FIRST CHARACTERIZATION OF A FULLY SUPERCONDUCTING RF PHOTOINJECTOR CAVITY

IPAC 2011 San Sebastián, Spain

A. Neumann

for a collaboration by

Jefferson Laboratory, DESY, A. Soltan Institute,
Brookhaven National Lab., MBI, BINP and HZB
Path towards a Photoinjector for BERLinPro

Goals for ERL SRF injector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$\geq 1.5$ MeV</td>
</tr>
<tr>
<td>Max. current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Nominal bunch charge</td>
<td>77 pc</td>
</tr>
<tr>
<td>Max. rep. rate</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>&lt; 1 mm mrad</td>
</tr>
</tbody>
</table>

Demanding goals!
3 stage approach

- Full SC injector for beam dynamics studies \( \rightarrow \textit{This talk} \)
- Peak brightness injector, study NC cathode insert
- High average current injector

T. Kamps et al., Journal of Physics: Conference Series, 298
A. Jankowiak et al., Proc. Linac 2010

+ THPC109
First step: SC RF Gun0

- **EM design**: Highest fields at cathode region

- **SC lead cathode on half-cell backwall**: $Q_{E_{Pb}} \sim 10 \cdot Q_{E_{Nb}}$

- **Study beam dynamics at short pulses**, ERL parameter range

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**Table: Design Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency $\pi$-mode</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>$E_{\text{peak}}/E_{\text{acc}}$</td>
<td>1.86</td>
</tr>
<tr>
<td>$H_{\text{peak}}/E_{\text{acc}}$</td>
<td>4.4 mT/(MV/m)</td>
</tr>
<tr>
<td>Geometry factor</td>
<td>212.2 $\Omega$</td>
</tr>
<tr>
<td>$R/Q$ (linac, $\beta=1$)</td>
<td>190 W</td>
</tr>
</tbody>
</table>

Sekutowicz et al., Proc. PAC 2009
Gun with Diagnostic beamline at HZB

- SC Solenoid
- SC Cavity
- Stripline BPM, ICT
- HoBiCaT cryostat
- Mass Spectrometer
- Viewscreens
- Faraday Cups
- Dipole magnet
- ΣQ
Gun with Diagnostic beamline at HZB

First time operated fully SC photoinjector ensemble (SC Cathode, Cavity, Solenoid) 
Source/upgrade for CW low current machines (POLFEL, XFEL, FLASH)
Extension of the HoBiCaT Cavity Test Facility

Laser hut

Laser beamline

Diagnostic e-beamline

HoBiCaT cryostat

RF amplifier
Extension of the HoBiCaT Cavity Test Facility

Laser hut

Laser beamline

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RF amplifier

Laser beamline
Extension of the HoBiCaT Cavity Test Facility

- Laser hut
- Laser beamline
- HoBiCaT cryostat
- RF amplifier
Cavity fabrication at Thomas Jefferson Lab (P. Kneisel, Proc. PAC 2011)

- Fundamental power coupler port
- Stiffening ring
- Pick-up Port
- "Helium vessel endplate"
- Large grain cavity backwall for cathode
- Passive stiffening System: "Spider"
- Cavity half-cells
- TTF-III FPC: $Q_L = 1 \cdot 10^9 - 6 \cdot 10^6$ including 3-stub tuner
- Cavity in helium vessel
Mechanical design: Countermeasures to increase field stability

- Beam quality dominated by field stability
- Field stability in SC cavity: Avoid detuning (deformation) of the cavity

Combined FEM mechanical and Electro-magnetic field simulations → low deformation (detuning) design

<table>
<thead>
<tr>
<th>Type</th>
<th>SuperFish</th>
<th>CST MWS</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without</td>
<td>527</td>
<td>615</td>
<td>-</td>
</tr>
<tr>
<td>Short bar</td>
<td>200</td>
<td>-</td>
<td>474</td>
</tr>
<tr>
<td>Long bar</td>
<td>130</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>“Spider”</td>
<td>-</td>
<td>-</td>
<td>146</td>
</tr>
</tbody>
</table>

Neumann et al., Proc. Linac 2010
Mechanical design: Countermeasures to increase field stability

