STATUS OF THE CARIE HIGH GRADIENT PHOTOCATHODE TEST FACILITY AT LANL*

E. I. Simakov[†], W. Choi, W. B. Haynes, S. S. Kurennoy, V. Pavlenko, D. Rai, T. Tajima, H. Xu
Los Alamos National Laboratory, Los Alamos, NM, United States

Abstract

This paper reports on the status of assembling and commissioning of the Cathodes And Radio-frequency Interactions in Extremes (CARIE) C-band high gradient photoinjector test facility and the status of high gradient testing of a 1.6 cell C-band RF photoinjector at Los Alamos National Laboratory (LANL). The construction of CARIE began in October of 2022. CARIE will house a high gradient copper RF photoinjector and other high gradient C-band accelerating structures (e.g., multi-cell cryo-cooled accelerating structures). The 50 MW 5.712 GHz Canon klystron powers the facility. The klystron was installed and conditioned in 2023. The output of the klystron is connected to a circulator that was conditioned to operate for up to 12 MW of power. The WR187 waveguide line brings the power from the circulator into a concrete vault that is rated to provide radiation protection for electron beam powers up to 20 kW. The first RF injector that was fabricated is made of copper and does not have cathode plugs. This injector is installed at the end of the waveguide line and is awaiting high gradient conditioning, which will validate operation of the CARIE facility. This paper provides the update on the status of the facility, the designs of the photoinjector and the beamline, and the status of the high-power testing of the injector.

INTRODUCTION

At Los Alamos National Laboratory (LANL), we conduct high gradient C-band accelerator studies motivated by multiple LANL projects and future mission needs. For example, LANL proposed a high gradient C-band upgrade to Los Alamos Neutron Science Center's (LANSCE) proton linac to enable higher energy proton radiography [1, 2]. There is also an identified need for a powerful directional high-repetition-rate narrow-bandwidth complementary X-ray Inverse Compton Scattering (ICS) light source at LANSCE [3]. The accelerator structures delivering beams for these proposed facilities must operate at high accelerating gradients because of the space limitations. For applications such as the LANSCE proton booster linac, testing of longer, multi-cell accelerating structures is also desired [4], which would result in production of energetic dark current that prevents testing these structures in a test stand with limited radiation protection such as LANL's C-band Engineering Research Facility in New Mexico (CERF-NM) [5].

The construction of Cathodes And Radio-frequency Interactions in Extremes (CARIE) [5, 6] test facility started in October of 2022. We prepared a new radiation protection vault rated for electron beam energy up to 20 MeV and electron beam power up to 20 kW. We procured and commissioned a new C-band klystron from Scandinova, designed, installed, and conditioned the waveguide line that includes a high-power circulator and brings the RF power from the klystron into the vault, and designed and installed the all-copper RF photoinjector structure at the end of the waveguide line. The photoinjector that is currently installed at the end of the line has a non-removable copper photocathode. Commissioning the photoinjector to its full operational parameters will verify the operational functionality of the constructed CARIE facility for testing of the high gradient structures. This paper describes the current status of CARIE and photoinjector commissioning work.

