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Thoughts on Tev BPM's

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Tev detector

- Stripline
- Two plates 110° wide
- 7.250” long
- 35mm plate radius

$$x \approx R\frac{A-B}{A+B} \approx R\log\frac{A}{B} = \frac{R}{20}\left.\frac{A}{B}\right|_{db}$$

$$\textit{accepted values}:$$

$$x \approx 26\left(\frac{A-B}{A+B}\right) \quad or \quad x \approx 1.5\frac{mm}{db}\left(\left.\frac{A}{B}\right|_{db}\right)$$

- Provides ok position near center…

Sinusoidal beam current

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- Voltage output is the sum of the signals produced at the ends and is proportional to beam current and plate impedance
- For a sinusoidal beam current (at the upstream end):

$$\frac{V_{plate}}{I_{beam}} = \frac{Z_O}{2}\frac{110^\circ}{360^\circ}\left\{\sin\omega\left(t+\frac{\Delta t}{2}\right)-\sin\omega\left(t-\frac{\Delta t}{2}\right)\right\}$$

$$\Delta t = \frac{2l}{c} \quad \textit{for plate length } l$$

$$\frac{V_{plate}}{I_{beam}} = Z_O\frac{110^\circ}{360^\circ}\sin\omega\frac{l}{c}\cos\omega t$$

Continuous gaussian bunch train

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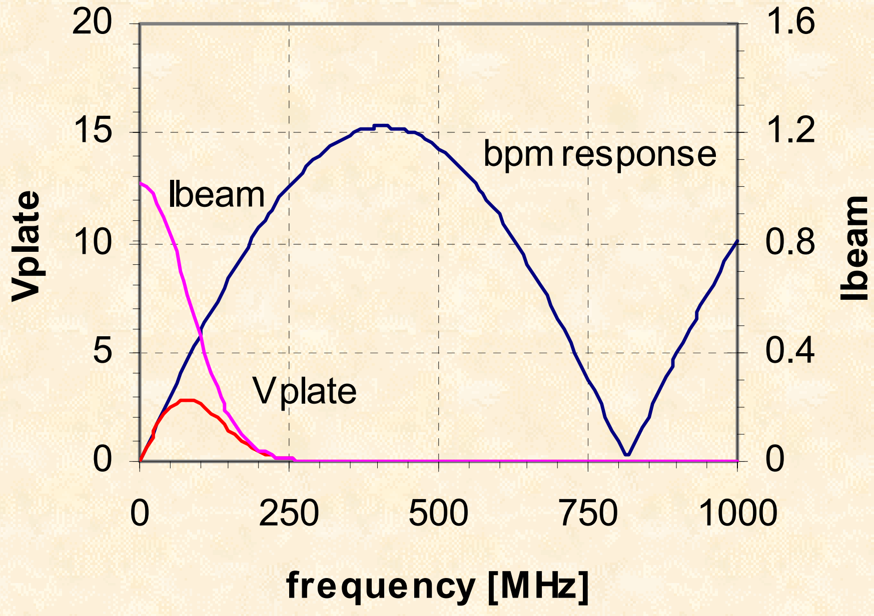
- 53MHz spacing, 2ns σt, 6e10/bunch, 50Ω plate
  - Peak response at 407MHz (plate is λ/4 long)
  - peak signal at 80MHz



