TRANSMISSION-LINE IMPEDANCE MEASUREMENTS OF BEAM PIPES FOR AN ADVANCED HADRON FACILITY*

L. Walling, D. Neuffer, H. A. Thiessen, and G. Spalek, MS-H817
Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

An Advanced Hadron Facility (AHF) requires a beam pipe with low eddy-current losses and a low beam-coupling impedance. The requirements cannot be met with a solid, conducting beam pipe but may be met by a ceramic pipe with conducting layers, which may have a higher coupling impedance. We have measured and compared the transmission-line impedances for several candidate pipe segments. The results are correlated with the beam-coupling impedance and are compared with calculated values and with AHF requirements.

Introduction

One of the most difficult problems in the design of a high-intensity rapid-cycling synchrotron is the beam-pipe design. The beam pipe must satisfy several conflicting requirements: (1) it must maintain a vacuum of $\simeq 10^{-7}$ torr, (2) it must shield the beam from high-frequency impedances to avoid collective instabilities, and (3) it must have a high impedance at the cycling frequency($\sim$60 Hz) to avoid unacceptable large eddy-current effects.

In one proposed scenario (LAMPF II),[1] it was necessary for the magnitude of the longitudinal coupling impedance, $Z_{\|}/n$, to be less than $\sim$10 Ω at frequencies greater than c/ℓ_B, where ℓ_B is the bunch length. Similar constraints were found for the transverse impedance: the scaled quantity, $Z_{\perp} R/2b^2$, must also be less than 10 Ω, where $Z_{\perp}$ is the transverse impedance, R is the mean synchrotron radius, and b is the beam-pipe radius. The contribution of the beam pipe to the total impedance should be limited to a small fraction of this.

A thin, solid beam pipe of stainless steel as used for DESY II (0.3 mm thickness) has a marginally acceptable impedance but, at LAMPF II parameters, has pipe heating and induced fields from eddy currents that are an order of magnitude too large. Thinner beam pipes are structurally unstable; however, similar electrical properties may be obtainable by depositing a thin, metal layer on a glass or ceramic pipe. It is difficult to find a solid layer that meets the conflicting requirements. For example, a 1-μm-thick copper layer has an unacceptably large low-frequency impedance and large eddy-current effects. Also, the dielectric can significantly increase the impedance.

Thicker metal stripes deposited on solid ceramic may provide a low impedance with small eddy-current effects.[1] The advantage of this geometry is that eddy-current heating is reduced by a factor of $(d/2b)^2$ from the continuous case, where d is the stripe width and b is the inner radius, and eddy-current fields are reduced by a factor of (d/2b). It is, however, difficult to predict the impedance of this complicated geometry. Therefore, a program was initiated at Los Alamos to measure the impedance of sample beam-pipe segments. The first results of that measurement program are reported in this paper.

Impedance Calculations in Simplified Models

Impedances for cylindrically symmetric beam pipes can be calculated analytically[2] using methods described by Zotter,[3] Piwinski,[4] and Chao.[5] These calculated values can be compared with measured impedances. To first order, we may expect the impedance of a striped geometry to be similar to that of a cylindrically symmetric case with a conducting layer of the same thickness as the stripes. Measured impedances can be compared to the most similar symmetric case and the comparisons used to identify effects specifically caused by the stripes. Three particular cases are described in Ref. 2. Only longitudinal impedances are explicitly calculated here; a first estimate of the transverse impedance may be found using $Z_{\perp} \simeq R(Z_{\|}/n)/2b^2$.

