Review on superconducting RF Guns

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Superconducting RF Photogun

Main advantages

• Low RF power losses, CW operation

• High peak field near the cathode

Main concerns

• Photocathode inside a superconducting cavity (RF leakage, heat transfer, pollution of the cavity)

• Emittance compensation Magnetic DC field, Magnetic RF field, RF - focusing
All-Niobium SRF Gun

No contamination from cathode particles

1/2 cell, 1.3 GHz
Maximum Field: 45 MV/m

Q.E. of Niobium @ 248 nm with laser cleaning
before: $2 \times 10^{-7}$
after: $5 \times 10^{-5}$

H. Bluem et al. EPAC 2000, June 2000, p. 1639
All-Niobium SRF Gun

$T \sim 2K$

$\lambda = 248 \text{ nm, QE } \sim 2 \times 10^{-5}$

$\lambda = 266 \text{ nm, QE } \sim 2 \times 10^{-6}$

SRF Gun with superconducting Cathode

Quantum efficiency of Pb at room temperature

\begin{align*}
\lambda = 248 \text{ nm} & \quad \text{QE} = 1 \times 10^{-4} \\
\lambda = 213 \text{ nm} & \quad \text{QE} = 1.7 \times 10^{-3}
\end{align*}

3 W laser power @213 nm

1 nC @1 MHz \quad \rightarrow \quad 1 \text{ mA}

J. Smedley et al., PAC2005
Knoxville May 2005
### SRF Gun with normal-conducting Cathode

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Niobium, gun cell + TESLA cells, $E_{acc} = 25$ MV/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Cathode</td>
<td>Cs$_2$Te, QE $\sim$ 5x10$^{-2}$</td>
</tr>
<tr>
<td></td>
<td>thermally isolated, LN$_2$ cooled</td>
</tr>
<tr>
<td>RF</td>
<td>choke filter</td>
</tr>
<tr>
<td>Laser</td>
<td>$\lambda = 262$ nm, cw, $f = 13$ MHz, $P = 1$-2 W</td>
</tr>
</tbody>
</table>
First operation of a SRF Gun


\[ T = 4.2 \text{K}, \quad Q = 2.5 \times 10^8, \quad E_{z\text{max}} = 22 \text{MV/m} \]

\[ E = 900 \text{keV}, \quad I = 520 \mu\text{A} \]

(1) Niobium Cavity
(2) Choke Flange Filter
(3) Cooling Insert
(4) Liquid Nitrogen Tube
(5) Ceramic Insulation
(6) Thermal Insulation
(7) 3 Stage Coaxial Filter
(8) Cathode Stem

Beamline Preparation Chamber
Design Parameter of the 3½ cell SRF Gun

1. 3 GHz, 10 kW
   optimized half cell & 3 TESLA cells
   \( E_{z,\text{max}} = 50 \text{ MV/m (T cells)} \)
   \( = 33 \text{ MV/m (1/2 cell)} \)

| \( I_{av} = 1 \text{ mA} \) |
| \( E = 9.5 \text{ MeV} \) |
| \( \varepsilon_{\text{trans}} = 0.5 \text{ mm mrad} \) |
| \( \varepsilon_{\text{trans}} = 2.5 \text{ mm mrad} \) |

RF focusing in SC gun cavities

Shape verification and warm tuning of the cavity
Cryomodule design of the SRF gun
Liquid $N_2$ Cathode Cooling

- Cathode cooler
- LN$_2$ reservoir
- Heater
- Cathode

$Q_{cath} = 20$ W
$\Delta T = 30$ K
Dual tuning system

<table>
<thead>
<tr>
<th></th>
<th>Gun cell</th>
<th>TESLA cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>range</td>
<td>±0.25mm</td>
<td>±0.3mm</td>
</tr>
<tr>
<td>resolution</td>
<td>2nm</td>
<td>2nm</td>
</tr>
<tr>
<td>load</td>
<td>±2250N</td>
<td>±2700N</td>
</tr>
<tr>
<td>frequency</td>
<td>±30kHz</td>
<td>±300kHz</td>
</tr>
</tbody>
</table>

- Gun-cell tuner
- TESLA-cell tuner
- Choke-cell setting
Cavity with cathode tuning system

- Cathode input
- End of the cryostat
- LN₂ reservoir
- Pic up flange
- Titanium bridge
- Cavity tube
### Present Status and next steps

