HIGH TEMPERATURE RADIO FREQUENCY LOADS

S. Federmann, F. Caspers, A. Grudiev, E. Montesinos, I. Syratchev, CERN, Geneva, Switzerland

Abstract

In the context of energy saving and recovery requirements the design of reliable and robust RF power loads which permit a high outlet temperature and high pressure of the cooling water is desirable. Cooling water arriving at the outlet with more than 150 °C and high pressure has a higher value than water with 50 °C under low pressure. Conventional RF power loads containing dielectric and magnetic materials as well as sensitive ceramic windows usually do not permit going much higher than 90 °C. Here we present and discuss several design concepts for "metal only" RF high power loads. One concept is the application of magnetic steel corrugated waveguides near cutoff – this concept could find practical use above several GHz. Another solution are resonant structures made of steel to be installed in large waveguides for frequencies of 500 MHz or lower. Similar resonant structures above 100 MHz taking advantage of the rather high losses of normal steel may also be used in coaxial line geometries with large dimensions.

INTRODUCTION

Commonly used loads can be divided into two types:

- Loads that heat up water directly and
- absorbing materials on water cooled metallic surfaces.

Both methods face different problems such as the necessity of using more or less fragile (ceramic) windows when heating water directly, or the application of the ceramic layers onto the cooled surfaces via soldering, brazing, press-fitting or gluing for the latter case. The soldering or pressing process itself may be rather complex and critical, since the applied absorber materials are very small bits.

The absorbing material faces differential thermal expansion as well as problems with inhomogeneous heat generation and transfer.

In general RF high power loads are designed for an outlet water temperature of $< 80\,°C$ and a rather low pressure of a few bar. Reliable RF loads that are mechanically uncritical (no ceramics), usable at a high temperature ($\geq 200\,°C$) and able to sustain high pressure (up to 100 bar) are particularly interesting. Two types of structures will be discussed in this paper:

- traveling wave structure
- resonant structure

Traveling wave high power loads without ceramic or ferrite absorbing materials based on waveguide near cutoff operation for high frequencies have already been built and tested [1]. This paper will first present a summary of this technique and secondly present a new narrow-band resonant load usable in a frequency range of 500 MHz or lower.

TRAVELING WAVE STRUCTURES

Originally the X-band RF load built from magnetic (μ = 6) stainless steel (SS430) was designed to operate at high peak (> 50 MW) and average (> 5 kW) RF power. In itself the load concept is based on the classical approach of a regular waveguide operated close to its cut-off frequency. To maintain the required bandwidth (about 1 GHz in X-band) and reasonably short length, we have introduced a waveguide with special cross-section, see Fig. 1. In this

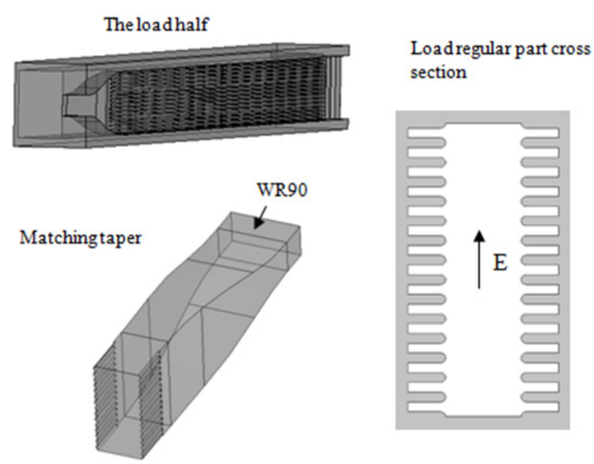

Figure 1: The general views of the load (top left), matching taper (bottom left) and load regular cross section (right).

system, when the central gap width is about half the waveguide width, the cut-off frequency is about 20% higher than that of a standard rectangular waveguide of the same width. This approach brought a number of benefits and allowed to reduce the electric and magnetic surface field concentration by increasing the waveguide width, while maintaining high enough RF losses along the line, even when operating far above cut-off. The height of the waveguide regular part (30 mm) was chosen to satisfy the constraints on the electric surface field (< 20 MV/m at 130 MW input RF power) and pulsed surface heating (dT < 100 K). To satisfy this constrains a special tapering of the wedges was introduced, providing constant heat load distribution for almost 20 cm along the initial load length, see Fig. 2. The load length (1 m) was optimized to satisfy the bandwidth requirements. The load is connected to the standard WR90 waveguide via a special taper (shown in Fig. 1), which provides good