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Case I. Thin Metallic Pipe

We consider a beam pipe of thickness Δ with conductivity σ and inner radius b. The resulting expression for the longitudinal impedance per unit length is

$$\frac{Z_{\|}(\omega)}{L} = \frac{Z_0 k}{2\pi b\lambda} \frac{(1 + e^{i2\lambda\Delta})}{(1 - e^{i2\lambda\Delta})} , \tag{1}$$

where

$$\lambda = \sqrt{\frac{\mu\sigma\omega}{2}}(1+i) = \frac{(1+i)}{\delta} \tag{2}$$

and δ is the skin depth, $k = \omega/c$, $Z_0 = \mu_0 c$ is the impedance of free space, and μ is the magnetic permittivity of the conductor. For high frequencies where $\delta \ll \Delta$, the impedance becomes that of a thick conductor

$$\frac{Z_{\|}(\omega)}{L} = \frac{Z_0\omega}{2\pi bc\lambda} = \frac{\mu_0}{2\pi b}\sqrt{\frac{\omega}{2\mu\sigma}}(1 - i) , \tag{3}$$

which is acceptably small for a good conductor.

At low frequencies, where $\delta \gg \Delta$, we obtain the impedance of a thin conductor

$$\frac{Z_{\|}}{L} = \frac{1}{2\pi b\sigma\Delta} . \tag{4}$$

In the measurements completed to date, only frequencies and pipe thicknesses corresponding to thick conductor cases have been explored.

Case II. Metallic-Dielectric Pipe (Metal Outside)

We now consider a dielectric layer for $b < r < b + \Delta$ with a thick conductor on the outside ($r > b + \Delta$). Under the long-wavelength approximations ($k\Delta \ll 1$ and $k\delta \ll 1$), we obtain an impedance that is the sum of the conductor resistive wall impedance plus a reactive term resulting from the dielectric[2]

$$\frac{Z_{\|}}{L} = \frac{Z_0 k}{2\pi b\lambda} - i\frac{Z_0 k}{2\pi}\frac{(\varepsilon - 1)}{\varepsilon}\frac{\Delta}{b}\frac{1}{S} , \tag{5}$$

where $S \simeq 1 - k^2 b\Delta(\varepsilon - 1)/2\varepsilon$ is near unity and where ε is the dielectric constant. This estimate does not include short-wavelength resonances within the dielectric layer ($k\Delta \simeq 1$).

Case III. Metallic-Dielectric Pipe (Metal Inside)

The next case we consider has a thin conducting layer for $b < r < b + \Delta$ with dielectric for $r > b + \Delta$. For $k^2 b/\lambda \ll 1$, we obtain the following expression:

$$\frac{Z_{\|}}{L} \simeq \frac{-iZ_0 k}{2\pi b\lambda}\frac{\left[sin(\lambda\Delta) + cos(\lambda\Delta)\frac{\sqrt{\varepsilon-1}}{\varepsilon}\frac{\lambda H_0(u)}{kH_1(u)}\right]}{\left[cos(\lambda\Delta) - sin(\lambda\Delta)\frac{\sqrt{\varepsilon-1}}{\varepsilon}\frac{\lambda H_0(u)}{kH_1(u)}\right]} , \tag{6}$$

where sin and cos are complex functions, H_0 and H_1 are Hankel functions and $u = \sqrt{\varepsilon - 1}\, k(b + \Delta)$. This expression has resonances at $H_1(u) = 0$. At short wavelengths, ($\lambda\Delta \gg 1$), the impedance reduces to that of a thick conductor; at long wavelengths, the impedance is dominated by the thin conductor impedance, provided $\lambda^2/(\Delta b) \ll 1$. The dielectric reactive impedance and resonant impedances can be substantially reduced from the previous unshielded case.

Impedance Measurements

Longitudinal

The longitudinal coupling-impedance measurements are performed in the usual way:[6] The cylindrical pipe was converted into a coaxial transmission line by inserting a center conductor; the transmission through a reference thick-walled brass pipe was measured and used to normalize all other transmission measurements of the "test" pipes.

An HP8510 network analyzer with time-domain option was used for the measurements. Matching from the network analyzer cables was performed far enough from the test pipe to allow for effective gating, thus eliminating the effect of multiple reflections. Blank spacers, identical to the reference pipe, were added between the matching section (a short taper) and the test pipe. If τ represents the minimum gate width, then the length of the spacers must be at least $c\tau/2$ to eliminate overlap of the time-domain waveforms (see Fig. 1). The major considerations in determining the gate width are the lowest frequency of interest and the frequency range of the measurement. For more information regarding gating consideration on the HP8510, see Ref. 7.

