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I. E. Campisi, K. E. Finger, L. K. Summers and A. M. Johnson
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606

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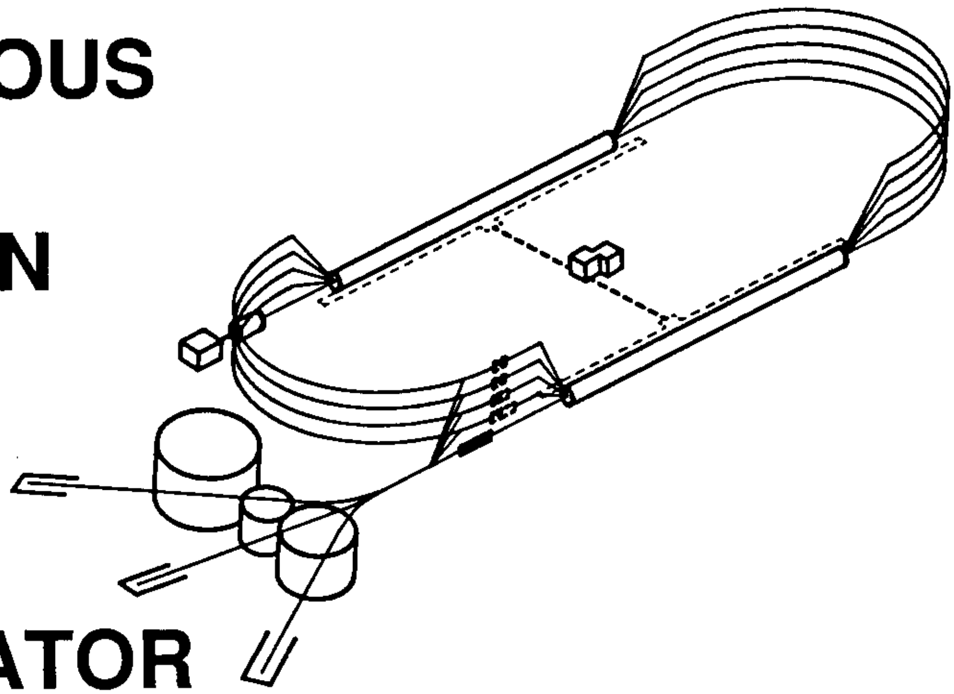

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1. INTRODUCTION

A special ceramic material for microwave absorption at low temperature has been developed at CEBAF to manufacture the 676 Higher-Order-Mode (HOM) loads for the machine. The accelerator includes 338 5-cell niobium cavities, resonating in the fundamental TM_{010} π mode at 1497 MHz, in two antiparallel linacs (160 cavities each) and an injector (18 cavities). Higher-Order-Mode (HOM) power generation in the machine is expected to be in the tens of milliwatts per cavity at the nominal beam current of 200μA. This amount of power constitutes a small fraction of the power dissipated by the superconducting cavities at the operating gradient of 5 MV/m (typically less than 5 W per cavity) and the HOM power is more efficiently absorbed at the bath temperature of 2K than at room temperature. The HOM extraction is done via two S-band waveguides located orthogonally to each other at one end of the cavities and a load is placed at the end of each waveguide. This HOM damping scheme is characteristic of CEBAF alone: the low operating temperature and the vacuum in common with the superconducting cavities prevent the use of standard absorbers. Totally new materials and a novel absorber shape [Figure 1] were developed for this application.

