European Workshop on Photocathodes for Particle Accelerator Applications

# R&D experience on $Cs_2Te$ photocathode for FEL accelerator applications


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Laboratorio Acceleratori e Superconduttività Applicata

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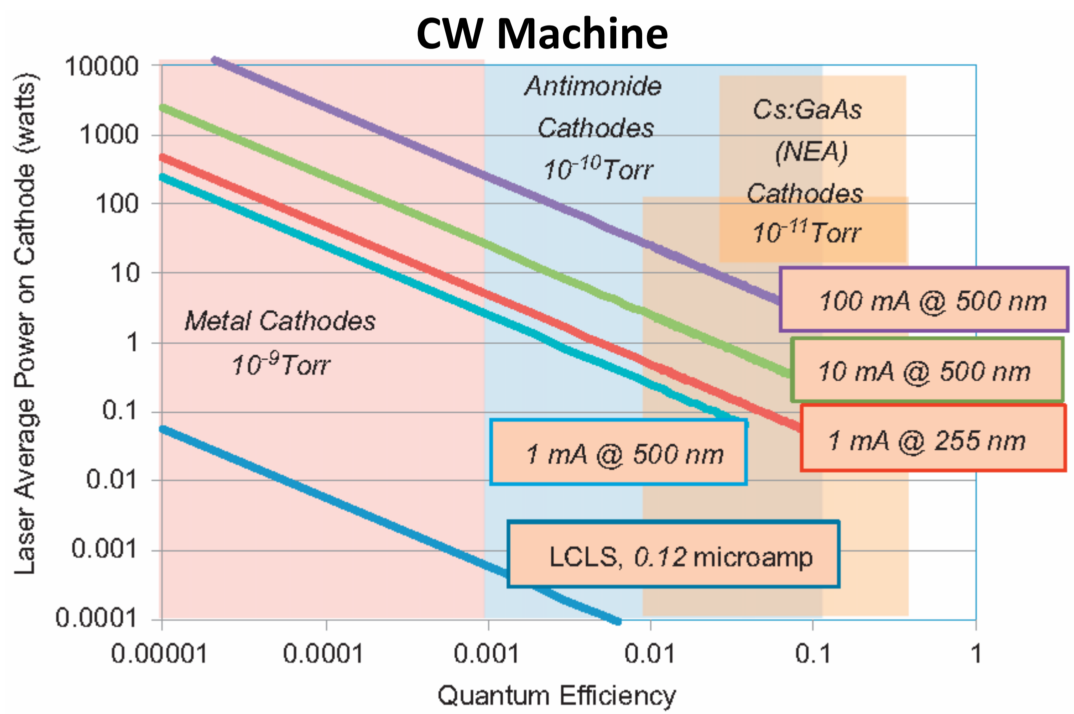
# High QE Photocathodes in RF Guns

- High charge, long pulses and high repetition rate machine require high QE photocathodes given the average laser power of some tens of Watts in IR.
- For example **FLASH** or European **XFEL** require to produce thousands to ten-thousands of bunches per second, each of nearly 1 nC.




D. Dowell et al., NIM A 622(2010) 685



# Photocathodes Choice

- **Semiconductor** photocathodes have high QE …
  - Their sensitivity to gas exposition requires UHV conditions.
- … the use in RF Gun requires also:
  - QE uniformity
  - Low dark current
  - Long operative lifetime
  - Stable operation along the train
  - Fast response time

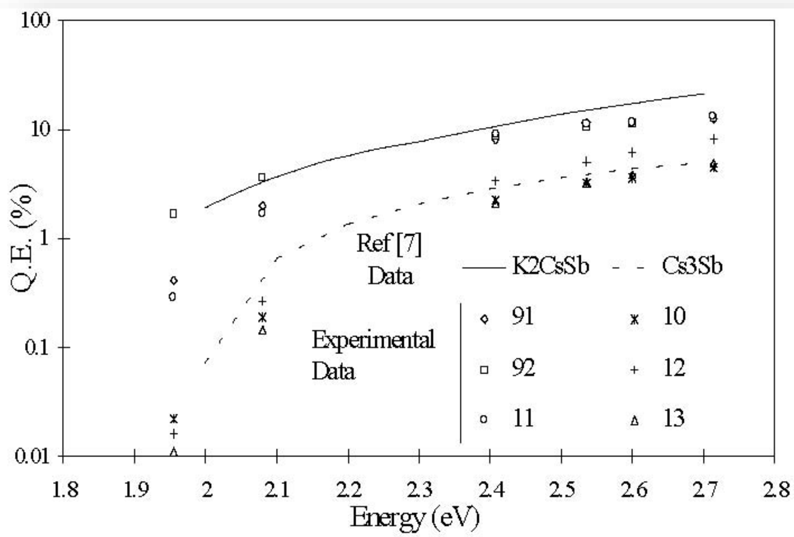
| Cathode type | Cathode | Typical wavelength & energy, $\lambda_{opt}$ (nm), (eV) | Quantum efficiency (electrons per photon) | Vacuum for 1000 h (Torr) |
|---|---|---|---|---|
| **PEA: mono-alkali** | $Cs_2Te$ | 211, 5.88 | 0.1 | $10^{9}$ |
| | | 264, 4.70 | – | – |
| | | 262, 4.73 | – | – |
| | $Cs_3Sb$ | 432, 2.87 | 0.15 | ? |
| | $K_3Sb$ | 400, 3.10 | 0.07 | ? |
| | $Na_3Sb$ | 330, 3.76 | 0.02 | ? |
| | $Li_3Sb$ | 295, 4.20 | 0.0001 | ? |
| **PEA: multi-alkali** | $Na_2KSb$ | 330, 3.76 | 0.1 | $10^{10}$ |
| | $(Cs)Na_3KSb$ | 390, 3.18 | 0.2 | $10^{10}$ |
| | $K_2CsSb$ | 543, 2.28 | 0.1 | $10^{10}$ |
| | $K_2CsSb(O)$ | 543, 2.28 | 0.1 | $10^{10}$ |
| **NEA** | GaAs(Cs,F) | 532, 2.33 | 0.1 | ? |
| | | 860, 1.44 | 0.1 | ? |
| | GaN(Cs) | 260, 4.77 | 0.1 | ? |
| | GaAs(1 − $x$)Px $x$~0.45 (Cs,F) | 532, 2.33 | 0.1 | ? |
| **S-1** | Ag–O–Cs | 900, 1.38 | 0.01 | ? |

