SRF-Seminars

Jacek Sekutowicz
5. SUPERCONDUCTING PHOTO-INJECTORS
SRF Photo-Injectors; Topics

1. Introduction
2. Projects; Specs and measured data
3. Cathodes
4. RF-performance of sc-cavities
5. RF-focusing
6. $\varepsilon$ growth compensation with DC- and RF-magnetic field
7. Nb-Pb gun
8. Conclusions
Acknowledgements

**BNL:**  A. Burrill, I. Ben-Zvi, R. Calaga, T. Rao, J. Smedley

**AES:**  T. Favale, A. Todd, J. Rathke

**FZR:**  D. Janssen, J. Teichert

**DESY:**  D. Kostin, B. Krause, A. Matheisen, W.-D. Möller, R. Lange

**IHIP:**  J. Hao, K. Zhao

**INFN:**  M. Ferrario

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Motivation to develop SRF electron guns:

- Operation in CW mode with high acc. gradient on photo-cathode.
- Low power dissipation and excellent thermal stability.

What is technically challenging:

- Integration of non-superconducting cathodes into the sc environment.
- Lower QE of superconducting cathodes than alkali cathodes.
- Emittance growth compensation with magnetic field is more difficult and needs novel approaches.
1. Introduction

**SRF Injectors**

- **FZR (since 1998)**
  - $f = 1.3 \text{ GHz}$
  - $\text{Cs}_2\text{Te} \Leftarrow E_{RF}$
  - Courtesy of Dietmar Janssen

- **IHIP PU (since 2001)**
  - $f = 1.3 \text{ GHz}$
  - $\text{Cs}_2\text{Te} \Leftarrow E_{DC}$
  - Courtesy of Hao Jiankui

- **BNL (since 2002)**
  - $f = 1.3 \text{ GHz}$
  - $\text{Nb} \Leftarrow E_{RF}$
  - Courtesy of Triveni Rao

- **BNL/AES (since 2004)**
  - $f = 703.75 \text{ MHz}$
  - Alkali$^+$ $\Leftarrow E_{RF}$
  - Courtesy of Alan Todd
## 2. Four projects: Spec/Measured

<table>
<thead>
<tr>
<th></th>
<th>(E) [MeV]</th>
<th>(\Delta E) [keV]</th>
<th>(q/\text{Bunch}) [nC]</th>
<th>(\text{Bunches/s} [10^6])</th>
<th>(I_b) [mA]</th>
<th>(\varepsilon @ q) [(\mu\text{rad})] @ [nC]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BESSY</strong></td>
<td>S: 5</td>
<td>S: ?</td>
<td>S: 2.5</td>
<td>S: 0.025</td>
<td>S: 0.063</td>
<td>S: 1.5 @ 2.5</td>
</tr>
<tr>
<td></td>
<td>FZR</td>
<td>S: 9.5</td>
<td>S: 5</td>
<td>S: 13</td>
<td>S: 1.0</td>
<td>S: 1.0 @ 0.077</td>
</tr>
<tr>
<td></td>
<td>FZR</td>
<td>S: 9.5</td>
<td>S: 1.0</td>
<td>S: 1</td>
<td>M: 26</td>
<td>S: 1.5 @ 1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 0.85</td>
<td>M: 0.020</td>
<td></td>
<td>M: 0.52</td>
<td>M: 1.0 @ 0.020</td>
</tr>
<tr>
<td></td>
<td>S: 2.61</td>
<td>S: 30</td>
<td>S: 0.060</td>
<td>S: 17</td>
<td>S: 1.0</td>
<td>S: 3.0 @ 0.060</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 0.58</td>
<td>M: 0.001</td>
<td>M: 81</td>
<td>M: 0.08</td>
<td>M: 2.7 @ 0.001</td>
</tr>
</tbody>
</table>

Cavities have been built mainly for measurements of QE of cold Nb

|                | S: 2.0       | S: 62               | S: 1.33                    | S: 352                      | S: 500       | S: 5.0 @ 1.33                             |

