PLANS FOR CRYOGENIC C-BAND PROTOTYPE TESTS FOR LANL PRAD BOOSTER LINAC*

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Abstract

We report the plans for testing a four-cell C-band (5.712 GHz) normal conducting radiofrequency (RF) accelerator cavity at liquid-nitrogen temperature under high accelerating gradient, being prototyped and proposed for the booster linear accelerator (linac) upgrade for the Proton Radiography (pRad) facility at Los Alamos National Laboratory. Operating RF structures at cryogenic temperature enhances copper conductivity, enabling higher accelerating gradients and greater RF-to-beam power efficiency. The prototype cavity will be housed inside a cryo-module with foam insulation for both low-power and high-power tests. Pulsed RF power up to 12 MW will be available for the high-power experiment. We also report the engineering and mechanical design of the prototype cavity.

INTRODUCTION

A Laboratory Directed Research and Development (LDRD) Directed Research (DR) project was funded at Los Alamos National Laboratory (LANL) to theoretically and experimentally research on using a high-gradient radiofrequency (RF) accelerator operating at liquid-nitrogen temperature (77 K) for building an energy booster linear accelerator (linac) [1], accelerating the negative hydrogen ion (H^-) beam from 800 MeV to 3–5 GeV, for the upgrade of the Proton Radiography (pRad) facility at Los Alamos Neutron Science Center (LANSCE) [2].

The fundamental RF frequency of LANSCE accelerator complex is 201.25 MHz. Downstream of the LANSCE Coupled-Cavity Linac (CCL), the H^- beam enters the energy booster linac with a kinetic energy of 800 MeV. The beam undergoes bunching and acceleration through L- (1408.75 MHz), S- (2817.50 MHz), and C-band (5635.00 MHz) structures in series, reaching 3–5 GeV before entering the imaging system [3]. In this project, we are designing, fabricating, and testing one S-band (2856.00 MHz) and one C-band (5712.00 MHz) prototype structure, respectively. Both cavities will comprise four cells using distributed coupling. The tests will include low-power characterization at both room temperature and cryogenic temperature, and high-power RF test. The cavity operating frequencies differ from their nominal values due to the unavailability of RF sources at the nominal frequencies.

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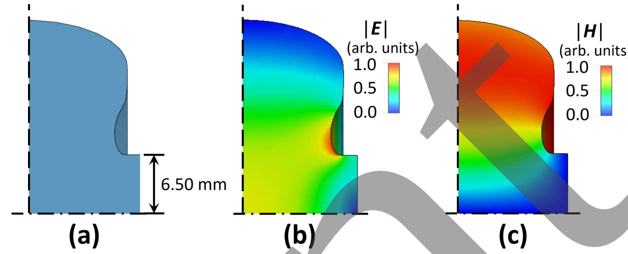

Figure 1: Optimized C-band cell design, with (a) cell profile, (b) normalized E-field distribution, and (c) normalized H-field distribution.

The C-band structure will be tested at LANL, whereas the S-band structure will be fabricated and tested at RadiaBeam Technologies, LLC.

C-BAND CELL DESIGN

The individual cell design for the C-band four-cell cavity was optimized in the code Superfish [4], driven by a Multi-Objective Genetic Algorithm (MOGA) implemented on LANL High-Performance Computing (HPC) clusters [5]. A quarter longitudinal cross section view of the optimized cell design is shown in Fig. 1. The Superfish results were validated in the CST Eigenmode Solver [6], and a summary is provided in Table 1. The cell length, L_{cell} = 24.38 mm, is matched to the H^- beam propagation distance over half an RF cycle at 5.712 GHz, at a kinetic energy of 1.6 GeV; the beam aperture radius, a = 6.50 mm, was determined taking into account the beam halo.

In the chart, Z_0 = 120 Ω is the impedance of free space, and E_{acc} is accelerating gradient. We performed iterative MOGA evaluations and converged to a set of criteria of $E_{pk}/E_{acc} \leq 2.50$, $H_{pk} \cdot Z_0/E_{acc} \leq 1.20$, $\max\{|\mathbf{E}| \cdot |\mathbf{H} \cdot Z_0|/E_{acc}^2\} \leq 2.00$, while maximizing the shunt impedance. In this paper, shunt impedance takes into account particle transit time.

Table 1: Optimized C-band cell eigenmode simulation results in Superfish and CST. Room-temperature (293 K) copper electrical conductivity, 5.8×10^7 S/m, was assumed.

