CEBAF PR-90-024
October 1990

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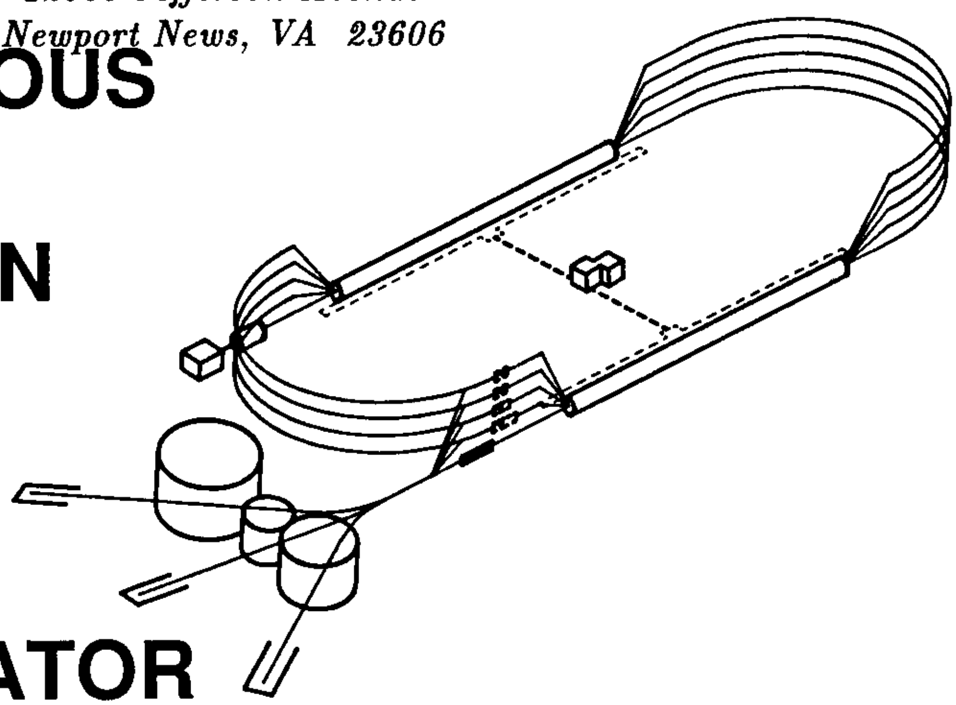

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A GENERAL ANALYSIS OF THIN WIRE PICKUPS FOR HIGH FREQUENCY BEAM POSITION MONITORS*

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Abstract

In many particle accelerators, a large number of high frequency beam position monitors (BPMs) are required to track and correct the orbit of the beam. Therefore, simple, sensitive, low cost pickup designs for such BPMs are of widespread interest. In this paper, a general analysis of arbitrarily terminated thin wire stripline or "wireline" pickups for BPMs is presented. Subsequently, three specific cases of interest, the open-circuited end, short-circuited end, and matched end wirelines are compared and contrasted in detail. Of these three cases, the open-ended wireline pickup BPM is found to be particularly well-suited for application in the arc regions of the Continuous Electron Beam Accelerator Facility (CEBAF). Measurements of a 1.5 GHz prototype of this type of BPM yielded a longitudinal (sum) pickup impedance of 72 Ω, a transverse pickup impedance of 3.8 Ω/mm, and a bandwidth of 470 MHz, all of which are in excellent agreement with the theory.

Introduction

It is presently estimated that 400–600 microwave BPMs operating at the machine frequency (1.497 GHz) are required for the CEBAF accelerator. Because of the large number of monitors involved, a simple low cost pickup design is of primary concern. In addition, the BPMs must be capable of accurately measuring the position of beams with average currents as low as 1 μA. For the extremely short bunch length at CEBAF, this results in a 2 μA AC component of beam current at 1.497 GHz. Consequently, the BPMs must be extremely sensitive as well as inexpensive.

A BPM pickup design well-suited to this application consists of a thin quarter wavelength antenna or "wireline" inside the beampipe and is similar to the standard stripline pickup design. However, in the present design, only the upstream end of the line is terminated, and the line impedance is not necessarily matched to the termination impedance. This results in a non-directional broadband pickup that, apart from a geometric factor, depends solely on the wireline impedance. This latter feature is most important because in practice, the line impedance can be made as high as 200 Ω which is a factor of four greater than the standard termination impedance of 50 Ω available at microwave frequencies.

The unterminated downstream or open-ended wireline pickup is a specific case of the more general wireline pickup with arbitrary upstream and downstream terminations. In this paper, a general analysis of the ideal wireline pickup is given. The characteristics of the open-ended wireline pickup are then discussed and compared to those of the conventional

* This work was supported by the U.S. Department of Energy under contract DE-AC05-84ER40150.

matched stripline and shorted-end or "loop" pickups which are presently in use in the CEBAF linacs.[1] In addition, the results of longitudinal and transverse bench tests on an open-ended pickup BPM which confirm the theory are presented.

Response Functions for Wireline Pickups

The BPM to be considered is illustrated schematically in figure 1. The monitor consists of four thin wire antennas (x plane shown in figure 1) located orthogonally to each other inside a circular beampipe of radius a. Each wire has length ℓ, diameter d and is located a distance b from the centerline of the monitor. As with conventional stripline pickups, each wire forms a transmission line with characteristic impedance Z_c determined by the dimensions a, b, and d. For the general wireline pickup, the output is terminated by a load impedance Z_1, and the downstream end is terminated with an impedance Z_2.

