Inverted Geometry Ceramic Insulators in High Voltage DC Electron Guns for Accelerators

C. Hernandez-Garcia, G. Palacios-Serrano, P. Adderley, D. Bullard, J. Grames, M. A. Mamun[1], M. Poelker,
M. Stutzman, R. Suleiman, Y. Wang, and S.A.K. Wijethunga[1]
Thomas Jefferson National Accelerator Facility
Newport News, VA 23606 USA
[1]Old Dominion University
Norfolk, VA 23529 USA

Abstract- **A direct current (dc) high voltage photo-emission electron gun operating at 130 kV is utilized at the Jefferson Lab (JLab) Continuous Electron Beam Accelerator Facility to generate spin-polarized electrons for nuclear physics experiments. Over the past decade, JLab has tested and implemented inverted-geometry ceramic insulators in photoguns, connecting the cathode electrode in vacuum to the high voltage power supply using commercial high voltage cables. The results of those tests showed that breakdown voltage was increased using triple-point shielding electrodes and bulk-doped insulators that allow charge drainage. This contribution describes ongoing work to develop a robust insulator-cable connector for reliably applying 500 kV dc to a future polarized beam photogun operating at 350 kV without field emission.**

I. Introduction

Direct current (dc) high voltage photoemission electron guns (photoguns thereafter) biased at negative ~100 kV are utilized to generate spin-polarized electron beams for nuclear physics experiments, such as those conducted at Department of Energy Continuous Electron Beam Accelerator Facility (CEBAF) in Jefferson Lab (JLab) [1]. The electron beam is generated when circularly polarized laser light with near-bandgap-energy illuminates a negative electron affinity GaAs-based photocathode [2]. The photocathode lifetime – defined by the quantum efficiency as a function of extracted charge– depends on the vacuum conditions in the photogun high voltage chamber. It is therefore essential that photoguns exhibit no field emission [3-5]. Typically, the electrode needs to be high voltage conditioned in the range of 10 kV to 100 kV above the photogun target operating voltage to process out field emission [6].

In contrast to photoguns relying on large cylindrical ceramic insulators to electrically isolate the cathode electrode [7-9], in 2010 JLab embarked on a R&D program to test and implement conical ceramic insulators, connecting the cathode electrode in vacuum to the high voltage power supply using a commercial high voltage cable. In this "inverted-insulator" design the insulator serves as the electrode support structure resulting in the following advantages:

- less metal biased at high voltage contributing to field emission [10]
- smaller vacuum chamber resulting in better achievable vacuum, and
- no exposed high voltage components; and thus, a sulfur hexafluoride (SF_6) tank is not required to suppress corona discharge.

The ongoing JLab program has produced and operated several inverted insulator photoguns: a 130 kV photogun [11] that has delivered polarized electron beams for the nuclear physics program at CEBAF reliably for over a decade, a 200 kV photogun delivering polarized beams at a testbed accelerator [12], and a 300 kV photogun that generated magnetized beams in a testbed beam line [13].

At even higher operating voltages, photoguns producing polarized beams under the stringent aforementioned requirements are needed for proposed electron beam-driven production of polarized positrons [14], the Electron Ion Collider and the proposed International Linear Collider [15]. These initiatives provide the motivation for this work - to develop an inverted insulator compatible with a commercial cable for applying 500 kV dc to a future polarized beam photogun. This photogun should operate reliably and field-emission-free at 350 kV dc. Such an insulator does not exist.

II. Experimental Background

The ceramic inverted insulators utilized in the 130 kV CEBAF and in the 200 kV testbed photoguns were readily available commercial products from the X-ray industry. The air side profile of such insulators matches the taper and size of high voltage cable terminations with the commercial designation "R28". The cable termination is inserted into the conical-shape ceramic insulator with an intervening layer of silicone grease that, in combination with maintaining it spring-loaded under compression, prevents air pockets. The R28 insulators are 0.13 m long with a 0.05 m diameter open end. Based on the success of these photoguns, a series of tests were conducted at JLab in 2016 to develop a 300 kV class insulator-electrode assembly compatible with commercial high voltage cable terminations [16]. Epoxy-based receptacles were readily available for 250 kV rated high voltage cable terminations with commercial designation “R30”, but these are not acceptable for use in photoguns due to their outgassing nature in vacuum. Thus, JLab collaborated with SCT [17] in France to develop R30-compatible ceramic insulators (0.20 m long, 0.06 m open end diameter). Two types of insulators were fabricated: a batch made from pure alumina, and a second batch made from alumina doped with a proprietary formulation to provide conductivity for draining accumulated charge [18].