SRF Injectors
### 3. Cathodes: Spec / Measured

<table>
<thead>
<tr>
<th>Emitter/T</th>
<th>$&lt;\text{QE}&gt;@\lambda_{Ph}$ at operation</th>
<th>$E_{\text{pulse}}/P_{\text{laser}}$ [µJ]/[W]</th>
<th>Cathode Life Time</th>
<th>Spot size [mm]</th>
<th>$E_{\text{cath}}$ [MV/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Cs}_2\text{Te} / 78,\text{K}$</td>
<td>$S_{\text{BESSY}}: 0.01/262 $&lt;br&gt;$S_{\text{FZR}} : 0.01/262$</td>
<td>$S: 1.19/0.03$&lt;br&gt;$M: 0.003/260$</td>
<td>$&gt;50\text{ days}$</td>
<td>$S: \varnothing,3.0$&lt;br&gt;$M: \varnothing,2.0$</td>
<td>$S: 25$</td>
</tr>
<tr>
<td>$\text{Cs}_2\text{Te} / 273,\text{K}$</td>
<td>$S: 0.01/266$&lt;br&gt;$M: 0.01/266$</td>
<td>$S: 0.015/1.2$&lt;br&gt;$M: 0.010/0.8$</td>
<td>$\sim100\text{ days}$</td>
<td>$S: \varnothing,5.6$&lt;br&gt;$M: \varnothing,6.0$</td>
<td>$M: 2.7$</td>
</tr>
<tr>
<td>$\text{Nb} / 2-4,\text{K}$</td>
<td>$10^{-5} / 266$</td>
<td>$0.002 / 0.15$</td>
<td>$\infty$ (?)&lt;br&gt;$4\times1.5$</td>
<td>$48$</td>
<td></td>
</tr>
<tr>
<td>$\text{S}: \text{Alkali} / ?$&lt;br&gt;$\text{S}: \text{Alkali+D}/?$</td>
<td>$S: 0.05 / 527$&lt;br&gt;$S: 5 / 527$</td>
<td>$0.071 / 25$&lt;br&gt;$0.0006 / 0.2$</td>
<td>$?$&lt;br&gt;$S: \varnothing,2.0$</td>
<td>$S: 40$</td>
<td></td>
</tr>
</tbody>
</table>
4. Cavities: Measured RF-performance

**FZR**

- 4 K-test
  - $2.5 \times 10^8$ @ $E_{peak} = 22$ MV/m
- 2 K-test
  - $5 \times 10^9$ @ $E_{peak} = 46$ MV/m

**IHIP-Peking**

- 4.2 K-test
  - $10^8$ @ $E_{acc} = 5$ MV/m

Test at JLab 2003

Test at JLab 2005
4. Cavities: Next Steps

**FZR**

Test cavity (RRR=40) received BCP in Sept. 2005

High RRR=300 cavity will be treated and tested at DESY soon

**BNL/AES 1.3 GHz**

QWC will be added for cathode with diamond: - 2005

**BNL/AES 703.85 MHz**

RF Design will be finished in 2005?

**IHIP-Peking University**

DC+1.5-cell → 3.5-cell

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{acc}$ [MV/m]</td>
<td>15</td>
</tr>
<tr>
<td>$V-DC$ [kV]</td>
<td>100</td>
</tr>
<tr>
<td>$I_{beam}$ [mA]</td>
<td>1</td>
</tr>
<tr>
<td>Energy [MeV]</td>
<td>4.9</td>
</tr>
<tr>
<td>Energy spread [%]</td>
<td>2.27</td>
</tr>
<tr>
<td>Emittance (rms) [$\mu$rad]</td>
<td>3.4</td>
</tr>
</tbody>
</table>

$\epsilon=1.99\ [\mu$rad$]$  
$\Delta E/E= 3.8\%$
5. E-field Focusing; Recessed cathode

Cathode shifted by 3 mm only

Ez, Er [MV/m]

Ez(r,+1mm) and Er(r,+1mm)
Since position of the cathode is a very sensitive “knob”

Cathode longitudinal position tuner as proposed by RFZ
5. E-field Focusing; Inclined back wall

