# INVESTIGATIONS ON ABSORBER MATERIALS AT CRYOGENIC TEMPERATURES*

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*Abstract*

In the framework of the 12 GeV upgrade project for the Continuous Electron Beam Accelerator Facility (CEBAF), improvements are being made to refurbish cryomodules housing Thomas Jefferson National Accelerator Facility's (JLab) original 5-cell cavities. Recently we have started to look into a possible simplification of the existing Higher Order Mode (HOM) absorber design combined with the aim to find alternative material candidates. The absorbers are implemented in two HOM-waveguides immersed in the helium bath and operated at 2 K temperature. We have built a cryogenic setup to perform measurements on sample load materials to investigate their lossy characteristics and variations from room temperature down to 2 K. Initial results are presented in this paper.


## INTRODUCTION

In April 2009 groundbreaking of the 12 GeV CEBAF upgrade project has been celebrated. The project aims to double the beam energy from 6 GeV to 12 GeV using 1497 MHz superconducting RF linac technology at 2K operating in CW-mode. To achieve the desired energy gain of 1.1 GeV per linac, old style five-cell cavities are presently refurbished aiming for an average usable accelerating field of 12.5 MV/m ("C50") [1]. This is a major improvement when compared to 5 MV/m at the time of installation thanks to advanced surface treatments available today. Furthermore, ten new cryomodules with upgrade style seven-cell cavities ("C100") will be produced targeting 19.2 MV/m in average [2]. The suppression of beam induced HOMs is of utmost importance for CEBAF to prevent potential multipass, multibunch beam break-up (BBU) instabilities [3]. HOM surveys carried out for the first C100 cavity pair installed in a cryomodule indicate, that impedance requirements can be met to support stable operational conditions either at 12 GeV or at desired lower pass, lower beam energies [4]. The C100 cavities utilize DESY-type coaxial HOM-couplers to extract the HOM energy to standard room temperature 50 Ω loads. On the other hand, the original CEBAF cavities dissipate the HOM energy intrinsically at 2 K. At CEBAF's design stage, absorbers at cryogenic temperature were favored since the extracted HOM power was estimated to only a few Milliwatts. Therefore comparably complex warm-to-cold transitions have been avoided beneficially also to minimize the static heat load. The HOM absorption is provided by lossy ceramics placed at the end of two bent waveguides - fully immersed in the helium bath - located on the opposing side from the fundamental power coupler (FPC) as shown in Figure 1. The rectangular waveguides (1.5"×3.11") have a $TE_{10}$ cutoff frequency of 1.9 GHz. It provides both a natural rejection of the fundamental mode and the broadband capture of parasitic modes including those at the lower frequency end.

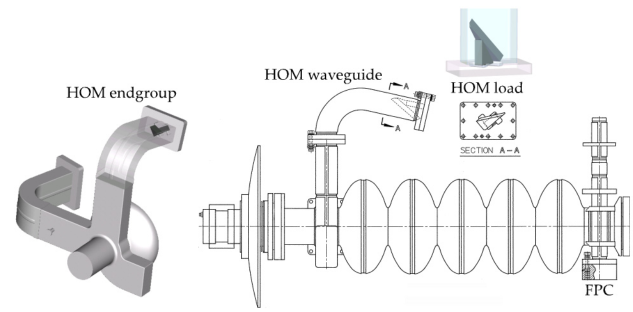


Figure 1: 1497 MHz original CEBAF five-cell cavity design (right) with the HOM absorber layout shown at the top. The HOM endgroup is illustrated separately (left).

## ABSORBER REQUIREMENTS

The absorber material currently in use has been optimized in the early 1990s to meet broadband damping requirements to stably operate CEBAF at nominally 200 µA beam current and 4 GeV energy after five recirculating passes [5]. The beam requirements resulted in a return loss specification of 10 dB for the absorbers, which takes into account an HOM frequency range of 1.9-10 GHz and even beyond [6] with the benefit of additional RF losses provided by stainless steel end flanges employed [7]. Fortunately at the time, due to lack of operational experience with a recirculating machine, the specification has taken into account a large safety margin to prevent potential transverse BBU instabilities up to at least 14 mA [8]. This keeps the specification valid for the 12 GeV upgrade requirements.