The tests described in Ref. [16] were conducted using a vacuum chamber, and a spherical cathode electrode. This electrode was polished by hand starting with 180 grit silicon carbide paper, progressively transitioning to finer grit paper until all scratches were removed and finishing with 600 grit paper. The electrode was then cleaned with a diluted degreaser in an ultrasonic tub and afterwards mounted to the narrow (high voltage) end of the particular insulator being tested. Test results in [16] showed that the smaller R28 doped insulator reached 365 kV despite being 0.07 m shorter than the R30 insulator; while the pure alumina R30 insulator suffered breakdown at ~ 300 kV. Implementing a triple point shield cathode electrode, this type of insulator reached 375 kV without breakdown. Higher voltages were not attempted to avoid damaging the insulators.

III. The 500 kV Insulator Concept

The results of the study described in section II were implemented to develop the first 300 kV inverted insulator photogun [13], and inspired the design of a second 300 kV inverted insulator photogun at Brookhaven National Lab [19]. Although those are the state of the art, even higher operating voltage inverted insulator photoguns with stringent vacuum conditions are required to generate high bunch charge, spin-polarized positron [14] and electron beams [15] from GaAs photocathodes. Thus, the efforts in this work focus on the design, implementation and high voltage testing of a custom cable termination connected to doped alumina inverted insulators that will reach 500 kV.

The insulators currently available for testing are about twice as long as the R30 insulators. These insulators were developed by SCT in collaboration with JLab over a decade ago for a proposed 500 kV dc photogun [21], but their taper and aperture do not fit the 350 kV rated commercial cable terminations. Fig. 1 shows a collection of high voltage components utilized at JLab for the various photoguns.

Fig. 1. Doped alumina conical insulators, cable terminations and epoxy receptacles utilized at JLab for various photoguns. Left: Insulator and R28 cable termination for the 100 and 200 kV photoguns. Center: Insulator and R30 cable termination utilized in the 300 kV photogun. Right: The 350 kV rated cable termination is utilized to connect the photoguns to their corresponding power supply via the shown epoxy receptacle. The large insulator was custom made for a different R&D program and thus is not compatible with commercial high voltage terminations.

The custom-sized doped alumina insulator for which no connector exists is shown to the right of the picture. The R28 and R30 epoxy receptacles are utilized for connecting the photogun to a 100 Mega-Ohm resistor in series with the high voltage power supply during the high voltage conditioning phase. The resistor resides inside a cylindrical tank with epoxy receptacles at both ends, and filled with SF_6 to 10 psig (pounds per square inch gauge). The pressure set point was chosen to maintain the design below the 14 psig pressure vessel threshold. The longest epoxy receptacle shown to the right in Fig. 1 is rated to 350 kV and is utilized to connect the other end of the resistor tank to the high voltage power supply, or directly to the photogun for normal operations.

A. Modified 350 kV rated epoxy receptacle with SF_6 intervening layer

A combined high voltage connector assembly will be comprised of a 350 kV rated cable plugged into an epoxy receptacle (both shown to the right in Fig. 1) and an intervening SF_6 layer between the receptacle and the conical insulator. The receptacle will be machined to match the taper of the 500 kV inverted insulator, and sized to leave a volume where SF_6 is contained and pressurized, connected to a SF_6 reservoir sealed at the top of the insulator/receptacle assembly. The assembly model is depicted in Fig. 2.

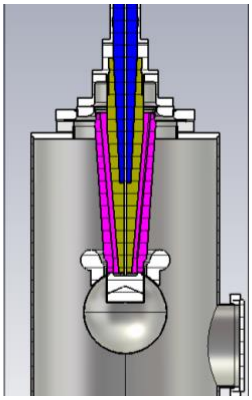

Fig. 2. SolidWorks model showing a cross section of the high voltage testing apparatus. Blue: Vulcanized rubber high voltage cable termination. Gold: Modified commercial epoxy receptacle. Pink: 500 kV doped alumina inverted insulator. The spherical electrode is 0.2 m diameter.

The motivation for using SF_6 instead of silicon grease is twofold. First, the epoxy receptacle is smaller in diameter than the ground side (open to air) of the insulator, thus the gap is too large to be filled with silicon grease as the large volume may trap air pockets. Second, the receptacle is rigid in contrast to the rubber cable termination which conforms tightly to the ceramic conical shape.

