Introduction to Electron Guns for Accelerators

Bruce Dunham

February 25, 2008
Outline

• The Basics
• Cathodes
• Details of Different Accelerator Guns
  • RF Guns
  • SRF Guns
  • DC Guns
  • Polarized Electron Guns
• Photoemission Guns for an ERL
  • High Voltage
  • Vacuum
  • Laser System
Components of an electron gun

- A cathode of some type for generating electrons
- A focusing structure
- An anode (with or without a hole)
- Vacuum
- Accelerating voltage
DC Type Guns

- DC – always on
- DC - pulsed
- DC – amplitude, frequency modulated
RF Type Guns

CW – bunch of $e^-$ in every RF bucket, typically from 100’s of MHz to GHz, up to 100’s of pC per bunch

pulsed – not every RF bucket is filled, RF frequencies of 100’s of MHz to GHz, up to ~nC per bunch, with bunch rep rates of Hz to 1 MHz
Other properties we care about

- average current
- Peak current
- Pulse length
- Emittance (beam quality)
- Reliability (lifetime)
- Physical size
- Cost
“I Want...”

• Lower emittance
  – higher gradient
  – lower QE
  – faster cathode
  – lower bunch charge
  – smaller emission radius

• Larger duty factor
  – lower gradient
  – higher QE
  – lower bunch charge

• Higher charge per bunch
  – higher gradient
  – higher QE
  – larger emission radius

No matter what – people always want more!
Electron Gun Examples
Microwave Oven Power Source

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Product Description
The NDI-225-21 is a 225 kV, water cooled stationary anode metal ceramic X-ray source. This source is specifically designed for Non-Destructive Imaging Applications.

X-Ray Tube Specifications

- Maximum Peak Voltage: 225 kV
- Focal Spot EN12543:
  - Small: D = 1.0 mm
  - Large: D = 3.0 mm
- Focal Spot IEC:
  - Small: 0.4 mm
  - Large: 1.5 mm
- Maximum Continuous Rating:
  - Small: 640 W with 4 Litre/min cooling flow
  - Large: 1600 W with 4 Litre/min cooling flow
- Target Angle: 20°
- Cooling Medium: Water
- Reference Axis: Perpendicular to port face.
- Radiation Coverage: 40°
- Loading Factors for Leakage Radiation: 225 kV, 7 mA
- X-Ray Tube Assembly Permanent Filtration: 0.8 mm Be
- High Voltage Cable: R24
- Weight (approx.): 11 kg (24.5 lbs)
<table>
<thead>
<tr>
<th>Model</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIR-160E</td>
<td>915328.11</td>
</tr>
<tr>
<td>MIR-200E</td>
<td>915328.01</td>
</tr>
<tr>
<td>MIR-201E</td>
<td>915352.01</td>
</tr>
<tr>
<td>MIR-301E</td>
<td>915338.01</td>
</tr>
</tbody>
</table>

Comet Corp. industrial x-ray tubes
Cathodes
Types of Electron Emission

• Give the conduction band electrons extra energy
  • Thermionic emission
  • Photoemission
  • Secondary emission

• Change the potential barrier
  • Field emission
  • Plasma emission
Work Functions for Various Metals

- Assume that the zero energy level represents the bottom of the conduction band.
- Electrons in the conduction band obey Fermi-Dirac statistics
  \[ f(\varepsilon) = \left(1 + \exp\left[\frac{\varepsilon - \varepsilon_F}{kT}\right]\right)^{-1} \]
  \[ \varepsilon_F = 3.64 \times 10^{-19} n_F^{2/3}, \quad n_F = N_V / d^3 \]
- \( N_V \) is the number of valence electrons per atom, and \( d \) is the lattice spacing.
- A crude estimate for the barrier height is
  \[ \varepsilon_B = 0.33 \left[ \varepsilon^2 N_V / (\pi\varepsilon_d) \right] \]
- The work function is the difference between the barrier height and the Fermi level:
  \[ \varepsilon_W = \varepsilon_B - \varepsilon_F = 8.3 - 6.9 = 1.4 \text{ eV}, \text{ for Cs} \]
  \( (N_V = 1, \text{ and } d = 2.3 \text{ Angstroms}) \)