Single gaussian bunch

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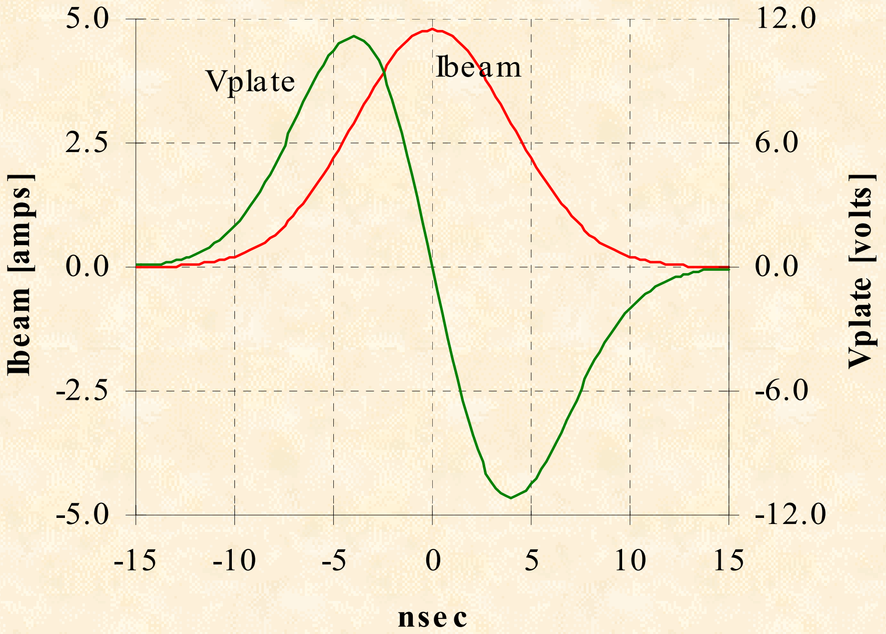
- Single gaussian bunch, 4ns σt, 3e11, 50Ω plate
  - Plate length 7.25” (dt = 2l/c = 1.2nsec)
  - Ibeam = 4.8Amps peak, Vplate = 11Volts peak

$$I = \frac{Ne}{\sigma_t\sqrt{2\pi}}\exp^{-\frac{1}{2}\left(\frac{t}{\sigma_t}\right)^2}$$

$$\frac{dI}{dt} = \frac{Ne}{\sigma_t\sqrt{2\pi}}\exp^{-\frac{1}{2}\left(\frac{t}{\sigma_t}\right)^2}\frac{t}{\sigma_t^{\ 2}}$$



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Effect of noise

- For N samples of a 14 bit digitizer
- 14 bit converter has 74db SINAD
  - SINAD = signal to noise and distortion
  - 74db/20log2 = 12.4bits ENOB (effective number of bits)

$$\frac{V_{noise}}{V_{plate}} \approx \frac{1}{\sqrt{N}}\frac{1}{2^{bits}}\frac{1}{\sqrt{2}}$$

$$X \approx r\frac{A-B}{A+B} \quad r \approx radius \quad of \quad the \quad plates$$

$$V_{A\ noise} \pm V_{B\ noise} = \sqrt{2}\,V_{noise}$$

$$X_{noise} \approx r\frac{\sqrt{2}\,V_{noise}}{A+B}$$

$$for \quad A = B$$

$$X_{noise} = \frac{r}{\sqrt{2}}\frac{V_{noise}}{V_{plate}}$$

- (<u>Non-linearity error does not improve with the number of samples</u>)

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Position noise with 84 bunch train

- For a signal that just reaches full scale input of a 14 bit A/D, 70MHz sample rate, measuring 84 - 53MHz bunches (N=111 samples)

$$X_{noise} = \frac{26}{\sqrt{2}} \frac{1}{\sqrt{111}} \frac{1}{2^{13}} = 0.22 \mu m \ Rms$$

- Position noise is inversely proportional to the beam intensity and the square root of the number of samples
- Cable loss will decrease the signal
  - 1.2db/100ft at 50MHz x 700ft = 8.4db (x 2.6)
  - Long cable with 20 bunches at 1% of the intensity
    - Xnoise = 117um Rms

Measuring single coalesced bunch

- Use a narrow band filter (or comb filter) to ring
  - Smoothes and stretches the signal out
- Simple RLC filter time constant $t_f = 2Q/2\pi f_o$
  - Measure about Q/π periods
  - Number of samples = fs * t_f = 8.4
    - For fs=70MHz, fo=53MHz, Q=20
  - Assuming the signal matches full scale of the A/D…

$$X_{noise} = \frac{26}{\sqrt{2}} \frac{1}{\sqrt{8.4}} \frac{1}{2^{13}} = 0.77\,\mu m$$

- (Bunches must be separated by several t_f)