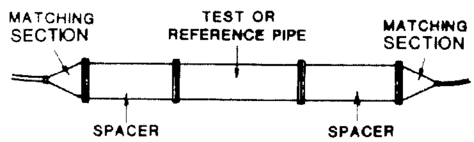
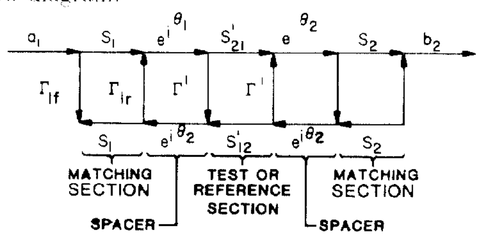


Fig. 1. Experimental setup for longitudinal coupling impedance measurements.

The transmission (S_{21}) of such a configuration can be calculated by S-parameter analysis, as in Ref. 7, from the following signal flow diagram:



$$S_{21}^{TOT} = \frac{S_1 S_2 e^{i(\theta_1+\theta_2)} S'_{21}}{(1 - e^{i2\theta_1}\Gamma'\Gamma_{1r})(1 - e^{i2(\theta_1+\theta_2)} S'_{21} S'_{12} \Gamma_{2f}\Gamma_{1r})(1 - e^{i2\theta_2}\Gamma_{2f}\Gamma')} . \tag{7}$$

The expressions in the denominator of Eq. (7) represent the terms resulting from multiple reflection. By gating around the initial pulse and transforming back to the frequency domain, the denominator of Eq. (7) is eliminated, resulting in

$$S_{21}^{TOT,GATED} = S_1 S_2 e^{i(\theta_1+\theta_2)} S'_{21} . \tag{8}$$

Thus, if S_{21}^{REF} represents the transmission of the reference pipe, then the normalized, gated measurement yields simply

$$S_{21}^{RATIO} = \frac{S_1 S_2 e^{i(\theta_1+\theta_2)} S'_{21}}{S_1 S_2 e^{i(\theta_1+\theta_2)} S_{21}^{REF}} = \frac{S'_{21}}{S_{21}^{REF}} \tag{9}$$

To extract the coupling impedance of the pipe from this coaxial transmission measurement, we turn to the infinitesimal element of the distributed model for the transmission line with an extra term, Z, added that represents the impedance in excess of that of the reference pipe (Fig. 2). The propagation constant γ' for such a distributed line is

$$\begin{aligned} \gamma' &= \sqrt{(R_0 + Z + i\omega L_0)(i\omega C_0)} \\ &\simeq \frac{R_0\left(1 + \frac{R}{R_0}\right)}{2Z_c\sqrt{1 + \frac{X}{\omega L_0}}} + i\beta_0\sqrt{1 + \frac{X}{\omega L_0}} , \end{aligned} \tag{10}$$

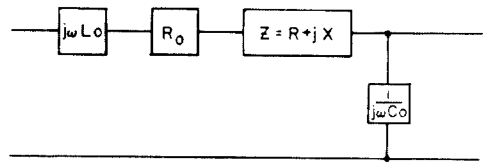


Fig. 2. Distributed impedance model, infinitesimal element, all impedance values are per unit length.