<table>
<thead>
<tr>
<th>Metal</th>
<th>( \varepsilon_W ) (eV)</th>
<th>Melting Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>3.7</td>
<td>660</td>
</tr>
<tr>
<td>Barium</td>
<td>2.3</td>
<td>725</td>
</tr>
<tr>
<td>Carbon</td>
<td>4.4</td>
<td>-3550</td>
</tr>
<tr>
<td>Cesium</td>
<td>1.9</td>
<td>28</td>
</tr>
<tr>
<td>Copper</td>
<td>4.5</td>
<td>1083</td>
</tr>
<tr>
<td>Gold</td>
<td>4.6</td>
<td>1064</td>
</tr>
<tr>
<td>Iridium</td>
<td>5.2</td>
<td>2410</td>
</tr>
<tr>
<td>Iron</td>
<td>4.4</td>
<td>1535</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>4.3</td>
<td>2620</td>
</tr>
<tr>
<td>Osmium</td>
<td>5.4</td>
<td>3045</td>
</tr>
<tr>
<td>Rhenium</td>
<td>5.1</td>
<td>3180</td>
</tr>
<tr>
<td>Thorium</td>
<td>3.4</td>
<td>1750</td>
</tr>
<tr>
<td>Tungsten</td>
<td>4.5</td>
<td>3410</td>
</tr>
</tbody>
</table>

Pure metals with low work functions have low melting points.
Thermionic Emission

- The kinetic energy of electrons in the conduction band depends on the temperature.
  $$ f(\varepsilon) = \left(1 + \exp\left[\frac{(\varepsilon - \varepsilon_F)}{kT}\right]\right)^{-1} $$

- The critical $z$-directed momentum for escape from the surface is
  $$ \frac{p^2_z}{2m} > \varepsilon_B = \varepsilon_F + \varepsilon_W $$

- The emission current density is found by integrating the $+z$ directed current of electrons in the conduction band over all momentum states.

- The result is the Richardson-Dushman equation:
  $$ j \ (\text{amps/m}^2) = 1.2 \times 10^{-6} T^2 \exp\left(-\varepsilon_W/kT\right) $$

The thermionic emission current density is a function of the temperature and the work function.
Tungsten is one of the most common thermionic emitters. A good figure of merit is how many electrons can be produced per mass of evaporated cathode surface that evaporates – before it breaks!
Tungsten can operate at high temperatures, but still has a high work function – what else can be used?

- oxide coated tungsten (W=1.6eV), but they are sensitive to vacuum and brittle
- dispenser cathodes
  - porous tungsten impregnated with BaO, CaO
  - maybe coated with Ir, Os, Rh
- scandate - 5% by wt of Sc$_2$O$_3$, can generate 10s of A/cm$^2$ for 1000’s of hours
Dispenser Cathodes

EIMAC (CPI)
Electron Field Emission

- When the electric field at the surface of a thermionic cathode reaches a critical level, the diode current is observed to rise sharply - the potential barrier is distorted by the applied field.
- Electrons are able to “tunnel” through the barrier. The barrier penetration probability depends on the work function, the Fermi level and the field strength:
  \[ \psi = \psi_0 \exp \left\{ \left[ (e/(4\pi\varepsilon_0))(2m_e^*) \right]^{1/2} \right\} \]

- The required electric fields are quite high (10^7-10^8 V/cm)
- The emission current density is given by the Fowler-Nordheim equation, corrected for space-charge effects. The current density is an extremely sensitive function of the field.
- To date, field emission cathodes have been fabricated in arrays (FEAs), with the tip design providing significant field enhancement.
  - Ion back bombardment can cause a serious deterioration of performance
  - Transition to explosive emission must be avoided

R.B Miller SureBeam Corp
Figure 1: Current-voltage characteristic in DC and pulsed regime for a XDI Inc. FEA (170 \mu m diameter, 3,000 diamond tips). Insert: SEM picture of some pyramidal diamond tips.

ULTRA-LOW EMITTANCE ELECTRON GUN PROJECT FOR FEL APPLICATION

Paul Scherrer Institut, Villigen, Switzerland
A. Candel, K. Li, Swiss, Federal Institute of Technology, Zürich, Switzerland

Photoelectric Effect

Einstein won his Noble prize for work on the photoelectric effect

- Electrons produced by shining light on surface of metal
  - Below threshold energy (wavelength) no electrons are emitted
  - Above threshold, electron energy is the same at any color (wavelength) of light independent of intensity
- Einstein proposed that this is due to the particle nature of light, predicted energy dependence of electrons on incident light wavelength
- Electrons emitted from metals are not polarized
Elements of the Three-Step Photoemission Model

Step 1: Absorption of photon
Fermi-Dirac distribution at 300 deg K

Step 2: Transport to surface
Electrons lose energy by scattering, assume e-e scattering dominates,
$F_{e-e}$ is the probability the electron makes it to the surface without scattering

