Stripline Detectors for Fermilab Main Injector

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Introduction

The Institute for High Energy Physics designed and built four stripline beam detectors for use at Fermilab. The detectors will be installed for general purpose use, two in the Main Injector and two in the Recycler. A round geometry with two stripline plates was chosen to allow installation as either horizontal or vertical position detectors. Electrical feedthroughs at both ends of the 1.4 meter long striplines allow measurement of both proton and antiproton signals. The 1 gigahertz bandwidth and 9.3 nsec doublet separation allow measurement of high frequency structure within the beam bunches.

Design features

The striplines are mounted in a 150 mm ID stainless tube. Torlon 4203 (made by Amoco Chemicals Corp.) was selected to make the insulators which hold the striplines in position. Torlon has a tensile strength of 22000 psi, is resistant to radiation damage, is easily machineable, can be baked to 260 °C, and has good vacuum properties. The 60 degree wide plates intercept and carry about 1/6 of the beam image current. The peak amplitude on the 50 Ω plates will be about 10 volts for $6 \cdot 10^{10}$ protons in a 3 nsec sigma gaussian bunch.

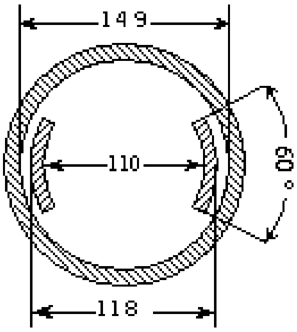

Figure 1: Cross section of stripline detector.

A plate length of 1.4 meters (l/4 wavelength at the rf frequency of 53 MHz) is used to maximize the doublet separation. In the time domain, this allows observation of the bunch shape and changes in position along it's length. In the frequency domain, zero's in transmission occur when the plate is a multiple of 1/2 wavelengths long. This occurs at even harmonics of their frequency. Type N vacuum feedthroughs are used at each end to access the signals. To allow easy replacement, the feedthroughs are welded into vacuum flanges and the center pin makes electrical contact by depressing stainless tabs on the stripline.

The detectors are placed in regions having 6 inch round vacuum tube. Both the Main Injector and Recycler use elliptical shaped vacuum tube through most of their circumference. A smooth transition between the two shapes is used to minimize beam impedance. The microwave cut off frequency has been measured to be 1.2 GHz in the striplines and 1.5 GHz in the elliptical pipe.

Ideal Stripline response

Beam traveling along a vacuum tube induces image charge of equal but opposite sign on the conducting walls. About 1/6th of this charge will be induced onto the plate at the upstream end and removed at the downstream end. The frequency response can be estimated by summing the voltage produced from these two opposing current sources taking into account their time difference. The voltage at both ends as a function of frequency is estimated below for a 60 ° wide plate, length (l), impedance (Zo), and beam velocity (c).

Ideal stripline frequency response

$$I_{\mathrm{beam}}(t) = I_{\mathrm{b}} \sin\omega\Big(t + \frac{l}{c}\Big),$$

$$V_{\mathrm{up}}(t) = I_{\mathrm{b}} \frac{Z_0}{2} \frac{60^\circ}{360^\circ} \Big[\sin\omega\Big(t + \frac{l}{c}\Big) - \sin\omega\Big(t - \frac{l}{c}\Big)\Big],$$

$$\Big|V_{\mathrm{up}}\Big| = I_{\mathrm{b}} Z_0 \frac{60^\circ}{360^\circ} \Big|\sin\omega\frac{l}{c}\Big|,$$

$$V_{\mathrm{down}}(t) = I_{\mathrm{b}} \frac{Z_0}{2} \frac{60^\circ}{360^\circ} \Big[\sin\omega t - \sin\omega t\Big] = 0.$$

All charge induced on the upstream end will be removed at the downstream end as the beam exits the detector. No signal is produced at the downstream end of an ideal stripline provided the charge on the plate travels at the same velocity as the beam and exactly matches the image charge removed as the beam passes the downstream end. This also requires a constant plate impedance and perfect match to the signal cables.

The two striplines within a detector couple to each other making their impedance depend on the balance of charge, or beam position. For the geometry used, the plate impedance is reduced by 3 Ω when driven differentially. This calculation was verified using time domain reflectometry. Thus, directionality depends on beam position.

Wire Measurements

The cutoff frequency for the TE11 mode inside the stripline is about 1.2 GHz making the response irregular and unusable above this frequency. Below cut off, there is excellent agreement with an ideal stripline. The measurements shown below were made by driving a wire placed along the center of the detector. Resistive dividers were used to minimize reflections on the wire by matching the impedance to 50 Ω at each end. Transmission through the wire was flat to ±1 db.