**FZR:** 1.3 GHz 1.5-cells and 3.5-cells have recessed cathode and inclined back wall

**BNL/AES:** 1.3 GHz and 703.85 MHz will have recessed cathode and inclined back wall

<table>
<thead>
<tr>
<th></th>
<th>Without RF focusing</th>
<th>With RF focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_n$ [µrad]</td>
<td>3.66</td>
<td>1.49</td>
</tr>
<tr>
<td>Recess [mm]</td>
<td>0</td>
<td>2-3.5</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th></th>
<th>With RF focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_n$ [µrad]</td>
<td>1.99</td>
</tr>
<tr>
<td>Recess [mm]</td>
<td>3</td>
</tr>
</tbody>
</table>

R. Calaga, Proceed. SRF2005,Cornell
Exposing a sc cavity to H-field may cause degradation in the performance.

1. One can put solenoid and the sc-cavity at different locations → split injector

(M. Ferrario, J.B. Rosenzweig):

- \( q = 1nC \)
- \( r_{\text{spot}} = 1.5\text{mm} \)
- \( t_{\text{pulse}} = 20\text{ps} \)
- \( \varepsilon_{\text{th}} = 0.45\mu\text{rad} \)

- \( I = 50\text{ A} \)
- \( E = 120\text{ MeV} \)
- \( \varepsilon_{n} = 0.6\mu\text{rad} \)

- \( E_{\text{cath}} = 60\text{ MV/m} \)
- \( E_{\text{cry}} = 13.5\text{ MV/m} \)
Example:

- 1 mm thick µ-metal shield
- Solenoid (0.3 T)
- Stainless steel
- Cathode
- Nb
- 2K ≤ 4K
- (20 μT)
- 410 mm (optimum 360 mm)
2. One can use solenoidal modes of (TE0xx) for the $\epsilon$ compensation (D. Janssen)

- 1.3 GHz TM010; E field
- 3.8 GHz TE011; B field

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_n$ for 1 nC</td>
<td>[\mu rad] 0.78-0.98</td>
</tr>
<tr>
<td>$\epsilon_n$ minimum at z</td>
<td>[m] 4.25</td>
</tr>
<tr>
<td>$B_{TE}$ on axis</td>
<td>[T] 0.324</td>
</tr>
<tr>
<td>Surf. $B_{max} = [B_{TM}^2 + B_{TE}^2]^{0.5}$</td>
<td>[T] 0.144</td>
</tr>
</tbody>
</table>

The low emittance results from: RF-focusing and $B_{RF}$ compensation and weakly depends on the phase of the solenoidal mode.

D. Janssen et al, Proc. of FEL2004
**Motivation** is to build cw operating RF-source of ~0.5-1 mA class for an XFEL facility.

An all **superconducting** RF-gun follows the all **niobium** RF-gun of BNL

\[ QE = 10^{-5} \ \text{at} \ \lambda = 266 \text{ nm} \]

In 2003 we proposed to investigate quantum efficiency of Pb


Lead is commonly used superconductor for accelerating cavities:

\[ T_c = 7.2 \text{ K}, \ B_c = 70 \text{ mT} \]
QE measured at 300K using setup at BNL  (J. Smedley, T. Rao)

Light sources:
- ArF- laser: 193 nm, KrF-laser: 248 nm, 4-th harmonic Nd: YAG laser: 266 nm
- Deuterium light source with monochromator (2 nm bandwidth): 190-315 nm
Surface Uniformity (Courtesy J. Smedley)

Arc Deposited

Vacuum Deposited

Sputtered

Solid

All cathodes laser cleaned with 0.2 mJ/mm² of 248nm light
Preparation

- Nb used as substrate
- Four deposition methods:
  - Electroplating
  - Vacuum deposition (evaporation)
  - Sputtering
  - Vacuum Arc deposition
- Solid lead, mechanically polished
- In situ laser cleaning
  - KrF Excimer (248 nm), 12 ns pulse, ~0.2 mJ/mm²
### 7. Nb-Pb RF-gun: Quantum Efficiency of Lead

