RF Electron Gun

Lecture No. 3:
Operation and Applications of RF Gun

Sakhorn Rimjaem

Department of Physics and Materials Science, Faculty of Science, Chiang Mai University (CMU), Thailand
Operation of RF Electron Gun
- Cathode preparation
- Operation conditions
- Measurements of electron beam properties

Applications of Electron Sources
- Electron sources for high energy physics accelerator
- Electron sources for light sources
- Electron sources for direct applications

Generation and Applications of Ultra Short Electron Bunches Produced by RF Gun
- Generation and applications of ultra short electron bunches at Chiang Mai University
Cathode assembly
- Cylindrical SST cathode holder with screws for adjusting cathode position.
- Cathode with flat circular emitting surface of 3 mm is heated via filament connected to an external power supply.
Thermionic cathode is an impregnated dispenser tungsten cathode coated with Os/Ru.

$\rightarrow$ Flat circular emitting surface of 3 mm radius.
“Type M cathode” is an improved version of the impregnated cathode, which coated with an alloy of platinum group metals on the emissive surface to lower the work function. → It can be operated at lower temperatures than the standard dispenser cathode for the same current density, which results in longer operating lifetime.
Comparison of current density as a function of cathode temperature from manufacturer’s calibration data and Richardson’s law.

![Graph showing comparison of current density as a function of cathode temperature. The graph plots current density (A/cm²) on the y-axis and cathode temperature (K) on the x-axis. Two lines are shown: one representing calibration data from the manufacturer and the other representing Richardson’s law.]
The cathode needs to be heated to a high temperature (~900-1000°C) for electron emission. If the heat leakage is too high, the cathode might not reach the electron emission temperature. Thermal radiation from hot cathode can heat up the cavity wall near the cathode to expand due to thermal expansion. This may result in a resonant frequency shift of the gun.

To prevent heat lost to the surrounding area, the cathode must be insulated from material. A flat heat-dam made of Hastelloy C-276 with copper electroplating is used. A narrow gap was made between the cathode stem and the heat-dam to function as a thermal insulator. A toroidal-tungsten-spring is placed around the cathode stem to minimize heat leakage. The cathode temperature depends greatly on the number of turns of the spring.
Pyrometric measurement after cleaning and baking

Pyrometric measurement for the gun, which installed in the beam line.
Cathode tests (Pyrometric measurements)
- To activate the cathode to temperature > 1050 °C
- Measure the cathode temperature by using an optical Pyrometer
- Required for new cathode or when cathode experiences poor vacuum or chemical contamination.

Operating temperature ~900-1000°C (cathode heating power ~ 13-17 W)
### Operation of RF Electron Gun
- Cathode preparation
- Operation conditions
- Measurements of electron beam properties

### Applications of Electron Sources
- Electron sources for high energy physics accelerator
- Electron sources for light sources
- Electron sources for direct applications

### Generation and Applications of Ultra Short Electron Bunches Produced by RF Gun
- Generation and applications of ultra short electron bunches at Chiang Mai University
Input (forward) RF power given to the RF-gun is

\[ P_{\text{forward}} = P_{\text{cavity}} + P_{\text{beam}} + P_{\text{reflected}} \]

Beam power is related to the kinetic energy of electron beam as

\[ P_{\text{beam}} \approx (\langle KE \rangle)I_{\text{beam}} \]

In of no electron emission from the cathode, the cavity wall losses is

\[ P_{\text{cavity}} = P_f - P_{\text{reflected}} \]

Compare with theoretical cavity wall losses (which can get from simulation) → Then, the average electric field gradient \( (E_o) \) can be calculated:

\[ P_{\text{cavity}} = \frac{V_{\text{acc}}^2}{r_s d} = \frac{E_1^2 d}{r_s} \quad \Rightarrow \quad E_1^2 = \frac{P_{\text{cavity}} r_s}{d} \]
RF Power vs. Electric Field Gradient (2)

Measured RF powers and calculated average electric field gradient
Beam Power and Beam Current

**Schematic model of current transformer**

**Actual current transformer**

**Peak current of ~ 1 A at ~2 MeV from RF-gun**
- Beam power $P_b \sim I_b \times E_{kin} = 2\,\text{MW}$
- Cavity wall losses $P_{cy} \sim 1.46\,\text{MW}$
- $P_{cy} + P_b = 3.46\,\text{MW}$

Peak current of 0.4-0.5 A at $\alpha$-magnet exit (50-60% is filtered out by the energy slits).
Beam Energy Measurements after RF Gun

Using energy slit inside alpha magnet vacuum chamber: $E_{\text{max}} = 2-2.4 \text{ MeV}$

$$x_{\text{max}} = 75.05 \sqrt{\frac{cp}{mc^2 g}}$$

<table>
<thead>
<tr>
<th>Current (Amp)</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient (Gauss/cm)</td>
<td>0</td>
<td>50</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>600</td>
</tr>
</tbody>
</table>

Max. Gradient = 450 G/cm
Max. current = 265 A
Dipole magnet is used as electron beam dump + energy spectrometer.

