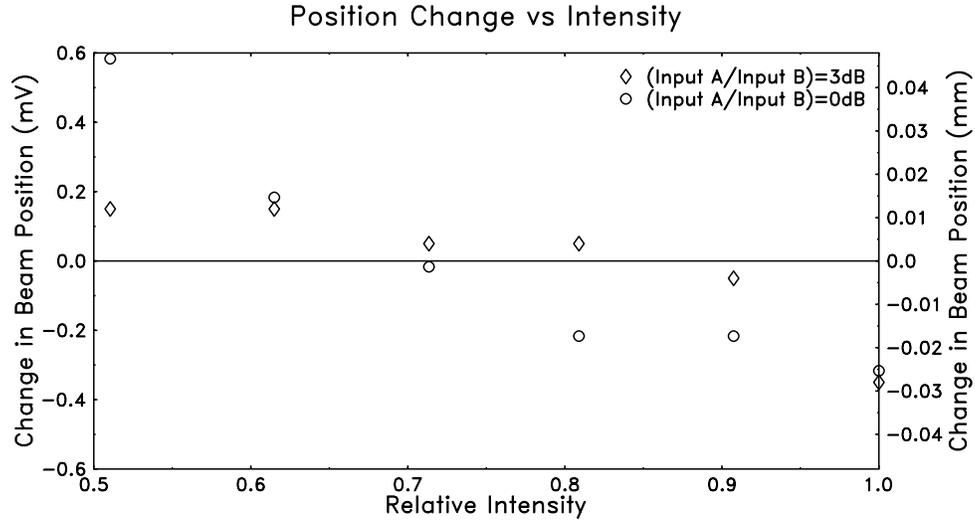
**Figure 15** When we zoom in on the crystal filtered bpm data, we can see the quantization of the readings.



**Figure 16** This is a block diagram of the circuit which produces a fake beam.

By measuring the intensity and position signals of the AM/PM module in the abort gap with the crystal filters, we can generate Figure 17 for two example cases: when the relative power between plates *A* and *B* is 3 dB and 0 dB. We can see that the absolute position change for halving the intensity is less than 0.1 mm for both cases if we use the 12.4 mm/mV calibration found earlier. The maximum intensity is  $-33.5$  mV, and

minimum intensity is  $-17.1$  mV when measured from the intensity output of the AM/PM module.

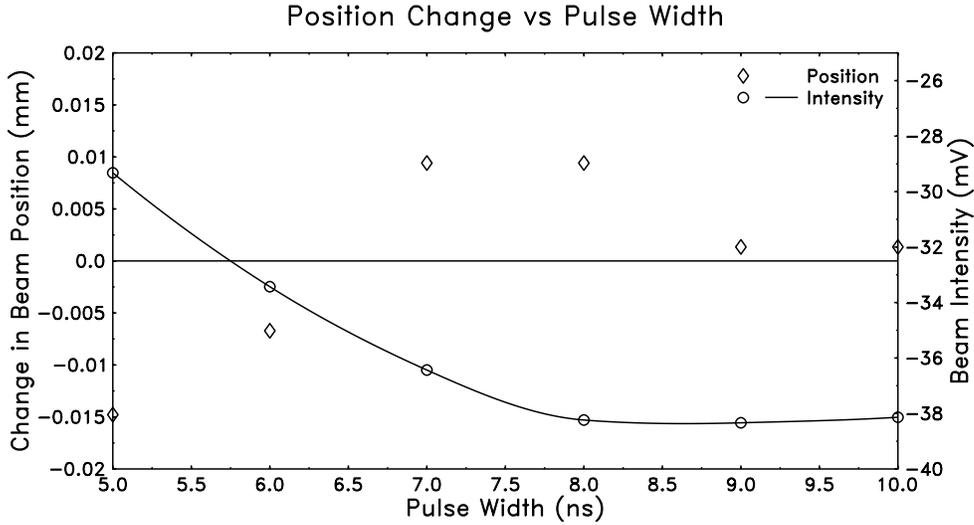


**Figure 17** The beam position as a function of intensity for two different cases.  $\diamond$  is for the case when the relative power between Plates  $A$  and  $B$  is 3 dB, and  $\circ$  is for the case when the relative power between them is 0 dB.

The next important question is the effect beam position when the bunch length is changed. We can fake this effect by simply changing the pulse width of the pulse generator. The results are shown in Figure 18 for the case when the relative power between plate  $A$  and  $B$  is 3 dB. For a change of pulse width by a factor of 2, we see that the position change is less than 0.02 mm. Surprisingly, the beam intensity measured by the AM/PM module changes by 9 mV over this range.

