ERL09 WG1 SUMMARY: DC GUN TECHNOLOGICAL CHALLENGES

N. Nishimori[1], I. Bazarov[2], B. Dunham[2], J. Grames[3], C. Hernandez-Garcia[3],

L. Jones[4], B. Militsyn[4], M. Poelker[3], K. Surles-Law[3], M. Yamamoto[5]

[1] JAEA, Tokai-mura, Ibaraki 319-1195, Japan

[2] Cornell University, Ithaca, NY 14853, U.S.A.

[3] Jefferson Lab., Newport News, VA 23606, U.S.A.

[4] STFC Daresbury Lab., Warrington, WA4 4AD, U.K.

[5] KEK, Tsukuba, Ibaraki 305-0801, Japan

Abstract

This paper summarizes technological challenges of photoemission DC guns being developed for the future energy recovery linac (ERL) light sources (LS). Anticipated new applications of ERL-LS demand an electron gun capable of producing an extremely low emittance beam at very high average current. The low emittance requires unprecedentedly high voltage equal to or greater than 500 kV between cathode/anode electrodes together with high accelerating gradient on the photocathode. The technological challenge is to develop a high voltage insulator system, which can withstand field emission from the electrodes. A high voltage processing technique and a challenge to suppress field emission are discussed. The high average current requires prolonged cathode life time, which is governed by ion back-bombardment. Challenges to mitigate the cathode damage caused by ion back-bompardment are surveyed. We also discuss high voltage power supply which can afford sufficient high average current, load-lock system capable of accomodating quick cathode exchange to minimize accelerator down time, and vacum technology to suppress both field emission and ion back-bombardment. A gun geometry satisfying both high gun voltage and high accelerating gradient is also proposed.

INTRODUCTION

Electron guns capable of providing reliable CW beam with average current ~100mA and emittance of a few microns (normalized RMS) are being developed for the next generation energy recovery linacs (ERL) light sources in various research laboratories [1,2]. A DC photoemission electron gun with an activated GaAs photocathode illuminated with 532 nm laser light is considered to be one of most promising candidates of the guns for the ERL light sources, since a 350 kV DC gun successfully delivered 9.1 mA CW electron beam to the Jefferson Lab (JLab) 10 kW IR upgrade Free Electron Laser (FEL) [3]. In this paper we survey technological challenges and related developments in DC photoemission electron guns as high current sources for ERLs.

The high voltage power supply determines limits of the maximum beam energy and current from the guns. The low emittance necessary for ERLs typically requires a DC voltage equal to or greater than 500 kV to reduce non-linear space charge effects in the low energy regime [4]. The fluctuation of beam arrival time at insertion devices should be suppressed for pump-probe experiments using fs x-rays from ERLs. A study shows synchronization stability of ERL systems is governed by injector stability [5]. This sets the requirement on the ripple of DC gun high voltage to be on the order of 10^{-3}. The next generation ERL light sources usually require the beam current from 10 mA to 100 mA. Consequently, a high voltage power supply with voltage greater than 500 kV, and stability of 10^{-3} or better and current greater than 10 mA needs to be developed. Conventional Cockcroft Walton high voltage power supplies with voltage above 500 kV and currents up to 10 mA are used in JLab, Daresbury Laboratory (DL), and JAEA/KEK. A high voltage power supply of 100 mA and 750 kV for Cornell Univ. is developed using cross transformer technology [6].

The ceramic insulator is a simple structure to support a cathode electrode inside the vacuum and is electrically connected to a high voltage power supply outside the vacuum. Operation of photoemission guns at voltages greater than 350 kV is however very difficult, since field emission from electrode structures can lead to voltage breakdown, insulator punch-through, and other problems on the ceramics. Recently three ways to resolve the field emission problem have been proposed. The first is the use of a ceramic insulator with a controlled bulk resistivity utilized at DL. This permits any charge build-up on the ceramic surface to be dissipated to ground. Using this insulator technology, 485 kV was achieved during conditioning at DL. The second is an inverted insulator similar to the metal-ceramic X-ray tubes where a high voltage feed passing through the insulator center is connected to a high voltage terminal. The inverted insulator eliminates the electrode structures typical for normal insulators, which might be the sources of field emission. The third is a segmented insulator, where a number of ceramics are stacked in series with Kovar ring electrode sandwiched between adjacent two ceramics. These insulators are widely used in electrostatic accelerators. The guard rings attached to each electrode prevents field emitted electrons from reaching the ceramic surface. Potentials on the guard rings are fixed with an external resistor divider.

High voltage electrode conditioning up to a voltage typically 20-30% higher than operational is required to reach high photocathode dark lifetime each time after the gun chamber is exposed to air. No unique recipe for high voltage conditioning exists. Gun conditioning using noble gases can be employed to successfully process field emission sites in the gun. Successful experience at JLab and DL using krypton in high voltage processing is described.

Suppression of field emission from the cathode electrodes is essential to protect the ceramic insulator, avoid pressure rise and other problems such as punch-through on the insulator surface. Several laboratories have developed test stands for dark current measurements between large area cathode and anode electrodes to determine the best materials and surface cleaning techniques for dark current suppression. A combination of molybdenum cathode and titanium anode was reported to be the best combination a few years ago by a group at Nagoya Univ. [7]. Employing high pressure rinsing technique used for SRF cavity cleaning is proved to be effective to suppress dark current from the cathode electrodes [8]. This was one of the highlights of the previous ERL workshop [9]. Since these separate measurements were performed with a gap shorter than the real scale electron gun system at voltage much lower than 500 kV, construction of real scale test stands is planned at several laboratories. A new real scale study by Jlab polarized gun group shows that niobium electrodes demonstrate smaller dark currents than stainless steel. Vacuum determined by pump system and outgassing rate of vacuum chamber materials governs the cathode lifetime [10]. Vacuum in the 10^{-10} Pa range with a partial pressure of oxidant like oxygen of less than 10^{-12} Pa are required in the gun chambers as the result. The NEG pump speed was measured as a function of pressure by the JLab polarized gun group [10]. A massive pump unit of 22,000 l/s NEG and 400 l/s ion pumps is used for the Cornell gun to reach mid 10^{-10} Pa [8]. Outgassing from vacuum chamber materials can be suppressed by treating the material or using different materials from stainless steels. A 400 °C/96 hours bakeout for SUS304 and SUS316L in the air as well as vacuum is found to reduce the outgassing rate to as low as 2×10^{-14} l·Torr/s^{-1}cm^{-2} [11]. This technique is used in JLab and Cornell Univ. The outgassing rate of chemically polished titanium is claimed to be 4.5×10^{-16} l·Torr/s^{-1}cm^{-2} [12]. This material is used in preparation and high voltage chambers for JAEA/KEK gun system.

Load-locked preparation systems are used to heat clean activate and store the photocathodes, then transfer them into the high voltage gun chambers. Separate preparation systems from the high voltage chamber are widely used in GaAs photocathode based polarized and un-polarized guns inclusive Cornell ERL installation [8], and currently implemented in the JLab FEL, DL ALICE, and JAEA/KEK guns. The separate system easily accommodates several photocathode pucks for reduction of machine down–time, and permit testing of different cathode materials. A survey of various preparation systems used in DC photoemission guns is presented.

Photocathode operational lifetime is limited by the ion back-bombardment, where residual gas between cathode and anode electrodes is ionized by the electron beam and accelerated towards the cathode surface. The lifetime can be improved by increasing the drive laser spot size, since the ion damage would be distributed over a larger area while the ion production rate remains the same. Lifetime enhancement was observed for larger laser spot sizes at JLab polarized gun [13]. The ion production in a beam transport line downstream from the anode electrode is another source of ion back-bombardment. A positive potential barrier to repel the ions [14] has been experimentally tested at JLab [15] and University of Mainz in their polarized guns. The results of the test are described in this paper.

The lower limit of achievable beam emitance was recently formulated [16], which shows that employing photocathode material with low thermal emittance and applying high accelerating field on the photocathode are the keys for generation of high brightness beam. An actual gun design requires additional design parameters such as optimal gun voltage, transverse focusing, and voltage breakdown criteria. The gun geometry can be optimized by a computer simulation which takes into account of all the gun parameters. A segmented gun design is proposed to decouple two conflicting requirements of a higher gun voltage with a large cathode/anode gap and a higher accelerating field with a small gap.

HIGH VOLTAGE POWER SUPPLY

B. Dunham

The high voltage (HV) power supply for a DC photocathode gun is one of the most important, but often overlooked components of the entire system. A well established set of demands is required prior to considering what power supply to obtain. In this section, a description of these requirements will be covered.

The first item to determine is the highest voltage needed for routine operation, and what overhead is needed for conditioning. All HV devices must be conditioned above the nominal values in order to obtain stable operation, with +20% being a typical number for industrial devices. Photocathode guns, particularly those using vacuum sensitive photocathodes, often require additional margin to have good cathode dark lifetime. Dark currents (from field emission) in the pA range are sufficient to produce noticeable local heating and light (x-rays and UV) which contribute to secondaries and vacuum level increases. For example, if 500 kV is the desired operating value, 600 kV would provide the minimum acceptable overhead.

For any gun that injects a beam into an RF accelerator, control of the arrival time, or phase jitter, of the electron bunch is of critical importance. The phase change at a distance L away from the gun caused by gun voltage variation is given by

$$\Delta\varphi = 2\pi f \frac{L}{c} \frac{\gamma - 1}{(\gamma\beta)^3} \frac{\Delta V_{gun}}{V_{gun}},$$

where φ is in radians, f is the RF frequency, c is the speed of light, and $\Delta V_{gun}/V_{gun}$ is relative ripple of the gun voltage. In terms of RF phase, variations of the order ± 1 degree are acceptable for low emittance beams. For example, at 1.3 GHz, ± 1° is approximately ± 2 ps, corresponding to a shift of ± 450 volts (0.18%) 1 meter away from a 250 kV gun. The voltage ripple needs to be specified over the frequency ranges present in the power supply, typically up to 60 kHz (or more) for modern switching supplies.

