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FIRST C-BAND HIGH GRADIENT CAVITY TESTING RESULTS AT LANL*

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Abstract

This paper reports the initial results of high gradient testing of two proton β=0.5 C-band accelerating cavities. The cavities for proton acceleration were fabricated at SLAC National Accelerator Laboratory (SLAC) and are in the process of being tested at the high gradient C-band accelerator test stand at Los Alamos National Laboratory (LANL). One cavity was made of copper, and the second was made of a copper-silver alloy. LANL test stand was constructed around a 50 MW, 5.712 GHz Canon klystron and is capable of providing power for conditioning single cell accelerating cavities for operation at surface electric fields up to 300 MV/m. These β =0.5 C-band cavities are the first two cavities to be tested at LANL's C-band test stand. This presentation reports achieved gradients, breakdown probabilities, and other characteristics measured during the high power operation.

INTRODUCTION

Particle accelerators are established tools for National Security (NNSA, DoD), medicine, and basic science missions. Modern day applications such as X-ray sources require accelerator facilities with optimized cost of construction and operation, naturally calling for high-gradient acceleration. Increasing gradients in normal-conducting radio-frequency (NCRF) copper-based accelerator structures have been a continuous research focus for the international high gradient community in the recent years. At Los Alamos National Laboratory (LANL) we initiated a new project with the major goal to use a multi-disciplinary approach that includes accelerator design, molecular dynamics simulations, and advanced manufacturing of metals to develop high-gradient, high-efficiency radio-frequency (RF) structures for both compact and facility-size accelerator systems [1]. As a part of the project we put together a new high gradient test stand called C-band Engineering Test Facility in New Mexico (CERF-NM) that allows for high gradient testing of the C-band accelerating structures. As a part of a collaboration with Stanford Linear Accelerator Center (SLAC) National Accelerator Laboratory, LANL has started testing two high gradient C-band accelerator cavities designed for operation with the proton beam traveling at half of the speed of light (β=0.5).

This work at LANL is conducted in the framework of the Technology Evaluation and Development program with the goal to assess parameter and performance ranges for the high energy pRad upgrade based on C-band high gradient copper accelerating structures. The purpose of the work at SLAC is to develop a compact beam delivery system capable of delivering protons with a rapid (order of seconds) 3D scanning for cancer therapy. Treatment of cancer using hadron particle beams (protons and light ions) has significant advantages over treatments using photons. However, the accelerators as well as the gantries supporting the beam delivery systems are significantly larger and more expensive than conventional radiation therapy machines and gantries. The particle beams also have slow energy scanning rates, which increases the overall treatment time and makes the treatment plan susceptible to patient motion. In addition, the full potential of these machines is compromised because the slow methods used to adjust beam energies, also introduce additional energy and momentum spread in the beam. SLAC goal is to enable 3D scanning over a tumor volume of up to 4 liters in both transverse and longitudinal dimensions [2, 3]. The cavity that is described in this paper is used to adjust the energy of the proton beam for longitudinal variation in dose deposition. It is designed for optimal operation with 150 MeV protons with a radial port for coupling power and no on-axis coupling. Each accelerating cell in the linac will be individually powered so that the phase can be adjusted for the beam energy to vary rapidly and dynamically. This allows the linac to maintain its efficiency whether accelerating or decelerating the beam within a range of at least 50 MV/m.

HIGH GRADIENT TESTING SYSTEM

The CERF-NM test stand is built around a 50 MW 5.712 GHz Canon klystron. The klystron system 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 is being output in a 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. The WR187 waveguide continues into a 3 foot by 4 foot lead box that is designed to protect equipment and operators from X-rays generated in cavities under high gradient testing. The lead box is radiologically certified for dark currents with electron energy up to 5 MeV and average current up to 10 μA. A vacuum window is installed in the waveguide before the entrance into the lead box. This allows to separate the vacuum in the magic tee and the long waveguide from the vacuum in the lead box and to quickly exchange the cavities for testing without the need to recondition the whole wave-

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guide system. The cavity's diagnostics in the lead box includes the vacuum gauge, the directional coupler that measures incident and reflected powers, and Faraday cups for the dark current measurements. The waveguide line and the cavity are pumped by multiple ion pumps. The whole waveguide line was fully conditioned for operation with the input power up to 30 MW, pulse length of 1 µs, and repetition rate of 100 Hz. For more details on the CERF-NM test stand please see [4].