Main Injector RG8/U cable

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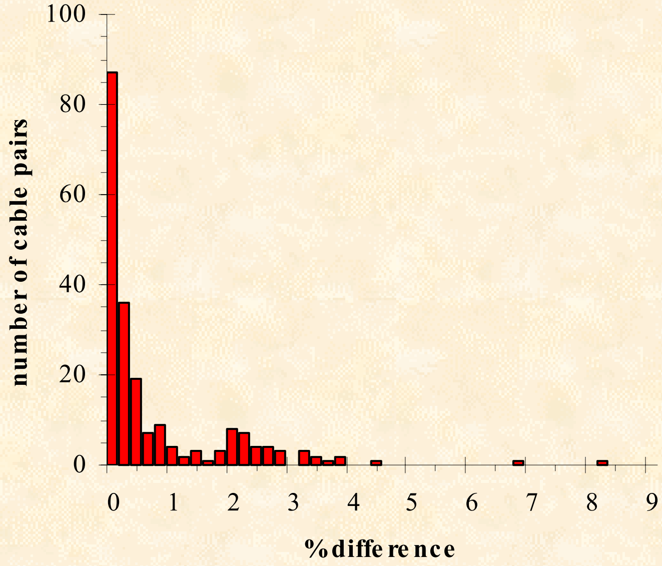

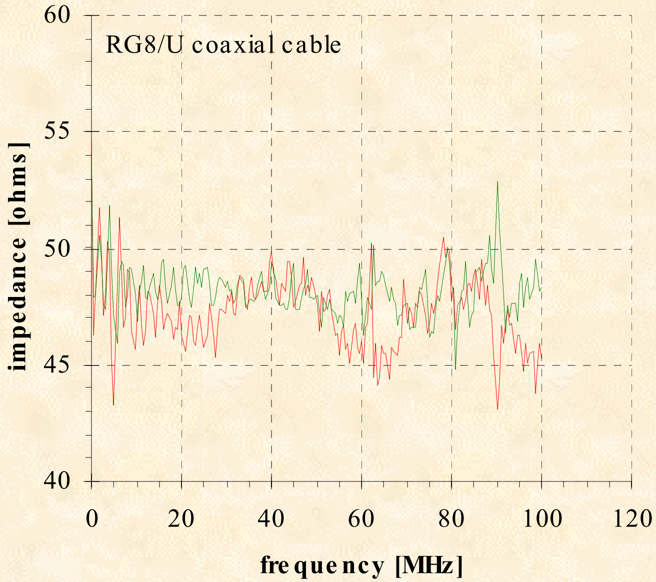

- Measured the length of all 416 cables and plotted distribution of percentage differences
- Also measured characteristic impedance of a few cables
- Manufacturer's specifications:
  - v/c = 78±1%   Zo=50 ±2Ω

Effect of impedance matching

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- Assuming kr << 1 and that A ≈ B

$$k_r = \frac{Z - Z_O}{Z + Z_O} \qquad A' = A\left(1 + k_r\right)$$

$$x \approx r\,\frac{A\left(1 + k_r\right) - B}{A + B}$$

$$X_{error} \approx \frac{r}{2} k_r$$

- For Z-Zo = 5Ω, kr = .05
  - Xerror = 0.66mm

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Cable attenuation

- The percentage change in attenuation is probably about the same as the percentage change in characteristic impedance

$$\alpha\left[\frac{Np}{m}\right]=\frac{R}{2Z_O}$$

- For a 5Ω or 10% variation in Zo

$$X=1.5\left[\frac{mm}{db}\right]20\log\left(\frac{A(1\pm0.1)}{B}\right)$$

$$X_{error}=1.5\left[\frac{mm}{db}\right]20\log(1\pm0.1)=1.2mm$$

VP801 cable problem

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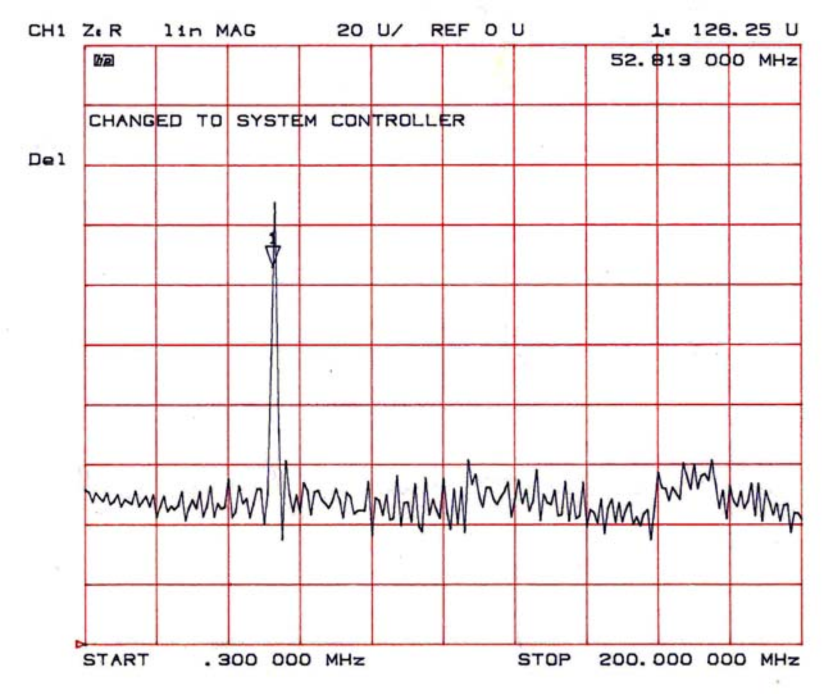
- Getting unstable positions from one location in MI8 beam line
- The cable on one plate had impedance bump at 53MHz?!