where $Z_c = \sqrt{L_0/C_0}$, the characteristic impedance of the coaxial line, and $\beta_0 = \omega\sqrt{L_0 C_0}$, the phase constant. The transmission through a line with propagation constant λ is $S'_{21} = \exp(\gamma\ell)$. Therefore,

$$phase\left[\frac{S'_{21}}{S_{21}^{REF}}\right] = \left[\frac{\omega}{c}\left(\sqrt{1 + \frac{cX}{\omega Z_c}} - 1\right)\ell\right] \approx \left[\frac{\ell X}{2Z_c}\right]$$

$$mag\left[\frac{S'_{21}}{S_{21}^{REF}}\right] = exp\left[-\frac{R_0}{2Z_c}\left(\frac{1 + \frac{R}{R_0}}{1 + \frac{cX}{\omega Z_c}} - 1\right)\ell\right] \simeq 1 - \frac{R\ell}{2Z_c} \tag{11}$$

$$\left(for\ \frac{cX}{\omega Z_c} \ll 1, \frac{R}{R_0} \ll 1\right)$$

where R_0 and Z_c are calculated from the geometry and materials. Our measurements were performed on 69.85-mm-ID pipes with 3.175-mm-diam center conductors, resulting in $Z_0 = 185\ \Omega$, and $R_0 = 2.27 \times 10^{-6}\ \sqrt{f}\Omega/\text{m}$. With a measurement repeatability of about 0.02 dB and 1° at 2.295 GHz, the resulting sensitivity of the measurements was $R_{min} \simeq 0.74\ \Omega$ (the pipes were 0.61 m long) and $X_{min} = 6.5\ \Omega$.

Transverse

The transverse impedance measurements are performed by inserting two rods inside the pipe to form a shielded, balanced line. The center conductors are driven by ANZAC 183-4 180° hybrids (see Fig. 3). The same considerations regarding normalization and gating were applied to the transverse measurements as for the longitudinal measurements. The two center conductors were 3.175 mm in diameter with a separation of 4.32 mm. Combined with an outer conductor diameter of 69.8 mm, this resulted in a $Z_c = 100\ \Omega$, which matches the two 50-Ω lines out of the hybrid. Thus, a repeatability error of 0.004 in magnitude and 1° in phase implies a sensitivity of

$$\frac{1}{\Delta X\,(meters)}\,(0.40\ \Omega) = 185\ \frac{\Omega}{m}\ \text{(resistive part of impedance)}$$

and $\frac{1}{\Delta X\,(meters)}\,(3.5\ \Omega) = 1600\ \frac{\Omega}{m}$ (reactive part of impedance).

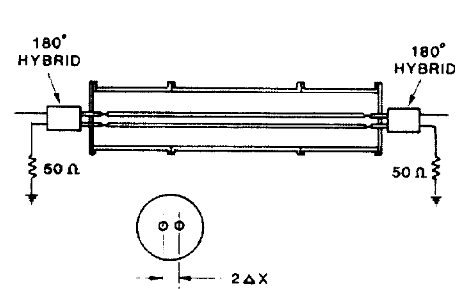


Fig. 3 Transverse coupling impedance measurement setup.

Results

We have measured the following sample test pipes (outer diameter of metallic layer 69.8 mm) (see Fig. 4):

1. Silver-stripe-coated ceramic (stripes on outer surface: thickness of coating, 0.04 mm; stripes, 1 cm wide; gaps between stripes, 1 mm; thickness of ceramic, 6 mm).

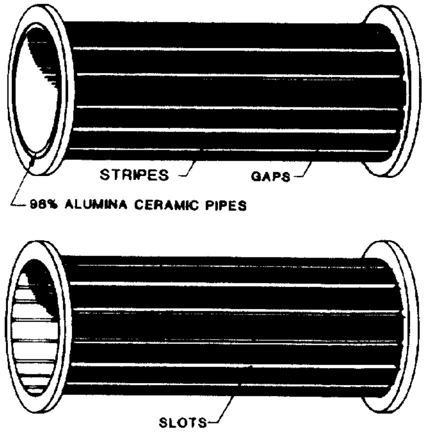


Fig. 4. Sample test pipes. Top: stripes over ceramic; bottom: slotted brass.

2. Solid-copper-coated ceramic (copper foil on outer surface: thickness of foil, 0.05 mm, thickness of ceramic, 6 mm).
3. Copper-stripe-coated ceramic (stripes on outer surface: thickness, 0.05 mm; width, 1 cm; gap between stripes, 6 mm; thickness of ceramic, 6 mm).
4. Slotted brass pipe (wall thickness, 0.32 cm; width of slots, 1 mm; distance between slots, 1.1 cm).