The R&D efforts on materials carried out at Jefferson Laboratory led to a patented ceramic absorber design [9], specifically optimized for CEBAF in being compact, UHV compatible and providing a sufficiently high and broadband loss tangent tan $\delta > 0.1$ at 2K from 1-6 GHz. The return loss is even independent of temperature between 1.5 - 300K in this frequency regime [5]. The material is a hot-pressed glassy carbon loaded AlN ceramic composite. In the frame of the refurbishment program, we recently checked the RF performance of 16 absorbers by means of the reflection response measured at room temperature. Seven of them exhibited partially broken joints and needed to be rebrazed. Figure 2 shows

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measurement results of five representative absorbers to illustrate typical data variability. Results principally agree with original experimental data presented in ref. [6], which exhibit no significant alterations with temperature down to 2 K.

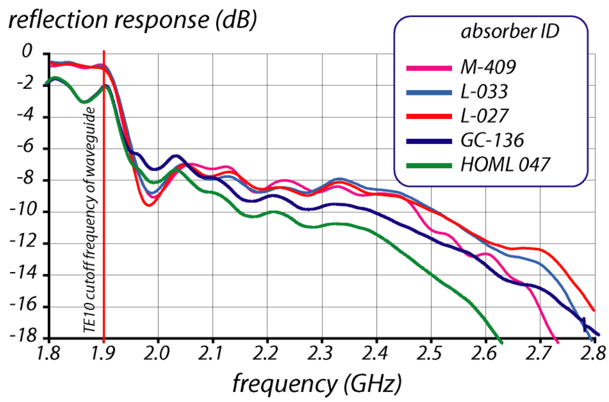


Figure 2: Reflection response of various CEBAF absorbers (glassy carbon AlN ceramic) measured at room temperature. The performance does usually not deteriorate after cool-down to 2K (comp. Figure 4.)

Originally, 676 absorbers were manufactured for 338 cavities by an industrial vendor [10]. However, the material is not produced anymore. Thus, we have started to test different new materials as potential alternatives.

## MEASUREMENT SETUP/TECHNIQUE

We have recently finalized a cryogenic setup for the RF characterization of absorbing materials in a vertical Dewar (Figure 3, left). Two materials can be tested in parallel each located in a separate straight rectangular waveguide of same size equaling the cross-section of C50 HOM waveguides. The waveguides - made of Cu-plated aluminum - by intention are comparably long (>1m meter). Each waveguide uses a 50 µm Kapton RF vacuum window placed outside the Dewar, thin enough to minimize spurious reflection responses. The Kapton's rather high permeability leads to vacuum pressures in the $10^{-5}$ mbar range. This is accepted since UHV is not required for the purpose of these tests. On the air side, tapered Cu waveguides (0.66m long) are attached, which end in a waveguide cross-section of 2.15”×4.3”. Hence, standard WR430 N-type coaxial-to-waveguide adapters can be attached. These are best suited for our investigations as they are specified for a spectral range of 1.7-2.6 GHz ($S_{11} \leq$ -20dB). This covers the HOM waveguide cutoff at the lower frequency end and exceeds the first $TE_{11}$ beam tube cutoff of C50 cavities (2.51 GHz) at the higher frequency end. Therefore the frequency regime of interest comprising $TE_{111}$- and $TM_{110}$-like cavity dipole modes trapped below the cutoff is included. Measurements have been carried out with a Vector Network Analyzer (VNA) at low power. To minimize measurement errors, it is obligatory to calibrate the external RF cables. More severely however is the unavoidable disturbance caused by the band-limited WR430 adapter. Instead of using a rather tedious TRL-calibration for this device, we have applied the powerful time domain gating option available for VNAs (e.g. [11]). It mathematically resembles TDR measurements by applying the Bluestein's Transform algorithm (also dubbed Chirp-Z Transform algorithm). The benefit of displaying data in time domain is to identify different RF components within the setup as their location is related to the time/distance with respect to the measuring port. By setting a time gate one can selectively gate out unwanted signals. The time resolution is limited by the upper frequency range of the VNA. Therefore comparably long waveguide sections are advantageous to clearly identify and gate out those signals arising from the WR430 adapter. A Fourier Transform of these manipulated data back to frequency domain eventually delivers the desired RF performance of the absorber. The time domain option is usually rather expensive (several k$). We therefore have recreated the standard mathematics to utilize the method offline with any available VNA by merely exporting the raw frequency data [12].