Step 3: Escape over barrier
Escape criterion:
$$\frac{p^2_{\text{normal}}}{2m} > E_F + \phi_{\text{eff}}$$

$$P_{\text{total}} = \sqrt{2m(E + \hbar \omega)}$$

$$P_{\text{normal}} = \sqrt{2m(E + \hbar \omega) \cos \theta}$$

$$\cos \theta_{\text{max}} = \frac{p_\perp}{P_{\text{total}}} = \frac{E_F + \phi_{\text{eff}}}{E + \hbar \omega}$$

Q.E. (ω) = (1 - R(ω))

$$\int_{E_F - \hbar \omega}^{E_F + \hbar \omega} dE \frac{N(E + \hbar \omega)(1 - f_{FD}(E + \hbar \omega))N(E)f_{FD}(E)}{\cos \theta_{\text{max}}(E)} \int_{-1}^{1} d(\cos \theta) F_{e-e}(E, \omega, \theta) \int_{0}^{2\pi} d\Phi$$

$$\int_{E_F - \hbar \omega}^{E_F + \hbar \omega} dE \frac{N(E + \hbar \omega)(1 - f_{FD}(E + \hbar \omega))N(E)f_{FD}(E)}{\cos \theta_{\text{max}}(E)} \int_{-1}^{1} d(\cos \theta) \int_{0}^{2\pi} d\Phi$$

Courtesy Dave Dowell (SLAC)
Types of Photocathodes

Metals – low efficiency, good time response (prompt), resistant to contamination, need UV laser (copper, Mg)

Semi-conductors – high efficiency, slower time response, sensitive to contamination, visible/IR lasers (GaAs, Cs₂Te, K₂CsSb, GaN)

Quantum Efficiency is the figure of merit for photocathodes

\[ QE = \frac{\# \text{ electrons emitted}}{\# \text{incident photons}} = S(mA/W) \frac{h \nu}{e} = 1.24 S(mA/W)/\lambda(nm) \]
Fig. 2. Performance of Cs₂Te under different operating conditions.
Table 1.1 Composition and typical characteristics of photocathodes

<table>
<thead>
<tr>
<th>Type of spectral response</th>
<th>Composition</th>
<th>Type of window</th>
<th>Photo-emission threshold (nm)</th>
<th>Wavelength at maximum sensitivity (nm)</th>
<th>Radiant sensitivity at $\lambda_{max}$ (mA/W)</th>
<th>Quantum efficiency at $\lambda_{max}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>AgOCs</td>
<td>1</td>
<td>1100</td>
<td>800</td>
<td>2.3</td>
<td>0.4</td>
</tr>
<tr>
<td>S4</td>
<td>SbCs$_3$</td>
<td>1,2,3</td>
<td>680</td>
<td>400</td>
<td>50</td>
<td>16</td>
</tr>
<tr>
<td>S11</td>
<td>SbCs$_3$</td>
<td>1</td>
<td>700</td>
<td>440</td>
<td>80</td>
<td>22</td>
</tr>
<tr>
<td>S13</td>
<td>SbCs$_3$</td>
<td>2</td>
<td>700</td>
<td>440</td>
<td>80</td>
<td>22</td>
</tr>
<tr>
<td>S20</td>
<td>SbNa$_2$KCs</td>
<td>1</td>
<td>850</td>
<td>420</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>S20R (ERMA*)</td>
<td>SbNa$_2$KCs</td>
<td>1</td>
<td>900</td>
<td>550</td>
<td>35</td>
<td>8</td>
</tr>
<tr>
<td>bialkali</td>
<td>SbKCs</td>
<td>1</td>
<td>630</td>
<td>400</td>
<td>90</td>
<td>28</td>
</tr>
<tr>
<td>bialkali</td>
<td>SbKCs</td>
<td>2</td>
<td>630</td>
<td>400</td>
<td>90</td>
<td>28</td>
</tr>
<tr>
<td>bialkali (GEBA**)</td>
<td>SbKCs</td>
<td>1</td>
<td>700</td>
<td>440</td>
<td>100</td>
<td>28</td>
</tr>
<tr>
<td>bialkali</td>
<td>SbNaK</td>
<td>1</td>
<td>700</td>
<td>400</td>
<td>50***</td>
<td>16***</td>
</tr>
<tr>
<td>solar blind</td>
<td>CsTe</td>
<td>2</td>
<td>340</td>
<td>235</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

