RF PERFORMANCE OF A SUPERCONDUCTING S-BAND CAVITY FILLED WITH LIQUID HELIUM*

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Abstract

Preliminary RF testing has been done on a 2.45 GHz single-cell elliptically-shaped niobium cavity filled with liquid helium. Low-field results indicate little or no increase in the power dissipation, consistent with predictions and measurements in the literature. The frequency shift with pressure for the cavity filled with saturated liquid is about 100 times greater than when the cavity is under vacuum, consistent with published values of liquid He permittivity as a function of temperature. An accelerating gradient of about 5 MV/m was reached at a bath temperature of 2.4 K and a bath pressure of 1.4 bars.

INTRODUCTION

Copper RF cavities filled with hydrogen gas at high pressure have been investigated recently in a collaboration between Muons, Inc., Fermilab, IIT, and Jefferson Lab for simultaneous acceleration and ionisation cooling of a muon beam [1]. A further step in this direction would be a superconducting RF cavity filled with liquid helium. One might hope that this would make the cavity less vulnerable to thermal breakdown, field emission, and multipacting. A superconducting cavity with liquid He inside has the advantage of presenting fewer safety concerns and opens up the possibility of CW operation. A disadvantage is that the higher nuclear charge of He would produce more scattering; also, magnetostatic focussing of the beam could not be done simultaneously.

RF measurements were done on an S-band superconducting cavity, with the cavity under vacuum and then filled with liquid He. Preliminary results are reported in this paper. We first review briefly the properties of liquid He.

DC Properties of Liquid He

The dielectric constant of liquid He as a function of temperature has been measured in several studies. Recommended values are tabulated in a recent survey article [2].

The DC dielectric strength has also been studied. Highlights of a recent review article [3]: (i) Dust particles can produce local field enhancements. These particles are pulled to high stress points by dielectrophoretic forces, and can initiate discharges there (field emission). (ii) Breakdown fields of 40 to 100 MV/m are typical under well-controlled conditions (short times, small gap between polished electrodes, careful filtering out of particulates). (iii) Breakdown fields for pressurised liquid can be as much as twice those of saturated liquid.

Microwave Properties of Liquid He

The loss tangent of liquid He was considered theoretically. If the dominant loss mechanism is radiation damping, $\tan\delta \sim 10^{-25}$ at 3 GHz was predicted [4].

X-band measurements were done with a liquid-helium-filled cavity operated in the TE_{011} mode at SLAC [5]. A low loss tangent was reported ($\tan\delta < 10^{-11}$) at low field; instabilities were observed at high power.

In more recent measurements, a dielectric or strip-line resonator (at about 10 GHz) was partially filled with liquid He. A frequency shift with temperature [6] and a non-linear response [7] due to the liquid were observed.

THE CAVITY

RF measurements reported in this paper were done on single-cell cavities made from 4 mm thick Nb sheet (Figure 1a). The cell shape is the same as that of the TeSLA Test Facility cavity [8], but the dimensions were scaled from 1.3 GHz to 2.45 GHz. The cavities were formed at Michigan State University and in the local area, with the electron beam welding done by industry. Nb-Ti flanges with knife edges were used; the flanges were TIG-welded to the Nb beam tubes. Most of the measurements were done on an electron-beam-welded cavity, although some initial low-field testing was done on another cavity which was TIG-welded at the equator and irises.

As the Nb beam tubes were a little too short, the copper gaskets were replaced with Nb disks (with smaller holes for RF antennae and pumping) to avoid power dissipation in the stainless steel end-caps while testing under vacuum.

RESULTS

Vacuum-Filled RF Testing

The cavity was etched for 1 hour and 45 minutes to remove about 150 μm from the inside surface. The cavity was then high-pressure rinsed with ultra-pure water in a Class 100 clean room for 45 minutes. After drying, the cavity was assembled onto the insert and pumped out in a Class 10 000 clean room.

Measurements at 1.5 K and 2 K are shown in Figure 4a below. The highest surface electric field reached was $E_p =$ 31 MV/m. The cavity was limited by a hard barrier, possibly associated with thermal breakdown. Some x-ray signals were observed (200 mrem/hour inside the radiation shield).

