Rossendorf SRF-Gun Operational Experiences

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on behalf of the ELBE Crew and
the DESY-FZD-HZB-JLab-MBI
collaboration
Outline

1. Introduction
2. RF Operation
3. Cathode
4. Beam Measurements
Three operation modes

- High peak current operation for CW-IR-FELs with 13 MHz, 80 pC
- High bunch charge (1 nC), low rep-rate (<1 MHz) for pulsed secondary particle beam production (neutrons, positrons for ToF)
- Low emittance, medium charge (100 pC) with short pulses for THz-radiation and x-rays by inverse Compton backscattering

Design

- Medium average current: 1 - 2 mA (< 10 mA)
- High rep-rate: 500 kHz, 13 MHz and higher
- Low and high bunch charge: 80 pC - 1 nC
- Low transverse emittance: 1 - 3 mm mrad
- High energy: 9.4 MeV with 3½ cells (stand alone)
- Highly compatible with ELBE cryomodule (LLRF, high power RF, RF couplers, He & N2 support, etc.)
- LN₂-cooled, el. isolated, exchangeable, semi-conductor photo cathode
Introduction – Cavity Design

A. Arnold, et al., NIM A 577, 440 (2007)

- Cavity Design

**Equations**

- Stored energy $U = 32.5 \, J$
- Quality factor $Q_0 = 10^{10}$
- Dissipated power $P_c = 25.8 \, W$
- Maximum beam power $P_B = 9.4 \, kW$
- Geometry factor $G = 241.9 \, \Omega$
- Accel. voltage $V_{acc} = 9.4 \, MV$
- Accel. gradient $E_{acc} = 18.8 \, MV/m$
- $R_a/Q_0 = 166.6 \, \Omega$
- $E_{peak}/E_{acc} = 2.66$
- $B_{peak}/E_{acc} = 6.1 \, mT/(MV/m)$
• No problems during cool down

• Frequency shift same as expected from TESLA cells

• After 1st cool down, frequency to high because change of $\Delta \varepsilon_r$ between N$_2$ filled cavity and vacuum was not considered

• Change in length: $\Delta l/l = -0.155\%$

• Coefficient of thermal expansion: $\alpha_{20} = +6.8 \times 10^{-6} \, K^{-1}$

• Field distribution determined by pass band freq. measurement [A. Arnold, proceedings of SRF07, pp. 689]:
  
  (-62% / 99.4% / -97.5% / 100%) @ 1.3 GHz

• Static helium heat load measured via boil off curve and comparison with calc.:
  
  $P_{\text{static}} = 6 – 7 \, W$
RF Operation – Pressure Sensibility

- Pressure sensibility evaluated via standard deviation of frequency and pressure:

\[
\frac{\sigma_f}{\sigma_p} = \frac{4 \text{ Hz}}{0.027 \text{ mbar}} = 150 \frac{\text{Hz}}{\text{mbar}}
\]

- DESY ~10 Hz/mbar, ELBE ~32 Hz/mbar

- Because of high bandwidth (~160 Hz) and good helium pressure stability (~0.1 mbar) operation not critical, but needs to be improved

- Lorentz detuning (CW) using network analyzer with inverse freq. sweep

reason in both cases: weak half-cell back plane → additional stiffener considered at new cavities
RF Operation – Microphonics

- Microphonics = detuning of the cavity frequency due to mech. vibrations
- LLRF-Controller (here analog) used to counteract amplitude and phase error
- By measuring the error signal of the closed phase loop one gets phase deviation (rms) seen by the beam
  \[ \sigma_{ph} = \sqrt{VAR} = 0.0433^\circ \]
- And with known loop gain \( K_p \) the disturbance variable of freq. detuning
  \[ \sigma_f = \frac{BW}{2} \tan(\sigma_{ph} \cdot (K_p + 1)) = 5.7 \text{ Hz} \]
- Significant freq. parts identified by calculation of PSD and integration
- Microphonics is gradient independent
- Residual phase error sufficient for ELBE
RF Operation – Cavity Tuner

stepping motor and gear box

screw drive

tuner half-cell

tuner TESLA-cells

measured tuner values

<table>
<thead>
<tr>
<th>½-cell</th>
<th>TESLA cells</th>
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<tr>
<td>± 78 kHz</td>
<td>± 225 kHz</td>
</tr>
<tr>
<td>1.2 nm/step</td>
<td>1.6 nm/step</td>
</tr>
<tr>
<td>0.3 Hz/step</td>
<td>0.7 Hz/step</td>
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</table>
Q vs. E measurement is an important instrument to identify cavity contamination!