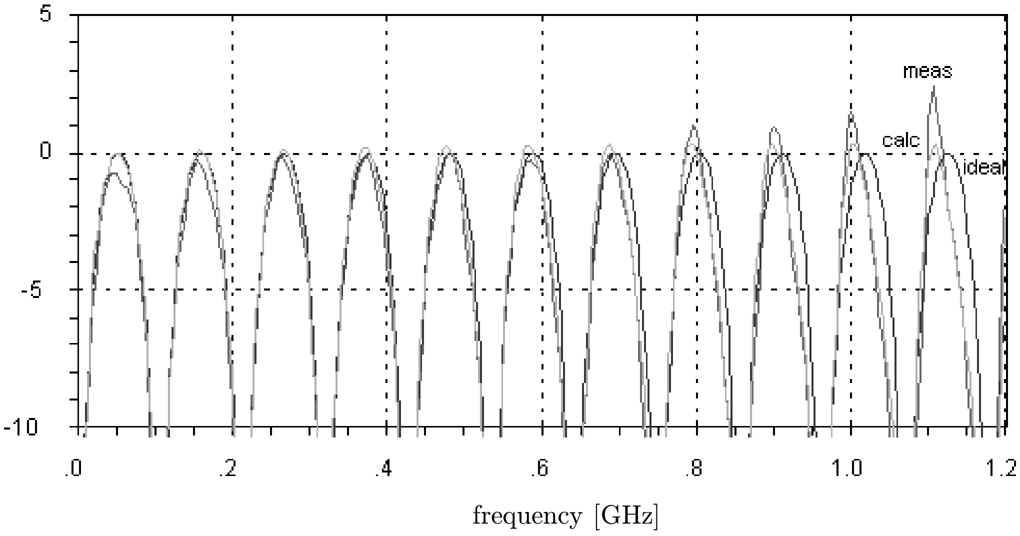

Figure 2: Measured, calculated, and ideal stripline response at the upstream end. The calculation used 53 Ω lines terminated with 50 Ω in parallel with 4 pf.

The model uses two current sources with the correct time difference and polarity driving both ends of a 53 Ω transmission line. Good agreement with measurement was obtained by terminating the lines with 50 Ω in parallel with 4 pf capacitors. The measured amplitude indicates about 1/4 of the beam current is induced on to the plates.

The excess capacitance at the ends is caused by the geometry used to hold the striplines in position. Mismatch from this capacitance causes reflections which reduce the directionality of the detectors. Because protons and antiprotons are never in the Main Injector or Recycler at the same time, directionality is not important for this application.

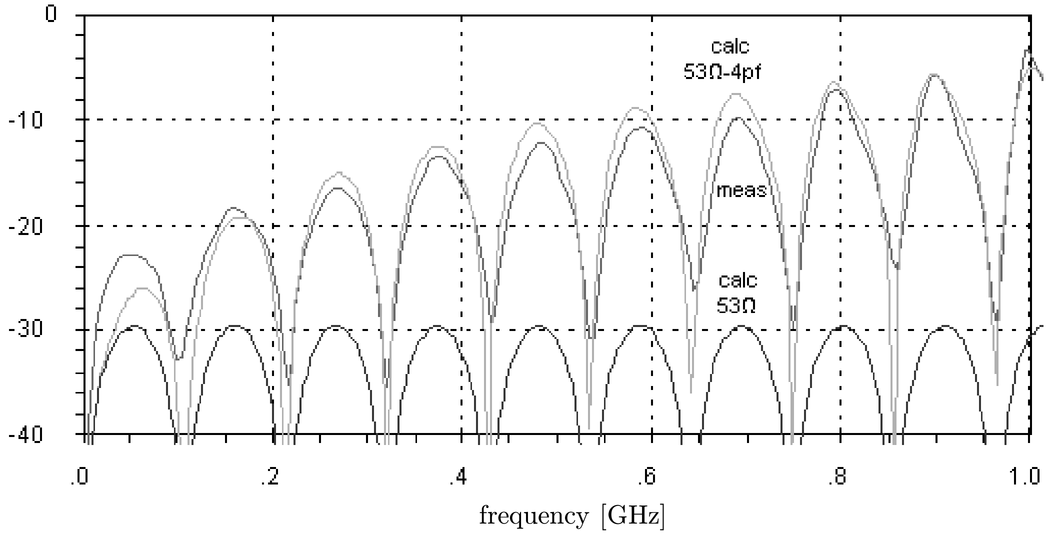

Figure 3: Measured and calculated stripline response at the downstream end. The calculation was done with and without 4 pf at the ends.