SLAC BETA=0.5 ACCELERATOR CAVITY

The SLAC proton β=0.5 cavity represents a single elliptically shaped resonator with the two beam pipes on each end. The power is being coupled into the resonator from a WR187 waveguide on the side of the resonator. The waveguide ends with a Riken-DESY flange. The accelerating characteristic of the cavity are summarized in Table 1.

Table 1: Characteristics of the C-Band β=0.5 Cavities

Frequency	5.712 GHz
Length	1.18 cm
Shunt impedance	77.78 MΩ/m
E_a	81.19 $\sqrt{P[MW]}$ MV/m
E_p/E_a	2.26
H_p*Z_0/E_a	1.25
Q_{ext}	8485
$2*\tau$	945 ns

Two cavities were fabricated at SLAC by conventional milling followed by brazing. One cavity was made of a pure high conductivity copper, and the other one was made of a copper-silver alloy with 0.085% of silver. The photographs of the two cavities are shown in Fig. 1 (left). The cavities were cold-tested and tuned to the frequency close to 5.712 GHz. The final measured coupling curves are shown in Fig. 2.

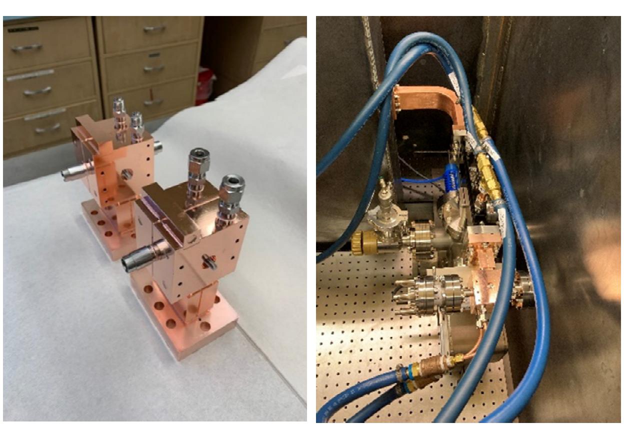

Figure 1: A photograph of the two β=0.5 accelerator cavities fabricated at SLAC (left). A photograph of the copper cavity installed on the test stand for high gradient testing (right).

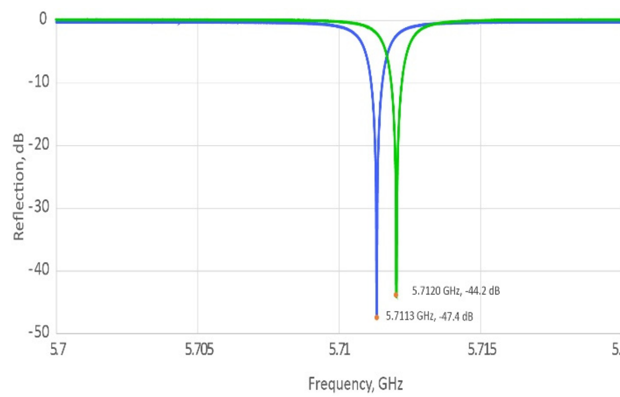

Figure 2: The results of the cold-test measurements for the two β=0.5 cavities. The green line is for the copper cavity, and the blue line is for the copper-silver cavity.

At the moment, the copper cavity is installed at the end of the waveguide line at CERF-NM (Fig. 1 (right)) and is undergoing the high gradient testing.

HIGH GRADIENT TESTING OF THE CAVITY

We started testing the copper cavity at the pulse length of 300 ns. The repetition rate is kept at 100 Hz through the whole testing. The testing was started with the power of 100 kW going into the cavity and increase it in 100 kW increments. We observed the first breakdowns at the power level of 700 kW. The breakdowns happened towards the end of the pulse and manifested with the strong dark current measured by a Faraday cup installed on the beam port of the cavity.

