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RF Guns for Generation of Polarized Electron Beams*

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Abstract

Several accelerators, including the SLC, JLAB, Mainz, Bates/MIT, and Bonn have successfully operated for medium and high energy physics experiments using polarized electron beams generated by dc-biased guns employing GaAs photocathodes. Since these guns have all used a bias on the order of 100 kV, the longitudinal emittance of the extracted bunch is rather poor. Downstream rf bunching systems increase the transverse emittance. An rf gun with a GaAs photocathode would eliminate the need for separate rf bunchers, resulting in a simpler injection system. In addition, the thermal emittance of GaAs-type cathodes is significantly lower than for other photocathode materials. The environmental requirements for operating activated GaAs photocathodes cannot be met by rf guns as currently designed and operated. These requirements, including limits on vacuum and electron back bombardment, are discussed in some detail. Modifications to actual and proposed rf gun designs that would allow these requirements to be met are presented.

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RF GUNS FOR GENERATION OF POLARIZED ELECTRON BEAMS*

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Abstract

Several accelerators, including the SLC, JLAB, Mainz, Bates/MIT, and Bonn have successfully operated for medium and high energy physics experiments using polarized electron beams generated by dc-biased guns employing GaAs photocathodes. Since these guns have all used a bias on the order of 100 kV, the longitudinal emittance of the extracted bunch is rather poor. Downstream rf bunching systems increase the transverse emittance. An rf gun with a GaAs photocathode would eliminate the need for separate rf bunchers, resulting in a simpler injection system. In addition, the thermal emittance of GaAs-type cathodes is significantly lower than for other photocathode materials. The environmental requirements for operating activated GaAs photocathodes cannot be met by rf guns as currently designed and operated. These requirements, including limits on vacuum and electron back bombardment, are discussed in some detail. Modifications to actual and proposed rf gun designs that would allow these requirements to be met are presented.

INTRODUCTION

Polarized electron beams have become a mainstay for much of accelerator-based medium- and high-energy physics. The most widely used technique for producing polarized electrons for accelerators is photoemission from an activated GaAs film using a dc-biased gun. However, because of the extremely high vacuum required for these photocathodes, extraction energies have generally been limited to about 100 kV to avoid high voltage breakdown. The Stanford Linear Collider (SLC) polarized electron source operated successfully from 1991 through 1998 with a cathode bias of 120 kV dc. A source more recently developed at Nagoya operates in the laboratory at 200 kV dc, while the JLAB FEL source, which utilizes a GaAs cathode for production of an unpolarized cw electron beam, operates at 350 kV dc. The principal limitation of the dc-biased source is the low energy of the electrons in the gun and in transit to the injector accelerator section. For the SLC source, the space charge forces were reduced by keeping the bunch radius and bunch length at the cathode relatively large. After extraction from the gun, the bunch was passed through an rf bunching system to reduce the bunch length for injection into a single S-band bucket, which meanwhile resulted in approximately an order of magnitude increase in the transverse emittance.

A polarized rf gun, i.e., an rf gun with a GaAs photocathode, should produce a low emittance short-bunch polarized electron beam eliminating the need for rf or magnetic bunchers. While an e^+e^- collider such as the ILC requires a much lower transverse normalized emittance at the IP than can be generated by rf guns as presently developed, the transport and acceleration systems between the injector and damping ring could be significantly simplified and operated more reliably using an rf gun. In addition, for certain types of FEL linacs, the emittance of the source is critical. The transverse normalized thermal emittance of GaAs cathodes has been shown to be on the order of 0.1 μm compared to 0.6 μm for metal cathodes.

A test at the CLIC Test Facility (CTF) using an unactivated GaAs cathode prepared at SLAC demonstrated that a highly doped GaAs cathode has no obvious negative effect on the operation of a high-field S-band gun.[1] An activated GaAs cathode was not tested. Separately, an S-band rf gun was specifically developed at BINP to accommodate an activated GaAs cathode. The NEA cathode was shown to have a normal lifetime in the gun prior to the application of rf power. However, with rf power on, the QE lifetime was only a few rf pulses.[2]

Since simulations indicate that ion back bombardment should not be a problem for an rf gun,[3] the two most obvious factors contributing to the BINP result are vacuum and back bombardment of the cathode by electrons. For a typical rf gun design, the vacuum in the gun is maintained by an ion pump (IP) attached to the waveguide near the rf input coupler. The pressure as read at the IP is typically mid to high 10^{-10} Torr with rf off, rising to low 10^{-9} Torr with full rf. The pressure at the cathode itself is significantly higher.

