Development of Pulsed High Gradient Photoelectron Gun

SwissFEL project

Presented by Martin Paraliev
Motivation

- X-ray Free Electron Lasers (XFEL) are important for future experimental physics.
- Cost and size of the XFEL facilities reduce availability for science.
- Low emittance electron beam relaxes beam requirements (peak current and energy) and reduces undulator saturation length.

\[
\lambda_{cr} \approx 18 \pi \varepsilon_n \sigma_E \frac{1}{\gamma \sqrt{I_A}}
\]

Critical wavelength \( \lambda_{cr} \) \[1\]

\[
L_g \approx \frac{\lambda_u}{4\pi \rho}
\]

Gain length \( L_g \) and FEL Pierce parameter \( \rho \) \[2\]

\[
\rho = \frac{1}{\gamma} \sqrt{\frac{I \varepsilon_n \beta}{I_A \gamma} \left(\frac{K \lambda_u f(\xi)}{8\pi}\right)^2}
\]


SwissFEL project - Compact X-ray Free Electron Laser

**SwissFEL**
- Wavelength tunable from 1 - 100 Å
- Pulse duration 1 - 20 fs
- Repetition rate 100 - 400 Hz
- Construction period 2012 - 2015
- Estimated investment cost 250 MCHF

**Novel experiments in:**
- Nanoscale Magnetization Dynamics
- Solution Chemistry and Surface Catalysis
- Coherent Diffraction by Nanostructures
- Ultrafast Biochemistry
- Time-Resolved Spectroscopy of Correlated Electron Materials
### SwissFEL Conceptual Layout and Target Parameters

<table>
<thead>
<tr>
<th>Branch</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wavelength range</td>
<td>0.1 - 0.7</td>
<td>0.7 - 2.8</td>
<td>1.8 - 7.0</td>
</tr>
<tr>
<td></td>
<td>Photon energy range</td>
<td>12 - 1.7</td>
<td>1.7 - 0.43</td>
<td>0.67 - 0.17</td>
</tr>
<tr>
<td></td>
<td>Polarization</td>
<td>planar</td>
<td>variable</td>
<td>variable</td>
</tr>
<tr>
<td></td>
<td>Peak power</td>
<td>2</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Peak brilliance</td>
<td>$10^{31} - 10^{33}$</td>
<td>$10^{30} - 10^{32}$</td>
<td>$10^{29} - 10^{31}$</td>
</tr>
<tr>
<td></td>
<td>Flux</td>
<td>$5.10^{10}$</td>
<td>$5.10^{11}$</td>
<td>$1.10^{12}$</td>
</tr>
<tr>
<td></td>
<td>Pulse Energy</td>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Spectral width (rms)</td>
<td>0.04 - 0.08</td>
<td>0.1 - 0.3</td>
<td>0.2 - 0.4</td>
</tr>
<tr>
<td></td>
<td>Beam-size (rms)</td>
<td>25</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Pulse duration (rms)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Repetition rate</td>
<td>10 - 100</td>
<td>10 - 100</td>
<td>10 - 100</td>
</tr>
</tbody>
</table>

- Modular approach – adding experimental stations.
- Final layout - Three split experimental lines.
250MeV test stand

Multi functional building

250MeV test stand layout

Total length ~70m
Emittance <0.4 mm mrad

laser beam: $\sigma_y = 270 \, \mu m$, $\Delta T = 9.9 \, ps$ (FWHM), rise & falling time = 0.7 ps
e-beams: $Q \sim 0.2 \, nC$, $\epsilon_{\text{thermal}} = 0.195 \, \mu m$, $I_{\text{peak}} = 22 \, A$

$\sigma_z = 840 \, \mu m$ $\rightarrow$ $58 \, \mu m$

$E = 255.5 \, MeV$, $\sigma_z = 1.665%$
$\sigma_x \sim 55 \, \mu m$, $\sigma_y \sim 55 \, \mu m$, $\sigma_z \sim 58 \, \mu m$
$\epsilon_{\text{ux}} \sim 0.379 \, \mu m$, $\epsilon_{\text{uy}} \sim 0.350 \, \mu m$