Even monitoring ripple at the levels required at the higher frequencies for a particular power supply may not be straightforward. In such a case, we consider using a time-of-flight detector (a beam position monitor, for instance) downstream from the gun to monitor the arrival time of the electron bunches. This can easily measure the arrival time with picosecond accuracy at many tens of kilohertz, and the resulting signal can be sent back to the power supply feedback control loop. For known problem frequencies or instabilities in the HV power supply, one could also consider *feed-forward* methods.

The current and current stability are the next most important requirements. The current is determined by the maximum needs of the accelerator at the nominal voltage, plus some headroom for controls and future development. Cost of these supplies is typically around $10 per watt, so careful consideration should be given to the maximum level requested. Additionally, much less average current is needed for processing than for beam operations, so it is possible to roll-off the current requirements at higher voltages.

For photocathode guns, the current stability and the response of the voltage to changes in the current is of utmost importance. Drive lasers should be stable in power to < 1%, so the HV should be insensitive to changes in current of this level over a wide frequency range. As the cathode efficiency drops over time, it is expected that the laser power will be increased to compensate and maintain a constant output.

Another concern for photocathode guns used in ERLs is how to ramp-up the current to reach the maximum operating value. Two strategies exist: 1) start in CW mode at low current and ramp up the bunch charge; or 2) start in pulsed mode a full bunch charge and increase the duty factor until CW mode is reached. Both methods have difficulties. For case #1, the focusing changes as the bunch charge is increased, requiring one to either adjust the optics settings to compensate, or pick a sub-optimal setting that can work for the full range of bunch charges. For case #2, one must have a flexible laser pulse generation system that can handle the full laser power without damage for duty factors from 0 to 100%. For existing systems, it is possible to turn on directly to a few mA without tripping of the RF systems. Beyond that, the HV power supply must be able to ramp up the current quickly (50 - 100 ms is desirable) while maintaining a constant voltage at low ripple.

Accelerator designers often want to modulate the beam current, or even make gaps in the pulse train, for numerous reasons. The effects on the power supply response must be studied carefully for such requests, and included in early design of the supply and the control circuitry. As we have seen already, the voltage must be kept constant to a few tenths of a percent in order to minimize phase jitter. An instantaneous drop to 0 current will cause the voltage to rise, and the subsequent turn-on will cause it to droop, leading to transients in the beam and possible beam loss.

There are a number of mechanical requirements to consider as well. Many facilities enclose the high voltage power supply and electron gun in a tank of pressurized SF_6 in order to reduce the size of the device. One alternative is to enclose the supply in a very large faraday cage, and connect the gun and power supply using a cable, and another is to submerse the gun and power supply in an oil tank (often used for klystron modulators) [17]. All three have advantages and disadvantages, for example, using oil is generally not desirable when dealing with the extreme ultra-high vacuum conditions needed for a photocathode gun. SF_6 gas is a greenhouse gas and expensive, so one must provide a means to recover it efficiently. For labs that do not cycle the HV pressure tank very often, commerical SF_6 recovery systems are available, but tend to take many hours to empty and fill a tank. A custom system can be constructed if frequent empty/fill cycles are needed. There has been some discussion about finding alternative dielectric gasses in case SF_6 is ever banned due to its deleterious effects on the atmosphere, and our community will have to follow any legislative changes closely. In addition, as pressures of 1 to 5 atm are commonly employed, many labs have to deal with recent pressure vessel regulations. The last area to be concerned about is mechanical vibrations, as most SF_6 systems have a fan (or blower) plus heat exchanger to cool and circulate the gas around the HV components. The fans should be either isolated or mounted remotely, and care should be taken to avoid any mechanical resonances in the pressure vessel that are close to the frequencies of the fans.

High voltage electrode conditioning techniques will be covered in another section of this paper. To use a DC power supply for conditioning, a processing resistor must be inserted between the gun and power supply to limit the amount of current drawn during an arc. Values between 10 and 100 M-Ohm are typically used, but the exact value will depend on the system. This resistor must be removed after processing to avoid the voltage drop when drawing high currents during operation. To do this, the SF_6 tank must be opened, or a method for remotely inserting a lower value resistor (or shorting rod) must be included in the design.

Finally, where does one find the kind of power supplies that can meet the requirements discussed above? For voltages up to 225 kV and currents of tens of mA, there are many products available, as this is in the range of industrial X-ray tube manufactures. Beyond this, only a few companies (in the US) produce the kind of supplies needed for very high voltage DC photocathode guns. For example, up to 500-600 kV and currents to ~10 mA, Glassman High Voltage Inc. and Kaiser Systems Inc. make good systems. Kaiser Systems has also made compact supplies to 750 kV/100 mA for the Cornell gun. Pulse Electronic Engineering Co. Ltd. in Japan has made a power supply to 550 kV/10 mA for the JAEA/KEK gun.

HIGH VOLTAGE INSULATORS

L. Jones

The use of a DC photocathode electron gun confers many design and operational advantages compared to RF guns. The flexibility to design a vacuum chamber with any number of ports permits extremely high vacuum levels (XHV) to be achieved, allowing the use of high quantum efficiency cathodes such as Gallium Arsenide, coupled with longer-wavelength drive laser with significantly reduced power compared to RF guns. However, the complication of applying the DC HV bias needed to accelerate the photoemitted electron beam is an issue which is pushing the current boundaries of engineering technology. The insulator must fulfil a number of key operational criteria, specifically: separating the gun XHV vacuum from the pressurised HV insulating gas; providing electrical insulation to the level of hundreds of kilovolts; withstanding field emission and dissipating charge.

Field emission is the primary limiting factor in the performance of a photoinjector gun. The presence of a field emitter can severely degrade the electron beam quality delivered by the gun, or can cause the charging of ceramic insulators. In extreme cases, this can cause failure of the ceramic due to punch-through or tracking, or damage/failure of the vacuum vessel due to localised heating through electron-stimulated desorption. Field emission also affects the vacuum, so severely degrades photocathode lifetime.

Early DC guns such as the IR-FEL gun at JLab [18] used an impregnated surface coating to dissipate any charge accumulated on the ceramic surface through field emission. However, the first embodiment of this coating was not successful as the gun failed to operate at the intended design voltage, though the upgraded gun did perform at its design voltage.

Another solution is the use of a ceramic with bulk-doped controlled resistivity. This approach has been successfully implemented at Daresbury Laboratory using the proprietary WESGO 970CD material. This insulator proved highly effective during HV conditioning to 485 kV, and in beam operations at 350 kV, though problems have been encountered with the long-term reliability of the vacuum joints under load due to thermal cycling during baking. The favourable electrical performance of the material prompted a 3-way collaboration between Daresbury, Jefferson and Cornell, with the aim of finding a workable solution using a bulk-doped ceramic with reliable vacuum joints. Presently, CPI have delivered a 14” unit with a ‘book-end’ style vacuum joint to Daresbury, and Kyocera have delivered a 16” version to Cornell, both using the WESGO material. Neither of these units have yet been tested under electrical or mechanical load.

SLAC proposed the use of an inverted ceramic, using standard components developed by X-ray tube manufacturers [19]. This had the significant advantage of using off-the-shelf parts, so was cheap, but the draw-back was that the power supplies and ceramics are only rated to 225 kV, so limiting the operational voltage of a gun based on this technology to perhaps 200 kV. At Jefferson Laboratory, the CEBAF source group have recently installed a polarised gun based on this ceramic technology, the characteristics of which match well with their 100 kV gun operating voltage. The IR-FEL group have designed a gun using two inverted ceramics mounted in opposition. These will use the WESGO bulk-doped material, and will be rated for operation at 500 kV. The use of two ceramics in opposition serves to balance mechanical loads within the gun, and to provide geometric symmetry. The shape of the inverted ceramic conveys an additional advantage in that the surface plane of the ceramic is almost perpendicular to the HV cathode ball, so significantly reducing the likelihood of field-emitted electrons impacting directly on the ceramics themselves, and increasing reliability.

The use of segmented ceramics is common in DC electrostatic accelerators. The complete ceramic comprises a series of small hoops stacked alternately with overlapping 'chevrons' which act as shields for the insulating material. The chevrons are highly effective at shielding the ceramic from field-emitted electrons, though clearly there is a large number of ceramic-metal joints which have to be made in the manufacture of such a device. The chevrons also have to be connected via a ladder of resistors to grade their potential, with one end tied to earth. This design has been used successfully for the 100 kV gun at NIKHEF [20], the 200 kV gun at Nagoya University [21], and the 230 kV gun at JAERI FEL [22]. The segmented ceramics employed in the JAEA/KEK 500 kV gun is made by Hitacahi-Haramachi [23, 24]. The high voltage conditioning is under progress. Cornell plan to use a similar design in their next ceramic to be made by Kyocera.

The use is growing of external load-lock cathode preparation systems, and this itself is an important step forward. The use of Caesium in the cathode activation process invariably leads to contamination of the insulator over time, ultimately resulting in its electrical failure. This has been experienced most recently at Daresbury where insulator failure resulted in the failure of the conditioning resistor.

The focus for development should be to design an insulator with appropriate levels of vacuum performance, operating at perhaps 600 kV, and conditioned to 750 kV. Technology and economics may dictate that such an insulator will be in multiple segments, so failure of a single segment will not then necessitate complete replacement of the insulator, though it does mean there are additional vacuum joints which must then withstand repeated cycles of baking under high mechanical load.

HIGH VOLTAGE PROCESSING

C. Hernandez-Garcia

Introduction

The surface chemistry on the Cs:GaAs photocathode imposes extreme requirements for the vacuum in the gun chamber, while the need to extract and quickly accelerate the electron beam demands hundreds of kV with gradients around 10 MV/m. It is not sufficient to polish and clean the electrodes to minimize field emission. After assembling the gun and establishing ultra high vacuum conditions, the electrodes need to be high voltage conditioned. At an average rate of 5 kV per hour, this is a time consuming but essential process before the gun can be operated at the desired voltage.

The JLab FEL team has successfully conditioned two generations of DC photoemission guns to 450 kV for operation at 350 kV [3,25]. However, field emission has caused numerous problems puncturing insulators, opening vacuum leaks and damaging electrodes. These problems are common to all DC photoemission guns.