*Photocathodes* The S designations (JEDEC No. 50, Oct. 1954, S curves) refer to the total spectral response, including the effect of the input window. They do not identify specific types of cathode or cathode materials, or absolute sensitivities, although they are often so used.
Night Vision Goggles

http://en.wikipedia.org/wiki/Photocathode
Combined Dispenser cathode with photoemission

Heat the cathode up to just below the threshold for emission, then use the laser energy to emit a pulse of electrons

http://www.ireap.umd.edu/FEL/Research/Photocathode.htm#thermionic
Diamond Amplifier

http://www.bnl.gov/cad/ecooling/DAP_principles.asp

Electron transmission gain

Electron Guns for Accelerators

- **Pulsed!**
  - $E_{\text{cath}} = 120 \text{ MV/m}$
  - $\tau_{\text{laser}} = 2.7 \text{ ps rms}$
  - $\sigma_{\text{laser}} = 0.5 \text{ mm rms}$

- **SRF**
  - $E_{\text{cath}} = 43 \text{ MV/m}$
  - $\tau_{\text{laser}} = 5.8 \text{ ps rms}$
  - $\sigma_{\text{laser}} = 0.85 \text{ mm rms}$

- **DC**
  - $E_{\text{cath}} = 8 \text{ MV/m}$
  - $\tau_{\text{laser}} = 13 \text{ ps rms}$
  - $\sigma_{\text{laser}} = 2 \text{ mm rms}$
31/2 cell SRF gun Rossendorf

Cathode transfer rod
He-vessel
HOM filter
LN2 reservoir
cathode cooler
cathode choke filter
gun half-cell
power coupler

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ERL 2007, May 21 – 25

B_{\text{max}} = 110 \text{ mT}
Cathodes for Superconducting RF cavities

![Graph showing QE vs Photon Energy (eV) with data points for Electroplated Pb, Arc Deposited Pb, Electroplated Plug, and DESY Cavity Arc Dep.](image)

Courtesy John Smedley (BNL)
BNL SRF Gun Design

Photoinjector designed to deliver 2 MeV beam, 5 nC/bunch at 9.38 MHz
BNL Gun Cryomodule
Photocathode choice and challenges

- CsK$_2$Sb is cathode of choice, with a diamond amplified photocathode as the next generation cathode
- Lots of experience with CsK$_2$Sb photocathode deposition, extensive R&D on diamond amplified photocathode

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solutions</th>
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</thead>
<tbody>
<tr>
<td>Cathode lifetime</td>
<td>No vacuum degradation</td>
</tr>
<tr>
<td>Thermal isolation</td>
<td>Actively cooled cathode stalk</td>
</tr>
<tr>
<td>Particulate and interface to gun</td>
<td>Proper engineering and design</td>
</tr>
</tbody>
</table>
BNL Photocathode deposition system

Designed by AES

Andrew Burrill, ERL 2007 Workshop
Normal Conducting RF Gun

PITZ NC RF gun, 1 nC, 10 kHz
Boeing RF Gun

Table 1
Parameters demonstrated during the 1992 high-duty test of the 433 MHz NCRF gun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode performance:</td>
<td></td>
</tr>
<tr>
<td>Photocathode material:</td>
<td>K$_2$CaSb Multialkali</td>
</tr>
<tr>
<td>Quantum efficiency:</td>
<td>5–12%</td>
</tr>
<tr>
<td>Peak current:</td>
<td>45–132 A</td>
</tr>
<tr>
<td>Cathode lifetime:</td>
<td>1–10 h</td>
</tr>
<tr>
<td>Angle of incidence:</td>
<td>Near-normal incidence</td>
</tr>
<tr>
<td>Gun parameters:</td>
<td></td>
</tr>
<tr>
<td>Cathode gradient:</td>
<td>26 MV/m</td>
</tr>
<tr>
<td>Cavity type:</td>
<td>Water-cooled copper</td>
</tr>
<tr>
<td>Number of cells:</td>
<td>4</td>
</tr>
<tr>
<td>RF frequency:</td>
<td>$433 \times 10^6$ Hz</td>
</tr>
<tr>
<td>Final energy:</td>
<td>5 MeV (4-cells)</td>
</tr>
<tr>
<td>RF power:</td>
<td>$600 \times 10^8$ Watts</td>
</tr>
<tr>
<td>Duty factor:</td>
<td>25%, 30 Hz and 8.3 ms</td>
</tr>
<tr>
<td>Laser parameters:</td>
<td></td>
</tr>
<tr>
<td>Micropulse length:</td>
<td>53 ps, FWHM</td>
</tr>
<tr>
<td>Micropulse frequency:</td>
<td>$27 \times 10^6$ Hz</td>
</tr>
<tr>
<td>Macro-pulse length:</td>
<td>10 ms</td>
</tr>
<tr>
<td>Macro-pulse frequency:</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Wavelength:</td>
<td>527 nm</td>
</tr>
<tr>
<td>Cathode spot size:</td>
<td>3–5 mm FWHM</td>
</tr>
<tr>
<td>Temporal and transverse distribution:</td>
<td>Gaussian, Gaussian</td>
</tr>
<tr>
<td>Micropulse energy:</td>
<td>0.47 µJ</td>
</tr>
<tr>
<td>Energy stability:</td>
<td>1–5%</td>
</tr>
<tr>
<td>Pulse-to-pulse separation:</td>
<td>37 ns</td>
</tr>
<tr>
<td>Micropulse frequency:</td>
<td>$27 \times 10^6$ Hz</td>
</tr>
<tr>
<td>Gun performance:</td>
<td></td>
</tr>
<tr>
<td>Emittance (µm, RMS):</td>
<td>5–10 for 1–7 nC</td>
</tr>
<tr>
<td>Charge:</td>
<td>1–7 nC</td>
</tr>
<tr>
<td>Energy:</td>
<td>5 MeV</td>
</tr>
<tr>
<td>Energy spread:</td>
<td>100–150 keV</td>
</tr>
</tbody>
</table>

