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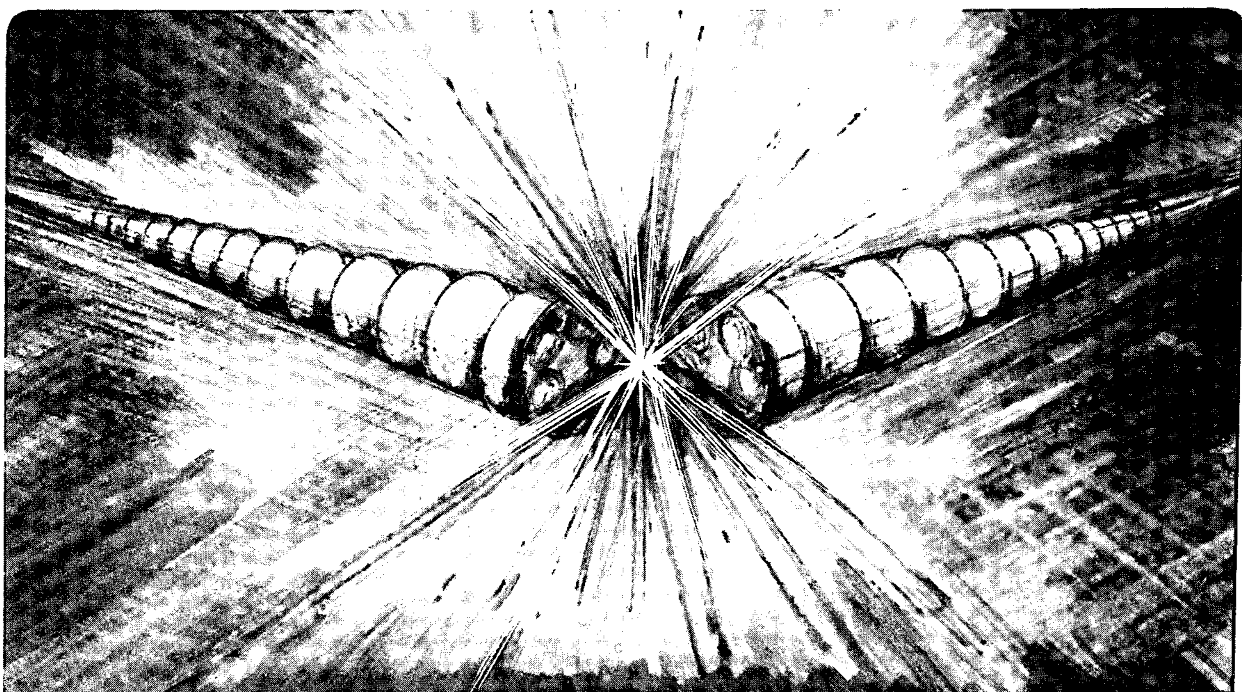

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TECHNIQUES FOR BEAM IMPEDANCE MEASUREMENTS ABOVE CUTOFF

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Abstract

Methods for measuring beam impedance above cutoff have been very limited. For design work on the ALS we have developed two techniques that yield data in the frequency domain with high sensitivity. The first is an extension of the wire method; the second utilizes traveling TM waves to simulate the beam's fields at the wall, and thus avoids the mechanical difficulties of mounting the wire. It is also more sensitive than the other method but the interpretation is complicated by the presence of higher order modes. With either method we were able to detect resonant peaks smaller than 1 Ohm at 10 GHz.

Introduction

In a cylindrical beam tube the geometric cross-section defines the cutoff frequency for TM modes. Below cutoff, the fields and image currents of the beam excite electric fields at a perturbing object and these are experienced locally by the particles of the beam. Above cutoff, the exciting mechanism is the same but the fields at the object launch traveling waves that can interact with the beam and other objects over an extended length of beam tube. Provision must then be made in measurements [1], to exclude effects arising from these waves that radiate from the object under test.

