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DC photoemission electron guns as ERL sources

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Abstract

Very-high-voltage DC electron guns, delivering moderate duration bunches from photoemission cathodes, and followed by conventional drift bunching and acceleration, offer a practical solution for an ERL injector. In a variant of this scheme, a DC gun is placed in close proximity to a superconducting RF accelerator cavity, with few or no active elements between the gun and cavity. The principal technical challenge with such electron guns arises from field emission from the cathode electrode and its support structure. Field emission may result in voltage breakdown across the cathode–anode gap, or a punch-through failure of the insulator holding off the cathode potential, as well as lesser though still serious problems. Various means to mitigate these problems are described. The operational lifetime of high quantum efficiency photocathodes in these guns is determined by the vacuum conditions, through phenomena such as chemical poisoning and ion back-bombardment. Minimization of the field strength on electrode structures pushes high-voltage DC guns toward large dimensions and, correspondingly, large outgassing loads, but it is also true that these guns offer many opportunities for achieving excellent vacuum conditions. Good solutions to vacuum problems that had previously limited cathode lifetime have been demonstrated in recent years. Designs for DC guns presently in use and planned for the near future will be described. The parameters necessary for a 100 mA average current, very-high-voltage DC gun with a photocathode operational lifetime greater than 100 h appear to be within reach, but have yet to be demonstrated. A 1 A average current source with good cathode operational lifetime will require developments beyond the present state-of-the-art.

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1. Introduction

Pierce-type DC electron guns with gridded thermionic cathodes, operating at voltages up to about 150 kV, have been the standard electron source for linear accelerators for many years. In the mid-1970s, physics requirements for polarized electron beams led to the development of similar DC guns using un-gridded negative electron affinity (NEA) GaAs photoemission cathodes. These first photoemission guns delivered average currents of several tens of μA in relatively long duration (few μs or more) pulses, and total charges of a few Coulombs, before it was necessary to either clean and reactivate, or replace the GaAs cathode. It is also worth noting that the first of these guns operated with the GaAs photocathode at liquid nitrogen temperature. To this day, the small community of scientists building and operating polarized electron sources continues to develop innovative DC photoemission electron gun designs.

In 1981, it was demonstrated that NEA GaAs photocathodes could support the delivery of high current and current density nanosecond duration pulses [1], leading to the development of DC guns with NEA photocathodes for applications other than polarized electron delivery. It is now standard to deliver bunches short compared to the time required for the bunch to transit the cathode–anode gap. In this case, good analytic estimates of the optimum locations and strengths of focusing elements are not available. The constraints added by designing an injector that can be physically assembled, that incorporates necessary elements like vacuum valves, and that accounts for the distances required between room temperature and superconducting elements only complicates matters. These

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complexities led to a recent computational optimization of a DC gun-based ERL injector [2]. This optimization produced a considerable reduction in the simulated transverse and longitudinal emittances.

Although RF guns have employed positive electron affinity (PEA) alkali antimonide and alkali telluride photocathodes since their initial development, these cathodes have been introduced in DC guns only very recently [3]. Conversely, NEA photocathodes have not yet been successfully used in RF guns. Although there are no fundamental reasons for either of these realities, one result is that any discussion of what has been accomplished to date in DC photoemission gun technology necessarily refers only to their use with NEA photocathodes. There are very significant technical differences between NEA and PEA photocathodes, and it seems clear that for application to an ERL electron source, both cathode types should be explored. In particular, the photocathode operational lifetime is very important for any ERL source, and may well be very different for NEA and PEA photocathodes. To put the lifetime issue in some perspective, present day DC photoemission guns have demonstrated the delivery of several hundred coulombs from a single illuminated spot before some cathode intervention is required. With the use of multiple illuminated spots, delivery of total charges approaching an Ampere-hour appears within reach. A high average current ERL realistically requires the delivery of many Ampere-hours before any intervention—a Faraday seems a reasonable goal for the total delivered charge from an ERL photocathode.

