RF LOADS FOR ENERGY RECOVERY

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Abstract

Different conceptional designs for RF high power loads are presented. One concept implies the use of solid state rectifier modules for direct RF to DC conversion with efficiencies beyond 80%. In addition, robust metallic low-Q resonant structures, capable of operating at high temperatures (>150 °C) are discussed. Another design deals with a very high temperature (up to 800 °C) air cooled load using a ceramic foam block inside a metal enclosure. This porous ceramic block is the microwave absorber and is not brazed to the metallic enclosure.

INTRODUCTION

There is a general need for RF termination loads in particle accelerator facilities, which sometimes release power in the MW range as heat to the environment. Up to now, little effort was taken to recover that otherwise wasted energy.

One way is to convert the energy directly to an intermediate DC voltage by Schottky rectifiers. A prototype of this concept, which was tailored to the 200 MHz RF system of the CERN Super Proton Synchrotron (SPS), has been successfully tested [1].

An alternative way to recover RF power is to convert it to a technically useful form of heat. Most thermal loads currently used can be divided into two types:

- Direct heating of cooling liquid
- Absorbers on cooled metal surfaces

Loads that heat up water directly use ceramic windows which sometimes can be rather fragile and delicate in handling. Absorbers on cooled metal surfaces are rather difficult to produce since the absorber has to be joined with the metal. This can be done via brazing, soldering, gluing or press-fitting — all very complex and expensive procedures. Furthermore, the junction of two different materials is subject to stress, when heated, due to the different thermal expansion coefficients of the materials as well as possible different heating patterns. In addition, unavoidable short high-peak power RF pulses can produce considerable thermo-acoustic shock waves which are a challenge, in particular, for metal-ceramic joints. For both types of loads it is difficult to find solutions that withstand cooling liquid temperatures higher than 100 °C as well as pressures higher than 16 bar.

Another type of load that has been developed at CERN addresses the above mentioned problems [2]. It is a load without any dielectric material, made entirely from metal. Water cooled, grooved surfaces are used as absorbers, rendering it capable of dissipating the incoming RF power while producing a cooling liquid with very high temperature and high pressures. However, these loads are designed only for frequencies in the X-band range. Similar solutions for a lower frequency range would require extremely large structures resulting in big and heavy loads.

This paper opens with a brief presentation of the direct energy recovery concept based on Schottky diodes. Subsequently, two different concepts for high power loads capable of covering a wide frequency range are discussed: all the issues are addressed. Both loads are relatively easy to handle and robust even against temperature shocks caused by pulsed RF signals. They can be operated in air and connected to the vacuum end of an accelerating cavity via standard vacuum seals. Both will be capable of delivering cooling media (water in one case, air in the other) with temperatures up to 300 °C (water) or 800 °C (air) and pressures higher than 20 bar. Such cooling media has a certain value (Carnot cycle) and can be used e. g. for domestic heating or energy recovery purposes via a Stirling engine.

DIRECT ENERGY RECOVERY

For direct energy recovery, the RF signal that needs to be dissipated is split into many channels, connected to rectifier modules handling 1 kW RF power each. The DC outputs of these are combined again in a single channel[1]. Commercial photovoltaic power inverters can be used to feed the recovered power back to the utility grid with optimum efficiency. Each RF/DC module contains four rectifiers, handling 250 W each. Each rectifier is built from two GaAs Schottky diodes and contains additional components to ensure a graceful degradation if one or more components fail. Two prototypes of this rectifier were built and evaluated with up to 400 W of pulsed RF power. The measured maximum RF to DC efficiency was 88.7%. However, due to the complexity, required space and cost of this technology, it is for the moment prohibitive compared to the value of the energy recovered over its estimated lifetime of 20 years.

HIGH TEMPERATURE RF LOADS

For both designs presented here, a waveguide of type WR1150 was chosen as carrier of the incident RF power since such waveguides are used in the 800 MHz systems at the CERN Super Proton Synchrotron (SPS) and were readily available. They are specified for a frequency range of 640 - 960 MHz which is well suited for the chosen operating frequency of 704 MHz[2].

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[1] This array concept was inspired by the rectifying antenna ("rectenna") which was invented and successfully utilized by W. C. Brown in 1964 to keep a small helicopter in the air exclusively by RF power.

[2] This frequency is the operating frequency of the ESS (Lund).