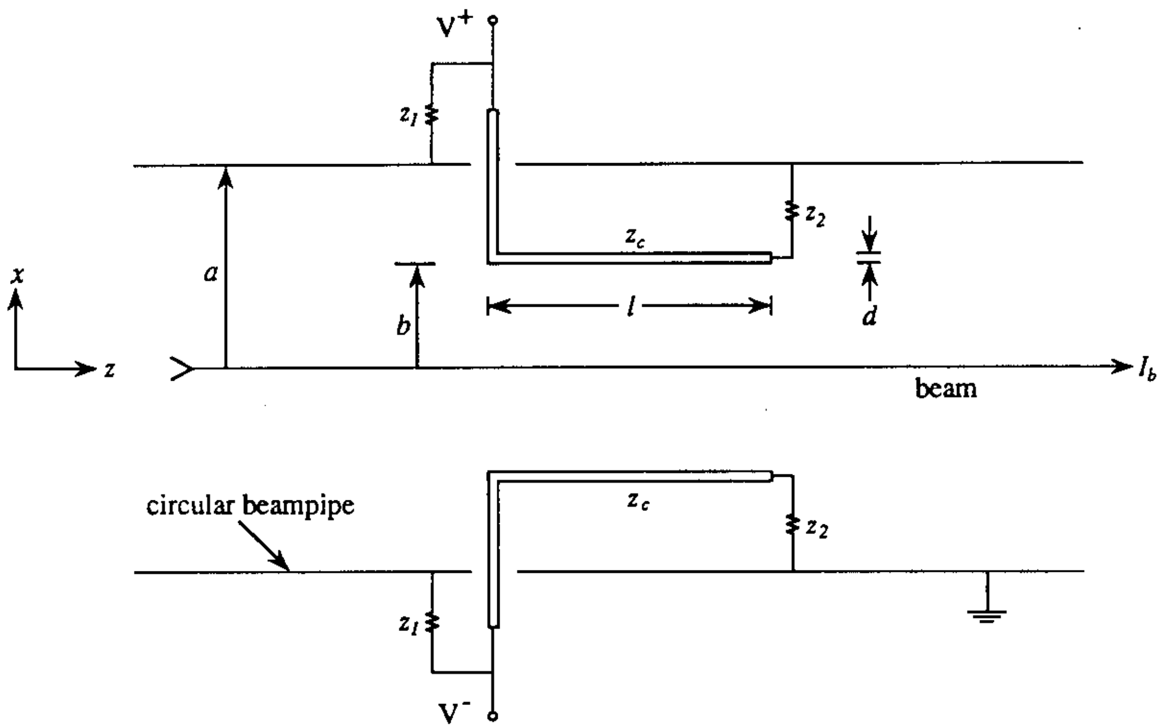

Figure 1 General wireline pickup BPM.

The goal of the analysis is to derive the frequency and impulse responses of the wireline pickup for arbitrary real impedances Z_1, Z_2, and Z_c. Subsequently, the special cases of the conventional stripline ($Z_1 = Z_2 = Z_c$), open-ended wireline ($Z_2 = \infty$) and shorted-end wireline or "loop pickup" ($Z_2 = 0$) can be examined in greater detail. In addition, the longitudinal and transverse pickup impedances for the open-ended monitor are derived.

It is well established through the application of the Lorentz reciprocity and Panofsky-Wenzel theorems that beam currents couple to pickups only in regions where electric fields parallel to the current exist when the pickup is driven as a kicker.[2] For the pickups in figure 1, these regions must be the discontinuities at the upstream and downstream ends of the wirelines because, when driven as kickers, the wirelines support pure TEM modes except at these locations. Assuming the longitudinal electric kicker fields are localized at these locations, a reasonable equivalent circuit, shown in figure 2, for modeling the wireline as a pickup can be devised.

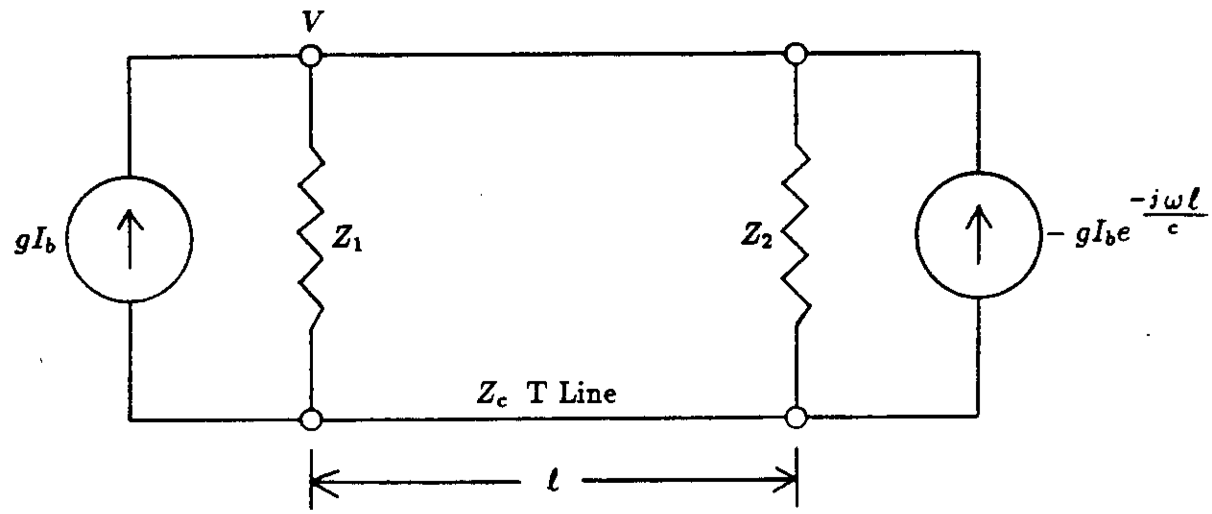

Figure 2 Equivalent circuit for general wireline pickup.

The equivalent circuit, shown in phasor form, consists of the wire transmission line and its associated terminations driven by current sources at the upstream and downstream ends. The magnitude of the sources is the magnitude of the phasor component of beam current, I_b, reduced by a geometric coupling factor, g, which depends on transverse beam position. The downstream source is delayed in phase by $\omega\ell/c$ to account for the propagation time of the beam. Here, the beam velocity is assumed to be c ($\beta = 1$) for simplicity. In addition, an overall minus sign on the downstream source accounts for the polarity difference between the upstream and downstream ends of the wireline. This polarity difference results because the direction of the beam current relative to the wireline is such that it is "entering" the upstream end of the pickup and "exiting" the downstream end. Equivalently, the downstream source in figure 2 could be drawn in the opposite direction while dropping the minus sign.

The basic quantity of interest is the transfer impedance, Z_T, defined for a single pickup as the output voltage from the pickup divided by I_b for a centered beam. The transfer impedance is generally a complex function of frequency and can be found by analyzing the equivalent circuit in figure 2. By applying the principle of superposition to the current sources and using standard transmission line analysis, the transfer impedance for the equivalent circuit model is found to be:

$$Z_T(\omega) = \frac{gZ_1 \| Z_c \left(1 - e^{-j\frac{2\omega\ell}{c}}\right)}{1 - \Gamma_1\Gamma_2 e^{-j\frac{2\omega\ell}{c}}} \quad \Omega \tag{1}$$

where:

$$Z_1 \| Z_c = \frac{Z_1 Z_c}{Z_1 + Z_c}$$

$$\Gamma_1 = \frac{Z_1 - Z_c}{Z_1 + Z_c}$$

$$\Gamma_2 = \frac{Z_2 - Z_c}{Z_2 + Z_c}$$

For real frequency independent terminations Z_1 and Z_2, the corresponding reflection coefficients Γ_1 and Γ_2 are also real and independent of frequency. In this case, the unit impulse response of the wireline pickup is readily obtained from the inverse Laplace transform of equation (1). The resulting impulse response is given as:

$$z_T(t) = g Z_1 \| Z_c \left\{ \delta(t) + \left(1 - \frac{1}{\Gamma_1 \Gamma_2}\right) \sum_{n=1}^{\infty} (\Gamma_1 \Gamma_2)^n \, \delta\left(t - \frac{2n\ell}{c}\right) \right\} \quad \Omega/\mathrm{sec} \tag{2}$$

Having the unit impulse response, the voltage at the output of the pickup for a beam current with arbitrary time dependence $i_b(t)$ may be found by convolution:

$$v(t) = \int_0^{\infty} i_b(\tau) \, z_T(t - \tau) \, d\tau \tag{3}$$

Expressions (1) and (2) completely characterize the general wireline pickup. However, at this point, three important specific cases of the wireline pickup are examined in more detail. The three pickup types of interest include the matched wireline ($Z_1 = Z_2 = Z_c$), the open-circuited wireline ($Z_2 = \infty$), and the short-circuited wireline ($Z_2 = 0$). In all cases, the transfer impedance given by equation (1) is a maximum at the frequency where ℓ is a quarter wavelength long. Designating this frequency ω_0 and using the relation $\pi/\omega_0 = 2\ell/c = t_0$, expressions for the amplitude and phase of the transfer impedance for the three pickup types, shown in table 1, may be derived from equation (1). In addition, table 1 contains expressions for the 3 dB bandwidth and unit impulse response for each pickup type.