1.1. *Field emission and the cathode–anode gap*

Field emission from large area electrodes is a poorly understood phenomenon. It is well known that the voltage supported by a vacuum gap increases more slowly than linearly with the gap dimension. Even in the limit of very small gaps, the field emission current from large area electrodes is observed to be much greater than that predicted by the Fowler–Nordheim equation. Many ideas have been put forth to explain these observations, but to date there is no way to know with confidence how well a particular high-voltage vacuum gap will perform, even at moderate field strengths of 10–15 MV/m. Empirically, cathode electrode smoothness and hardness correlate well with improved field emission performance. As one might expect, a higher work function appears to help, but the work functions of metal surfaces in vacuum are generally different from pure metal values, and typically show patchy spatial variations. Micro-particle contamination is a known source of DC gap breakdown, and its reduction, through techniques such as high-pressure water rinsing, has been demonstrated to be useful in reducing field emission in superconducting RF cavities. This is likely to prove useful for DC gaps as well.

The material of the anode as well as the cathode is important to the overall performance of a DC gap.

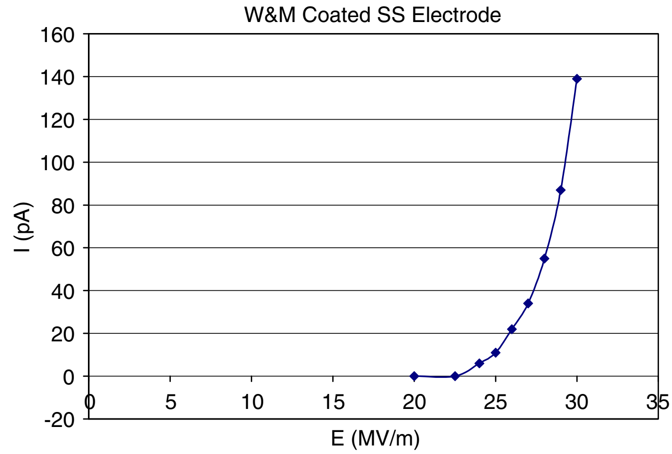

Fig. 1. Measured field emission current from a 116 cm^2 uniform field area stainless-steel electrode PVD-coated with ~0.5 μm of silicon oxy-nitride.

Recently, it was shown that, in the small gap case with small electrode areas, a molybdenum cathode and a titanium anode gave better performance than all other combinations of stainless steel, molybdenum and titanium tested [4]. While one must always be careful in extrapolating small gap, small area results to the large gap, large area case, the measurements reported in Ref. [4] were carefully done, and the underlying physics is sound. Based on the models for what is happening physically at the anode [5], it might be expected that a very low Z, high thermal conductivity anode would perform very well, leading to the possibility that beryllium may be a very good anode material.

Dielectric coatings on the cathode electrode can dramatically reduce field emission. At Jefferson Lab, we developed a medium gap, large electrode area test system to evaluate field emission reduction by various surface treatments. This system was used to demonstrate that a 0.5–1 μm coating of silicon oxy-nitride on stainless steel, developed in collaboration with the College of William and Mary, reduced the field emission from electrodes with $>116\,cm^2$ of uniform field area to $<1\,pA/cm^2$ at fields up to ~30 MV/m, as shown in Fig. 1 [6]. More recently, reduced field emission has been demonstrated from a stainless steel electrode of the same dimensions as above, by the formation of a hard, dense and pinhole-free surface oxide by gas cluster ion bombardment (GCIB) in an oxygen ambient [7], as shown in Fig. 2. Both these processes are adaptable to use on the large, non-planar shapes of real electrodes, and it is reasonable to expect these or similar processes to produce DC gun electrodes that can operate reliably with maximum field strengths of 20 MV/m or more.

2. Ceramic insulators

In all but one DC gun designs to date, the cathode electrode, or its support structure, is located within a ceramic insulator that supports the cathode potential. The

