Introducing the SRF Photoinjector Project

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A lot of concepts for future light sources like cw-FELs, ERLs, compact X-ray sources rely on a high brightness cw electron beam DC with 100mA 1300MHz@77pC

4GLS proposal for an ERL lightsource

I could find five projects following different approaches, these four plus Wisconsin (200 MHz re-entrant cavity and Cs$_2$Te cathode)

**BNL / JLAB / DESY (since 2002)**
- $f = 1.3$ GHz
- Nb/Pb $\leftrightarrow E_{RF}$

**BNL/AES (since 2004)**
- $f = 703.75$ MHz
- Alkali+$\uparrow \leftrightarrow E_{RF}$

**IHIP Peking (since 2001)**
- $f = 1.3$ GHz
- Cs$_2$Te $\leftrightarrow E_{DC}$

**FZD (since 1998)**
- $f = 1.3$ GHz
- Cs$_2$Te $\leftrightarrow E_{RF}$

ERL05/07 websites: [http://www.jlab.org/intralab/calendar/archive04/erl/](http://www.jlab.org/intralab/calendar/archive04/erl/) and [http://www.erl07.dl.ac.uk](http://www.erl07.dl.ac.uk)
Proposal for a superconducting photoemission source of high brightness by H. Piel et al at Wuppertal Uni in 1988

- Re-entrant cavity at 500 MHz
- Cs$_2$Sb cathode
- Doubled Nd:YAG laser with 12ps pulse length

A. Michalke et al operated a photocathode in a SRF S-Band cavity in 1992

Setup of the successor of the current effort at Dresden, this time with L-Band ½ cell cavity and optimized cathode insert

Our project group concentrates on the technical and physical problems arising from the integration of the photocathode into the SRF cavity structure

<table>
<thead>
<tr>
<th>Cathode and SRF cavity</th>
<th>• Contamination of cavity with sputtered particles</th>
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<tr>
<td>SRF cavity and beam dynamics</td>
<td>• QE performance of cathode affected at cryogenic temperatures</td>
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<td>• Cavity performance with cathode insert and exchange system</td>
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<td>• Emittance performance</td>
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<td>• Operation with high space charge and low gradient</td>
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Two operation modes for the injector: ELBE to replace the thermionic gun for the IR-FEL, and High Charge as R&D mode

<table>
<thead>
<tr>
<th>Parameter / mode</th>
<th>ELBE</th>
<th>High Charge</th>
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</thead>
<tbody>
<tr>
<td>Electron kinetic energy</td>
<td>9.5 MeV</td>
<td></td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.3 GHz</td>
<td></td>
</tr>
<tr>
<td>RF power</td>
<td>10 kW</td>
<td></td>
</tr>
<tr>
<td>Photocathode</td>
<td>Cs₂Te</td>
<td></td>
</tr>
<tr>
<td>Drive laser</td>
<td>262 nm</td>
<td></td>
</tr>
<tr>
<td>Bunch charge</td>
<td>77 pC</td>
<td>1 nC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>13 MHz</td>
<td>500 kHz</td>
</tr>
<tr>
<td>Pulse length FWHM</td>
<td>4 ps</td>
<td>15 ps</td>
</tr>
<tr>
<td>Average current</td>
<td>1 mA</td>
<td>0.5 mA</td>
</tr>
<tr>
<td>Transverse rms emittance</td>
<td>1 mm mrad</td>
<td>2.5 mm mrad</td>
</tr>
</tbody>
</table>
Several possibilities will be studied to improve emittance performance

- SRF cavity is sensitive to external magnetic fields
- Emittance compensation scheme with solenoid magnet put over gun cavity cannot be used with SRF cavity
- Alternative schemes:
  - Pulled back and shaped cathode
  - Focusing with downstream solenoid
  - Additional TE mode in last cell
Get emittance performance by pulling back the cathode to achieve RF focusing


F. Staufenbiel, et al., NIM A584(2008)259
Pushing in the cathode results in higher gradient

- Pushing in the cathode results in 29 MV/m gradient on the cathode
- Illuminate cathode by 30 fs RMS, 0.95 mm $\sigma_x$ laser pulses
- Obtain ellipsoidal bunch with 50 A peak current and uniform charge density

Design rationale of the cavity: in line with TESLA, plus ½ cell, and optimized for low charge production at high repetition rate

- ½ cell plus three full TESLA cells to accelerate electrons up 10 MeV
- RF coupler can handle up to 10 kW average power, resulting in max. average current of 1 mA
- Cathode insert cooled with LN$_2$ with vacuum shield
- Choke filter to prevent RF leakage into cathode waveguide

During cavity treatment with high pressure rinsing two crashes happened due to equipment not adopted to the shape of the ½ cell.