Several observations about the three pickup types can be made from table 1. All three pickups exhibit repeated symmetric band pass characteristics centered at odd integer multiples of ω_0. Although theoretically these pass bands repeat indefinitely with increasing frequency, several effects not incorporated into the theory presented here limit the high frequency response of the pickups. As the frequency increases beyond cutoff for the lowest order TM waveguide mode in the beampipe ($f_c = .383\ c/a$), an increasing number of waveguide modes can be excited, significantly altering the response of the pickup. At extremely high frequencies, the possibility of higher order modes on the wirelines themselves exists. In view of these and other high frequency effects, the practical operating range of the pickups is usually limited to the fundamental bandpass region centered at ω_0.

Table 1. Frequency and Impulse Characteristics of Various Wireline Pickups

	Matched Line	Open Circuit Line	Short Circuit Line
$\lvert Z_T \rvert$	$gZ_1 \lvert \sin\theta \rvert$	$\frac{gZ_c \lvert \sin\theta \rvert}{\sqrt{R^2\cos^2\theta + \sin^2\theta}}$	$\frac{gZ_1 \lvert \sin\theta \rvert}{\sqrt{R^{-2}\cos^2\theta + \sin^2\theta}}$
$\angle Z_T$	$\frac{\pi}{2} - \theta$	$\tan^{-1}(R\cot\theta)$	$\tan^{-1}(R^{-1}\cot\theta)$
$\Delta\omega_{3\mathrm{dB}}$	ω_0	$2\omega_0\left(1 - \frac{2}{\pi}\tan^{-1}R\right)$	$2\omega_0\left(1 - \frac{2}{\pi}\tan^{-1}R^{-1}\right)$
$z_T(t)$	$g\frac{Z_1}{2}\,[\delta(t) - \delta(t - t_0)]$	$gZ_1 \Vert Z_c \left\{\delta(t) + \left(1 - \frac{1}{\pm\Gamma_1}\right)\sum_{n=1}^{\infty}(\pm\Gamma_1)^n\,\delta(t - nt_0)\right\}$	

Notes: $R = Z_c/Z_1$ + for open line
$\theta = \frac{\pi}{2}\frac{\omega}{\omega_0}$ − for shorted line
$t_0 = 2\ell/c$

As can be seen from table 1, the 3 dB bandwidths of the bandpass regions for all three pickups depend on the ratio of line impedance to load impedance (R). As this ratio is increased from zero to infinity, the bandwidth of the open circuit pickup decreases from $2\omega_0$ to zero, whereas the bandwidth of the short circuit pickup increases from zero to $2\omega_0$. For $R = 1$ (matched line case) the bandwidth is ω_0, and in addition the transfer impedances of the open- and short-circuited pickups reduce to that of the matched line pickup. This is consistent with the well-known property of pickup response being independent of the downstream termination for conventional stripline pickups. It should be pointed out that, although the pickup responses of the open and short circuit pickups reduce to that of the matched line for $R = 1$, these pickups are always non-directional regardless of the value of R, whereas the true matched line pickup is completely directional. These directionality properties (not embodied in table 1) can be verified by considering an equivalent circuit similar to that of figure 2 for a beam travelling in the opposite direction. Performing this calculation reveals that all pickups with $Z_1 = Z_2$ are always completely directional, the open and short circuit line pickups ($Z_2 = \infty$, $Z_2 = 0$) are always non-directional, and all other cases exhibit partial directionality.

Perhaps the most important characteristic of the three pickups is $|Z_T|$ at center frequency ($\omega = \omega_0$). From table 1, $|Z_T(\omega_0)|$ is seen to be strictly proportional to the load impedance, Z_1, for the matched and short-circuited line pickups. In the case of the open-circuited line pickup, $|Z_T(\omega_0)|$ is proportional to the line impedance, Z_c, and is independent of the loading. These properties illustrate the duality between the open-circuited line pickup and short-circuited line pickup for at ω_0, the former can be modeled as an ideal voltage source of strength gZ_cI_b and the latter as an ideal current source of strength gI_b.

Typically, the characteristic impedance of a wireline pickup can be made as high as 200 Ω, which is a factor of four greater than the standard termination impedance of 50 Ω available at microwave frequencies. Therefore, at microwave frequencies, a BPM utilizing open-circuited wireline pickups offers up to four times the sensitivity of the traditional matched line pickup BPM. Of course, as with all pickups, this increase in sensitivity brings with it a decrease in bandwidth. From the open-circuited line bandwidth equation in table 1, a calculation of 3 dB bandwidth for $R = 200\ \Omega/50\ \Omega = 4$ gives approximately $\omega_0/3$ or $Q \approx 3$. However, this is still a relatively broadband device, and in applications where beam position measurements are made using a single CW harmonic of the accelerator RF (as in the CEBAF arcs), extremely large bandwidth is generally of little concern any way.

To further emphasize the properties described above, plots of the amplitude and phase of the transfer impedance for the three pickup types are shown in figures 3 and 4. The amplitude plots are normalized to gZ_1 and carried out to $4\omega_0$ to emphasize the relative sensitivities and multiple bandpass characteristics of the pickups. The amplitude plots confirm all of the characteristics described above. The phase plots are self-evident with the following major features: the matched line phase is linear with frequency, the open-circuited line phase takes on a resonant circuit characteristic, and the short-circuited line phase has an inverted resonant shape with a constant phase band about ω_0.