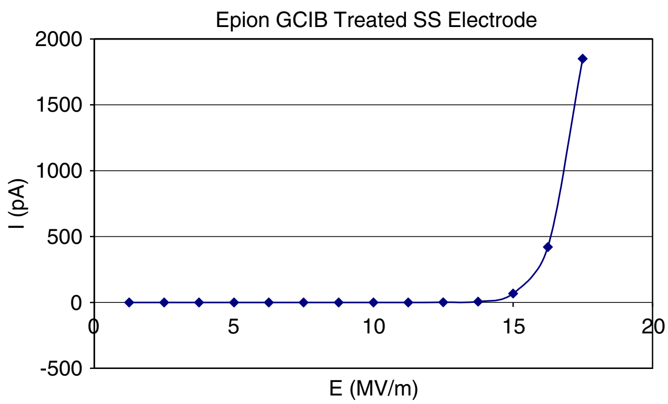

Fig. 2. Measured field emission current from a 116 cm^2 uniform field area stainless-steel electrode with a thin oxide layer prepared by gas cluster ion bombardment (GCIB).

inner surface of the ceramic thus intercepts electrons field-emitted from the electrodes. These electrons penetrate a relatively short distance—a few hundred μm—into the ceramic body. Most ceramics have an exceptionally high bulk resistivity, and thus become charged in areas struck by these electrons. This charging can lead to a punch through failure of the ceramic, destroying the vacuum. It is highly desirable that a ceramic have either a finite bulk resistivity, or a suitable sheet resistance on its inner surface, to draw-off this charge before such a catastrophic failure. Bulk resistivities of about $10^{11}\,\Omega\,cm$, or sheet resistivities of about $5\times10^{10}\,\Omega$ per square, are appropriate for 500–750 kV ceramic insulators. Such restivities lead to power dissipation in the ceramics of a few tens of W. Most ceramics have very low thermal conductivity, making it important that the variation of resistance with temperature, particularly in the case of a sheet resistance on the inner ceramic surface, does not lead to a thermal runaway.

While it is, in principle, possible to make large ceramic insulators with suitable bulk resistivity values, none have yet been demonstrated in the size required for a very-high-voltage gun. Corderite [8], and suitably doped zirconia [9] are promising materials for this application. Several processes may be used to prepare a suitable sheet resistance on the inner surface of a large ceramic, but finding commercial vendors for these processes can be problematic. Ideally, a sheet resistance should have an effective thickness comparable to the electron penetration depth. A metal ion implantation process originally developed at LBNL [10] was successfully applied to the ceramics of the original Jefferson Lab FEL gun, but this process is no longer done in the US, and is difficult to apply to very large ceramics. Furthermore, the metal ions penetrate less than a μm into the ceramic. Very recently, Communications and Power Industries has demonstrated a very good high-resistance coating, which can be diffused into the ceramic to some depth [11].

3. Cathode issues—vacuum and cooling

The delivery of average photoemission beam currents of tens of mA or more, having the RF time structure desired for ERL applications, and using presently practical laser systems, requires photocathodes with quantum efficiencies (QEs) above 1–2%. The wavelengths of these laser systems restricts the cathode choices to either the positive electron affinity (PEA) alkali antimonides or the negative electron affinity (NEA) semiconductors. In future, the PEA alkali tellurides may also prove useful, but lasers supporting the delivery of high average current from these cathodes are presently challenging. All these photocathodes involve the use of alkali metals in their preparation, and all are readily poisoned by small quantities of chemically active gases such as water, oxygen and carbon dioxide. Relatively inert gases such as hydrogen, methane, nitrogen and carbon monoxide have small to negligible poisoning effects on these cathodes.

Chemical poisoning of quantum efficiency occurs independent of any gun operation for beam delivery, and is well characterized by the dark lifetime—the exponential decay of the photocathode quantum efficiency in the static vacuum environment. It is possible to achieve levels of water, oxygen and carbon dioxide that are undetectable by a high-gain quadrupole mass analyzer with an electron multiplier in a well-designed, carefully baked and properly pumped vacuum chamber. This condition has been achieved in the polarized electron guns in use at Jefferson Lab [12]. In one of these guns, a NEA GaAs photocathode was measured to have no detectable loss of quantum efficiency after storage in the static gun vacuum for over 3 months. If we (arbitrarily) assume that we could not have detected a 10% loss of QE over this time interval, this corresponds to a 1/e dark lifetime of over 2.2×10^4 h.

