

ABSORBER MATERIALS AT ROOM AND CRYOGENIC TEMPERATURES*

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Abstract

We recently reported on investigations of RF absorber materials at cryogenic temperatures conducted at Jefferson Laboratory (JLab) [1]. The work was initiated to find a replacement material for the 2 Kelvin low power waveguide Higher Order Mode (HOM) absorbers employed within the original cavity cryomodules of the Continuous Electron Beam Accelerator Facility (CEBAF). This effort eventually led to suitable candidates as reported in this paper. Furthermore, though constrained by small funds for labor and resources, we have analyzed a variety of lossy ceramic materials [2], several of which could be usable as HOM absorbers for both normal conducting and superconducting RF structures, e.g. as loads in cavity waveguides and beam tubes either at room or cryogenic temperatures and, depending on cooling measures, low to high operational power levels.

INTRODUCTION

The suppression of beam induced HOMs is of utmost importance in modern accelerator facilities, particularly electron machines destined for high peak and/or average beam currents such as synchrotron storage rings, Free Electron Lasers and Energy Recovery Linacs. Even for CEBAF's recirculator operating at rather low peak (tens of pC) and thus average beam currents (<1mA), HOM suppression is still an issue, as evidenced by a multipass, multibunch beam break-up (BBU) instability observed in 2007 in a deformed upgrade-type cavity using two DESY-type HOM couplers [3]. The original CEBAF 5-cell SRF cavities (figure 1), of which 338 are operating in total (including the injector), are in fact more efficient than upgrade-type cavities with regard to HOM damping, though much lower accelerating gradients can be sustained. At CEBAF's design stage, absorbers at cryogenic temperature were favored since the extracted HOM power was estimated to be only a few milliwatts. This allows placing the absorbers at 2 K. Therefore each cavity employs two waveguide dampers bathed in liquid Helium. The fundamental power coupler (FPC) by design is functioning as a third waveguide damper. For each FPC waveguide, cryomodule external HOM filters are utilized for power dissipation. At the same time, each filter provides attenuation of parasitic klystron harmonics to intercept the associated power reaching the cryogenic environment.

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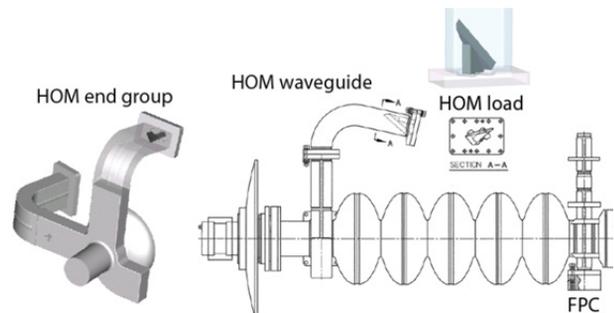


Figure 1: 1497 MHz original CEBAF five-cell cavity design (right) with the HOM absorber layout shown at the top. The HOM end group is illustrated separately (left).

The beam requirements resulted in a return loss specification of ~ 10 dB for the HOM loads in a frequency range of 1.9-10 GHz. In fact, it yields a large safety margin to potential transverse BBU instabilities up to at least 14 mA, i.e. far beyond CEBAF's operating currents [4]. The original load development was conducted in the early 1990s at JLab in an R&D effort with Ceradyne, Inc. [5], specifically optimized for CEBAF in being compact and UHV compatible with the absorber material providing a sufficiently high and broadband loss tangent ($\tan \delta > 0.1$) at 2K from 1-6 GHz [6]. The achieved return loss does not vary with temperature within 1.5 - 300K in this frequency regime [7]. The absorber material is Aluminum Nitride (AlN) sintered with 7% glassy carbon (AlN/GC) as the lossy ingredient. This material is no longer produced at Ceradyne for JLab. Instead, a substitute named Ceralloy 137 CA is available, but is less effective in damping than the original material within the critical HOM frequency range [1]. We therefore have tried to find a better substitute material, enforced by a shortage of HOM loads that became apparent during the refurbishment of ten original cryomodules in recent years [8]. During this initiative, cavities have undergone up-to-date chemical SRF surface treatments to boost accelerating fields from 5 MV/m (at the time of installation) to an average usable field of 12.5 MV/m. These activities required disassembly of waveguides and HOM loads. Hereby a significant amount of HOM ceramic wedges were found damaged and/or with broken braze joints. The HOM loads could only be repaired laboriously at the time, as substitute absorbers were not available in sufficient quantity.

RESULTS

In search for substitute materials, several ceramics comprising Silicon Carbides (SiC) and AlN composites were tested. All tests were performed at low power using a Vector Network Analyzer. The wedge-shaped absorbers were placed in evacuated CEBAF HOM waveguides (1.5"×3.11") immersed in a Helium bath, while recording the reflection response as a function of temperature during cool-down and/or warm-up. The measurement setup and technique have been detailed in [1]. It covers the frequency of 1.9-2.8 GHz, i.e. the regime of trapped TE₁₁₁- and TM₁₁₀-like cavity dipole modes.