Liquid-Filled RF Testing

After testing under vacuum, the cavity was tested with liquid He inside, with no additional etching in between. As shown in Figure 1b, open-ended copper tubes were used

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instead of stainless steel end-cap flanges. Copper was used for reduced RF power dissipation relative to stainless steel tubes. The RF antennae were installed on side ports of the copper tubes (Figure 1c). The cavity was prepared inside the clean room; the open beam tube ports were sealed off with plastic (which was removed just before putting the insert into the Dewar). The inside of the Dewar was scrubbed just before putting in the cavity.

Another round of liquid-filled testing was done after a light etch of the cavity (45 μm) and another high-pressure water rinse. A ceramic filter was installed on the liquid He supply pipe with the goal of reducing any possible particulate contamination in the He bath. A copper mesh was added to the end of the bottom beam tube to reduce RF leakage between the input and pick-up antennae (which was observed in the previous test). A video camera on top of the Dewar was used to provide a view of the inside of the cavity and the pick-up antenna (Figure 2). The RF performance was similar for both tests.

In all of the liquid-filled tests, the cavity frequency was unstable at 4.2 K, producing spontaneous self-modulation of the field amplitude at high power; the frequency was stable at 2 K and below.

We measured the low-field Q as a function of temperature while pumping down to 2 K. Results are compared in Figure 3. Between 2 K and 4 K, the quality factor was nearly the same as measured with the cavity under vacuum.

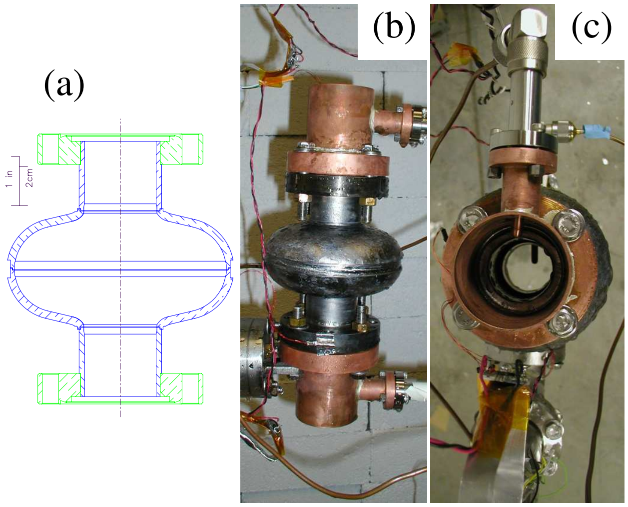

Figure 1. (a) Drawing of the 2.45 GHz $\beta = 1$ cavity. (b) Side view and (c) top view of the cavity on the insert.

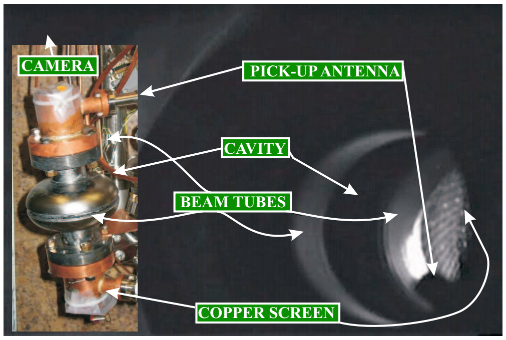

Figure 2. Inside view of the liquid-filled cavity from the video camera. Inset: cavity on the insert, prior to test.

Measurements at high field were done at 2 K and 1.6 K at low pressure (saturated liquid conditions). Results are shown in Figure 4b. At 2 K, we lost lock while raising the field and observed a subsequent degradation in the low-field Q. We then continued pumping down to 1.6 K. We observed a partial recovery in the Q after losing lock again at high field at $T = 1.6$ K.

We re-pressurised the Dewar and did additional measurements at 1.4 bars. The bath temperature was about 2.4 K (with the liquid not yet in thermodynamic equilibrium). We were able to reach a higher field with the bath pressurised.