At a physical object, such as a cavity or a resistive structure, one can visualize its impedance generating electric fields as image currents pass. Above cutoff, one must add a conductance to account for the energy radiated in traveling waves. Radiation from a narrow annular band on the tube wall creates a conductance of about 1/30 mho for each TM_0 mode that is well above cutoff. Thus the impedance above cutoff is reduced by the radiating waves.

Wire Method above Cutoff

The use of a wire carrying current to simulate the beam in impedance measurement is based upon the assumption that the fields produced at the surrounding wall are equivalent to those of a relativistic-beam current [2]. Except for currents induced in the wire, this simulation is quite good both below and above cutoff [3]. However, currents induced in the wire by impedances diminish the exciting wire current, couple to and reflect from other impedances and variations in the characteristic line impedance of the wire, and alter the cutoff frequencies of traveling waves. These undesired interactions within the section of beam tube under measurement are reduced by using a thin wire having high characteristic TEM line impedance and also by depending upon the induced current being a small fraction of the exciting wire current. To transform the exciting current from 50 ohm circuits to a higher line impedance in the test sections, it is best to use a matching taper that is free of TEM reflections in the frequency range of interest. Unlike the TEM waves, traveling waveguide modes (TWs) reflect from the tapers and can resonate in the test setup. Those reflected TWs induce spurious signals in the wall impedance; these are detected by the wire and typically obscure and distort the desired signal.

In the method presented here, reflection of TWs is prevented by absorbtive pads placed in the wire setup between the tapers and the object to be tested, as sketched in Fig. 1. Joints and adapters in the region between taper and pad must be made smooth to avoid signals from TWs generated there. The absorbers will also attenuate the TEM signal; this loss of dynamic range, however, should not be a problem with modern network analysers. Under these ideal assumptions the data can be interpreted in terms of beam impedance in the same way as in the traditional below-cutoff measurement. The beam impedance Z_B is then given by

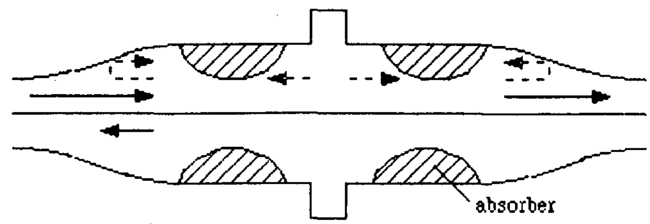

Fig.1 Wire setup with pads to absorb TM modes, shown dashed. TEM signals are shown solid.

$$Z_B = -2 Z_L \frac{\Delta I}{I + \Delta I} = 2 Z_L\left(\frac{S21ref}{S21obj} - 1\right) \qquad (1)$$

where the transmission coefficient S21ref is the result of a normalizing measurement through a smooth reference pipe, S_{21obj} is the response with the actual object, and Z_L is the coaxial line impedance of the wire in the beam tube.

We set up apparatus for measurement from 1 to 26 GHz; cutoff with the wire in place was 6GHz. The shape and material of the absorber was the result of many trials with both dielectric and magnetic absorbers. The material chosen was from a flexible foam sheet 1 cm thick (Eccosorb AN73 from Emerson and Cuming); two crescent-shaped pads 25 cm long were cut from this material and mounted with flat edges on opposing sides of the beam-tube wall. The intent was to obtain a reasonably constant attenuation over the entire frequency range. Fig. 2 shows the effect of a set of these dampers at each end of a test beam tube 60 cm long with matching tapers and a 1/8-inch diameter wire, $Z_L = 160\ \Omega$. The trace shows the magnitude of the transmission of the TEM signal divided by the response without damping material. It is difficult to assess the absorption of TM modes; therefore the absorber was adjusted experimentally until observable spurious resonances caused by an inserted obstacle were damped.

