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Ongoing efforts to construct a 350 kV dc high voltage photogun with inverted insulator geometry

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A number of new initiatives at Jefferson Lab will benefit from the construction of a dc high voltage photogun operating at 350 kV bias voltage. These initiatives include: a) the construction of a compact 10 MeV electron accelerator for commissioning new hardware destined for CEBAF, including the polarized target HDIce, b) replacing the vent-and-bake photogun at the Jefferson Lab energy recovery linac with a load-locked photogun and alkali-antimonide photocathode deposition chamber, and c) a 350 kV photogun used to study high bunch-charge magnetized beams needed for cooling proton beams at the Electron Ion Collider. There has been great progress worldwide developing photoguns operating at 350 kV and even higher. This contribution describes Jefferson Lab's efforts to build such a gun, but with an inverted-insulator geometry. The inverted-insulator geometry offers advantages over gun designs that employ large cylindrical insulators, but it introduces at least one new challenge, namely, how to reliably apply voltage to the cathode electrode via a high voltage cable without breakdown, which sometimes leads to puncture and catastrophic failure of the insulator. In addition, this contribution describes recent studies devoted to improving our understanding of field emission, and methods to eliminate it.

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1. Introduction

DC high voltage photoguns at most polarized electron beam facilities operate at ~ 100 kV. Higher bias voltages would serve to improve beam quality and simplify injector design, but historically, attempts to operate photoguns above 100kV have proven very difficult, primarily due to field emission which degrades vacuum conditions and reduces the operating lifetime of the photogun. Recent worldwide interest in producing bright beams for accelerator-based light sources has renewed efforts to operate dc high voltage photoguns at considerably higher voltages (500kV or more). At Jefferson Lab, an inverted-geometry ceramic insulator approach has been adopted, where the term "inverted" describes an insulator that extends into the vacuum chamber serving as the cathode electrode support structure [1]. This represents an alternative to designs that employ large cylindrical insulators with long metal electrode support tubes passing through the insulator bore [2, 3]. The inverted-insulator design helps to reduce field emission because there is considerably less metal biased at high voltage. However, the inverted-geometry ceramic insulator introduces a new problem compared to other photogun designs, namely, how to effectively apply high voltage to the cathode electrode without encountering high voltage breakdown across the relatively small inverted insulator.

The Jefferson Lab inverted-insulator design employs one conical-shaped insulator that extends into the vacuum chamber. The insulator is a common component of medical x-ray devices, with the commercial designation "R28", which specifies the length and angle of the interior conical shape. Because these insulators are widely used, they are relatively inexpensive, and they mate to commercial high voltage cables. Two photoguns have been constructed at Jefferson Lab using the R28 insulator: one provides spin-polarized electron beams for the Continuous Electron Beam Accelerator Facility (CEBAF) at 130kV bias voltage, and the other was used at a test facility to produce beam at 200kV and at average current up to 4 mA [4]. The objective of this work was to develop an inverted-ceramic/electrode geometry capable of reaching 375kV, without electrical breakdown for nominal operation at 350kV. At 350kV bias voltage, the extracted electron beam is sufficiently relativistic to accommodate beam injection directly into a standard CEBAF superconducting RF accelerating module, without pre-acceleration using a graded-beta RF "capture" cavity, thereby significantly reducing the cost and complexity of the injector design.

Three types of inverted insulators were tested: unaltered alumina, vendor-proprietary doped alumina that provides a small level of bulk conductivity, and alumina coated with zirconium oxide (ZrO) intended to provide a small level of surface conductivity. Most tests were performed using insulators with the R30 designation, which are longer than R28 insulators. In addition, one of the unaltered alumina insulators was evaluated using a screening electrode near the cathode-vacuum-insulator triple point junction. All tests were conducted using a spherical stainless steel test electrode that was mechanically polished to mirror-like finish to minimize field emission. The test electrode did not accommodate a photocathode. All tests employed commercial high voltage cables connected to a Cockcroft-Walton 580 kV dc high voltage power supply within a pressure vessel that was filled with sulfur hexafluoride (SF_6) at 69 kPa (10 pounds per square inch). Results from two of the four test configurations show that the electrode can be biased to higher voltages without breakdown at the insulator/cable interface.