**SRF Injectors**

#### Lead Surface Finish and Damage Threshold (Courtesy J. Smedley)

*(Electroplated Lead)*

<table>
<thead>
<tr>
<th>Prior to Laser Cleaning</th>
<th>0.11 mJ/mm²</th>
<th>0.26 mJ/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.52 mJ/mm²</td>
<td>1.1 mJ/mm²</td>
</tr>
</tbody>
</table>
7. Nb-Pb RF-gun: Quantum Efficiency of Lead at 300 K

The best QE was demonstrated by arc-deposited samples prepared at INS-Swierk.

Magnetic field distribution in the Aksenov-type magnetic filter and in the T-type magnetic filter;
1 – cathode, 2 – anode, 3 – focusing coil, 4 – filter inlet, 5 – filter exit, 6 – high-current cable,
7 – ion collector position, 8 – plasma stream, 9 - correcting coil.

Calculated magnetic field strengths: - near-cathode region – 16 mT
- magnetic duct region – 12 – 14 mT
Effect of Temperature and Vacuum on QE (Courtesy J: Smedley)

Arc Deposited Cathode QE @ 200 nm

- Vacuum (warm) = 8 nTorr
- Vacuum (-170°C) = 6 nTorr
- Vacuum (warm) = 1.3 μTorr
- Vacuum (-170°C) = 0.2 μTorr
### Parameter Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi )-mode frequency</td>
<td>[MHz]</td>
<td>1300</td>
</tr>
<tr>
<td>0-mode frequency</td>
<td>[MHz]</td>
<td>1286.5</td>
</tr>
<tr>
<td>Cell-to-cell coupling</td>
<td>-</td>
<td>0.015</td>
</tr>
<tr>
<td>Active length ( 1.6 \cdot \lambda/2 )</td>
<td>[m]</td>
<td>0.185</td>
</tr>
<tr>
<td>Nominal ( E_{\text{cath}} ) at cathode</td>
<td>[MV/m]</td>
<td>60</td>
</tr>
<tr>
<td>Energy stored at nominal ( E_{\text{cath}} )</td>
<td>[J]</td>
<td>20</td>
</tr>
<tr>
<td>Nominal beam energy</td>
<td>[MeV]</td>
<td>6</td>
</tr>
</tbody>
</table>

### Graph

- **B-field on the cathode at 60 MV/m**
- **High RRR Nb cavity**
- **"small" emitting Pb spot**

- **6 mT \( << B_c \)**
HOM damping scheme:
- FPC is not sufficient
- 1 or 2 HOM couplers must be attached

<table>
<thead>
<tr>
<th>Mode</th>
<th>f [MHz]</th>
<th>(R/Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopole: Beam Tube</td>
<td>793.9</td>
<td>57.9 [Ω]</td>
</tr>
<tr>
<td>Dipole: TE111-1a</td>
<td>1641.8</td>
<td>1.85 [Ω/cm²]</td>
</tr>
<tr>
<td>Dipole: TE111-1b</td>
<td>1644.9</td>
<td>1.30 [Ω/cm²]</td>
</tr>
<tr>
<td>Dipole: Beam Tube-a</td>
<td>1686.3</td>
<td>3.33 [Ω/cm²]</td>
</tr>
<tr>
<td>Dipole: Beam Tube-b</td>
<td>1754.7</td>
<td>5.13 [Ω/cm²]</td>
</tr>
<tr>
<td>Dipole: TM110-1a</td>
<td>1883.5</td>
<td>10.1 [Ω/cm²]</td>
</tr>
<tr>
<td>Dipole: TM110-1b</td>
<td>1884.0</td>
<td>9.99 [Ω/cm²]</td>
</tr>
<tr>
<td>Dipole: TM110-2a</td>
<td>1957.0</td>
<td>3.90 [Ω/cm²]</td>
</tr>
<tr>
<td>Dipole: TM110-2b</td>
<td>1957.1</td>
<td>3.85 [Ω/cm²]</td>
</tr>
<tr>
<td>Monopole: TM011</td>
<td>2176.5</td>
<td>43.2 [Ω]</td>
</tr>
</tbody>
</table>
Modeling of the FPC and HOM coupler region (D. Kostin)
7. Nb-Pb RF-gun: RF-performance of test cavities