High Voltage Processing

High voltage conditioning in DC guns is nominally performed under vacuum conditions. Basic requirements include a current-limiting (conditioning) resistor in series with the high voltage power supply (HVPS), the ability to immediately shut-off the voltage at a desired current set point, plus radiation monitors and vacuum gauges in the form of ion pump read-back. It is important to shut the voltage off instead of lowering the voltage when the current reaches the desired limit set point, this allows for any charge accumulation in the insulator to drain while the voltage is ramped back up.

There are commonly three cases of field emission for a particular voltage set point: a) erratic current, b) current increasing with time, and c) self-sustained current. In case a), the usual procedure is to maintain the voltage for a few minutes until the field emission current self-extinguishes, although in some occasions a sudden current burst precedes the emitter burn-off. For case b), while the voltage is held constant, the current slowly increases, eventually reaching the trip limit and turning-off the HVPS. In some occasions, the trip limit is reached suddenly with a current burst, and when the voltage is recovered the field emission current has extinguished; in other occasions, the field emitter can sharpen by surface migration, leading to higher current at the original onset voltage. A sharp emitter is relatively easy to burn off by adjusting the voltage to limit the field emission current at ~10 μA until it self-extinguishes. Case c) is probably the most difficult to process since the field emission current can be self-sustained at levels beyond 100 μA. At hundreds of kV, there is enough power to cause damage. Pulsing the voltage for a few μs would be ideal, as is done in RF cavity processing. However, the response time of the HVPS is in the order of tens of ms. Typically this type of field emitter burns off in tens of minutes if the voltage is held constant until the field emission current extinguishes.

Beyond ~150 kV, voltage-induced gas desorption contributes to the complexity of the process. In the absence of field emission, the pressure in the gun vacuum chamber rises from 10^{-10} Torr to 10^{-8} Torr with every kV increment, and the Residual Gas Analyzer (RGA) indicates increases in H_2, CH_4, CO and CO_2. The time taken for the vacuum to recover is voltage dependent. Below 200 kV, it takes around 5 minutes; near 400 kV it can take up to 60 minutes. However, field-emitted electrons striking the chamber walls and desorbing gas dominate the vacuum behaviour. This voltage-induced gas desorption phase has a very sharp onset. If the gun is fully-conditioned to 350 kV, it can operate for years at that voltage, but if it is increased by 1 kV, gas desorption is observed again.

High Voltage processing with inert gases

Gas processing is very effective in burning field emitters with self-sustained current. Field emission current ionizes the inert gas atoms that are accelerated towards the negatively biased electrodes, effectively back-ion bombarding the field emitter until the geometry or the work function is altered.

Helium is commonly used for processing superconducting RF cavities and has also shown good results for the Cornell gun [26]. However, there is always a risk to develop a leak especially in the ceramic insulator due to the lack of vacuum diagnostics at the 10^{-5} Torr level where the gas processing takes place. It must be ensured that the pressure is set at the vacuum chamber and not by ion gauges near the turbo pump, where the pressure will be lower. The NEGs do not react with inert gasses and continue pumping other gasses. It should be noted that this process is not a DC glow discharge since the pressure is too low to ignite plasma.

In the JLab FEL gun helium processing was less effective, but krypton quickly burned emitters off below 250 kV, as shown in Fig. 1. A detailed description of the setup is given in [27], later this procedure has also been highly successful used at DL.

After processing a field emitter, the Kr gas can be pumped–out, and the ion pumps turned back on to resume normal high voltage conditioning. However, this procedure did not work for the FEL at 270 kV, and Kr gas processing continued for tens of hours. At 315 kV a pattern was observed in both the current and radiation traces with every kV increment. The pattern resembled the gas desorption phase observed under nominal vacuum conditions, only that the signal from the radiation monitors behaved as the ion pump pressure. The radiation tracked the high voltage current with every voltage increment, showing a sharp rise followed by an exponential decay. High voltage conditioning with Kr was successful in eliminating emitters and at the same time the process had evolved into the gas desorption phase, which continued to 415 kV at a rate of 1 kV/hour, until both the current and the radiation were at baseline. Progress was monitored every ten hours with the gun under nominal vacuum conditions, by verifying that the on-set voltage for observing radiation increased by about 10 kV. Finally, the voltage was ramped to 365 kV and maintained for several hours while both current and radiation remained at background levels [28]. The FEL gun is currently operational at 350 kV.

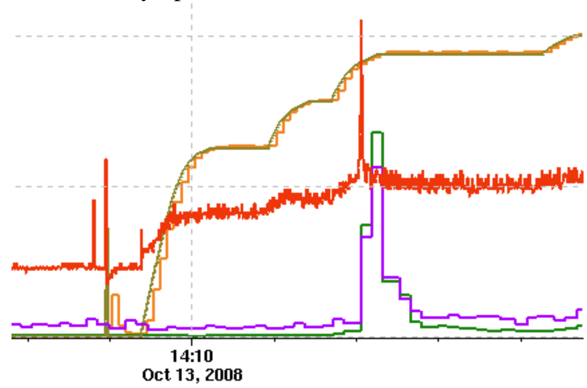

Figure 1: Emitter burning off while ramping up to 250 kV. The horizontal scale is in minutes. The red trace is the current (0-0.5 mA), purple and green traces are the radiation monitors signals (0-100 mR/h), and yellow trace is the voltage (0-400 kV).

FIELD EMISSION MEASUREMENS AT JEFFERSON LAB

M. Poelker and K. Surles-Law

Intdoduction

As mentioned numerous times above, field emission inside DC high voltage photoguns can lead to big problems at accelerator facilities. Constant low-level field emission degrades vacuum within the gun, reducing gun operational lifetime via electron stimulated desorption of gas and subsequent photocathode QE loss from ion back-bombardment. Large bursts of field emission can be catastrophic, leading to damage of the photocathode and other gun components, particularly the high voltage insulator, which sometimes results in a complete loss of vacuum. These problems were particularly difficult to overcome in older "vent/bake" style photoguns, where the photocathode was activated to negative electron affinity within the high voltage chamber, with cesium serving to reduce the work function of the GaAs photocathode surface, but also inadvertently reducing the work function of the metallic cathode electrode structure as well. Often, a vent/bake gun could support just a few photocathode activations before cesium-enhanced field emission made the gun inoperable. Today, gun groups adopt a load lock-style design, with cesium applied to the photocathode in a separate vacuum chamber isolated from the high voltage region of the gun. The key factors that influence field emission inside modern load-lock style photoguns are the desired operating voltage of the gun, the gun geometry which determines field gradient, and the choice of electrode materials and polishing techniques. Vacuum may not play a role in the onset of field emission, but can contribute to enhancement of field emission via ionization of residual gas and ion back-bombardment. Other factors are frequently discussed, for example, surface cleanliness and contamination, and more academic topics such as the role of hydrogen diffusing from the electrode material and grain boundaries.

Extremely demanding emittance requirements of proposed ERLs necessitate very high bias voltages: ~ 350 kV or more. The field gradient within the gun can be adjusted to some extent, for example by choosing an appropriate cathode/anode gap, and by prudently choosing large distances to other grounded gun components such as the vacuum chamber - but just as ERL emittance requirements dictate high bias voltage, a high gradient within the photogun is unavoidable because the beam must be quickly accelerated to relativistic speed to overcome deleterious effects of space charge. It seems certain that DC high voltage guns for ERLs must operate with gradients of 10 MV/m or more, roughly a factor of two higher than gradients inside the original DC high voltage photoguns used for decades to generate polarized electron beams at nuclear and high energy physics accelerator facilities.

Traditionally, photogun electrodes have been manufactured from vacuum-arc remelt stainless steel, polished by hand to sub-micron finish with diamond grit [29]. More recently, groups have begun to explore in earnest different electrode materials and polishing techniques, recognizing the need to reliably manufacture "quiet" electrodes that can operate at very high bias voltage and gradient without field emission [7,30]. Of note is the extremely thorough study of ref. [7] that explored primary field emission from the cathode electrodes and subsequent field emission enhancement due to ionization of residual gas and ion-back-bombardment of the cathode electrode, including the effect of stimulated desorption of gas from the anode. Their work indicated molybdenum performed very well as cathode material, and titanium serving best for the anode.

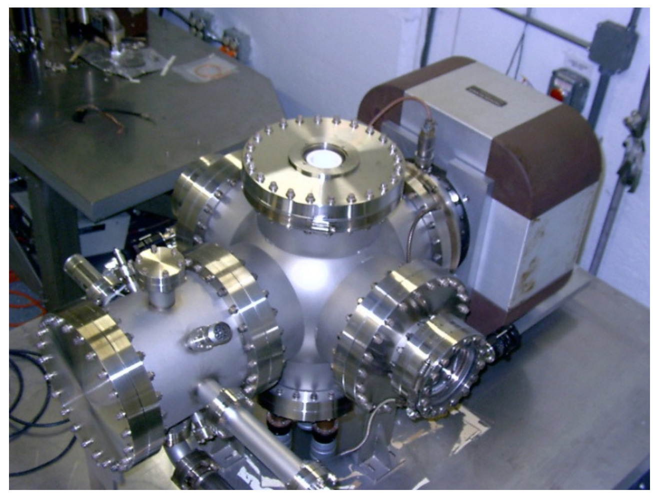

Figure 2: The Jefferson Lab High Voltage Test Stand. Bias voltages up to 250 kV can be applied to cathode electrodes attached to the inverted insulator that extends into the UHV chamber, visible at top of photograph. Vacuum translation stages, bottom of photograph, provide a means to reduce the cathode/anode gap to a few millimeters, to reach gradients > 30 MV/m, but larger gaps more closely explore the field emission properties of actual gun designs.

At Jefferson Lab, a high voltage test stand was constructed (Fig. 2) with an inverted insulator that allows high voltage processing of full-size photogun electrodes up to 250 kV, with a GaAs photocathode installed (but not activated) and with anode/cathode gap that can be adjusted from 4 to 50 mm, to vary the gradient over a large range. Besides providing a means to study different electrode materials and polishing/processing techniques, the test stand provides a means to operate cathode electrodes at actual CEBAF voltage and gradient before installation inside a photogun - electrodes can be re-worked or discarded if found unacceptable without wasting accelerator time. In addition, the test stand provides a means for more "aggressive" high voltage processing techniques without fear of damaging the actual photogun. More recently, the test stand was used to quantify benefits of krypton-ion processing (krypton-ion back bombardment of field emitters) [28].

