UPDATE ON THE STATUS OF C-BAND RESEARCH AND FACILITIES AT LANL*

E. I. Simakov[†], A. M. Alexander, D. V. Gorelov, T. W. Hall,
M. E. Middendorf, D. Rai, T. Tajima, M. R. A. Zuboraj
Los Alamos National Laboratory, Los Alamos, NM, USA

Abstract

This paper reports on the status of two C-band test facilities at Los Alamos National Laboratory (LANL): C-band Engineering Research Facility in New Mexico (CERF-NM), and Cathodes and Rf Interactions in Extremes (CARIE). Modern applications such as X-ray sources require accelerators with optimized cost of construction and operation, naturally calling for high-gradient acceleration. At LANL we commissioned a high gradient test stand 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. CERF-NM was fully commissioned in 2021. In the last year, multiple C-band high gradient cavities and components were tested at CERF-NM. Currently we work to implement several updates to the test stand including the ability to autonomously operate at high gradient for the round-the-clock high gradient conditioning. Adding capability to operate at cryogenic temperatures is considered. The construction of CARIE will begin in October of 2022. CARIE will house a cryo-cooled copper RF photoinjector with a high quantum-efficiency cathode and a high gradient accelerator section.

INTRODUCTION

High gradient C-band (5.712 GHz) accelerator research, development, and facility construction 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 high energy (~100 keV) photons that may be produced by a multi-MeV energy electron beam through Inverse Compton Scattering (ICS). These needs must be met with an accelerator of a limited length and footprint due to the space limitations of the 50-year-old LANSCE facility, which naturally calls for acceleration at a high gradient. The number of photons generated by an ICS source is also highly dependent on the quality (low emittance and high brightness) of the accelerated electron beam, which may be achieved through a ground-up redesign of the core technology underpinning modern accelerators, the radio-frequency (RF) photoinjector to allow operation of the photoinjector and the photocathode at high gradients. Achieving high gradient in normal-conducting radio-frequency (NCRF) copper-based accelerator structures and in RF photoinjectors with high quantum efficiency (QE) photocathodes requires understanding of material behavior under extreme electromagnetic fields and at its core is the material science problem. Understanding and designing new materials specifically suited for high gradient operation is the problem that LANL is perfectly positioned to address leveraging its extensive expertise in material science and specifically its specialization in materials-in-extremes.

C-BAND ENGINEERING RESEARCH FACILITY IN NEW MEXICO (CERF-NM)

At LANL, we constructed and commissioned the C-band Engineering Research Facility in New Mexico (CERF-NM) (Fig. 1) [1, 2], the very first high gradient C-band test facility in the United States. The high performance accelerator structure test stand CERF-NM is built around a 5.712 GHz Canon klystron made to supply up to 50 MW of power into an RF cavity. The klystron produces 50 MW RF pulses with the pulse length that can be varied 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 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 that may come from the device-under-test. The WR187 waveguide brings power into a 3 foot by 4 foot lead box built to provide radiation protection to equipment and operators during 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.

Various cavities and components have been tested at high gradients at CERF-NM in the last two years (Fig. 2). The first two cavities were 5.712 GHz single-cell proton accelerating cavities fabricated by SLAC National Accelerator Laboratory. The first cavity was made of copper and the second cavity was made of copper-silver with 0.085% of silver. The surface electric fields measured in the copper cavity at the end of high gradient conditioning were higher than 300 MV/m with breakdown probabilities below 10^{-4} 1/pulse/m. The surface electric fields measured in the copper-silver cavity at the end of high gradient conditioning were higher than 400 MV/m with breakdown probabilities below 10^{-4} 1/pulse/m [3].

---

*This work was supported by Los Alamos National Laboratory's Laboratory Directed Research and Development (LDRD) Program.

† smirnova@lanl.gov

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 to 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 [4].

Figure 1: Photographs of the CERF-NM: the control station and the lead box for radiation protection (top); the 5.712 GHz Canon klystron (bottom).

