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structures***

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RADIAL TRANSMISSION LINE ANALYSIS OF MULTI-LAYER STRUCTURES*

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Abstract

The analysis of multi-layer beam tubes is a standard problem and involves axially propagating waves. This treatment is ill suited to a short multi-layer structure such as the present example of a ferrite covered ceramic break in the beam tube at the ERL photo-cathode electron gun. This paper demonstrates that such structure can better be treated by radial wave propagation. The theoretical method is presented and numerical results are compared with measured network analyser data and Microwave Studio generated simulations. The results confirm the concept of radial transmission lines as a valid analytical method.

INTRODUCTION

An Energy Recovery Linac (ERL) is being constructed at this laboratory for the purpose of research towards an envisioned Electron Ion Collider. One of the pertinent topics is damping of Higher Order Modes (HOM). In this ERL, the damping is provided by ferrite absorbers in the beam tube. A modified version thereof, a ceramic break surrounded by ferrite, is planned for the superconducting electron gun. The damper here is located at room temperature just outside of the gun. If used in a cavity chain, the ceramic break is in the vacuum tube at helium temperature whereas the ferrite is moved into the cryostat insulating vacuum allowing higher temperatures. The general properties of the ferrite HOM dampers have been published [2] but are more detailed in this paper.

The “ferrite break”, shown in Fig. 1, can be simplified for the analysis into a structure with a radial sequence of circular symmetric layers. The electromagnetic properties of multi-layer beam tubes have been treated by many authors, with the “standard” axial transmission line solution [3]. The short axial length and the presence of the metallic boundary disks points to the treatment as “radial” transmission line, with its basic concept discussed in Section 2. For the purpose of this study, a model with a glass tube replacing ceramic but equal in length to the ferrite disks was constructed. Section 3. brings the network analyzer measurements of the transmission coefficients, primarily S21, that were performed on the model with a central conductor (rod). The impact of the beam tube break by glass were numerically analyzed with the Wolfram Mathematica program. The measured data are also compared with simulation results from the CST Microwave Studio. For Section 4, the central rod was removed and the additional measurements and simulations confirmed the ferrite damping properties, although they depend on frequency.

RADIAL TRANSMISSION LINE

Radial propagation in a “wave guide horn”, formed by two perfectly conducting annular disks, spaced with a gap, g can be described by a formalism similar to the better-known axial propagation in straight tubular wave guides [4, 5]. Assuming harmonic time dependence, e^{jkt} , and circular coordinate system, r, ϕ, z , the radial field propagation is fully defined by the transverse components E_ϕ, E_z, H_ϕ, H_z in analogy to the E_r, E_ϕ, H_r, H_ϕ for axial propagation. This geometry allows transverse magnetic TM and electric TE modes. In a material with normalized ϵ and μ , the radially propagating fields are derived in terms of Hankel functions from the potential,

$$\begin{Bmatrix} u^{TM} \\ u^{TE} \end{Bmatrix} = \begin{Bmatrix} \cos k_{zn} \\ \sin k_{zn} \end{Bmatrix} \cos(m\phi) \begin{Bmatrix} H_m^{(1)}(v_n r) \\ H_m^{(2)}(v_n r) \end{Bmatrix}, \quad \begin{cases} n = 0, 1, 2, \dots \\ n = 1, 2, 3, \dots \end{cases}$$

where $k = \omega / c$, $k_{zn} = n\pi / g$, and $v_n = \sqrt{\epsilon\mu k^2 - k_{zn}^2}$.

Considering here only TM_{mpn} modes yields the fields

$$E_z = \begin{Bmatrix} H_m^{(1)}(v_n r) \\ H_m^{(2)}(v_n r) \end{Bmatrix}, \quad H_\phi = -j \frac{\epsilon k}{v_n} \begin{Bmatrix} H_m^{(1)\prime}(v_n r) \\ H_m^{(2)\prime}(v_n r) \end{Bmatrix}$$

and the radial wave impedance of an out-going wave

$$Z_m = -\frac{E_{zn}}{H_{\phi n}} = j \frac{v_n}{k\epsilon} \frac{H_0^{(2)}(v_n r)}{H_1^{(2)}(v_n r)} \rightarrow j \frac{H_0^{(2)}(kr)}{H_1^{(2)}(kr)} \text{ in vacuo.}$$

