

S-BAND LOAD DESIGN FOR SLAC*

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Abstract

S-Band vacuum loads at the SLAC linac are encountering operational problems, now that they have to operate under the stringent requirements of: 50 MW peak power, 6 kW average power, and extremely-tight phase stability for the linac. Failure mechanisms have been studied which suggest an RF surface breakdown of the 200 μm Kanthal layer in original RF loads.

Currently there are two approaches for RF load design. The first is based on employing highly resistive materials inside of WR284 waveguide [see SLAC-PUB-15229 or MOPB087 in LINAC12]. An alternative approach is based on using lossy dielectric. This is the approach discussed in this paper.

We have proposed a novel solution which incorporates mode conversion from TE₁₀ in rectangular waveguide to TE₀₁ in round waveguide. Lossy material will be placed in the round waveguide, and the selection of the TE₀₁ mode minimizes the electric field normal to the surface of the lossy material. This lossy material in the TE₀₁ round waveguide will be mechanically confined in compression (without brazing), in order to eliminate tensile stresses in the lossy material. The mode converter will be based upon an X-band mode converter invented at SLAC, and the TE₀₁ waveguide load design is based upon HOM load designs developed by Muons, Inc.

We are presently performing additional materials testing, in preparation for fabrication of a full power prototype load. A TE₁₀ to TE₀₁ SLAC converter design will be fabricated for both cold and hot testing.

Operational improvements to the SLAC LCLS linac may require the replacement of all SLAC linac vacuum RF loads. The new design can be scaled for use at other frequencies in a multitude of commercial RF applications.

INTRODUCTION

Recently at SLAC, the increasingly-stringent requirements for phase and amplitude stability of the linac beam have increased the sensitivity to the performance of the present load design. Ten of the current Kanthal loads were inspected, and all ten showed evidence of multipactor. Fifteen spare loads were tested and exhibited multipactor between 1 and 20 MW. An attempt to shift the multipactoring resonance using permanent magnets was not successful.

Dry loads are generally designed using high strength lossy ceramics due to the manufacturing processes used in the construction of such loads. The interface between the lossy ceramic and the support structure is brazed or soldered to make a thermally conductive path between the lossy ceramic, mechanical support, and the cooling

circuit. The fact that brazing or soldering is used requires the lossy ceramic to survive large tensile stresses due to the mismatch in thermal expansion between the ceramic and the mechanical support. Efforts to either reduce these thermal stresses, or survive these stresses during thermal cycling, has led to creating strengthened ceramics such as SiC_{whiskers} + Al₂O₃, or using thermally matched materials for the mechanical support such as W_{powder} + Cu in a sintered alloy. Both of these techniques have led to expensive structures due to low manufacturing yields. These low yields are typically due to large manufacturing variables, and narrow process limits, for successful fabrication of dry loads.

In our design, the dry load operates in the TE₀₁ mode to significantly reduce the chance of multipactor, and incorporates mode converters designed by SLAC. The lossy ceramic components are cast into cylinders, from slurries composed of mixtures of SiC and porcelain, and processed to full densification and vitrification. These lossy cylinders are held in mechanical compression rather than being brazed. The microwave characteristics of the lossy ceramic cylinders have been measured, and further measurements will be made to determine the optimum mixture for various loading elements.

TECHNICAL APPROACH

TE₀₁ Mode

The most reliable high peak power load will have no normal electric field components on the lossy material. This should simply eliminate the occurrence of multipactoring and arcing. Since the TE₀₁ mode is a low loss mode, the uniformity of loss within the lossy dielectric is not as critical as it would be if compared to operation using other modes. This fact serves to relax the manufacturing process limits, as compared to those which are required in loads utilizing other modes and designs, such as the TE₁₀ mode in rectangular waveguide utilizing lossy walls.

A SLAC designed TE₁₀ - TE₀₁ mode converter from WR284 rectangular waveguide to 6 inch round waveguide was used for the initial measurements (Figure 1). With two mode converters the insertion loss of lossy cylinders can be measured in the TE₀₁ circular mode. The wrap-around mode converter is primarily scaled from the X-band version that was invented by Sami Tantawi of SLAC [1]. The VSWR of these mode converters back-to-back was 1.13 at 2856 MHz, likely due to out-of-round circular waveguide and non-matching edges at the mating flanges. Some slight tuning on the endplates could improve that number to less than 1.11 at 2856 MHz.

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Figure 1: Two wrap-around mode converters for insertion loss measurements of lossy ceramic cylinders. S11 was measured to be less than -23.2 dB at the center frequency.

Novel Lossy Ceramic Cylinders

The lossy material chosen during the program was SiC_{powder} + porcelain. This lossy ceramic material is our new contribution to the design of high power microwave loads. It was chosen because of our system approach to the design and fabrication of a dry load. The fundamental concept that allows for its use is simply that high tensile strength lossy material is **not** a requirement of our design, as the ceramic material is held in compression.