<table>
<thead>
<tr>
<th>Component</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cavity:</strong></td>
<td>Fabrication of 2 (RRR 40 &amp; 300) cavities at ACCEL finished</td>
</tr>
<tr>
<td></td>
<td>warm tuning in Rossendorf is running</td>
</tr>
<tr>
<td></td>
<td>next step: BCP, HPR, tests at 2K at DESY</td>
</tr>
<tr>
<td><strong>Cavity tuners:</strong></td>
<td>Fabrication finished</td>
</tr>
<tr>
<td></td>
<td>test bench: design finished, in the workshop</td>
</tr>
<tr>
<td><strong>Cathode cooling system:</strong></td>
<td>Fabrication and tests finished</td>
</tr>
<tr>
<td></td>
<td>Cathode transfer system: Design finished, in the workshop</td>
</tr>
<tr>
<td><strong>Cathode preparation chamber:</strong></td>
<td>Design and fabrication finished, assembling and tests running</td>
</tr>
<tr>
<td><strong>Cryomodule:</strong></td>
<td>Design and fabrication finished</td>
</tr>
<tr>
<td></td>
<td>next step: assembling</td>
</tr>
<tr>
<td><strong>He-Transfer Line:</strong></td>
<td>ordered</td>
</tr>
<tr>
<td><strong>First beam:</strong></td>
<td>2006</td>
</tr>
</tbody>
</table>
Core Elements of DC-SC Photoinjector

(Pierce Gun, SC Cavity)

$T = 4.4K$

$I_{ave} = 200 \mu A$, $E = 0.5 \text{MeV}$, $Q = 50 \text{pC}$, $L_{laserpuls} = 6 \text{ps}$, $\varepsilon_{rms} = 5.4 \text{mm.mrad}$,

$I_{ave} = 70 \mu A$, $E = 0.59 \text{MeV}$, $Q = 18 \text{pC}$, $L_{laserpuls} = 6 \text{ps}$, $\varepsilon_{rms} = 2.8 \text{mm.mrad}$,

$U_{DC} = 40 \text{kV}$, $E_{cath} = 2.7 \text{MV/m}$

Courtesy of Hao Jiankui
High Current SRF Gun

SRF Gun Performance Goals

- 703.75 MHz
- 1.42 nC @ 703.75 MHz => 1 A
- For 1 A => ~ 2 MeV delivered
- 2 MW into ½ cell
- 2 opposed 1 MW couplers
- ½ cell => ~ 0.1 m
- 2 MeV / 0.1 m => ~ 20 MV/m

\( \varepsilon_{\text{trans}} = 5 \text{ mm mrad} \)
High Current SRF Gun

Tuner Assembly

Helium Vessel

Beam Pipe Transition (for HOM propagation)

Cathode Assembly

Quarter Wave Choke

Niobium Cavity Assembly

Power Coupler Port

Courtesy of Alan Todd
High Current SRF Gun

QW Choke Configuration

Courtesy of Alan Todd
Emittance compensation by a static B field

- Connection to tuner
- µ-metal shield
- Coupler port
- He tank
- 20 mGauss
- niobium
- 166 mG
- 320 mG
- 500 mm
- 130 mm
- ≤4K
- 2K
- solenoid
- stainless steel

Courtesy of Massimo Ferrario
Emittance compensation by a static B field

HOMDYN Simulation

Q = 1 nC
R = 1.69 mm
L = 19.8 ps
\( \varepsilon_{th} = 0.45 \text{ mm-mrad} \)

\( E_{acc} = 32 \text{ MV/m} \) (Gun)
\( E_{acc} = 13 \text{ MV/m} \) (Acc)
\( B_{peak} = 143 \text{ mT} \) (cavity)

\( \varepsilon_n = 0.6 \text{ mm-mrad} \)

I = 50 A
E = 120 MeV

6 MeV
3.3 m

Z [m]

Courtesy of Massimo Ferrario

Radiation Source ELBE
Dietmar Janssen
13.07.2005
20
Emittance compensation by a magnetic RF field

Electric RF focusing region

Magnetic RF focusing region

1 – Heat sink
2 – Choke cell
3 – Photocathode Cu stalk
4 – Cathode cell
5 – Electric TM field pattern
6 – Magnetic TE field pattern
7 – Cavity full cell
8 – TE mode coupler (90° routed)
9 – TM mode coupler pipe
Magnetic RF fields in the 1 ½ cell cavity