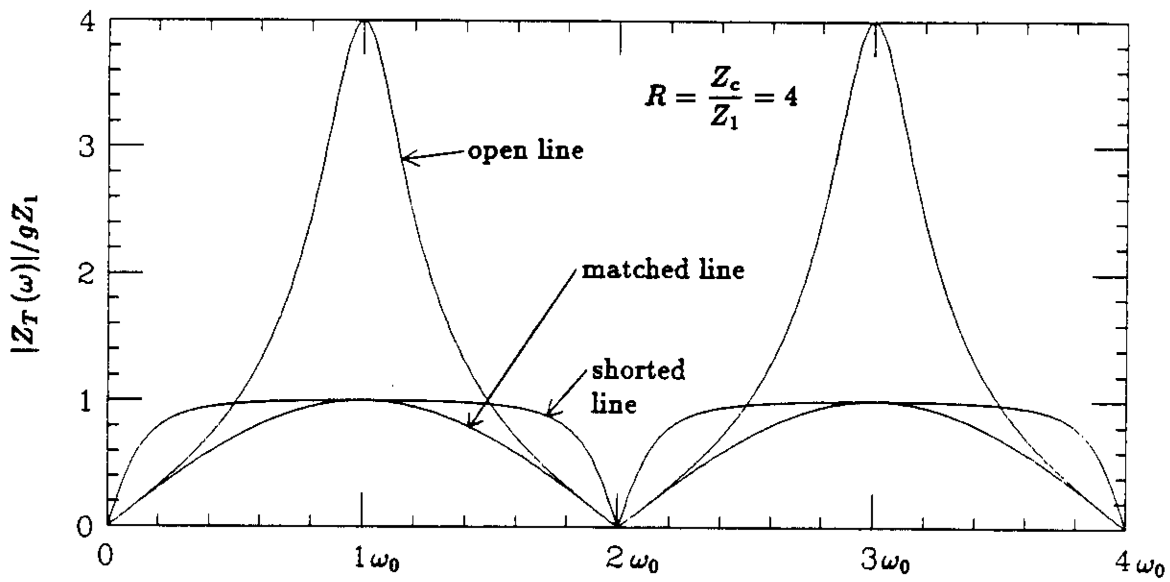

Figure 3 Amplitude of transfer impedance vs. frequency.

It is also noted from the amplitude plots that the low frequency response of the short-circuited line pickup is considerably better than that of the matched line or open-circuited line pickup. This suggests the use of short-circuited line or "inductive loop" pickups in low frequency applications where quarter wavelength pickups are impractical. These loop pickups are currently being utilized in the CEBAF linac BPMs where a 100 MHz beam current modulation is detected.[1] In general, it can be concluded that in virtually every application in which a conventional matched line BPM can be used, an open- or short-circuited line BPM can be used with a possible increase in performance and with a reduced cost because complicated downstream terminations are eliminated. Notable exceptions to this include applications where directionality is required or where the pickups are also used as kickers. It is pointed out that when used as kickers, the open and short-circuited lines present reactive loads and are therefore incompatible with most high power/high frequency sources.

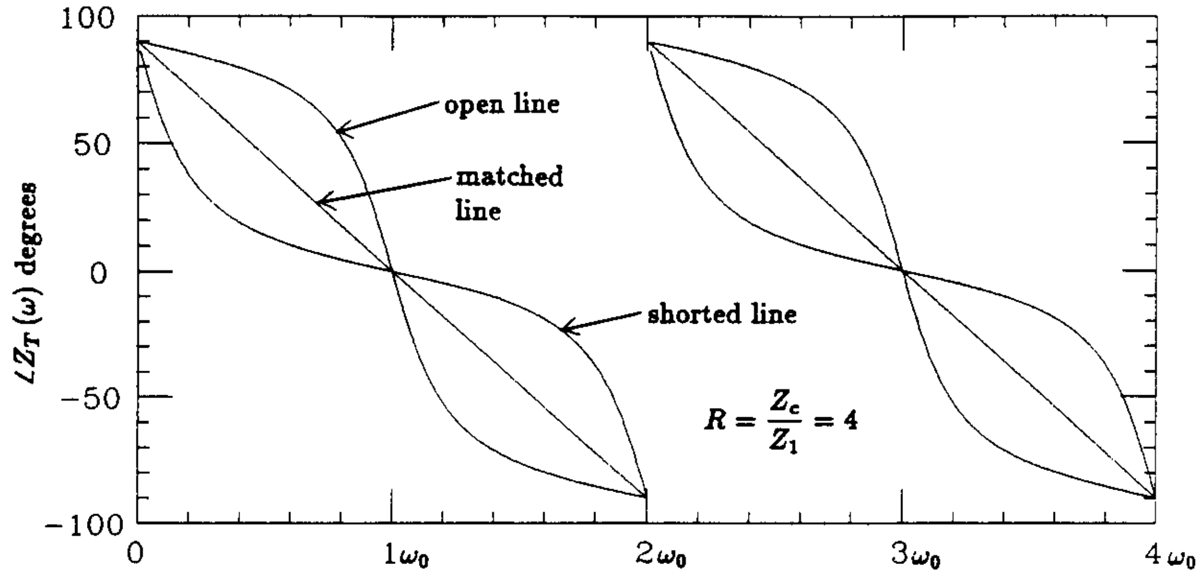

Figure 4 Phase of transfer impedance vs. frequency.

For completeness, the impulse responses of the three pickup types with $Z_1 = 50\ \Omega$ and $Z_c = 200\ \Omega$ are presented in figure 5. The impulse response of the matched line consists of the well-known pair of impulses of height $Z_1 \| Z_c = 25\ \Omega$ and separated by twice the transit time of the pickup, $t_0 = 2\ell/c$. In the case of the open-circuited pickup, the first pulse has height $Z_1 \| Z_c = 40\ \Omega$. The second pulse has height $1 + \Gamma_1$ times the sum of the induced downstream pulse, $-Z_2 \| Z_c = -Z_c$, and the reflected first pulse. The amplitude of the pulses at the output terminal then decrease geometrically with $\Gamma_1 \Gamma_2 = \Gamma_1$ as the second pulse reflects back and forth along the line. Because Γ_1 is negative, the output pulses alternate in sign. Finally, in the case of the shorted-line pickup, the first pulse amplitude is again $Z_1 \| Z_c$. However, because $Z_2 = 0$, no voltage can be induced at the downstream end of the pickup and $\Gamma_2 = -1$. Therefore, the second output pulse has amplitude $-(1+\Gamma_1)$ times that of the first pulse. The output pulses then decrease geometrically with $-\Gamma_1$. This time, since Γ_1 is negative, the pulses are all of the same sign (that of the second pulse).

As stated in the introduction, a very large number of microwave BPMs are required for the arc regions of the CEBAF accelerator. These BPMs are required to respond to CW beam currents as low as 2 μA and below at the fundamental RF frequency of 1.497 GHz. In view of the pickup properties described above, it is obvious that the quarter wave open-circuited wireline BPM is technically best suited for this application. In addition, this type of BPM is desirable from a practical standpoint because the simple wire pickups and absence of downstream terminations make it inexpensive and easy to construct. The remainder of this paper describes in more detail the characteristics of the open-circuited pickup BPM, along with results from bench tests of a prototype.