The comparison of various mechanical properties of alumina and porcelain is shown in Table 1.

Table 1: Comparison of Porcelain and Alumina

	Porcelain	Alumina	
Flexural Strength	130(19)	380(55)	Mpa(ksi)
Tensile Strength	105(15)	170(25)	Mpa(ksi)
Compression	590(86)	2700(391)	Mpa(ksi)
Youngs Modulus	70	370	
Dielectric Strength	25	8.6	MV/m
Fracture Toughness	2	4.5	MPa-m ^{1/2}
Thermal Conductivity	5	30	W/m-K

From these values it is clear that porcelain is mechanically inferior to alumina, which explains to a large degree why porcelain has not been used as a lossy ceramic the way that alumina and aluminum nitride have been. This again points to the very important and critical aspect of our systems design approach to this load. *The lossy ceramic is held in compression. It is not brazed and the assembly technique never allows for tensile stress to build up within the material.*

Tests

A number of lossy porcelain ceramics were fabricated with varying amounts of SiC_{powder} incorporated.



Figure 2: Photo of a 6" diameter lossy cylinder.

Their loss was measured using the back-to-back converters configuration of Figure 1 and a Network Analyzer. Using an Agilent 85070E the dielectric constant was measured for similarly made porcelain test disks which incorporated various amounts of SiC_{powder}.

The test disk results indicated that with percentages of SiC_{powder} less than 30% by dry volume, the uniformity of the material was difficult to control. With greater than 30%, the standard deviation was 5-6% of the real part of the dielectric constant, and the standard deviation of the loss tangent was less than 25%. The case where 52% by dry volume of the SiC_{powder} was used produced a lossy ceramic with an average dielectric constant of 7.44-0.37i, yielding a loss tangent of 0.05 as measured by the Agilent probe method.

It should be noted that the Agilent probe is not recommended for materials with loss tangents less than .05, and for materials with ε_r' > 5 with loss tangents < 0.5[2]. Unfortunately these measured values are exactly in that range, so it is best to assume the error around these values is fairly large. Fortunately, it does suggest the material concentrations that will be best suited for the lossy ceramic cylinders, in terms of tolerances in the manufacturing process, are in the range of 30-50% SiC.

The test assembly of Figure 1 was also modeled on Comsol (Figure 3) to compare measured results with simulated results. Once the model agrees well with the measured results, we will be able to model the loss effects of varying material parameters thus allowing a complete multi-section load model to be simulated with varying amounts of loss per section.

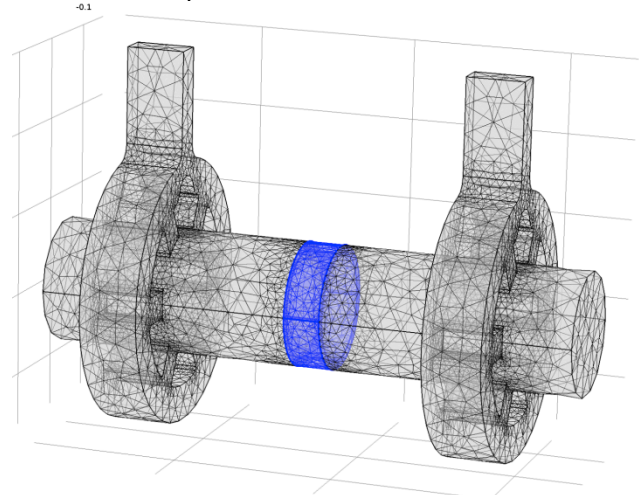


Figure 3: Comsol model of the back-to-back converters and a porcelain test cylinder.

The test cylinders were made by a slip casting process, ground on the outside diameter to 5.990 inches, and placed in the Figure 1 test fixture for S-parameter measurements. As expected, the results show a loss proportional to the percentage of SiC in the cylinder.

The measurements of each test cylinder are considered to be roughly the equivalent of what would comprise a single section of the load, the full load being approximately 10 such sections. Based upon our initial

measurements, Table 2 shows the approximate %SiC needed for the cylinder of each load section, in order to distribute the losses evenly along the length of the load.