- SRF cavity preparation follows a detailed recipe, steps include
  - Buffered Chemical Polishing (BCP) on the in- and outside
  - Annealing and outgasing in UHV oven
  - More BCP and clean water rinsing
  - High pressure rinsing (HPR)
- Two crashes during HPR
- After each step the cavity was checked in a vertical test cryostat
Cavity treatment proved to be disastrous for cavity performance

\[ \frac{E_{\text{peak}}}{E_{\text{acc}}} = 2.70 \]

<table>
<thead>
<tr>
<th>Values @ ( Q_0 = 5 \times 10^9 )</th>
<th>1st (16.06.06) BCP/HPR</th>
<th>2nd (01.08.06) HPR (Crash)</th>
<th>3rd (03.11.06) BCP/HPR</th>
<th>4th (15.02.07) BCP/HPR + Choke HPR (Crash)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{acc}} )</td>
<td>14.6 MV/m</td>
<td>2.8 MV/m</td>
<td>7.4 MV/m</td>
<td>9.3 MV/m</td>
</tr>
<tr>
<td>( E_{\text{peak}} )</td>
<td>39.0 MV/m</td>
<td>7.4 MV/m</td>
<td>19.6 MV/m</td>
<td>24.6 MV/m</td>
</tr>
<tr>
<td>( P_{\text{diss}} )</td>
<td>32 W</td>
<td>1 W</td>
<td>8 W</td>
<td>13 W</td>
</tr>
</tbody>
</table>
The achievable gradient is limited to $E_{\text{acc}} = 6 \text{ MV/m}$ due to field emission from the backplane of the $\frac{1}{2}$ cell.
The cryomodule ist derived from the FZD two-cavity module with a cathode load-lock
A photocathode preparation lab has been setup at FZD to prepare, store and exchange cathodes under UHV condition

- Cathode is a Cs$_2$Te coated Molly plug on Copper actuator
- Co-evaporation of Cs and Te with online monitoring of QE
- Exchange system allows replacement of cathodes without venting
The laser system consists of two lasers for the 13 MHz/low charge and 500 kHz/high charge operation modes.

- 500 kHz laser is an actively-modelocked Nd:YLF 27 MHz oscillator, pumped by 8 fiber coupled diodes
- 500 kHz laser setup and running, the 13 MHz laser will be installed soon
- Transverse profile shaped by over-filled aperture
  - Tests with spatial light modulator
- Temporal profile is Gaussian

Diagnostics beamline for projected beam parameters must be able to deal with all operation modes.
The bunch charge and average current is measured with Faraday cups and integrating current transformers.

- Measured averaged currents of 50 nA, corresponds at 100 kHz repetition rate to bunch charge of 0.5 pC.
Six stripline beam position monitors of ELBE type, come in a compact package with reliable signal processing electronics.

The transverse charge distribution is imaged with Ce:YAG screens at six positions in the beamline

- Each station is equipped with calibration target and Ce:YAG plate in normal incidence
- GigE compliant CCD camera with hardware trigger from ELBE clock
- Camera readout and actuator controls with labview apps
After adjusting the laserspot position on the cathode we were able to extract more round beam from the gun
One screen station is also equipped with two multi-slit masks, which can be inserted to measure the transverse beam emittance

- Slit mask technique to measure emittance of space charge dominated beam
- Calculate rms beam emittance from size and position of beamlets
- Phase space reconstruction method from SPARC (A. Mostacci, et al.)

Cartoon and trace space plot from A. Mostacci, et al., Rev. Sci. Instrum. 79, 013303 (2008), beamlet image from ELBE
The bunch length will be measured by converting the electron pulses with a prompt radiator and readout with a streak camera.

- Fused silica (n=1.46) and silica aerogel (n=1.008 and 1.028) considered as Cherenkov radiator.
- Fused silica produces x10 more photons but in a x4 larger cone.
- Chose silica aerogel due to higher capture efficiency (x10^3).
Complex vacuum chamber with differential pumping scheme required to protect the beam pipe vacuum

- Alignment mirror
- Mirror for Cherenkov light
- Aerogel
- Calibration target
- Ce:YAG screen
- Inner vacuum chamber
- Mirror
The radiation pulse will be transported over a low dispersion, low loss (transport efficiency = 10%) optical transport line of 20m length from Aerogel to the streak camera.
Measured pulse length of:
laser pulses with streak camera, and
electron beam with phase scan
The beam mean momentum and momentum spread are measured with a 180 degree dipole spectrometer.
The diagnostics high level apps communicate with the ELBE Siematic controls in OPC (OLE (Object Linking and Embedding) for Process Controls)

PC running control apps

PC running controls and high-level apps, Labview and Matlab

TCP/IP
In the short run we want to operate the injector with Cs$_2$Te cathodes, characterize the beam and then accelerate to 40 MeV with the ELBE linac

- What we achieved/measured so far
  - Electron beam with momentum 2.0 MeV/c
  - Beam current of 50 nA
  - Electron pulse length of 15 ps FWHM

- We want to increase the charge by using a Cs$_2$Te cathode

- In the long run
  - New cavity with higher gradient
  - Slice diagnostics with ELBE linac