SRF Photoinjector development for BERLinPro
J. Knobloch, Helmholtz-Zentrum Berlin
(Some of) the BERLinPro Project Goals

• Demonstration facility for ERL Technology and Accelerator Physics.
• 50 MeV
• High current: 100 mA @ 77 pC per bunch
• Low normalized emittance: 1 mm mrad
• Short pulses < 2 ps
• Project period: 2011 – 2018

One of the main challenges

• 2.3 MeV SRF Photoinjector
• Development in three stages
Try to separate out the big challenges of an SRF injector

**Injector 0**: Get the “feet wet” with an all SRF system (SC cavity, SC Pb cathode, SC solenoid) → low charge, low-average current (2011-12)

**Injector 1**: Next worry about the NC cathode (CsK$_2$Sb) and its integration in the SRF cavity → nominal charge, mA average current (2014)

**Injector 2**: Finally add high power (input/HOM) capabilities for 100 mA current (2016)
### 3 stages towards a BERLinPro injector

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goal</strong></td>
<td>Beam Demonstration (First beam April 2011)</td>
<td>High brightness R&amp;D gun with NC cathode</td>
<td>High average current &amp; brightness with NC cathode</td>
</tr>
<tr>
<td><strong>Cathode material</strong></td>
<td>Pb (SC)</td>
<td>CsK$_2$Sb (NC)</td>
<td>CsK$_2$Sb (NC)</td>
</tr>
<tr>
<td><strong>Cathode QE$_{\text{max}}$</strong></td>
<td>$10^{-4}$ @258 nm$^*$</td>
<td>$10^{-2}$ @532 nm</td>
<td>$10^{-2}$ @532 nm</td>
</tr>
<tr>
<td><strong>Drive laser wavelength</strong></td>
<td>258 nm</td>
<td>532 nm</td>
<td>532 nm</td>
</tr>
<tr>
<td><strong>Drive laser pulse length and shape</strong></td>
<td>2.5 ps fwhm Gauss</td>
<td>$\leq$ 20 ps fwhm Gauss</td>
<td>$\leq$ 20 ps fwhm Gauss</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>8 kHz</td>
<td>54 MHz/25 Hz</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td><strong>Electric peak field in cavity (on cathode)</strong></td>
<td>20 MV/m$^*$</td>
<td>$\leq$ 20...30 MV/m</td>
<td>$\leq$ 20...30 MV/m</td>
</tr>
<tr>
<td><strong>Operation launch field on cathode</strong></td>
<td>5 MV/m$^*$</td>
<td>$\geq$ 10 MV/m</td>
<td>$\geq$ 10 MV/m</td>
</tr>
<tr>
<td><strong>Electron exit energy</strong></td>
<td>1.8 MeV$^*$</td>
<td>$\geq$ 1.8 MeV</td>
<td>$\geq$ 1.8 MeV</td>
</tr>
<tr>
<td><strong>Bunch charge</strong></td>
<td>6 pC$^*$</td>
<td>77 pC</td>
<td>77 pC</td>
</tr>
<tr>
<td><strong>Electron pulse length</strong></td>
<td>2...4 ps rms$^{\circ}$</td>
<td>$\leq$ 6 ps rms</td>
<td>$\leq$ 6 ps rms</td>
</tr>
<tr>
<td><strong>Average current</strong></td>
<td>50 nA$^*$</td>
<td>4 mA/40 µA</td>
<td>100 mA</td>
</tr>
<tr>
<td><strong>Normalized emittance</strong></td>
<td>2 mm mrad$^*$ (proj.)</td>
<td>1 mm mrad (proj.) and 0.5 mm mrad (sliced)</td>
<td></td>
</tr>
</tbody>
</table>

*T. Kamps et al., Proc. IPAC 2011, PRST-AB (in preparation)
A. Neumann et al., Proc. IPAC 2011, PRST-AB (in preparation)
R. Barday et al., Proc. of PSTP 2011
J. Völker, et al., Proc of IPAC 2012