GUN TDS1 S-band LINAC X-band BC TDS2

100.0 MV/m 13.59 & 18.86 MV/m 17.5 MV/m 21.2 MV/m $E = 255.6 \, MeV$
37.89 degree 0.0 degree -34.2 degree 180 degree $\sigma_z \sim 1.674%$
from zero crossing $\Delta E = -20 \, MeV$ $R_{56} = 46.8 \, mm$
$\theta = 4.1 \, \text{deg}$
s = 0.0 m 2.95 m 12.3 m 32.839 m 43.339 m 51.75 m 56.89 m 65 m

$\theta = 3.0 \, \text{deg}$
Two photo injector technologies considered:

- RF - base line (CTF RF photo gun – 3GHz, 2.5 cell)
- High gradient pulsed - more innovative and risky - based on field and photo-assisted field emission (including Field Emitting Arrays).

Main topics

- Test stand overview
- High Gradient tests
- Beam characterization
- Field emitter arrays development
Test stand overview

- 500kV pulse generator
- Vacuum chamber with pulsed accelerating diode
- Two cell 1.5GHz RF cavity
- Focusing solenoids
- Diagnostic screens
- Emittance monitor (pepper pot, slits)
- Quadrupole magnets
- Dipole magnet
- Beam dumps with faraday caps
- BPMs
- Laser table
- 5 degree of freedom mover
- Clean cubicle and air filter
- 3D CAD model of 4MeV test stand
System parameters

- Max accel. diode voltage - 500kV
- Diode pulse length FLHM – 250ns
- Two sell RF cavity 1.5GHz
- Max RF power - 5MW
- RF pulse length – 5us
- Beam energy - 4MeV
- Rep. rate - 10Hz
- Laser pulse length – 10ps
- Laser wave length – 262nm
- Max laser pulse energy – 250uJ

Features

- Variable anode cathode distance
- Adjustable cathode position
- Exchangeable electrodes
- Differential vacuum system
- Bolts-free vacuum chamber
- Scintillator based dark current monitoring system

↔ Vacuum chamber and cavity cross section
Diode Accelerating Voltage

Emission is triggered by laser pulse (green waveform) at maximum negative peak of the accelerating voltage (yellow waveform) - Infinite persistence mode

Laser pulse is short (10ps FWHM) with respect to accelerating voltage change - quasi DC acceleration.

The scintillator (blue waveform) registers some parasitic X-ray activity form the RF cavity.

In case of break down or extended dark current, some distinctive pulses appear, synchronized with the high voltage waveform.

The scintillator signal copies the filling of RF cavity

⇐ Accelerating voltage, laser pulse and scintillator signal waveforms
Stainless steel electrodes – surface quality

There are clearly defects on the surface (embedded particles, inclusions, voids) but it is hard to correlate them with a breakdown location.

Typical SEM picture of polished electrode surface

Polished electrode surface under scanning electron microscope

Thanks to E. Kirk

M. Paraliev
Stainless steel electrodes - roughness

Hand polishing reproducibility is an issue!

The gross geometric surface features (like iris edge radius) are not necessarily the location of a breakdown.

Surface roughness

Surface roughness evaluation was performed “on fly”. There are not enough samples measured to get a correlation between vacuum breakdown voltage and surface roughness on a micro scale. There are some systematic issues as well. (measurement area, “post mortem” measurement…)

A more systematic study is required to evaluate the possible correlation between roughness (type of suitable roughness measurement) and breakdown voltage.

Further attempt to improve the polishing did not give significant improvement in breakdown voltage (limited ~ 120MV/m)

Thanks to S. Spielmann-Jaggi
Stainless steel electrodes - metallurgy

Breakdown performance vs. metallurgical characteristics of the SS.