Stacked Waveguide Structure

The load is implemented as a cavity resonator, optimized for narrow band operation around the chosen design frequency, with a quality (Q) factor as low as possible. The resonator concept has the advantage that the load's reflection coefficient does not primarily depend on the absorbing properties of the material and can always be tuned for < -20 dB reflection. Nonetheless, high Q values are not practical for two reasons. Firstly the load needs to accommodate large temperature swings leading to drift in its resonant frequency: this is not possible with a large Q as its operating bandwidth becomes too narrow (see Table 1). The second reason is related to the enhancement of the electric field inside the cavity by a factor of $\sqrt{Q}$. The breakdown voltage of air might easily become the bottleneck for the maximum input power.

Table 1: Maximum allowable temperature increase, keeping the tune of the resonator within its 20 dB operational bandwidth BW. For the calculations the thermal expansion coefficient of stainless steel ($1.73 \times 10^{-5}\,\mathrm{K}^{-1}$) was used.

Q_0	BW [MHz]	max. ΔT [K]
10	7.042	575
15	4.694	383
17	4.142	340
50	1.408	115

The first design was a rectangular stainless steel waveguide of dimensions 146 mm × 292 mm × 311 mm. However, this structure had an unsuitably high unloaded Q value, of about 2500, which could be reduced by a factor 10 by changing the height of the waveguide from 146 mm to 10 mm. Unfortunately, this structure had much less surface area and, hence, was more sensitive to thermal stress. Also the heat transport would have been difficult. To circumvent this, several such waveguides were stacked (Fig. 1) upon each other, not effecting the overall Q value.

To achieve critical coupling to the incoming waveguide, an iris was placed at the entrance of the stacked structure. In between the stacked resonators, metal pipes carrying the cooling water can be placed. These are capable of withstanding high temperatures (up to 200 °C) and high pressures (< 20 bar). A taper connecting the waveguide with the stacked structure can be used to gain height for accommodating the cooling pipes. Made from thin sheet metal, this would also bridge the temperature gradient between the hot RF load and the incoming waveguide at ambient temperature. A prototype for the stacked structure containing five resonators upon each other is shown in Fig. 1.

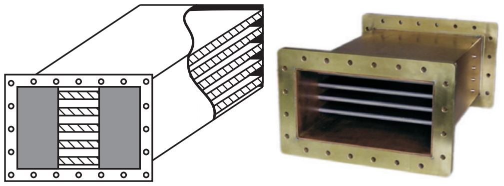

Figure 1: Prototype for the stacked structure built at CERN.

Additional ideas to further decrease the Q value include coating (via plasma spraying) of the inside of the resonators with a thin layer of ferrite (typically 100 – 200 μm). Such a thin ferrite layer can be heated up to its Curie temperature (roughly 300 °C) without loosing its properties. To determine the ferrite coating parameters that best suit our needs, different samples have been ordered and will be tested inside the waveguide structure. However, since this type of coating is a costly procedure, the prototype was equipped with ECCOSORB MCS©[3], which is a commercial ferrite absorbing sheet on a silicone rubber carrier of 1 mm thickness. ECCOSORB is rated to keep its properties up to a temperature of 177 °C which is a sufficiently good start for a first proof of principle test.

Air Cooled Waveguide

The second structure presented here is a regular waveguide loaded with silicon carbide (SiC) foam. The design was inspired by the work of I. Hirschier who developed a solar energy absorber [3].

The SiC foam used for this application is a material widely used, in metal casting applications, as a filter for purification of molten metal. Thus it can withstand temperatures up to 1550 °C and it is commercially available in different sizes and shapes.

A possible first design of the structure is shown in Fig. 2. It consists of a waveguide, which is a high temperature metal enclosure for the microwave absorbing foam, which has a tapered form to minimize RF reflections. The waveguide is thermally insulated from its surrounding using e. g. fire clay. The connection of the load to the accelerator structure is equipped with an inlet for pressurized air, which is guided through the foam with a velocity of roughly 2 – 3 m/s, acting as an efficient heat exchanger. Both inlets will be covered with meshes to avoid RF power losses. In addition, a thin metal sheet is put between the

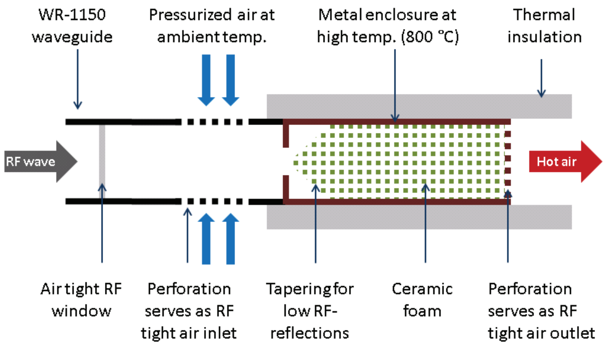

Figure 2: Possible design of an air cooled waveguide load.

