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HIGH GRADIENT C-BAND CRYOGENIC COPPER SILVER STRUCTURES

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Abstract

We report the first high-gradient testing of C-band accelerating structures at liquid nitrogen temperatures. Two single cell off-axis coupled standing-wave accelerating structures were tested: one made of pure copper (Cu), and one made of a copper-silver (CuAg) alloy with a silver concentration of 0.08 %. Accelerating gradients of up to 250 MeV/m were achieved in both structures. The structures were tested to peak surface fields high enough to produce a significant amount of dark current emission and beam loading. We report on the initial results from these tests.

INTRODUCTION

In the design and upgrades of accelerator facilities there is always competing interest between reducing the overall physical footprint and power consumption of the particle accelerator, while still meeting the user requirements of the beam energy and beam charge. This has become important for many accelerator applications in industry, medicine, national security, and basic sciences [1–4]. In response, there has been a concerted effort to develop high gradient accelerating structures which would achieve the required beam energies within a shorter length. These compact accelerators can be used for many applications such as high brightness light sources [1, 2], high energy facilities [3–5], medical radiotherapy [6, 7] and industrial LINACs [8]. To further reduce power consumption, many facilities have switched to being cryogenic or superconducting in nature. Operating at these temperatures increases the conductivity and subsequently quality factor of the accelerating structure, achieving the same operational gradient with significantly less power consumption [1–5].

Recent advancements in high gradient technology have led to the use of advanced techniques for normal conducting structures, including cryogenically cooled copper structures, optimized geometry using distributed coupling techniques, and copper alloys. Each of these separately have shown the ability to prove accelerating gradient significantly. Here we present a direct follow-on to our previous 2022 report where it was found that by using a copper silver alloy structure whose geometry was optimized using distributed coupling techniques, the peak surface field of the copper silver structure could exceed 400 MV/m [9]. We now have performed high power tests of these same cavities at cryogenic temperatures, utilizing all three afore-mentioned techniques to improve the maximum achievable gradient in a C-band accelerating structure.

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The important figures of merit for any high gradient structure are the achievable peak surface fields, accelerating gradient and subsequent breakdown rate (BDR) at the given field [10–14]. A breakdown is a vacuum arc discharge inside of the structure which generates an excursion of gases, particulates, and ions from the surface. Radiofrequency (RF) breakdowns are related to multiple phenomena including pulsed surface heating and field emission/dark current [12, 15]. The BDR is defined as the probability of a breakdown event per a RF pulse normalized to the length of the accelerating structure for a given RF pulse length.

C-band accelerating structures have been previously studied by multiple institutions and projects, such as SwissFEL [16], SINAP [17], SPARC LAB [18], the FEL Spring-8 [19], and the Korean National Fusion Research Institute (KNFRI) [20]. All previous projects used traveling-wave C-band structures with exception of KNFRI [20] that used standing-wave structures. The peak surface fields in those C-band structures were in the range of 80-150 MV/m while requiring input power from the klystron on the order of 10 MW. The breakdown rates in these multi-cell accelerating structures varied between $1{\times}10^{-5}$ and $1{\times}10^{-6}$ (1/pulse/meter) for the pulse length in the range of 0.5-1 µs.

EXPERIMENTAL SETUP

The two structures used for this experiment were the exact same cavities used for previous high power tests at LANL [9]. One was made of pure Cu and the other one was made of a CuAg alloy with 0.08 % concentration of Ag to further investigate breakdown rates in CuAg structures compared to Cu structures [13]. Table 1 shows the quality factors and resonant frequencies extracted from the RF cold test results of the two fabricated cavities conducted at 77 K, with the CuAg cavity having a slightly higher quality factor.

Table 1: Cavity parameters measured in the RF cold test of the Cu and CuAg cavities at 77 K.

Parameter	**Cu**	**CuAg**
Frequency	.714 GHz	5.714 GHz
Q_0	25784	27597
β	2.688	2.967
R_s	305 MΩ/m	352 MΩ/m
$E_a \times \sqrt{P[\mathrm{MW}]}$	131 MeV/m	141 MeV/m

The high gradient testing of the two structures was performed at Radiabeam Technologies in Santa Monica over

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a two week period. The testing bunker is powered with a C-band klystron that can provide up to 10 MW of RF power into the bunker at a 100 Hz repetition rate. In order to test both cavities simultaneously, a 3 dB hybrid was used to split incoming power from the klystron between both cavities, as shown in Figure 1. The reflected power would then recombine in the hybrid and be sent to 3D printed spiral dry load [21].