$^*$Preliminary data / results, $^{\circ}$value represents emission time
Stage 1: All SC Photoinjector System

Photoinjector 0

- Don’t worry about NC cathode: use SC Pb cathode
- Idea first developed by J. Sekutowicz (DESY)
- Produced at JLAB (P. Kneisel) and cathode coated at Nat. Centre for Nucl. Research (R. Nietubyc)
- Add SC NbTi solenoid (Niowave)
- Of interest for low-ave-current CW LINACs (e.g., FEL)
Beam tests in HoBiCaT

- SRF system was integrated in HoBiCaT cryostat
- Simple beamline for diagnostics, UV Drive laser (MBI, I. Will)
- First tests in March 2011
**Q-measurement history**

- Cavity Q suffered due to application of Pb cathode
- Installation in HoBiCaT $\rightarrow$ significant degradation
- 10’s nA of dark current from cathode. Improved by laser cleaning (excimer laser) but Q dropped slightly further
- Solenoid close to cavity but no performance Q degradation due to solenoid observed

![Diagram showing Q-measurement history](image)

After laser cleaning

**Vertical test measurements at JLAB**

- Vertical test w/o cathode
- Vertical test with cathode

**Horizontal test**

- SC solenoid

**P. Kneisel et al, Proc. PAC 11**
**A. Neumann et al., Proc. IPAC 11**

Dark current focussed by SC solenoid (before laser cleaning)
Stage 1: All SC Photoinjector System

First beam

- Pb cathode not evenly coated → may explain observed FE and QE variation.
- Emittance about seven times the therm. emittance.
- Irregularities on the cathode modeled and likely source of degradation.
- Misalignment (solenoid, cavity) caused astigmatism and emittance degradation → cold mover essential

G. Lorenz, FHI Berlin

Now include “lessons learned” in a second version of Injector 0

- Includes tuner system
- Demountable cathode plug & helium tank
- Solenoid mover
- Cavity design & production DESY/JLAB

Injector 2.1 as installed at HoBiCaT
Stage 1.2: All SC Photoinjector System

Photoinjector 0.2

- Commiss. @ HoBiCaT under way
- Much less field emission (< 1 nA at 20 MV/m) after much processing
- $Q$ lower than in VT but still OK. (Problem = no cold mag. shield=?)
- Measurements ongoing
  - Beam dynamics
  - Solenoid mover
  - LLRF
  - Microphonics and impact on beam

Images of FE current

Vertical tests at JLAB with Nb/Pb-Plug at 2K

Horizontal test @ HoBiCaT based on gHe flow @ 1.8 K (14.10.12)
Stage 1.2: All SC Photoinjector System

Transfer-function measurement at different tuner settings

P. Lauinger, A. Neumann, O. Kugeler, HZB
Intermediate step towards high current gun:

- Optimize cavity shape for beam dynamics
- Include a NC cathode (CsK$_2$Sb) via choke filter
- Moderate beam loading (< 10 mA): “BESSY-style” TTF-III couplers
- Solenoid mover

What do we care about?

- $V_{\text{acc}}$ limited by coupler power (< 2.3 MeV)
- Maximum $E$-field limited by FE
  $\rightarrow$ keep $E_{pk}/E_0$ small.
  $\rightarrow$ keep $0.6 < E_{\text{cath}}/E_0 < 1$.
- Avoid space-charge issues at launch
  $\rightarrow$ design cavity for max energy gain at $\phi$ near 90° (high $E_{\text{launch}}$ while $E_{\text{cath}}$ reasonable)
- RF focusing for beam emittance preservation
- Design cavity for heavy HOM damping.
Study two different layouts: 0.x-cell and 1.x-cell

\[
\begin{align*}
R/Q &= 90 \ \Omega \\
H_{pk}/E_{pk} &= 2.3 \text{ mT/(MV/m)} \\
E_{pk}/E_0 &= 1.5 \\
E_{cath}/E_0 &\approx 0.8 \\
\end{align*}
\]