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MI8bpm problem

- possibility: The cable reel sat on one side making a periodic deformation or change in Zo?
- ½ wavelength corresponds to 2.3ft diameter reel
  - About right
- nearby bpm's had similar "bumps" at higher and lower frequencies.
  - Could be different layers from same reel
- Something in the manufacturing process?
  - Manufacturer says no way

Effect of nonlinear BPM's

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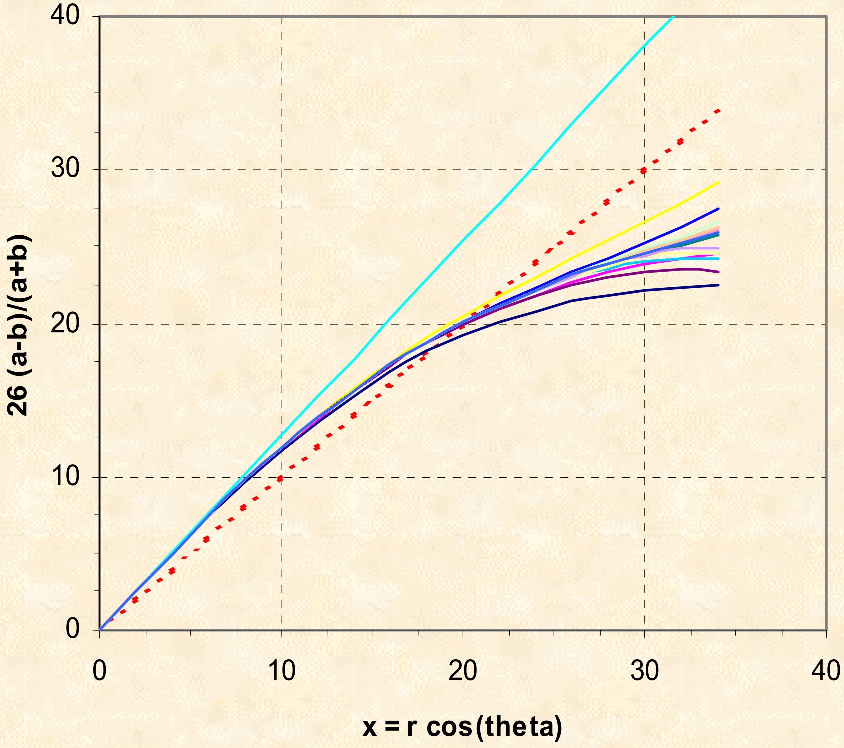
- Radial position r at angle theta in bpm of radius b with plate width theta (n = 1 to 26)

$$\frac{I_A}{I_{beam}} = \frac{\phi}{2\pi}\left\{1+\sum_{n=1}^{\infty}\frac{4}{n\phi}\left(\frac{r}{b}\right)^n \cos(n\theta)\sin\left(n\frac{\phi}{2}\right)\right\}$$

$$\frac{I_B}{I_{beam}} = \frac{\phi}{2\pi}\left\{1+\sum_{n=1}^{\infty}\frac{4}{n\phi}\left(\frac{r}{b}\right)^n \cos(n\theta)\sin\left(n\left(\pi+\frac{\phi}{2}\right)\right)\right\}$$



- (Convolve transverse bunch shape with bpm respsonse to obtain position)