Parameter	Superfish	CST
Resonant frequency [MHz]	5712.44	5710.40
Shunt impedance [MΩ]	1.75	1.74
Unloaded quality factor	12599	12554
E_{pk}/E_{acc}	2.50	2.49
$H_{pk} \cdot Z_0/E_{acc}$	1.16	1.18
$\max\{\lvert\mathbf{E}\rvert \cdot \lvert\mathbf{H} \cdot Z_0\rvert/E_{acc}^2\}$	1.99	1.93

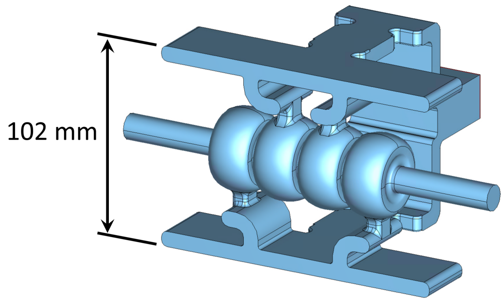

Figure 2: Vacuum model of the four-cell cavity.

FOUR-CELL CAVITY DESIGN

With the individual-cell design selected, we performed distributed RF coupling design. As the first step, we needed to evaluate the coupling coefficient at 77 K. The goal was to achieve 95% field filling at the end of the 1.25-μs square-pulse of forward RF (5.712 GHz) power, which led to the required loaded quality factor being $Q_L = 7488$.

To evaluate the coupling factor, we followed the established anomalous skin effect (ASE) calculation workflow [7, 8], assuming residual resistance ratio (RRR) of 100 for Unified Numbering System (UNS) Oxygen-Free Electronic (OFE) copper, UNS C10100. Our result showed that at 77 K, the unloaded quality factor Q_0 increases by a factor of 2.654, compared to its value at 293 K. Therefore, our estimate was that $Q_0 \approx 33324$ at 77 K, and thus the coupling factor would be $\beta \approx 3.45$.

In the four-cell cavity design, forward RF power enters the cavity through a WR187 waveguide port, split first through an H-plane junction and propagating to the two manifold waveguides, and then split for a second time through an E-plane junction to enter the respective manifold waveguide [9]. The vacuum model of the cavity is provided in Fig. 2. The complex, asymmetric fillets of the coupling slots were modeled in SolidWorks. The entire RF modeling was performed using dimensions at 77 K; RF simulations were performed in CST Frequency-Domain Solver. Normalized E- and H-field magnitude contour plots of the cavity at the resonant frequency of 5.712 GHz are provided in Fig. 3.

To determine the model dimensions for fabrication and to evaluate the RF performance of the cavity at room temperature (293 K), we referred to the polynomial fit recommended by the National Institute of Standards and Technology (NIST) [10]; our result indicated that the linear thermal contraction factor of UNS C10100 copper from 293 K to 77 K was $\alpha_L = 0.996962$. In parallel, we performed ANSYS Mechanical simulation of the cavity cooling down from 293 K to 77 K; the linear contraction of the accelerator cells was by a factor of 0.996872, which was in excellent agreement with the analytical calculation using the NIST reference. The RF response and the normalized on-axis accelerating field distribution of the cavity at both temperatures are provided in Fig. 4 and Fig. 5, respectively. It can be seen that the field balance is independent of the temperature.

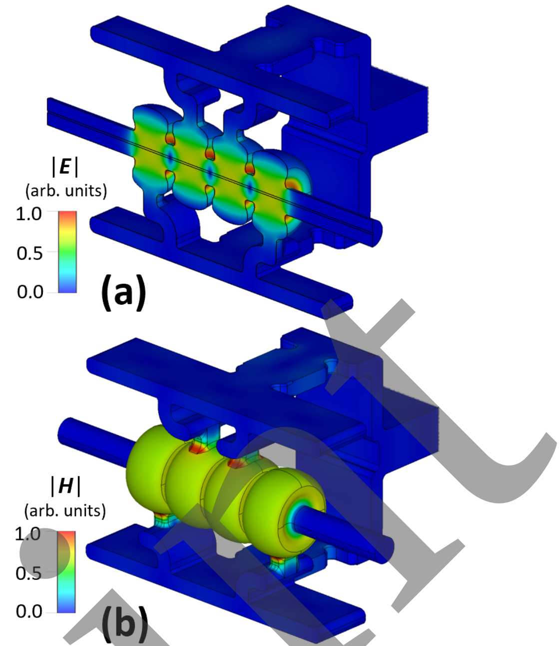

Figure 3: Normalized (a) electric and (b) magnetic field magnitude contour plots of the four-cell cavity.

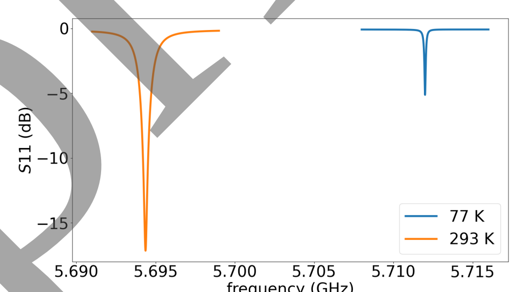

Figure 4: Reflection coefficient ($S11$) of the four-cell cavity.