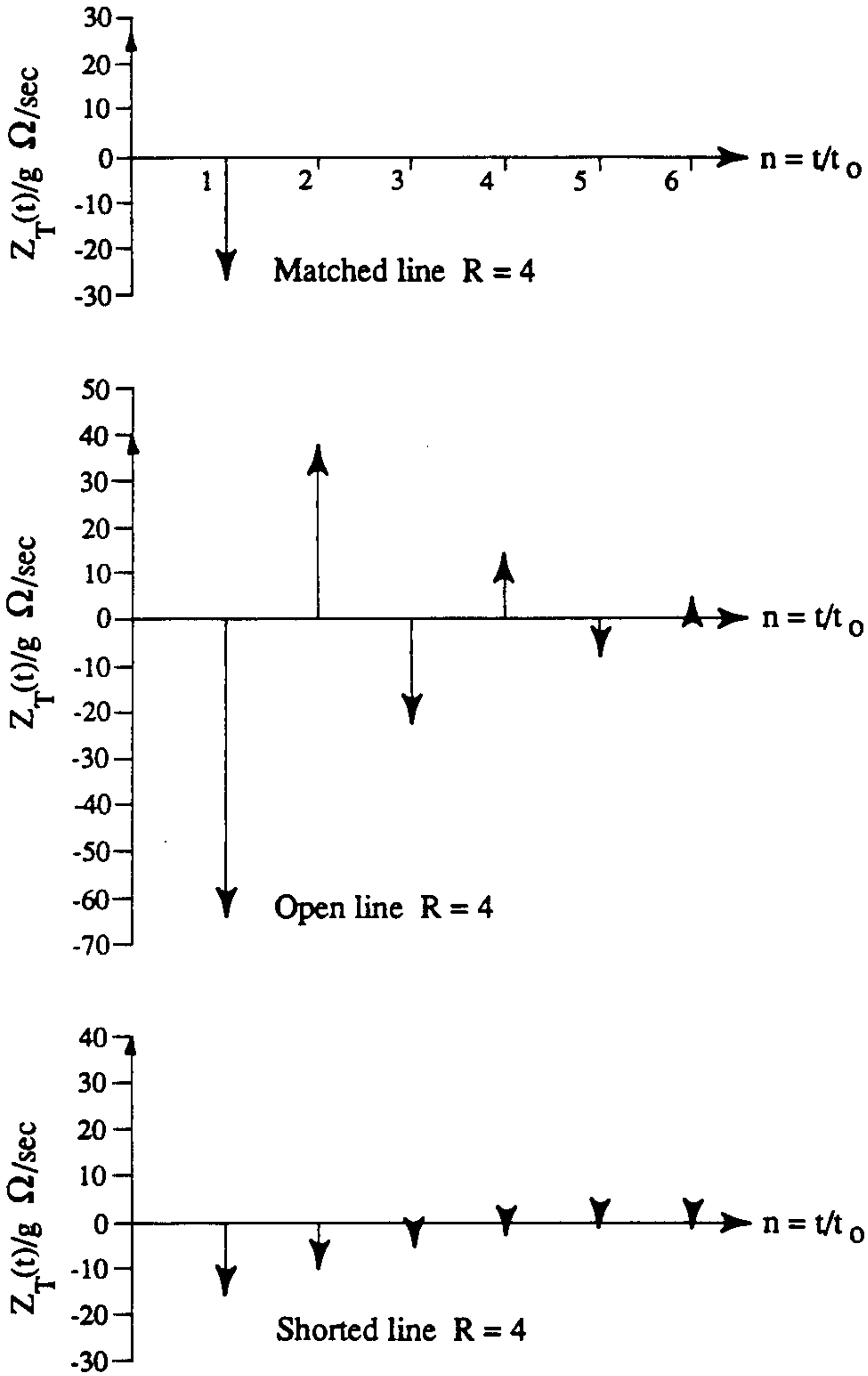

Figure 5 Impulse response of wireline pickups.

Longitudinal and Transverse Impedances of Open-Ended Wireline Pickups

In order to absolutely characterize the open-ended or any wireline pickup, the geometric coupling factor, g, must be determined. The coupling factor depends only on the wireline geometry and hence is independent of frequency and line terminations. Therefore, to calculate g, consider the transfer impedance given by equation (1) for the short-circuited wireline case at very low frequencies:

$$Z_T(\omega) \approx \frac{jg\omega L Z_1}{Z_1 + j\omega L} \quad \Omega \quad Z_2 = 0, \qquad \frac{\ell}{\lambda} \ll 1 \tag{4}$$

where:

$$L = \frac{Z_c \ell}{c} \quad \text{henries}$$

In equation (4), L is the total self-inductance of the "loop" formed by the short-circuited wireline. At low frequencies, the total voltage coupled to the loop is proportional to the time rate of change of magnetic flux from the beam passing normally through the loop. This coupling is conveniently quantified by the mutual inductance, M, between the beam current and the pickup loop. This leads to a simple lumped element equivalent circuit for the short-circuited line pickup at low frequencies (figure 6). A trivial analysis of this circuit gives the following result for the transfer impedance:

$$Z_T(\omega) = \frac{V}{I_b} = \frac{j\omega M_0 Z_1}{Z_1 + j\omega L} \quad \Omega \tag{5}$$

where: M_0 = mutual inductance between a <u>centered</u> beam and the loop pickup

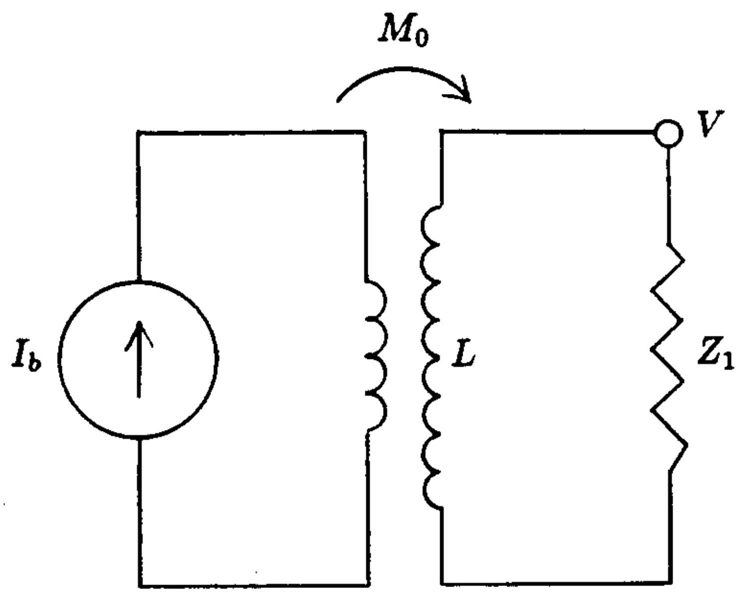

Figure 6 Low frequency equivalent circuit for short-circuited line pickup.

Comparing this expression to (4) gives $g = M_0/L$ or equivalently M_0'/L' where the primes indicate per unit length. The conclusion is that the g factor for all thin wireline type pickups is given by the ratio of mutual inductance per unit length between the beam and the pickup to the self-inductance per unit length of the pickup.