Compare diff/sum with log ratio

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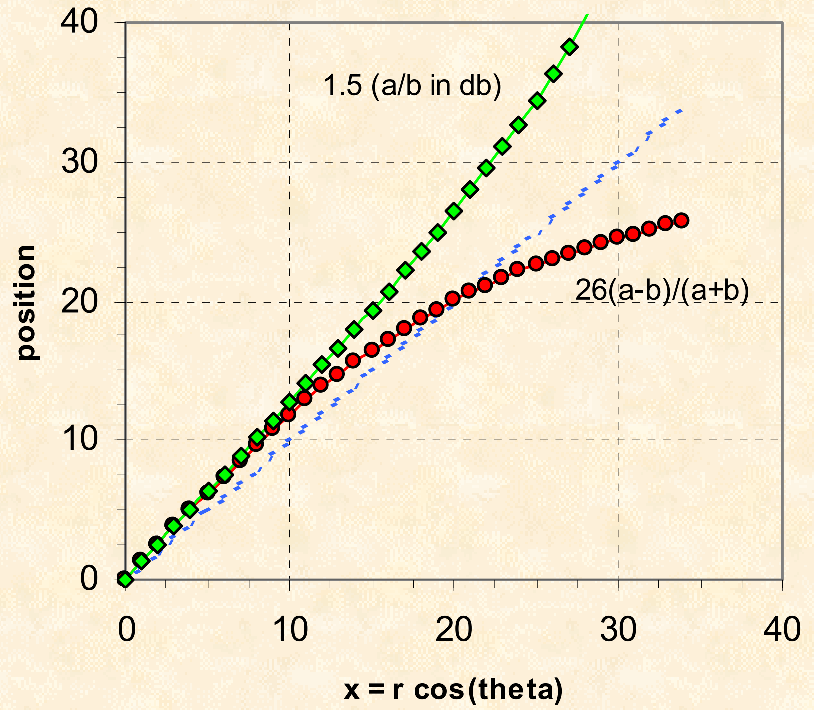
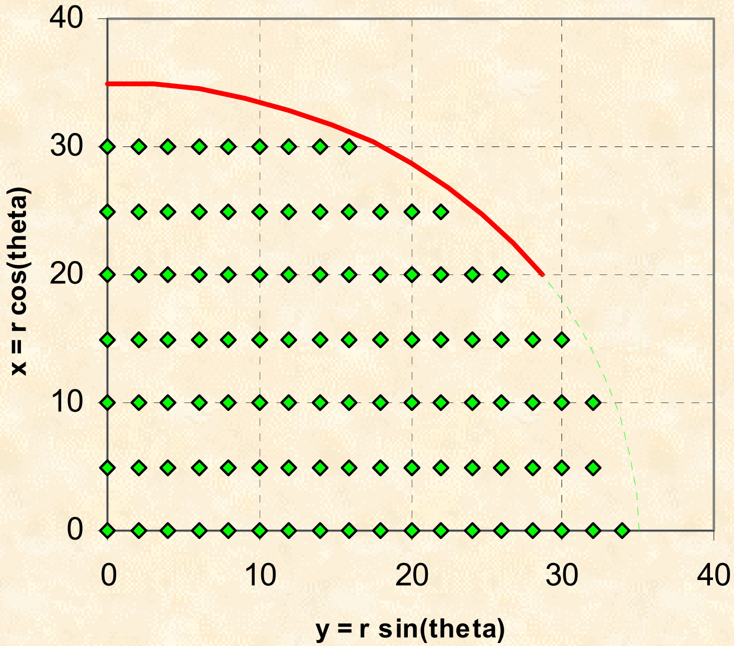
- From calculated bpm signals at the center of the orthogonal plane