Table 2: Typical Loss Requirements for Each Section of the Load and %SiC

Section #	Input	1	2	3	4	5	6	7	8	9	10
Watts	6000	5400	4800	4200	3600	3000	2400	1200	600	300	150
db	67.8	67.3	66.8	66.2	65.6	64.8	63.8	60.8	57.8	54.8	51.8
db/section		0.46	0.51	0.58	0.67	0.79	0.97	3.01	3.01	3.01	3.01
Reflected											51.8
Return Loss	-32.0	35.7	36.2	36.7	37.3	38.0	38.8	39.7	42.7	45.7	48.8
Loss (db/in)*		0.18	0.20	0.23	0.27	0.32	0.39	1.20	1.20	1.20	1.20
% SiC		25	26	28	29	31	32	43	43	43	43

*assuming 2.5 inch long cylinders .25 inches thick

RF Design

The final load design will consist of a number of “identical” (in appearance) sections, with each section designed to be self-matching. That is, for a cylinder length of $\lambda/4$ the reflection off the leading edge of the lossy ceramic cylinder is canceled by the reflection off the back edge of the cylinder.

For a cylinder with a dielectric constant of 8 and a loss tangent of 0.04, a 1.1:1 VSWR (26 dB return loss) is achieved over 50 MHz, and the sensitivity to length is ± 0.1 inch for a VSWR of less than 1.1:1.

We are currently exploring a manufacturing process that we feel will improve the mixing of the slip and casting of the cylinders, in order to produce a high degree of uniformity throughout the volume of the cylinder.

Mechanical Design

As shown in Table 2, the load is currently planned to be made up of 10 sections with a loss per section of about 600 watts to balance the heat load along the load length. Each section of the load will be constructed to be self-matching as described above, and in a compression assembly similar to what is shown in Figure 4.

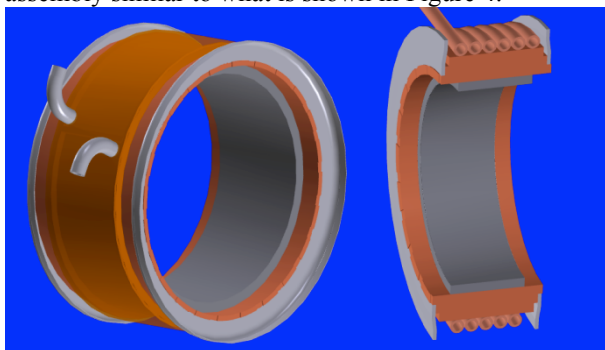


Figure 4: Cross section view of the lossy ceramic cylinder in the compression assembly and different cooling channel options for the prototype assembly.

The compression assembly is designed to be an interference fit at room and operating temperatures. Assembly is accomplished by flowing 100°C water through the cooling channel of the compression ring. The copper expands and easily slips over the lossy ceramic cylinder. This process has been successfully utilized by Muons, Inc. in a number of applications, from HOM load

construction techniques to braze assemblies for coaxial RF windows.

The exact details of the construction of the compression ring will be worked out during Phase II.

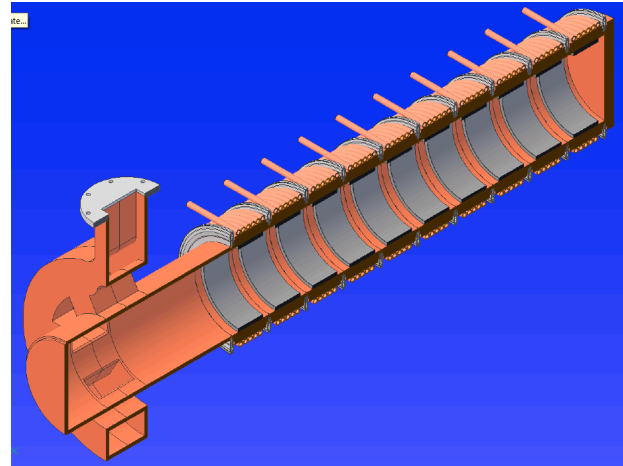


Figure 5: Final prototype configuration of the complete dry vacuum load.

Figure 6 shows ANSYS calculations of the cooling and anticipated operating temperature of the lossy ceramic. It shows that the conservative value of 600 watts of power dissipation raises the maximum temperature of the lossy ceramic by only 2 °C above the cooling water temperature. The reason for this low value is that the surface area of the 6” x 2.5” cylinder is quite large. Thus, we do not expect thermal issues to be significant in this load design.

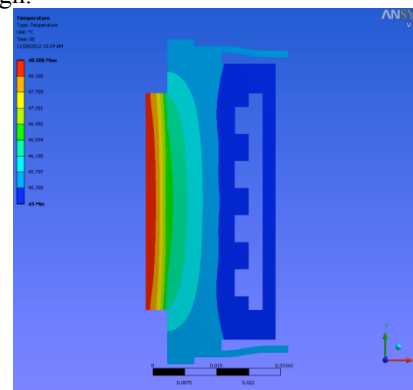


Figure 6: ANSYS results for a single section model.

ACKNOWLEDGEMENTS

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- [2] Agilent 85070E Dielectric Probe Kit 200 MHz to 50 GHz. Technical Overview. Published in USA, June 14, 2012 5989-0222EN.