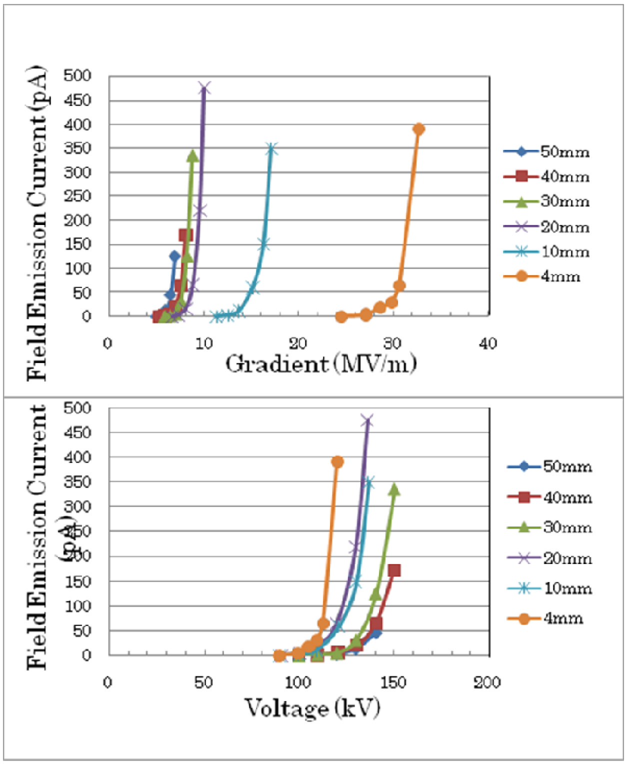

Figure 3: "Benchmark" results from diamond-paste polished 304 stainless steel. The cathode electrode had been used inside a CEBAF 100 kV photogun for many years. Same field emission data, but plotted versus gradient (top) and bias voltage (bottom).

Results

Tests using stainless steel electrodes provide a benchmark against which other electrode materials and polishing techniques are compared. The data in Fig. 3 were obtained using electrodes made of vacuum-arc remelt 304 stainless steel (SS), first polished with silicon carbide paper and then with diamond grit of successively finer grit size. The cathode electrode had been used inside a CEBAF photogun for years, and is considered thoroughly "processed". One obvious feature of these plots is that results obtained with small gaps are not particularly useful – i.e., one cannot assume that since this cathode electrode exhibited no measureable field emission at 25 MV/m with a 4 mm gap, it would perform well at 50 mm gap. Rather, these plots suggest field emission from diamond-paste polished stainless steel electrodes, when configured with typical gun anode/cathode gaps, "turns ON" at disappointingly low values of ~ 5 MV/m and ~ 100 kV.

Everyone knows diamond-paste polishing (DPP) is a labor-intensive process – it can take weeks to polish a complicated electrode structure. And because results often vary sample-to-sample and across laboratories, there are nagging fears that results depend on subtle variations in polishing technique: for example, diamond particles can become embedded beneath "peaks' that get rolled over due to excessive pressure applied to the sample during polishing. For these reasons, groups have re-visited electropolishing as alternative to DPP. Full details of experimental results must wait for another publication, but preliminary results from Jefferson Lab indicate electropolishing provides comparable results as shown in Fig. 3, but requiring significantly less time and effort.

Two single-crystal niobium electrodes were manufactured and evaluated inside the high voltage test stand. Both electrodes were polished using the standard SRF practice known as BCP (buffer chemical polish). Another SRF-practice was employed: high pressure rinsing as a means to remove contaminants. Niobium electrode #1 performed very well, exceeding the performance of DPP stainless steel (Fig. 4), "quiet" to ~ 150 kV with 50 mm gap. Niobium electrode #2, however, performed poorly initially, but improved after several iterations of krypton processing. Regrettably, both electrodes suffered high voltage breakdowns and could not sustain subsequent application of comparable high voltage. This work will continue at Jefferson Lab, including studying other niobium electrodes: polycrystalline material referred to as fine grain and large grain niobium, and using the electropolishing technique.

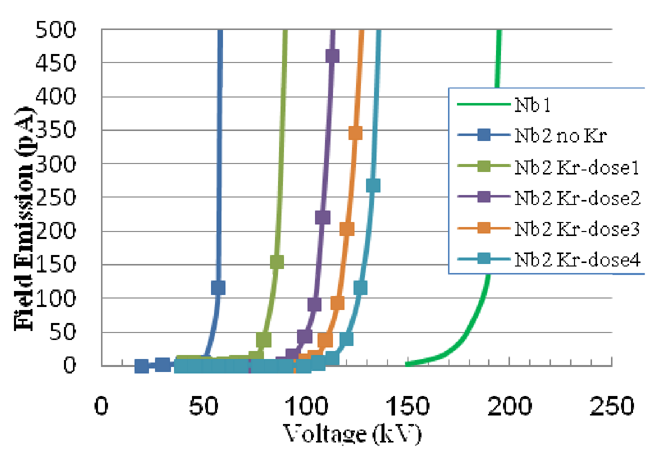

Figure 4: Field emission measurements of two single crystal niobium electrodes, polished with BCP. See text for details.

Table 1: Basic information of gun vacuum systems

Institute	Chamber material	Chamber treatment	Vacuum pump system	Bake out condition	NEG activation	Ultimate Vacuum
Cornell	SUS316L	400°C air-bake, 100 hours	NEG: 20000 L/s IP: 400 L/s	150 °C, 24 hours	400 °C, 45 min	4 E-10 Pa
JLAB FEL	SUS316 LN	400°C air-bake, 360 hours	NEG: 3000L/s IP: 80L/s	250°C 160hours	400°C, 60min	5E-10 Pa
CEBAF	SUS316L & SUS316LN	EP-ed, 400°C vacuum-bake, 200 hours	NEG: 8800 L/s (ten WP1250s) IP: 30 L/s	250°C 30 hours	400°C, 60 min	4 E-10 Pa
Daresbury	SS304L & SS316LN	--	NEG:3,900 l/s IP: 150 L/s	200 - 220 °C ~ 2 weeks	~500 °C, 60 min	2 to 4 E-9 Pa
JAEA(250kV)	Titanium	CP	NEG: 2000 L/s IP: 500 L/s	200 °C 20 hours	450 °C, 60 min	5 E-9 Pa
KEK/Nagoya (200kV)	SUS316L & SUS304L	EP	NEG: 850 L/s IP: 400 L/s	200 °C, ~100 hours	400 °C, ~ 3 hours	2 E-9 Pa

Conclusion

For stainless steel electrodes, keeping gradient below ~ 5MV/m seems prudent, although understandably, this might be impossible for very high voltage ERL photoguns. So the search for materials and polishing techniques that provide quiet electrodes to 10 MV/m at actual gun voltage must remain a critical R&D focus for the DC high voltage photogun community.

VACUUM

M.Yamamoto

The ultra-high vacuum system is indispensable for suppressing ion back-bombardment in photocathode DC guns. This is because the residual gases in the gun vacuum chamber are ionized by the extracted electron beams and accelerated back into the photocathode, resulting in damage of the cathode crystal structure or degradation of the negative electron affinity of the cathode surface. Improving the ultimate vacuum is straightforward way to solve the ion back-bombardment problem.

The ultimate pressure p [Pa] is denoted by $p=qA/S$, where q [Pa m/s] is the outgassing rate of the vacuum chamber material per unit area and unit time, A [m^2] the internal vacuum chamber area and S [m^3/s] the pump speed. Use of a massive pump system and a chamber material with low outgassing rate is essential for achieving the extremely high vacuum (XHV).

The basic information on vacuum system of electron guns at various laboratories are summarized in Table 1. For reduction of outgassing, components installed in the vacuum chamber and chamber itself are rinsed in ultrasonically cleaned acetone, ethanol, or deionized water solutions. They are polished electrolytically or chemically, and degassed by vacuum firing before assembling. The gun chamber is then baked to 150~250 °C for about a day to a week to eliminate hydro-carbons, carbon dioxide, carbon monoxide, nitrogen and water. The partial pressure of water and carbon dioxide should be sufficiently low 10^{-11} Pa or less for long cathode dark-lifetime [2,31]. The most significant source of outgassing in UHV/XHV is mainly hydrogen dissolved in materials. There are two ways to reduce the outgassing rate. One is formation of a passive layer, which acts as a barrier for bulk hydrogen diffusion or inhibits surface processes of adsorption and recombination. The other is formation of a surface layer with low hydrogen content.

Air-baked stainless steel is employed in Cornell University and Jefferson FEL [8,11]. The thick oxide layer formed on the stainless surface after the air-baking reduces the subsequent baking temperature to ~150°C for shorter time duration around a day. The CEBAF injector group employs vacuum baked stainless steel (400°C for 200 hours), which was electro-polished and high pressure rinsed before vacuum baking. A chemically polished titanium used for JAEA/KEK gun has very low outgassing rate of $6x10^{-13}$ Pam/s [12]. Use of other low outgassing materials such as BeCu and SUS316L with TiN coat may help improve vacuum of gun vacuum chambers [32-34].

A non-evaporable getter (NEG) pump and an ion pump (IP) are employed in gun vacuum chambers. The NEG pump provides extensive pumping of the dominant residual gas of hydrogen under UHV/XHV condition, while the IP pumps noble gasses and methane that are poorly pumped by the NEG pump. The IP pump speed decreases as the operating pressure decreases under UHV condition less than 10^{-6} Pa, since ionization rate of residual gases inside IP becomes low. Recently, M. Poelker et al. performed pump speed measurements of some commercially available IPs under XHV condition. The preliminary data indicates the effective pump speed decreases down to almost zero in the range of 10^{-10} Pa. A cryopump designed carefully to fulfill the XHV specifications may be a candidate as an alternative of IP [35,36].

A limit of ultimate pressure of NEG pumps is estimated from Sievert's law. This gives extremely low equilibrium pressure of hydrogen at the room temperature. However, there are few experimental data of the NEG pump speed in the XHV environment except for ref. [37].

In order to achieve ultimate vacuum of the order 10^{-10} Pa or less with several m^2 vacuum area of a gun chamber, one should use low-outgassing chamber materials of $\leq 10^{-10}$ [Pa m/s] and a vacuum pump with large effective pump speed of >5 m^3/s under XHV condition.

