Photocathodes Studies @ FLASH: Quantum Efficiency (QE)

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Main Topics

- **Overview Photocathode Production**
  - Production at LASA
  - Transportation to DESY
  - Database

- **CW QE measurements (Hg lamp)**
  - Experimental set-up
  - Results of measurements at FLASH

- **Pulsed QE measurements**
  - Laser energy calibration
  - Measurements on different cathodes
  - Results
  - QE maps

- **Conclusions**
Cathode in the RF Gun

- Photocathode inserted into the gun backplane
Quantum Efficiency

$QE(\%) \approx 0.5 \times \frac{Q(nC)}{E(\mu J)}$

The design asks for 72000 nC/sec

- QE required for FLASH: 
  $> 0.5 \%$ to keep the laser in a reasonable limit: within an average power of $\sim W$
- Design of present laser accounts for 
  $QE=0.5\%$ with an overhead of a factor of 4 and has an average power of 2 W (IR)
- $Cs_2Te$ cathodes found to be the best choice
Photocathode Production: Preparation Chamber

Photocathodes are grown @ LASA on Mo plugs under UHV condition.

- UHV Vacuum System - base pressure $10^{-10}$ mbar
- 6 sources slot available
- Te sources out of 99.9999 % pure element
- Cs sources from SAES®
- High pressure Hg lamp and interference filter for online monitoring of QE during production
- Masking system
- 5 x UHV transport box
Production: from Mo plugs...

1. Milling and/or lathing of the plug from the rod (arc cast / sintered)
2. Buffer Chemical Polishing (BCP)
3. Polished to optical finishing (roughness about 10 nm)
4. Reflectivity measurement to check optical polishing

Reduced dark current by an one order of magnitude

Reflectivity [%]
- Sintered: $R = 56.3 \pm 1.6 \%$
- ArcCast: $R = 56.5 \pm 1.0 \%$

Polishing procedure
- before
- after

Production: from Mo plugs...

Polishing procedure
- before
- after

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Reflectivity [%]
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- ArcCast: $R = 56.5 \pm 1.0 \%$
Production: ...to photocathodes growth

$Cs_2Te$ photocathode recipe:

- during the evaporation, the plug is heated to 120°C.
- The dimension of the film is determined by a circular masking (the actual one is 5mm diameter)
- first, a thin layer of 10nm of Te is produced
- then Cs is evaporated at a rate of 1nm/min
- during the deposition, the film is illuminated with UV ($\lambda=254\text{ nm}$) of a Hg-lamp to monitor the quantum efficiency.
- the evaporation is stopped, when the QE is at maximum.

Different stoichiometric compounds form during Cs deposition till the “correct” Cs/Te ratio is reached corresponding to the QE maximum.
Production: diagnostic on photocathodes

The photoemissive properties of produced cathodes are checked performing spectral response measurements and QE maps (also at different wavelengths).

- QE map @ 254nm
  (Hg lamp, interferential filter, 1mm spot diameter)

- Spectral response
  (Hg lamp, interferential filters, 3mm spot diameter)

Just after the deposition

d=5mm

QE map: 73-1i(254nm) of cathode #73.1 (23-03-2004), +/-4mm, step 0.5mm
Produced cathodes, are loaded in the transport box and shipped to FLASH or PITZ keeping the UHV condition.

The box is then connected to the RF gun.

Since 1998, we have shipped to TTF phase I, FLASH and PITZ:

- 49 x Cs$_2$Te
- 2 x KCsTe
- 25 x Mo

• Total transfers from LASA: 25
Production: The Photocathode Database

Many of the data relative to photocathodes (production, operation, lifetimes) and transport box are stored in the “photocathode database” whose WEB-interface is available at:

http://www.lasa.mi.infn.it/ttfcathodes/

The database keeps track of the photocathodes in the different transport boxes and in the different labs (TTF, PITZ and LASA).
**CW QE measurements: Experimental set-up**

The experimental set-up for the CW QE measurements is mainly composed by:

- a high pressure Hg lamp
- Interferential filters (239nm, 254nm, 297nm, 334nm)
- Pico-Amperemeter
- Power energy meter
- Neutral density filters
- Optical components (1 lens, 1 mirror, 2 pin-holes)
CW QE measurements: Results

Measured @ DESY on March 31 2006

Data have been fitted to evaluate: the QE @ 262nm and Eg+Ea

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Dep. data</th>
<th>QE@254nm (LASA)</th>
<th>Operation lifetimes</th>
<th>QE@254nm (DESY)</th>
<th>QE@262nm (DESY)</th>
<th>Eg+Ea (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73.1</td>
<td>23-Mar-05</td>
<td>7.9%</td>
<td>86</td>
<td>1.64%</td>
<td>0.79%</td>
<td>4.165</td>
</tr>
<tr>
<td>72.1</td>
<td>22-Mar-05</td>
<td>9.2%</td>
<td>166</td>
<td>0.44%</td>
<td>0.33%</td>
<td>4.168</td>
</tr>
<tr>
<td>23.2</td>
<td>16-Sep-04</td>
<td>7.2%</td>
<td>161</td>
<td>0.22%</td>
<td>0.15%</td>
<td>4.157</td>
</tr>
</tbody>
</table>

Cathode 73.1: QE@262nm = 0.79% - Slope = 1.2417

Cathode 72.1: QE@262nm = 0.33% - Slope = 1.2422

Cathode 23.2: QE@262nm = 0.15% - Slope = 1.6375

FLASh seminar - October 26, 2006
CW QE measurements: Data Analysis

- **CW data analysis**
  - Fitting of the spectral response

\[
QE = A \cdot \left[ h\nu - (E_G + E_A) \right]^m
\]

where \( A \) is a constant, \( E_G \) and \( E_A \) are energy gap and electron affinity.