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2. Experiment

The photogun high voltage test chamber was cylindrical (46 cm diameter) with a flat-front plate and dish-head back plate, made of 304 stainless steel (Figure 1a). The inverted insulators were welded to custom 25.4 cm diameter stainless steel Conflat vacuum flanges. The chamber was previously vacuum baked at 400 °C for 100 hours to reduce outgassing from the chamber walls [5]. Vacuum pumping was provided using a small ion pump and a non-evaporable getter (NEG) pump module positioned where the anode electrode would normally reside, when the photogun is eventually configured to provide an electron beam. Prior to each high voltage test, the chamber was evacuated using a turbo pump and the entire system baked within an oven at 250 °C for 48 hours. The bakeout served to eliminate water vapor from the vacuum apparatus and to partially activate the NEG module. Vacuum in the low 10^{-9} Pa was routinely achieved and a residual gas analyzer (200 atomic mass unit resolution) was used to verify the system was free of vacuum leaks.

As mentioned above, most tests were conducted using the R30 insulators that position the test cathode electrode in the middle of the vacuum chamber as shown in Figure 1a. The test electrode was spherical (15.24 cm diameter), without the means to accept a photocathode. It was manufactured from two hemispheres of hydroformed 304 stainless steel sheet that were welded together and polished by hand using silicon carbide paper to obtain a mirror-like surface finish. Toward the end of the experiment, while waiting for the arrival of a machined component, time was available to polish the test electrode further using diamond grit. In retrospect, diamond-paste polishing was not required, as field emission was already very low. The anode for these measurements was simply the grounded vacuum chamber wall that provided a minimum cathode/anode gap of approximately 10 cm. For an actual photogun, the cathode electrode would possess additional apertures to accommodate a photocathode that could be inserted or removed from the electrode using a vacuum sample manipulator.

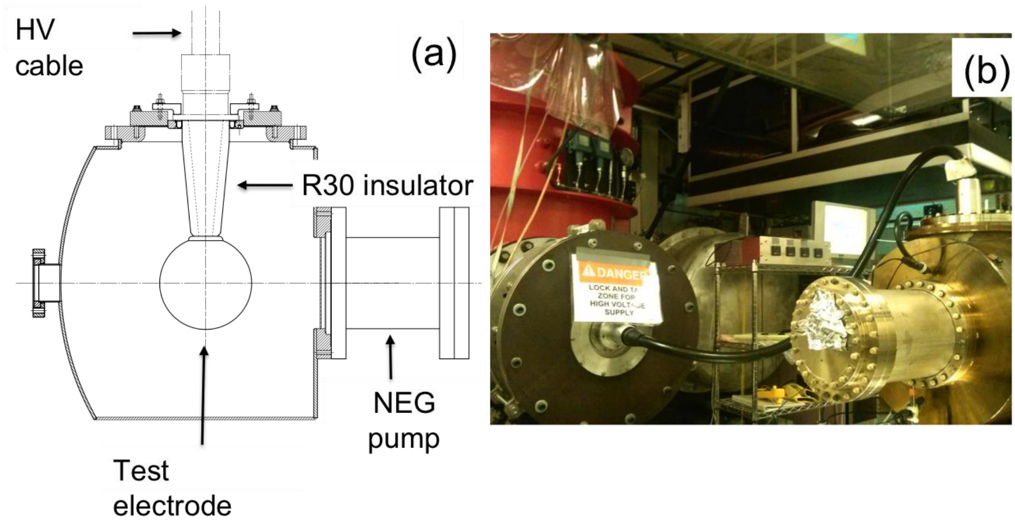

Figure 1. Schematic representation of the photogun high voltage vacuum chamber showing the test electrode (15.25 cm diameter) supported by an R30 inverted insulator (a) and photograph of the high voltage test chamber connected to the power supply via a commercial high voltage cable (b). The high voltage power supply resides within the red-colored SF_6 tank.

Commercial industrial high voltage cables with appropriate R28 or R30 terminations were used to connect the photogun to the high voltage power supply. Cables were typically 4 meters

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long, with capacitance of 102 pF per meter, providing stored energy of 25 Joules at 350 kV including the 12 pF capacitance of the photogun. One end of the cable was connected to an R28 or R30 inverted-insulator at the test chamber, and the other end was connected to the dc high voltage power supply inside the SF_6 pressure vessel, via a molded epoxy receptacle. The epoxy receptacles were also commercial components with R28 and R30 designations. A 300 Mega-Ohm conditioning resistor was placed in series between the epoxy receptacle and the high voltage power supply, within the SF_6 vessel, to limit the available current that could be delivered from the high voltage power supply, and to protect the electrode via a negative feedback mechanism – as current increased due to field emission or breakdown, a larger voltage drop occurred across the resistor, thus reducing the voltage at the electrode. However, the placement of the resistor does not protect the insulator/electrode assembly from the stored energy in the high voltage cable.