Fig. 3 shows a CST EM [22] electrostatic model cross section of the apparatus simulated for applying 500 kV to the ball cathode.

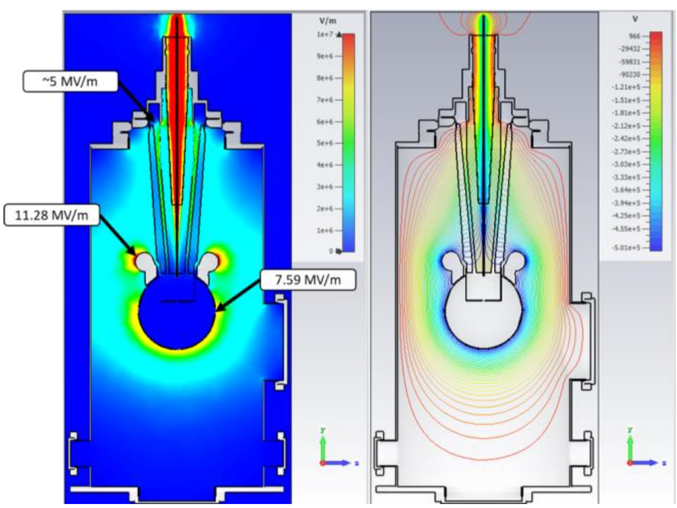

Fig. 3. CST EM studio simulation at 500 kV of the testing apparatus with high voltage cable inserted into modified epoxy receptacle, and intervening SF_6 layer. Left: Electric field contour. Right: Equipotential lines. The spherical electrode is 0.2 m diameter.

The 3D model was developed in SolidWorks®, and then imported into CST EM studio for the electrostatic simulations. The spherical cathode is 0.2 m in diameter, and the cylindrical vessel is 0.5 m diameter and 1.0 m tall. The shape of the triple point shield electrode is still in the preliminary design phase. Its final shape will be optimized by minimizing the electric field at the triple point and at the cusp of the shield, and on linearizing the potential across the length of the insulator (see e.g. [13]).

B. Custom high voltage cable termination

A second approach will involve partnering with industry to develop a custom rubber termination for a commercial 350 kV cable, that conforms to the 500 kV inverted insulator tapered profile and size. In this approach, silicon grease would be used as the intervening layer between the custom rubber cable termination and the insulator to avoid air pockets, as is done with the smaller R28 and R30 insulators. Fig. 4 shows a preliminary cross section simulation of the custom rubber cable termination matching the 500 kV insulator profile. The electric field at the ground triple point is lower compared to that in the epoxy receptacle with intervening SF_6 layer concept (Fig. 3).

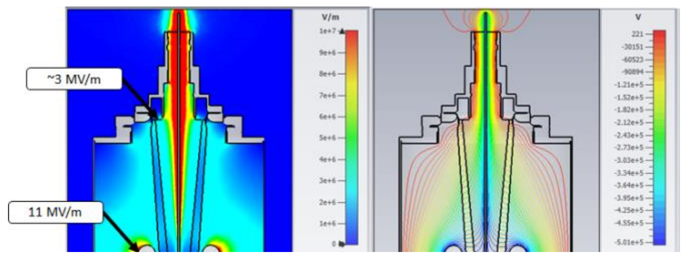

Fig. 4. CST EM studio simulation at 500 kV of the upper section of the testing apparatus with custom high voltage cable termination. Left: Electric field contour. Right: Equipotential lines.

C. Custom 500 kV insulator design compatible with commercial cable termination

The ultimate goal is to design a custom inverted insulator with triple point junction shielding cathode electrode capable of reaching 500 kV without breakdown, connected to a commercial cable termination (shown to the right in Fig. 1). The test inverted geometry insulator will be machined from a block of ultra-high molecular-weight polyethylene (UHMWPE) [23], and will be tested in SF_6. High voltage feedthroughs made with this material have demonstrated 300 kV in liquid argon [24]. Due to the stringent photogun vacuum requirements, ultimately the insulator must be manufactured from alumina. Such an endeavor requires close collaboration with industry, as national accelerator laboratories and facilities like JLab do not have the capability to develop ceramic insulators of the scale needed for the 500 kV connector.