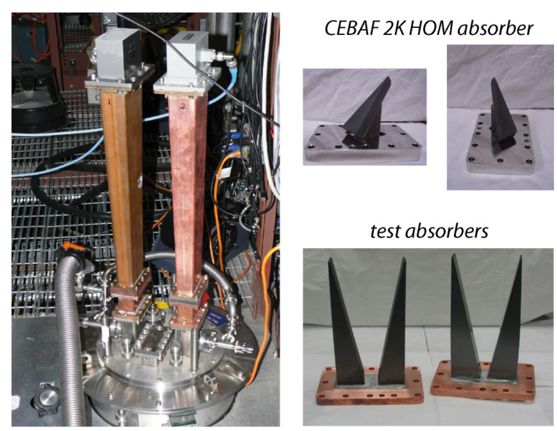


Figure 3: Test setup in the vertical Dewar (left), CEBAF absorber (top right) and two different wedge absorber assemblies (bottom right) made of ceramic AlN-based composites.

## RESULTS

Typically, most existing lossy ceramics lose their ability to absorb RF energy below ~20 K. So far we could only test two materials, i.e. Ceralloy 137 CA manufactured by Ceradyne Inc. (patent pending [10]) and STL-100 from Sienna Technologies, Inc. [13]. These materials were favored as they are lossy AlN-based composites like the C50 absorbers. The exact material composition is unknown to us. Ceradyne, Inc. specifies Ceralloy 137 CA with a constant loss tangent tan $\delta$ = 0.2 independent on temperature down to 3 K with relative dielectric constants $\varepsilon_r$ = 28 at 1 GHz and $\varepsilon_r$ = 18 at 8 GHz and 10 GHz respectively. Based on these material properties, we designed a preliminary wedge shaped absorber by 3D numerical simulations using CST Microwave Studio (MWS) [14]. The overall wedge length was fixed at 160 mm. This is rather long compared to C50 absorbers (70 mm). The intention was to provide improved measurement accuracy for extracting material properties to subsequently optimize the absorber layout. For the experiments presented here, two wedge shaped loads have been joined to a Cu flange to build the absorber as shown in Figure 3 right. In Figure 4 the corresponding reflection responses for both Ceralloy 137 CA and STL-100 are plotted as measured at room temperature and at 2 K. The result achieved for a CEBAF absorber at 2 K (same setup) is shown for comparison.

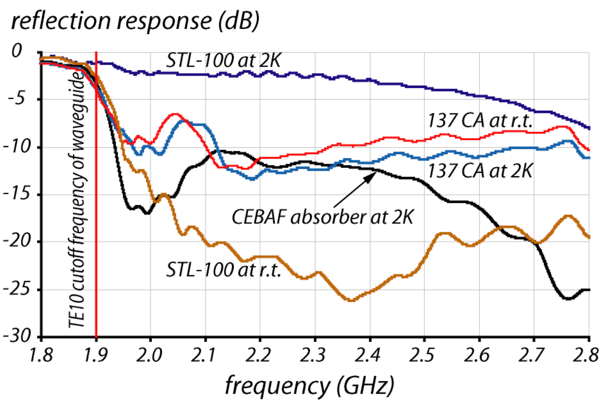


Figure 4: Reflection response of different AlN-based composites measured at room temperature (r.t.) and 2 K.