In general, the mutual inductance per unit length between the beam current and a wireline depends on the position of the beam. Referring to the geometry of figure 1, a solution to Laplaces equation in cylindrical coordinates for magnetic vector potential enables the mutual inductances between the beam and the pickups to be calculated as a function of beam position:

$$M'(r,\theta,\theta_0) = -\frac{\mu_0}{2\pi}\left\{\ln\frac{b}{a} + \sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{a}\right)^n\left[\left(\frac{b}{a}\right)^n - \left(\frac{a}{b}\right)^n\right]\cos n(\theta-\theta_0)\right\} \tag{6}$$

where: r, θ are transverse beam coordinates
θ_0 is azimuthal location of pickup
a, b are as in figure 1

For the $+x$ and $-x$ pickups ($\theta_0 = 0, \pi$) shown in figure 1, equation (6) becomes:

$$M'_{\pm}(r,\theta) = -\frac{\mu_0}{2\pi}\left\{\ln\frac{b}{a} \pm \sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{a}\right)^n\left[\left(\frac{b}{a}\right)^n - \left(\frac{a}{b}\right)^n\right]\cos n\theta\right\} \tag{7}$$

An expression identical to (7) with $\sin n\theta$ replacing $\cos n\theta$ is obtained for a y-axis pair of pickups. From expressions (6) or (7) for $r = 0$ (centered beam) the following equation for M_0' is obtained:

$$M_0' = \frac{\mu_0}{2\pi}\ln\frac{a}{b} \quad \text{henries/m} \tag{8}$$

Upon substituting (8) into the definition of g and using the relation $L' = Z_c/c$, a simple expression for the open-circuited wireline pickup transfer impedance at center frequency is obtained from $Z_T(\omega_0) = gZ_c$:

$$Z_T(\omega_0) = \frac{\eta}{2\pi}\ln\frac{a}{b} \quad \Omega \tag{9}$$

where: $\eta = \mu_0 c = 377\ \Omega$

Two important quantities for describing the performance of a BPM are the longitudinal and transverse pickup impedances. Referring to the pickup pair in figure 1, these impedances are defined for $\omega = \omega_0$ as follows:

$$Z_{\parallel} = \frac{V^+ + V^-}{I_b} \quad \Omega \tag{10}$$

$$Z_\perp = \frac{\partial(V^+ - V^-)}{I_b\,\partial x} \approx \frac{V^+ - V^-}{I_b x} \quad \Omega/\mathrm{m} \tag{11}$$

where: x = transverse beam position

Using equations (10), (7) and the equivalent circuit of figure 2, the longitudinal pickup impedance of the open-circuited wireline pair becomes:

$$Z_\parallel = \frac{M'_+ + M'_-}{L'}\,Z_c = \frac{\eta}{\pi}\ln\frac{a}{b} \quad \Omega \tag{12}$$

From equation (9), $Z_\parallel$ is seen to be equal to $2Z_T(\omega_0)$. The most important feature of $Z_\parallel$ for wireline BPMs is that it is independent of beam position. In fact, it is easily verified using equation (6) that the sum of the voltages from any pair of diametrically opposed wireline pickups is completely independent of beam position. This is generally not true for pickup geometries other than that of the wireline. Because the sum voltage is position independent, the wireline BPM is also quite useful in applications requiring position independent measurements of beam current amplitude and phase. Examples of these kinds of measurements at CEBAF include absolute beam current and a proposed bunch length measurement technique.[3]

The transverse pickup impedance is most easily obtained by relating it to $Z_\parallel$. From definitions (10) and (11):

$$Z_\perp = Z_\parallel \frac{\partial(\Delta/\Sigma)}{\partial x} \quad \Omega/\mathrm{m} \tag{13}$$

where:

$$\Delta/\Sigma = \frac{V^+ - V^-}{V^+ + V^-}$$

The difference over sum voltage, Δ/Σ, is linearly related to beam position throughout 40% or more of the aperture defined by the pickups and is the standard quantity used to determine beam position in most BPM systems. For a pair of identical wireline pickups, the difference over sum voltage ratio is also equal to $(M'_+ - M'_-)/(M'_+ + M'_-)$. Using equation (7) to first order, a simple but accurate approximation for the slope of the difference to sum voltage vs. position curve is obtained:

$$\frac{\partial(\Delta/\Sigma)}{\partial x} = \frac{\left(\frac{a}{b} - \frac{b}{a}\right)}{a\ln\frac{a}{b}} \approx \frac{2}{a} \quad \mathrm{m}^{-1} \tag{14}$$

Therefore for the open-circuited wireline BPM:

$$Z_\perp \approx \frac{2}{a} Z_\parallel = \frac{2\eta}{\pi a}\ln\frac{a}{b} \quad \Omega/\mathrm{m} \tag{15}$$

Equations (9), (12), (14), and (15) characterize the absolute longitudinal and transverse sensitivity of the open-circuited wireline BPM. The transfer, longitudinal and transverse pickup impedances of the matched and short-circuited line BPMs may be obtained by dividing equations (9), (12), and (15) by the ratio $R = Z_c/Z_1$.

Bench Tests of Prototype BPM

A mechanical drawing of a 1.497 GHz prototype open-circuited wireline BPM for use in the CEBAF arc regions is shown in figure 7. The monitor consists of a 2.75" beam tube with four simple wire antennas connected to Ceramaseal ultra-high vacuum SMA feedthroughs. The wire lengths have been trimmed for peak response at 1.497 GHz. Using the dimensions given on the drawing, the theoretical impedance values for the monitor can be computed using equations (9), (12), and (15) giving: $Z_T(\omega_0) = 36.1\ \Omega$, $Z_{\|} = 72.2\ \Omega$, and $Z_{\perp} = 4.3\ \Omega/\mathrm{mm}$. In addition, the ratio factor, $R = Z_c/Z_1$, can be computed using the following formula for the characteristic impedance of an eccentric wire transmission line:[4]

$$Z_c = \frac{\eta}{2\pi} \cosh^{-1}\left\{\frac{a}{d}\left[1 - \left(\frac{b}{a}\right)^2\right] + \frac{d}{4a}\right\} \tag{16}$$

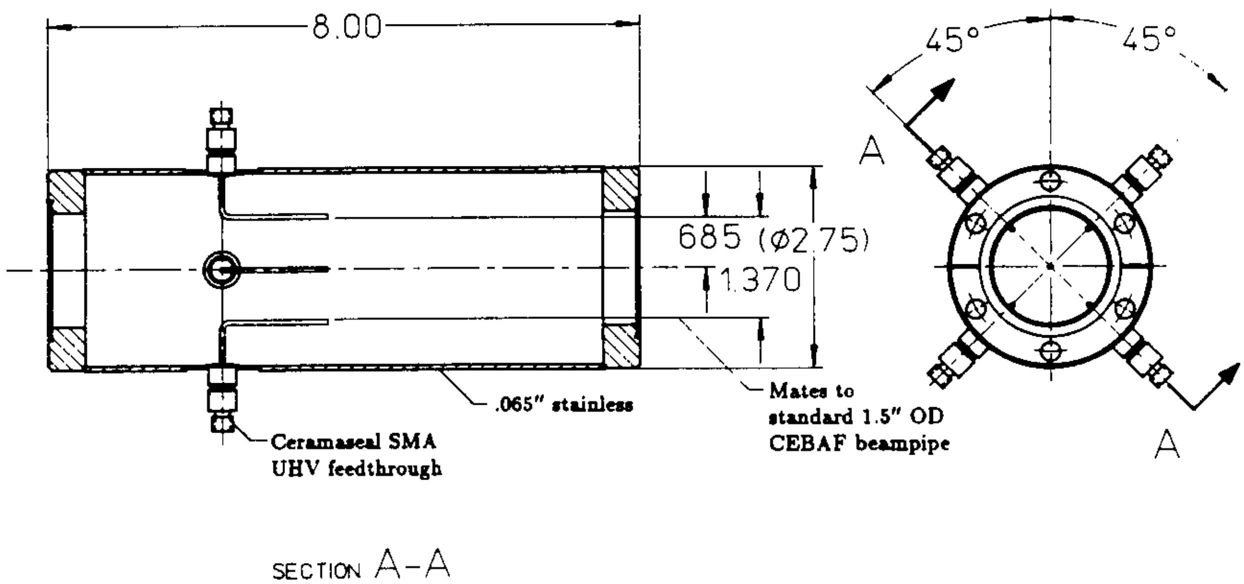

Figure 7 Open-circuited wireline BPM.