A total of five inverted insulators were tested: three R30 insulators each 20 cm long composed of 97.7% alumina and labeled as ‘R30 unaltered alumina’. A fourth R30 unaltered alumina insulator was coated on the vacuum side with a ZrO film to test if reducing the insulator surface resistivity would increase the breakdown voltage by facilitating surface charge drainage [6]. A commercial vendor, Atkinson Thin Film Systems INC, applied the coating by sputtering zirconium from a source attached to a fixed arm in an oxygen-rich environment, with the insulator nearby and rotating. Two source positions were used to obtain a more uniform coating. Preliminary tests with coupons indicated that the resistivity of the coating could be adjusted by varying the sputtering time, and consequently the coating thickness. However we subsequently learned resistance values were not stable, as the coating oxidized in air. The fifth insulator was a shorter R28 version, 13 cm long and composed of 94.4% alumina doped with a proprietary formulation that served to reduce the insulator bulk resistivity. As with the R30 ZrO-coated insulator, the intent was to test if a certain degree of conductivity served to increase the breakdown voltage by providing charge buildup drainage [7, 8]. All of the insulators were purchased from Solutions in Ceramic Technologies (SCT-France). Each insulator was delivered with a brazed molybdenum end piece at the narrow end of the taper to provide vacuum isolation as well as mechanical and electrical contact to the electrode at the vacuum side, and to the cable plug on the air side. The outer rim of the insulator, on the wide end of the taper, was brazed to a kovar ring and welded (vacuum tight) to a custom 25.4 cm diameter stainless steel Conflat vacuum flange.

Two insulator/electrode configurations were evaluated. The majority of tests were conducted using a mounting cup with a rounded collar manufactured from 304 stainless steel that provided a means to attach the test spherical electrode to the insulator. The mounting cup was affixed to the electrode using four setscrews that protrude from the cup and press against the interior of the spherical shell electrode. The spherical electrode and mounting cup were then screwed onto the molybdenum plug of the insulator using a short threaded rod. The other configuration employed a screening electrode also manufactured from 304 stainless steel intended to linearize the potential gradient across the insulator length. In this configuration, the narrow end of the R30 insulator was recessed into the now larger cathode electrode assembly, resembling configurations tested in [9] that yielded increased voltage holdoff compared to electrodes without screening. Figure 2 shows all types of insulator and electrode configurations tested.

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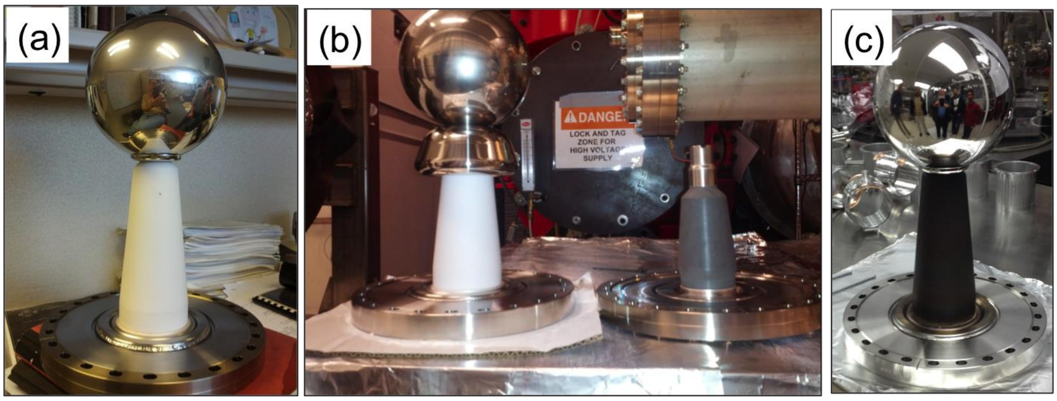

Figure 2. Photographs of insulators and electrode configurations, each shown welded to 25.4 cm diameter stainless steel Conflat vacuum flange. The same spherical electrode (15.25 cm diameter) was used for every test. In (a) the R30 unaltered alumina insulator ~ 20 cm long. In (b) the R30 unaltered alumina insulator with screening electrode covering the triple point junction. For comparison, the shorter R28 doped alumina insulator (~ 13 cm long) was placed nearby, without an electrode attached, and (c) the R30 unaltered alumina insulator with ZrO coating on the vacuum side.