Deflect electron beam 60° respect to beam axis

Actual 3D-field distribution of dipole magnet

$E(\text{GeV}) = \frac{0.2998 \int B \, dz}{\beta \alpha}$

$B \sim 0.8 \text{ Tesla at current of 16 A}$
Schematic layout of beam profile measurement setup and a 2.4 MeV electron beam image (SC2)

- Phosphor screen ($\text{Gd}_2\text{O}_2$:Tb deposited on Al-plate)
- CCD camera
- Frame grabber board (DT3315 Data-Translation)
- PC with DT-Acquire software

Relative intensity distribution of electron beam in 2D and 3D and the horizontal and vertical beam profiles

(MATLAB code BAP, S. Chumphongphan)
High-power RF parameters, typical operating condition and electron beam-loading parameters of the PBP-CMU RF-gun.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency in $\pi/2$-mode</td>
<td>2856</td>
<td>MHz</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>27.5</td>
<td>°C</td>
</tr>
<tr>
<td>Input RF peak power</td>
<td>3.55</td>
<td>MW</td>
</tr>
<tr>
<td>Dissipation RF power</td>
<td>1.36</td>
<td>MW</td>
</tr>
<tr>
<td>External RF-coupling coefficient</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>Maximum kinetic energy</td>
<td>$\sim$2.5</td>
<td>MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>0.7–1</td>
<td>A</td>
</tr>
<tr>
<td>RF-pulse length (FWHM)</td>
<td>$\sim$2.8</td>
<td>μs</td>
</tr>
<tr>
<td>RF repetition rate</td>
<td>10</td>
<td>Hz</td>
</tr>
<tr>
<td>Beam-pulse length (FWHM)</td>
<td>1–2</td>
<td>μs</td>
</tr>
<tr>
<td>Charge per micro-bunch</td>
<td>$\sim$0.2–0.25</td>
<td>nC</td>
</tr>
</tbody>
</table>
Lecture No. 3

- Operation of RF Electron Gun
  - Cathode preparation
  - Operation conditions
  - Measurements of electron beam properties

- Applications of Electron Sources
  - Electron sources for high energy physics accelerator
  - Electron sources for light sources
  - Electron sources for direct applications

- Generation and Applications of Ultra Short Electron Bunches Produced by RF Gun
  - Generation and applications of ultra short electron bunches at Chiang Mai University
Example: Stanford Linear Accelerator Laboratory (SLAC)

3-miles linear accelerator at SLAC can accelerate electron beam to 10 GeV.
Example: the International $e^{-} - e^{+}$ Linear Collider (ILC)

It is initially planned to have a collision energy of 500 GeV, with the possibility for a later upgrade to 1000 GeV (1 TeV).

(A. Sessler and E. Wilson, Engines of Discovery: A Century of Particle Accelerators)
Radiation brightness

- In geometric optics, spectral brightness is defined as photon flux density in phase space about a certain frequency (number of photons per unit time per unit area per unit solid angle):

$$B = \frac{d^2 I}{dA d\Omega} = \frac{d^2 I}{dx dx' dy dy'} \propto \frac{2I_p}{\varepsilon_x \varepsilon_y}$$

- We need electron beams with small emittance and high peak current.
Synchrotron Light Sources

Thermionic DC guns
Thermionic RF guns

PETRAIII @ DESY (Germany)
Diamond (UK)
ALBA, Spain
ESRF, France

Shanghai light source (China)
Spring 8 (Japan)
Siam Photon (Thailand)
Australia light source (Australia)
Evaluation of Light Sources

- **1st Generation** (1970s): Many HEP rings are parasitically used for X-ray production
- **2nd Generation** (1980s): Many dedicated X-ray sources (light sources)
- **3rd Generation** (1990s): Several rings with dedicated radiation devices (wigglers and undulators)
- **4th Generation** (Present): Free Electron Lasers (FELs) driven by linear accelerators