Two samples of SS 316L from different ingots (different base form as well – rod and plate) were sent for analysis. The “rod” electrodes gave 109 MV/m (average of 5 pairs), “plate” electrodes 81 MV/m (average of 7 pairs)

It was not possible to draw a credible conclusion.

Electrode M4 (SS 316L rod)

Electrode A39 (SS 316L plate)

Electro-etched, top view

Electro-polished and Beraha tint etched by immersion

Electro-polished and tint etched by immersion in Beraha solution (M4 - Longitudinal, A39 - Top)

Better?!

Thanks to H. Leber
Diamond Like Carbon (DLC)

There is a broad spectrum of opinions about breakdown and emission properties of DLC. The technology is able to deposit DLC with tailored properties (thickness and conductivity) on virtually any type of metal surface (www.bekaert.com).

Features:

- Smooth and stable surface
- Mechanical properties comparable to those of diamond
- Unique electrical properties

Thanks to E. Kirk
DLC – photo emission

- DLC coating structure is complex – hard to determine the exact emission process [1].
- DLC and Diamond Like Nanocomposite (DLN) properties are not well defined since they depend on the sp2/sp3 bonding ratio (graphite/diamond) and doping levels [2].

Two possible electron photoemission mechanisms – simplified energy band diagrams


Simplified energy band diagram data:
- Copper work function $W_{Cu} = 4.7$ eV
- Titanium work function $W_{Ti} = 4.33$ eV
- DLC (DNL) assumptions:
  - DLC relative dielectric constant $\varepsilon_r = 4$
  - DLC band gap energy $E_G = 5.54$eV (intrinsic)
  - DLC electron affinity $-0.5 < \chi < 0.5$ eV
- External field $E = 100$ MV/m
- DNL conductivity is not taken in account
- Photon energy $h\nu = 4.7$ eV (262 nm)

- 0 MV/m
- 100 MV/m

0.4um 0.2um 2um

Typical DLC layer structure (PSI 080815-UF)
DLC – First results

Results for DLC type PSI 080815-UF (2μm thick, Resistivity $10^6..10^7\ \Omega\cdot\text{cm}$)

- Electrode pair A4/A3 – $227\text{MV/m@1.76mm}$
- Electrode pair A6/A5 – $270\text{MV/m@1.5mm}$
- Electrode pair A8/A7 – $100\text{MV/m@4mm (with laser)}$

The results were unexpectedly good!

No dark current was detected using the scintillator. (Solid angle factor $\sim 2\times10^{-4}$)

The photo emitted charge was $10..15\text{pC}$.

Quantum efficiency (relative) was measured over large electric field strength range – $25..100\text{MV/m}$

A breakdown occurred after an attempt to increase the laser power on the cathode surface, at $50\text{MV/m}$.

Measured quantum efficiency and analytical fit using single Schottky barrier photo-field emission assumption.

Thanks to R. Ganter
DLC – parametric study

DLC types tested to study the influence of coating layer parameters.

- **First configuration** – 2μm thick DLC on polished stainless steel, ρ ~ 5x10^6 Ω.cm (PSI 080815-UF) – 3 pairs
- **Thicker coating layer** - 4μm thick DLC, ρ ~ 5x10^6 Ω.cm (PSI 080815-UF) – 4 pairs
- **Higher conductivity** - 2μm thick DLC, ρ ~ 5x10^4 Ω.cm (PSI 080815-RG) – 4 pairs
- **Low conductivity** - 2μm thick DLC, Resistivity ~ 5x10^11 Ω.cm (PSI-080815-HR) – 4 pairs
- **Base metal** - 2μm thick DLC, ρ ~ 5x10^6 Ω.cm (PSI 080815-UF) – bronze 8 pairs, copper 5 pairs
- **Base metal roughness** 2μm thick DLC, ρ ~ 5x10^6 Ω.cm (PSI 080815-UF) rougher stainless steel – 1pair