Fig. 1. Photograph of the Boeing/LANL 433 MHz NCRF gun in the test vault.

Fig. 2. Drawing of the 433 MHz gun showing the re-entrant design and the locations of the emittance compensation coil and cathode field-bucking coil. Cells 5 and 6 indicated in Table 1 are not shown. The cathode was fabricated in an a vacuum deposition chamber and inserted into the gun under vacuum via a long cathode stick. See Fig. 1 and Refs. [2,3].
Development of Cs$_2$Te compact load-lock system for multi-bunch electron beam generation

(Collaborating with KEK, Waseda Univ.)
Los Alamos High Avg Current RF Gun

Fundied by NAVSEA and the JTO, Los Alamos and Advanced Energy Systems (AES) have designed a water-cooled 700MHz copper photocathode gun with a dense array of cooling channels for thermal management and sufficient vacuum pumping to provide a good vacuum in the photocathode cell [5]. The design of a normal-conducting, 700MHz gun operating at 7, 7 and 5MV/m is shown in Fig. 3. The photocathode gun is designed to produce 2.5 MeV electron beams. It consists of a 7-mode, \( \frac{2}{7} \)-cell, RF cavity with on-axis electric coupling and emittance compensation, and a non-resonant vacuum plenum. The non-resonant vacuum plenum can accommodate up to eight ion pumps to ensure adequate vacuum pumping of the RF injector. Large-diameter apertures between the resonant cells and the non-resonant vacuum plenum are used to maintain high-conductance passages for pumping the photocathode cell. Heat removal in the resonant cells is achieved via dense arrays of internal cooling passages capable of handling high-velocity water flows. The septum walls are almost flat to keep the cooling channels as close to the RF surface as possible. Megawatt RF power is coupled into the gun through two tapered ridge-loaded waveguides [6]. PARMELA simulations show that the room-temperature RF photocathode gun can produce a 6nm-mrad emittance at 3 nC bunch charge.
LBNL VHF quarter-wave coaxial cavity gun

- **Cathode position**
- **Coaxial center conductor**
- **Cathode insertion system**
- **External beamline components**

**Specifications:**
- **65 MHz CW**
- **Normal conducting Cu-plated Al**

**RF power sources:**
- Can be based on commercially available broadcast tubes.

**Design Features:**
- Large outer diameter provides good accessibility for ion- and cryo-pumps.
- All metal structure suitable for bake-out.

Steve Lidia, LBNL, ERL 2007 Workshop
Example VHF gun performance

- Frequency: 65 MHz
- Pulse rate: CW
- Gap Voltage: 0.6-1.0 MV
- Unloaded Q: $3.5 \times 10^4$
- Effective Gap Length: 4 cm
- Range of field in planar gap: 15-25 MV/m
- Cavity length: 1 meter
- Cavity diameter: 1.4 m
- Inner conductor diameter: 0.3 m
- RF power for 0.75 MV on gap: 65 kW
- Peak wall power density: 7 W/cm²
- Vacuum: $10^{-11}$ Torr
- Required pumping speed: 25000 liter/sec
- Stored energy: 5-8 J

Steve Lidia, LBNL, ERL 2007 Workshop