At \( E_0 = 30 \text{ MV/m} \)
\[
\begin{align*}
E_{pk} &= 45 \text{ MV/m} \\
E_{kin} &= 1.2 \text{ MeV} \\
\Phi_{launch} &= 18 \text{ deg} \\
E_{cath} &= 24 \text{ MV/m} \\
E_{launch} &= 7.4 \text{ MV/m} \\
\end{align*}
\]

\[
\begin{align*}
R/Q &= 150 \ \Omega \\
H_{pk}/E_{pk} &= 2.3 \text{ mT/(MV/m)} \\
E_{pk}/E_0 &= 1.5 \\
E_{cath}/E_0 &\approx 0.8 \\
\end{align*}
\]

At \( E_0 = 30 \text{ MV/m} \)
\[
\begin{align*}
E_{pk} &= 45 \text{ MV/m} \\
E_{kin} &= 2.4 \text{ MeV (coupl. limit)} \\
\Phi_{launch} &= 50 \text{ deg} \\
E_{cath} &= 24 \text{ MV/m} \\
E_{launch} &= 18.4 \text{ MV/m} \\
\end{align*}
\]

To achieve same kinetic energy, 0.4 cell would have to operate near \( E_{pk} = 90 \text{ MV/m}, E_{cath} = 48 \text{ MV/m} \)!

**Concentrate on 1.4 cell**
Mechanical optimization

- EM design is complete. Now mechanical modeling ongoing (E. Zaplatin, FZ-Jülich) to reduce pressure sensitivity.
- Typical: $\frac{df}{dP} \approx 100 \text{ Hz/mbar}$ without stiffening (due to back plate)
- Can be reduced to zero with proper placement of stiffening rings and choice of material thickness.
Stage 2: Photoinjector 1 design

- Cryomodule concept based on Cornell booster module system
- Cathode insert/choke filter based on HZDR design
- HOM absorber: based on SiC design (DESY)

First tests
- Mid 2014 @ HoBiCaT/gunlab (low average current)
- Early 2016 @ BERLinPro (> 1 mA)
Final step: 100-mA capable photoinjector

- Lessons learned regarding photocathode
- Lessons learned regarding beam dynamics
- Lessons learned regarding HOMs
- …
- High power couplers (120 kW each) based on KEK design.
  - Must be modified to increase power capability (warm part). Current limit 40 kW.
  - Must be modified to permit horizontal installation in cryomodule.
- First beam with Injector 2: 2016, > 10 mA ops by 2017
Many labs are key to the development of the injector

**Apologies if this list is incomplete!**

- **DESY** (J. Sekutowicz)
  - Design and tests of Injector 0.1 and 0.2, HOM absorber
- **HZDR** (P. Michel, J. Teichert, A. Arnold, P. Mulczek)
  - Production of Injectors 0.1 via CRADA with JLAB
  - Cathode insert mechanism for Injector 1
  - Photocathode studies + more …
- **JLAB** (P. Kneisel)
  - Production/preparation/vertical tests of Injector 0 and Injector 1
- **Cornell University**
  - Booster cryomodule design
- **National Centre for Nuclear Research** (R. Nietubyc)
  - Coating of Pb cathodes
- **Max-Born Institut** (I. Will)
  - Development and commissioning of UV photocathode laser
- **Brookhaven National Lab** (J. Smedley)
  - Commissioning Injector 0.1 and laser cleaning
  - Production of photocathodes
- **KEK** (E. Kako)
  - High-power coupler systems
- **Budker Institut** (V. Volkov)
  - Gun simulations, incl. dark current simulations
- **FZ-Jülich** (E. Zaplatin)
  - Photoinjector RF and mechanical simulations
- **UCLA** (P. Musumeci)
  - Beam diagnostics
- **TU Dortmund** (T. Weis, A. Ferrarotto)
  - Beam instrumentation
- **JGU Mainz, Moscow State U, St. Petersberg State Polytechnik**
  - Photocathode development

**The HZB team**