Using the pickup dimensions given in figure 7, $Z_c = 200\ \Omega$, and $R = 4$ for $Z_1 = 50\ \Omega$. Therefore, $Z_T(\omega)$ for the prototype should be given by the open-circuited line curves of figures 4 and 5 with $|Z_T| = 36.1\ \Omega$ at $\omega_0 = 2\pi \times 1.497$ GHz.

To measure the impedances of the prototype, the standard technique employing a thin current carrying wire stretched through the center of the monitor to simulate the beam was used. The transfer impedance as a function of frequency is then obtained by measuring S_{21} with a microwave network analyzer. As indicated in figure 8, the stretched wire inside the BPM forms a transmission line with characteristic impedance Z_ℓ. In order to ensure that only a forward current wave exists on the wire, the line must be matched at the downstream end. In addition, matching to the 50 Ω system of the network analyzer at the upstream end ensures all of the incident power is transmitted into the monitor. As shown, the upstream and downstream matching from Z_ℓ to 50 Ω is obtained with broadband multiple quarter wavelength section transformers. Knowing that all of the incident power is transmitted to the line inside the monitor, it is simple to relate $Z_T(\omega) = V^-/I_\ell$ to $S_{21}(\omega) = V^-/V^+$:

$$Z_T(\omega) = S_{21}(\omega)\sqrt{50\ Z_\ell} \quad \Omega \tag{17}$$

For the test configuration used, the stretched wire diameter was .118″ (3 mm) so that $Z_\ell = 186\ \Omega$. Therefore, from equation (17), $Z_T = 96.4\ S_{21}$.

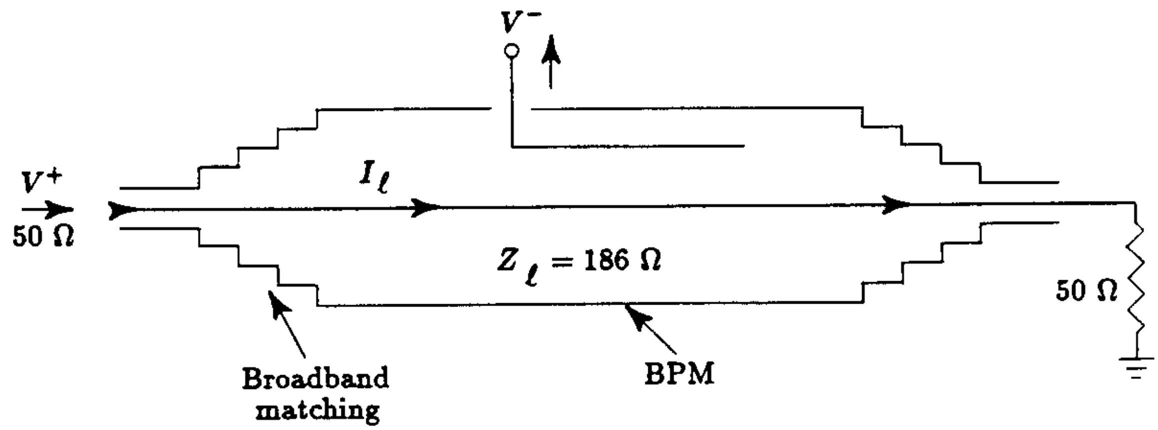

Figure 8 Wire technique for measuring BPM impedance.

Plots of S_{21} amplitude and phase measured for a single pickup of the prototype monitor over the frequency range .5 to 2.5 GHz are given in figure 9. At center frequency, $|Z_T(\omega_0)|$ is $96.4 \times .375 = 36.1\ \Omega$, which is in exact agreement with the theoretical impedance. Also contained in figure 9 are plots of the theoretical amplitude and phase (dashed) of $S_{21}(\omega)$ obtained from the equations in table 1 for $R = 4$ and equation (17). Both amplitude and phase show good agreement with the measured data over the entire 2 GHz band. It is pointed out here that the SMA vacuum feedthroughs used on the prototype were the non-50 Ω type which obviously work quite well. This is quite fortunate because the 50 Ω versions cost five to six times as much as the non-50 Ω feedthroughs.

The transverse properties of the prototype were measured by moving the stretched wire in the transverse plane of the monitor along the line adjoining a pair of pickups. For each wire position the difference over sum voltage ratio for the plus and minus pickup pair was measured in terms of S_{21}:

$$\frac{\Delta}{\Sigma} = \frac{S_{21}^+ - S_{21}^-}{S_{21}^+ + S_{21}^-} \tag{18}$$

The position of the wire relative to the monitor was changed by fixing the wire and matching sections and moving the monitor with a precision micro-adjustable stage. Of course, once the wire is moved off center it is no longer matched to 50 Ω, especially for extreme transverse positions. However, because the quantity of interest is the <u>ratio</u> of difference over sum S_{21}, the reflections caused by the mismatches are of no concern.

