USING A RESISTIVE MATERIAL FOR HOM DAMPING*

Valery Shemelin# and Sergey Belomestnykh
CLASSE, Cornell University, Ithaca, NY 14853, U.S.A.

Abstract

Ferrites and lossy ceramics, used in HOM (higher order mode) loads for superconducting accelerators, have shortcomings such as poor batch-to-batch reproducibility of electromagnetic properties, extremely low electric conductivity at cryogenic temperatures leading to accumulation of charge on the material surface, brittleness, which may cause contamination of the nearby SRF cavities by lossy dust, etc. A proposal to use a resistive material free of these shortcomings is presented.

INTRODUCTION

A new composite material, consisting of silicon carbide reinforced by carbon fibers, is, possibly, free of many shortcomings inherent to ferrites or lossy ceramics. It has high thermal conductivity of 160 W/m·K at 293 K, 30 W/m·K at 50 K [1], and the electric conductivity of about 15 kS/m according to our measurements. The trade name for the C/SiC material produced by ECM (Germany) is Cesic® [2].

For this material to be useful in lining an HOM load, it must satisfy certain requirements. To assure this, we have measured its microwave losses in a wide frequency range. Also, we need to check its compatibility with ultra-high vacuum and clean room (for superconducting RF applications) environments. Once the properties of the material are known, one can design a load and calculate efficiency of damping HOM modes.

The difference between ferrites and lossy ceramics on one hand and materials with high ohmic losses on the other hand is that in the former case the losses are volumetric and in the latter case – surface. Hence the power density in a surface absorber could be higher and having high thermal conductivity is important.

To increase absorption at frequencies of the most dangerous HOMs, resonant grooves [3] can be used.

In this paper we describe measurements of the Cesic electric conductivity at microwave frequencies, discuss the results, and present an HOM load design and a model for estimation of the external quality factor.

MEASUREMENTS OF LOSSES IN THE RECTANGULAR WAVEGUIDE

Three short sections of different size rectangular waveguides made of Cesic were fabricated. A network analyzer was used to measure the transmission coefficient S21 in the through-pass set up and the reflection coefficient S11 with the shorted waveguide in the frequency range from 12.4 to 40 GHz, Fig. 1. Then the power loss and electric conductivity were calculated.

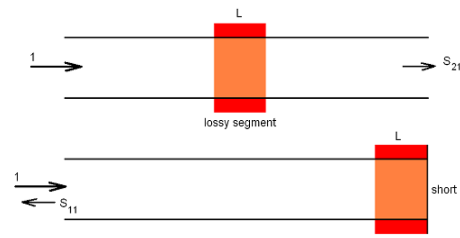

Figure 1: Measurement set ups.

Through-pass Waveguide

The attenuation constant of the TE_{10}-wave in a rectangular waveguide is

$$\alpha = \frac{R_s}{b \cdot Z_0 \cdot \sqrt{K}}\left[1 + \frac{2b}{a}\left(f_c/f\right)^2\right],$$

where R_s is the surface resistivity, $a\times b$ are the dimensions of the waveguide cross-section, Z_0 is the impedance of the free space, f_c is the cutoff frequency, and $K = 1-\left(f_c/f\right)^2$.

From this, using $R_s = 1/(\sigma\delta)$, we derive:

$$\sigma = \frac{k^2 L^2\left[1 + \frac{2b}{a}\left(f_c/f\right)^2\right]^2}{b^2 \cdot K\pi f\mu_0 \ln^2(1-Abs)},$$

where σ is the electric conductivity of the waveguide walls, δ is the skin depth, $Abs = 1 - \exp(-2\alpha L)$ is the absorption, k is the wave number. On the other hand,

$$Abs = 1-|S_{21}|^2 - |S_{11}|^2 \approx 1-|S_{21}|^2 \text{ if } |S_{11}| << |S_{21}|.$$

Thus, when the reflection is small:

$$\sigma = \frac{kL^2\left[1 + \frac{2b}{a}\left(f_c/f\right)^2\right]^2}{2b^2 K Z_0 \ln^2|S_{21}|}.$$