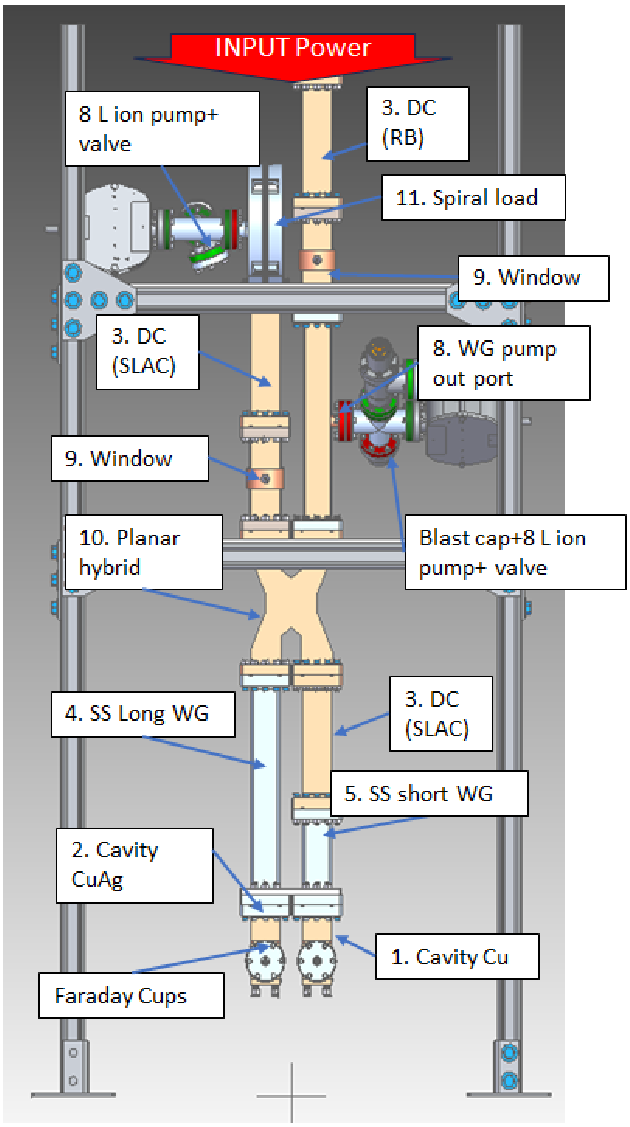

Figure 1: (A) The schematic of the RF network at RadiaBeam Technologies test bunker with various elements labeled. A 3 dB hybrid was used to split incoming powers, and send reflected power to a spiral dry load. Directional couplers placed before the copper cavity and before the load monitor both forward and reflected power.

Directional couplers were placed before the copper cavity and before the load to monitor both forward and reflected power as shown in Figure 1. During the conditioning process, the forward and reflected pulse shapes were recorded continuously at both directional couplers. In addition, RadiaBeam had a directional coupler placed outside of the bunker to verify forward and reflected klystron power. The dark current was monitored using Kimball Physics FC73a Faraday cups which were mounted on both flanges of each cavity. The breakdown events were identified by monitoring the Faraday cup signal with the trigger set to twice the noise floor.

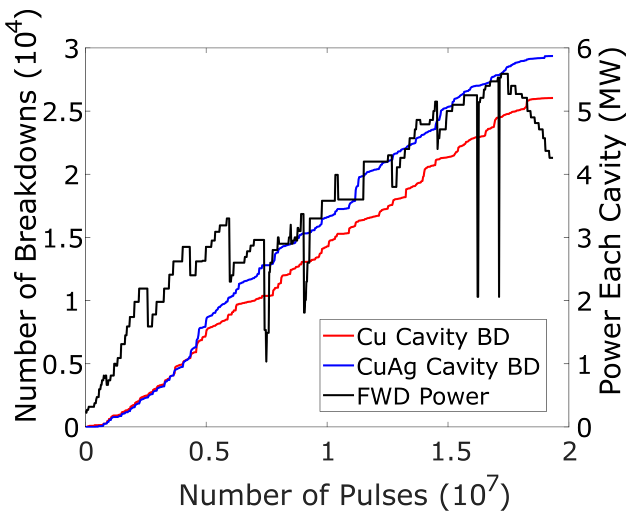

Figure 2: Executive summary of conditioning statistics over the two week high power test.

Conditioning would proceed by ramping up the pulse length from 400 ns to 1 μs and total power into each cavity up to 5 MW. Once the observed BDR dropped below 100 breakdowns per hour, power would be increased in 300 kW steps. For each step, around 20 traces would be recorded from all of the directional couplers and at least 2 Faraday cups. The conditioning summary is shown in Figure 2, confirming that the forward power into each cavity exceeded 5 MW. The breakdown rate within the CuAg started to exceed the Cu cavity, despite the power balance remaining fairly even.

HIGH POWER ANALYSIS

To compute the gradient and peak surface fields in the cavity for the given coupled power and pulse shape, the conventional analysis for high gradient normal conducting structures was used based upon a linear equivalent circuit model assuming a constant quality factor [22]. This modeled data is only utilized during the time when the RF drive signal for the klystron is on (up to t=1 μs). After the klystron drive is off a small amount of signal is detected on the forward power detector, either from a reflection or leakage of the emitted power from the cavity (nominally measured as the reflected power). The forward power detector cannot determine the phase or direction of travel for this signal. However, modeled data is only needed during the time that the klystron drive is on in order to determine the peak fields and gradient. At this time, the high power analysis for the CuAg cavity is still underway. All high gradient analysis presented in these proceedings is for the Cu cavity only.

