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C-BAND HIGH GRADIENT TESTING OF THE BENCHMARK a/λ=0.105 CAVITY*

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Abstract

This paper reports the design and status of high gradient testing of the benchmark C-band three-cell radio-frequency (RF) cavity. Modern applications such as X-ray sources require accelerators with optimized cost of construction and operation, naturally calling for high-gradient acceleration. At Los Alamos National Laboratory (LANL) we commissioned a C-band Engineering Research Facility of New Mexico (CERF-NM) powered by a 50 MW, 5.712 GHz Canon klystron. The test stand is capable of conditioning accelerating cavities for operation at surface electric fields in excess of 300 MV/m. CERF-NM is the first high gradient C-band test facility in the United States. An important milestone for this test stand is demonstration of conditioning and high gradient testing of the most basic high gradient RF cavity of geometry that has been extensively studied at other frequencies, such as X-band. The cavity is the three-cell structure with the highest gradient in the central cell and two coupling cells, and the ratio of the radius of the coupling iris to the wavelength a/λ=0.105. This paper reports current conditioning status, achieved gradients, and other characteristics measured during the high-power operation of this cavity.

INTRODUCTION

High gradient C-band (5.712 GHz) accelerator structure research is ongoing at Los Alamos National Laboratory (LANL) motivated by a number of LANL-specific mission needs. LANL has proposed a high gradient C-band upgrade to Los Alamos Neutron Science Center (LANSCE) proton linac to increase the final energy of the proton beam to 3 GeV. Material science research at LANL may benefit from a powerful directional high-repetition-rate X-ray source of 43 keV photons that may be produced by a 42 MeV electron beam through Inverse Compton Scattering (ICS). Achieving high gradient in normal-conducting radio-frequency (NCRF) copper-based accelerator structures requires understanding of copper alloys behavior under extreme electromagnetic fields and at its core is the material science problem which LANL is perfectly positioned to address leveraging its extensive expertise in material science and metallurgy [1].

We have recently commissioned the C-band Engineering Research Facility of New Mexico (CERF-NM) [2]. The CERF-NM is built around a 50 MW 5.712 GHz Canon klystron that produces 50 MW pulses with the pulse length between 300 ns and 1 microsecond, repetition rate up to 200 Hz, and is tunable within the frequency band of 5.707 GHz to 5.717 GHz. The RF power from the klystron is coupled into WR187 rectangular waveguide. The power is split into two halves by a magic tee that is installed at the klystron's output and protects the klystron from excess reflected power that may come from the device-under-test. The WR187 waveguide brings power into a 3 foot by 4 foot lead box that provides radiation protection to equipment and operators. The lead box is radiologically certified for dark currents with electron energy up to 5 MeV and average current up to 10 μA.

Many cavities that we plan to test at CERF-NM are to be coupled on axis to reduce peak surface magnetic fields. Thus, the mode launchers were designed and fabricated for the test stand. The mode launchers convert the TE_{10} mode of the rectangular WR187 waveguide into the TM_{01} mode of the cylindrical waveguide for the on-axis coupling. Four mode launchers were fabricated and conditioned up to the maximum input power of 10 MW. For more details on the mode-launcher design, fabrication, and testing see ref. [3].

One of the first cavity tests to be performed at CERF-NM aimed to establish the benchmark for high gradient performance at C-band. For this test we designed and fabricated a three-cell test structure with the ratio of the iris radius, a, to the wavelength, λ, of a/λ=0.105. The structure was a direct scale of the similar test structures fabricated and tested by other institutions at the frequencies of X-band and S-band [4,5]. This exact cavity shape is most commonly used to make comparison between high gradient performance of cavities fabricated of different alloys and by different fabrication methods. Testing the cavity of this most common shape at the frequency of 5.712 GHz allows us to eliminate the effects of specific cavity geometry on the high gradient performance and compare high gradient performance of C-band structures to that of the higher frequency structures (X-band) and lower frequency structures (S-band).

This paper summarizes the design parameters of the a/λ=0.105 test cavity, describes the results of fabrication and cold-testing of the two copper cavities, and reports the initial results of the high gradient testing of the first cavity and achieved peak surface fields.

DESIGN OF THE a/λ=0.105 BENCHMARK CAVITY

The scaling and design of the test cavity was performed with the CST Microwave Studio [6]. Distribution of the magnitude of the electric field in the three-cell structure is shown in Fig. 1 (top). The maximum electric field in the two coupler cells was approximately two times smaller

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than in the central cell that was designed to be subject to the highest surface fields. The structure had three resonant modes and the frequency of the highest (π-mode) was tuned to 5.712 GHz (Fig 1. (bottom)). The final design parameters of the cavity are summarized in Table 1.

