A high-peak and high-average current, low emittance, long lifetime electron source* for ERL applications

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* Patent applied for.
New Electron Source Needed

• Modern energy recovery linac (ERL) based applications (E-cooling of ion beams, high average power Free Electron Lasers and Terahertz Light Sources) need electron sources with:
  – High peak-current
  – High average-current
  – Low emittance
  – Long lifetime

• The MEIC project in JLab requires ultimately an electron source with:
  – High bunch charge (3.2 nC)
  – Short bunch length (~ 2 cm)
  – High average current (1.5 A)
  – High bunch repetition rate (476 MHz)
  – Magnetization of ~ 590 µm.

• Existing sources cannot meet the needs.
Overview of Current Electron Source Technologies

Photocathode electron sources

• Advantages:
  – Capable of generating high peak current beams in DC or RF guns.
  – Low emittance.

• Disadvantages:
  – Hard to obtain high average current beams (state-of-the-art: ~75 mA).
    ▪ Metal photocathodes have low QE (<10^{-3}).
    ▪ Multi-alkali cathodes and semiconductor cathodes:
      ◇ Require UHV
      ◇ Short lifetime
  – Expensive. Require UHV, cathode preparation system and laser system.
  – Metal photocathodes have higher thermal emittance (~0.4 eV) than thermionic cathodes.
Overview of Current Electron Source Technologies

Thermionic electron sources

• Advantages:
  – High current (DC).
  – Low thermal emittance (thermal energy of ~0.12 eV).
  – Long lifetime (a few thousand hours for LaB₆ cathode).
  – Low cost. No UHV; No laser.

• Disadvantages:
  – DC beam can not be directly used in linac systems.
  – Can not generate high-average current, high-brightness beam in RF guns.

Field emitter sources and secondary emission sources.
  – Hard to obtain high average current beam or operation in RF guns not yet demonstrated
Thermionic RF Gun Issue: Back-bombardment

A typical RF gun (BNL/SLAC/UCLA 1.5 cell gun). 
f=2856 MHz, 
$E_{\text{peak}}=100$ MV/m

Electron energy at gun exit or back-bombardment (BB) energy vs. cathode launching phase (initial phase).

- Electrons from section I and section II can escape from the cavity.
- Electrons from section III strike back on cathode (back-bombardment) under decelerating field.
Back-bombardment power density is large (a few - tens kW/mm$^2$) and is directly on cathode surface.

- Rapid temperature increase of the cathode during the RF macro pulse causes the current to increase and the beam energy to decrease
- Typical macro-pulse width is a few μs with low duty cycle.
Thermionic RF Gun Issue: Emittance Growth

- Section I beam (from 0° to somewhere after $\phi_{\text{Peak}}$) has small emittance
- Section II beam has large emittance
Suppressing BB & section II beam

Conventional way suppressing BB beam include applying deflecting magnetic field on cavity which has finite effect. Alpha magnet is used suppressing the section II beam.

Deflecting magnet for reducing BB beam.

α magnet for suppressing section II beam.
1. **CW mode for high average current by eliminating the back-bombardment** and

2. **Improved beam quality by suppressing the section II beam**
Step I, a **short accelerating gap** RF cavity

- Pushes $\phi_{\text{peak}}$ close to $90^\circ$ ($75^\circ$) and $\phi_{\text{BB}}$ close to $180^\circ$ ($152^\circ$).
- Still has considerable back-bombardment power.

![Diagram of a short accelerating gap 476 MHz RF gun](image1)

![Energy at gun exit vs. initial phase](image2)
300 MHz cavity

- Frequency: 300 MHz
- Acc. gap: 3 cm
- Aperture: 2 cm
- \( E_{\text{Cathode}} \): 12 MV/m
- \( E_{\text{Peak}} \): 21 MV/m
- \( r/Q \): 180 \( \Omega \)
- \( P_{\text{Total}} \): 10 kW
- Peak power density: 18 W/cm\(^2\)
- Beam energy: 235 keV
- \( \phi_{\text{Peak}} = 82^\circ \)
- \( \phi_{\text{BB}} = 159^\circ \)
75 MHz cavity

- Frequency: 75 MHz
- Acc. gap: 4 cm
- Aperture: 2 cm
- $E_{\text{Cathode}}$: 11 MV/m
- $E_{\text{Peak}}$: 20 MV/m
- $r/Q$: 200 $\Omega$
- $P_{\text{Total}}$: 8 kW
- Peak power density: $1.5 \text{ W/cm}^2$
- Beam energy: 330 keV
- $\phi_{\text{Peak}} = 87^\circ$
- $\phi_{\text{BB}} = 168^\circ$
Step II, use a **floating grid cathode**.

