Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

EXPERIMENTAL DESIGN TO STUDY RF PULSED HEATING[*]

D. P. Pritzkau[†], G. Bowden, A. Menegat, R. H. Siemann
Stanford Linear Accelerator Center, Stanford University, California 94309

Abstract

An experiment to study the effects of RF pulsed heating on copper has been developed at SLAC. The experiment consists of two circularly cylindrical cavities operating in the TE_{011} mode at a resonant frequency of 11.424 GHz. These cavities are connected by a magic tee and driven by a 50 MW X-band klystron. Each cavity receives an input pulse of 20 MW with a pulse length of 1.5 μs. This input corresponds to a maximum temperature rise of 350 K on the copper surface. The details of the experimental setup will be described.

1 INTRODUCTION

RF pulsed heating results from local Joule heating on a metal surface due to surface magnetic fields created from pulsed RF. Lateral stresses are induced in the material since the metal cannot expand fast enough. Cyclic stress results from the pulsing of RF and can lead to metal fatigue if the stress amplitude is larger than the elastic limit for the material. This effect represents high power limitations of metals like copper and may determine feasible accelerator structures at short wavelengths. For more information on pulsed heating please refer to the references [1], [2], [3].

2 EXPERIMENTAL SETUP

Due to the availability of 50 MW X-band klystrons at SLAC, we designed a circular cylindrical resonant cavity to be operated in the TE_{011} mode at 11.424 GHz to study the effects of pulsed heating on OFE copper. Two such cavities are used in conjunction with an asymmetric magic tee in order to protect the klystron from reflected power. The cavity design presented in this paper is a revised version compared to the design presented in ref. [1].

2.1 Cavity Design

We chose the TE_{011} mode to be the operating mode for several reasons. In order to accommodate multiple experiments without having to machine additional cavities, we require the endcaps to be removable. The TE_{011} mode does not require current to flow between the endcaps and the cylindrical sidewall of the cavity, thus the endcaps may be inserted or removed without the need for physical contact. This mode only has azimuthal electric fields, so no perpendicular electric fields exist on the metal surface. This property reduces the likelihood of breakdown and field emission from interfering with our study of pulsed heating. Removable endcaps also facilitate study of surface damage using optical and electron microscopes. One such cavity is shown in Figure 1 with one of the endcaps in the foreground.

Figure 1: Picture of test cavity with one of the endcaps in the foreground.

Since it is our desire to reuse the cylindrical sidewall, the dimensions of the cavity were chosen to maximize the power dissipation on the endcaps while minimizing it on the sidewall. The cavities have diameters of 4.415 cm and axial lengths of 1.9 cm. Although the surface of the cylindrical sidewall will also heat up, a general property of cyclic metal fatigue is that the lifetime of the material depends exponentially on the stress amplitude [4]. Hence, many experiments can be performed with the same cavities before they become unusable.

The mode is excited through a circular aperture with a WR-90 waveguide coupler mounted on the sidewall of the cavity with the waveguide's long dimension parallel with the axis of the cavity. The coupling is accomplished with a circular aperture designed with a coupling coefficient β=1.28 assuming a 10% degradation of the theoretical Q of 21890 due to machining. The coupling was chosen to maximize the heating in the cavity taking the fill time of the mode into account. Since the long dimension of the waveguide is longer than the length of the cavity, the sidewall and the endcaps are made longer than necessary to create the cavity in order to mount the waveguide.

For easy placement of the endcaps into the cavity a 0.1 mm gap exists between the outer radius of the endcap and

---

[*] Work supported by Department of Energy contract DE-AC03-76SF00515

[†] Email: pritzkau@slac.stanford.edu

0-7803-5573-3/99/$10.00@1999 IEEE.

the inner radius of the cavity. This gap is rather long due to the problem with the size of the waveguide coupler. A RF spring gasket from BalSeal© is used to shunt this gap to prevent other spurious modes from being excited. A groove of 1.0 mm by 1.0 mm also exists on the outer radius of the endcap to remove the degeneracy of the operating mode with the TM_{111} mode. According to 2D simulations using MAFIA [5], the resonant frequency of the TM_{111} mode is reduced over 100 MHz and other modes are at least 400 MHz away. The unloaded Q's of all of these modes are at least 10000.

The endcaps are mounted on bellows to facilitate tuning of the cavity using differential screws. The endcaps were made even longer to also allow vacuum pumping behind the RF spring gaskets in addition to the pumping that will occur through the coupling aperture. Water channels were cut in the back of the endcap to allow cooling of the average heating that occurs from multiple RF pulses. Water-cooling is also implemented for the cylindrical sidewall as well.