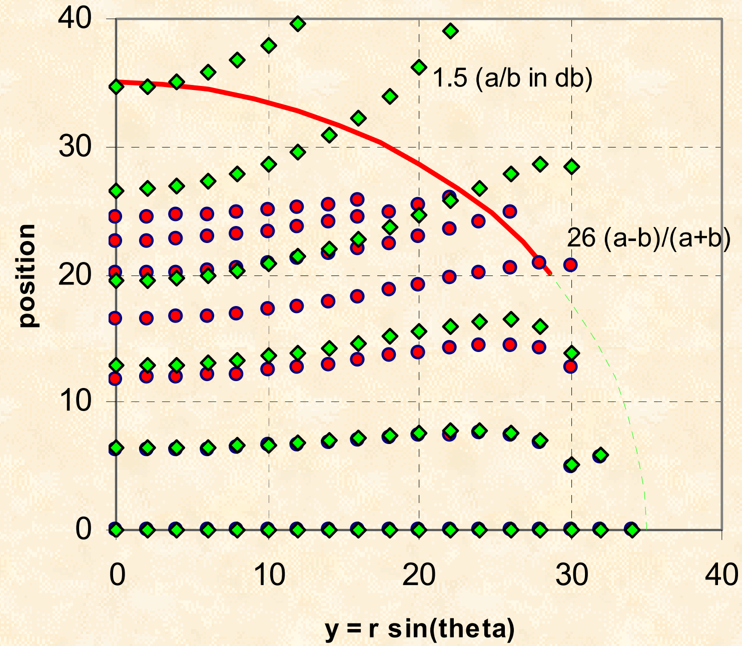


Scan over aperature

- Simulated beam positions



- position using diff/sum and log ratio scaling



Linearity and Directionality

- So far we have assumed the plates do not talk to each other
- In reality, the plates have different common mode and differential mode characteristic impedance.
  - For the beam at the center, the plate signals will be identical and things work as described.
  - For an off center beam, the signals will not be the same and the impedance will be less
    - I believe this causes the non-linear response of the bpm
    - Gain and directionality are a function of beam position
- (We can build a perfect detector only if the beam doesn't move off center)

Directionality

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- The voltage at the downstream end of the stripline is the sum of the signals produced at the ends
  - However, at the downstream end, the signals arrive at the same time ($\Delta t = 0$)

$$\frac{V_{plate}}{I_{beam}} = \frac{Z_O}{2}\frac{110°}{360°}\left\{\sin\omega\left(t+\frac{\Delta t}{2}\right)-\sin\left(t-\frac{\Delta t}{2}\right)\right\} = 0$$

- This happens iff
  - the beam velocity matches the velocity of the signal on the plate
  - The beam induced signals at the ends exactly cancel
- The Tev bpm's are said to have a directionality of 26db
  - The signal on the downstream end is about $1/20^{th}$ of the upstream signal
    - (changes a lot with frequency and beam position)
  - It can never be better than the error caused by plate to cable impedance match
    - (cable impedance changes by 10% which changes signal amplitude by 5% resulting in 26db directionality)

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VSWR

- VSWR – voltage standing wave ratio
  - Ratio of the max to the min voltage along a cable that is not properly terminated

$$vswr = \rho = \frac{1+|k_r|}{1-|k_r|} \qquad k_r = \frac{Z - Z_O}{Z + Z_O}$$

$$\rho = larger\ of \quad \frac{Z}{Z_O}\ or\ \frac{Z_O}{Z} \qquad (always\ greater\ than\ 1)$$

- Assume both cables have the same vswr but max and min's probably don't align at the receiver
  - Use the square root of the vswr to estimate position error

$$X = 1.5\left[\frac{mm}{db}\right] 20\log\left(\frac{A}{B}\sqrt{\rho}\right)$$

$$X_{error} = 1.5\left[\frac{mm}{db}\right] 20\log\left(\sqrt{\rho}\right) = 0.6mm\ \ for\ \ \rho = 1.1$$

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Reflections

- The Tev bpm cables range from 200 to 700 feet.
- Reflections will be separated by 400 to 1400 nsec.
- The amplitude of the reflections will be about 5% and will depend on frequency content of the beam
  - .42db or .64mm error
- In general, a kicker gap is required and necessitates a gap in the beam
  - Best if position is measured from beam following one of these gaps

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State of the art

- position is about 1.5mm/db
- $35k HP network analyzer
  - 0.04db (60um)
  - reasonably soon after a full 2 port cal using short well behaved cables with good quality connectors in a nice quiet lab environment
- 1 bit error on full scale 14 bit A/D is .00053db (0.8um)
  - Noise might be this good but, accuracy will not be!