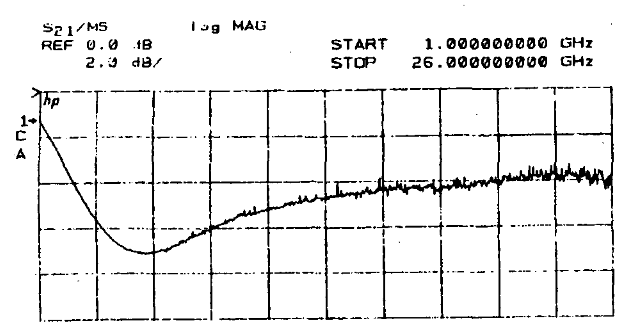

Fig.2 Attenuation of wire current by absorbers

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Except for the presence of the absorbing pads, the measurement technique is the same as the usual wire method. Of course the higher frequencies require greater care. In our apparatus the tapers have a precision Chebyshev contour and the setup has provision to adjust the length to assure that the wire has neither gaps at joints nor buckles. A small resonator was inserted as a test object; it showed an impedance of about 10 Ω at 10.2 GHz. An impedance of 1 Ω was measurable.

The TM Wave Method

The electromagnetic fields at the wall of a tube in which a TM waveguide mode is propagating produce wall currents that are similar to the image current of a beam. A local structure on the wall experiences the passage of a sinusoidal wave of current. That the wave velocity is greater than the beam velocity appears as a failure of this simulation to have the proper phase difference between points that are longitudinally separated. Considering these comparative aspects, it seemed worthwhile to examine the use of TM waves to measure beam impedance above cutoff, in view of the paucity of techniques available. For this purpose we shall assume that a wall current I, whether driven by beam current or traveling TM wave, induces at a local object in the wall a voltage V related to the beam impedance by $V = I\,Z_B$.

The first step in the analysis is to derive the amplitudes of the waves that are excited by the voltage V. To simplify the analysis, a circular beam tube of radius b and a rotationally-symmetric wall impedance of short length $\Delta\ell$ will be assumed as diagrammed in Fig. 3. If voltage V is developed across this length it will excite upstream and downstream TM_{om} waves. Apply the reciprocity theorem to the volume inside the tube between the planes at z_1 and z_2. If there are no sources within the surface S that bounds the volume, the theorem states

$$\int_S (Eo \times H - E \times Ho)dS = 0 \qquad (2)$$

in which fields E and H arise from the voltage V and we may choose an incident TM_{on} wave as a second source to give fields E_0 and H_0.

The fields produced by the first source are, in cylindrical coordinates,

$$E_z = V/\Delta\ell \qquad (3)$$

within $\Delta\ell$, and

$$E_r^{\pm} = \pm j\sum_m C_m^{\pm}\frac{\beta_m}{k_m}J_1(k_m r)e^{\mp j\beta_m z}$$
$$H_\Phi^{\pm} = j\sum_m \frac{C_m^{\pm}}{Z_o}\frac{k_o}{k_m}J_1(k_m r)e^{\mp j\beta_m z} \qquad (4)$$

in the planes at z_1 for upstream (–) waves and z_2 for downstream (+) waves. Modes below cutoff are assumed to have been attenuated to negligible strengths at those planes. βm and the cutoff wave number k_m are related by $k_0^2 = k_m^2 + \beta_m^2$. Z_o is 377 ohm. The second source that we assume will launch an unperturbed downstream mode TM_{on} with amplitude E_n.

Applying Eq. 2 to the fields of these two sources yields a result involving only the upstream waves with m = n, which for the nth mode is

$$C_n^- = -jV\frac{k_n}{\beta_n b J_1(k_n b)} \qquad (5)$$

Similarly, choosing an alternate second source that launches an upstream wave, one finds that

$$C_n^+ = C_n^-. \qquad (6)$$

With these results we now turn to the physical case in which a

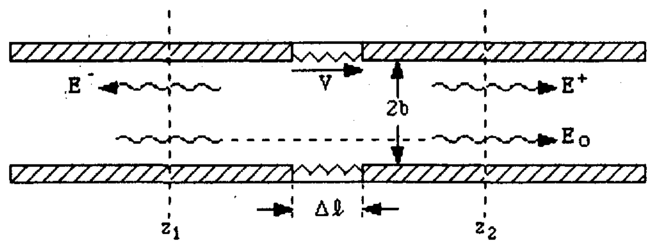

Fig.3 Geometry for analysis of radiated TM waves

number of modes with fields E_i and H_i are launched into the beam tube. The wall current from these is (with z-dependences suppressed)

$$I = 2\pi b\sum_i H_{i\Phi} = j2\pi b\sum \frac{E_i}{Z_o}\frac{k_o}{k_i}J_1(k_i b). \qquad (7)$$