Formulas:

\[ E_{\text{acc}} \approx \frac{1}{L} \sqrt{4P_i^2r_iQ_L} \quad \& \quad Q_0 = \frac{4P_i}{P_d} Q_L \]

- measured \( Q_0 \) is 10 times lower than in vertical test
- cavity pollution during string assembly?
- Maximum achievable field 1/3 of the design value 50 MV/m)
- Cavity performance limited by FE & He consumption

Good News
- No \( Q \) degradation seen since 4 years of operation!
- Same performance of cavity with or w/o cathode!

Summary:

<table>
<thead>
<tr>
<th>Condition</th>
<th>( E_{\text{acc}} ) [MV/m]</th>
<th>( E_{\text{peak on Axis}} ) [MV/m]</th>
<th>( E_{\text{kin}} ) [MeV]</th>
</tr>
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<tbody>
<tr>
<td>CW</td>
<td>6.5</td>
<td>17.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Pulsed RF</td>
<td>8</td>
<td>22</td>
<td>4.0</td>
</tr>
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</table>
RF Operation – Multipacting at the Cathode

- MP was expected in the gap between cathode and cavity at surface fields of 0.1-0.2 kV/m since the early design stage!
- So biasing of the cathode up to -7 kV was considered in the cathode design (el. isolated)

- During increase of RF field, a hard MP barriers are observed, depending on the bias voltage level, the position and the used cathode
- MP characterized by high current (1 mA) measured at the high voltage power supply
- Electron flash at view screens
- Not possible to get above this level not even in pulsed mode and 10kW!

The onset level is different for every single cathode and its position!
RF Operation – Multipacting Suppression

- Rounding all edges to reduce field enhancement factor
- Anti multipacting grooves to suppress resonant conditions

- Coating with TiN to reduce secondary electron yield

Diagram:
- Light blue: gradient
- Dark blue: multipacting current
- No processing seen during second ramp up
Inside the preparation chamber

- Cathodes mech. polished and cleaned with Ar⁺
- Heated to 120°C and evaporated with Cs and Te (successive- or simultaneously)
- Online thickness and QE measurement
- After prep. also QE distribution scan
- Vacuum requirement: ~10⁻⁹ mbar

Requirements for Transfer:

- Load lock system with $< 10^{-9}$ mbar to preserve QE $\geq 1\%$

- Exchange w/o warm-up & in short time and low particle generation

- Fresh QE 15.5%, in gun 1%
- Total beam time 1013 h
- Extracted charge 35 C

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Operation days</th>
<th>Q.E. in gun</th>
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<tbody>
<tr>
<td>#090508Mo</td>
<td>30</td>
<td>0.05%</td>
</tr>
<tr>
<td>#070708Mo</td>
<td>60</td>
<td>0.1%</td>
</tr>
<tr>
<td>#310309Mo</td>
<td>109</td>
<td>1.1%</td>
</tr>
<tr>
<td>#040809Mo</td>
<td>182</td>
<td>0.6%</td>
</tr>
<tr>
<td>#230709Mo</td>
<td>56</td>
<td>0.03%</td>
</tr>
<tr>
<td><strong>#250310Mo</strong></td>
<td><strong>427</strong></td>
<td><strong>1.0%</strong></td>
</tr>
<tr>
<td>#090611Mo</td>
<td>From 2011-7-26</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
Beam Measurements

Diagnostics Beamline
- Current & charge (faraday-cup & ICTs)
- Transverse emittance (slit mask, solenoid scan)
- Energy and ΔE (C-bent)
- Bunch length (Cherenkov radiator and streak camera or electro-optical sampling)

Dogleg to ELBE
- Achromatic compensated connection

diagnostics beamline designed and built by HZB (BESSY) Berlin
• Schottky scan for different laser pulse energies (15 ps FWHM, \( \varnothing 3 \) mm flat top): \( \rightarrow \) space charge limit \( \sim 300 \) pC (for 2-3 MeV)
• Energy and energy spread via 180° bending magnet \( \rightarrow 3.0 \) MeV (CW) and 4.0 MeV (pulsed RF)

Screen DV04 (YAG)
4.4 m from cathode

Screen DV05 same optical path

Control panel of diagnostic beam line

Schottky scan
space charge smoothing

Energy and energy spread @ 5 pC

Energy spread

29.05.2009
2 kHz
5 kHz
50 kHz
125 kHz

25.02.2010, \( E_m = 6.5 \) MV/m, 5 kV DC

Phase scan (a.u.)