Residual gas molecules in the cathode–anode gap are ionized by electrons traversing this gap, and are accelerated back to the photocathode, where they cause QE degradation. If only a small fraction of the photocathode area is illuminated in a gun, with focusing provided by the cathode electrode, a map of the QE will show a clear path of QE degradation along a line joining the illuminated spot and the electrostatic center of the photocathode. This damage occurs independent of whether the residual gas ion is of a chemically active species or not and, thus, the only cure for this problem is to reduce the absolute pressure in the gun.

The ultimate pressure in a gun vacuum chamber is limited by outgassing from the chamber walls, with hydrogen by far the predominant residual gas [13]. At the present time, outgassing rates of about 10^{-12} mbar l/s cm^2 are reached in carefully prepared and baked stainless steel vacuum chambers. It is practical to add non-evaporable getter (NEG) pumps to achieve a hydrogen pumping speed approaching 1 l/s cm^2 of chamber surface area, and thus ultimate pressures approaching 10^{-12} mbar should be achievable. Measurement of these low outgassing rates and base pressures is not a simple matter, and one should maintain a skeptical eye toward reported pressure measurements below even 10^{-11} mbar.

There is much literature on various means to achieve low hydrogen outgassing rates, and a considerable spread in the reported results. The two techniques that seem to give consistently low outgassing rates are air bakeout of the chamber at 400–450 °C [14], and vacuum firing of the chamber at ~900 °C for extended times [15]. Each of these methods shows promise to deliver outgassing rates well below the 10^{-12} mbar l/s cm^2 value. Given the temperatures involved, the use of 316 LN stainless flanges and 316 L or 316 LN stainless for the chamber walls seems appropriate.

An appropriate characterization for cathode QE degradation by ion back-bombardment is the number of coulombs delivered per unit illuminated area of the cathode. This is an imperfect characterization, since all the ions do not strike the area from which the electrons were emitted in a gun with focusing provided by a cathode electrode. In the Jefferson Lab polarized guns, an array of NEG pumps was located in the gun cathode chamber, to improve the vacuum. These guns have achieved a value of 2×10^5 C/cm^2 for a 1/e degradation in the QE from ion back-bombardment. An improvement in this value by even one order of magnitude seems possible with some of the outgassing reduction techniques noted above, and would nearly eliminate the cathode ion back bombardment lifetime issue for average currents up to 100 mA.

If the 1/e QE degradation from ion back bombardment is characterized by a value of Q_o C/cm^2, then the cathode can be operated at a constant current I_o for a time T given by

$$T = \frac{Q_o A}{I_o}\ln\left(\frac{P_{max}\lambda\eta_o}{1.24 I_o}\right),$$

where A is the illuminated area (assumed uniform), η_o is the initial absolute quantum efficiency, λ is the operating wavelength in μm and P_{max} is the maximum available laser power in W. With the Q_o value achieved in the Jefferson Lab polarized guns, a 10 W green ($\lambda = 0.527$ μm) laser will support the delivery of 100 mA from a 4 mm diameter uniformly illuminated spot on a cathode of 10% initial QE for 100 h. After 100 h, the QE would be degraded to 2.39%, and the photocurrent would drop below 100 mA. These values are typical, and serve to demonstrate that few % QEs and lasers powers of 10 W or greater are required to deliver 100 mA average current for useful periods of time.

Photocathode heating by the absorbed laser power cannot be neglected at high average current. For example, with a GaAs cathode, about 30% of the incident light is reflected. If we assume that the fraction of the absorbed light appearing as heat in the photocathode is the ratio of the quantum defect to the photon energy, about 40% of the absorbed energy shows up as heat—2.8 W in the above example. While this seems a small power, the photocathode is typically isolated from the external room temperature environment by a considerable thermal impedance, resulting in an unacceptably high cathode temperature.

Finally, it was observed in the Jefferson Lab polarized guns that electrons originating from the edge of the photocathode, near the junction with the Pierce focusing electrode, followed extreme trajectories, ultimately striking the vacuum wall and increasing the pressure, leading to a reduction in the photocathode lifetime from ion back-bombardment [12]. By anodizing the large radius area of the photocathode to eliminate the quantum efficiency there, a dramatic increase in the cathode operating life is obtained. This result has been verified in the polarized guns of the MAMI accelerator, and other ways to eliminate the quantum efficiency at large radius have been demonstrated [16]. This is an important issue for the use of GaAs photocathodes in focusing gun structures.