The BINP group eventually concluded that back bombardment of the cathode by electrons was the chief culprit.[4] A runaway condition is readily established since the secondary electron coefficient for NEA GaAs is very high.

REDUCTION OF FIELD EMISSION

Field emission (FE) electrons from the cathode and/or the backplane of the cathode cell that do not exit the cell before the rf phase reverses, present one problem. In fact the rf joint made by the cathode holder is a classic source of rf breakdown for high power rf guns. Two other potential significant sources are the irises and the rf input coupler. Mitigation measures for each of these FE sources exist. For the cathode holder, the holder surface can be in the same plane as the GaAs emitting surface. The outer

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diameter of the holder might be made quite large so that the rf seal is in a lower field region.

To reduce field and secondary electron emission from a disk, the iris diameter can be made larger without decreasing the shunt impedance.[5]

The rf input coupler is a potential source of FE. For the BNL 1.6-cell gun design, θ coupling was used to minimize the dipole mode. If dual rf feed is used, the dipole mode is not generated, so z coupling can be used. Z coupling results in significantly lower surface temperatures and in addition is easier to fabricate.[5] Alternatively, one can use a co-axial feed.

Despite the design changes discussed above, it would still be desirable to decrease the peak fields. For a given gun design, the path of FE electrons may be simulated to determine if there is a range of peak field values for which the electrons are unlikely to hit the GaAs cathode, e.g., see Fig. 1. Careful simulation studies are underway to better understand the secondary electron emission effects in an rf gun.[6]

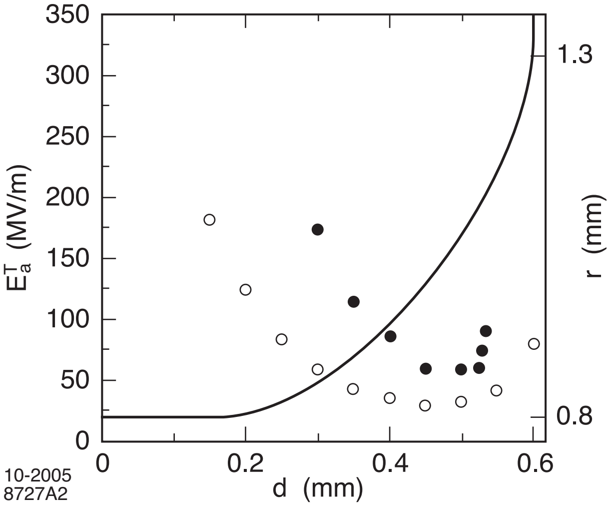

Figure 1: Threshold peak axial field, E_a^T, for electrons emitted from the first iris at an annular distance r from the cell axis (d from the center plane of the disk) in an S-band rf gun to reach the cathode surface: open and closed circles are data points for 0 and 90° rf phase at emission respectively; the solid line represents the iris profile in the r-d plane. (Data from ref. [8].)

A polarized rf gun must include a high-quality cathode preparation chamber and load-lock for introducing the activated cathode into the rf chamber. The gun can be baked and then rf processed using a *dummy* cathode prior to inserting the activated cathode. Extensive rf processing will be needed both to reduce the dark current and to regain the original vacuum. Tests at KEK have demonstrated that if proper attention is paid to the fabrication and assembly of a Cu S-band rf cavity, it can be rf processed to a peak surface field of 140 MV/m (limited by the available rf power) and with a corresponding peak dark current of <25 pA.[7] For an L-band rf gun, the peak surface field will be < 60 MV/m.