SRF gun, 5 kV DC, 6 MV/m, 125 kHz CW, 06.08.2010

1 pC
10 pC
20 pC
40 pC
• Transverse emittance with solenoid and quad Scan
• slit mask not useable because design is for 9 MeV
• improved setup needed!

- Good agreement with ASTRA
- measured normalized emittance 3±1 mm mrad @ 77 pC
- Good enough for ELBE injection
First ELBE Injection Febr. 5, 2010 using achromatic dogleg

- Up to 60 pC with 100% transmission
- Maximum bunch charge injected and accelerated in ELBE: 120 pC @ 50 kHz
- Dogleg acceptance needs low ΔE (correlated ΔE compensated by module 1)
ELBE - Longitudinal phase space Part 1

**general longitudinal beam ellipse**

\[ T = \begin{pmatrix} \tau_{11} & \tau_{12} \\ \tau_{12} & \tau_{22} \end{pmatrix} \quad \sqrt{\tau_{11}} = \sigma_t \quad \text{...rms bunch length (ps)} \]
\[ \sqrt{\tau_{22}} = \sigma_E \quad \text{...rms energy spread (keV)} \]

**general cavity transport matrix**

\[ R_{C2} = \begin{pmatrix} 1 & 0 \\ -\omega_{RF}V_{C2} \sin(\varphi_{C2}) & 1 \end{pmatrix} \]

energy gain = \( V_{C2} \cos(\varphi_{C2}) \)

\( \varphi_{C2} \) in reference to crest phase

**longitudinal beam ellipse at spectrometer:**

\[ T(1) = R_{C2}^T T(0) R_{C2}^T \]

\[ \tau_{22}(1) = \sigma_E^2(1) = \left[ \tau_{22}(0) - 2\tau_{12}(0) V_{C2} \sin(\varphi_{C2}) + \tau_{11}(0) (V_{C2} \sin(\varphi_{C2}))^2 \right] \]

\[ \epsilon_{\text{long}} = \sqrt{\tau_{11} \tau_{22} - \tau_{12}^2} \]
• Same energy spread measured as in the 180° bending magnet of the diagnostic beamline
• Bunch compression in SRF-gun as expected from ASTRA simulation
• So far phase space measured at the exit of cavity 1 but projection to gun in progress
• Successful test of long. phase space measurement for future gun optimization
- Fixed energy imprint for correlation between energy spread and long. bunch distribution
- Spectrometer → longitudinal distribution transferred to transverse distribution → longitudinal slices accessible
- Combination with quadrupole scan technique allows to reconstruct the vertical emittance for each slice
- Tool for future emittance compensation

ELBE – Thomson Backscattering (Laser Group)

- Production of x-ray photons (some tens keV) in small-scale linear accelerators like ELBE
- Head-on collision of ≤150 TW laser pulse and 20 - 30 MeV electron bunch of ELBE linac
- Electrons are driven by the electric field of the laser pulse to an oscillatory motion (undulator)
- emit Doppler up-shifted radiation at an angular frequency of $\omega_{sc}=(10-20 \text{ keV})/\hbar$ (for ELBE)

ELBE – Thomson Backscattering (Laser Group)

- 1st setup ELBE linac with therm. injector than switch to SRF-Gun (E_{acc}=6 MV/m, exit energy 2.85 MeV)
- Switch to 10 Hz single bunch mode (10 pC, 24 MeV) and optimized temporal overlap with laser
- CdTe detector found same X-ray spectrum but lower photon yield than with therm. gun

→ 1st Demonstration of the Reliability of the SRF-Gun during an user experiment with critical needs in terms of bunch phase stability and laser-bunch synchronization
• Long lifetime of NC photo cathodes in SRF-Guns (>1 yr, total charge 35 C @ QE = 1%)
• No Q degradation since 4 years (RF operation ≈ 2500 h, beam time ≈ 1400 h)
• Strong MP was defeated by DC Bias and Grooves
• First successful measurements using the ELBE accelerator
  - Slice emittance measurements (J. Rudolph and HZB)
  - Longitudinal phase space
  - Inverse Compton backscattering (Laser Group at HZDR)
• But gun performance limited by low RF-field ($E_{pk} \leq 18$ MV/m and $Q_0 \leq 3 \times 10^9$)
  (so far a problem for all SRF-Guns!)