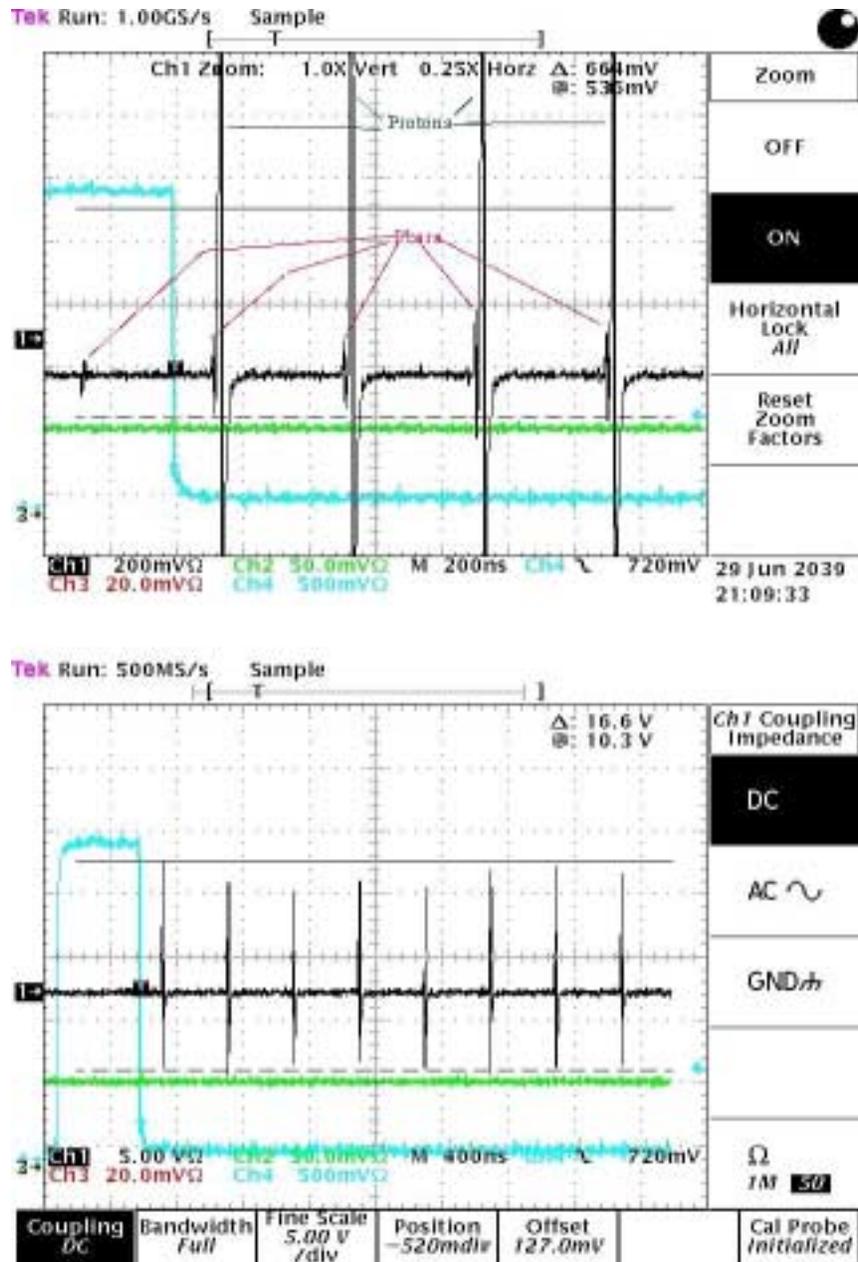
### Other Effects

Other effects that are important are:



**Figure 18** The beam position as a function of pulse width. As the pulse width is changed, the beam intensity measured by the AM/PM box also changes.

- (i) Pbars. There are pbars in the Tevatron during HEP. Therefore there is some contribution to the ringing by pbars. However, if we examine Figure 19 taken during HEP, we see that the proton signal is between 50 to 150 times larger than the pbar signal. This means that the pbars contribute between 0.6% to 2% to the proton position signal with the crystal filter.
- (ii) Drift. Crystals are devices which vibrate mechanically and thus will suffer from drift due to temperature variations. We have noticed that there is a  $1 \text{ mV} \approx 0.1 \text{ mm}$  drift in the AM/PM position signal when the crystals first start to vibrate (i.e. no beam and then beam on). This warmup time is  $\sim 5$  minutes. But once warmed up, if the beam position does not shift, the AM/PM signal is rock steady.
- (iii) Aging. The effect of aging is unknown at this time.