The results of the measurements are shown in Fig. 5 and in Table I.

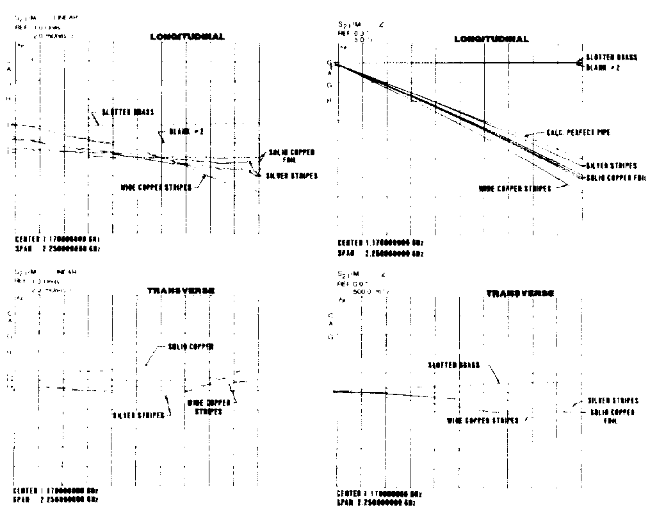


Fig. 5. Measurement results: top-longitudinal, bottom-transverse; left-linear magnitude, right: phase.

TABLE I

RESULTS OF IMPEDANCE MEASUREMENTS (at 2.295 GHz)

	Longitudinal Impedance			Transverse Impedance	
		Reactive (Ω)			
Pipe[a]	Resistive (Ω)	Measured	Calculated Estimate [using Eq. (5)]	Resistive (Ω/m)	Reactive (Ω/m)
Ceramic with silver stripes	<1	176		<290	<4800
Ceramic with solid copper coating	<1	193	185[b] at 2.295 GHz	<290	<4800
Ceramic with copper stripes (widely spaced)	1.5 ± 0.6	215		<290	<4800
Brass slots	<1	<7		<290	<4800

[a]Each sample pipe is 0.61 m long

[b]Because of the nonuniformities of the ceramic pipe, this calculation could vary on the order of ± 10%

Conclusions

We are designing our next generation of tests for greater sensitivity (lower Z_0 for longitudinal tests, greater spacing between balanced lines). We expect to see an increase in sensitivity of up to a factor of 4 on the longitudinal measurements and a factor of 6 on the transverse measurements.

Some important conclusions of the measurement program to date are as follows:

- An unshielded ceramic pipe with an exterior conductor introduces a large reactive impedance. The measurements of this reactive impedance are in good agreement with the values calculated using Eq. (5). Therefore, it is desirable to have a conducting layer or conducting stripes on the interior of the pipe.
- The measurements have not yet discovered any large transverse or longitudinal impedance differences between a longitudinally striped conductor and a solid conducting layer over the frequency range explored to date (0.05-2.3 GHz). The measurement sensitivity (see Table I) sets limits on the extra impedance that may be introduced by the striped geometry.
- The measurement limits (Table I) may be compared with AHF impedance tolerances. For an AHF with a circumference of 1200 m, total impedance limits of the following magnitudes are obtained:

$$\frac{Z_{\|}}{n} \leq 10\ \Omega ; Z_{\perp} \leq 2.5\ M\Omega/m\ ,$$

where n is the harmonic number. A sensitivity of 1 Ω (longitudinal) for our 0.6-m samples extrapolates to 2000 Ω for an AHF or a $Z_{\|}/n$ of 10 Ω at 50 MHz (n = 200). A transverse impedance sensitivity of 1000 Ω/m corresponds to 2 MΩ/m in the AHF. The current measurement sensitivities are of the same magnitude as the maximum allowed total AHF impedance; greater sensitivity is desirable.

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