Novel, Hybrid RF Injector as a High-average-current Electron Source

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Outline

- Normal- Conducting RF Gun Problems
- Superconducting RF Gun Problems
- Hybrid RF Photoinjector
  - Normal-conducting 1½-cell + SRF cells
  - How might it solve the above problems?
- Preliminary Cavity Design
- Preliminary PARMELA Simulation Results
- Summary
Normal-Conducting RF Gun Problems

- Ohmic loss scales with \((\text{gradient})^2\). Using a high gradient multi-cell cavity leads to large ohmic losses and requires careful thermal management.

- Thermal distortion in a multi-cell cavity leads to cavity detuning and loss of RF field flatness.

- High Q.E. photocathodes are poisoned by contaminations desorbed from the heated cavity walls.
Superconducting RF Gun Problems

- Magnetic field for emittance compensation near the cathode is incompatible with SRF cavities.

- Operating a semiconductor cathode at low temperature in an SRF cavity leads to low Q.E.

- Debris released from semiconductor cathodes could quench the SRF cavities.
Hybrid, NC-SRF Gun Concept

- Independently Power Niobium Full-cells (3x)
- Thermal Standoff
- Magnetic Shield
- Copper 1.5-cell Cavity
- Non-resonant Vacuum cell
- Solenoid Magnet
How the hybrid gun may solve the NC or SRF gun problems

- Solutions to NC gun problems
  - Cryo-pumping reduces cathode contamination
  - Ohmic loss is reduced with only 1.5-cell NC injector

- Solutions to SRF gun problems
  - NC gun can admit solenoid field for emittance compensation at high bunch charge
  - NC cathode is isolated from SRF cavities
    - Allows semiconductor cathode to operate at RT
    - Protect SRF cavities
Basic Injector Design Physics

- **Gradients**
  - Image charge field
    \[ E_z(0, \phi_{inj}) \geq 2E_{IC} \]
  - Invariant Envelope
    \[ \sigma_i = \left(\frac{2}{\gamma'}\right)\sqrt{\frac{I}{3I_0\gamma'}} \]
  - Space-charge emittance growth in drift
    \[ \varepsilon_{SC} = \left(\frac{I}{I_0}\right)\frac{G(\gamma/\beta)}{(\beta\gamma')^2}D \]

- **Keep the thermal standoff relatively short to reduce emittance growth in drift**

\[ E_z(z, t) = E_0 \cos(kz) \sin(\omega t) \]

- \( q \) = Bunch charge
- \( A \) = Emission area
- \( E_z \) = Cathode cell gradient
- \( E_{IC} \) = Image charge field
- \( \sigma_i \) = input rms radius
- \( \gamma \) = beam’s gamma
- \( \gamma' \) = gradient (d\gamma/dz)
- \( I \) = peak current
- \( I_0 \) = Alvén current
- \( G(L/a) \) = geometric factor
  - 0.05 (parabolic)
- \( D \) = drift distance
Example Parameter Set

- Frequency: \( f \) = 700 MHz
- Bunch charge: \( q \) = 1 nC
- Beam energy: \( E_k \) = 5 MeV
- Emission area: \( A \) = 1.13 cm\(^2\)
- Image charge field: \( E_{IC} \) = 1 MV/m
- Injection phase: \( \phi_{inj} \) = 15°
- Cathode cell gradient: \( E_C \) = 5 MV/m
- Drift distance: \( D \) = 0.7 m
- SRF cell gradient: \( E_{SRF} \) = 10 MV/m
- Invariant rms radius: \( \sigma_i \) = 2.6 mm
Minimizing Emittance

- Thermal emittance $\varepsilon_{n,T}$ scales with radius
- Space charge emittance $\varepsilon_{n,SC}$ scales with radius$^{-1}$
- RF-induced emittance $\varepsilon_{n,RF}$ scales with radius$^2$
- Total emittance $\varepsilon_n$

**Thermal emittance**

$$\varepsilon_{n,T} = \sigma_r \sqrt{\frac{kT}{mc^2}}$$

**Space-charge emittance**

$$\varepsilon_{n,SC} = \frac{I}{\gamma I_A \left( \frac{3\sigma_r}{\sigma_z} + 5 \right)}$$

**RF induced emittance**

$$\varepsilon_{n,RF} = \gamma k_{RF}^2 \sigma_r^2 \sigma_z^2$$

**Total emittance**

$$\varepsilon_n = \sqrt{\varepsilon_{n,SC}^2 + \varepsilon_{n,RF}^2 + \varepsilon_{n,T}^2}$$
Preliminary Design of 1.5-cell Normal-conducting Injector

- Cathode cell
- Full cell with RF feeds
- Cathode stem
- Non-resonant pumping cell

Resonant frequency = 700.176 MHz at 20 deg. C. Hole radius = 6.5 cm. F = 700.60159 MHz
RF Loss in RT Cu 1.5-cell Gun

Ohmic loss (kW)

Gradient (MV/m)

Total RF consumption = Ohmic loss + Beam power
At 5 MV/m and 100 mA  139 kW  100 kW
At 5 MV/m and 1 A 139 kW  1 MW
The calculated power density at 7 MV/m is $\sim 100\ W/cm^2$. 

![Graph showing fields and power on segments 1 through 44 for 7MV/m in cathode cell]
On-axis Magnetic Fields for Emittance Compensation

A magnetic shield is used to reduce stray magnetic field in SRF region
All solenoids have to be off when SRF cavities are being cooled down
A similar 2.5-cell NC injector is in fabrication at AES with 9/05 delivery.
Preliminary Design of SRF Cavity

High-Power Coax Coupler

Asymmetric SRF Cavity

Gradient = 10 MV/m
Hybrid injector at 5 MV/m NC and 10 MV/m SRF yields >5 MeV
PARMELA Simulations

Phase-space Plots at $z = 43.5$ cm
PARMELA Simulations
Phase-space Plots at $z = 423$ cm
PARMELA simulation for 1 nC shows rms emittance <3 microns
Summary

- A novel hybrid injector with 1½-cell normal-conducting gun and 3 independently powered superconducting RF cells is presented.
- The hybrid injector admits an external magnetic field near the cathode for emittance compensation.
- PARMELA simulations show the feasibility of achieving 5 MeV energy from 1½-cell NC at 5 MV/m and 3 SRF cells at 10 MV/m.
- Preliminary simulations show emittance from the hybrid injector is less than 3 microns for 1 nC.