2. DESIGN CONSTRAINTS

2.1. *HOM RF Specifications for BBU Control*

Although CEBAF will operate at the design current of 200 μA, the threshold current for transverse beam-breakup (BBU) instability should not occur up to at least 14 mA [1,2,3]. The safety factor compensates for the little experience in operating multiple-recirculation superconducting machines, which could have HOMs with Q's as high as 10^9-10^{10} if not properly damped. The return losses for each of the coupling ports (HOM and fundamental power coupler [FPC]) have been specified based on that threshold current of 14 mA. Because the cutoff frequency of the HOM waveguide is 1900 MHz, some modes of the TE_{111} passband can only be damped through the FPC, which is outfitted with a WR-650, room temperature waveguide filter. The fundamental mode is below the cutoff of the HOM waveguide and its attenuation is 212 dB/m. Above 1900 MHz the HOM waveguide TE_{10} mode starts to propagate and at higher frequencies (3800 MHz and up) other waveguide modes (TE_{01}, TE_{20}, TM_{11}, etc.) contribute to the extraction of HOM power from the cavity. The HOM absorbers must provide adequate absorption from 1900 MHz up to, in principle, 400 GHz, the maximum frequency for which the CEBAF bunch has Fourier components. Because the CEBAF HOM spectrum can extend to such high frequencies, most of the HOMs will propagate as waveguide modes other than the TE_{10}, thus the HOM loads must be capable of absorbing many waveguide modes simultaneously. The loads should provide return losses of 10 dB or more at any frequency and for any waveguide mode.

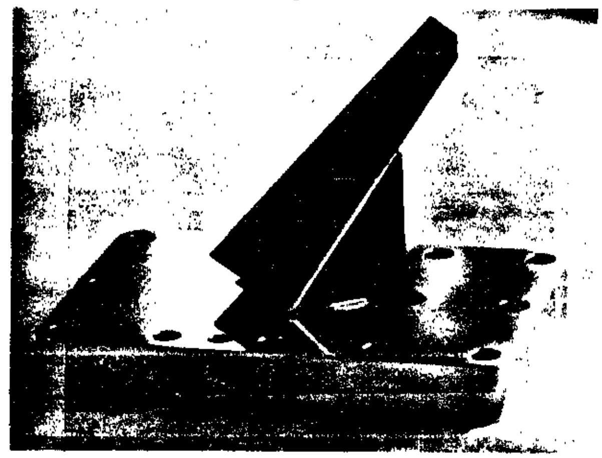

Figure 1. HOM load for CEBAF. The load protrudes by about 7 cm into the HOM waveguide.

2.2 *Cryogenic Requirements*

Because the CEBAF HOM loads are in contact with the 2 K environment, their absorption should be temperature independent; the material must retain good thermal conductivity at low temperature and be thermally anchored to the helium bath to avoid overheating and infrared emission from the load. The material's differential thermal contraction must be taken into account in the load's design.

2.3 *Vacuum Requirements*

Very tight vacuum requirements are imposed on the HOM loads' material: the loads share the same vacuum of the superconducting cavity at a level of 10^{-10} torr or lower. The load material must not produce any particulate and it cannot have open porosity, which could trap contaminants, later adsorbed onto the cavity surface. The desorption rate from the loads must be lower than the allowed leak rate from cavity joints, a limit which is placed at around 10^{-10} atm cc/sec.

2.4 *Geometric and Mechanical Constraints*

Since the loads are located within the cryostat, limited space is available and they must be compact and mechanically stable to avoid the excitation of microphonic vibrations. The load material must be braseable to ensure thermal contact to the bath and strong mechanical construction.

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3. DESIGN SOLUTIONS

3.1 Options Investigated

Various options were considered and some of them investigated in the development of the HOM loads for CEBAF:

The use of a separating window between the load and the cavity vacuum was deemed too complicated and prone to vacuum failures. Also, a window with low VSWR over a very broad frequency range and for a multitude of waveguide modes is difficult to achieve.

Nichrome films of various, temperature independent, surface resistance deposited onto alumina substrate cards were also considered. This solution works well for a single mode in a waveguide over a narrow band, but it is not effective for modes with electric field orthogonal to the plane of the film and even a careful placement of the card in the waveguide and a proper choice of angles may not provide adequate absorption.

As an extension of the card concept, catalytic converter substrates were tested: many planes are available perpendicular to each other with proper projection of the electric field components for many waveguide modes. The problem of depositing the resistive film in the narrow channels was overcome, but the manufacturing steps were complicated and cumbersome. Finally, the large surface area of the honeycomb ceramics, incompatible with the ultra-high vacuum requirements, and the poor thermal conduction to the bath led us to reject this solution.