ACHIEVEMENT OF ADEQUATE VACUUM

Charged particles that hit the walls of the rf gun desorb molecules that raise the pressure in the gun. These molecules can drift to the cathode surface where they can be adsorbed, decreasing the QE. For dc-biased guns, residual pressures for oxidizers such as H_2O, CO_2, and O_2 must be kept $<10^{-12}$ Torr. Residual pressures of some gas species, such as H_2 and CO, are not as critical. To achieve the desired pressure, two things are necessary. First the gun must be fabricated and assembled so as to minimize the number of molecules available for desorption. HIP Cu can be used to minimize gasses in the grain boundaries. Lubricant-free single-crystal diamond machining along with simple alcohol and distilled water rinsing can be used to minimize residual molecular layers. Brazed joints must avoid virtual leaks. A high temperature bake is necessary to drive gases from the walls. All assembly must be done in at least a class 100 clean room to avoid contamination by dust. Following these procedures one can expect at least an order of magnitude decrease in the outgassing rate in the gun. The base pressure should not change significantly during rf processing other than during rf breakdown.[7] The high temperature bake will assure that the pressure at the cathode is dominated by H_2.

In addition to the BNL 1.6-cell gun design, there are at least 2 other rf gun designs that might prove advantageous for operation with GaAs. Any of these designs can be scaled to L-band. In the plane wave transformer (PWT) design, the disks are suspended inside a larger radius cylindrical tank. The side-coupled rf is transformed from a TEM-like mode at large radius to a TM-like mode on axis. The open structure would appear to lend itself to efficient pumping of the cathode. For an integrated function design (e.g., 7-10 cells), a lower accelerating gradient can be used without a significant increase in the transverse emittance.

Recently an HOM TM012 single-cell design has been proposed.[9] This design eliminates the intermediate disk of the 1.6-cell gun, but if the radius and length of the cell are appropriately chosen, the accelerating field on axis is essentially equivalent. For equal peak accelerating field the radius of the HOM cell is about twice that of a standard TM010 cell (see Fig. 2), while the shunt impedance is significantly lower requiring a higher total rf power. By altering the radius of the outer cylinder as a function of axial distance, the required rf power can be reduced to about twice that of the 1.6-cell gun.[10]

Both the PWT and HOM designs have a significantly larger radius than the BNL 1.6-cell gun. The larger surface area increases the gas load in the gun.

There are a number of techniques for improving the pumping that should work for any of the 3 gun designs discussed here. The most obvious idea is to increase the number of pumping ports and to include NEG pumping. A variation on this theme is to immerse all or a fraction of the outer cylinder in a UHV system and pump either through a large number of z-slots as for the AFEL[11] or through an even larger number of small holes.[12] Thus the pumping speed through the outer cylinder can be increased by an order of magnitude, so that including a massive array of NEG pumps in the surrounding vacuum chamber will account for a factor of 10 improvement in the vacuum.

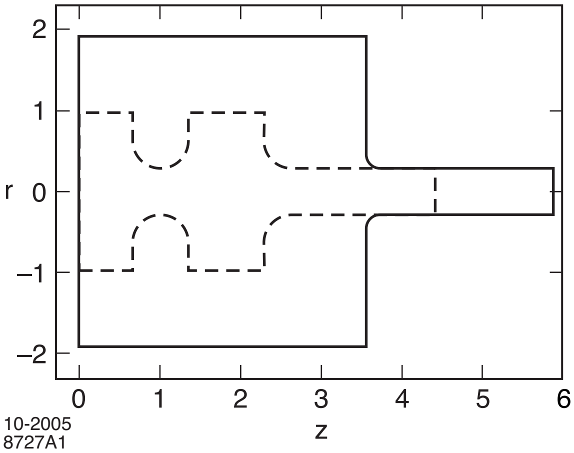

Figure 2: Cross section of the HOM TM012 rf gun (solid line) superimposed on standard 1.6 cell TM010 gun (dotted line), where the units for r and z are the same. (Similar to ref. [9].)