• Beam quality dominated by field stability
• Field stability in SC cavity: Avoid detuning (deformation) of the cavity

Combined FEM mechanical and Electro-magnetic field simulations ➔ low deformation (detuning) design

Neumann et al., Proc. Linac 2010
Plasma arc deposition setup in 30° configuration

16 x 5min depositions result in a few hundred nm thick Pb cathode film

Cavity with helium vessel

Mask to protect cavity

Pb cathode film

Final diameter by BCP + special mask: 5 mm

R. Nietubyc
Quality factor measurements: Vertical and Horizontal tests (JLab and HZB)

- Vertical test after fabrication, treatment and mounting $Q_0 > 1 \times 10^{10}$ for $E_{\text{peak}} < 35 \text{ MV/m}$
- After lead deposition $Q$ drops significantly and field emission (FE) onset lowered
- Installation in HoBiCaT further $Q$ degradation, FE onset 12 MV/m
- After additional cooldown cycle even worse, cavity collects residuals
  - Excimer Laser cleaning of lead cathode increased onset of FE to 15 MV/m
- Operation of up to 20 MV/m, $E_{\text{acc}} \sim 11 \text{ MV/m}$ possible

Note: Horizontal RF tests at $\beta_c \sim 3-4$, error bar!

A. Neumann et al., SRF 2011
Dark current studies

- Before first laser cleaning
- After laser cleaning
- After high power cleaning

![Graph showing dark current vs. electric field peak]

- 14.6 MV/m
- 15.0 MV/m
- 15.6 MV/m
- 15.9 MV/m
- 16.4 MV/m

Images of dark current focused by SC solenoid before laser cleaning.
First laser cleaning treatment of cathode increased onset level of field emission!

- Before first laser cleaning
- After laser cleaning
- After high power cleaning

Dark current studies

![Graph showing dark current vs. electric field with data points indicating before and after laser cleaning.]

14.6 MV/m 15.0 MV/m
15.6 MV/m 15.9 MV/m
16.4 MV/m

Dark current focussed by SC solenoid before laser cleaning.

A. Neumann, IPAC 2011 San Sebastián, Spain, MOODA03
Dark current studies continued

Tracking studies suggest cathode region as field dark current source

Measured dark current energy hints at 90 degree launch phase of field emission

V. Volkov, in preparation
R. Barday et al., Proc. Dipac 11
Dark current studies continued

Fowler-Nordheim fit of dark current/field emission shows reduction of field enhancement factor $\beta_{NF}$.

Effectively emitting $A_e$ area increases

Discuss at THPC109

SEM images of comparable samples show droplets and tip on tip like structures

Laser cleaning levels small defects? ($\lambda=248$ nm, 0.1 mJ/mm²) Tests with Niobium are planned

Arc deposited lead samples SEM image  S. Schubert et al., in preparation
Quantum Efficiency and beam measurements

First beam
21st of April 2011
on YAG viewscreen

Beam current (nA)

Laser phase (deg)

Beam at E\text{peak} \approx 18 \text{ MV/m}
Quantum Efficiency and beam measurements


First beam
21st of April 2011
on YAG viewscreen
Quantum Efficiency and beam measurements


Arc deposited lead BNL
Electro-plated lead BNL
Bulk niobium BNL

Beam current (nA)
Laser phase (deg)

First beam
21st of April 2011
on YAG viewscreen

Visit T. Kamps at THPC109 for Beam results!

3-4 ps pulse length during extraction
Bunch charge: 5-6 pC

I_{beam} = 50 nA at E_{cath} = 20 MV/m
at 8 kHz Laser rep. Rate, λ = 258 nm

J. Smedley, T. Kamps, T. Quast, A. Neumann, R. Barday
Cavity field trips
Cavity field trips

- 500 nA at specific cathode positions!
- Field decays within <1 µs

Formation of Plasma discharge?

