A Design Study of a 100-MHz Thermionic RF Gun for the ANL XFEL-O Injector

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For
ANL XFEL-O Injector Study Group

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Outline

- Electron gun requirements
- Why a thermionic Low frequency rf gun?
- ANL 100-MHz rf gun design
- Preliminary multipacting simulation result
- Future R&D plans
Gun Requirements

- Meeting the XFEL-O performance goals:
  - High repetition rate
    - Bunch repetition rate ~1 MHz
  - Bunch charge
    - 40 pC
  - Bunch length
    - < 1 ps
  - Average beam current
    - 40 µA
  - Normalized transverse emittance (rms)
    - < 0.2 mm-mrad
  - Beam kinetic energy @gun exist
    - 1 MeV (300 ps rms)

- More on XFEL-O injector beam dynamics
  - N. Sereno, WG5: Thursday morning
Why a thermionic LF Gun?

- For a given mean transverse kinetic energy, a thermionic cathode produces a much lower beam emittance by mainly reducing the cathode size

\[ \epsilon_{n,rms} = \frac{\gamma r_c}{2} \sqrt{\frac{E_{\perp,kin}}{m_0 c^2}} \]

- Ultra-low emittance is possible due to small charge per bunch
  - 40 pC (80 mA, 0.5 nsec bunches)

- Lower frequency allows for a larger cavity
  - Significant reduction of the power density in the structure
  - Makes it possible to operate in CW mode
  - A lower frequency gun implies smaller accelerating gradient, is not a disadvantage
    - RF power level is reasonable for 1 MV operation. Accelerating voltage is higher than DC gun.

- Low-frequency, normal-conducting RF guns with low wall power density are well suited for high rep. rates (CW) operation
  - Proven and mature technology
  - Alternative to DC/SRF guns
Staples, Sannibale, and colleagues have designed and developed an optimized 187 MHz rf gun at 750 kV with beam pulse rate to 1 MHz.

- Re-entrant geometry
  - Optimized for high shunt impedance (~ 6.5 MΩ)
- Both Cs₂Te and GaAs cathodes are being considered
  - Requires operational vacuum pressure in the low 10⁻¹¹ Torr range
  - Incorporates NEG pump modules

1 K. Baptiste, *et al.*, Proc. PAC09
Designs were investigated for capacitively loaded structures to reduce overall dimension of cavity.

Design eventually morphed into a folded coax with short circuited endplate.

Optimizing this design resulted in a geometry similar to LBNL with the addition of a reentrant gap.
**ANL 100MHz CW RF Gun**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>100 MHz</td>
</tr>
<tr>
<td>$Q_U$</td>
<td>44,991</td>
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<tr>
<td>$V_{gap}$</td>
<td>1.0 MV</td>
</tr>
<tr>
<td>Energy</td>
<td>6.06 J</td>
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<tr>
<td>$R_s$</td>
<td>11.81 Mohm</td>
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<tr>
<td>$E_{cathode}$</td>
<td>25.6 MV/m</td>
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<tr>
<td>Peak $E_{surf}$</td>
<td>33.8 MV/m</td>
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<tr>
<td>$P_{loss}$</td>
<td>85 kW</td>
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<tr>
<td>Peak $P_{density}$</td>
<td>12 W/cm²</td>
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<tr>
<td>Radius</td>
<td>0.68 m</td>
</tr>
<tr>
<td>Length</td>
<td>0.73 m</td>
</tr>
</tbody>
</table>

Dimensions:

- Height: 680 mm
- Length: 730 mm
- Diameter: 40 mm
- Channel: 60 mm
- Reentrant width increases
  - Shunt impedance improves
  - Frequency increases
  - Results in larger cavity with lower wall losses

- Cathode surface increases
  - Shunt impedance reduces
  - Frequency decreases
  - More uniform gradient, less transverse kick
  - Results in smaller cavity with larger wall loses

![Diagram of cavity design]
- Peak surface losses ~12 W/cm² which requires only standard cooling.
- Cooling channels on cavity must also accommodate thermal load due to electron back bombardment.
- Wall losses are scaled to 90kW.
- Cavity wall thickness is ½ inch with a thermal film coefficient assumed to be 0.5 W/cm².
- Stresses and displacements are due to rf loading with 90kW wall losses.
- Cavity is assumed to be fixed along the beampipe. A more realistic cavity support system has not yet been modeled.
- The stress levels and displacements are reasonable and may be addressed with mechanical supports, if necessary.
- 1 atmosphere external pressure applied to cavity walls with ½” wall thickness.
- APS design uses a contoured shape to increase cavity rigidity and reduce cavity displacement.
- Vacuum optimized design is useful to maximize vacuum pumping area but is more susceptible to deformation.

Peak stress: 64 MPa
Peak displacement: 4.0 mm
Peak stress: 98 MPa
Peak displacement: 7.3 mm
Displacement and stresses due to external pressure may be addressed by using mechanical supports.

Mechanical supports for vacuum optimized shape are shown to reduce deflection by a factor of 70 using mechanical supports.

Displacements and stresses due to 1 atm external pressure

Deflection reduced from 7.3mm to 0.1mm

Stresses reduced to easily manageable levels
- LBNL design was evaluated by J. Staples for multipacting probability around 0.75 MV gap voltage using 2-d Fishpact code.
- SLAC code suite Omega3P and Track3P was used at ANL to model EM field and multipacting of LBNL VHF gun.
- TRACK3P produced similar results over analysis range from 200 kV to 1.2 MV gap voltage.
- Multipacting was predicted to exist along the corners at the outer radius of the cavity at various voltages.

*J. Staples, “Multipactors Calculations for the VHF Photoinjector Cavity Using Fishpact”, CBP Technical Note 377
- Omega3P and Track3P were used to evaluate multipacting from 0.3MV to 1.2MV.
- Multipacting was not predicted to be present within a large operating band around 1.0MV gap voltage.
- Increased rounding of the corners on the outer radius of the cavity was designed to reduce multipacting susceptibility and increase mechanical rigidity.

Scalar plot of electric field from Omega3P

Multipacting-free region shows a wide band around operating voltage

Impact energies > 50eV and < 5keV are susceptible to multipacting in copper

1.0 MV XFEL-O gap voltage
ANL XFEL-O DC Gun

- 300kV APS DC gun based on 500kV Spring-8 design.
- APS gun will be used to test cathode materials at low currents.
- Gun length ~0.8m and will be submerged in oil. Ceramic radius ~135mm
Future work

- Number of stages: 150
- Peak voltage: 300 kV
- Gun beam current: 200 mA
- Gun capacitance charging current: 200 Amps
- Pulse rise time: < 500 ns
- Flat top: 2 μs
- Voltage droop: 0.3%
- Fall time: 2 μs
- Repetition rate: 1 Hz
- Gun discharging method: Solid-state crowbar

N. Sereno, WG5 – Thursday morning

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