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Thickness</th>
<th>Resistivity</th>
<th>Base</th>
<th>Av. Gradient</th>
<th>Samples</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>First configuration</td>
<td>2 μm DLC</td>
<td>5.10^6 Ω.cm</td>
<td>Polished st. steel</td>
<td>248 MV/m</td>
<td>2 (+1(^1))</td>
<td>Range 227..270 MV/m 1(^1) Used for photo emission</td>
</tr>
<tr>
<td>Thicker layer</td>
<td>4 μm DLC</td>
<td>5.10^6 Ω.cm</td>
<td>Polished st. steel</td>
<td>145 MV/m</td>
<td>4</td>
<td>Range 140..150 MV/m</td>
</tr>
<tr>
<td>Higher conductivity</td>
<td>2 μm DLC</td>
<td>5.10^4 Ω.cm</td>
<td>Polished st. steel</td>
<td>200 MV/m</td>
<td>2 (+2(^2))</td>
<td>Range 167..233 MV/m 2(^2) 2 samples died at ~55MV/m</td>
</tr>
<tr>
<td>Low conductivity</td>
<td>2 μm DLC</td>
<td>5.10^11 Ω.cm</td>
<td>Polished st. steel</td>
<td>185 MV/m</td>
<td>4</td>
<td>Range 137..291 MV/m</td>
</tr>
<tr>
<td>Copper base</td>
<td>2 μm DLC</td>
<td>5.10^6 Ω.cm</td>
<td>Polished copper</td>
<td>&gt;200 MV/m(^3)</td>
<td>2 (+3(^4))</td>
<td>3(^3) Used for emission 4(^4) Used in other configurations</td>
</tr>
<tr>
<td>Bronze base</td>
<td>2 μm DLC</td>
<td>5.10^6 Ω.cm</td>
<td>Polished bronze</td>
<td>232 MV/m</td>
<td>5 (+2(^5))</td>
<td>Range 150..324 MV/m 5(^5) 2 samples died at ~50MV/m</td>
</tr>
<tr>
<td>Rough surface</td>
<td>2 μm DLC</td>
<td>5.10^6 Ω.cm</td>
<td>Rough st. steel</td>
<td>122 MV/m</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Other materials

Even the detailed vacuum breakdown mechanism is not yet well understood there is some evidence that following mechanical properties affect the vacuum breakdown strength.

- **Melting temperature**
- **Hardness**

**Preliminary results for other materials**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>AISI</th>
<th>DIN</th>
<th>Surface</th>
<th>Deposition</th>
<th>Av. Gradient</th>
<th>Samples</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Steel (ref.)</td>
<td>~316L</td>
<td>1.443</td>
<td>polished</td>
<td>No</td>
<td>87 MV/m</td>
<td>7</td>
<td>Range 61..128 MV/m</td>
</tr>
<tr>
<td>SS (Decolletage)</td>
<td>~316L</td>
<td>1.4404+S+Cu</td>
<td>polished</td>
<td>No</td>
<td><strong>119MV/m</strong></td>
<td>4</td>
<td>Range 90..142 MV/m</td>
</tr>
<tr>
<td>SS (Implant)</td>
<td>~316LVM</td>
<td>1.4441</td>
<td>polished</td>
<td>No</td>
<td>99 MV/m</td>
<td>7</td>
<td>Range 57..137 MV/m</td>
</tr>
<tr>
<td>Mo coating</td>
<td>~316L</td>
<td>1.443</td>
<td>polished</td>
<td>Mo 2μm</td>
<td>138 MV/m</td>
<td>1</td>
<td>Without plasma cleaning</td>
</tr>
<tr>
<td>Mo coating</td>
<td>~316L</td>
<td>1.443</td>
<td>polished</td>
<td>Mo 2μm</td>
<td><strong>212 MV/m</strong></td>
<td>1</td>
<td>Plasma cleaning before deposition</td>
</tr>
<tr>
<td>ZrN coating</td>
<td>~316L</td>
<td>1.443</td>
<td>polished</td>
<td>ZrN 0.5μm</td>
<td>38 MV/m</td>
<td>1</td>
<td><strong>Bad adhesion</strong></td>
</tr>
</tbody>
</table>

“Hollow” cathode geometry:
- Emission from other materials
  - small sample
  - reduced surface field
- Emission from FEA chips
- Explore the effect of electrostatic focusing
Electron beam characterization

OPAL simulation of beam emittance and beam envelope, compared with measurements

Beam on emittance ⇒ monitor screen.