**Figure 19** These two pictures show the size of the pbar and proton signals from the BPM going into the crystal filter. Top picture is a zoomed in view of the lower picture. The proton signal is between 50 to 150 times larger than the pbars.

## CONCLUSION

We have shown that the use of crystal filters as an interim improvement to the AM/PM module is a promising way to enable us to measure the beam position accurately during HEP. Clearly this is not cost free and there may also be other problems which we have not thought of. It must be pointed out that as of this writing, some machine studies are going on to see that even with the slope in the position signal of the AM/PM module, the error is small enough that it still allows us to smooth the orbits during HEP. (*Update as of 27 June 2003: it has been determined that the current BPM system is good enough to do orbit smoothing with coalesced beam despite calibration errors and slope in the raw BPM position signal.*)

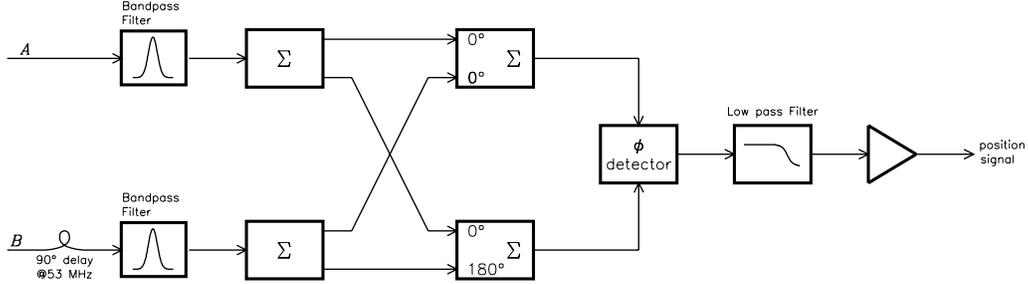
## ACKNOWLEDGEMENTS

The author wishes to thank J. Steimel and D. Sun for helpful discussions, R. Webber and W. Schappert for setting up the MADC channel for datalogging the position signal from the crystal filtered BPM at HA17.

## APPENDIX I: AM/PM MODULE

The AM/PM module has been discussed in great detail by Webber [3]. We will discuss quickly how the position signal part of the AM/PM module works here and refer the interested reader to Webber's paper. The AM/PM position module block diagram is shown in Figure 20. If we trace through the blocks, we can see that the output phase  $\phi$  is related to the input  $A$  and  $B$  by

$$\phi = 2 \tan^{-1} \frac{B}{A} \quad (6)$$



**Figure 20** This is the block diagram of the position signal part of the AM/PM module. The  $A$  and  $B$  signals come from the stripline BPM.

For simplicity, let us assume that the bandpass filter only allows the RF component through then for stripline BPMs we can write

$$\left. \begin{aligned} A(t) &= \frac{\lambda I_0}{2} \left( 1 + \frac{2\Delta x}{D} \right) e^{i\omega_{\text{RF}} t} \\ B(t) &= \frac{\lambda I_0}{2} \left( 1 - \frac{2\Delta x}{D} \right) e^{i\omega_{\text{RF}} t} \end{aligned} \right\} \quad (7)$$

where  $\lambda$  lumps together the Fourier component at  $\omega_{\text{RF}}$  and stripline geometric factors etc.,  $I_0$  is the beam current,  $\Delta x$  is the offset of the beam w.r.t. centre of the BPM,  $D$  the

diagonal distance between the striplines. For  $2\Delta x/D \ll 1$ , it is easy to show that

$$\begin{aligned} \frac{B}{A} &\approx \left(1 - \frac{2\Delta x}{D}\right)^2 \approx 1 - \frac{4\Delta x}{D} \\ \Rightarrow \frac{\phi}{2} = \tan^{-1} \frac{B}{A} &\approx \frac{\pi}{4} - \frac{4\Delta x}{D} \end{aligned} \tag{8}$$