IV. HIGH VOLTAGE TESTING

A spherical shell stainless steel electrode 0.2 m in diameter with triple point shield cathode electrode will be mounted to the narrow end (high voltage) of the large inverted insulator. These electrodes will be mechanically polished to mirror-surface finish as in [25]. The electrode-insulator assembly will protrude into the volume of a stainless-steel cylindrical vacuum vessel when mounted to the top flange, as depicted in Fig. 2. High voltage testing will be conducted with the vessel filled with SF_6 at a pressure of 10 psig to focus on the connector-insulator assembly performance without the need of time-consuming field emission processing. The power supply is a 500 kV, 5 mA dc Cockcroft-Walton generator inside a vessel filled with SF_6 gas at 10 psig. A 300 Mega-Ohm resistor in series with the high voltage power supply will be utilized for the tests. The resistor is coaxial to a cylindrical appendage of the power supply vessel. The 350 kV rated epoxy receptacle connects to the other end of the resistor, and is mounted on a flange to the appendage thus sealing the SF_6 environment. The high voltage cable connects to the epoxy receptacle on one end, and to the high voltage testing apparatus on the other. The power supply features a voltage shutdown on pre-set over current limit. Tests will be conducted monitoring the high voltage power supply current as voltage is applied.

V. Conclusions

The success of photoguns with inverted geometry insulators at JLab has prompted interest to consider this design for the Electron Ion Collider, the proposed International Linear Collider and electron beam-driven production of polarized positrons [15,19,26,27]. These photoguns must operate in the range of 350 to 400 kV without field emission for achieving long operational lifetimes when producing spin-polarized electrons beams from GaAs-based photocathodes, and must operate reliably at even higher voltage when processing field emission. Consequently, there is a need for inverted-geometry insulators which exceed what has been previously demonstrated [13,16], and operate reliably at 500 kV using commercial high voltage cables. Ongoing work at JLab focuses on developing such an insulator-cable connector.

Acknowledgment

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.

References

[1] C. K. Sinclair, P. A. Adderley, B. M. Dunham, J. C. Hansknecht, P. Hartmann, M. Poelker, J. S. Price, P. M. Rutt, W. J. Schneider, and M. Steigerwald, “Development of a high average current polarized electron source with long cathode operational lifetime”, Phys. Rev. ST Accel. Beams 10, 023501 (2007).

[2] D. T. Pierce, R. J. Celotta, G. C. Wang, W. N. Unertl, A. Galejs, C. E. Kuyatt, and S. R. Mielczarek, “The GaAs spin polarized electron source ”, Rev. Sci. Instrum. 51, 478 (1980)

[3] R. Forbes, J. Deane, A. Fischer, and M. Mousa, “Fowler- Nordheim plot analysis: a progress report”, Jordan Journal of Physics 8, 125 (2015).

[4] W. T. Diamond, “New perspectives in vacuum high voltage insulation. i. the transition to field emission”, Journal of Vacuum Science & Technology A 16, 707 (1998), https://doi.org/10.1116/1.581051.

[5] M. Stutzman, P. Adderley, J. Brittian, J. Clark, J. Grames, J. Hansknecht, G. Myneni, and M. Poelker, “Characterization of the CEBAF 100 kV dc GaAs photoelectron gun vacuum system”, Nucl. Instrum. Methods Phys. Res., Sect A 574, 213 (2007).

[6] C. Hernandez-Garcia, S. V. Benson, G. Biallas, D. Bullard, P. Evtushenko, K. Jordan, M. Klopf, D. Sexton, C. Tennant, R. Walker, and G. Williams, “DC high voltage conditioning of photoemission guns at Jefferson Lab FEL”, AIP Conference Proceedings 1149, 1071 (2009), https://aip.scitation.org/doi/pdf/10.1063/1.3215595.

[7] N. Nishimori, R. Nagai, S. Matsuba, R. Hajima, M. Yamamoto, Y. Honda, T. Miyajima, H. Iijima, M. Kuriki, and M. Kuwahara, “Experimental investigation of an optimum configuration for a high-voltage photoemission gun for operation at ⩾ 500 kV”, Phys. Rev. ST Accel. Beams 17, 053401 (2014).

[8] J. Maxson, I. Bazarov, B. Dunham, J. Dobbins, X. Liu, and K. Smolenski, “Design, conditioning, and performance of a high voltage, high brightness dc photoelectron gun with variable gap”, Rev. Sci. Instrum. 85, 093306 (2014), https://doi.org/10.1063/1.4895641.

[9] C. Hernandez-Garcia, T. Siggins, S. Benson, D. Bullard, H. F. Dylla, K. Jordan, C. Murray, G. R. Neil, M. Shinn, and R. Walker, “A high average current DC GaAs photocathode gun for ERLs and FELs, in Proceedings of the 2005 Particle Accelerator Conference (2005) pp. 3117– 3119.