3. Results

Two R30 unaltered alumina insulators were tested, and both failed at voltages between 300 and 330 kV, with no associated field emission activity (i.e., Geiger counters reading < 10 counts per second). For both tests, the high voltage power supply tripped off indicating an over-current fault. Upon removing the high voltage cable from the insulator, a carbon track was observed at the bottom of the insulator. For one instance, the insulator was punctured. Upon inspection, an obvious carbon track was visible, spanning the entire length of the insulator from the high voltage end to ground. There was no evidence of puncture in this instance.

A third R30 unaltered alumina insulator was installed but this time using a screening electrode that shields the vacuum-metal-insulator triple-point junction (Figure 2b). Field emission levels during high voltage gas conditioning were three orders of magnitude higher than those observed during tests of the R30 unaltered alumina insulators without the screening electrode. Despite tens of hours of high voltage krypton gas processing, field emission could not be eliminated. However, under high voltage conditions with krypton gas, the R30 unaltered alumina insulator with screening electrode reached 375 kV without breakdown, and sustained 370 kV for 4 hours. After pumping away the krypton gas, this configuration successfully soaked at 350 kV under ultrahigh vacuum conditions for 4 hours, albeit still exhibiting field emission three orders of magnitude higher than observed during tests of same type of insulator without the screening electrode**.** Given that the target voltage was reached, and in order to preserve the R30 insulator for future tests, the voltage was not increased further. The only difference between this successful result, and tests with the other two R30 unaltered alumina insulators that suffered breakdown at lower voltage, was the addition of the screening electrode.

A fourth R30 unaltered alumina insulator with a ZrO film on the vacuum side, to investigate if a slightly conductive coating would serve to dissipate surface charge buildup, and therefore increase the voltage holdoff. With the purpose of isolating the performance of the coating, the insulator was tested with the spherical electrode only as shown in Figure 2c. Measured field emission levels were low and similar to those observed prior to the additional polishing procedure (Geiger counters reading < 10 counts per second), suggesting in retrospect, additional polishing with diamond paste was unnecessary. High voltage conditioning with

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krypton gas proceeded similarly as with the previously tested R30 unaltered alumina insulators. At 340 kV, the high voltage power supply tripped off upon reaching the over current trip limit (400 μA). Upon recovering the voltage, field emission was observed at 200 kV, but processed out at 240 kV. At 300 kV, the high voltage power supply tripped off once more, but in this instance the vacuum level had increased two orders of magnitude. Upon inspection, a carbon track was observed, originating at the high voltage connection, and terminating about 2 cm below the ground end of the ceramic, with two punctures. It is interesting to note that the punctures in the R30 ZrO coated insulator occurred near the ground end, while the puncture in the R30 unaltered alumina occurred at the opposite location near the high voltage end.

The short R28 doped alumina insulator was tested using only the spherical electrode. This insulator had lower bulk resistivity compared to the R30 unaltered alumina insulators (Table 1). High voltage conditioning with krypton gas was performed following the same procedure as with the R30 insulators, observing typical field emission processing and voltage induced gas desorption. Excess current without associated field emission was never observed, indicating the problems associated with breakdown at the insulator/cable interface were not present. Despite being 7 cm shorter than the R30 insulators (Figure 2b), the R28 doped alumina insulator reached 360 kV for one hour without field emission, under krypton gas conditions. The voltage was not increased further with the intention to preserve the integrity of the insulator and high voltage cable plug. After gas conditioning, nominal ultrahigh vacuum conditions were re-established and the voltage was set to 350 kV for 5 hours on two separate occasions. Minimal field emission was observed in these two instances. The high voltage performance for all tested configurations along with insulator material properties are summarized in Table I.

TABLE 1. Material properties for each insulator/electrode test configuration and corresponding high voltage performance. The R30 insulators were composed of unaltered 97.7% alumina, while the R28 doped insulator was 94.7% alumina. The manufacturer provided the alumina concentration for each insulator type and corresponding transversal resistivity and dielectric constant. All test were performed using the same spherical test electrode.