Combine this current with Eq. 5 in the equation $V = IZ_B$ to obtain

$$Z_B = -\frac{Z_o}{2\pi}\frac{1}{\sum_i \frac{k_o E_i}{\beta_i C_i}} \qquad (8)$$

To use this relation in measurements to determine the beam impedance would require measurement of the complex amplitudes of all the incident modes E_i and of the corresponding radiated modes C_i. If the TM couplers that launch and receive the waves can be made to pass predominantly only one mode, Eq. 8 simplifies to

$$Z_B \approx -\frac{Z_o}{2\pi}\frac{\beta_i}{k_o}\frac{C_i}{E_i} \equiv -\frac{Z_o}{2\pi}\frac{\beta_i}{k_o}\frac{\Delta E}{E} \qquad (9)$$

a form directly analogous to that for the wire method for small perturbations, $Z_B = -2Z_L\Delta I/I$. We see by comparison that the single-mode TM wave responds as a TEM wave with line impedance

$$Z_B = \frac{Z_o}{4\pi}\sqrt{1-\left(\frac{k_i}{k_o}\right)^2} = 30\sqrt{1-\left(\frac{k_i}{k_o}\right)^2}\ \text{ohm} \qquad (10)$$

In our first application of this method, some reflections and residual transmission of higher modes complicated the interpretation of phase; therefore we used only the values of input and output powers. For that case, the value of the impedance when Z_B is resistive was calculated from the relative power loss

$$\frac{\Delta P}{P_{in}} = \frac{P_{in} - P_+}{P_{in}} \qquad (11)$$

using

$$R_e Z_B \approx \frac{Z_o}{2\pi}\frac{\beta_i}{k_o}\left[1 - \sqrt{1 - \frac{\Delta P}{P}}\right] \qquad (12)$$

In the wire method a correction for the reduction of the incident TEM wave in passing the test object is effected by dividing by $1 + \Delta I/I$. It seems reasonable that some such correction should be applied in the use of the TM wave but it has not been calculated.

A broadband annular antenna (Fig. 4) was designed to launch TMon waves into a circular waveguide with diameter 1 7/8 inch. It consists of a linearly tapered coaxial line that ends abruptly in an annular gap of 1/8 inch radial width. The small end fits the 50 Ω APC-7 connector. Absorbing material (AN73 from Emerson and Cuming) was

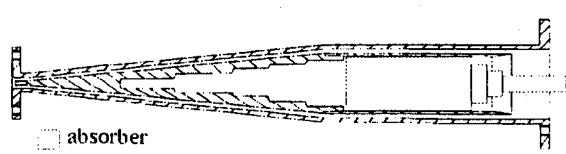

Fig.4 TMon waveguide-mode launcher

placed in the hollow center. Its shape was experimentally optimized to yield the most smooth transmission over the frequency range. In particular the narrow central projection well into the waveguide region was needed to improve the rejection of higher waveguide modes.

Fig.5 shows responses through two antennas joined by a 30 cm tube. Figure 5a, without the full absorber clearly shows the interference patterns produced as the frequency rises above the cutoffs for higher modes. The more random pattern, fig.5b, with the full absorber is interpreted as evidence that the transmission is primarily through the fundamental TM_{01} mode. Spurious transmission below cutoff at 5 GHz is due to TE modes that are excited because of imperfect centering of the inner conductor.