An additional decrease in the pressure could be achieved by operating the gun at 20 K, which would lower the vapor pressures for most of the residual gases to the order of 10^{-10} Torr.[13]

A typical 1.6-cell S-band gun operates at 8×10^{-10} Torr at the ion pump corresponding to an outgassing rate of ~1.2×10^{-11} Torr-l/s cm^{-2} for Cu. Under these conditions, the pressure difference at the cathode is estimated to be $\Delta P_0=2\times10^{-9}$ Torr. NEG pumping through extra slots or a sieve would drop the differential at least a factor of 3. For the PWT design with a sieve at cell 5, the pressure difference is $\Delta P_0/7$, while for the HOM it is $\Delta P_0/20$ due to the absence of any internal disk. With careful preparation the outgassing rate for Cu can be reduced by an order of magnitude. Thus a pressure of 10^{-11} Torr or better at the cathode is feasible with either the HOM or PWT design. A summary of the estimated conductances and the resulting pressure differentials for 2 assumed outgassing rates is presented in Table 1. The pressure at the cathode is given by adding the pressure at the pump (which depends primarily on the size and type of pump) to the pressure differential in the table. Since the surface area and the conductance both scale approximately inversely with the resonant frequency, to first order the results in the table should be independent of the resonant frequency of an rf gun.

Table 1: Conductance and pressure differential at cathode for various S-band gun designs with 2 assumed outgassing rates for Cu.

Gun Design	**Conductance**	**ΔP (Torr) for:**	
	(l/s)	**10^{-11} Torr-l/s cm^{-2}**	**10^{-12} Torr-l/s cm^{-2}**
BNL 1.6-cell SB with conventional pumping	3.7	1.6×10^{-9}	1.6×10^{-10}
with sieve	12	5×10^{-10}	5×10^{-11}
PWT (2/2+7 to 10 cells)	28	2×10^{-10}	2×10^{-11}
PWT (1.5 cells)	50	1.2×10^{-10}	1.2×10^{-11}
HOM	75	8×10^{-11}	8×10^{-12}

THERMAL EMITTANCE

The uncorrelated or “thermal” emittance of a given cathode material determines the lower limit of the normalized transverse emittance that can be generated using a given cathode material and beam radius. The thermal emittance for a Cu photocathode has been measured for a low charge (2 pC), short (<5 ps FWHM) pulse by varying the spot size of the UV laser on the cathode. A normalized rms emittance ($\varepsilon_{n,rms}$) of about 0.6 μm for a hard edge radius of 1 mm was found.[14] By contrast, polarized electrons from an activated GaAs-type photocathode originate from near the conduction band minimum where they arrive at the surface fully thermalized. Thus the uncorrelated energy at the cathode surface should correspond to the crystal lattice temperature, or about 25 meV for room temperature, which corresponds to $\varepsilon_{n,rms}$ = 0.1 μm per mm radius.[15] The thermal emittance of GaAs has been measured using the method of adiabatic expansion of the beam in an axial magnetic field, $B_{//}$.[16] An important advantage of this method is that it is independent of charge. Under conditions in which $E_\perp / B_{//}$ is an adiabatic invariant, $B_{//}$ is decreased as the beam drifts to a retarding-potential detector, in which case transverse energy, $E_\perp$, is transferred to longitudinal energy, $E_{//}$. By measuring $\langle E_{//} \rangle$ at the detector as a function of the ratio of original and reduced $B_{//}$, the value of $\langle E_\perp \rangle$ at the cathode surface can be calculated. In an additional important refinement, the experimental apparatus allowed the vacuum level and thus the value of $E_{//}$ at the surface to be controlled. The overall result was a measured value of

$\left\langle E_{\perp} \right\rangle$ ~ 25 meV, but only if the electron affinity is maintained zero or positive. The corresponding emittance is 0.1 μm per mm radius.

CONCLUSION

The prospects for successfully operating an rf gun with an activated GaAs photocathode have been discussed. Achieving the required vacuum will require new fabrication and pumping techniques. Reducing the dark current to a level that will protect the cathode from runaway secondary electron effects is a serious challenge, but there is experimental evidence that dramatic reductions are possible. A successful GaAs photocathode rf gun promises low transverse and longitudinal emittances for a polarized electron beam.

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