Production of electron beams using lasers at CERN: research, development and operation.

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EN-STI-LP
Outline

- Overview on CERN photoinjector activities
  - CTF3 / CLEAR Facilities
  - AWAKE experiment
  - Laser upgrades for photoinjectors
- Photocathode preparation facility at CERN
  - Development of co-deposition of $\text{Cs}_2\text{Te}$ and $\text{Cs}_3\text{Sb}$ photocathodes
- Lifetime studies in RF and DC guns
- XPS surface analysis
- Conclusions and outlook
Photoinjectors at CTF3

1.5 GHz RF bunching system
3 GHz fully loaded accelerating structures
Delay Loop (42 m)
Combiner Ring (84 m)

Thermoionic Gun
DogLeg experiment
Magnetic chicane
Feed-forward experiment

CTF2 experimental area
Test Beam Line (TBL)
CLEX experimental area
Two Beam Module (TBM)
CALIFES injector

DRIVE beam
MAIN beam

PHIN
Cs$_2$Te / Cs$_3$Sb Co-deposition

Cs$_2$Te @ CALIFES In-situ, dual layer

Now at: AWAKE

Test facility for:
- X-band technology
- Bunch compression
- Advanced beam dynamics
- Plasma lens, AWAKE...
- Wakefield physics
- Radiation studies
# CLIC / CTF3 requirements for e- guns

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Main beam</th>
<th>Drive beam</th>
<th>CLIC requirem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge per bunch (nC)</td>
<td>0.6</td>
<td>2.3 (9.2)</td>
<td>8.4</td>
</tr>
<tr>
<td>Macro pulse length (μs)</td>
<td>&lt;0.2</td>
<td>1.2 (1.6)</td>
<td>140</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>0.66</td>
<td>0.66</td>
<td>2.0</td>
</tr>
<tr>
<td>Gun RF / bunch rep. rate (GHz)</td>
<td>3 / 1.5</td>
<td>3 / 1.5</td>
<td>1 / 0.5</td>
</tr>
<tr>
<td>Number of bunches in macro pulse</td>
<td>1 – 300</td>
<td>1800 (2400)</td>
<td>70000</td>
</tr>
<tr>
<td>Macro pulse rep. rate (Hz)</td>
<td>5</td>
<td>5 (5)</td>
<td>50</td>
</tr>
<tr>
<td>Charge per macro pulse (μC)</td>
<td>&lt;0.18</td>
<td>4.1 (5.5)</td>
<td>590</td>
</tr>
<tr>
<td>Beam current in macro pulse (A)</td>
<td>0.9</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Bunch length (ps)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Charge stability</td>
<td>&lt;3%</td>
<td>&lt;0.25% (&lt;1%)</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Cathode lifetime (Cs₂Te)</td>
<td>1 y (QE&gt;0.3%)</td>
<td>&gt;50 h (QE&gt;3%)</td>
<td>&gt;150 h (QE&gt;3%)</td>
</tr>
<tr>
<td></td>
<td>(300 h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathode type</td>
<td>Cs₂Te (in-situ, dual layer)</td>
<td>Cs₂Te, Cs₃Sb (co-deposition)</td>
<td>To be defined</td>
</tr>
<tr>
<td>Norm. emittance (μm)</td>
<td>&lt;20</td>
<td>&lt;25 (14)</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

CALIFES and PHIN lasers at CLEAR

<table>
<thead>
<tr>
<th></th>
<th>DRIVE beam</th>
<th>MAIN beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHIN</td>
<td>CALIFES</td>
<td></td>
</tr>
<tr>
<td>charge/bunch (nC)</td>
<td>2.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Number of subtrains</td>
<td>8</td>
<td>NA</td>
</tr>
<tr>
<td>Number of pulses in subtrain</td>
<td>212</td>
<td>NA</td>
</tr>
<tr>
<td>gate (ns)</td>
<td>1272</td>
<td>20-150</td>
</tr>
<tr>
<td>bunch spacing (ns)</td>
<td>0.666</td>
<td>0.666</td>
</tr>
<tr>
<td>bunch length (ps)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Rf reprete (GHz)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>number of bunches</td>
<td>1802</td>
<td>32</td>
</tr>
<tr>
<td>machine reprete (Hz)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>margin for the laser</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>charge stability</td>
<td>&lt;0.25%</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>QE(%) of Cs2Te cathode</td>
<td>3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
AWAKE experiment at CERN
Recap Photocathodes Properties and Materials

<table>
<thead>
<tr>
<th>Class</th>
<th>Material</th>
<th>QE</th>
<th>Wavelength</th>
<th>Gun</th>
<th>Application</th>
</tr>
</thead>
</table>
| Normally conducting metals   | Cu, Mg                         | $10^{-5}$ - $10^{-4}$ | UV         | NC-RF | Low Rep rate FELs (LCLS, SwissFEL…)
| Super-conducting metals      | Nb, Pb                         | $10^{-5}$ - $10^{-4}$ | UV         | SC-RF | High Rep rate FELs           |
| Positive electron affinity semiconductor | Cs$_2$Te, Cs$_3$Sb, K$_2$CsSb ...and others... | 0.1 – 0.2 | Visible – UV | NC-RF, DC | FELs, ERLs                   |
| Negative electron affinity semiconductor | GaAs, etc                    | 0.1-0.35 | IR – Visible | DC (XHV) | Polarized sources, ERLs (ALICE) |

- **Metals**
  - Low quantum efficiency -> requires high power lasers -> plasma is formed
  - Robust and simple

- **Semiconductors**
  - High quantum efficiency at extended wavelength range.
  - More difficult to maintain – ions can cause decomposition and surface damage, vacuum...
  - Cs$_2$Te is quite standard, but requires UV

Cs$_2$Te is quite standard, but requires UV
Photocathode Preparation Facility at CERN

Originally designed for producing photocathodes for the CLIC project:

- CERN Photocathode Preparation Facility has been working without interruption since >25 years.
- Focus on development of manufacturing techniques for Cs$_3$Sb and Cs$_2$Te photocathodes.