<table>
<thead>
<tr>
<th>$F$, MHz</th>
<th>RPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2572.5</td>
<td>0.539</td>
</tr>
<tr>
<td>3787.8</td>
<td>0.358</td>
</tr>
<tr>
<td>3899.7</td>
<td>0.819</td>
</tr>
<tr>
<td>3947.2</td>
<td>0.863</td>
</tr>
</tbody>
</table>

Pipe cut off TE frequency 5226 MHz
Emittance dependence on TE field phase

\[ \varepsilon_n = \varepsilon_{av} + A_\varepsilon \cdot \sin\left(2 \cdot \varphi_{TE} + \varphi_o\right) \]

- \( \varepsilon_n \) – transverse normalized rms emittance
- \( \varepsilon_{av} \) – average emittance
- \( A_\varepsilon \) – emittance amplitude
- \( \varphi_{TE} \) – TE mode phase
- \( \varphi_o \) – constant phase
- \( B_{TE} \) – TE mode peak induction at the axis, T
- \( R \) – laser spot radius at the photocathode, mm
- \( \varphi_{TM} \) – launch phase (here \( \varphi_{TM} = 50^\circ \) at maximum bunch energy)

Set examples

<table>
<thead>
<tr>
<th>Set examples</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_{av}, \mu m )</td>
<td>0.805</td>
<td>0.712</td>
</tr>
<tr>
<td>( A_\varepsilon, \mu m )</td>
<td>0.212</td>
<td>0.08</td>
</tr>
<tr>
<td>( B_{TE}, T )</td>
<td>0.28</td>
<td>0.3</td>
</tr>
<tr>
<td>( R, mm )</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>
## Results for a 1 ½ cell cavity

<table>
<thead>
<tr>
<th>Optimized settings &amp; performances</th>
<th>Without any RF focusing</th>
<th>Electric RF focusing only</th>
<th>Magnetic RF focusing only</th>
<th>Electric and magnetic RF focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_n$, $\pi$ mm mrad</td>
<td>3.66</td>
<td>1.49</td>
<td>1.28</td>
<td>0.62</td>
</tr>
<tr>
<td>$(e_n^2 + e_{th}^2)^{1/2}$</td>
<td>3.76</td>
<td>1.72</td>
<td>1.44</td>
<td>0.89</td>
</tr>
<tr>
<td>R (laser), mm</td>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>$\phi_{TM}$, deg</td>
<td>49.4°</td>
<td>46.3°</td>
<td>49.4°</td>
<td>55°</td>
</tr>
<tr>
<td>Cathode depth, mm</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>B$^{TE}$ (axis, peak), T</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>B (surf., peak), T</td>
<td>0.128</td>
<td>0.128</td>
<td>0.132</td>
<td>0.132</td>
</tr>
</tbody>
</table>
Results for the 3 ½ cell cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch transv. norm. emitt., μm</td>
<td>0.78-0.98</td>
</tr>
<tr>
<td>Emitt. minimum disposition, m</td>
<td>4.25</td>
</tr>
<tr>
<td>Average Energy, MeV</td>
<td>8.82</td>
</tr>
<tr>
<td>Launch phase of TM 1300 MHz</td>
<td>74.6°</td>
</tr>
<tr>
<td>Laser spot radius, mm</td>
<td>1.5</td>
</tr>
<tr>
<td>$B_{TE}$ (peak, axis), T</td>
<td>0.324</td>
</tr>
<tr>
<td>$B_{TM}$ (peak, surface), T</td>
<td>0.136</td>
</tr>
<tr>
<td>RPI</td>
<td>0.42</td>
</tr>
<tr>
<td>$B_{TM}$ (surface), mT</td>
<td>0.115</td>
</tr>
<tr>
<td>$</td>
<td>B_{TM} + B_{TE}</td>
</tr>
</tbody>
</table>
Diamond amplifier

Secondary Emission Enhanced Photoinjector

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Brookhaven National Laboratory
Upton NY 11973 USA
Conclusion

• Superconducting RF guns are the ideal injectors for high current- low emittance application.

• For average currents I > 1mA on has to put a normal conducting cathode into a superconducting cavity. The proposed design works for T = 4.2K and Q = 2.5*10^8. For T = 2K and Q ~ 10^{10} one has to check it.

• For SRF guns with I < 1mA a superconducting cathode is an interesting alternative, which one has to prove.

• New ideas and developments as the diamond amplifier and the magnetic RF modes can enlarge the performance of superconducting RF guns.

• I dare the prediction, that within the next three years the first SRF photoelectron gun will work as injector for a linac in routine run.