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[3] This material is similar to crisp or browning plates used in domestic microwave ovens.

inlet and the actual load to compensate thermal expansion. At the inlet side a thin layer of kapton foil seals the structure from the air flow. At the outlet of the high power load an array of stainless steel pipes of roughly 1 cm diameter is placed to serve as an RF tight air outlet (honey-comb style RF filter). The outlet air temperature for such a structure may be roughly 800 °C. This is similar to the use of industrial hot air blowers put in series.

It is important that the ceramic is not brazed to the metallic enclosure but is just in loose contact; this avoids complex manufacturing processes as well as problems due to thermal stress caused by the different expansion coefficients. This concept is similar to the use of fire clay bricks in a domestic stove except here the RF losses cause the heating of the structure.

A prototype for proof of principle measurements is shown in Fig. 3.

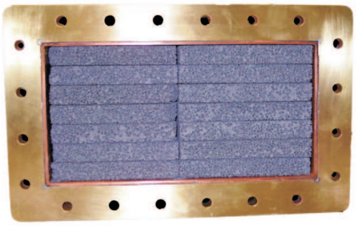

Figure 3: Front view of the silicon carbide foam filled load

MEASUREMENT RESULTS

A first low power test was carried out with both prototypes using the setup shown in Fig. 4. On each end of the structure, metal plates were used to form an iris to ensure very weak coupling to the selected mode, allowing the approximate unloaded Q_0 of the resonator to be determined with little influence by the measurement instrument.

Figure 4: Setup to measure the protoypes of both proposed RF loads.

Transmission measurements were conducted with: (a) the empty waveguide, (b) the waveguide containing plates to simulate a stacked structure, (c) the waveguide containing plates covered with ECCOSORB and (d) the waveguide filled with SiC foam.

The measurement results with the corresponding Q_0 factors are shown in Fig. 5 and Fig. 6, allowing a comparison of the absorption properties of the materials in a realistic setup.

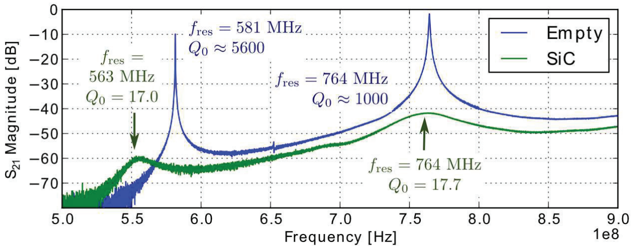

Figure 5: Comparison between the SiC filled and the empty waveguide. The Q decreases with filling length, which was 435 mm.

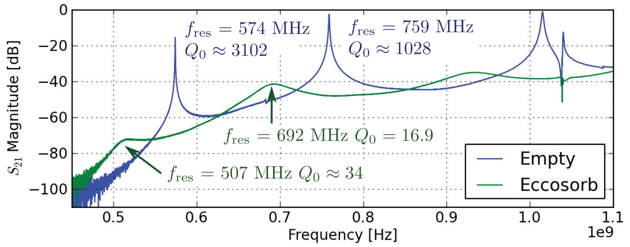

Figure 6: Comparison between the ECCOSORB filled and the empty waveguide.

It can be clearly seen that both materisals, ECCOSORB and SiC, reduce the Q value significantly. This allows an operation of the loads over a temperature range from ambient temperature up to approximately 350 °C (Table 1).

CONCLUSIONS

A direct method to recover the otherwise wasted RF power from an accelerator facility is to convert it to DC by an array of semiconductor rectifiers. A more indirect way is to generate heat-flow, at a high temperature level, which is technically useful. Two conceptional designs of high power, high temperature RF loads have been shown. For both structures prototypes were built and tested with very promising results.

ACKNOWLEDGEMENTS

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