The STL-100 absorber performed well at room temperature, but gradually lost its absorption ability starting around 110 K and settling in a comparably bad reflection response below 20 K. For the Ceralloy 137 CA we found an almost temperature-independent loss mechanism providing about 10 dB return loss over the whole frequency range. An even slightly improved performance compared to room temperature is visible at 2 K. Yet the C50 absorber material outperforms Ceralloy 137 CA almost over the full frequency range, even though the design is much more compact.

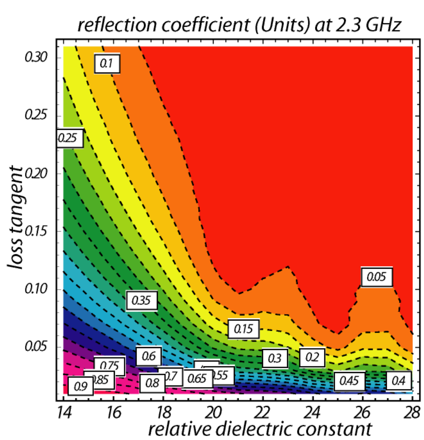


Figure 5: Reflection coefficient simulated with MWS by varying $\varepsilon_r$ and tan $\delta$ at 2.3 GHz. Absorber model used is as built for the Ceralloy 137 CA material.

With the given experimental data we estimated the complex material properties of Ceralloy 137 CA by performing an S-Parameter scan using MWS varying both $\varepsilon_r$ and tan $\delta$. Within 1.9-2.8 GHz the material properties have been exactly defined at discrete frequencies - spaced by 0.1 GHz- to avoid averaging effects from broadband material models (e.g. Debye functions). An example of such a scan is shown in Figure 5 for 2.3 GHz. With a known $\varepsilon_r$, the tan $\delta$ can be extracted from the measured reflection response. Preliminary analysis indicates that the tan $\delta$ is in the range of 0.05 rather than 0.2 as specified by the vendor. With such rather low loss performance, a more compact absorber design - considering both the required return loss and space constraints - might not be possible. We therefore look forward to alternative materials planned to be tested this year.

## SUMMARY

With the aim to find alternative absorber materials for CEBAF HOM loads operating at 2 K, we have started to measure RF properties of potential candidates in a vertical Dewar. So far we have tested lossy AlN-based ceramic composites, i.e. Ceralloy 137 CA form Ceradyne, Inc. and STL-100 from Sienna Technologies, Inc. Two similar wedges of each material were used to build a yet non-optimized absorber for material analysis. Whereas STL-100 loses its main loss capabilities below 20 K, the absorbing properties for Ceralloy 137 CA did not alter significantly upon cool-down. However, preliminary analysis indicate, that the loss tangent seems to be much lower than specified by the vendor. We are planning to test a couple of alternative materials within this year.

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## REFERENCES

[1] M. Drury et al., Proc. PAC07, WEPMS059.
[2] C. Reece at al., Workshop on SRF Superconductivity, Peking University, Beijing, China, 2007, WEP31.
[3] R. Kazimi et. al., Proc. EPAC08, Italy, WEPP087.
[4] F. Marhauser et al. these proceedings.
[5] I.E. Campisi et. al, Proc. of EPAC1992.
[6] I.E. Campisi et. al., Workshop on SRF Superconductivity", CEBAF, Newport News, 1993.
[7] I.E. Campisi et. al., "Proc. of PAC 1993.
[8] J.J. Bisognano, TN-0147, Newport News, July 1989.
[9] I.E. Campisi, U.S. Patent No. 07/522,131.
[10] www.ceradyne.com.
[11] Agilent Technologies, Application Note 1287-12.
[12] F. Marhauser, "De-embedding of RF Devices using Vector Network Analyzers without Time Domain Option", to be published.
[13] www.siennatech.com.
[14] www.cst.com.