The typical RF and Faraday cup pulses for the cavity are shown in Fig. 3. The filling time for the cavity is close to 1 microsecond. Therefore, the cavity does not reach the maximum gradient for the given power during the 300 ns RF pulse. This is evident from the reflected power that does not go all the way to zero. The conditioning process is monitored by a data acquisition software developed specifically for the test stand (for more details see [5]). The software computes the frequency of breakdown pulses that decreases with time when operating at a given power level. When the number of breakdowns goes below 100 in one hour, the power to the cavity is increased. The conditioning will be complete and the final gradients will be attained at the power level when the breakdown rate stops decreasing. At this time we will measure the breakdown probability as a function of the peak surface field in the cavity.

Currently the cavity is operated at the input power of 1.3 MW. For the fully filled cavity that would correspond to the accelerating gradient of 92.5 MV/m, and the peak surface electric field of 209 MV/m. Once the conditioning at the pulse length of 300 ns is complete, the process will be repeated at the pulse lengths of 400 ns, 700 ns, and 1 microsecond.

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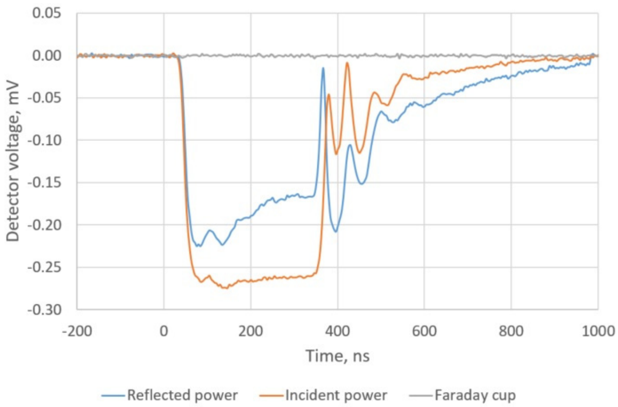

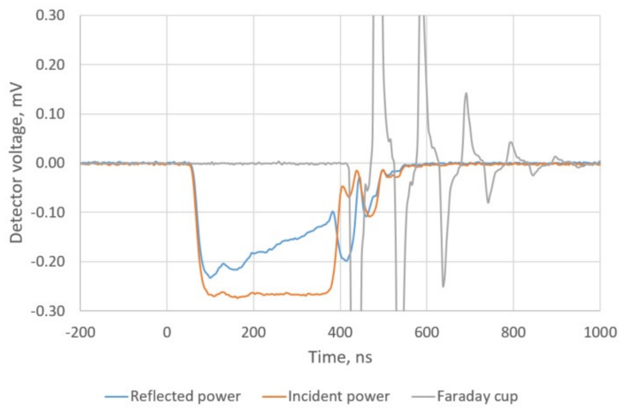

Figure 3: Two typical RF pulses measured during the conditioning of the copper β=0.5 cavity: the 300 ns pulse delivered with no breakdown (top); the 300 ns pulse during the breakdown (bottom). The breakdown usually happens towards the very end of the pulse and is characterized by the strong current measured on the Faraday cup.

CONCLUSIONS AND FUTURE PLANS

In summary, a new C-band high gradient test facility called CERF-NM has been commissioned at LANL, and high gradient testing of accelerator cavities has commenced. The first accelerator cavity has now been installed at the facility and is undergoing the high gradient conditioning. This cavity was manufactured by SLAC National Accelerator Laboratory. It is a proton accelerator cavity with a side WR187 waveguide coupler designed to resonate with β=0.5 protons. At this point the cavity is operated with 300 ns long pulses, 100 Hz repetition rate. The maximum power that was coupled into the cavity was 1.3 MW. During conditioning we observe multiple RF breakdowns characterized by a strong current measured by the Faraday cup. The frequency of breakdowns seem to steadily decrease during the conditioning. The RF power is increased each time the number of breakdowns gets as low as 100 breakdowns per hour. We will continue conditioning at the current pulse length as long as the frequency of breakdowns keep decreasing. The conditioning will then be repeated at the pulse lengths of 400 ns, 700 ns, and 1 microsecond. Once the conditioning is complete, we will measure breakdown's probability as a function of the peak surface fields. When conditioning and characterization of the copper β=0.5 cavity is complete, the copper-silver cavity will be tested in a similar manner. We expect to complete this project in summer of 2021.

The team plans to continue with conditioning of the mode launchers for testing the cavities with on-axial couplers [6] and to test other accelerating cavities. We expect that the test stand will be open to multiple collaborators starting in fall of 2021.

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