4th Generation Light Sources (XFELs)

- European XFEL, Germany (λ~0.1-1.6 nm)
- FLASH @ DESY, Germany (λ~0.1-7 nm)
- SPARC, Italy (λ~0.6-40 nm)
- FERMI @ Elettra, Italy (λ~1.0-100 nm)
- SwissFEL, Switzerland (λ~0.1-7 nm)

- LCLS FEL @ SLAC, USA (λ~0.15-1.5 nm)
- HGHG FEL @ NSLS, BNL, USA (λ~193 nm)

Photocathode RF guns
(SACL A XFEL uses DC gun)
4th Generation Light Sources (IR-FELs)

RF Electron Gun
S. Rimjaem

Fritz Haber Institute THz FEL
Max Planck Institute
Berlin, Germany

UCSB FEL, Santa Barbara, USA

KU-FEL, Kyoto University, Japan

ELBE @ HZDR
Germany

Thermionic DC guns
Thermionic RF guns
Photocathode RF guns
A modern system for treating a patient with x-rays produced by a high energy electron beam.

The whole device is mounted on a gantry. As the gantry is rotated, so is the accelerator and the resulting x-rays.

Then the radiation can be delivered to the tumor from all directions with precise control for positioning.
Lecture No. 3

Operation of RF Electron Gun
- Cathode preparation
- Operation conditions
- Measurements of electron beam properties

Applications of Electron Sources
- Electron sources for high energy physics accelerator
- Electron sources for direct applications
- Electron sources for light sources

Generation and Applications of Ultra Short Electron Bunches Produced by RF Gun
- Generation and applications of ultra short electron bunches at Chiang Mai University
Direct Applications:
- Ultrafast time-resolved electron diffraction for studying dynamic of chemical reaction (A. Zeweil Noble Price Winner 2002)
- Ultrafast electron pulse radiolysis (K. Ka et al., Rev. of Sci. Instr., 2012)

Production of short (femtosecond) photon pulses:

- Femtosecond X-ray pulses for dynamic study at atomic scale
- Intense far-infrared/THz radiation at frequencies of 100 GHz - 10 THz ($\lambda$: 3 – 0.03 mm) via, e.g.,
  - Transition radiation
  - Undulator radiation
  - Free-electron lasers (FELs)
Examples: Photocathode RF guns

- Ultrafast time-resolved electron diffraction for studying dynamic of chemical reaction

http://www.fhi-berlin.mpg.de/pc/PCres_methods.html
Examples:

- Ultrafast electron pulse radiolysis

http://labs.eng.hokudai.ac.jp/lab/qsre/field/summary/semiconductor/
Examples: Head-on Inverse Compton scattering (ICS)

N.Y. Huang et al., Proceedings of PAC09, Vancouver, BC, Canada
Examples: Parametric X-rays

PXR as diffraction of virtual photons associated with relativistic charged particles
• gap between Microwaves and Infrared
• frequency from 100 GHz to 10 THz
• wave length from 30 mm – 0.3 cm
• In last 10-15 years, this area is unexplored region
  - lack of source and applications
• Now, THz technology is growing rapidly.
• Penetrate non-conducting material - e.g. clothes, wood, plastic, ceramic, paper

• Blocked by metals, water

• Chemical sensitive ‘finger print’ absorption spectra

• Corresponds to intermolecular vibration and rotation

Weak hydrogen bond
THz Imaging: Advantages

✔ **Safer**: low photon energies

✔ **Signature**: specific fingerprinting

✔ **More selective in soft materials**

e.g.,

- Security screening of hidden weapons or explosives
- Narcotics smuggling, suspicious packages
- Food quality control in frozen product
- Agriculture water-content check
- Medical diagnostic for cancerous cell
- Semiconductor wafer inspection
Defense applications

Standoff distance detection of weapon and explosives

(http://www.thznetwork.org/wordpress/index.php/thz-images)
Medical applications

THz imaging diagnostic of cancer tissues

Nakagima et al. [Appl. Phy Let. 90 041102(2007)]

Inspection

Non-destructive THz imaging of drugs in an envelop

Kodo Kawase et al (RIKEN, Japan)
Fourier transform of the short electron bunch provides broad radiation spectrum

\[
|\tilde{E}_0(\omega)|^2 = \tilde{E}_0(\omega)\tilde{E}_0^*(\omega)\alpha \int_{-\alpha}^{\alpha} I_0(\delta) e^{i\omega \delta/c} d\delta = FT\{I_0(\delta)\}
\]

Calculated radiation brightness

\[B(\text{ph/s/mm}^2/100\%\text{BW})\] vs. wave number for CTR, SR and black body radiation.
Short electron bunches in the order of femtosecond scale can be generated by using an **RF gun** and a **magnetic bunch compressor**.