For a consistent comparison of measurement data, the different composites were manufactured to similar dimensions (L/H/W = 6.3"/1.32"/0.71"). Two wedges were used to form an absorber (see Fig.2). The only exception were pre-existing wedges made from CoorsTek material [9] (L/H/W = 6.0"/1.0"/1.58") with only a single wedge fitting into the waveguide.

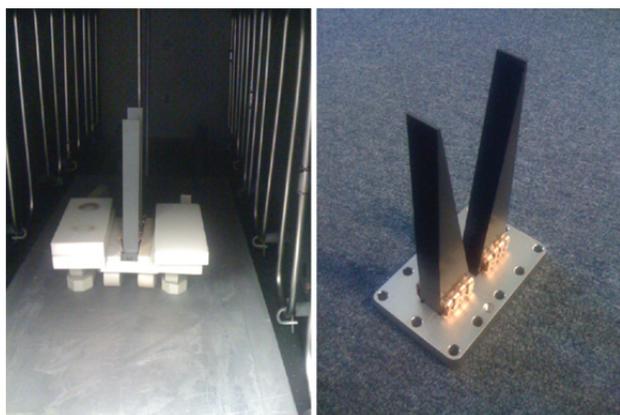


Figure 2: Ceramic loads in vacuum brazing furnace (left) and after brazing (right) to stainless steel flange.

To join the ceramic absorbers to stainless steel flanges (SS 316L), several brazing methods have been investigated with the aim to avoid cracking of the joints during thermal cycling. One successful method utilizes flexible copper fingers brazed to the broad walls of the wedges to hold the ceramics in place while compensating tensile stresses. The fingers are part of a single bracket made from copper sheet (0.015" thick), which is brazed beforehand to the SS flange using 50/50% CuAu foil (0.003" thick). Utilizing this brazing technique, no absorber cracked during routine cold-shock cycling in LN₂ or during the cool-down to 2K and the subsequent warm-up.

The summary of measurement results is plotted in Fig. 3 showing the reflection response over frequency recorded at room temperature (top) and 2 K (bottom), respectively. In addition to the material presented in [1], commercially available materials from CoorsTek [9] have been investigated, which includes the direct sintered SiC composite SC-DS (SC-30) and the graphite-loaded sintered SiC composite SC-DSG (SC-35) as well as several new composites from Sienna Technologies, Inc.

(STL) [10]. Notable materials containing SiC are CoorsTek SC-30, CoorsTek SC-35 and STL-100 HP-179. All have shown excellent performance at room temperature with favorable lossy properties. However, having SiC as the lossy element alone (no carbon loading) is not suitable for RF absorption at cryogenic temperatures since it becomes gradually less effective below ~110 K, as evidenced by SC-30 and HP-179 in Fig. 3 (bottom). This behavior is attributed to the carrier freeze out in the semiconducting SiC component, which is responsible for the loss through conduction.

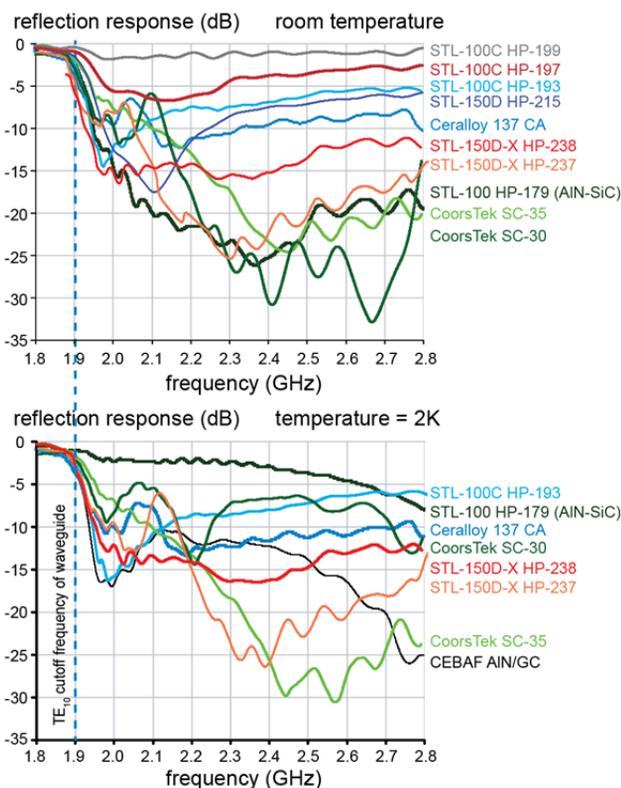


Figure 3: Reflection response over frequency for different ceramic absorbers recorded at room temperature (top) and 2 K (bottom) (color coded).

Surprisingly, CoorsTek SC-35 was identified to possess a temperature-independent loss characteristic that can only be attributed to the graphite loading. The vacuum out-gassing rate of the SC-35 was measured after bake out and 60 hours of pumping to be 10⁻⁹ Torr•l/(s•cm²) and still declining logarithmically with time. This is about an order of magnitude higher out-gassing than typical ceramics, but may be acceptable after sufficient pumping and cool-down. Following the waveguide tests, small samples of SC-35 were machined and used for measurement of the complex permeability and permittivity [11]. When the measurements were fed back into a simulation code, there was good agreement with the experimental results in the lower frequency regime [2]. The material may be a valuable candidate as a beam tube absorber at lower temperatures showing sufficiently high DC conductivity

[11], i.e. avoiding charging of the ceramic induced by the traversing electron bunches.