2.2 Diagnostic Setup

Damage to the metal due to surface fatigue will manifest itself in degradation of the unloaded Q of the cavity. We wish to measure this degradation as well as the local pulsed temperature rise of the surface while high power is applied to the cavity. Exciting and measuring the properties of a low-power steady-state TE_{012} mode in the cavity allows us to perform such a measurement.

The TE_{012} mode is excited through a circular aperture by a waveguide coupler with a width of a WR-42 waveguide and a height of a WR-62 waveguide. Including the effects of the coupling aperture the resonant frequency of this mode is 17.811 GHz. The so-called diagnostic coupler is mounted similarly to the fundamental mode coupler except it is placed one-fourth of the cavity length away from the center where the maximum of the magnetic field for the TE_{012} mode occurs. The width of the diagnostic coupler is tapered to the width of a WR-62 waveguide after a length of 10 cm to allow the use of available vacuum windows. The diagnostic coupler is cutoff to the fundamental mode frequency of 11.424 GHz. After 10 cm, this signal is attenuated by over 150 dB to ensure no damage occurs to the diagnostic equipment.

The TE_{012} mode is designed to be critically coupled assuming a 10% degradation in the theoretical Q of 21906. As with the fundamental mode, MAFIA was used to model the endcap groove and radial gap in the cavity. The resonant frequency of the degenerate TM_{112} mode is reduced by 200 MHz and all other spurious modes are at least 150 MHz away. The unloaded Q's of all these modes are at least 8000.

The measurement of the pulsed temperature rise will be performed as follows. Before the application of a high-power RF pulse, the TE_{012} mode will be set up in steady state using a frequency generator. The surface of the cavity will heat up as high power is applied. Since the resistivity of the surface of the metal will increase with temperature, the unloaded Q of the mode will decrease. This Q degradation will result in a change of coupling over the time of a RF pulse causing a change in the reflected power seen from the diagnostic port. The phase of the reflected signal will also change because of the change in resonant frequency due to thermal expansions and a changing Q. The local temperature rise of the surface of the cavity can be inferred from the knowledge of the amplitude and phase of the reflected power over time and the variation of the surface magnetic field.

The diagnostic apparatus used to perform these measurements is shown in Figure 2. A quadrature IF mixer is used to measure the amplitude and phase of the reflected signal over time. A RF switch is also utilized to allow the measurement of Q between RF pulses when the effects of pulsed heating have disappeared. This measurement allows us to determine when the Q gets permanently degraded from surface fatigue. Not shown in Figure 2 is the ability to use an event-counter to count the number of RF pulses applied to the cavity and bin them by power level. The counter will allow us to determine the number of RF cycles it takes to cause a certain amount of Q degradation.

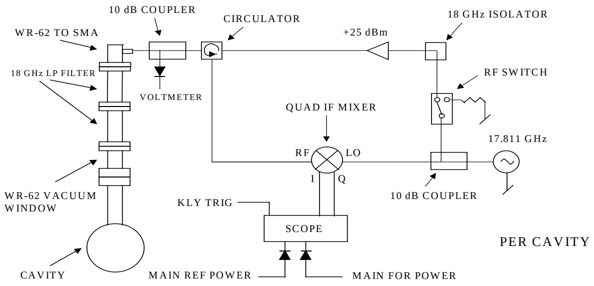

Figure 2: Diagram of diagnostic setup

3 COLD-TEST RESULTS

Some problems have arisen during the cold-test phase of the experiment. Broadband resonances are noticed while measuring the reflected signal of the TE_{012} mode. A representative spectrum is shown in Figure 3. These broadband resonances change the apparent coupling to the TE_{012} mode as well as its unloaded Q. Accurate values for these quantities cannot be determined at the time of this writing.

There are two possible explanations for these problems. One is the coupling aperture for the fundamental mode greatly affects the coupling of the diagnostic coupler to the TE_{012} mode and perhaps introduces spurious modes. High transmission (-7 dB) is measured from the diagnostic coupler to the fundamental mode coupler and it is known that the signal propagates in the fundamental TE_{10} mode in the WR-90 waveguide at 17.8 GHz.

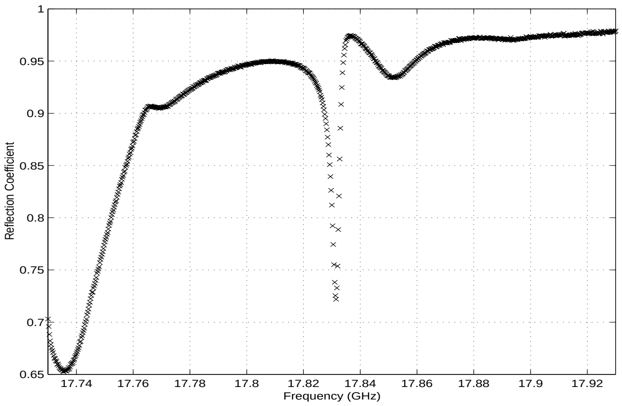

Figure 3: Frequency spectrum of TE_{012} mode. Resonant frequency is approximately 17.83 GHz.