Finally, a three-cell test structure with the ratio of the iris radius, a, to the wavelength, λ, of a/λ=0.105 was fabricated to establish a benchmark for the high gradient structure performance at C-band. 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 [5, 6]. The cavity is currently undergoing high gradient conditioning and has been processed up to the input power of 13 MW at the pulse length of 1 microsecond that corresponds to the peak surface electric field of close to 300 MV/m [7].

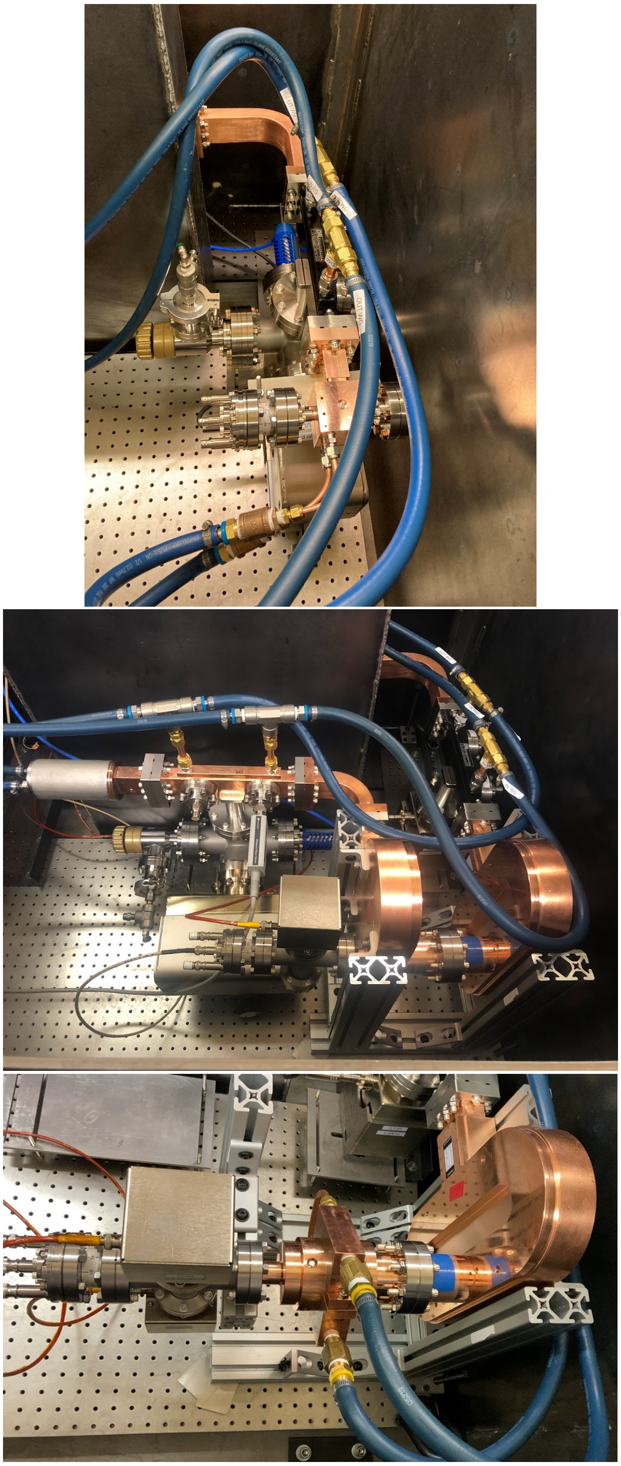

Figure 2: Photographs of various cavities and components tested at CERF-NM: proton cavity (top); two mode launchers (middle); and one mode launcher and the three-cell benchmark cavity (bottom).