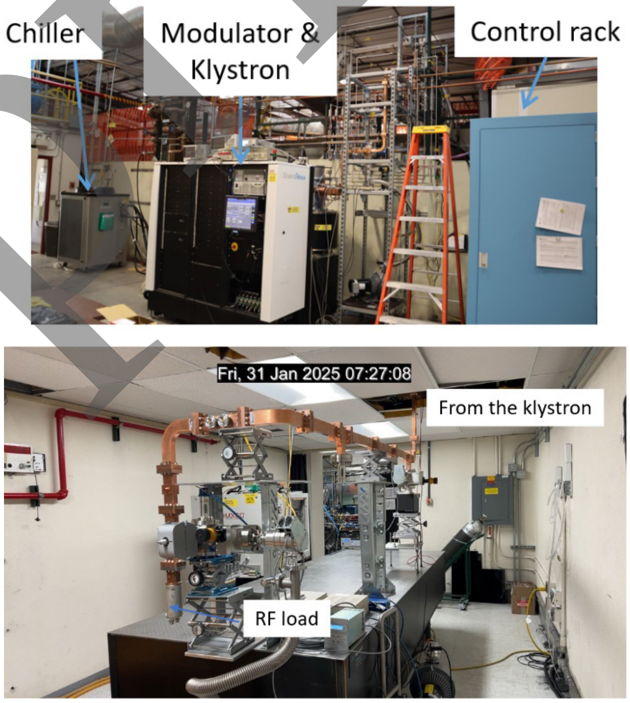

Figure 1: A photograph of the CARIE klystron (top); a photograph of the waveguide line inside of the CARIE vault before installation of the RF photoinjector (bottom).

STATUS OF THE INSTALLATION AND COMISSIONING OF THE WAVEGUIDE LINE

The RF power to the CARIE facility is provided by the 50 MW C-band klystron received from Scandinova Systems and installed in 2023 [Fig. 1 (top)] [7]. The klystron was fully conditioned to the peak output power of approximately 30 MW with 30 Hz repetition rate limited by the

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† smirnova@lanl.gov

cooling capacity of the available chiller. The waveguide line to the high-power circulator on the roof of the vault was assembled and conditioned in early 2024. The circulator was conditioned up to 12.5 MW of power, its operation limited by the SF6 pressure inside of the circulator that had to stay below 25 psig due to LANL's pressure safety regulations as opposed to the manufacturer specified pressure of 50 psig [6].

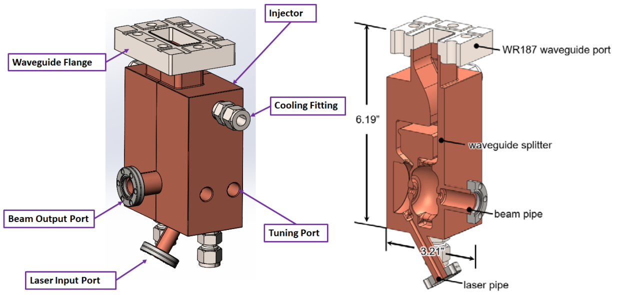

Figure 2: The CAD model of the 1.6 cell all-copper RF photoinjector for CARIE (left); a longitudinal cross-section of the CAD model showing details of the design (right).

Table 1: Design Characteristics of the 1.6-Cell Injector with a Copper Cathode

Frequency	5.712 GHz
Phase advance per cell	π
Iris radius	2.0 mm
Ohmic quality factor, Q_w	11934
Filling time, 2τ	665 ns
Power for 100 MV/m cathode field	1.64 MW
Power for 240 MV/m cathode field	9.45 MW
Power for 240 MV/m cathode field in 1 μs long pulse	10.46 MW
Final beam energy for 240 MV/m cathode field (lowest emittance)	6.67 MeV
E_{max}/E_{cath}	1.28
$H_{max}*Z_0/E_{cath}$	0.882

The remaining waveguide line into the load was assembled and conditioned in early 2025 [Fig. 1 (bottom)]. The line ended with a high-power load. The maximum power coupled into the RF load at the pulse width of 1 μs and repetition rate of 30 Hz was 11.8 MW. This power was slightly less than the maximum power measured at the circulator because of the ohmic losses over the length of the waveguide.

STATUS OF THE INSTALLATION AND COMISSIONING OF THE PHOTOINJECTOR

Operation of the CARIE facility will be first tested with a 1.6-cell C-band high-gradient RF photoinjector. The goal for the first photoinjector design and installation was to demonstrate operations with a simple cavity and electron beam production. The first photoinjector was made with a copper photocathode. The cell profile was optimized to reduce peak surface fields for the high gradient and to keep the injector operating below the threshold of notable dark current emission even at 240 MV/m electric fields at the cathode [8]. Approximately 10.46 MW of peak RF power is required to operate this photoinjector at 240 MV/m cathode field at room temperature with a 1 μs pulse length. The CAD model of this RF injector and its cross-section is