4. Operating DC guns

Presently, only the DC gun of the Jefferson Lab FEL is operated at average currents of interest to ERLs [17]. This gun, shown in Fig. 3, has delivered a 74.85 MHz pulse train at over 9 mA average current. The gun is designed with no focusing at the cathode, to avoid the larger field strengths associated with the use of a Pierce type cathode electrode. Though designed to operate at 500 kV, the gun is presently operated at 350 kV. Currently, the gun can deliver several hundred coulombs from a several mm diameter illuminated area, before it is necessary to re-cesiate or reform the photocathode. 1/e lifetimes between 1 and 2×10^3 C/cm^2 are reported. At this level, the photocathode lifetime is much too short to be practically used as a 100 mA ERL injector. The reasons for this lifetime being two orders of magnitude smaller than that observed in the Jefferson Lab polarized guns are not apparent.

5. Future guns

ERL injectors based on DC photoemission guns are presently in design and construction at three laboratories—Daresbury Lab, Jefferson Lab and Cornell University. The Daresbury gun, being built for their ERLP project, is very similar to the gun developed for the IRFEL at Jefferson Lab, and is not presently planned to operate at a very high

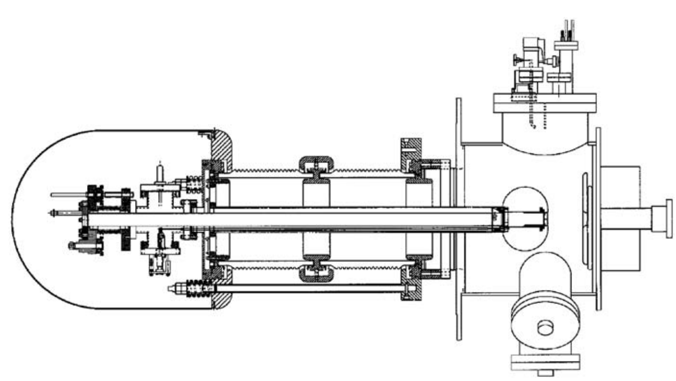

Fig. 3. Outline drawing of the DC gun of the Jefferson Laboratory FEL.

average current. One innovation is the use of a ceramic insulator with a bulk resistivity [18]. At the time this article was written, the high-voltage performance of this ceramic is unknown.

A group at SLAC constructed a so-called ‘‘inverted’’ DC gun, in which the cathode electrode was supported on insulating rods [19]. This novel design might greatly simplify the issue of the large ceramic insulator typical of DC guns. This gun was operated at 200 kV, although at this voltage the field emission current from the cathode electrode was unacceptably high. The cathode fields in this gun were not particularly high, and the field emission problem is almost certainly not a fundamental aspect of this gun design. Future DC gun designers might profitably examine this clever gun design for its suitability for use at very high voltages.

Another topic that should be examined for DC gun development is that of using alkali antimonide photocathodes. Though the thermal emittance from antimonide photocathodes is not as low as from GaAs photocathodes, the antimonides have a much faster temporal response than GaAs, which may be desirable for some applications. Furthermore, there is reason to believe that the antimonides may have a longer operational lifetime from ion back bombardment. Unlike GaAs photocathodes, which have a single atomic layer lowering the work function to produce NEA, the antimonide cathodes are stoichiometric compounds. To the extent that the ion bombardment lifetime results from sputtering of the NEA producing layer, a stoichiometric compound might be much less affected. The operational lifetime of GaAs photocathodes is an important issue for the 100 mA average current guns currently being developed, and a significantly better lifetime would be a powerful reason to use the antimonide photocathodes.

Jefferson Lab is developing a gun to deliver 100 mA average current for a higher power FEL. This gun is very similar to their original gun and, like its predecessor, will have no focusing at the cathode electrode. The gun will be closely coupled to a 748.5 MHz superconducting accelerator, with only a solenoid between the gun and cavity. As space between the gun and the superconducting accelerator is at a premium, the flat gun anode will also serve as a mirror to direct light onto the GaAs photocathode. Neither the Jefferson Lab gun nor the Daresbury gun is presently planned to have a load lock for photocathode introduction into the gun. Rather, they withdraw the GaAs cathode into the cathode electrode structure for heat cleaning and activation.