LANL has plans to offer CERF-NM test facility to collaborators interested in high gradient testing of other C-

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYD3

band cavities and components. To decrease the time and effort required to operate the facility and to simplify operations, we are currently working to get approvals for remote operation of the test stand under continuous monitoring by operators at LANSCE central control room (CCR). This requires interlinking the control software for CERF-NM with EPICS control system of the LANSCE accelerator, as well as ensuring safety of operations when the operator is not directly stationed on site at the test stand. Some potential collaborators also expressed the need to perform high gradient testing of their RF structures at cryogenic temperatures. Thus, a possibility of adding a cryo-cooler to CERF-NM is being investigated.

CATHODES AND RF INTERACTIONS IN EXTREMES (CARIE) – NEW HIGH GRADIENT PHOTOINJECTOR TEST FACILITY AT LANL

Beyond operating CERF-NM, LANL further develops its C-band accelerator capabilities by starting construction of a new C-band accelerator test facility for cathode, accelerator, and material science studies. The name of the new facility is Cathodes and Rf Interactions in Extremes (CARIE). 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 QE cathode and a high gradient accelerator section.

With the central role played by electron beam brightness, B_e, in determining the performance of modern X-ray sources and other applications, raising B_e provides motivation for this project. It is known that B_e cannot be improved beyond the intrinsic value obtained at the cathode with current density limited by the space charge. The beam brightness scales with electric field on the cathode as $B_e \sim E^{3/2}$, with higher field resulting in brighter beams. We plan to exploit this scaling by operating the photoinjector at cryogenic temperatures to attain a significant increase in electron beam brightness through enhancement of the launch field at the photocathode.

The unexplored challenge related to operating photocathodes at high gradients is the behavior and stability of high-QE photocathode materials when exposed to the very high electric fields. Predicting this behavior requires in-depth understanding of properties of cathode (semiconductor) materials in extreme conditions. One of the innovations of the new project is to employ heterostructured semiconductors to improve performance and increase lifetime of high-QE photocathode materials at high electric fields and increase the brightness of the beam. Heterostructures (shown in Fig. 3) are essentially layered, engineered combinations of semiconductors, often in the form of superlattices. In particular, cathode heterostructures may include diffusion barriers or smoothing layers to prevent Cs_3Sb deposited on copper surface of the RF photoinjector's cavity from creating Sb-Cu alloys on the copper substrate [8]. LANL-developed special techniques (so-called "2D atomic armors") will be used to create diffusion barriers on the surface of the metal substrate [9] followed by growing high quality photocathode materials on graphene coated substrates [10,11].

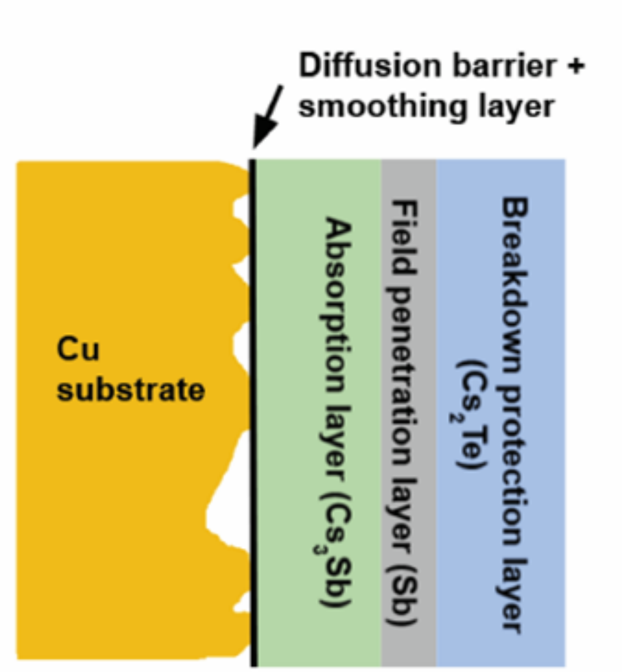

Figure 3: The proposed heterostructured cathode for CARIE test facility will include multiple layers to ensure atomic flatness of the surface, high QE, and the ability to withstand high electric fields with no breakdown.

