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HIGH-VOLTAGE TESTING FOR A HIGH-CURRENT ELECTRON GUN*

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Abstract
Cornell University has designed an Energy Recovery Linac (ERL) X-ray facility, necessitating high-brightness electron beam emittance to be provided by the injector. This has posed a continuing technical challenge in the design and construction of a DC photoemission gun, which is intended to give 100 mA average beam current in a 1300 MHz CW bunch train (77 pC/bunch), as well as to operate at up to 750 kV cathode potential. Construction experience in light of difficulties in meeting the injector requirements will be described. Additionally, in a separate but related topic of interest, the application of Fowler-Nordheim theory to photoassisted field emission is discussed.

INTRODUCTION
The electron gun for the ERL faces many challenges. Cornell University’s program to develop a high-performance injector (see Fig. 1) is aimed toward meeting specific requirements which have been reported elsewhere [1]. The source of electrons is the DC photoemission gun which is used with a GaAs cathode. The beam line exits the cathode assembly and travels through focusing solenoids, and then into a normal conducting buncher cavity. The beam then is accelerated inside a cryomodule composed of five superconducting RF cavities, and then into diagnostics, which permit detailed characterization of the beam. It is then disposed of in a dump.

The GaAs photocathode, which is the source of the electrons, is kept under vacuum. The cathode wafer is mounted on a puck and slid into the electrode, permitting easy replacement of the wafer, a process aided by two bellows, one corresponding to one plane of motion and the other to a second. These act like hands, moving wafers in and out of the electrodes. Before a wafer can be inserted into the electrode, it must be cleaned, which is done by heating it and exposing it to hydrogen. The entire process of replacing the cathode wafer takes approximately half an hour, and must be done roughly once a week when the gun is run at 100 mA. Cathode lifetime is limited by several factors, one of which is that the beam can ionize residual gas molecules not removed by the vacuum, with these ions being accelerated back toward the cathode surface, a process known as ion back-bombardment.

A photoemission gun is used rather than a thermionic electron gun, which generates electrons when a wire, filament, or cathode is heated to a very high temperature. A photoemission gun produces electrons as a byproduct of the photoelectric effect, and permits a higher level of control over the beam than a thermionic gun. Further, a photoemission gun has a higher performance, producing a beam line with low emittance. This low emittance is important to reducing space charge effects, and generating x-rays usable on a nanoscale.

CONSTRUCTION AND TECHNICAL ISSUES
The current DC photoemission gun is limited by field emission, which has resulted in damages. The mark II design (see Fig. 2) incorporates larger insulators, whose separation helps decrease the electric field present in the interior. Cu guard rings populate the insulators, permitting unwanted field emitted electrons to strike them and conduct through to the exterior, at which point they are grounded (see Fig. 3). There is a resistor between each layer, which is used to drain off the charge on the layers. If the resistors were not all connected electrically then the rings would charge up, eventually charging enough that the rings could field emit to the insulators. This guard ring design prevents destructive levels of electric charge from building up and eventually punching through the insulators.

Cleaning
Components have to be very clean to achieve a good vacuum, with the vacuum itself maintained at 10-12 torr. This high vacuum is employed to increase the photocathode lifetime, removing particles to prevent ion-backbombardment or chemical reactions on the surface of the cathode, which reacts negatively with oxygen, causing it to lose its negative electron affinity. Both ion pumps and non-evaporable getter (NEG) pumps are used to remove particles from the

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Figure 1: Diagram of the Cornell ERL injector prototype.

Figure 2: Diagram of the Cornell ERL injector prototype.

Figure 3: The mark I electron gun’s insulator design (left) suffered damages from field emission, shown as an electron field emitting from the stalk and landing on the interior of the insulator. The mark II electron gun (right) is designed to prevent such damages.

interior of the gun, which is counteracted by outgassing in the materials. Methods of cleaning components included blowing them off with nitrogen gas, performing high pressure rinses, using chemical baths, double-bagging them and opening them only inside the clean room, and wearing clean room suits to prevent outside contamination. Each component was cleaned using soap and water to remove dust and large particles, and then scrubbed with alcohol to remove fingerprints and other oils. Then the high pressure rinsing process was used, which involved hosing each part with clean, deionized water at 1000 PSI (see Fig. 4).

THEORY

The lifetime of the photocathode is the greatest challenge currently faced due to its chemical reactivity and degradation due to ion-backbombardment. Further, the cathode structure can field emit, leading to insulator punchthrough and vacuum leak [2]. Field emission prevents higher voltages from being applied, ultimately limiting the performance of the ERL itself, as higher voltages would provide a greater initial acceleration of electrons and thus lower emittance.

We need to derive an equation for the tunneling current, which is the Fowler-Nordheim equation. To arrive at an expression for current density, we begin with the Schrödinger equation

\[-\frac{\hbar^2}{2m} \nabla^2 \Psi + V\Psi = E\Psi,\]  

In one dimension, we have

\[\frac{d^2 \Psi}{dx^2} = \frac{2m(V - E)}{\hbar^2} \Psi,\]  

This equation can be solved based upon the assumption that \(V - E\) is independent of position between \(x = 0\) and \(x + dx\), giving

\[\Psi(x + dx) = \Psi(x) e^{-kdx},\]  

where

\[k = \sqrt{\frac{2m(V - E)}{\hbar}},\]  

We may apply the WKB approximation and relate the potential of the wave function at \(x = L\) to that at \(x = 0\), which permits us to find tunneling probability \(Q\) for a triangular barrier where \(V - E = q\phi_B (1 - x/L)\), and \(E = \phi_B / L\)

\[Q = e^{-2 \int_0^L} \frac{dx}{\sqrt{\pi \phi_B (1 - x/L)}} dx,\]  

where
In order to make Fowler-Nordheim agree with physical re-
tions is that there is only one field emitting location on the
to be useful. Current in metal oxide semiconductors is re-
ly-doped semiconductors with metal semiconductor
theoretical value called beta is used,
In order to better understand the problem posed, it is of
to consider whether or not there are multiple sites
Fowler-Nordheim theory is especially applicable to thin
Field emission is an experimentally-obtained value called beta is used,
theoretical value called beta is used, and Richardson velocity

\[ Q = e^{ \frac{1}{4} \sqrt{\frac{\pi}{2}} \frac{q}{b} } \]  

The tunneling current \( J \) is the product of carrier charge,
For the successful experiment would permit beta and the work
be used in conjunction with a Fowler-Nordheim plot to deter-
the smooth material under question, with its small field
Field emission from the conducting material to the insulating material inside the semi-
are known, current density can be found

\[ J = qvnQ \]

This gives us the general Fowler-Nordheim equation defined

\[ I = AaN^2 \Phi^{-1} F^2 e^{-\frac{h\nu\Phi}{3kT}} \]  

where \( I \) is the emission current, \( a \) and \( b \) are universal con-
and \( \Phi \) is the local work function,

\[ \nu = \frac{I}{Aa} \]

\[ \Phi = \frac{1}{2} \left( \frac{3}{4} \frac{kT}{q} \right)^{2/3} \]

\[ F = \frac{2}{\Phi^3} \]

\[ J = \frac{qvnQ}{A} \]

\[ P = e^{\frac{1}{4} \sqrt{\frac{\pi}{2}} \frac{q}{b}} \]

The tunneling current \( J \) is the product of carrier charge, density, and Richardson velocity

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