The analysis of the ferrite break with its ceramic and ferrite layer is done in analogy to Hahn’s axial matrix method treatment of multi-layer beam tubes [6]. The radial transmission matrix for a single mode from the outer radius to a radius within the layer is:

$$\begin{pmatrix} E_{zn}(r) \\ H_{\phi n}(r) \end{pmatrix} = M_n(r, r_o) = \begin{bmatrix} m_{nee}(r, r_o) & m_{neh}(r, r_o) \\ m_{nhe}(r, r_o) & m_{nhh}(r, r_o) \end{bmatrix} \begin{pmatrix} E_{zn}(r_o) \\ H_{\phi n}(r_o) \end{pmatrix}$$

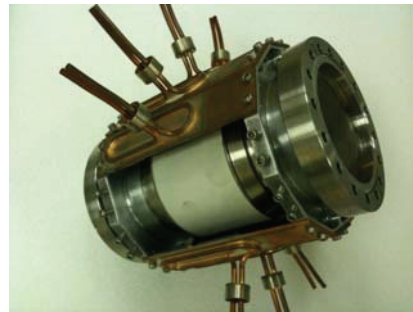


Figure 1: Ceramic break with ferrite HOM damper

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The elements of the field transfer matrix are found as

$$m_{nee}(r, r_o) = j \frac{\pi}{4} v_n r_o \left[H_0^{(2)}(v_n r) H_1^{(1)}(v_n r_o) - H_0^{(1)}(v_n r) H_1^{(2)}(v_n r_o) \right]$$

$$m_{neh}(r, r_o) = -\frac{\pi}{4} \frac{v_n^2 r_o}{\epsilon k} \left[H_0^{(2)}(v_n r) H_0^{(1)}(v_n r_o) - H_0^{(1)}(v_n r) H_0^{(2)}(v_n r_o) \right]$$

$$m_{nhe}(r, r_o) = -\frac{\pi}{4} \epsilon k r_o \left[H_1^{(2)}(v_n r) H_1^{(1)}(v_n r_o) - H_1^{(1)}(v_n r) H_1^{(2)}(v_n r_o) \right]$$

$$m_{nhh}(r, r_o) = -j \frac{\pi}{4} v_n r_o \left[H_1^{(2)}(v_n r) H_0^{(1)}(v_n r_o) - H_0^{(1)}(v_n r) H_1^{(2)}(v_n r_o) \right]$$

The field at the inner radius of a layer must be summed over the individual modes,

$$\begin{pmatrix} E_z(r_i) \\ H_\varphi(r_i) \end{pmatrix} = \begin{pmatrix} \sum_n E_{zn}(r_i) \\ \sum_n H_{\varphi n}(r_i) \end{pmatrix} = \sum_n M_n(r_i, r_o) \begin{pmatrix} E_{zn}(r_o) \\ H_{\varphi n}(r_o) \end{pmatrix}$$

In the case of several layers, the modes propagate uncoupled through the layers and the overall matrix is obtained by matrix multiplication of the individual matrices [6]. In contrast to the radial wave impedance of the infinitely extended layer given above, the impedance of a multi-layer finite structure is

$$Z_r = \frac{M_{ee}(r, r_o) Z(r_o) - M_{eh}(r, r_o)}{M_{hh}(r, r_o) - M_{he}(r, r_o) Z(r_o)}$$

which is reduced by a perfectly conducting outer tube to

$$Z(r_c) = -M_{eh}(r_c, r_o) / M_{hh}(r_c, r_o)$$

As a numerical test, the surface impedances of a ferrite ring with $\epsilon = 13$, $\mu = 29/(1+j2.5 f_{\text{MHz}})$ and an inner radius of $r_i = 75.4$ mm are shown in Fig. 2 for unbound, 4.9 mm thick with perfect conducting, or vacuum outside.