While at high RF power, we observed flashes of light and arcing inside the cavity with the camera. Some still images are shown in Figure 5. As can be seen, the light was not localised to a particular area inside the cavity. Sound associated with the flashes of light could also be heard from inside the Dewar. We did not detect any x-ray signals during the liquid-filled tests.

Microwave Properties of Liquid He

The resonant frequency was measured at low field while decreasing the pressure and temperature, maintaining a saturated liquid (Figure 6a). The net frequency shift was ~ 70 kHz with the cavity under vacuum and ~ 10 MHz with the cavity filled with liquid He. The shift in frequency with temperature might explain the observation of the frequency being unstable at high power at $T = 4.2$ K.

The frequency difference between the vacuum-filled and liquid-filled cavity allows us to infer the permittivity of the liquid He. Results are compared with values from the literature [2] in Figure 6b. As can been seen, the agreement is reasonable. Thus the permittivity's dependence on temperature accounts for the frequency shift.

The Q drop due to the liquid allows us to infer the loss tangent of the liquid He. The differences in Q between the liquid-filled and vacuum-filled cases between 1.6 K and 2 K correspond to $\tan\delta$ values between $5 \cdot 10^{-11}$ and $2 \cdot 10^{-10}$.

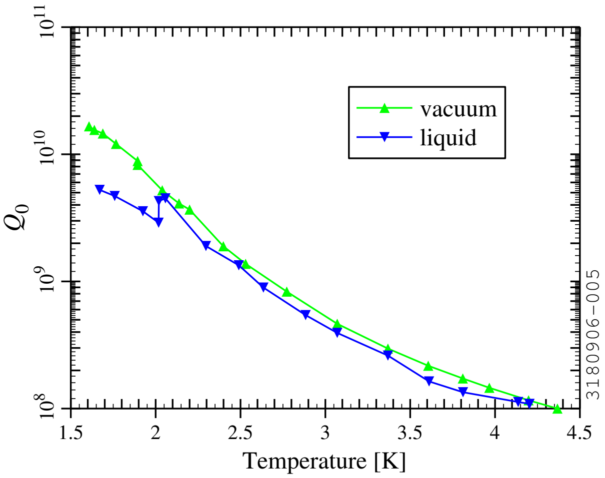

Figure 3. Comparison of the low-field Q between the cavity under vacuum and filled with liquid helium.

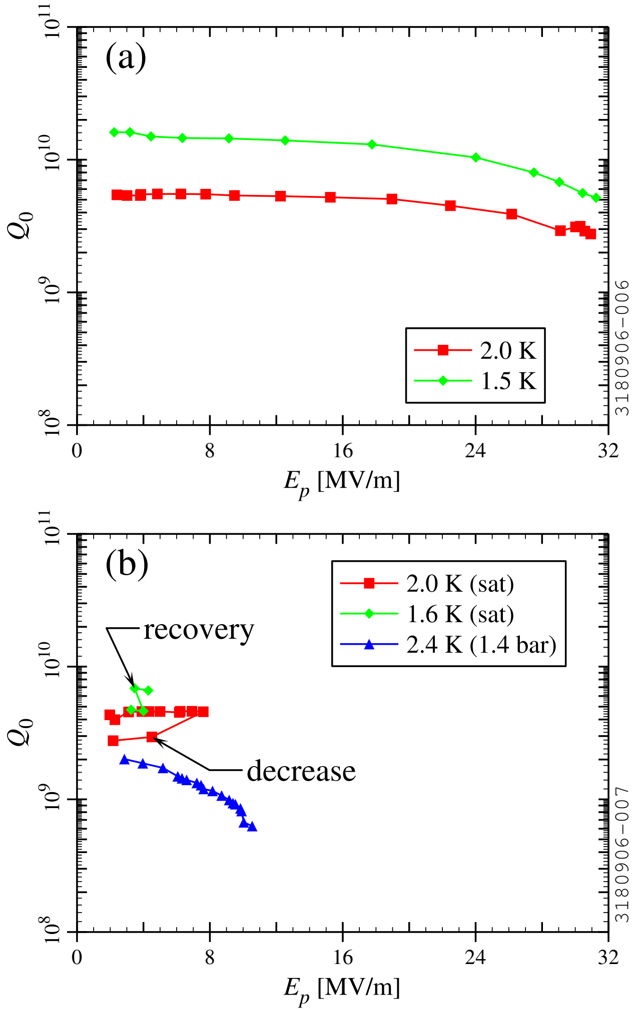

Figure 4. CW measurements with the cavity (a) under vacuum and (b) filled with liquid helium.