An example is given for the analysis of the CW QE data for cathode 73.1.

In this case:

- \( E_G + E_A = 4.165 \text{ eV} \)
- \( m = 1.24 \)

(for a “fresh” \( \text{Cs}_2\text{Te} \) cathode we typically have \( E_G + E_A = 3.5 \text{ eV} \))
Pulsed QE measurements: laser energy calibration experimental set-up

The laser energy transmission (from the laser hut to the tunnel) has been evaluated for different iris diameters (3.5mm, 2.0mm and 0.16mm) and different energies.

The laser energy has been measured using a Pyroelectric gauge (Joulemeter), varying the laser energy using the variable attenuator ($\lambda/2$ wave plate + polarizer).
Pulsed QE measurements: laser beamline transmission analysis

- The QE measurement procedure uses the laser energy measured on the laser table
- Transmission to the vacuum window is regularly measured
- Transmission of the vacuum window (92 %) and reflectivity of the vacuum laser mirror (90 %) are accounted for

iris = 3.5 mm as an example:

- Laser energy is measured as a function of the variable attenuator setting
- fitted by sin² to evaluate the transmission

Laser energy is measured as a function of the variable attenuator setting and fitted by sin² to evaluate the transmission.
Pulsed QE measurements: laser beam line transmission measurements

The laser beamline transmission has been evaluated four times (from March to August 2006) to take care of changes in the optical transmission path.

<table>
<thead>
<tr>
<th>Iris Φ (mm)</th>
<th>Iris (step)</th>
<th>Date (tunnel file)</th>
<th>Date (laser room file)</th>
<th>Transmission</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>16512</td>
<td>12-Mar-06</td>
<td>12-Mar-06</td>
<td>13.21 %</td>
<td>From 12 March to 31 March</td>
</tr>
<tr>
<td>2.0</td>
<td>17280</td>
<td>12-Mar-06</td>
<td>12-Mar-06</td>
<td>6.64 %</td>
<td></td>
</tr>
<tr>
<td>0.16</td>
<td>18208</td>
<td>not done</td>
<td>not done</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>16512</td>
<td>31-Mar-06</td>
<td>31-Mar-06</td>
<td>17.1 %</td>
<td>From 31 March to 6 June</td>
</tr>
<tr>
<td>2.0</td>
<td>17280</td>
<td>31-Mar-06</td>
<td>31-Mar-06</td>
<td>8.75 %</td>
<td></td>
</tr>
<tr>
<td>0.16</td>
<td>18208</td>
<td>31-Mar-06</td>
<td>31-Mar-06</td>
<td>0.85%</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>16512</td>
<td>not done</td>
<td>not done</td>
<td>-</td>
<td>From 6 June to 7 Aug</td>
</tr>
<tr>
<td>2.0</td>
<td>17280</td>
<td>6-June-06</td>
<td>6-June-06</td>
<td>7.18 %</td>
<td></td>
</tr>
<tr>
<td>0.16</td>
<td>18208</td>
<td>not done</td>
<td>not done</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>16512</td>
<td>not done</td>
<td>not done</td>
<td>-</td>
<td>From 7 August till now</td>
</tr>
<tr>
<td>2.0</td>
<td>17280</td>
<td>7-Aug-06</td>
<td>7-Aug-06</td>
<td>4.49 %</td>
<td></td>
</tr>
<tr>
<td>0.16</td>
<td>18208</td>
<td>not done</td>
<td>not done</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Pulsed QE measurements: measurement analysis

The QE measurement is done following this procedure:

1. Measurement of the charge (toroid T1, $Q[C]$)
3. Calculation of the energy on the cathode $E_{\text{cath}} [J]$ using transmission (considering the losses due to the vacuum window and mirror)

The QE value is then obtained fitting the charge trend @ low charge to be sure not to be affected by the space charge

$\text{QE}[$%$] = \frac{n_e}{n_{\text{ph}}} \cdot 100 = \frac{Q[C] \cdot E_{\text{ph}} [eV]}{E_{\text{cath}} [J]} \cdot 100$

262 nm: $\text{QE}($%) $\approx 0.5 \cdot \frac{Q(nC)}{E(\mu J)}$

✓ The relative and systematic error are in the order of 20 %.
✓ The systematic error is mainly due to the uncertainty of identifying the linear part for the fit and due to the transmission measurement uncertainty
Pulsed QE measurements: cathode lifetime

QE of cathodes are measured frequently within months.