III-V PHOTOCATHODE PREPARATION SYSTEMS

B.Militsyn

Originally III-V family photocathodes such as GaAs, GaAsP, InGaAsP and similar were mainly used in DC guns for production of polarised electrons. As grown, these materials have a positive electron affinity, which for GaAs is 4 eV. In order to make GaAs photocathodes able to emit electrons when illuminated by 532 nm light, typical for ERL DC guns, its surface should be brought to Negative (NEA) or small, less than 1 eV, Positive Electron Affinity (PEA) state. This process basically comprises deposition on the atomically-clean photocathode surface of a thin layer of Cs and an oxidant, typically O_2 or NF_3, and is called activation. Before the activation, the surface of the photocathode is heat cleaned in order to remove As and Ga oxides.

At earlier stages of the photocathode gun development and at certain installations operating currently, heat cleaning and activation of the photocathodes were performed directly in the gun [21,38-40]. Eventually it was recognised that activation in the gun had serious disadvantages: activation process control was poor, it was difficult to provide extra high vacuum conditions for photocathode operation, products of the photocathode heat cleaning and vapour of caesium could contaminate the gun ceramic which limited the maximum high voltage achievable in the gun and, finally, replacement of the photocathode required several weeks which was not acceptable for practical installations.

In modern photoinjectors, activation takes place in a dedicated Photocathode Preparation System (PPS). The first PPS was developed at SLAC [41] and operated with polarized electron source of the Stanford Linear Collider. It was a dedicated vacuum system consisting of two chambers - loading and preparation. The photocathode was brought into the loading chamber, and then transferred to the preparation chamber, whose vacuum is maintained at extreme high vacuum (XHV) conditions, with a vacuum manipulator. For replacement of the photocathode, the PPS was temporally attached to the gun forming united vacuum system; the photocathode activated in the preparation chamber was then transferred to the gun with a manipulator. The SLAC preparation system was a great step forward for improving quality of photocathode preparation, although the downtime required for photocathode exchange was still high – a several hour period.

The next step in PPS development was made at the University of Mainz in the framework of the development of a polarized electron source for the MAMI project [42]. In the MAMI design, a side-loading mechanism for the photocathode was implemented which allowed the PPS to be permanently connected to the gun. This dramatically reduced the downtime required for photocathode exchange to the order of one hour. Another solution, which permits the PPS to be permanently connected to the gun and allows the more preferable back-loading of photocathodes, was proposed at SLAC in their so-called "Inverted gun" [17]. Permanent PPS connection was also used in traditional guns with a double insulator scheme [19,43] where the PPS was connected to the gun from the high voltage side with an additional full voltage insulator. Recent gun designs are based on vertical orientation of the insulator and horizontal orientation of the electrode system [8,44] also allowing back-loading of the photocathode.

Modern PPS consist typically of two chambers: a loading chamber (LC) and an activation chamber (AC). Recently, some PPS have also been equipped with a Hydrogen Cleaning Chamber (HCC). Figure 5 shows an engineer's view of the three chambers PPS which has been designed for operation with ALICE ERL [45].

As activated photocathodes are very sensitive to the presence of oxidants in the residual atmosphere, for example the 1/e lifetime of GaAs does not exceed $2 \cdot 10^{-8}$ mbar·s of oxygen exposition [46], XHV conditions are maintained in the AC. The typical pressure in an AC is less than 10^{-11} mbar, with partial pressures of oxygen, water vapours and CO_2 of less than 10^{-14} mbar. In order to

Table 2: Basic parameters of the preparation photo cathode systems designed for operation with high average current photoinjectors.

Institution/ Installation	Design	Preloading treatment	Preactivation treatment	Activation procedure	Results with bulk GaAs	Rejuvenation procedure	Vacuum conditions	Remarks
Cornell University	Two chambers	Chemical etching (H_2SO_4) and anodizing	Heat cleaning at 550°C for 2 hours	Cs-NF_3 "Yo-Yo"	10-15% at 532 nm	Heat cleaning	PC $5.0\cdot10^{-12}$ mbar LC $5.0\cdot10^{-11}$ mbar	
STFC Daresbury Laboratory	Three chambers (up to 6 samples in carousel)	HCl etching (not yet implemented)	Heat cleaning at 450°C	Cs-O_2/NF_3 "Yo-Yo"	15% at 635 nm	Atomic hydrogen cleaning	PC $1.4\cdot10^{-11}$ mbar LC $5.0\cdot10^{-10}$ mbar HCC $4.0\cdot10^{-11}$ mbar	
JAEA	Two chambers	HCl etching	Heat cleaning at 500°C for 1 hour	Cs-O "Yo-Yo"	7-10% at 633 nm	Atomic hydrogen cleaning (optional)	AC $2.5\cdot10^{-9}$ Pa LC $5.0\cdot10^{-8}$ Pa	
KEK (Nagoya)	Two chambers	HCl etching	Heat cleaning at 500°C for 1 hour	Cs-O "Yo-Yo"	7-10 % at 780 nm	Atomic hydrogen cleaning (optional)	AC $1.0\cdot10^{-8}$ Pa, LC $1.0\cdot10^{-7}$ Pa	
TJNAF/CEBAF	Four chambers inclusive suitcase and bakable adapter		Heat cleaning at 550°C for 2 hours	Cs-NF3 "Yo-Yo"	20% at 532 nm	Heat cleaning	PC $7.0\cdot10^{-12}$ mbar LC high 10^{-11} mbar	Mask activation

routinely maintain such extreme vacuum conditions, AC is usually equipped with a high performance Ion Pumps (IP) and Non-Evaporable Getters (NEG), and it is never ventilated to atmosphere. Vacuum in the AC is measured with an extractor gauge and a RGA.

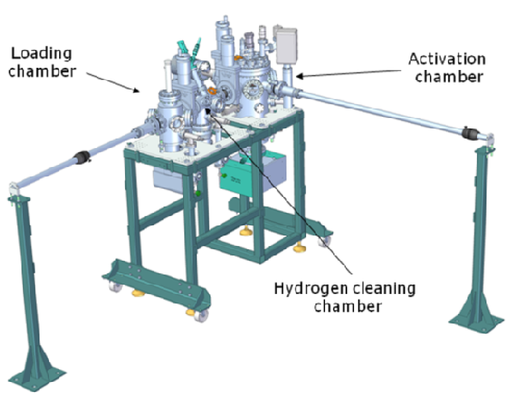

Figure 5: Engineer's view of the Photocathode Preparation System designed for ALICE ERL.

Loading of the photocathode is performed via the LC, which is preferably vented to dry nitrogen gas only during loading. The pumping system of the LC includes an IP and an oil-free preliminary pumping station. After the photocathode is placed into the LC, it is pumped down to a pressure of 10^{-9} mbar and eventually baked out at a temperature of 120-150 °C in order to remove water from the samples. Once acceptable vacuum in the LC is established, the photocathode is heat cleaned at a temperature of typically 600 °C for 1-2 hours. This procedure, depending on PPS design, may take place either in the LC, HCC or AC. Temperature of the samples is measured with a pyrometer. In some installations the surface is etched before loading in a pure nitrogen atmosphere using hydrochloric or sulphuric acid to remove oxides. Thereafter the photocathode is transferred into the LC in a transport vessel in pure nitrogen atmosphere to prevent appearance of new oxides. The heat cleaning temperature of the etched photocathodes may be reduced to 450 °C. Some vendors cover photocathodes with a thin arsenic layer in order to prevent its oxidation. This "arsenic cap" is evaporated before activation. A heat cleaned photocathode is then activated by means of a Cs-O_2 or Cs-NF_3 "Yo-Yo" procedure.

Caesium is evaporated from a Cs dispenser while the high purity oxidant gas is delivered from a cylinder via a leak valve. Sometimes for better control of the gas stream, a computer-controllable piezoelectric leak valve is used. During activation the photocathode is illuminated with a lamp or laser and the photocurrent is monitored with a pico-ammeter. As at high temperature the Cs source may emit ions which mask photocurrent, a modulated laser is preferable. A synchronous detector is then used for current detection.

Activated photocathodes are transferred to the gun using a vacuum manipulator. For a short time, the vacuum valve between PPS and gun is opened, and the depleted photocathode is retracted back to the AC. The freshly activated photocathode is transferred to the gun and the valve is closed. The depleted photocathode may be cleaned and reactivated again. For rejuvenation of a depleted photocathode, atomic hydrogen cleaning is carried out in the HCC [47].

As the lifetime of photocathodes expressed by total extracted charge when operating in a DC gun is restricted to only a few hundred Coulombs [48], corresponding to operational life-time of a few hours at ERL operational conditions with average extracted current of 100 mA, the PPS should be ready to deliver an activated photocathode every few hours. For this, the PPS will normally contain several photocathodes, one of which is activated.

Presently, PPS design may be considered to be well established. The typical initial quantum efficiency of the activated photocathode can reach 20% at a wavelength of 532 nm making it sufficient for operation in ERL high-current guns.

ION BACK-BOMBARDMENT

J. Grames and M. Poelker

Ion back-bombardment is the key factor limiting photogun operating lifetime. Residual gas inside the gun vacuum chamber and nearby beam line can be ionized by the extracted electron beam or field emission from the high voltage electrodes. Ions produced within or reaching the cathode/anode gap are accelerated toward the photocathode by the gun's static electric field. Ions with sufficient kinetic energy can strike the photocathode surface and sputter away the chemicals used to create the negative electron affinity condition necessary for photoemission. Energetic ions can also penetrate the photocathode surface, damaging the GaAs crystal structure or serving as unwanted dopant species that alter the photocathode band structure, reducing quantum efficiency (QE). This process is illustrated in Fig. 6, with a characteristic photocathode "QE scan" exhibiting the effect of ion back-bombardment.

At CEBAF and other accelerators, production photoguns exhibit charge lifetime of a few hundred Coulombs (i.e., before QE falls to 1/e of initial value). Some ERLs however must deliver thousands of Coulombs per day. To put high current ERL requirements into perspective, consider that a photogun with just 100C charge lifetime could satisfy accelerator requirements for only minutes before some sort of action would be required, for example, move the drive laser spot to a fresh photocathode location, heat/reactivate the photocathode, or replace the photocathode. Each of these actions represents downtime for the accelerator. Therefore, improving vacuum inside the gun is critical for high average current, milliampere-class ERLs: both static vacuum without beam, and during gun operation with beam.