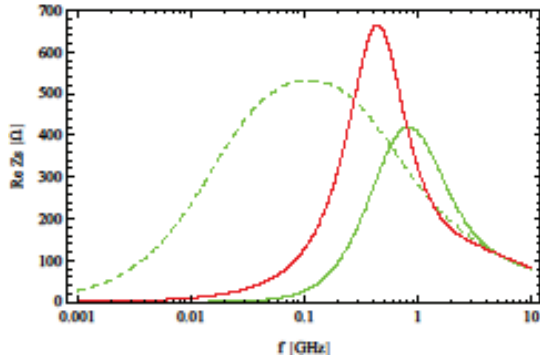


Figure 2: Impedance of a ferrite ring for unbound (dashed), vacuum (red) and shorted (green) outside

IMPEDANCE OF THE BREAK

The complex geometry of the break effectively prevents the use of standard analytical methods to find its electromagnetic properties. Creating a simplified model reduces the break into a prototypical example for the radial transmission method. The computer model shown in Fig. 3 serves this purpose and allows comparisons with MWS simulations. In addition, a physical model was produced for S_{21} measurements with a network analyzer as viewed in Fig. 4. This model was assembled from the ferrite plates intended for the gun damper, but by

replacing the ceramic break with a glass tube. The cavity model is flexible and can be assembled in several configurations allowing to study it as reference cavity without ferrite or glass, as pure ferrite damper, as pill box with glass ring, or in its final form as glass break with ferrite layer.

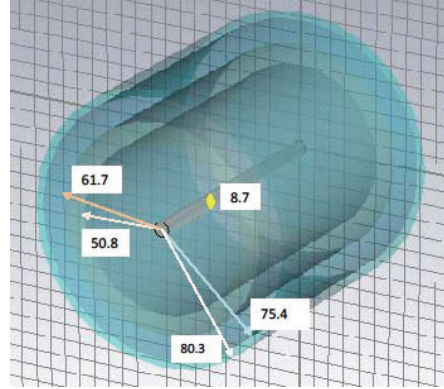


Figure 3: Break model for MWS simulations and radial transmission analysis

The intended gun cavity damping properties and the unintended beam coupling impedance are determined by the wall impedance at the inner layer of the break. The break can be represented by a lumped impedance, different for each azimuthal field configuration, that together with the local H determines gun cavity damping or beam coupling impedance.

Computational results shown in Fig. 4 follow directly from the radial transmission line treatment. Note that large Z values imply strong damping. One purpose of the present study was to establish the interaction of the relatively lossless ceramic (here glass) with the strong damping properties of the ferrite. The numerical results point to a frequency dependence, but reduced damping at the frequencies of interest to the gun operation.

The break damping effect is also obtained from the S_{21} measurements as pictured in the setup in Fig. 5 or the frequency domain simulations with the MWS model. Both measurements and simulations involve N type EIA couplers with unknown frequency dependence and transformer ratios that limit a direct comparison of the results in Fig 6 to the analytical results in Fig.4. Note also that S_{21} and Z_{Tr} have inverse impact.

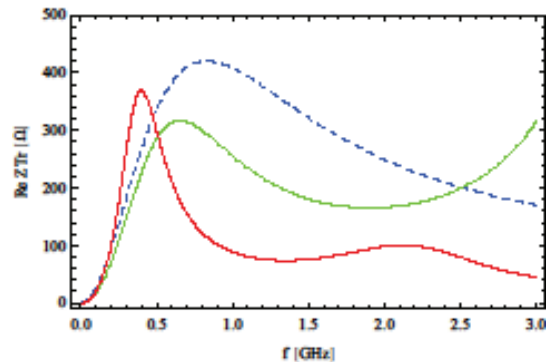


Fig. 4. Break impedance of the model with ferrite and glass (red), with ferrite (green) and the wave impedance at the ferrite i.d. (dashed blue)

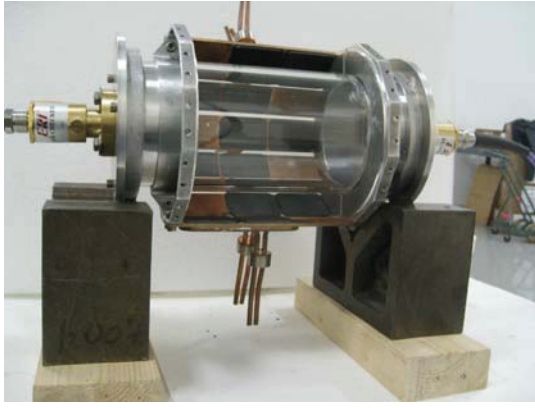


Figure 5: Setup for network analyzer measurements

Considering Fig. 6, one finds minimal glass induced effects on the achievable ferrite damping. The oscillation with frequency are believed to be caused by the intrinsic cavity resonances in axial direction that are made possible by the insertion of the central conductor marked as rod.