Pepper-pot image

Cathode imaging helps to study the beam propagation and laminarity

PSI logo projected on the cathode

Electron beam images on YAG screen two

Measured thermal emittance vs laser spot size (extraction field 50MV/m, $\lambda_{\text{laser}} = 262$)
Field Emitter Arrays (FEA) as a low emittance electron beam source

Double-gated emitter array

- First emitter gate controls the emission
- Second emitter gate focuses individual beamlets (reduces overall emittance)
- High gradient acceleration

Individual emitter $\varepsilon_n \sim 5 \times 10^{-3}$ mm mrad
($\sigma_x \sim 1 \mu$m, $\delta \theta \sim 15^\circ$, $U_e \sim 100$ V)

Envelope of whole array (single gate) $\varepsilon_n \sim 2.5$ mm mrad
($\sigma_x \sim 0.5$ mm, $\delta \theta \sim 15^\circ$, $U_e \sim 100$ V)

Envelope (double gate) $\varepsilon_n < 0.1$ mm mrad
($\sigma_x \sim 0.5$ mm, $\delta \theta \sim 0.5^\circ$, $U_e \sim 100$ V)
FEA fabrication

1. Etching mask patterning
   - SiO₂
   - Si (100) 4’ wafer

2. Mold (anisotropic) etching and oxidization

3. Multi-layer deposition and electro-plating
   - Ti/Pd
   - Mo
   - Ni

4. De-molding

[Images of FEA structures]
FEA fabrication

1. Etching mask patterning
2. Mold (anisotropic) etching
3. Multi-layer deposition and electro-plating
4. De-molding
5. Dicing (sawing)
6. Deposition of insulator and gate electrode
7. Planarization by polymer PR
8. Etch-back
9. Through-hole opening and polymer removal
10. Gate-electrode patterning (photolithography and etching)

[11. Dicing (sawing)]

12. For second-gate, repeat 6-9
**FEA evaluation**

Emission Scaling

- 40x40 tips: Current \(\sim x16\)
- 10x10 tips

**Projected current at high extraction field**

- > 10 MV/m

**Measured space-charge limit at low extraction field**

- \(\sim 0.1\) MV/m

**Thanks to S. Tsujino**
Summary

- Very encouraging results with DLC coated electrodes (present limits):
  - Breakdown field up to 300 MV/m
  - Photo emission at up to 170 MV/m
  - Stable emission at 100 MV/m (~40 pC)
  - Charge up to 80pC (~10 ps laser)
  - Quantum efficiency ~10^{-6}

- 200 MV/m breakdown with 2 um Mo on stainless steel
  - The emission properties are to be explored further

- Beam parameters evaluation
  - Low energy beams emittance preservation
  - Improvement of low emittance measurement techniques
  - Comparison of different emitting materials

- Progress with single and double gated FEA devices
  - Demonstrated working double gated device
  - Control apex radius in 10 nm scale (single gate FEA – current homogeneity)
  - Single tip current capability – 3 – 20 uA per tip for small arrays
Outlook

- In parallel with the RF photo injector base line design we continue to investigate alternatives for high brightness electron sources.

- 4 MeV pulsed high gradient photo gun test stand is used to study new cathode materials and techniques for generation and handling of low emittance electron beams.

- An extensive R&D work is continuing on field emitter arrays based, room temperature cathode.

Thank you for your attention!
Discussion