The relative error for conductivity is

$$\frac{\Delta\sigma}{\sigma} = \left[\frac{\partial\sigma}{\partial S_{21}}\Big/\sigma\right]\cdot\Delta S_{21} = -\frac{2\cdot\Delta S_{21}}{S_{21}\cdot\ln(S_{21})}.$$

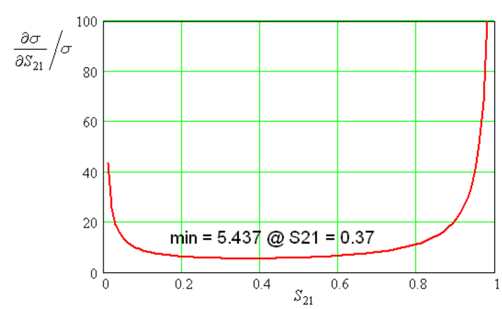

Figure 2: Logarithmic derivative of σ with respect to S_{21}.

*Work supported by the NSF Award PHY-0131508, Empire State Development Corporation, and Cornell University
vs65@cornell.edu

As we can see from Fig. 2, for the S_{21} error of $\Delta S_{21} = 1\%$, the relative error $\Delta\sigma/\sigma$ is about 5.4% at the minimum, and rapidly grows for S_{21} approaching 0 or 1.

Shorted Waveguide

To improve the accuracy of measurements, a scheme with a shorted waveguide was proposed. When a wave passes twice through the lossy segment, maximum field increases approximately two times, and the losses are higher. They are exactly 2 times higher for segments with the length equal to a multiple number of $\Lambda/4$. This is due to non-uniform distribution of losses in the standing wave. A detailed derivation of the formula for σ is presented in [4], here we provide the final result:

$$\sigma = \frac{kF^2(L,f)\cdot(\lambda\Lambda)^2}{2Z_0\left(1-S_{11}^2\right)^2\left(a^3b\right)^2},$$

$$F(L,f) = L\left(\frac{4a^3}{\Lambda^2}+a+2b\right)+\frac{\Lambda}{4\pi}\left(\frac{4a^3}{\Lambda^2}-a-2b\right)\sin\left(\frac{4\pi L}{\Lambda}\right)$$

To calculate errors, we have to find the logarithmic derivative:

$$\frac{\Delta\sigma}{\sigma} = \frac{1}{\sigma}\frac{\partial\sigma}{\partial S_{11}}\Delta S_{11} = \frac{4S_{11}}{1-S_{11}^2}\Delta S_{11}.$$

For small losses $S_{11} = 1-\varepsilon_{11}$, $\varepsilon_{11} << 1$, and

$$\frac{4S_{11}}{1-S_{11}^2} \approx \frac{2}{\varepsilon_{11}}.$$

For the through-pass method the error has the same form:

$$\frac{1}{\sigma}\frac{\partial\sigma}{\partial S_{21}} = -\frac{2}{S_{21}\cdot\ln S_{21}} \approx \frac{2}{\varepsilon_{21}},$$

but the value of ε_{21} was approximately 2 times smaller than the ε_{11} and the error, accordingly, 2 times bigger. However, this is true for $\varepsilon_{21} << 1$ only because the calculation of P_t is performed under this condition.

MEASUREMENT RESULTS

The lengths of waveguide segments were calculated assuming the conductivity of 164 S/m taken from [2]. In this case S_{21} would be about 0.5 and σ could be measured with an acceptable accuracy. However, the actual conductivity is two orders of magnitude bigger. The through-pass scheme produced big errors because S_{21} was about 0.95. This method could work for smaller σ or longer sections of the lossy waveguide.

Using a more accurate method with shorted waveguide, the conductivity of Cesic (Fig. 3) was found constant in a wide frequency range and equal to 15×10^4 S/m. Error bars correspond to 1% error in S_{21} measurements.

Q_{EXT} WITH AN IMPERFECT LOAD

Consider a cavity's higher-order mode with very high intrinsic quality factor Q_0 loaded by a beam-line HOM load as shown in Fig. 4. In this case the loaded quality factor is approximately equal to the external one.