3.2 Lossy Ceramic Dielectrics

Lossy dielectrics in a ceramic form were then considered, for their excellent thermal, vacuum and structural properties. Initially, ceramics loaded with silicon carbide were used, but it was later discovered that their low temperature properties were sensitive to small deviations from the standard manufacturing processes, and this material was abandoned. A thorough evaluation of the ceramics market revealed that no material existed which satisfied all of the requirements described above, and new materials had to be developed for this application. The basic loss mechanisms in solids were investigated to design the absorbing material.

4. RF LOSSES

4.1 Loss Mechanisms in Solids

In solids, energy conversion from a propagating electromagnetic wave into heat can occur through two basic mechanisms[4]: direct photon to phonon conversion in insulators, or through the intermediate scattering of a charged particle in conductors, usually an electron in a solid's conduction band.

Direct photon to phonon conversion occurs in insulating dielectrics: the electromagnetic wave polarizes the material which then relaxes by dissipating some of the incoming energy into the available normal modes of the lattice. Because the losses rely on the existence of those modes, they are usually strongly temperature dependent, since the available degrees of freedom for conversion decrease at the lower temperatures.

Conducting and semiconducting materials rely instead on the presence of electrons in the conduction band to transfer the energy from the electromagnetic wave to the crystal lattice. In powders or in highly amorphous materials, scattering can be dominated by grain boundary scattering and the losses are due to hopping conductivity across the grain boundaries. The latter mechanism is temperature dependent. If the mean free path (MFP) of an electron is commensurable with, or larger than the grain size of a material, then the losses will be temperature independent. Similar behavior will be observed in the dirty limit, in which the MFP is very short. Intermediate cases will exhibit, at worst, an anomalous skin effect behavior, which is only mildly temperature dependent.

4.2 Artificial Dielectrics

Among the materials which rely on electron-phonon scattering to effect electromagnetic losses, are the artificial dielectrics. These materials consist of a dielectric insulating medium in which conducting particles are distributed with various densities [5,6]. Four parameters can be varied in these materials in order to obtain a well defined complex permittivity: 1) the intrinsic permittivity of the dielectric material (usually with a small loss tangent); 2) the size and size distribution of the conductive grains; 3) their resistivity and 4) their volume concentration. For volume concentrations at or below about 15%, the minority conductive grains have, on the average, no contact with each other, so that no thermally dependent loss mechanism is activated. This property makes these materials ideal for low temperature applications, since they can be tested at room temperature and then used at the lower temperature with minimal testing. In the 15% concentration regime, each grain dissipates independently, with electric and magnetic dipole radiation coupling from one grain to another [7]. Between 15% and about 45%, the conductive grains aggregate to form clusters for which a fraction of the losses are due to hopping conductivity and are therefore temperature dependent. Above about 45% concentration, percolation sets in, with the possibility of DC current transport and with bulk screening of currents by the the material. In general, increasing concentrations lead to increased permittivity [6]. The size of the grains and their conductivity can be chosen such that the maximum losses occur when the skin depth is equal to the diameter of the grains [6]. In this regime ($\delta=2r$ δ is the skin depth, r is the grain radius) the number of electrons per unit volume which participate in the loss process is maximized. The absorption bandwidth can be increased by widening the grain size distribution. Thus, materials can be designed with maximum absorption for each specific application.

4.3 Ceramic Artificial Dielectrics

For typical microwave frequencies (1-10 GHz) and for commonly found resistivities (10-100 μOhm cm), the optimum grain sizes are of the order of 1-10 μm, a size suitable for ceramic sintering. In practice, the resistivity of individual grains is a poorly known quantity. Moreover, when sintered at high temperature in a ceramic form, the conducting grains are subject to recrystallization and/or impurity diffusion and their resistivity can change in opposite directions. A choice of conductive powders is thus impossible on the basis of the published bulk resistivities, and their selection is made by requiring that they do not melt nor react chemically at the sintering temperature (over 2000 C in the case of AlN).

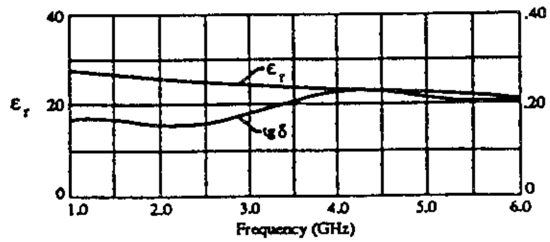

Figure 2. Dielectric permittivity and loss tangent of the AlN-glassy carbon ceramic.