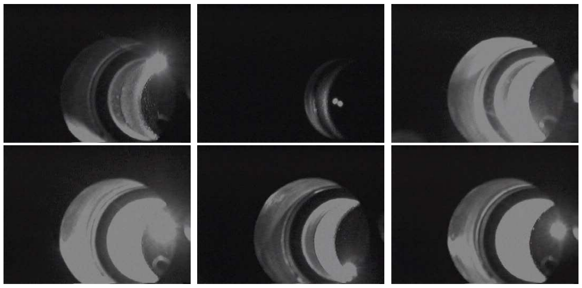

Figure 5. Video images looking inside the cavity.

CONCLUSION

Low-field measurements on a superconducting cavity filled with liquid He indicate that there can be little or no increase in the power dissipation, consistent with previous results. The shift in the cavity frequency with pressure is about 100 times greater with saturated liquid present due to the liquid He permittivity's dependence on temperature. We can reach higher field by pressurising the liquid, consistent with DC breakdown studies in the literature. We reached $E_a \approx 5$ MV/m at $T = 2.4$ K, with $P = 1.4$ bars. DC breakdown studies suggest that higher fields might be possible with improved cleanliness and independent control of the liquid He's temperature and pressure.

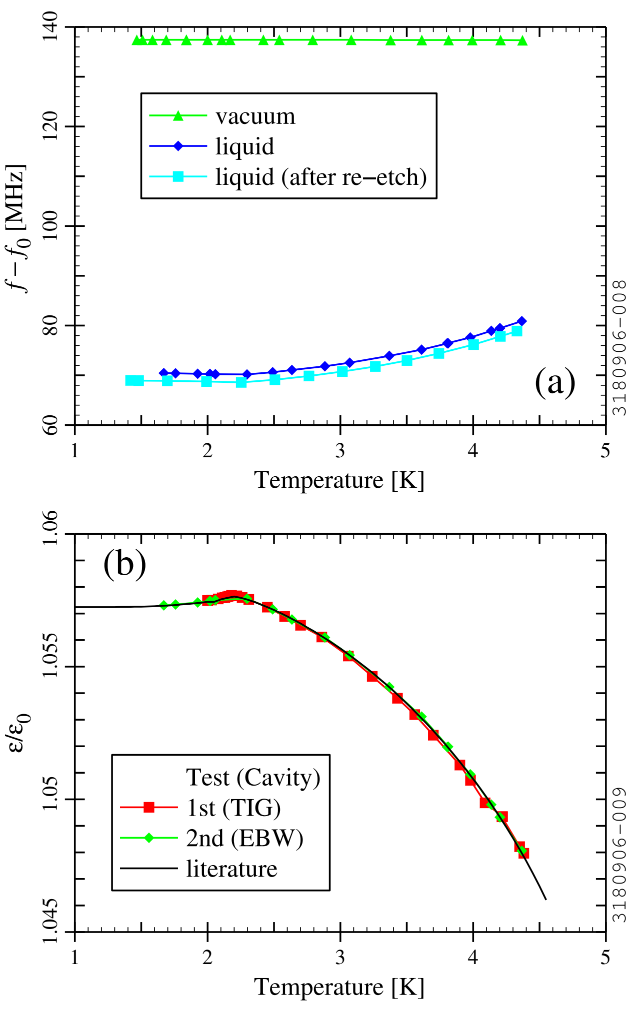

Figure 6. (a) Cavity frequency as a function of temperature ($f_0 = 2300$ MHz). (b) Inferred permittivity of liquid He.

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