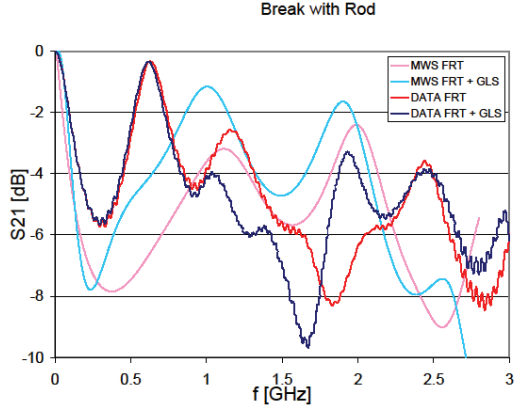


Figure 6: Forward scattering coefficient across the cavity.

Both, the damping of the gun cavity resonances and the coupling impedance seen by the beam generated by the break is best defined by its equivalent series impedance Z_{TR} . This impedance is conveniently measured as ratio of the S_{21} of the “device under test” divided by the S_{21} of the reference structure. In the present structure, the reference is provided by the damper structure without ferrite or the glass tube. The equivalent impedance follows then directly from the network analyzer measurement by using the conversion of the S_{21} data into a forward impedance while applying a 810 nsec delay to represent the reference. Fig 7 shows the signal for the reference (gold) after the 810 nsec adjustment to avoid a negative real part of the impedance. Also shown here is the real part of the damper impedance, raw (light blue) and then with the delay applied (blue). The signal for the ferrite without glass is also given (red). The difference in strength here versus Fig. 4 is due to the unknown coupler transformer. It must be mentioned that this geometry provides only the impedance of TM modes with axial electric fields and transverse electric modes are not excited by the axial conductor.

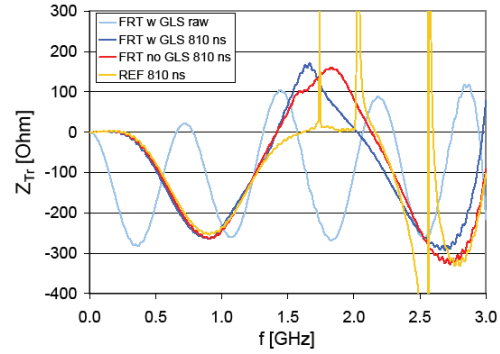


Figure 7: Series impedance of the break from S_{21} conversion

DAMPING OF BREAK RESONANCES

In the cavity without central conductor, the lowest intrinsic TM_{01n} resonances are at ~1.39 and 1.71GHz, but are strongly damped resulting in the smeared-out S_{21} transmission curve in Fig. 8. Intrinsic and the damped resonances are found in the radial transmission theory by matching the break impedance, real and imaginary part, to the radial wave impedance at the inner ceramic radius, $jJ_0(kr_c)/J_1(kr_c) = Z(r_c)$. The damping is given by $Q^{-1} \approx 2k_{im} / k_{re}$, although note the existence of numerical difficulties for large permittivities of the ceramic.

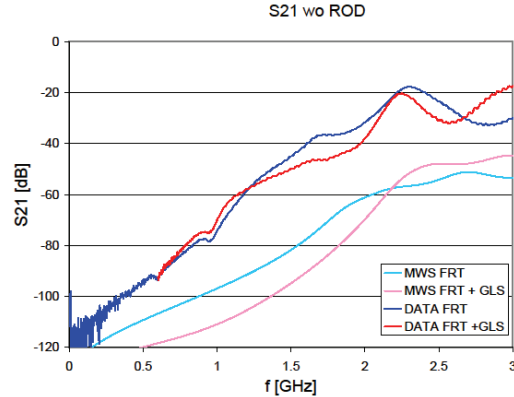


Figure 8: Achieved S_{21} signal damping, measured and simulated for ferrite alone and with a glass tube added.

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