Cathode position during PRODUCTION

Bunch charge measured by:
- Wall Current Monitor (WCM)
- Fast Current Transformer (FCT)
- Faraday Cup (FC)
Photocathode preparation by co-deposition

Co-Deposition setup

- **Substrate**: Copper with diamond powder polished surface
- **Good isolation** for each quartz
- **Substrate is heated** to 125°C for Cs₃Sb, and not heated for Cs₂Te.
- **Thickness monitors**: Quartz microbalances for Cs and Te/Sb.
- **Mask** allow to measure both evaporation rates separately.
- **Online QE measurement**: Main tool for optimizing the deposition process -> Mandatory for co-deposition.

<table>
<thead>
<tr>
<th></th>
<th>Quartz1 (Cs) (nm)</th>
<th>Quartz2 (Te) (nm)</th>
<th>Isolation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te (S64)</td>
<td>0.25</td>
<td>40.05</td>
<td>160</td>
</tr>
<tr>
<td>Cs (S68)</td>
<td>23.12</td>
<td>0.16</td>
<td>145</td>
</tr>
</tbody>
</table>
Co-deposition process

- Co-deposition: Cs and Sb (or Te) evaporated at the same time. The metallic elements can mix together in the vapour phase.
- The evaporators power is adjusted in order to reach a maximum value of QE.
- Average pressure during the process is 1e-8 mbar.
- Tricky business, depends on the skills of the operator (and experience).
Example: Deposition results for Cs$_3$Sb

- In contrast to the Cs$_2$Te results, the QE of Cs$_3$Sb cathodes initially continues to increase during beam production in DC gun.

- Reason for this behavior still unclear, but maybe due to re-organization of Cs and Sb atoms.

- Maximum QE achieved is 7.5 % (measured in DC gun)
Cs$_3$Sb vs Cs$_2$Te (QE comparison)
Cs$_2$Te / Cs$_3$Sb photocathode lifetime studies

- Operation with 1.6 $\mu$s, 2.3 nC/bunch at 0.8 Hz repetition rate.
- **Vacuum** at the exit of the gun stayed low e-10 mbar range.
- No real decrease of the QE visible over >100h of beam operation.

Cs$_2$Te

- 1/e lifetime ~100 hours, corresponding to a lifetime of ~170h above QE = 0.5%

Cs$_3$Sb

Collaboration with LAL to construct UHV carrier vessel allows transfer of photocathodes from production laboratory to other facilities and laboratories.

Successful transfer to XPS laboratory at CERN.

XPS allows material characterization of the surface.

Aim: Study the correlation between the chemical composition and the QE.
XPS Surface analysis of photocathodes

**Fresh Photocathode:**
- Sb-rich phase
- O 1s peaks could be explained by Cs$_3$O$_{11}$ and H$_2$O

**Used Photocathode:**
- Sb-rich peak has increased.
- Oxygen and carbon contamination is present and can be explained by CO$_3^{2-}$
- Results indicate that perhaps Cs probably reacted with CO$_2$ to produce Cs$_2$CO$_3$
- Cs$_3$O$_{11}$ or H$_2$O not excluded.
Some conclusions related to Cs$_3$Sb

• Cs$_3$Sb seems to be **less robust** than Cs$_2$Te and more sensitive to non-optimal operation conditions.

• For obtaining good lifetimes with Cs$_3$Sb cathodes it is important to have the following conditions:
  • Excellent vacuum
  • Very stable phase between RF and laser
  • Linear charge extraction regime of the gun. Otherwise non-extracted e- can cause desorption in the gun -> bad lifetime.
  • Good laser beam shape characteristics

• More studies are needed, but mature technology with great potential for high charge production in ERLs for example.
Conclusions & Outlook

• CTF3 was closed at the end of 2016. But since 2017 the CLEAR facility makes use of the existing e- accelerator for a variety of tests:
  • X band technology.
  • Plasma lens development.
  • Novel diagnostics based on THz...
  • Instrumentation development.

• The production of photocathodes at CERN continues, in particular alkali antimonide and telluride.

• Capability of adapting photocathode design to specific projects, including future accelerators such as LHeC and FCC-eh.
Thanks for your attention!
Example 1: Cs$_2$Te Photocathodes for CLIC (CTF3)

- Photocathodes produced by co-evaporation seem to be quite sensitive to the quality of vacuum.

Achieved quantum efficiency (QE):

$QE[\%] = \frac{124 \times Q[nC]}{\lambda[nm] \times E[\mu J]}$

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>Min QE</th>
<th>Mean QE</th>
<th>Max QE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs$_2$Te (20 u.)</td>
<td>8.2 %</td>
<td>14.9 %</td>
<td>24 %</td>
</tr>
</tbody>
</table>