The log of the ratio of the signals on the two striplines is proportional to position. The sensitivity is 2 mm/db through 75 % of the 110 mm aperture as shown below.

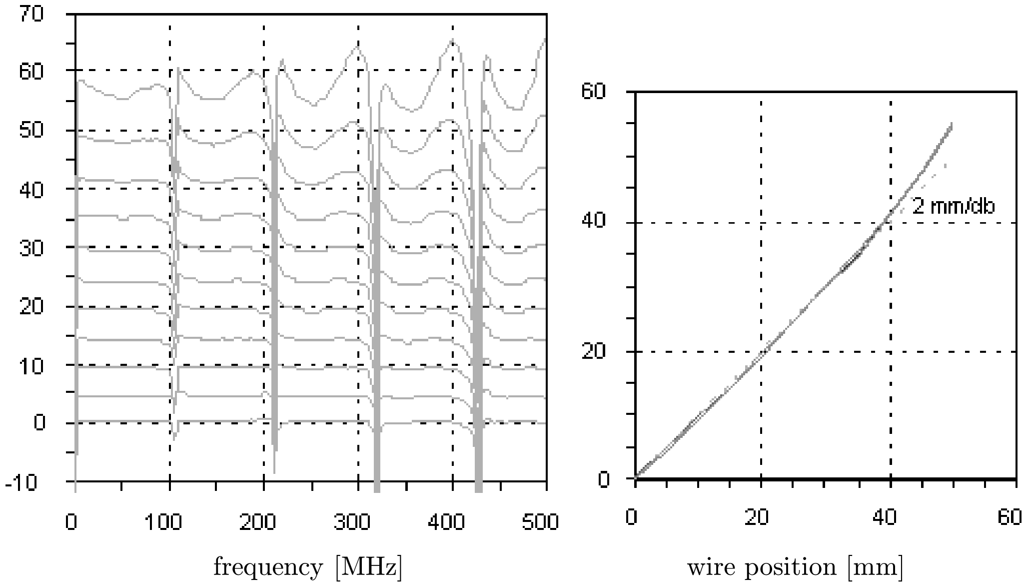

Figure 4: A/B scaled by 2 mm/db for wire positions from 0 to 50 mm in 5 mm steps versus frequency and at 1, 3, 5, 7 and 9 times 53 MHz versus wire position.

The time domain response was measured with a gaussian shaped pulse having a sigma width of 0.5 nsec, the shortest length we could easily generate. The pulse traveled along a wire placed at the center of the detector. The Fourier transform of a gaussian pulse is itself a gaussian having a sigma width of 320 MHz. The frequency components of such a pulse fall easily within the bandwidth of the detector as evidenced by the excellent agreement between measurement and the model shown below.

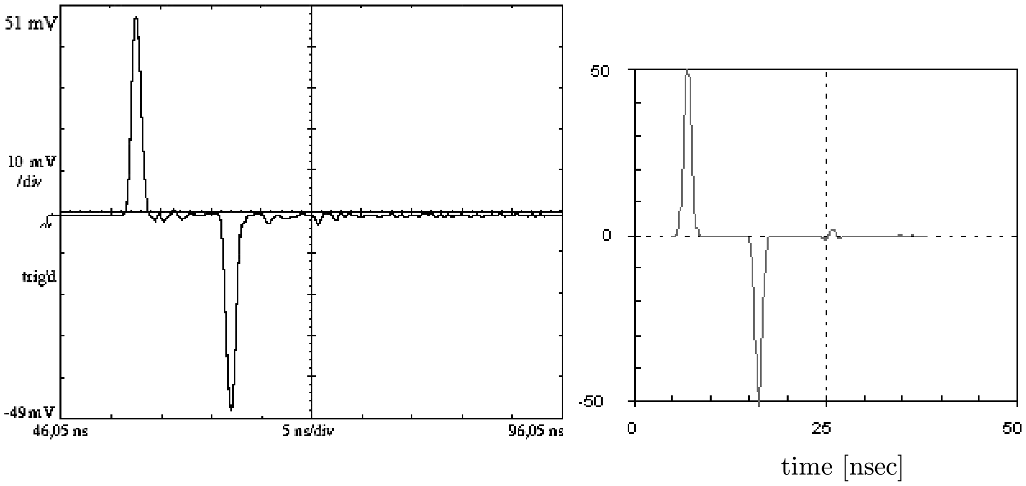

Figure 5: Measured and calculated response to gaussian pulse with 0.5 nsec sigma width.