Improving static vacuum inside DC high voltage photoguns has been a central R&D focus for years, with all photoguns today relying on non-evaporable getter (NEG) pumps and ion pumps (to pump inert gasses not pumped by NEGs). It is now typical that vacuum inside NEG/ion-pumped photoguns is in the upper-10^{-12} to low-10^{-11} Torr range but accurate pressure measurement in this range is difficult.

On the static vacuum front, the Cornell group recently verified the efficacy of reducing the outgassing rate of vacuum chamber materials via the LIGO "high temperature" 400C bake process [11], with more than an order of magnitude reduction in outgassing rate compared to "typical" stainless steel baked at 250C. The technique is relatively easy to implement and should provide significant base pressure improvement - provided there are no fundamental limitations of NEGs and ion pumps.

On the "dynamic" vacuum front (i.e., vacuum while operating the gun), it is extremely important to eliminate field emission from the cathode electrode, which can degrade vacuum via electron stimulated desorption. In addition, it is extremely important to effectively manage all of the extracted beam leaving the photocathode, including beam not intentionally produced, for example, from extraneous laser reflections or background light illuminating the activated surface of the photocathode. Anodizing the edge of the photocathode [2], or limiting the active area with a mask [49], are helpful steps toward eliminating this unwanted electron beam. In addition, cathode/anode designers must consider beam transport from the entire photocathode surface, not just from the desired location of the beam. The gun electrodes must be designed to capture the "extra" beam and deliver it far from the gun.

Short of improving vacuum, there are several techniques that can be employed to prolong photocathode lifetime. Hydrogen is the dominant gas species inside a UHV/XHV chamber and the hydrogen ionization cross-section peaks at ~ 30 V, falling sharply at higher voltages [50]. One technique – employed "for free" by the very-high-voltage ERL gun community - is to operate at very high bias voltage. At very high bias voltage (assuming there is no field emission), there should be considerably fewer hydrogen ions created by the extracted beam, although this claim awaits experimental verification.

It has been known for years that ions created near the anode are preferentially directed toward the electrostatic center of the photocathode [51]. Another technique to prolong photocathode lifetime is to operate with the laser beam positioned away from the electrostatic center of the photocathode. Unfortunately, modeling predictions suggest this leads to emittance degradation of the beam [52].

More recently, Grames et al., determined that ions produced downstream of the anode contribute to photocathode QE decay [15], and these ions are also delivered to the electrostatic center of the photocathode. It is relatively easy to eliminate these ions by simply applying a small positive bias (~ few hundred volts) to an electrically isolated anode.

Finally, Grames et al., determined that operating the photogun with a larger laser spot size can improve lifetime [13], by effectively distributing ion back-bombardment over a larger area of the photocathode. However, this technique (like off-axis drive laser operation) leads to emittance degradation.

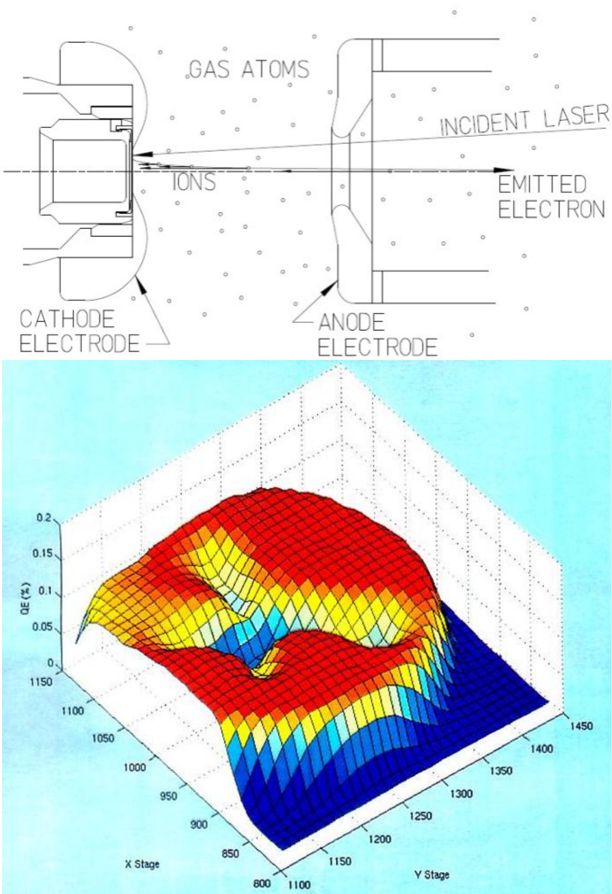

Figure 6: Top: Illustration showing cathode/anode structure, photoemitted electrons and ion back-bombardment for off-axis illumination of photocathode. Bottom: plot of QE across the surface of the photocathode damaged by ions. The electron beam was extracted from three different radial locations. Note QE "trenches" that terminate at a common "electrostatic center".

Conclusion

The "tricks" described above to prolong photogun operating lifetime certainly help enhance our understanding of these complicated devices, but are unlikely to provide sufficient means to meet the requirements of high current ERLs. Therefore, improving vacuum inside DC high voltage photoguns remains an extremely important task. In the realm of improving static vacuum, there are a number of topics that need R&D attention: cryogenic-pumping as an alternative to NEGs and improved vacuum gauging, to accurately measure pressure in the 10^{-12} Torr range and lower. Complimentary studies to identify limitations of NEGs and ion pumps also seem warranted. Finally, there needs to be greater appreciation for the role of cathode electrode design, in terms of transporting all of the extracted beam from the photocathode – both wanted and unwanted beam.

NEW IDEAS AND DESIGN CONSIDERATIONS

I. Bazarov

The photoemission DC guns have been reliably delivering up to about 10 mA of average currents with normalized RMS emittances of ~5-8 mm·mrad. A number of emerging applications nevertheless require substantially improved emittances (on the order of 0.1 mm·mrad) at comparable or higher beam currents. R&D programs are underway in several laboratories to address the outstanding issues for very low emittance DC photoemission guns capable of delivering beam currents of 10-100 mA. Below we survey some new directions under exploration to achieve the improved performance.

Cathode field and thermal emittance

Even for the DC guns operating currently at voltages of up to 350 kV, a significant improvement in beam brightness will be made possible through emittance compensation processes, and a better control of the initial electron bunch 3D distribution via laser shaping. A lower limit to the achievable emittance has been recently formulated for photoemission guns in terms of the cathode field and intrinsic (thermal) emittance of the photocathode material [16]

$$\varepsilon_{\mathrm{nx}}(\mathrm{mm}\cdot\mathrm{mr}) = \alpha\times 0.015\sqrt{q(\mathrm{pC})\frac{kT_{\perp}(\mathrm{meV})}{E_{cath}(\mathrm{MV/m})}}, \quad (1)$$

with q being the charge per bunch, E_{cath} the accelerating gradient at the photocathode and $kT_{\perp}$ the effective transverse energy (temperature) of the photoemitted electrons. The parameter α depends on additional details such as the 3D laser pulse distribution, the degree of emittance compensation, etc. For a well-designed injector system, $\alpha \approx 0.3-0.9$. For example, using typical DC gun parameters: $E_{cath} = 3.5$ MV/m (the gun voltage 350 kV and the cathode-anode gap of 10 cm), $kT_{\perp} = 120$ meV corresponding to GaAs at 520 nm wavelength illumination [53], and the bunch charge of 80 pC, one concludes from Eq. (1) that emittances of no larger than 0.8 mm·mrad should be achievable. Similar conclusion follows from computer optimizations of the beam dynamics with experimentally benchmarked space charge codes [54]. Therefore, proper realization of space charge emittance compensation is the primary route towards significant reduction in emittance beyond that which has already been demonstrated from DC guns.

Additional improvements in achievable beam brightness will become possible when employing photocathodes with lower transverse energy spread and by increasing the cathode electric field. Without further discussing the important subject of photocathodes for low emittance beam production, we point out several additional considerations to low emittance beam production arising from the gun electrode design.

Optimal Gun Voltage

While the gun voltage is not a parameter that directly defines the beam brightness at the photocathode, $1/\gamma^2$ scaling of space charge forces in the gun vicinity as well as operational experience make it a key design objective for DC guns. Previous simulation studies suggest that a properly designed 400-600 kV DC gun can allow low emittances (0.2 mm·mrad at 80 pC), and that the emittance improvements are modest for gun voltages above 750 kV at these charges [4]. Besides, this gun voltage level is well matched to the use of an RF buncher downstream of the gun for velocity compression.

Transverse focusing

Ideally, external focusing in the gun, either due to electric or magnetic fields should counteract the defocusing due to the space charge, which at the gun exit can be estimated using

$$\frac{1}{f_{s.c.}} \approx -\frac{I}{I_0}\frac{d}{r^2}\frac{mc^2}{eV_{gun}}\frac{1}{\beta\gamma}\ln\frac{2d}{(1+\gamma)z_i},$$

for a cylindrical beam with radius r, (peak) current I, cathode-anode gap d, and normalized momentum $\beta\gamma$ corresponding to kinetic energy eV_{gun}, and z_i being on the order of the bunch dimension ($z_i \sim r$). $I_0 = 17$ kA.

Additional defocusing due to anode is always present in DC guns and contributes further to beam divergence. The effective defocusing is largely independent from the anode geometry and is given by:

$$\frac{1}{f_{anode}} \approx -\frac{1}{4d}\frac{1+eV_{gun}/mc^2}{1+\frac{1}{2}eV_{gun}/mc^2}$$

The required focusing can be achieved through appropriate electrode shaping (Pierce-like electrode geometry) and magnetic solenoidal fields. The former allows focusing in the vicinity of the photocathode but does so at the expense of a somewhat reduced E_{cath} possible otherwise for a flat cathode with the same cathode-anode gap. Magnetic focusing, on the other hand, requires a vanishingly small field at the photocathode to avoid emittance increase due to canonical momentum conservation, and is most effective when the solenoid is placed some distance from the cathode unless a bucking solenoid can be employed. The DC gun geometry typically prevents bucking solenoid coil placement in the immediate vicinity of the photocathode, thus, a combination of both cathode Pierce-like angle and an external solenoid placed right after the gun are needed to achieve the desired focusing effect.