Another possibility to consider are the effects of the RF spring gaskets used to shunt the gap between the endcaps and the cylindrical sidewall. The data show that the TE_{011} and TE_{012} modes are sensitive to the placement and type of springs used. It should be noted that most of the material behind the RF spring gaskets is stainless steel.

A plunger with copper tape was used to short the fundamental coupling aperture from the waveguide side while measurements were taken of the reflected signal from the diagnostic coupler. One such spectrum is shown in Figure 4. It can be seen from this figure that the coupling to the TE_{012} mode is greatly affected by some broadband resonance. This spectrum suggests that power is leaking through the spring gaskets and being dissipated in the stainless steel. It is also seen that when the springs are removed the transmission from the diagnostic coupler to the fundamental coupler is reduced from -7 dB to -14 dB. This suggests much power loss behind the endcaps to the stainless steel.

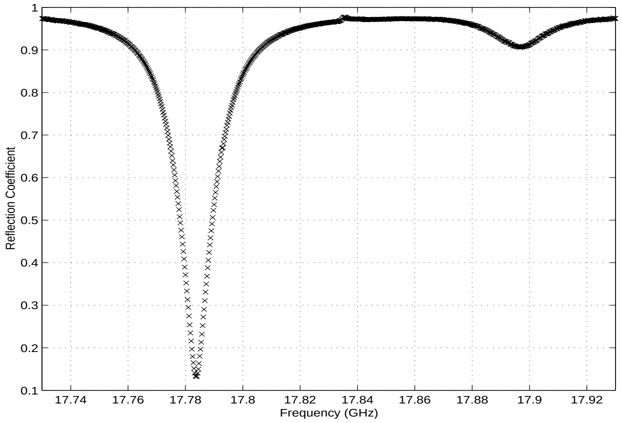

Figure 4: Frequency spectrum of TE_{012} mode with plunger inserted. The TE_{012} mode is washed away by the broadband resonance.

The effect of the springs is better characterized by looking at the TE_{011} mode. There are fewer modes nearby to the TE_{011} mode and the diagnostic coupling aperture does not affect this mode. The unloaded Q of the TE_{011} mode is measured while varying the wire diameter, compression, and material of the springs. The results are given in Table 1. In one case shown in the table, one particular type of spring was inserted into the cavity twice and the unloaded Q changed by over 1000. These results suggest that the TE_{011} and TE_{012} modes are highly sensitive to the presence of the springs. The springs are known to become less effective at higher frequencies, which may help explain the behavior seen at the diagnostic frequency.

In the present design the springs are housed in rectangular grooves on the endcaps. There are plans to perhaps modify the groove shape to improve contact with the springs as well as to determine the best type of spring to use. There are also plans to modify an older cavity [1] to isolate the effect of the apertures on one another from the effect due to the springs. In this way, the problem will be isolated and a solution sought.

Material	Wire Diam (.001 in.)	Compression Ratio (%)	Q_0
No Spring	N/A	N/A	10465
SS	6.0	22	11940
1 SS/1 SS-Au plated	6.0	32	20154
SS	4.5	32	17931
BeCu	4.5	32	17491
BeCu	4.5	32	18505

Table 1: Table of values for unloaded Q for various spring configurations. SS=Stainless Steel 302, BeCu=Beryllium Copper. External Q ≈ 13000.

4 CONCLUSION

An experimental design to study RF pulsed heating has been presented. Cold-test results show some problems with the initial design. There are plans to fully characterize and isolate the effects of these problems and to design a solution. In the meantime, a high-power test will be conducted; although, accurate data cannot be collected from the diagnostic TE_{012} mode.

5 REFERENCES

[1] D. P. Pritzkau, A. Menegat, R. H. Siemann, T. G. Lee, D. U. L. Yu, "Experimental Study of Pulsed Heating of Electromagnetic Cavities", Proceedings of the 1997 Particle Accelerator Conference, 1998, pp. 3036-3038

[2] D. P. Pritzkau, G. B. Bowden, A. Menegat, R. H. Siemann, "Possible High Power Limitations From RF Pulsed Heating", 1998, SLAC-PUB-8013

[3] O. A. Nezhevenko, "On the Limitations of Accelerating Gradient In Linear Colliders Due to the Pulse Heating", Proceedings of the 1997 Particle Accelerator Conference, 1998, pp. 3013-3014

[4] A. Weroński and T. Hejwowski, Thermal Fatigue of Metals, New York: Marcel Dekker, Inc., 1991, p.164

[5] MAFIA User Guide Version 4.00, CST GmbH, Darmstadt, Germany