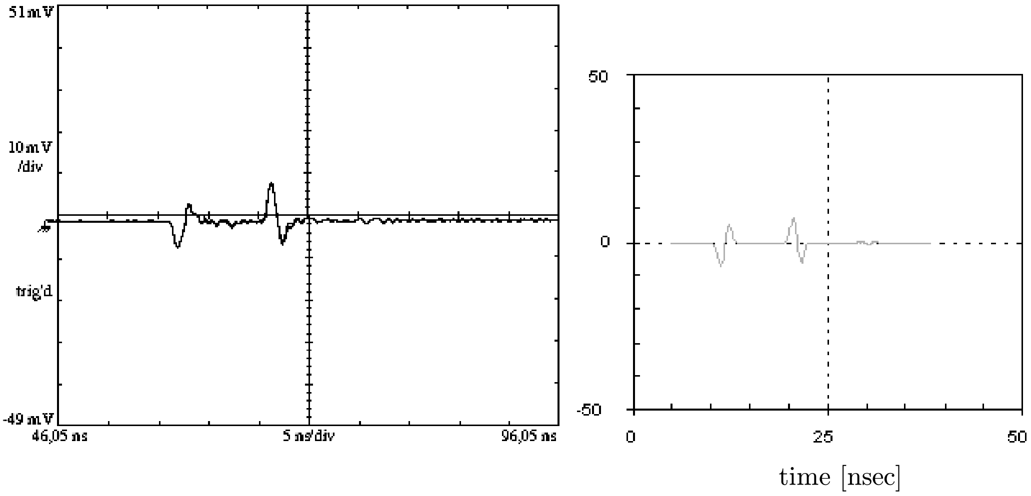

Figure 6: Measured and calculated response to gaussian pulse with 0.5 nsec sigma width at the downstream end.

Beam position can be estimated with the ratio of the difference to the sum of the two stripline signals. Excellent position sensitivity with a well behaved time structure was measured by changing the wire position and taking the difference between the two striplines, shown below.

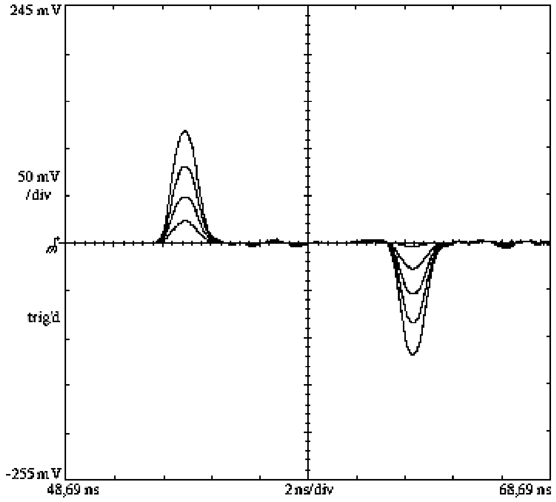

Figure 7: A–B for 0, 10, 20, 30, and
40 mm wire position.

Beam Measurement

On October 10th, beam was successfully circulated around the new Fermilab Main Injector. Intensities were limited to avoid unnecessary contamination, but $5 \cdot 10^{10}$ protons in 84 bunches were routinely circulated without rf for 25 seconds when they were intentionally aborted. The figure below was taken on the first turn while beam was still longitudinally bunched.

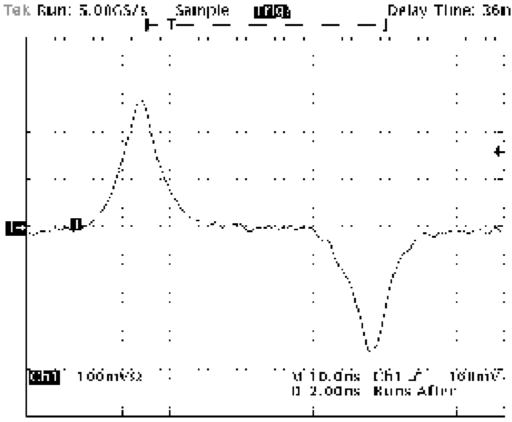

Figure 8: A+B produced with circulating
beam in the Fermilab Main Injector.

Conclusion

The only significant improvements to the existing design would be to reduce the capacitance at the ends of the plates and perhaps adjust the plate position slightly to make them 50 Ω.

Fermilab is grateful for the excellent detectors designed and built by IHEP. Their response is nearly ideal and will provide excellent measurements for years to come.