Voltage breakdown criteria

The main technological challenge to the DC guns is due to problems of field emission and the voltage breakdown, which limit the maximum available gradient and voltage. The best practices to the material selection, surface preparation and cleanliness are required in order to achieve the best performance. A body of experimental work on performance of large area electrodes has been accrued over the years, which should serve as a guide when arriving at the actual gun geometry. Most notably, the trade-off of the highest achieved voltage data versus the gap for large area parallel electrodes is summarized in Fig. 7. As a rule of thumb, the electric field should not exceed the breakdown condition anywhere on the surface of the cathode electrode. The actual electric field on the photocathode itself for a given voltage and gap can be noticeably smaller than what's suggested in Fig. 7 when electrode shaping for transverse focusing is employed.

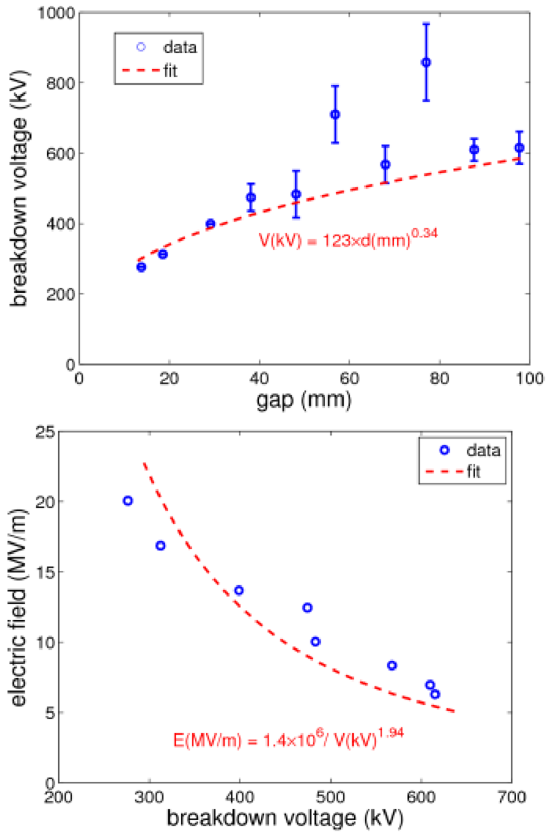

Figure 7: Adopted from [55]: (top) voltage breakdown vs. gap; (bottom) maximum field vs. voltage.

Parameterized gun geometry

Overall, the optimal gun geometry is subject to several potentially conflicting requirements: maximize E_{cath} , increase the gun voltage, and provide a stronger electrostatic focusing at the photocathode. The last two generally lead to a reduced maximum E_{cath} when operating at the voltage breakdown limit. The problem of choosing optimal gun geometry in the cathode-anode region can be most efficiently addressed via computer optimizations: field maps corresponding to a parameterized gun geometry are calculated and the smallest emittance possible with this geometry is numerically determined via space charge code simulations. A scan of the gun geometry parameters (e.g. the gap and the cathode angle) and the gun voltage is then performed subject to a number of realistic constraints to arrive at the optimum geometry for best emittance performance [56]. Figure 8 shows results of such study with optimizations performed for 80 pC/bunch with emittance minimized after a short beamline (1.3 m) consisting of the gun and a favourably placed solenoid. Each point in Fig. 8 corresponds to an optimized gun geometry for the given voltage. The cathode angle and the gap in the plot vary from 20 to 30° and 32 to 42 mm respectively across the gun voltages span.

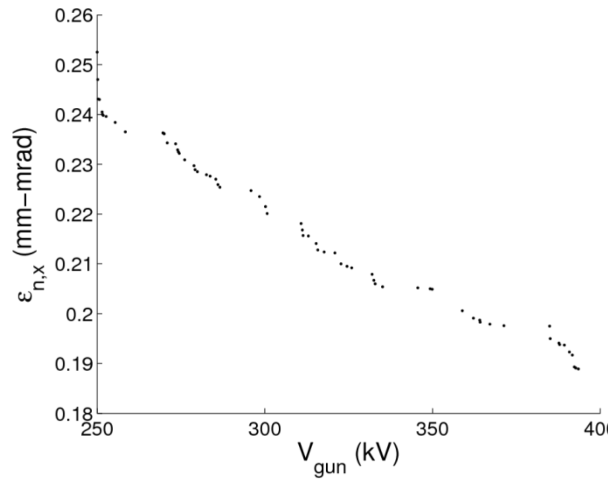

Figure 8: Beam emittance performance for optimized gun geometry at different gun voltages. The bunch charge is 80 pC, and the rms laser pulse duration is 12 ps.

Segmented gun

To a certain extent, it is possible to decouple the two conflicting requirements of a higher gun voltage (a large gap) and a higher E_{cath} (a small gap) by considering a two gap DC gun. Figure 9 illustrates the concept. Such a gun will feature a small (1.5-2 cm) gap with a modest 250 kV voltage followed by a larger gap with uncritical dimension of 5-10 cm with a larger 350-500 kV voltage. This would allow the creation of a high field at the photocathode (>10 MV/m) together with the more optimal overall gun voltage of 600-750 kV. Further investigations about the practicality of this approach are required.

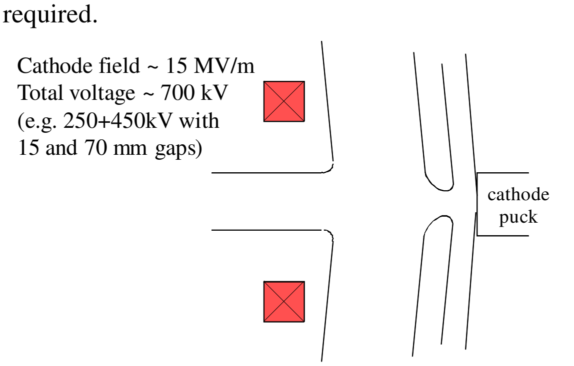

Figure 9: A double-gap DC gun.

CONCLUSION

This paper summarizes the presentations and discussion of DC gun sessions of Working Group 1 at ERL09 Workshop. The superconducting and normal conducting RF guns, drive laser and cathode sessions are summarized in an accompanying paper [57]. The technological challenges presented and discussed at ERL09 will be addressed worldwide to promise a brighter future of ERL light sources. The conveners of WG1 express their appreciation to all the participants and organizers of ERL09 for a fruitful workshop.

ACKNOWLEDGMENTS

This work is supported by the Office of Naval Research, the Joint Technology Office, the Air Force Research Laboratory, USA, the U.S. Night Vision Lab, the Commonwealth of Virginia, by DOE Contract DE-AC05-060R23177, both USA, and Science and Technology Facilities Council, UK, MEXT Quantum Beam Technology Program, JSPS Grants-in-Aid for Scientific Research in Japan (20360424).

REFERENCES

[1] Charles K. Sinclair, "DC photoemission electron guns as ERL sources", Nucl. Inst. and Meth. A 557 (2006) 69

[2] 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 (2007) 023501

[3] 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", PAC05, Knoxville, Tennessee, 2005, p. 3117

[4] Ivan V. Bazarov and Charles K. Sinclair, "Multivariate Optimization of a high brightness dc gun photoinjector", Phys. Rev. ST Accel. Beams 8 (2005) 034202

[5] Florian Loehl, "Synchronization Needs", ERL09, Cornell University, Ithaca, 2009, http://www.lepp.cornell.edu/Events/ERL09/Agenda.html

[6] Uwe Uhmeyer, "KSI's Cross Insulated Core Transformer Technology", Proceedings of the 18th International Symposium on High Energy Spin Physics (SPIN2008), AIP Conf. Proc. 1149, (AIP, New York, 2009), 1099

[7] F. Furuta , T. Nakanishi, S. Okumi, T. Gotou, M. Yamamoto, M. Miyamoto, M. Kuwahara, N. Yamamoto, K. Naniwa, K. Yasui, H. Matsumoto, M. Yoshioka, K. Togawa, "Reduction of field emission dark current for high-field gradient electron gun by using a molybdenum cathode and titanium anode", Nucl. Inst. and Meth. A 538 (2005) 33

[8] B. M. Dunham, C. K. Sinclair, I. V. Bazarov, Y. Li, X. Liu, and K. W. Smolenski, "Performance of a Very High Voltage Photoemission Electron Gun for a High Brightness, High Average Current ERL Injector", PAC07, Albuquerque, New Mexico, 2007, TUPMS021, 1224

[9] A. Burrill and M. Poelker, "ERL07 Working Group 1 Summary: Electron Guns and Injector Designs", ERL07, Daresbury, UK, 2007, 139

[10] M. Poelker, P. Adderley, J. Brittian, J. Clark, J. Grames, J. Hansknecht, J. McCarter, M.L. Stutzman, R. Suleiman, K. Surles-Law, "Status of High Polarization DC High Voltage Gallium Arsenide Photoelectron Guns", PAC07, Albuquerque, New Mexico, 2007, FRXAB01, 3756

[11] C.D. Park, S.M. Chung, Xianghong Liu, and Yulin Li, "Reduction in hydrogen outgassing from stainless steels by a medium-temperature heat treatment", J. Vac. Sci. Tech. A 26 (2008) 1166

[12] H. Kurisu, G. Kimoto, H. Fujii, K. Tanaka, S. Yamamoto, M. Matsuura, K. Ishizawa, T. Nomura, and N. Murashige, "Outgassing Properties of Chemically Polished Titanium Materials", J. Vac. Soc. Jpn. 49, (2006) 254 [in Japanese]

[13] J. Grames, M. Poelker, P. Adderley, J. Brittian, J. Clark, J. Hansknecht, D. Machie, M.L. Stutzman, and K. Surles-Law, "Measurements of Photocathode Operational Lifetime at Beam Currents up to 10 mA using an Improved DC High Voltage GaAs Photogun", Proc. of the 17th Spin Physics Symposium, Kyoto, Japan, 2006, 1037

[14] E. Pozdeyev, "Ion trapping and cathode bombardment by trapped ions in dc photoguns", Phys. Rev. ST Accel. Beams 10 (2007) 083051