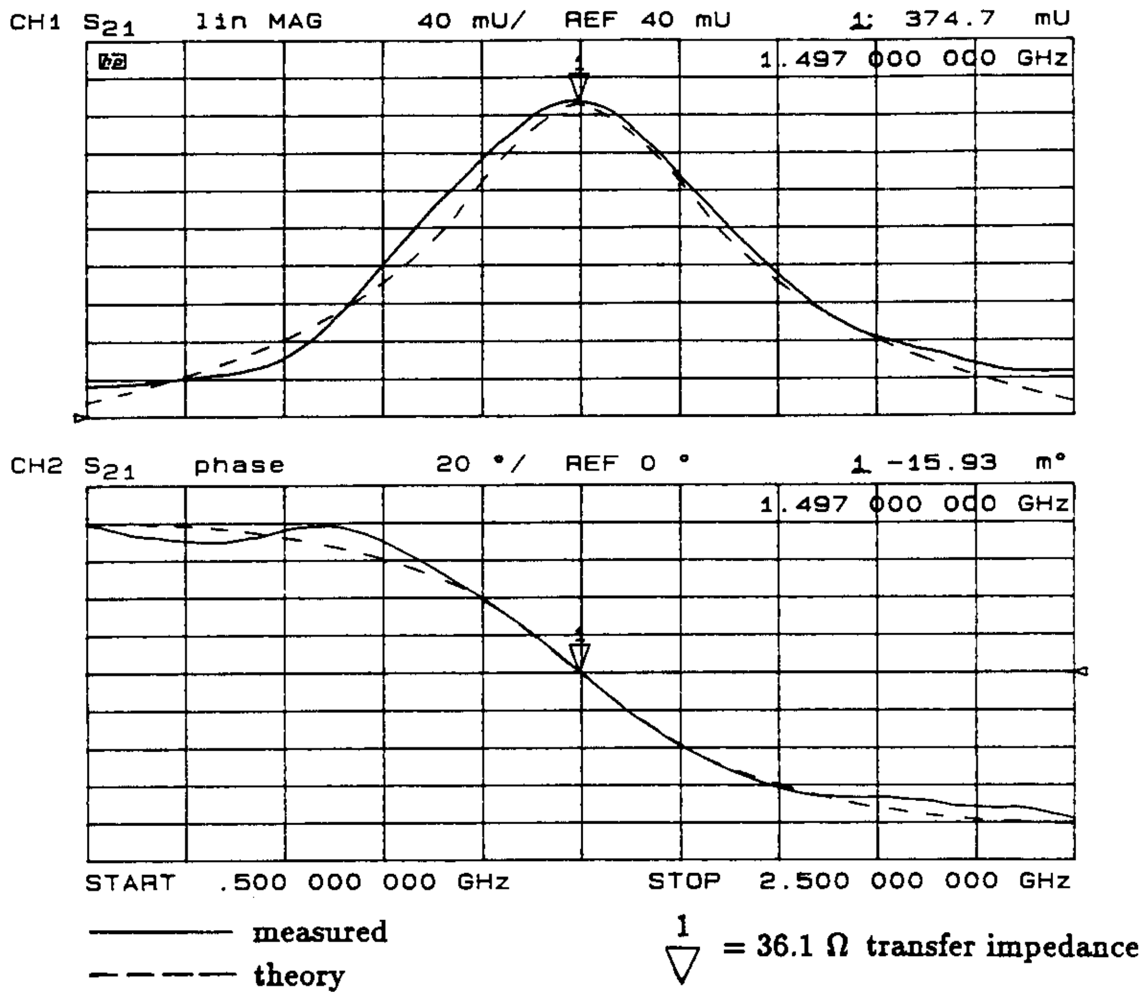

Figure 9 S_{21} amplitude and phase for open-circuited wireline BPM prototype.

Figure 10 shows a plot of difference over sum voltage vs. transverse wire position for a pickup pair in the prototype BPM. As shown, Δ/Σ is linear with position over a ± 8 mm range and has slope $\partial(\Delta/\Sigma)/\partial x = .053\ \mathrm{mm}^{-1}$, which is within 12% of the approximate theoretical value given by $2/a = .060\ \mathrm{mm}^{-1}$. This small difference between theory and measurement is attributed to the idealized calculation of transverse pickup response which does not include the effect of the radial section of wire connecting the feedthrough to the section of the pickup parallel to the beam. Therefore, the accuracy of the theory should increase as the ratio b/a gets larger. This is in fact found to be the case. Transverse measurements on another model BPM with b/a 10% greater than the prototype described here yielded 6% agreement between theory and measurement.

Having measured $\partial(\Delta/\Sigma)/\partial x$, the BPM is completely characterized. In summary, $Z_T(\omega_0) = 36.1\ \Omega$, $Z_{\|} = 72.2\ \Omega$, and $Z_{\perp} = 3.8\ \Omega/\mathrm{mm}$ (from equation (13)).

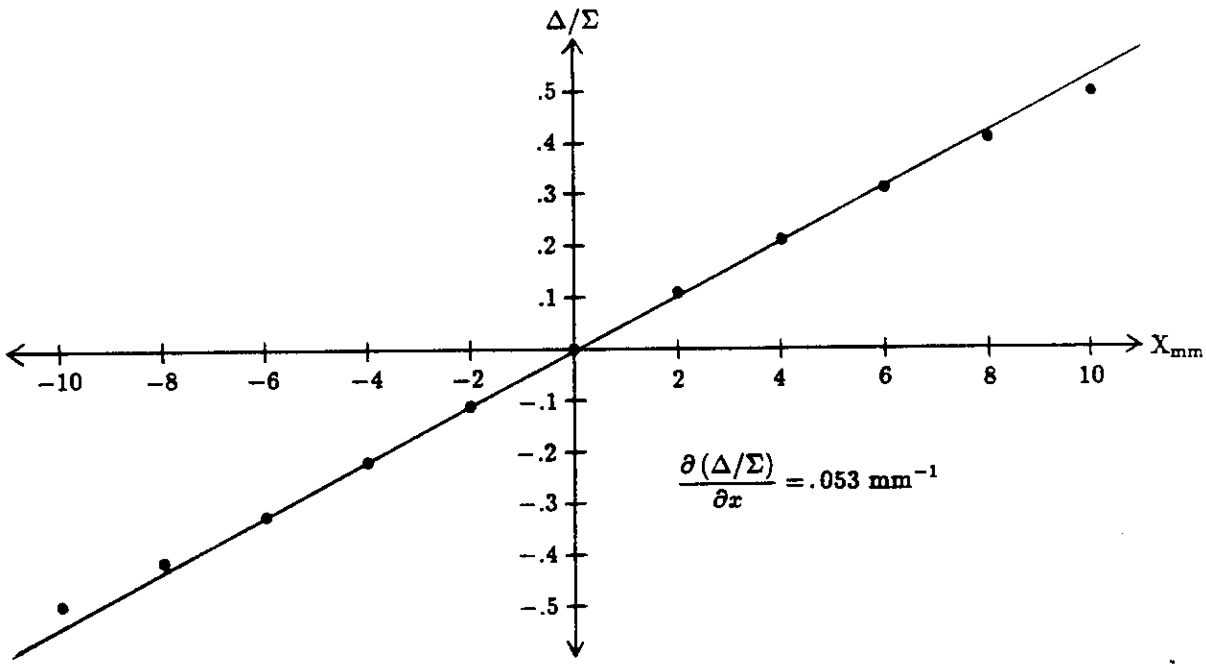

Figure 10 Δ/Σ vs. position measurements for 1.497 GHz BPM.

Summary and Conclusion

A simple and general analysis of wireline pickup BPMs has been presented. Special attention has been paid to three important pickup types: the matched wireline, the open-circuited wireline, and the short-circuited wireline. In particular, the open-circuited wireline is well-suited for application in BPMs for the CEBAF arc regions where 1.497 GHz CW beam currents are detected. The most important characteristics of the open-circuited wireline BPM are: high sensitivity, easy and inexpensive construction, and sum signals that are independent of beam position.

Acknowledgements

The author wishes to thank Karel Capek of CEBAF for the excellent fabrication of BPM prototypes and wire matching sections.

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