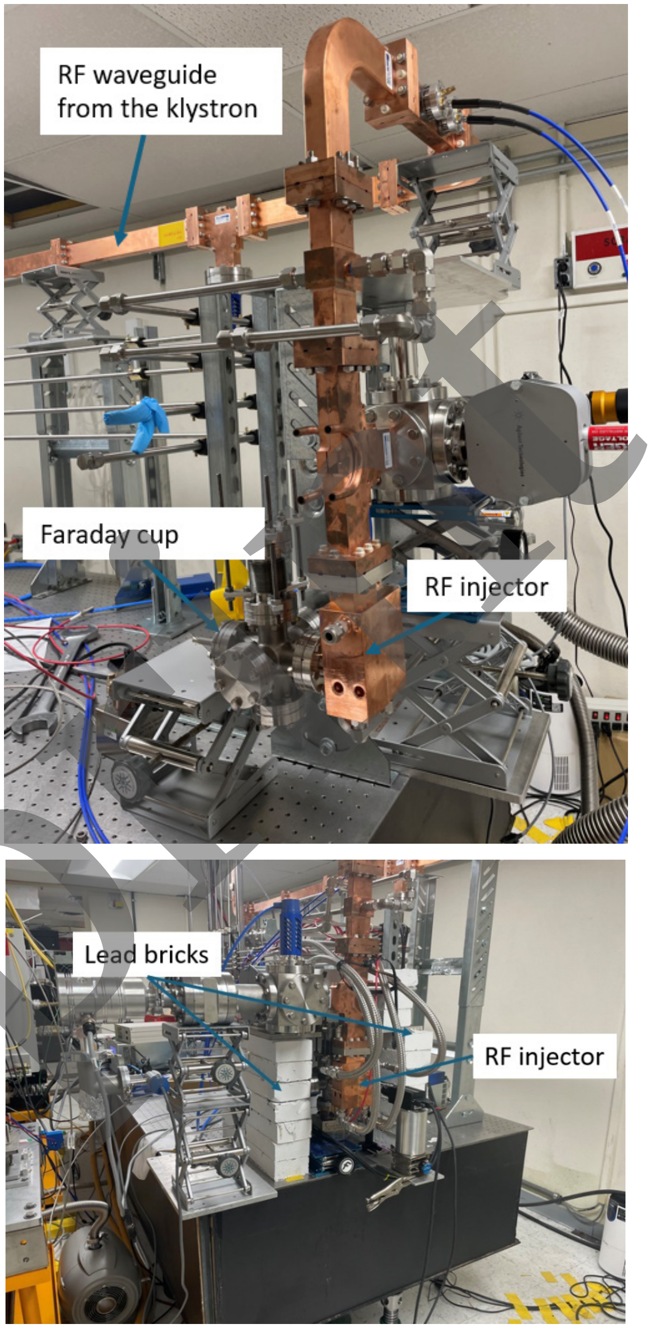

Figure 3: A photograph of the RF injector installation at the end of the waveguide line (top); a photograph of the RF injector covered with the lead igloo for radiation protection (bottom).

shown in Fig. 2. Its dimensions and computed electromagnetic characteristics are summarized in Table 1.

The all-copper RF photoinjector was fabricated by Dymenso, LLC and delivered to LANL in Fall of 2023. The injector was cold-tested and tuned to achieve the correct coupling frequency and the uniform field profile. Tuning of the injector was performed with pushing and pulling on the stainless-steel tuning studs in both cells. The bead pull test was performed after each round of tuning until a balanced field profile was measured in the two cells. Final measured characteristics were in good agreement with the design and CST simulations and reported in Ref. [7].

The injector was installed at the end of the waveguide line as shown in Fig. 3 (top). A small diagnostics beamline was attached to the output beam port which included a movable YAG screen for imaging the dark current and the Faraday cup.