**Outlook 2012**

- Installation of upgrade cavity built by **Peter Kneisel and the JLab guys** to twice $E_{pk}>35$ MV/m and Energy to 6-7 MeV
- 13 MHz laser upgrade and start high average current operation (1 mA)
Thanks to our collaborators (HZB for diagnostics, MBI for the laser and DESY for their help in preparation and testing the 1st cavity) and thank you for your attention!

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From in-house clean room cavity string assembly to SRF Gun module completion

SRF-Gun in the Acc. hall

connected to all peripherals and diagnostics

developed & manufactured by BESSY Berlin
An important issue in this context is the dark current

- Operation at high fields especially in pulsed RF regime up to 22 MV/m can increase beam energy to 4 MeV and reduce emittance, but
- Dark current increases to μA level with mostly the same energy as the photo current.
- Most of the current comes from the cavity surface and not from cathode
- Dark current kicker needed because too much for some experiments e.g. inverse Compton backscattering

**Further investigations within German Gun-Cluster collaboration**
<table>
<thead>
<tr>
<th>Issue</th>
<th>Demonstration for low average current &amp; low energy (3 MeV)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>stable QE &gt; 1 %</td>
<td>1% for &gt; 1000 h beam time <strong>OK</strong></td>
<td>test of cathodes with &gt; 5 % reducing early QE drop</td>
</tr>
<tr>
<td>life time in gun</td>
<td>&gt; 1 year <strong>OK</strong></td>
<td><strong>OK</strong> test of cathodes with &gt; 5 % reducing early QE drop</td>
</tr>
<tr>
<td>pollution of SC cavity</td>
<td>no Q₀ degradation or increased field emission up to now <strong>OK</strong></td>
<td>needs demonstration for high current &amp; gradient ?</td>
</tr>
<tr>
<td>extracted charge</td>
<td>≈ 35 C</td>
<td>36 C = 1 mA * 10 h 360 C / cathode is minimum ?</td>
</tr>
<tr>
<td>dark current</td>
<td>≈ 120 nA (for 3 MeV or 30 W dissipated power)</td>
<td>needs demonstration for high current &amp; gradient ?</td>
</tr>
<tr>
<td>multipacting</td>
<td>shaping of the cathode stem <strong>OK</strong></td>
<td>TiN coating planed ?</td>
</tr>
<tr>
<td>cathode cooling</td>
<td>&lt; 300 mW laser &amp; low gradient <strong>OK</strong></td>
<td>up to 1 mA not critical</td>
</tr>
<tr>
<td>easy and quick exchange</td>
<td>cathode exchange needs &lt; 30 min in cold gun <strong>OK</strong></td>
<td>Vacuum improvements needed for GaAs and Cs₂KSB ?</td>
</tr>
</tbody>
</table>
### SUMMARY OF BEAM PARAMETERS

<table>
<thead>
<tr>
<th>parameter</th>
<th>present cavity</th>
<th>new “high gradient cavity”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measured</td>
<td>ELBE</td>
</tr>
<tr>
<td>final electron energy</td>
<td>2.1 MeV</td>
<td>3 MeV</td>
</tr>
<tr>
<td>peak field</td>
<td>13.5 MV/m</td>
<td>18 MV/m</td>
</tr>
<tr>
<td>laser rep. rate</td>
<td>1 – 125 kHz</td>
<td>13 MHz</td>
</tr>
<tr>
<td>laser pulse length (FWHM)</td>
<td>15 ps</td>
<td>4 ps</td>
</tr>
<tr>
<td>laser spot size</td>
<td>2.7 mm</td>
<td>5.2 mm</td>
</tr>
<tr>
<td>bunch charge</td>
<td>≤ 200 pC</td>
<td>77 pC</td>
</tr>
<tr>
<td>max. aver. Current</td>
<td>1 µA</td>
<td>1 mA</td>
</tr>
<tr>
<td>peak current</td>
<td>13 A</td>
<td>20 A</td>
</tr>
<tr>
<td>transverse. norm. emittance (rms)</td>
<td>3±1 mm mrad @ 80 pC</td>
<td>2 mm mrad</td>
</tr>
</tbody>
</table>