Cornell University is presently constructing a load-locked DC gun for their 100 mA ERL injector. This gun is physically larger than the Jefferson Lab design, resulting in field strengths at 500 kV, that are quite comparable to the Jefferson Lab gun at 350 kV outside the region of the cathode–anode gap, where the fields in the Cornell gun are higher. It will have a single ceramic insulator 22 in long, brazed into 16.5 in Conflat flanges, and have the resistive coating developed by CPI on its inner surface. A beryllium anode will be used initially, which should help resolve any questions regarding the suitability of a low Z, high thermal conductivity anode material. The gun chamber will be made of 316L stainless steel, and all flanges will be of 316LN stainless steel. These choices will allow the entire chamber to be brought to a very high temperature if that is required to obtain a low hydrogen outgassing rate. A total of 21 NEG pump modules will be mounted in the gun chamber, along with a 400 l/s DI-style ion pump. The total pumping speed for hydrogen will be nearly 1 l/s per cm^2 of chamber surface area.

The ceramic insulator of the gun and the high voltage stack of the 750 kV, 100 mA power supply will be located side-by-side in a pressure vessel holding 5 atm of SF_6. Power dissipation in the high-voltage stack will require that the SF_6 gas be cooled. The photocathode will have a high thermal conductivity connection to the SF_6 environment. The material for the cathode electrode and its support will be selected based on field emission tests of a number of candidate materials and material treatments. The photocathodes themselves will be prepared in a separate chamber, which incorporates means for atomic hydrogen cleaning and heating to high temperatures as well as for cathode activation. The cathode itself will be moved into position in the cathode electrode in the way chosen for the Jefferson Lab polarized gun [20]. Both the gun chamber and the cathode preparation chamber will be mounted on thermally insulating tables that have easily assembled oven walls to surround them for bakeouts. Finally, the beamline from the gun will have correction coils immediately following the anode electrode, and both correction coils and a stripline BPM mounted at the physical center of the focusing solenoids. This gun is presently being fabricated, and we hope to begin first tests with an electron beam before the end of this year.

6. Conclusions

A DC gun-based electron injector for an ERL is currently in operation on the Jefferson Lab FEL, delivering average currents as high as 9.1 mA in a 74.85 MHz bunch train. The photocathode operational lifetime in this gun is presently inadequate for a 100 mA operation. However, much higher photocathode operational lifetimes from similar photocathodes have been demonstrated in the polarized electron guns for the CEBAF accelerator at Jefferson Lab. The photocathode operational lifetime is believed to be limited at present only by ion back-bombardment, implying that a sufficiently low base pressure should give an adequate lifetime for a 100 mA average current ERL injector. For the next version of the Jefferson Lab FEL and the Cornell ERL, 100 mA DC gun injectors are under development, and should resolve this issue. If the cathode operational lifetime achieved in the polarized guns for the CEBAF accelerator can be achieved in these new guns, it will be possible to operate at 100 mA for 100 h (0.37 Faraday total delivered charge) from a reasonably small cathode area.

The DC gun under development at Cornell incorporates a number of new ideas that should improve the cathode operating life, reduce the problems associated with field emission and address the issue of photocathode cooling. A computational optimization of the full injector using this gun indicates that it should be possible to deliver beams of exceptional brightness at the full average current. Tests of the gun should begin by the end of this year, and operation of the full injector is planned for 2008. This latter date is determined by the availability of the injector accelerator cryomodule.

A 1 A average current injector would require an increase by about an order of magnitude in the photocathode operational lifetime. Furthermore, since the planned 100 mA average current injectors already populate every RF bucket, the microbunch charge would have to be increased by about an order of magnitude as well, since changing to a significantly higher RF frequency does not presently appear attractive. This latter reality will almost certainly have a negative impact on the average beam brightness. While this may not be particularly detrimental for high-current FELs or electron cooling applications, it is definitely undesirable for light source applications, where the highest brightness is important. Any conventional photocathode would require active cooling at 1 A average current. Of course, there are a great many other considerations spanning a large spectrum of accelerator technology that will have to be satisfactorily addressed before a 1 A average current ERL is a reality.

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