[15] J. Grames, P. Adderley, J. Brittian, J. Clark, J. Hansknecht, D. Machie, M. Poelker, E. Pozdeyev, M. Stutzman, K. Surles-Law, "A Biased Anode to Suppress Ion Back-Bombardment in a DC High Voltage Photoelectron Gun", 12th International Workshop on Polarized Ion Sources, Targets and Polarimetry, AIP Conf. Proc. 980, (2007) 110

[16] I.V. Bazarov, B.M. Dunham, C.K. Sinclair, "Maximum achievable beam brightness from photoinjectors", Phys. Rev. Lett. 102 (2009) 104801

[17] K. Togawa, T. Shintake, T. Inagaki, K. Onoe, T. Tanaka, H. Baba, and H. Matsumoto ,"CeB6 electron gun for low-emittance injector", Phys. Rev. ST Accel. Beams 10, (2007) 020703

[18] C.K. Sinclair, "A 500 kV photoemission electron gun for the CEBAF FEL", Nucl. Inst. And Meth. A318 (1992) 410

[19] M. Briedenbach, M. Foss, J. Hodgson, A. Kulikov, A. Odian, G. Putallaz, H. Rogers, R. Schindler, K. Skarpaas, M. Zolotorev, "An inverted-geometry, high voltage polarized electron gun with UHV load lock", Nucl. Inst. and Meth. A350 (1994) 1

[20] C.W. de Jager, V.Ya. Korchagin, B.L. Militsyn, V.N. Osipov, N.H. Papadakis, S.G. Popov, M.J.J. van den Putte, Yu.M. Shatunov, Yu.F. Tokarev, "The Photocathode Gun of The Polarized Electron Source at NIKHEF", The Seventh International Workshop on Polarized Gas Targets and Polarized Beams, AIP Conf. Proc. 421 (AIP, New York, 1998), 483

[21] Tsutomu Nakanishi, "Polarized electron source using NEA-GaAs photocathode", Proc. of LINAC2002, Gyeongju, Korea, 811

[22] N. Nishimori, R. Nagai, R. Hajima, T. Shizuma, E.J. Minehara, "A Thermionic Electron Gun System for the JAERI Superconducting FEL ", EPAC00, Vienna, Austria, 2000, 1672

[23] N. Nishimori, R. Nagai, H. Iijima, Y. Honda, T. Muto, M. Kuriki, M. Yamamoto, S. Okumi, T. Nakanishi, and R. Hajima, "Development of an electron gun for an ERL based light source in Japan", Proceedings of the 18th International Symposium on High Energy Spin Physics (SPIN2008), (Ref. [6]), 1094

[24] R. Hajima et al.,"Design and Fabrication of a 500-kV Photocathode DC Gun for ERL Light Sources", in Proc. of PAC09, Vancouver, Canada, 2009

[25] T. Siggins, C. Sinclair, C. Bohn, D. Bullard, D. Douglas, A. Grippo, J. Gubeli, G.A. Krafft, B. Yunn, "Performance of a DC GaAs photocathode gun for the Jefferson lab FEL", Nucl. Inst. And Meth. A 475, (2001) 549

[26] B. Dunham, Private communication.

[27] C. Hernandez-Garcia, JLab Technical Note JLAB-TN-08-065.

[28] 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", Proceedings of the 18th International Symposium on High Energy Spin Physics (SPIN2008), (Ref. [6]), 1071

[29] J. Francis, SLC Procedural Note FP-238-042-94 (1991)

[30] N. Theodore et.al., "Nitrogen-Implanted Silicon Oxynitride: A Coating for Suppressing Field Emission From Stainless Steel Used in High-Voltage Applications", IEEE Trans. Plasma Sci., 34, 1074 (2006)

[31] R. Alley, H. Aoyagi, J. Clendenin, J. Frisch, C. Garden, E. Hoyt, R. Kirby, L. Klaisner, A. Kulikov, R. Miller, G. Mulhollan, C. Prescott, P. Saez, D. Schultz, H. Tang, J. Turner, K. Witte, M. Woods, A.D. Yeremian, M. Zolotorev, "The Stanford linear accelerator polarized electron source" Nucl. Instr. and Meth. A 365 (1995) 1

[32] Fumio Watanabe, "Extremely low-outgassing material: 0.2% beryllium copper alloy", J. Vac. Sci. Technol. A 22, (2004) 181

[33] K. Saito, S. Inayoshi, Y. Yang, and S. Tsukahara, "TiN thin film on stainless steel for extremely high vacuum material", J. Vac. Sci. Technol. A 13 (1995) 556

[34] H. Akimichi and M. Hirata, "Generation and pressure measurement of extremely high vacuum (XHV) using a TiN coated chamber", Metrologia 42 (2005) S184

[35] T. Kikuchi, N. Ohsako and Y. Hayashi, "Capability of Obtaining Extreme High Vacuum by Commercial G-M refrigerator-Cooled Cryopump", Vacuum 41 (1990) 1941

[36] Hiroyuki Yamakawa, "Development and performance of bakeable cryopumps for extreme high vacuum", Vacuum 44 (1993) 675

[37] M.L. Stutzman, P. Adderley, J. Brittian, J. Clark, J. Grames, J. Hansknecht, G.R. Myneni, M. Poelker, "Characterization of the CEBAF 100 kV DC GaAs photoelectron gun vacuum system", Nucl. Instr. and Meth. A 574 (2007) 213

[38] B.M. Dunham, Ph.D. thesis, University of Illinois at Urbana-Champaign (1993)

[39] G.D. Cates, V.W. Hughes, R. Michaels, H.R. Schaefer, T.J. Gay, M.S. Lubell, R. Wilson, G.W. Dodson, K.A. Dow, S.B. Kowalski, K. Isakovich, K.S. Kumar, M.E. Schulze, P.A. Souder, D.H. Kimet, "The BATES polarized electron source", Nucl. Inst. and Meth. A278 (1989) 293

[40] L.B. Jones, S.P. Jamison, Y.M. Saveliev, K.J. Middleman and S.L. Smith, "Status of the ALICE Energy-Recovery Linac", Proceedings of the 18th International Symposium on High Energy Spin Physics (SPIN2008), (Ref. [6]), 1084

[41] R.E. Kirby, G.J. Collet, K. Skarpaas, "An In-Situ Photocathode Loading System for the SLC Polarized Electron Gun", Proc. of PAC'93, 3030

[42] K. Aulenbacher, Ch. Nachtigall, H.G. Andresen, J. Bermuth, Th. Dombo, P. Drescher, H. Euteneuer, H. Fischer, D.v. Harrach, P. Hartmann, J. Hoffmann, P. Jennewein, K.H. Kaiser, S. Kobis, H.J. Kreidel, J. Langbein, M. Petri, S. Plutzer, E. Reichert, M. Schemies, H.-J. Schope, K.-H. Steffens, M. Steigerwald, H. Trautner, Th. Weis, "The MAMI source of polarized electrons", Nucl. Inst. and Meth. A391 (1997) 498

[43] M.J.J. van den Putte, C.W. De Jager, S.G. Konstantinov *et al.*, "The Polarized Electron

Source at NIKHEF", Seventh International Workshop on Polarized Gas Targets and Polarized Beams, (Ref. [20]), 260

[44] W.J. Schneider, P. Adderley, J. Clark, A. Day, B. Dunham, J. Hansknecht, P. Hartmann, J. Hogan, R. Kazimi, D. Machie, M. Poelker, J.S. Price, P.M. Rutt, K. Ryan, C.K. Sinclair and M. Steigerwald, "A load-locked gun for the Jefferson Lab Polarized Injector", PAC99, New York, 1999, 1991

[45] B.L. Militsyn, I. Burrows, R.J. Cash, B.D. Fell, L.B. Jones, J.W. McKenzie, K.J. Middleman, S.N. Kosolobov, H.E. Scheibler, A.S. Terekhov, "Design of an upgrade to the ALICE photocathode electron gun", EPAC08, Genoa, Italy, 235

[46] S. Pastuszka, A.S. Terekhov, A. Wolf, "'Stable to unstable' transition in the (Cs, O) activation layer on GaAs (100) surfaces with negative electron affinity in extremely high vacuum", Applied Surface Science 99, (1996) 361

[47] D.A. Orlov, C. Krantz, A. Wolf *et al.*, "Long term operation of high quantum efficiency GaAs(Cs,O) photocathodes using multiple re-cleaning by atomic hydrogen", J. App. Phys. In print.

[48] J. Grames, P. Adderley, J. Brittian, D. Charles, J. Clark, J. Hansknecht, M. Poelker, M. Stutzman, K. Surles-Law, "Ion Back-Bombardment of GaAs Photocathodes Inside DC High Voltage Electron Guns", PAC05, Knoxville, Tennessee, (2005) 2875

[49] K. Aulenbacher et.al., "Status of the polarized source at MAMI", 15th International Spin Physics Symposium, AIP Conf. Proc. 675, (2002) 1088

[50] H2 ionization cross section plot

[51] K. Aulenbacher et al., SLAC Report 432 (1993)

[52] Fay Hannon, private communication

[53] I.V. Bazarov, B.M. Dunham, Y. Li, X. Liu, D.G. Ouzounov, C.K. Sinclair, F. Hannon, T. Miyajima, "Thermal emittance and response time measurements of negative electron affinity photocathodes", J. Appl. Phys., 103 (2008) 054901

[54] I.V. Bazarov, B.M. Dunham, C. Gulliford, Y. Li, X. Liu, C.K. Sinclair, K. Soong, "Benchmarking of 3D space charge codes using direct phase space measurements from photoemission high voltage DC gun", Phys. Rev. ST Accel. Beams 11 (2008) 100703

[55] P.G. Slade, The vacuum interrupter: theory, design, and application, CRC Press, 2008

[56] M. Lakshmanan et al., "Geometry Optimization of DC and SRF Guns to Maximize Beam Brightness", these proceedings

[57] J.W. Lewellen, H. Bluem, A. Burrill, T.L. Grimm, T. Kamps, R. Legg, K. Liu, T. Rao, J. Smedley, J. Teichert, S. Zhang, "ERL 2009 WG1 Summary Paper: Drive Lasers and RF GUn operation and challenges", these proceedings