CONCLUSION AND PLANS

In summary, this paper reported the current status of C-band research and facility construction at Los Alamos National Laboratory. We constructed and commissioned a new C-band high gradient test facility CERF-NM, and high gradient testing of accelerator cavities is on-going. The following components have already been tested at CERF-NM: the two side-coupled proton accelerator cavities and four mode-launchers. The first three-cell $a/\lambda=0.105$ cavity with the on-axis coupling is now undergoing the high gradient testing. The maximum power of 13 MW was coupled into the cavity at the pulse lengths of 400 ns, 700 ns, and 1 μs. Later in 2022 we plan to condition and test the second $a/\lambda=0.105$ copper cavity. After that we plan to test several cavities of the same geometry fabricated with different fabrication methods and of different materials

Beyond operating CERF-NM, LANL further develops its C-band accelerator capabilities. In October of 2022 we will start constructing a high gradient photoinjector and accelerator test facility CARIE. A radiation protection vault was identified on LANSCE mesa capable of accommodating an electron beam with the beam power up to 20 kW. CARIE will house a cryo-cooled copper RF photoinjector with a high quantum-efficiency cathode and a high gradient accelerator section and will deliver 250 pC electron bunches with emittance below 100 nm-radians.

REFERENCES

[1] E. I. Simakov *et al.*, “High Gradient High Efficiency C-Band Accelerator Structure Research at LANL”, in *Proc. NAPAC’19*, Lansing, MI, USA, Sep. 2019, paper WEPLO20, pp. 882-884. doi:10.18429/JACoW-NAPAC2019-WEPLO20

[2] D. Gorelov *et al.*, “Status of the C-Band Engineering Research Facility (CERF-NM) Test Stand Development at LANL”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, paper MOPAB146. doi:10.18429/JACoW-IPAC2021-MOPAB146

[3] M. R. A. Zuboraj *et al.*, “High Gradient Conditioning and Performance of C-Band ß=0.5 Proton Normal-Conducting Copper and Copper-Silver Radio-Frequency Accelerating Cavities”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, paper TUPOMS060. doi:10.18429/JACoW-IPAC2022-TUPOMS060

[4] E. I. Simakov *et al.*, “Design, Fabrication, and Commissioning of the Mode Launchers for High Gradient C-Band Cavity Testing at LANL”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 1060-1063. doi:10.18429/JACoW-IPAC2021-MOPAB342

[5] E. I. Simakov, V. A. Dolgashev, and S. G. Tantawi, “Advances in High Gradient Normal Conducting Accelerator Structures”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 907, p. 221, Nov. 2018. doi:10.1016/j.nima.2018.02.085

[6] V. Dolgashev, S. Tantawi, Y. Higashi, and B. Spataro, “Geometric dependence of radio-frequency breakdown in normal conducting accelerating structures”, *Appl. Phys. Lett.*, vol. 97, p. 171501, Oct. 2010. doi:10.1063/1.3505339

[7] E. I. Simakov *et al.*, “C-Band High Gradient Testing of the Benchmark a/λ=0.105 Cavity”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, paper TUPOMS058. doi:10.18429/JACoW-IPAC2022-TUPOMS058

[8] J. Smedley *et al.*, “High efficiency visible photocathode development”, in *Proc. IPAC’11*, San Sebastian, Spain, Sep. 2011, p. THPC136. doi:10.18429/JACoW-IPAC2011-THPC136

[9] F. Liu *et al.*, “Photoemission from bi-alkali photocathodes through an atomically thin protection layer”, *ACS Appl. Mater. Interfaces*, vol. 14, p. 1710, 2022. doi:10.1021/acsami.1c19393

[10] L. Guo *et al.*, “Graphene as reusable substrate for bialkali photocathodes”, *Appl. Phys. Lett.*, vol. 116, p. 251903, 2020. doi:10.1063/5.0010816

[11] H. Yamaguchi *et al.*, “Quantum efficiency enhancement of bialkali photocathodes by an atomically thin layer on substrates”, *Phys. Status Solidi A*, vol. 216, p. 1900501, 2019. doi:10.1002/pssa.20190050