- High energy electron bunches with inversely linear correlation between energy-time distribution are normally compressed with **chicane**.

http://www.psi.ch/swissfel/swissfel-accelerator

http://cerncourier.com/cws/article/cern/28925
Low energy electron bunches with linear correlation between energy-time distribution can be compressed with $\alpha$-magnet.

- Electrons with different momenta have different path lengths inside the $\alpha$-magnet field.
- Energy slits are placed in a magnetic vacuum chamber to select only the core of the beam.
  - Emittance and energy spread are reduced.
  - The peak current is increased.
Linac System @ CMU

RF Electron Gun
S. Rimjaem

Dipole Magnet

Linear Accelerator

Alpha Magnet

RF Electron Gun

PXR

Dipole Magnet

Linear Accelerator

Alpha Magnet

RF Electron Gun

PXR
RF Electron Gun
S. Rimjaem

**Generation of Short Electron Source at CMU**

- **S-band thermionic RF-gun** (2-2.5 MeV (30 MV/m @ cathode))
- **Linac** (10-15 MeV (up to 30 MeV with higher RF power))
- **Transition radiation stations** (0.23 nC/bunch, ≤ 200 fs)

**Alpha magnet** (bunch compressor)

---

Accelerator Technology and its Applications, Nathiagali Summer College 2014, Pakistan, August 4-9, 2014
Generation of Short Electron Bunches (3)

@ experimental station ($l_b \leq 200$ fs)

1 µs beam pulse (2856 bunches/1 µs)

1.5 µs beam pulse (2856 bunches/1 µs)

350 ps ~100 ps

macropulse

1 µs 100 ms
Generation of Transition Radiation

\[ E_{\text{kin}} \sim 2-2.5 \text{ MeV} \ (E_Z \sim 30 \text{ MV/m @ cathode}) \]

- \(~10-15 \text{ MeV} \) (up to \(~30 \text{ MeV} \) with higher RF power)
- \(~1.8-2.5 \text{ MeV} \), \( l_b \sim 10-20 \text{ ps} \)
- \( Q \sim 0.23 \text{ nC/bunch} \), \( l_b \sim 200 \text{ fs} \)
At wavelengths about or longer than the bunch length
↓
Radiation field add up coherently
↓
Electron short bunches is desired to produce coherent radiation
↓
Radiation intensity $\alpha N^2$

Detector signal of coherent transition radiation intensity vs. number of electrons.
Bunch Length Measurement

Measured electron bunch ~ 200 fs (120 µm)

Michelson Interferometer

interferogram
Fourier transform of the short bunch provides broad radiation spectrum

\[ \left| \tilde{E}_0(\omega) \right|^2 = E_0(\omega) \tilde{E}_0^*(\omega) \alpha \int_{-\alpha}^{+\alpha} I_0(\delta)e^{i\omega\delta/c} d\delta = FT\{I_0(\delta)\} \]

Measured electron bunch ~ 200 fs (120 μm)

Measured THz radiation covers wave number of 5-80 cm\(^{-1}\) (frequency range of 0.3 – 2.4 THz)

Using a room-temperature detector

\[ FT \text{ detector signal (a.u.)} \]

\[ Energy \text{ density (a.u.)} \]
Water vapor spectrum & absorption lines

interferogram in vacuum

interferogram in humid air
Design of THz imaging system at PBP, Chiang Mai University
THz imaging of holes on Al-foil in an envelope

Al-Foil

e-Beam

Parabolic Reflector

Cu cone

polyethylene Window

Sample on x-y translation stage

pyroelectric detector

THz radiation

THz image of holes on Al-foil in an envelope
Water drop

Cooked vs. Un-cooked Rice
THz image of live leaves (better resolution)

with 180x180 µm copper mesh filter (20–40 cm⁻¹ transmission band)
### Properties of Coherent THz Radiation @ CMU