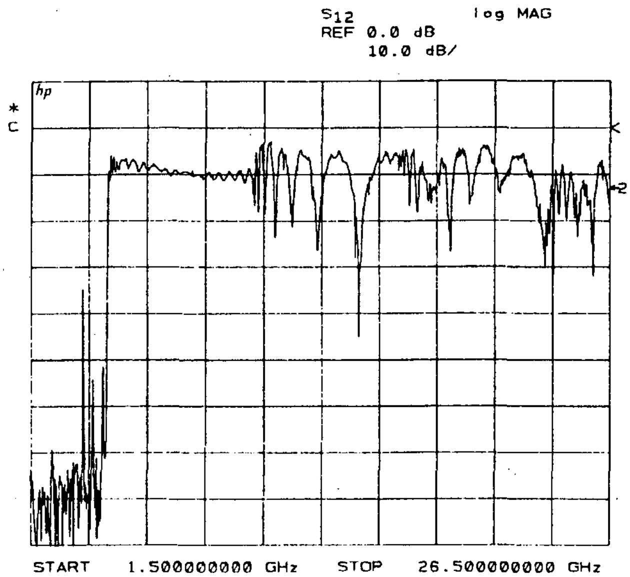

Fig.5a TM setup transmission with recessed absorber

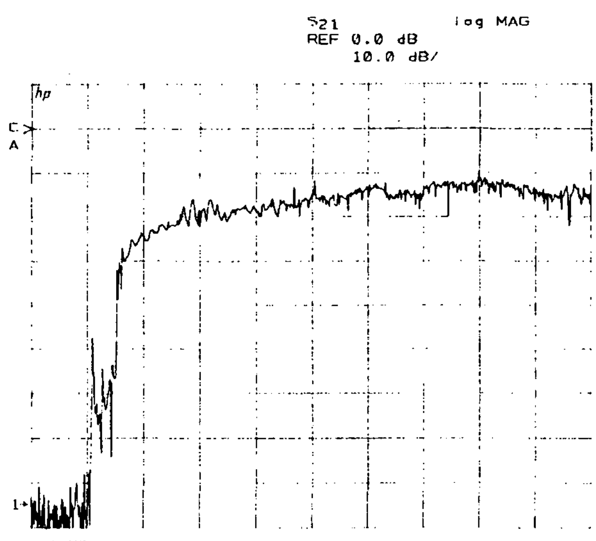

Fig.5b TM setup transmission with extended absorber

The use of this TM-wave apparatus to measure small test resonators gave results that agreed with the wire method in the range 10-to-19 GHz. A resolution of about 1 Ω was obtained, the inherent high sensitivity of the TM wave being offset by the additional ~20 dB of attenuation. It is clear that in its present state of development there is some arbitrariness and uncertainty in interpreting measurements by this TM method. Its quantitative application may be limited to small perturbations in otherwise simple beam tubes. However, it avoids the mechanical complications of the wire apparatus and it does not require intrusion into the interior of the beam tube. Similar techniques have been used to check assembled vacuum chambers [4].

Measurements performed with both the wire and this method are reported elsewhere in these proceedings [5].

References

[1] F. Caspers, "Beam Impedance Measurement by the Wire Method Using a Synthetic Pulse Technique," Proc. of the 1985 Particle Accelerator Conference, IEEE, NS-32, 1985, pp. 1914-1916.

[2] M. Sands and J. Rees, SLAC Report PEP-95, 1974.

[3] R. L. Gluckstern and R. Li, "Analysis of Coaxial Wire Measurement of Longitudinal Coupling Impedance," Proc. of the 14th Int. Conf. on High Energy Accel., Tsukuba, Japan, 1989, p. 861.

[4] M. Poole, "SRS Broad Band Impedance," Proc. Workshop in Impedance and Current Limitations, European Synchrotron Radiation Facility, BP220, 1988.

[5] R. Rimmer, D. Goldberg, A. Jacob, G. Lambertson, and F. Voelker, "Beam Impedance Measurements on the ALS Curved Sector Tank." Proc. of European Particle Accel. Conf., Nice, France, 1990.

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