Insulator type	Length (cm)	Transversal resistivity (Ohm-cm)	Dielectric constant $\varepsilon_1/\varepsilon_0$	Maximum voltage (kV)	Performance
R30 sample 1	20	$5.0x10^{15}$	9.1	329	Breakdown and puncture near high voltage end
R30 sample 2	20	$5.0x10^{15}$	9.1	300	Breakdown
R30 with additional screening electrode	20	$5.0x10^{15}$	9.1	375	370 kV with krypton 4-hr soak, 350 kV in vacuum 4-hr soak. Significant field emission in both cases
R30 ZrO-coated	20	$5.0x10^{15}$	9.1	340	Breakdown and puncture near ground end
R28 doped	13	$7.4x10^{15}$	8.4	360	360 kV with krypton 1-hr soak, 350kV in vacuum 5-hr soak, 2 times Minimal field emission in both cases

4. High voltage gas conditioning with krypton

Key to the success of these high voltage tests was krypton-gas conditioning, a technique in which the inert gas was introduced into the vacuum chamber with the cathode electrode biased at a voltage high enough to produce field emission [10]. Gas conditioning serves to eliminate field emitters from the cathode electrode through ion bombardment and resultant sputtering and ion implantation [11]. In addition, this technique is much more reliable than high voltage processing in vacuum and more importantly, it helps to limit damage to photogun components

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that often result from unregulated field emission [12]. To implement gas conditioning and prior to enabling high voltage, a constant flow of krypton was introduced into the vacuum chamber. A manual leak valve was set to provide a stable pressure of ~10^{-5} Pa at the turbo pump, which provided continuous pumping through a valve that was throttled closed, to reduce the pumping speed of the turbo pump. Pressure inside the vacuum chamber was ~ 10^{-3} Pa, based on conductance assumptions of the vacuum plumbing. The ion pumps on the vacuum chamber and pump cart were not energized. Three signals were monitored during gas conditioning: the vacuum inside the photogun (via residual gas analyzer and a cold-cathode vacuum gauge), field emission via Geiger counters mounted around the photogun vacuum chamber, and the high voltage power supply current. Some current draw was expected, as a result of non-problematic Ohmic current paths to ground, including the current across the high voltage power supply current measuring stack. Current draw above normal baseline values was an indication of field emission or breakdown. The voltage was initially set to 50 kV. If no field emission or excess current activity was observed, the voltage was increased in ~ 10 kV steps. If excess current activity was observed, the voltage increase was paused until field emission was extinguished. In some instances, voltage was increased regardless but ensuring the current would not exceed 100 μA above baseline. The high voltage power supply was operated in over-current trip mode, typically set to 400 μA. Gas conditioning was always implemented each time a new insulator/electrode configuration was tested.

Under ideal conditions, an electrode-insulator configuration would reach 375 kV during krypton gas conditioning, and with negligible field emission. The insulator-electrode configuration would then "soak" at 375 kV for several hours to determine the stability (robustness) of the configuration. Afterwards, the voltage was decreased to zero, the krypton gas evacuated and once vacuum conditions were below 10^{-8} Pa, the voltage was slowly increased again to just 365 kV. By applying less voltage under vacuum conditioning (~ 10 kV), one avoids voltage-induced gas desorption, which can contribute to the formation of new field emitters, thereby necessitating further krypton gas conditioning [13].

Discussion and Conclusion

Three types of inverted-geometry ceramic insulators, and two electrode configurations, were tested inside a photogun vacuum chamber with the purpose of developing an inverted-ceramic/electrode geometry capable of reaching 375kV, without electrical breakdown for nominal operation at 350kV. Two configurations were found to improve the voltage holdoff capabilities of tested insulators: an alumina insulator 13 cm long with commercial denomination R28 and doped with proprietary formulation for low bulk resistivity, and a 20 cm long unaltered alumina insulator with commercial denomination R30 with an additional screening electrode. Both of these configurations reached the stated goal of sustained operation at 350 kV. Electrostatic modeling (not reported here, see ref. 14) indicates that the holdoff voltage between the photogun insulator and the commercial high voltage cable connecting to the high voltage dc power supply, was effected by a combination of factors including the potential gradient across the length of the insulator, the electrode/insulator geometry, and the insulator bulk resistivity. These parameters likely influence the level of trapped charge that can accumulate on the insulator surfaces, and the electric field strength at the triple-junction, however, the contribution

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of each factor, as it relates to the ultimate performance of each insulator/electrode configuration, was difficult to decouple. We have conducted other high voltage studies aimed at better understanding the origins of field emission, and methods to eliminate it. A description of these experiments can be found in references 15 - 17.

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