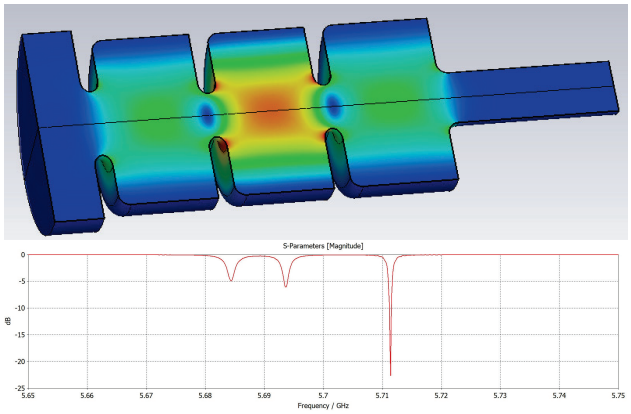

Figure 1: CST Microwave Studio design of the C-band a/λ=0.105 cavity: distribution of the electric field's magnitude (top), Reflection coefficient versus frequency (bottom).

Table 1: Design Parameters for the C-band Three-cell Benchmark a/λ=0.105 Cavity

Frequency	5.712 GHz
Cell length	1.034 inches
Iris radius, a	0.217 inches
a/λ	0.105
Q	12682
E/√P[MW]	87.1 MV/m
H/√P[MW]	127 kA/m

FABRICATION AND TESTING OF THE a/λ=0.105 BENCHMARK CAVITIES

Fabrication of the two cavities was done commercially by Dymenso, LLC in San Francisco, CA [7]. The three-cells were fabricated with the high precision milling and brazed together in a hydrogen oven. A photograph of the two fabricated cavities is shown in Fig. 2 (top). The cold test was performed by connecting a mode launcher to the input flange of the cavity and measuring the reflection coefficient (S_{11}). The on-axis electric field profile was measured with a beadpull to ensure the correct field distribution between the central cell and the two coupling cells. The results of the cold-test and beadpull for the first cavity are shown in Fig. 3. The cold-test and beadpull results for the second cavity looked very similar. The frequency of the first cavity in air was measured to be 5.7122 GHz that corresponded to the resonance frequency in vacuum of 5.7139 GHz. The frequency of the second cavity in air was measured to be 5.7120 GHz that corresponded to the resonance frequency in vacuum of 5.7137 GHz. Since both frequencies were found to be well within the bandwidths of the klystron and the mode-launchers, and the measured field profile looked very reasonable, tuning of the cavities was not performed.

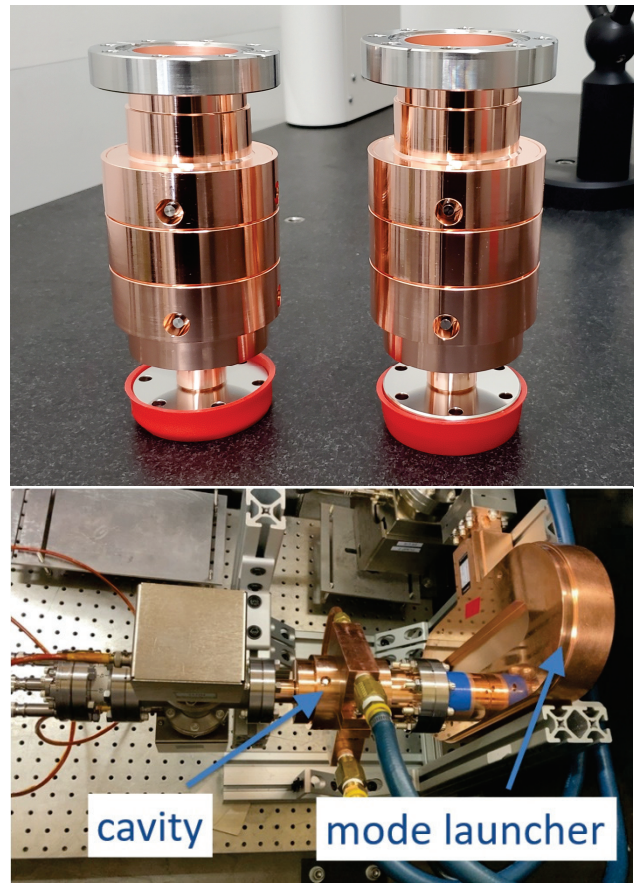

Figure 2: Photograph of the two fabricated C-band a/λ=0.105 cavities (top), Photograph of the C-band a/λ=0.105 cavity installed for high gradient testing at CERF-NM (bottom).