Laser spot

Scan of trip occurrence versus laser pulse energy

Beam current (nA)

Time

Before test
After processing
Beam energy

- Phase calibration
- Orbit errors by steering of solenoid
- Systematic errors due dipole and cavity field calibration
- Need to optimize setup for next run
Field stability

**Microphonics spectrum**

- Frequency (Hz)
- Amplitude $A_f$ (Hz)
- $Q_L$, $E_{\text{peak}}$, $\sigma_f$, $\sigma_\Phi$, $\sigma_{A/A}$

<table>
<thead>
<tr>
<th>$Q_L$</th>
<th>$E_{\text{peak}}$ (MV/m)</th>
<th>$\sigma_f$ (Hz)</th>
<th>$\sigma_\Phi$ (deg)</th>
<th>$\sigma_{A/A}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6.6 \cdot 10^6$</td>
<td>20</td>
<td>7.0</td>
<td>0.017</td>
<td>$1.2 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$1.4 \cdot 10^7$</td>
<td>12</td>
<td>5.0</td>
<td>0.02</td>
<td>$1.5 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

Using Cornell LLRF system+ slow PLL loop
• Measurements of beam emittance and thermal emittance of lead are in progress, please visit T. Kamps on Thursday

• More detailed studies about laser cleaning, QE measurements, also XPS analysis will be published in the near future (S. Schubert, R. Barday in prep.)

• Further studies about the cavity trips will be done, improvement of $Q_0$ by helium processing is planned for

• J. Sekutowicz and P. Kneisel are working on an improved version of the 1.6 cell cavity, this time with tuning system
  R. Nietubycz et al. are building a new improved cathode deposition set up

• New cavity will be installed early 2012 in HoBiCaT
Acknowledgement

Thanks for your attention!
Gracias por su atención!
Eskerrik asko zure arretagatik!

This work is a collaborative effort by:
J. Sekutowicz, DESY, Hamburg, Germany
P. Kneisel, JLAB, Newport News, Virginia, USA
R. Nietubyc, The Andrzej Soltan Institute for Nuclear Studies, Swierk/Otwock, Poland
J. Smedley, BNL, Upton, Long Island, New York, USA
I. Will, MBI, Berlin, Germany
W. Anders, R. Barday, A. Jankowiak, T. Kamps, J. Knobloch, O. Kugeler, A. Matveenko, A. Neumann, T. Quast,
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany (BESSY)
V. Volkov, BINP SB RAS, Novosibirsk, G. Weinberg, FHI, Berlin, Germany
+ the support of many more……..
The three stage approach

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HoBiCaT Stage A</th>
<th>Gun lab Stage B</th>
<th>BERLinPro Stage C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal</td>
<td>Beam Demonstrator</td>
<td>Brightness R&amp;D gun</td>
<td>Current Production gun</td>
</tr>
<tr>
<td>Electron energy</td>
<td>≥ 1.5 MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.3 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design peak field</td>
<td>≤ 50 MV/m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation launch field</td>
<td>≥ 10 MV/m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch charge</td>
<td>≤ 77 pC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>30 kHz</td>
<td>54 MHz</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Cathode material</td>
<td>Pb</td>
<td>Cu, CsK₂Sb</td>
<td>CsK₂Sb</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>238 nm</td>
<td>355, 526 nm</td>
<td>526 nm</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>0.15 µJ</td>
<td>≤ 1 µJ</td>
<td>4 nJ</td>
</tr>
<tr>
<td>Laser pulse shape</td>
<td>Gaussian</td>
<td>Gaussian, Flat-top</td>
<td>Flat-top</td>
</tr>
<tr>
<td>Laser pulse length</td>
<td>2.5 ps FWHM</td>
<td>≤ 15 ps</td>
<td>15 ps</td>
</tr>
<tr>
<td>Average current</td>
<td>0.5 µA</td>
<td>≤ 10 mA</td>
<td>100 mA</td>
</tr>
</tbody>
</table>

Stage A (Beam dynamics):
- Study beam dynamics of SC RF photoinjector:
  - Emittance
  - Field levels
  - Stability
- Fully SC design
- Starting point for design and operation of SRF gun

Stage B (Peak Brightness):
- Study + develop cathode insert into SC injector:
  - Lifetime and QE of cathode materials
  - Reliable cathode replacement scheme

Stage C (High avg. Current):
- SC design for ERL design current
- High power operation
- HOM damping
- Cathode lifetime

Started here