[10] P. A. Adderley, J. Clark, J. Grames, J. Hansknecht, K. Surles-Law, D. Machie, M. Poelker, M. L. Stutzman, and R. Suleiman, “Load-locked dc high voltage GaAs photogun with an inverted-geometry ceramic insulator”, Phys. Rev. ST Accel. Beams 13, 010101 (2010).

[11] P. A. Adderley, J. Clark, S. Covert, J. Grames, J. Hansknecht, K. Surles-Law, D. Machie, M. Poelker, M. L. Stutzman, R. Suleiman, “Photoinjector improvements at CEBAF in support of parity violation experiments”, Il Nuovo Cimento C, Vol. 35 C, N. 4, DOI 10.1393/ncc/i2012-11288-3, (2012).

[12] R. R. Mammei, R. Suleiman, J. Feingold, P. A. Adderley, J. Clark, S. Covert, J. Grames, J. Hansknecht, D. Machie, M. Poelker, T. Rao, J. Smedley, J. Walsh, J. L. McCarter, and M. Ruiz-Os ́es, “Charge lifetime measurements at high average current using a K2CsSb photocathode inside a dc high voltage photogun”, Phys. Rev. ST Accel. Beams 16, 033401 (2013).

[13] C. Hernandez-Garcia, B. Bullard, J. Benesch, J. Grames, J. Gubeli, F. Hannon, J. Hansknecht, J. Jordan, R. Kazimi, G. A. Krafft, M. A. Mamun, M. Poelker, M. L. Stutzman, R. Suleiman, M. Tiefenback, Y. Wang, and S. Zhang, C. A. Valerio Lizarraga, R. Montoya Soto, and A. Canales Ramos, “Compact -300 kV dc inverted insulator photogun with biased anode and alkali-antimonide photocathode”, Phys. Rev. Accel. Beams 22, 113401 (2019).

[14] D. Abbott, et. al., “Production of Highly Polarized Positrons Using Polarized Electrons at MeV Energies”, Phys. Rev. Lett., 116, 214801 (2016).

[15] V. Shiltsev, and F. Zimmermann, “Modern and future colliders”, Rev. Mod. Phys, 93, 015006, (2021).

[16] C. Hernandez-Garcia, M. Poelker, and J. Hansknecht, “High voltage studies of inverted-geometry ceramic insulators for a 350 kV dc polarized electron gun”, IEEE Transactions on Dielectrics and Electrical Insulation 23, 418 (2016).

[17] https://www.sct-ceramics.com/en/

[18] Y. J. Lei, B. H. Tang, X. J. Huang, Y. Huang, X. F. You, M. Zeng, “Effects of bulk doping on surface insulating performance of alumina ceramic in vacuum”, IEEE Trans. Dielectr. Electr. Insul., Vol., 18, pp. 2103-07, 2011.

[19] E. Wang, “Polarized Electron Source R&D for the EIC”, International Workshop on Future Linear Colliders, LCWS2021, March 15-18, 2021, https://indico.cern.ch/event/995633/

[21] F.E. Hannon, P. Evtushenko, and C. Hernandez-Garcia, “Electrostatic modeling of the Jefferson Laboratory inverted ceramic gun”, Int’l. Particle Accelerator Conf., Kyoto, Japan, pp. 383-385, 2010.

[22] CST EM studio, http://www.cst.com.

[23] M.G. Andersson, J. Hynynen, M.R. Andersson, V. Englund, P.-O. Hagstrand, T. Gkourmpis, and C. Müller, “Highly Insulating Polyethylene Blends for High-Voltage Direct-Current Power Cables”, ACS Macro Lett. 6, 78 (2017)

[24] B. Aimard, et. al., “A 4 tonne demonstrator for large-scale dual-phase liquid argon time projection chambers”, J. Instrum. 13, P11003 (2018)

[25] C. Hernandez-Garcia, D. Bullard, F. Hannon, Y. Wang, and M. Poelker, “High voltage performance of a dc photoemission electron gun with centrifugal barrel-polished electrodes”, Rev. Sci. Instrum. 88, 093303 (2017).

[26] J. Dumas, J. Grames, and E. Voutier, “A Polarized Positron Source for CEBAF”, AIP Conference Proceedings **1160**, 120 (2009).

[27] C. Hernandez-Garcia, “Development of a 500 kV Polarized Electron Source”, International Workshop on Future Linear Colliders, LCWS2021, March 15-18, 2021, https://indico.cern.ch/event/995633/