Radiation safety simulations were conducted with MCNP code [9] for this configuration to ensure adequate radiation protection with the expected dark current produced during the conditioning. The results of these simulations are shown in Fig. 4. To model the worst-case scenario, the energy of the dark current was assumed to be 7 MeV, and the average current was assumed to be 1 μA. The Radiation Engineering Design Analysis (REDA) stipulated that the equipment will be in operation for a maximum of 1000 hours per year. Per the report, the primary radiological effects of this setup were the X-rays produced via Bremsstrahlung from the high energy electrons impinging on the stainless-steel Faraday cup. The production of neutrons was also considered for this operation due to the neutron generation threshold in copper of approximately 5.7 MeV and found to have a negligible contribution to possible radiation doses. Two scenarios were modelled with MCNP. In the first scenario, the injector was positioned on the steel optical table approximately 43 inches above the ground with no additional shielding. In the second scenario, a lead igloo was proposed to be constructed around the beam pipe and the Faraday cup. REDA recommended the igloo to be constructed with a minimum of 4-inch-thick walls (the width of a 1 standard lead brick) on the downstream side of the beamline and on the top of the igloo, and of 2-inch-thick (the thickness of a 1 standard lead brick) walls on other sides of the beamline.

Simulations suggested that addition of the shielding lead igloo brought the dose rates throughout the experimental building to near background levels with the exception of the roof of the building and the roof of the CARIE vault. The highest doses expected in both scenarios were found on the roof of the CARIE vault, particularly around the waveguide penetration opening. Addition of the lead igloo reduced those rates by 97% to about 8 mrem/hr. Due to remote potential of a higher dose, however, it was recommended that the ladder access to the roof of the CARIE vault was posted and interlocked. It was also recommended to coordinate with the facilities department to ensure that workers do not go to the roof of the building during electron beam injector operations. Given recommendations from the REDA, the lead igloo was constructed around the injector [Fig. 3 (bottom)]. Conditioning of the injector is allowed to commence once the appropriate interlocks are implemented.

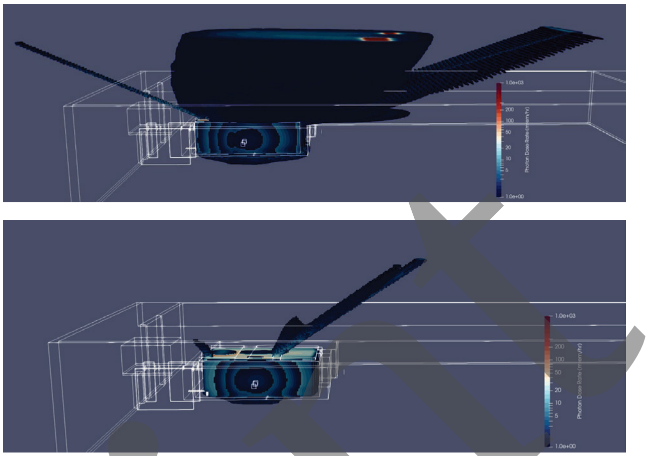

Figure 4: 3D radiation dose map without shielding lead igloo in place (top); 3D radiation dose map with the shielding lead igloo around the injector, beam pipe, and the Faraday cup (bottom).

CONCLUSION AND PLANS

In summary, this paper reported the status of construction and commissioning of the high gradient photoinjector and accelerator test facility CARIE. CARIE will soon come online with an RF photoinjector operating at a high accelerating gradient up to 240 MV/m on the copper cathode. The components for CARIE, including the 50 MW Canon klystron, the RF circulator, the first all-copper photoinjector cavity, and multiple waveguides and vacuum pumps, are now installed at the facility. The last year was spent to satisfy various engineering and radiation safety requirements for CARIE operation. The high-power testing of the all-copper RF photoinjector is expected this summer. The near-future plans for operation and testing at CARIE include cryogenic temperature testing of the four-cell C-band prototype proton booster linac for the proposed LANL's pRad upgrade [1, 4].

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