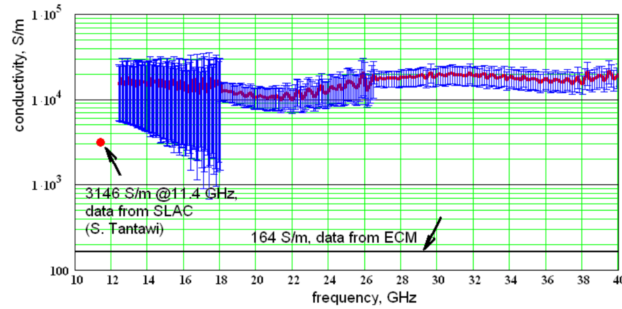

Figure 3: Electric conductivity of Cesic vs frequency.

An ideal HOM load with the external quality factor Q_{ext0} presents a perfect match to the incident wave and absorbs all its power. As any realistic load can absorb only part of the incident power and is not a perfect match to the impedance of a beam pipe, its external Q depends on the absorbing properties of the load, on the connecting beam pipe length L_{bp} and boundary condition at the end.

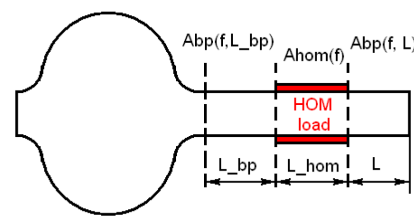

Figure 4: A cavity connected to a beam-line HOM load.

To calculate the external quality factor $Q_{ext,short}$, we use the *RLC* circuit model representation of the HOM and transmission line theory. For simplicity, we assume the HOM load to be a section of the beam pipe made of a lossy material. However, this does not affect generality of the described approach as any different load can be used with an appropriate substitution of the ABCD matrix. The HOM is assumed to be transformed to the detuned-short position at the beam pipe. Different boundary conditions can be simulated by a shorted beam pipe of a variable length *L*. Then the quality factor can be expressed as

$$Q_{ext,short} = \left|Z_{in,short}(f,L)\right| / (R/Q),$$

where $Z_{in,short}(f,L) = A(f,L)_{1,2} / A(f,L)_{2,2}$, and

$$A(f,L) = A_{cav}(f)\cdot A_{bp}(f,L_{bp})\cdot A_{\text{hom}}(f)\cdot A_{bp}(f,L)$$

is the product of ABCD matrices of individual components of the system. Details of further derivations are presented in [4]. Solutions for a fixed length $L_{bp} = 0.5\Lambda(f_0)$ are shown in Fig. 5 for $f = 2500 \pm 0.2$ MHz. We can note that the $Q_{ext,short}$ does not depend on $L_{bp} + L$, and that its maximum occurs at zero detuning from the central frequency [4]. Thus we can define this maximum as the worst position of the load between the beam pipes. For the single-pass absorption through the HOM load, we can write $Abs = 1 - \exp(-2\alpha\cdot L_{\text{hom}})$.

Now we can plot the value of $Q_{ext,short} / Q_{ext0}$ vs *Abs,* Fig. 5. One can see that for a given Q_{ext0} and the HOM load with 20% one-pass absorption, the quality factor $Q_{ext,short}$ does not exceed 10 times Q_{ext0} for any Q_0.

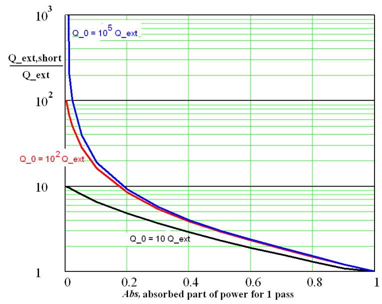

Figure 5: Worst $Q_{ext,short}$ for a given absorption.

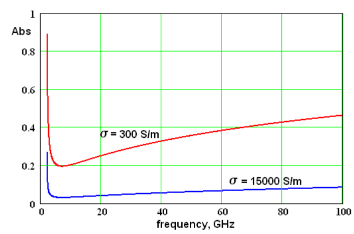

Figure 6: One-pass absorption in a round pipe HOM load with ID = 78 mm and L_{hom} = 300 mm.