Thoughts on receiver

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- Traditional bpm receiver isolates a single frequency component and measures the amplitude on the 2 plates
  - Wastes a lot of energy outside this bandwidth
  - Bandwidth inversely proportional to signal duration
- optimum receiver matches the frequency content of the signal
  - Use a digital filter who's coefficients match the expected signal samples (like doing an auto-correlation)
- In the Echoteks, to measure 84 bunches simply multiplied by 53MHz sinewave and summed the results
  - Timing inaccuracies required a shorter gate
- Use the impulse response of RLC filter to make optimum digital receiver for single bunch
  - (Limited bandwidth requires bunch separation)
  - (Could try splitting and summing through several cable lengths)

14bit 100MHz or 12 bit 200Mhz

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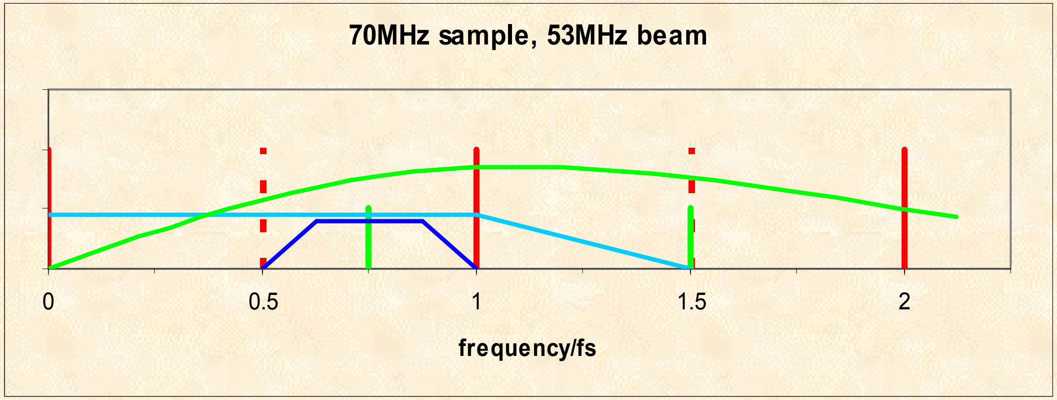
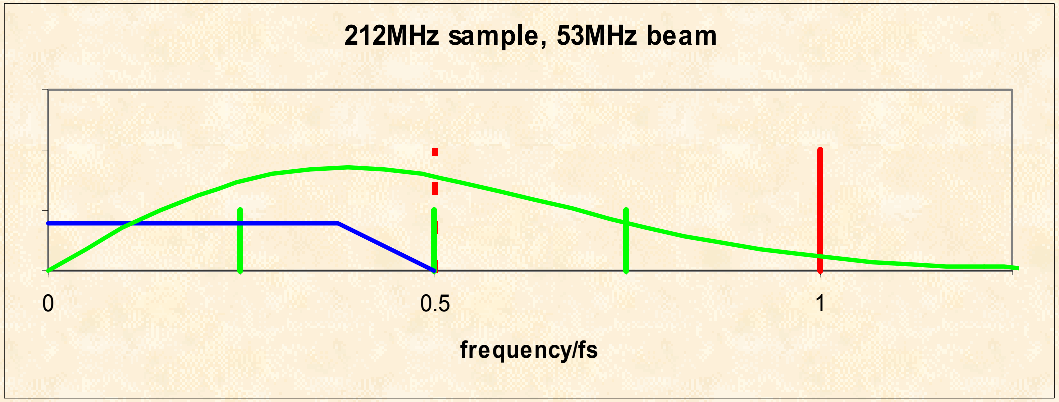
- Spectrum of sample frequencies and 53MHz beam component
- Posible filters are indicated
- Tev stripline response to 2ns sigma t bunches is also shown





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12 or 14 bit?

- A/D chips available today are 14bit 100MHz and 12bit 200Mhz
- 12 bit gives up factor of 4 in resolution
  - Loose 12db of resolution or dynamic range
  - Twice as many samples provides square root of 2 noise reduction
  - Requires 75MHz lpf
- 14 bit
  - Better resolution and dynamic range
  - Square root of 2 higher noise from fewer samples
  - Requires 35MHz bpf
  - 75MHz lpf if there are no signal components in the unwanted band

- Attractive to use same Echotek card in Tevatron
  - **Very fast project**

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Summary

- Cable impedance, vswr, attenuation, reflections, detector impedance, directionality, linearity, receiver noise, input impedance, linearity depend on frequency and limit ultimate accuracy.
- Frequency dependant errors result in time dependant position error
- I suspect noise will be small ~100um even at modest intensities
- Repeatability between identical beam and position will be about the same <100um
- Relative accuracy over a range of intensity, position, and bunch structure <1mm
- Absolute accuracy will likely be <2mm
- Sensitivity to position in the orthogonal plane may make things worse.
- Need to find a good algorithm to linearise the bpm output
- Buying Echotek cards would provide a **substantial, timely** improvement for less than $500k