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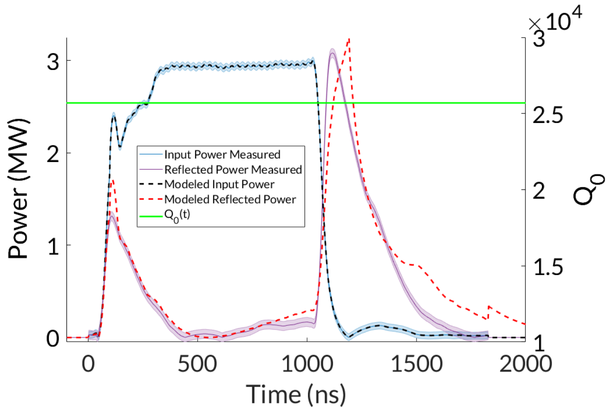
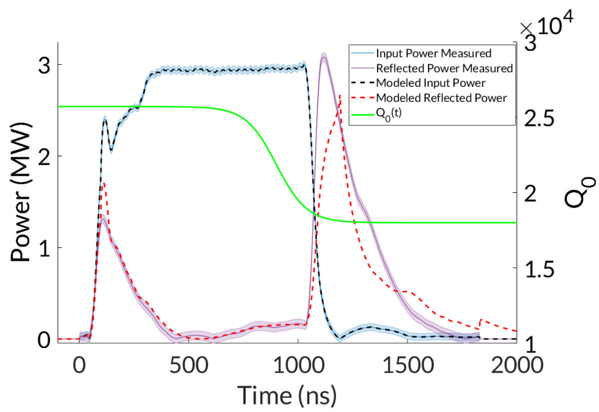


(a)

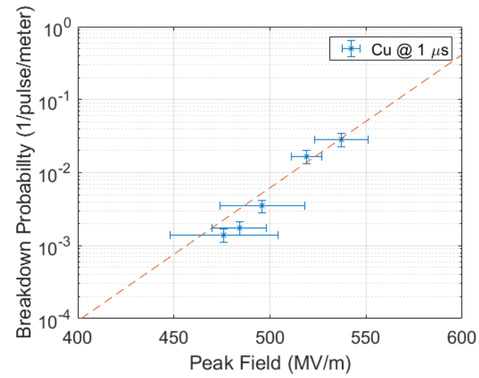


(b)

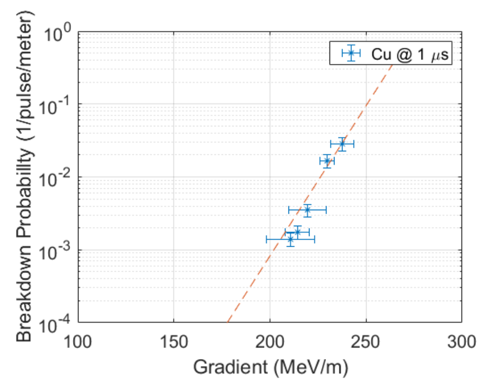
Figure 3: Pulse shapes for the forward and reflected power into the copper cavity measured and calculated assuming (a) constant quality factor within the cavity and (b) a transition in quality factor during the forward pulse. The time varying model fits the reflected power data better, implying the onset of beam loading within the cavity.

For this analysis we used the Ohmic and external quality factors, Q_0 and Q_{ext}, obtained during RF cold testing. During data processing, we found that, there was a small difference between the model and measured reflected power towards the end of the time when the klystron RF drive signal was on (from t=700 ns up to approximately t=1000 ns). Based on previous tests at X-band this was likely due to a change in quality factor within the pulse, which can occur at higher power levels as beam loading becomes more prevalent [23]. Refitting the data with a time-varying quality factor can improve this fit, and has a minor impact on the calculated gradient and peak surface fields.

Figure 4 shows the collected breakdown statistics for Cu cavity, where the probabilities of RF breakdowns are plotted as functions of peak surface electric field (E_p) and acceleration gradient. Already the improvement in overall field strength from cooling the cavity is apparent, with peak surface fields as high as 500 MeV/m. Similarly the gradient observed almost reached 250 MeV/m. Extrapolating back down to typical operating breakdown rates, this still would provide gradients well over 120 MeV/m.



(a)



(b)

Figure 4: BDR plotted as a function of (a) peak electric field on the surface of the copper cavity (E_p) and (b) acceleration gradient (E_{acc}). The trendlines are the data fitted to an exponential fit.

CONCLUSION

In summary, we have conducted high power tests in C-band copper and copper-silver cavities with as high as 5 MW dissipated within each cavity. These tests have demonstrated a tremendous gain in achievable surface field and acceleration gradient for a given breakdown rate, validating the cryogenic copper paradigm. In addition, the use of CuAg appears to maintained a slight improvement in quality factor even after high power testing. Future work will involve finalizing analysis of CuAg data to verify the cryogenic improvements over Cu and testing new cavity designs incorporating damping slits and different phase advances.

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