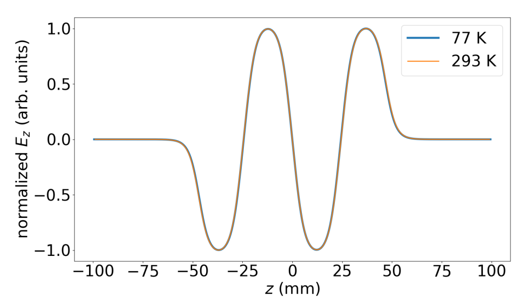

Figure 5: On-axis E-field distribution of the four-cell cavity.

The RF performance of the cavity at both 77 K and room temperature (293 K) is summarized in Table 2. Compared to the eigenmode simulation results shown in Table 1, the shunt impedance of the realistically designed cavity is smaller by 3.4%, likely due to the additional ohmic loss introduced at the coupling port. The normalized peak H-field is higher after the coupling port is introduced, located at the coupling port fillets; the H-field enhancement factor is 1.38, which is defined as the ratio of peak H-field in the coupled model

Table 2: RF performance of the four-cell C-band cavity at 77 K and room temperature (293 K), predicted by CST Frequency-Domain Solver.

Parameter	77 K	293 K
Resonant frequency [MHz]	5712.00	5694.37
Shunt impedance [MΩ]	4.56	1.68
Unloaded quality factor	32605	12289
Loaded quality factor	7261	5292
Coupling factor	3.49	1.32
E_{pk}/E_{acc}	2.50	2.50
$H_{pk} \cdot Z_0/E_{acc}$	1.63	1.63

divided by that in the corresponding eigenmode model. At steady state, to reach an accelerating gradient of 100 MV/m, the required forward RF power is 7.56 MW; considering the transient RF filling, the attainable accelerating gradient at the end of a 1.25-μs, 12-MW RF pulse is 120 MV/m.

MECHANICAL DESIGN

An overview of the mechanical design of the C-band four-cell cavity is shown in Fig. 6. This cavity was modeled in SolidWorks and is currently under fabrication at Dymenso, LLC. The dimensions were modeled according to their room-temperature values. The waveguide network splitting the forward RF power and the four-cell array are machined separately, each divided into two halves; the main body of the cavity is therefore brazed with four copper components.

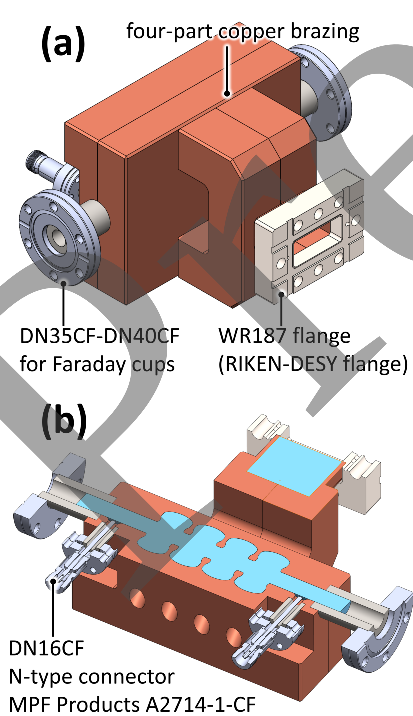

Figure 6: Mechanical design overview of the four-cell cavity, showing (a) the cavity as a brazed body of four major copper components, and (b) the half-section view illustrating the field probes.

We introduced two field probes at the two ends of the four-cell array, respectively, for measuring the RF field strength during the high-power test. The RF power transmission measured from the WR187 waveguide port to the probe is −77 dB. With a forward RF power of 12 MW, the peak value of the RF voltage measured at the coaxial transmission line port of each probe will be around 3 V.

EXPERIMENTAL PLANNING

The C-band cavity will be tested on-site at LANL using the established ScandiNova K300 modulator-klystron system, inside the vault previously used by the CAthodes and Rf Interactions in Extremes (CARIE) project [11, 12]. The available pulsed RF power is 12 MW, limited by the certification of the RF windows of the Microwave Techniques high-power circulator. The K300 system can output up to 50 MW.

A liquid nitrogen cryo-module will be designed and fabricated, drawing on a foam-insulated concept developed at SLAC National Accelerator Laboratory. Relevant safety interlocks, including oxygen deficiency monitoring, have been established. A Radiation Engineering Design Analysis (REDA) will be performed following the finalization of the nitrogen vapor venting configuration. In particular, neutron radiation safety will be carefully evaluated, as dark-current electrons may reach energies above the neutron production threshold in copper.

CONCLUSIONS

A four-cell, C-band (5.712 GHz) prototype accelerator cavity for Proton Radiography (pRad) energy booster linac was designed and is under fabrication, for high-power testing at 77 K at Los Alamos National Laboratory, using a liquid-nitrogen cryo-module.

The individual-cell profile was optimized using Superfish, driven by a Multi-Objective Genetic Algorithm. The four-cell cavity was designed to be over-coupled, theoretically capable of reaching an accelerating gradient of 120 MV/m with the existing RF infrastructure. The cavity design took into consideration the anomalous skin effect and thermal contraction of structure cool-down.

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