**S. Rimjaem**

#### How to obtain brighter radiation?

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>5 - 80</td>
<td>cm⁻¹</td>
</tr>
<tr>
<td>Energy per macropulse</td>
<td>8.8</td>
<td>µJ</td>
</tr>
<tr>
<td>(21.5% collection efficiency)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>radial</td>
<td></td>
</tr>
<tr>
<td>Macropulse power</td>
<td>11</td>
<td>W</td>
</tr>
<tr>
<td>Microbunch power</td>
<td>19</td>
<td>kW</td>
</tr>
<tr>
<td>Average power (at 10 Hz rep. rate)</td>
<td>88</td>
<td>µW</td>
</tr>
<tr>
<td>Micropulse duration ($\sigma_z$)</td>
<td>200</td>
<td>fs</td>
</tr>
<tr>
<td>Micropulse separation</td>
<td>350</td>
<td>ps</td>
</tr>
<tr>
<td>Macropulse duration</td>
<td>0.8</td>
<td>µs</td>
</tr>
<tr>
<td>Number of radiation pulses/macropulse</td>
<td>2300</td>
<td>pulse</td>
</tr>
</tbody>
</table>

**Electron beam parameters**

- Resonant frequency: 2856 MHz
- Beam energy: 10 MeV
- Electron bunch length: 200 fs
- Bunch charge: 230 pC
- Macropulse length: 1 µs
- Repetition rate: 10 Hz
How to obtain brighter radiation?

**The greater the brightness, the more photons that can be concentrated on a spot.**

**Improvement of electron beam**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Beam energy</td>
<td>10 MeV</td>
</tr>
<tr>
<td>Electron bunch length</td>
<td>100 fs</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>~100-200 pC</td>
</tr>
<tr>
<td>Macropulse length</td>
<td>1 µs</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

**Brightness:** number of photons produced per second, angular divergence of photons, cross-sectional area of beam, photons falling within a **bandwidth (BW)** of 0.1% of central wavelength.

*Undulator Radiation* ~factor of $10^6$

*Transition Radiation*
Planar Electromagnet Undulator (EMU)
- Economical & simple choice
- Based on some experience of electromagnet dipoles and quadrupoles development in house
- Magnetic field strength is adjusted by varying the applied current
→ To avoid difficulty of mechanics for adjusting the gap

Preliminary parameters for CMU EMU

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-parameter</td>
<td>1-1.2</td>
</tr>
<tr>
<td>Max. on-axis peak magnetic field</td>
<td>~0.2 T</td>
</tr>
<tr>
<td>Period length</td>
<td>55 mm</td>
</tr>
<tr>
<td>Undulator gap</td>
<td>10 mm</td>
</tr>
<tr>
<td>Number of periods</td>
<td>40</td>
</tr>
<tr>
<td>Radiation wavelength</td>
<td>~100 um</td>
</tr>
</tbody>
</table>
Electromagnet Undulator with 40 Periods (1)

Pole optimization for non-saturation of magnetic field

Design electromagnet undulator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-parameter</td>
<td>1.2</td>
</tr>
<tr>
<td>Max. on-axis peak magnetic field</td>
<td>0.23 T</td>
</tr>
<tr>
<td>Period length</td>
<td>55 mm</td>
</tr>
<tr>
<td>Undulator gap</td>
<td>10 mm</td>
</tr>
<tr>
<td>Number of periods</td>
<td>40</td>
</tr>
<tr>
<td>Radiation wavelength</td>
<td>~100 um</td>
</tr>
</tbody>
</table>
**Electromagnet Undulator with 40 Periods (2)**

**B_y along distance in undulator (z)**

\[ B_0[T] = \frac{2\pi mcK}{(e\lambda_u)} = K' / (0.934\lambda_u [cm]) \]

**Transverse trajectory of electron along z**

\[ x = \frac{K\lambda_u \sin(2\pi z / \lambda_u)}{2\pi\beta\gamma} \]

**Fundamental frequency**

\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} + \theta^2\gamma^2 \right) \]

**B2E simulated undulator spectrum**

- Fundamental frequency: \(~ 2.4 \, \text{THz}~\)

---

*Image*
RADIA model (8 main poles + 2 end poles)

B-H curve of the material used to construct the undulator was measured by using Split-coil permeameter @ DESY.
Characteristics of particle beams and reliability in operation of an accelerator facility strongly depend on properties of the source.

- Development of high-brightness electron beams is a key and a critical issue in the success of most electron accelerator projects.
- RF electron guns are the powerful source with specifications depending on types of accelerators and applications.
- RF gun technology is one of main streams in the development of particle accelerators.
Thank you for your attention!

Questions & Discussion