Example: cathode 72.1 and 73.1.

- We define the end of lifetime when the QE reaches 0.5%
- The CW QE of cathode 73.1 is compared with the pulsed QE measured the same day.
- The difference may be explained considering the increase of the charge due to the field enhancement.

- All cathodes show a drop of the QE over time, with different characteristics.
Pulsed QE measurements: drop of QE with time

We can relate the drop of QE with the vacuum condition in the RF gun.

- As an example, early 2006, the RF gun has been operated with 300 μs long RF pulses.
- Up to this, the pulse length was restricted to 70 μs.
- During the long pulse operation period, the pressure increased from $5 \div 7 \cdot 10^{-11}$ mbar to $2 \cdot 10^{-10}$ mbar.
- This coincides with the drop of QE of cathode 73.1.
Pulsed QE measurements: cathode 78.1

Referring to cathode 78.1, several measurements have been done during about 3 months (period: April, 19 to July, 11).

Also this cathode shows a drop of the QE vs. time.

- long pulse operation (increase of vacuum)
- different growth of the cathode during deposition
- damaging due to dark current coming from ACC1

![Graph showing QE measurements over time]

- 78.1 just after the deposition
- 78.1 during operation
Comparison between:

**Pulsed QE and CW QE measurements**

The pulsed QE measurements of cathode $72.1$ and $73.1$ have been compared with the CW QE value @ $\lambda = 262$nm, evaluated from the spectral response.

The CW QE respect to the pulsed QE value is lower:

- this can be due to the high accelerating field on the cathode in pulsed QE measurements.
Pulsed QE measurements: QE vs. phase laser/RF gun

- Measurements have been performed on two cathodes varying the laser/RF gun phase.

For cathodes 72.1 and 78.1, the measured QE @ 70 deg is higher respect to the one measured @ 38 deg.
Pulsed QE measurements: analysis (1)

- RF data analysis - QE enhancement
  - QE @ given acc. gradient \( E_{\text{acc}} \) and phase \( \phi \)
  - with a given laser energy without space charge

\[
QE = A \cdot \left[ h \nu - (E_G + E_A) + q_e \cdot \sqrt{\frac{q_e \cdot \beta \cdot E_{\text{acc}} \cdot \sin(\phi)}{4 \cdot \pi \cdot \varepsilon_0}} \right]^m
\]

where \( E_{\text{acc}} \) is the accelerating field, \( \phi \) is the phase RF/laser, \( \beta \) is geometric enhancing factor.

Using the values calculated before for \( A \), \( E_G + E_A \) and \( m \), the geometric enhancing factor results:

\( \beta = 10 \)

with \( E_{\text{acc}} = 40.9 \text{ MV/m} \) and the phase \( \phi = 38^\circ \) from the experimental measurement.
**Pulsed QE measurements: analysis (2)**

- **RF data analysis - Laser spot profile influence**
  - QE @ given $E_{\text{acc}}$ and $\phi$, at different laser energies
  - Space charge forces have to be taken into account and depends on the laser transverse profile.

\[
\begin{align*}
\text{Charge} &= \frac{q_c}{1 + \frac{q_c}{2} \left( \frac{r_{\text{beam}}}{r_{\text{acc}}} \right)^2} \\
q_c &= E_{\text{acc}} \cdot \phi \cdot \frac{\pi}{180} \cdot \pi r_{\text{beam}}^2 \cdot nC
\end{align*}
\]

**Extracted Charge vs. Laser Energy**
Pulsed QE measurements: Comments to the analysis

- The influence of the laser spot profile mainly affects the shape of the charge vs. laser energy curves.
- With this “simple” model, we can explain the shape of the curve and some of the asymptotic values.
- It would be very helpful to have CW QE and pulsed QE measurements in the same day (QE constant) to further study the model.

Example for cathode 73.1

- Laser spot/iris diameter = 3.5mm.
- Extrapolated spot size = 3.8mm.
- QE from the linear fit = 3.1%
- QE from this analysis = 3.23%
Pulsed QE measurements: QE map (1)

QE maps by scanning a small laser spot over the cathode tiny iris = 0.16mm ($\sigma$), step size 0.3 mm.

Map of the charge emitted from the cathode moving the iris only.

**cathode 73.1**

Map of charge emitted from the cathode moving iris and mirror together.

The photoemissive layer is 5 mm in diameter.

Well reproduced, center position: (-0.2,-2.2) mm.

5mm diameter of the photoemissive layer
Pulsed QE measurements: QE map (2)

QE maps cathode 77.1, used to center the laser beam on the cathode.

 QE maps before alignment

 QE maps after centering of the laser beam
Conclusion

• **CW QE measurements:**
  - Experimental set-up in the tunnel
  - The CW QE of 3 cathodes has been measured @ FLASH

• **Pulsed QE measurements:**
  - Laser beamline transmission calibration
  - QE vs. time and vs. RF phases
  - Analysis of the pulsed QE measurements:
    • $E_{acc}$, RF phase, etc.

• **QE maps**
  - Tool to check the centering between the laser spot and the photoemissive film

• **For the future**
  - On-line measurements of the laser beamline transmission