The two cavities were delivered to Los Alamos and the first cavity was installed at the CERF-NM for high gradient testing in May of 2022. The photograph of the high gradient test setup inside of the lead box is shown in Fig. 2 (bottom). The diagnostics on the waveguide line included the directional coupler installed right before the mode launcher to measure forward and reflected power and the Faraday cup for dark current measurements. Ion pumps were installed before the mode launcher and right after the cavity to ensure good vacuum during conditioning.

The first cavity is currently being conditioned to the highest gradient. At this point the conditioning is finished at the pulse lengths of 400 ns and 700 ns up to the highest input power of 10 MW. Estimated achieved peak fields in the cavity are E_{surf}=260 MV/m, H_{surf}=380 kA/m. Conditioning at the pulse length of 1000 ns is currently in progress. Upon conclusion of the high gradient conditioning the probabilities of breakdown in the cavity will be mapped at different pulse lengths as functions of the peak surface fields and the pulse heating.

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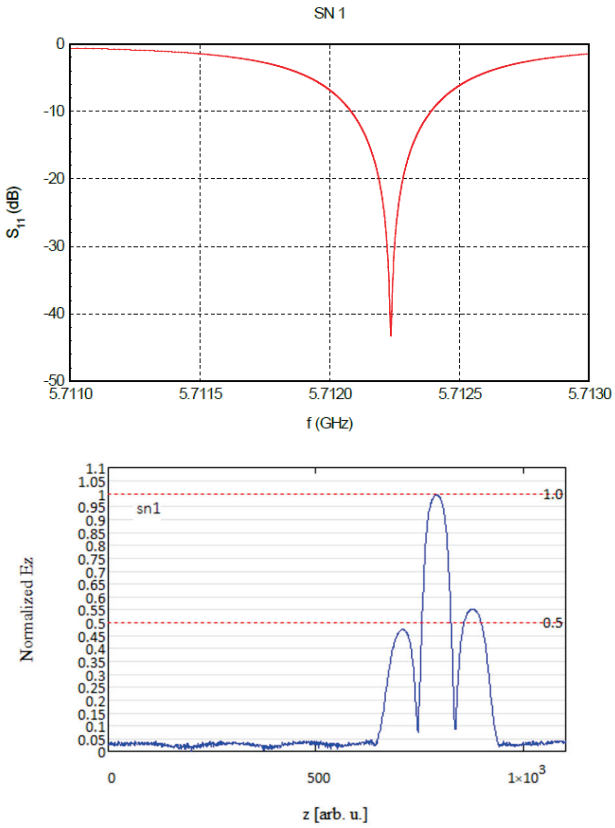

Figure 3: Cold-test results for the first C-band a/λ=0.105 cavity: S-parameter measurements (top), beadpull measurements of the electric field profile on-axis (bottom).

CONCLUSION AND PLANS

In summary, this paper reported the design, fabrication, cold testing of the two benchmark three-cell a/λ=0.105 copper cavities, and the initial results of high gradient conditioning of the first cavity. At LANL we commissioned a new C-band high gradient test facility CERF-NM, and high gradient testing of accelerator cavities has commenced. The two side-coupled proton accelerator cavities have already been tested at CERF-NM and the results of these tests are reported in [8]. The mode launchers were designed to convert the TE_{10} mode of the rectangular waveguide into the TM_{01} mode of the cylindrical waveguide for on-axis coupling into the test cavity. The mode launchers were successfully conditioned, and the first cavity with the on-axis coupling is now undergoing the high gradient testing. The maximum power of 10 MW was coupled into the cavity at the pulse lengths of 400 ns and 700 ns. Later in 2022 we plan to condition and test the second a/λ=0.105 copper cavity fabricated by milling and brazing. After that we plan to test several cavities of the same geometry fabricated with different fabrication methods and of different materials. A welded copper has been recently delivered to LANL and is undergoing cold-testing and tuning. This cavity has been fabricated by milling the two halves made of hard copper and then welding them along the longitudinal seam with electron beam welding. Two more cavities are currently in fabrication, one cavity will be fabricated of copper-silver alloy with 0.085% of silver, and another one of copper-silver alloy with 2% of silver. LANL's team recently came up with a theoretical prediction that a copper-silver cavity made of an alloy with higher concentration of silver should be able to condition to higher peak surface fields and accelerating gradients [9].

The newly established C-band high gradient test facility is open to collaborators. Beyond operating CERF-NM, LANL has plans for further development of its C-band accelerator capabilities. As a next step, LANL plans to construct the C-band accelerator test facility for cathode, accelerator, and material science studies. A radiation protection vault was identified on LANSCE mesa capable of accommodating an electron beam with the beam power up to 20 kW. The new location will house a cryo-cooled copper rf photoinjector with a high quantum-efficiency cathode and a high gradient accelerator section. The ultimate goal for the test facility would be to demonstrate production of a 42 MeV electron beam in a very compact footprint and generate 43 keV photon bursts for material science studies.

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