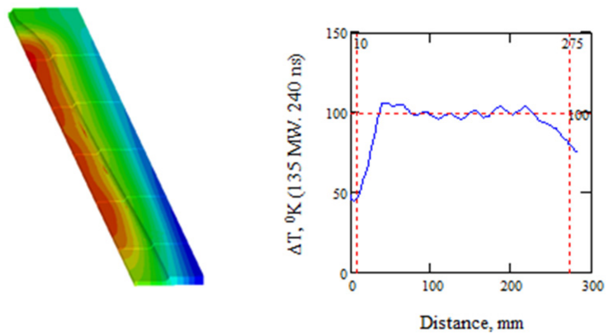

Figure 2: The magnetic field distribution on the quarter geometry of the single period tapered part is shown left. The pulsed heating profile along initial load length is shown right.

matching in a broad frequency range. The measured S-parameters of the load compared with HFSS simulation are shown in Fig. 3. We have built about 50 of such loads. The

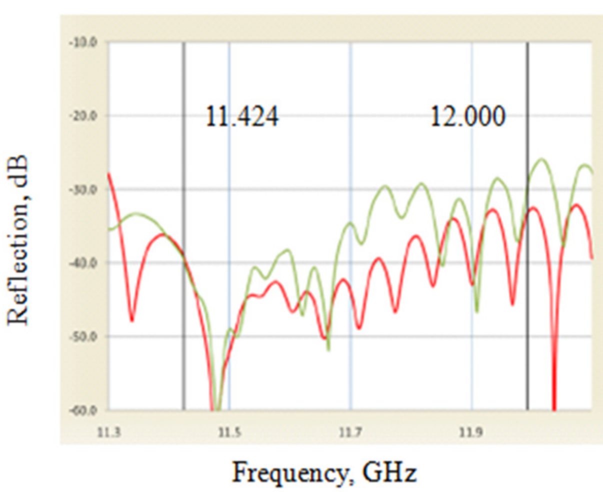

Figure 3: Measured (red) and calculated with HFSS (green) reflections in the typical load.

load was successfully tested up to 60 MW peak RF power at 11.424 GHz and they are used now in different test areas worldwide [1].

The dimensional scaling of the load down in frequency is a straight-forward task. Furthermore, if the bandwidth of the load is not a dominating issue and technology allows to reduce the relative period of corrugation, the length of the load can be kept relatively short ($\approx$ 1 m) even in S-band. Currently a similar load design at 6 GHz is ongoing at PSI [2]. As for operating this type of the load at a very high (>150 °C) average temperature, a number of issues should certainly be addressed. First of all, at a high peak RF power the load should be operated under vacuum conditions. Thus the metal surface out-gassing process can become a problem. At low frequencies, if operated at moderate peak and high average RF power levels under atmospheric pressure, this will not be an issue. The load by design provides broad enough bandwidth. In this way, no special care is needed to operate the load at different average temperature regimes.

RESONANT STRUCTURE

The presented resonant coaxial structure is reliable, robust even against temperature shocks caused by pulsed RF signals and radiation hard. Its properties were investigated by simulations using CST MICROWAVE STUDIO®code. A prototype of the structure is currently under construction at CERN. Further investigations of a waveguide type resonant load are ongoing.

The working principle of the presented structure is similar to one of a resonant network [3]. In the present case however the load relies on metal rods that are inserted into the structures instead of holes. The maximum achievable coupling to the resonating structure is limited by mechanical constraints, which in turn dictates the Q value of the resonant circuit. Since we aim for a high Q value we use materials with low surface impedance and hence have a good conductivity (contrary to initial expectation). For ferrite type materials that are widely used in other structures, the magnetic losses decrease with rising temperature whereas the dielectric losses grow larger [4]. According to simulations the coupling for both structures is via the electric field. This will be discussed in more detail in the section on simulation results.

For the connection of the presented high temperature and high pressure load, operated in dry air, to parts at ambient temperature under vacuum a transition piece is required. This piece should be a very thin metallic tube with a small copper layer with thin gold plating to avoid deterioration on the inside. This will ensure low electromagnetic losses and at the same time provide a high thermal resistance.

Coaxial Absorber

For this RF load, we considered to use a 200 MHz coaxial line similar to the power lines used in CERN SPS. The inner diameter of the outer conductor is 345 mm, the outer diameter of the inner conductor is 150 mm [5]. For all simulations a coaxial cable of 2 m length was used and equipped with a set of 8 rods. These rods were placed symmetrically around the inner conductor (Fig. 4). The structure was shortened by putting a disk of copper at a distance of $\lambda/2$ from the end of the rods. Different simulations were carried out varying the diameter of the rods from 15 to 35 mm. The materials used for the rods were stainless steel and iron with different magnetic permeability. Furthermore the distance between the outer conductor and the rods was varied. The results are summarized in Tables 1 and 2.

The coupling was done via the electric field. The distribution of the magnetic field is depicted in Fig. 4. The maximum of the magnetic field at the beginning and the end of the rods is clearly visible.