DESY; 1.3 GHz good for test of the final coating

JLab (P. Kneisel) ; 1.42 GHz good for test of various coatings

Nb plug without and with Pb coating:
D=10mm, h=10µm

7. Nb-Pb RF-gun: RF-performance of test cavities

SRF Injectors

JLab, CASA Seminar, March 2nd, 2006.
J. Sekutowicz, DESY
1. Relaxation time of Cooper pairs after the illumination

How does intrinsic $Q$ changes when laser illuminates the Pb cathode?

An example:

$$\text{QE} = 0.17\% @ 213\text{nm} \Rightarrow q = 1\ \text{nC} \quad \text{requires} \quad 3.4\ \mu\text{J/pulse.}$$

$\text{Ph} \text{o} \text{n} \text{i} \text{r} \text{e} \text{n} \text{t} \text{i} \text{r} \text{o} \text{n} \text{a} \text{t} \text{i} \text{o} \text{n} \text{d} \text{s} \text{h} \text{e} \text{p} \text{t} \text{i} \text{d} \text{e} \text{s} \text{i} \text{n} \text{t} \text{i} \text{o} \text{n}$$

$$\text{All CPs in the 10 nm layer are}$$

$$\text{broken.}$$

$$\text{The layer is in the normal-}$$

$$\text{conducting state after the laser}$$

$$\text{pulse.}$$

$$F = 60\ \text{MeV/m}$$

$$T_{\text{rf}}/4 = 200\ \text{ps later the diffusion and recombination processes of}$$

$$\text{quasiparticles in the Pb layer start.}$$
The relaxation time to the thermal equilibrium

![Graph showing the relaxation time to thermal equilibrium for Nb and Pb]

This has to be verified experimentally.
2. Thermal emittance?

\( \text{Pb work function is } \sim 4.25 \text{ eV} \)

\( \text{for: } \lambda_{ph} = 213 \text{nm (5.8 eV)} @ \text{ spot radius } r = 1.7 \text{ mm} \)

Estimation of the thermal emittance:

\[
\varepsilon_{TH} = \frac{r}{2\sqrt{3}} \sqrt{\frac{E_k}{mc^2}} = 0.0017 \sqrt{\frac{5.8-4.25+0.26}{mc^2}} = 1.27 \mu\text{rad!}
\]

If experiment with 1.5-cells confirms this estimation we will reduce \( r \) to \( \sim 1 \text{ mm} \) and charge to \( \sim 0.4 \text{ nC} \), to get \( \varepsilon_{TH} = 0.7 \mu\text{rad} \)

\[
B \approx \frac{Q}{\varepsilon^2 \cdot \sigma_t} \approx \frac{r^2}{r^2 \cdot \sigma_t}
\]

HOMDYN (M. Ferrario)
There is visible progress in the SRF-gun projects:

- But still some years of R&D are needed to reach spec in the performance.

Ad 1. Spec vs. Measurements:

- The FZR gun and IHIP gun have demonstrated almost emittance spec but with much lower charge.

Ad 2. Cathodes:

- IHIP $Cs_2Te$ cathode has demonstrated QE=0.01 and 100 days lifetime what is almost the spec.

- $Nb$ cathode showed lower QE at cold than expected but vacuum during the cool down was not as good as it should be.

- Deposition of the $Pb$ cathode on $Nb$ wall is challenging. Thermal emittance of $Pb$ may cause some limitation in the emitted charge/bunch.

- Intrinsic Q and recovery time of broken Cooper pairs ($Nb, Pb$ cathode) need experimental verification.
8. Conclusions

Ad 3. New emittance compensation:

- The compensation by means of the solenoidal mode is interesting and should be demonstrated experimentally.

All these questions show that coming years will be very exciting for the community involved in the SRF-gun R&D programs.