We like to emphasize that, besides finding a proper material substitute for AlN/GC, a simplification of the original rather complex CEBAF wedge design and brazing concept was envisaged at the same time. Note that the original CEBAF absorber length is only $\sim 2.8''$, and the load can be placed behind a waveguide bend in a short waveguide section (see Fig.1). The drawback with CoorsTek SC-35 for CEBAF's application is a high relative permittivity at lower frequencies, as listed in Table 1. The length of the absorber cannot be simply reduced without a major impedance mismatch, thus presenting an issue with respect to the given space constraint.

Table 1: Material properties of lossy dielectric for HOM absorbers (ρ = density, CTE = coefficient of thermal expansion, κ = thermal conductivity, ϵ_r = relative permittivity, $\tan \delta$ = loss tangent, σ = flexural strength).

Parameter	ρ	CTE (25-800°C)	κ	ϵ_r	$\tan \delta$	σ
Unit	g/cm ³	10 ⁻⁶ /°C	W/m•K			MPa
CEBAF AlN/GC [7]	3.0	4.7	55	20	> 0.1	300
Ceralloy 137 CA [5]	2.99	5.0	85	28 ^a 18 ^b 11 ^c	0.2 ^a 0.2 ^b 0.2 ^c	-
CoorsTek SC DS (SC-30) [9][11]	3.15	4.4	150	14 ^a 11 ^b 11 ^c 12 ^d	0.46 ^a 0.18 ^b 0.18 ^c 0.15 ^d	480
CoorsTek SC- DSG (SC-35) [9][11]	2.8	4.4	125	70 ^a 37 ^b 36 ^c 33 ^d	0.71 ^a 0.58 ^b 0.57 ^c 0.57 ^d	220
Sienna STL- 100 AlN-SiC	3.26	5.1	115	38 ^b 36 ^c 33 ^d	0.27 ^b 0.33 ^c 0.36 ^d	590
Sienna STL- 150D-X doped AlN	3.21	5.1	130	26 ^b 26 ^c 25 ^d	0.69 ^b 0.54 ^c 0.53 ^d	350

a = at 1 GHz, b = at 8 GHz, c = at 10 GHz, d = at 12 GHz

It should be mentioned that industrial applications of CoorsTek SC-35 material do not include the use as microwave absorber. Further development to tailor the product for RF needs is unlikely for low quantity markets. Sienna Technologies, on the other hand, has offered their support to design a more suitable material for CEBAF. The company has specialization for AlN-composites from prototype development to production quantities. Both Ceradyne and Sienna Technologies have introduced a family of AlN-based lossy dielectrics, including the AlN-SiC composites, as drop-in replacements for BeO-SiC composites for HOM absorbers in microwave tubes.

Initially, Sienna Technologies delivered a series of AlN-composites (STL-100) including HP-199, HP-197, HP-193 and HP-215 to JLab, all of which performed inferior to HP-179 at room temperature. Further cryogenic tests were therefore abandoned with the exception of HP-193. Though less attractive than Ceralloy 137 CA, HP-193 maintained its lossy characteristic down to 2K. Based

on this encouraging result, a new series (STL-150D-X) was produced subsequently, including HP-237 and HP-238 (orange and red curves in Fig. 3) using a special conductive nanomaterial additive rather than SiC particles. Both materials revealed a superior performance to Ceralloy 137 CA, surpassing the envisaged goal of 10dB return loss, with the exception of HP-237 in a narrow spectral band peaking at ~ 2.1 GHz. Both materials also exhibit an improved performance compared to CABAF's AlN/GC within 2.2-2.5GHz, for HP-237 with typically more than 10dB better damping performance.

Table 1 comprises important material properties of the various composites investigated. The properties for STL materials were measured by Sienna. It reveals that STL 150D-X is well suited for a compact load with a relatively high thermal conductivity (130 W/m•K). The RF parameters should be regarded as those measured at room temperature, although several similar materials maintained their lossy properties down to 2 K in the investigated frequency regime, as detailed above.

CONCLUSION

Sienna Technologies has developed a new doped-AlN lossy dielectric that uses a special conductive nanomaterial additive to achieve the necessary loss characteristics, rather than SiC particles or glassy carbon materials. This special nanomaterial conductor is not subject to carrier freeze out at cryogenic temperatures as investigated at JLab. With the use of these nanomaterials at low particle concentrations in STL-150D-X, the necessary losses tailored for the application in CEBAF have been achieved satisfactorily, while maintaining a comparably high thermal conductivity and flexural strength. Moreover, the relative permittivity is rather low, allowing good impedance matching in a compact waveguide load design.

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This paper is dedicated to our good friend and co-author Thomas Elliot, who has left us ultimately. His exciting spirit will be missed, but shall always be remembered.

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