In most cases the coupling was under-critical. Only in the cases with very high losses we had achieved coupling

Table 1: Summary of the simulation results for a distance of the rods of 50 mm to the outer conductor. All values in dB.

	diameter of rods [mm]			
μ	**15**	**20**	**30**	**35**
1	-11.7	-14.2	-12.9	-5.8
5	-19.2	-14.7	-5.2	-2.5
10	-12.2	-10.1	-3.8	-1.9
25	-7.6	-6.4	-2.6	-1.3
50	-5.6	-4.8	-1.9	-1

Table 2: Summary of the simulation results for a distance of the rods of 60 mm to the outer conductor. All values in dB.

	diameter of rods [mm]			
μ	**15**	**20**	**30**	**35**
1	-6.5	-8.4	-29	-10.9
5	-17.3	-30.9	-8.7	-4.5
10	-47.3	-18.9	-6.1	-3.3
25	-14.1	-10.3	-4	-2.3
50	-9.7	-7.3	-3	-1.7

close to critical coupling. The coupling can be improved by moving the position of the copper disk.

In general, a distance between the rods and the outer conductor of 60 mm improves the coupling for all cases significantly. For reasons of mechanical simplicity, we chose the design with 30 mm rods made of stainless steel (μ = 1) put in a distance of 60 mm to the outer conductor for the construction of our prototype. Simulation results of S_{11} can be seen in Fig. 5. According to simulations the bandwidth of the structure at -20 dB is $\approx$ 40 kHz and the Q value is $\approx$ 630.

As can be seen, the introduction of the rods causes a detuning of the structure. The resonance is slightly shifted up to a frequency of 207 MHz.

For practical application the rods can be made hollow and hence would allow water-cooling. Also the inner conductor will have to be cooled. In general heating of the structure would cause an elongation of the rods and hence

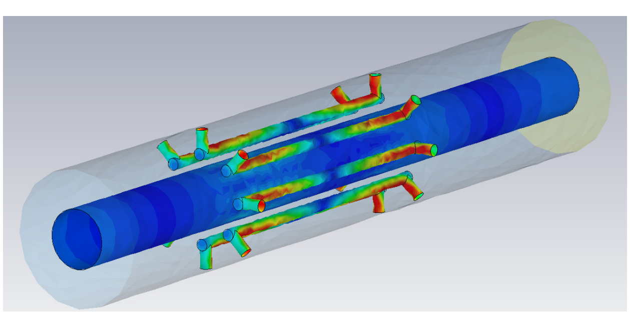

Figure 4: The magnetic field in the coaxial structure as determined by simulations.

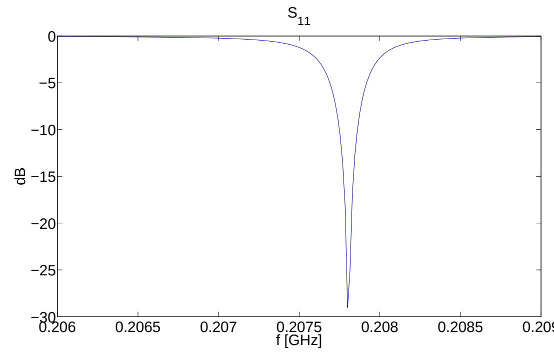

Figure 5: Simulation results for S_{11} of the chosen design with 30 mm rods of μ = 1 (optimal diameter for this permeability) in a distance of 60 mm to the outer conductor.

a detuning of the load. The use of Invar instead of stainless steel can solve this issue since this material has a very low thermal expansion coefficient.

CONCLUSIONS

Two types of high temperature "fully metal" loads without dielectric material have been presented. The broadband traveling wave loads have been successfully tested at high peak RF power at X-band. Operating this load at lower frequency, moderate (few MW) peak power and high average temperature should not be the problem. The resonant load aims for high Q values and conductor losses using materials with low surface impedance. Simulation results conducted for this type of load are very promising. A prototype for this kind of high power load is currently built at CERN and investigations for a similar waveguide type load are currently ongoing.

REFERENCES

[1] S. Matsumoto, T. Higo, I. Syratchev, G. Riddone, W. Wuensch: High Power Evaluation of X-band High Power Loads, CERN-ATS-2010-217, October 2010

[2] R. Zennaro, private communication

[3] M. S. Kheir, H. F. Hammad, A. Omar: Graphical Representation and Evaluation of Attenuation and Coupling Parameters of Whispering-Gallery-Mode Resonators, IEEE Transactions on Instrumentation and Measurement, Vol. 60, No. 8, August 2011

[4] C. Larsson, D. Sjöberg, L. Elmkvist: Waveguide Measurements of the Permittivity and Permeability at Temperatures of up to 1000°C, IEEE Transactions on Instrumentation and Measurement, Vol. 60, No. 8, August 2011

[5] H.P. Kindermann, W. Herdrich, W. Sinclair: The RF Power Plant of the SPS, IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983