A floating grid thermionic cathode

- $E_{\text{grid-Main Emitter}} = E_{\text{DC}} + E_{\text{RF}}$
- $E_{\text{DC}}$ is determined by the geometry of the floating grid and net charge on it.

The floating grid net charge can be adjusted by changing the emission of charging / discharging emitters through changing their operating temperatures or apply bias fields.
Emission Window of A Floating Grid Cathode

- At sufficient high $E_{DC}$, $\phi_{End} < \phi_{BB}$, the **back-bombardment beam is eliminated and section II beam is suppressed.**
- Allows CW operation, every RF bucket filled, high average current.
- Small emittance.

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Proprietary
Example: JLab’s Magnetized Beam for MEIC e-cooling

- Frequency: 476 MHz
- Acc. gap: 1.5 cm
- Aperture: 2 cm
- $E_{\text{Cathode}}$: 13.6 MV/m
- $E_{\text{Peak}}$: 24.2 MV/m
- r/Q: 135 Ω
- $P_{\text{Total}}$: 9.4 kW
- Peak power density: 22 W/cm$^2$.
- Cath. size: 1.2 cm
- Solenoid for magnetization and beam focusing.

RF cavity

Proprietary
Example: JLab’s Magnetized Beam for MEIC e-cooling

Peak energy: 200 keV
Φ_{Peak}: 75°
Φ_{BB}: 152°

Phase space @ gun exit

RF field induced emittance: 13 μm
We choose LaB$_6$ (2.65 eV, >100 A/cm$^2$) as the emitter material.

**Floating grid**

- Material: Pyrolytic graphite (>3000°C)
- Diameter: 12 mm
- RF heating power: Negligible
- Heating/dissipating:
  - Radiation
  - Conduction
  - Charging current
  - Temperature: ~ 1500 K

**Main emitter**

- Material: LaB$_6$/CeB$_6$, dispenser, FEA, etc.
- Diameter: 12 mm
- Temperature: ~1800 K
- Current density: ~20 A/cm$^2$
- Effective emission area: ~60%
- Effective thermal energy of the beamlets at virtual cathode position (beamlet waist after floating grid) is < 0.3 eV.
- Cathode lifetime > 1,500 hrs.

$G_B \sim 250 \mu m.$
Emittance of Multiple Beamlets

- Space charge is strong near cathode \( \propto 1/(\beta \gamma)^3 \).
- A focusing near cathode helps suppress emittance growth, like a double-gate FEA (~0.2 μm/mm) compared to a single-gate FEA (~2μm/mm).
- Negative biased floating grid also provides a focusing (like in an Einzel lens), provides the beamlets collimation like in the double-gate FEA.

- \( \varepsilon_{z=0.08\text{cm}} = 150\% \times \varepsilon_{z=0} \), beam divergence @ \( z=0.08\text{cm} \) is o (virtual cathode position).
- Equivalent beam thermal energy of <0.3eV, better than many metal photocathode.
Current design parameters can be improved!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current design</th>
<th>Up to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>3.2 nC</td>
<td>&gt; 10 nC</td>
</tr>
<tr>
<td>Average current</td>
<td>1.5 A</td>
<td>&gt; 1.5 A</td>
</tr>
<tr>
<td>Beam energy</td>
<td>200 keV</td>
<td>&gt; 1 MeV</td>
</tr>
<tr>
<td>Thermal emittance (of multiple beamlets)</td>
<td>~ 3μm</td>
<td>&lt; 1μm</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>~ 2 cm</td>
<td>&lt; 1 cm</td>
</tr>
<tr>
<td>Cathode lifetime</td>
<td>1,500 hours</td>
<td>&gt; 15,000 hours</td>
</tr>
</tbody>
</table>
Proof of Principle Experiment

Objective: to demonstrate that the floating grid DC bias can be adjusted and the electron emission phase window is therefore controlled.