An absorption of 20% and higher can be obtained with 300 S/m. However, for higher conductivity the absorption is worse, Fig. 6. One can use resonant grooves to enhance losses at selected frequencies as described below.

RESONANT GROOVES IN THE LOSSY WAVEGUIDE

Single Resonant Groove

A resonant groove in a round waveguide (a choke) reflects most of RF power if the electric conductivity of walls is high. However, if the conductivity is not high, a significant part of the power can be absorbed in the groove. The maximum absorption at 15 kS/m is achieved for a 4-mm wide groove, Fig. 7.

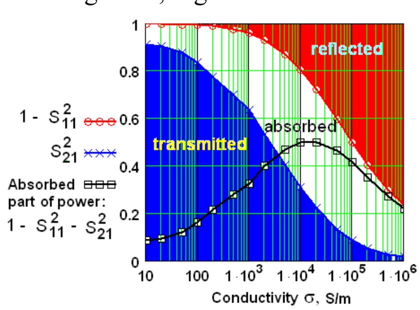

Figure 7: Transmitted, reflected, and absorbed RF power in a 4-mm wide resonant groove in a 78-mm ID pipe.

Double Resonant Grooves

Effectiveness of an absorbing groove can be increased if two or more grooves are tuned to the same frequency. This was used in [3] to develop a RF load for high power.

If one needs to increase absorption at several frequencies, several pairs of grooves can be used; each pair tuned to a different frequency. These pairs can be placed embracing each other, Fig. 8. Parasitic interaction between the pairs can be compensated by optimization of their positions and dimensions.

A result of such optimization using Microwave Studio(R) [6] is shown in Fig. 8 for three frequencies (2500, 3000, and 3400 MHz) chosen to cover the dipole bands of the Cornell ERL cavity [5]. The losses can be increased up to 80% for one passage through the grooved pipe.

This example was calculated for σ = 15 kS/m, 300 mm long pipe with an inner diameter of 78 mm. The part of the pipe between the extreme grooves and the butts is assumed perfectly conducting so that losses occur in the inner part between grooves and in the grooves themselves. The *S*-parameter matrix calculated for an HOM load with resonant grooves can be converted to an ABCD matrix and used to estimate external quality factors as described in the previous section.

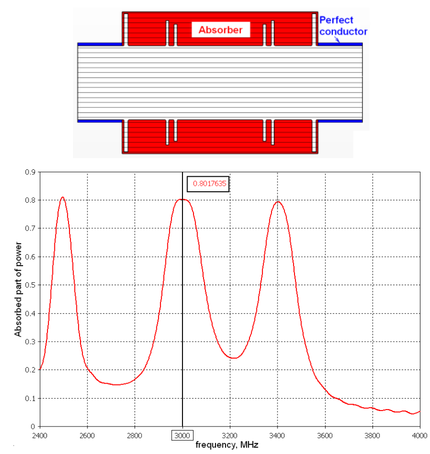

Figure 8: Matched pairs of absorbing grooves for three HOM frequencies and conductivity of 15 kS/m (Cesic).

CONCLUSIONS

Preliminary results for a new HOM load made of a resistive material are presented. The minimal needed level of losses in an HOM load is estimated. Measurements of conductivity in the waveguide are discussed and results of the measurements are presented. Use of resonant grooves for a multi-frequency HOM load is proposed and results of optimization for a specific case are shown.

ACKNOWLEDGEMENT

The authors are thankful to S. Tantawi for information about Cesic and details about the all-metal RF load.

REFERENCES

[1] T. Ozaki et al. Proc. SPIE, 5868:58680H-1, 2005.
[2] www.cesic.de
[3] W. Fowkes et al., PAC97, Vancouver, Canada, 1997.
[4] V. Shemelin, S. Belomestnykh, Cornell Report ERL10-1, www.lepp.cornell.edu/public/ERL/2010/ERL10-1.pdf.
[5] N. Valles and M. Liepe, WEPEC068, this conference.
[6] www.cst.com