5. THE CEBAF LOADS

At CEBAF mixtures of AlN and various metals and alloys were tested [8]. Metals such as W, Mo and their alloys, and carbides such as TiC, WC were sintered in various concentrations. For the production of loads for the accelerator a glassy carbon powder was chosen, with a volume concentration near 15% and with diameters distributed between 3 and 12 μm. The material was extensively tested and found to have the necessary dielectric permittivity [Figure 2] to give sufficient absorption for various modes with the shape shown in Figure 1 [9]. This shape also allows simple manufacturing and assembly steps. The absorption of this material is independent of temperature between 2 and 300 K. The HOM loads dissipate by dielectric losses, thus the best matching to the waveguide modes occurs when the leading edge of the load is in a corner of the waveguide, where the electric field is zero for all modes. Around 1975 MHz, where the last member of the TE_{111} bandpass falls (the lowest cavity mode damped by the HOM loads), the loads adequately damp the modes to Q_{ext} in the 10^3 range, even though the load's length is less than 1/10 the guided wavelength. The RF properties of the loads have been tested in waveguide as well as in the cavities. The return losses have been measured between 2.1 and 18 GHz for several modes with a pulsed reflectometry method and between 1.9 and 2.6 GHz with a standard network analyser, and found to be well above specifications at all frequencies. Figure 3 shows the TM_{011} passband in the undamped and damped cases: the loads limit the external Q's to few 10^2 in the band around 2.9 GHz. Almost all observed bands are damped in the 10^3 range or better. The load material shows zero porosity and an upper limit to its outgassing rate has been set at 3×10^{-11} torr l/cm^2 s.

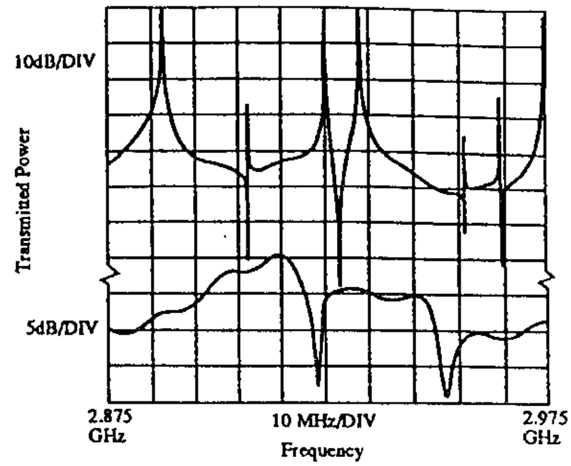

Figure 3. HOM spectra in the TM_{011} passband for a cavity without (above) and one with (below) HOM loads.

6. CONCLUSIONS

HOM loads have been developed at CEBAF using a ceramic material manufactured explicitly for this low temperature application and with a very compact and original geometric design [9]. This could also be used in a wide range of applications which require ultra-high vacuum and cryogenic operation, high power density, compact and light construction, good thermal conductivity and temperature independent absorption.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] J.J. Bisognano, CEBAF Note TN-0147, July 1989

[2] R.M. Sundelin, CEBAF Note TPN 91-013, Sept. 1991

[3] J.J. Bisognano, Private communication, Nov. 1991

[4] See, *e.g.*, J.M. Ziman, Electrons and Phonons, Oxford (1960), Ch. 9

[5] R.E. Collin, Field Theory of Guided Waves (2nd ed.), New York (1991), Ch. 12

[6] I.S. Jacobs, "Advanced Artificial Dielectric Materials for Millimeter Wavelength Applications," Report 90-SRD-001, GE CRD, Schenectady, 1990, and references therein

[7] N.E. Russell, J.C. Garland, and D.B. Tanner, "Absorption of Far-infared Radiation by Random Metal Particle Composites," Phys. Rev. vol. B23, pp. 632-639 Jan. 1981 and references therein

[8] Manufactured by Ceradyne, Inc., Costa Mesa, California

[9] I.E. Campisi, US Patent No. 07/522,131