Schematic diagram of the POP experiment
Proof of Principle Experiment

Main emitter & discharging emitter

Floating grid: TEM grid

Experimental setup

Vacuum chamber during conditioning
Voltage Pulser Test

We’ve observed qualitatively in the pulser test:

- The electron emission from a floating grid structure.
- Emission suppression by the floating grid due to its charging. No emission current without discharging of the floating grid.
Summary

• This research is to develop a thermionic RF gun (cathode can also be other cathode like field emitter array) without back-bombardment and suppressed poor quality beam.
  – Allows CW operation for high average current.
  – Small emittance.
  – Long lifetime (a few thousand hours).
  – Simple, robust and reliable. Assemble in air and operate at 10^{-7} Torr.
  – Current is stable.
  – Cheap. No expensive laser or load lock / preparation chamber required.

• This technique makes it possible to generate the 1.5 A average current bunched beam required by JLab’s MEIC project.

• Our initial proof of principle test results support of model.

• Flexible design for various applications. This technique could also be applied to other accelerator based applications requiring high average current, such as the high average power free electron lasers and terahertz sources.

• Limitations:
  – Not suitable for initially short bunch beams.
  – Not suitable for polarized electron beam
  – Not suitable for high frequency RF cavities.
Thank you!
# Charging / Discharging Emitters

<table>
<thead>
<tr>
<th></th>
<th>Charging emitter</th>
<th>Discharging emitter</th>
<th>Discharging anode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>LaB$_6$/CeB$_6$, dispenser, FEA, etc</td>
<td>LaB$_6$/CeB$_6$, dispenser, FEA, etc</td>
<td>Carbon tube, other high temperature martials.</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>~ 1 mm diameter</td>
<td>~ 2 mm diameter</td>
<td>~ 2 mm diameter</td>
</tr>
<tr>
<td><strong>Operating temperature</strong></td>
<td>~ 1600 K</td>
<td>~ 1450 K</td>
<td></td>
</tr>
<tr>
<td><strong>Current density</strong></td>
<td>~ 1.4 A/cm$^2$</td>
<td>~ 0.16 A/cm$^2$</td>
<td></td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>~ 1 mA ($I_{CH}$)</td>
<td>$I_{DS} = I_{CH}$</td>
<td>~ 1 mA</td>
</tr>
<tr>
<td><strong>Current control methods</strong></td>
<td>• Ohmic heating</td>
<td>• Radiation heating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Laser heating</td>
<td>• Laser heating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Adjusting gap</td>
<td>• Adjusting gap</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Applying bias</td>
<td>• Applying bias</td>
<td></td>
</tr>
<tr>
<td><strong>Beam heating power</strong></td>
<td>~ 0.06 W (on floating grid)</td>
<td>~ 2.6 W (on carbon tube)</td>
<td>~ 2.6 W</td>
</tr>
</tbody>
</table>
Cathode Lifetime

- Cathode lifetime is primarily determined by the evaporation of the LaB$_6$ material. We define the lifetime of the emitter as a thickness decrease of 25 μm (1/10$^{th}$ of the main emitter gap). At 1800 K operating temperature, the evaporation rate is 2.2 X 10$^{-9}$ g/cm$^2$s, and the lifetime is 1,500 hours.

- Lowering operating temperature can increase lifetime dramatically, for example, at 1700 K, lifetime becomes 15,000 hours. Meanwhile the current density drops to 1/3 that of 1800 K, which requires 73% diameter increase to have the same charge.

- Charging and discharging emitter operate at much lower temperature than that of the main emitter, their lifetimes are not critical.
A floating grid in an inductive output tube

The floating grid can aid in the suppression of cathode arcing in the vacuum electron device.
Current density vs. temperature

Current density enhancement by field
Emittance compensation of a strongly magnetized beam

- Electron cooling prefers electron beam with small Lamor radius in cooling section.
- If a beam is strongly dominated by magnetization, the Lamor radius is determined by the B field and electron thermal energy (instead of emittance).
- A strongly magnetized beam like Jlab’s magnetized e-cooling beam (590 μm), prefers a large size, low temperature cathode, which also benefit the cathode lifetime.
- Although emittance compensation of a magnetization dominated beam is less effective than that of a space charge dominated beam, it is still doable (keep beam envelope large).