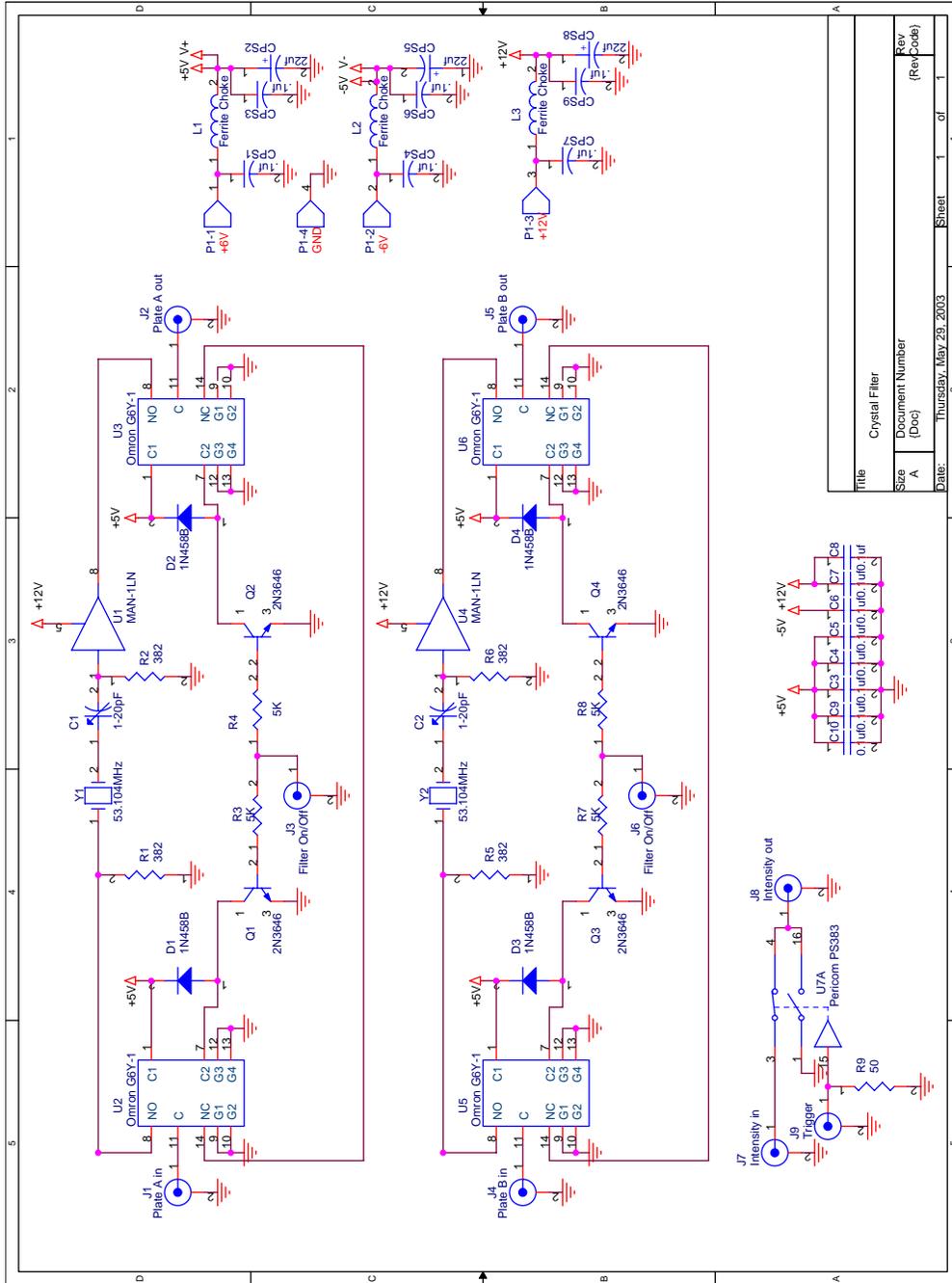
And thus the output signal from the AM/PM module gives the position  $\Delta x$  of the beam in the linear portion of the stripline BPM.

Note that in the above analysis, steady state is assumed. If we have nice sine waves oscillating at  $\omega_{\text{RF}}$  going into the AM/PM module, there should not be any problem retrieving  $\Delta x$  with accuracy. However, as we have discussed in the *Introduction*, the coalesced beam presents an impulse to the AM/PM module and the  $\omega_{\text{RF}}$  component decays away too quickly for it to get to steady state. For the uncoalesced beam, the bunches look like a steady sine wave which explains why the AM/PM module works well in this mode.

## APPENDIX II

Figure 21 shows the schematic of the NIM module used for testing out the crystal filters with actual beam in the Tevatron. RF relays G6Y-1 are used to bypass the crystal filters entirely so that this module does not disturb normal BPM measurements. The analogue switch PS383 takes the intensity signal of the AM/PM module and switches it to ground when pulsed by an external trigger to fake a beam pulse so as to trigger the digital sampling backend.

**Figure 21** The schematic of the crystal filter used at VA16.



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