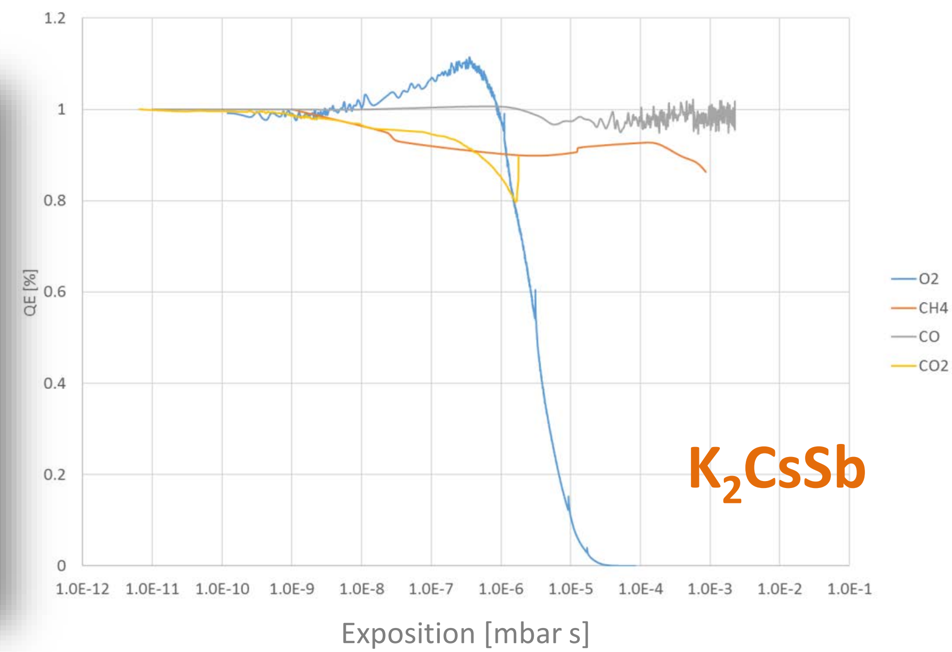
D. Dowell et al., NIM A 622(2010) 685



# Multi Alkali Antimonied

- We started in the late '90s studying multialkali compounds based on Sb ($Cs_3Sb$ and $K_2CsSb$).
- $Cs_3Sb$ was also tested in a SC Gun at Wuppertal University.
- High QE in the visible ***BUT*** ….



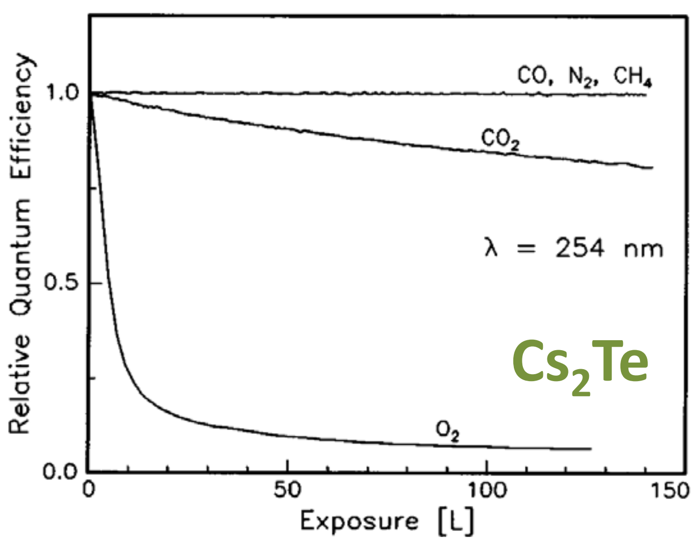



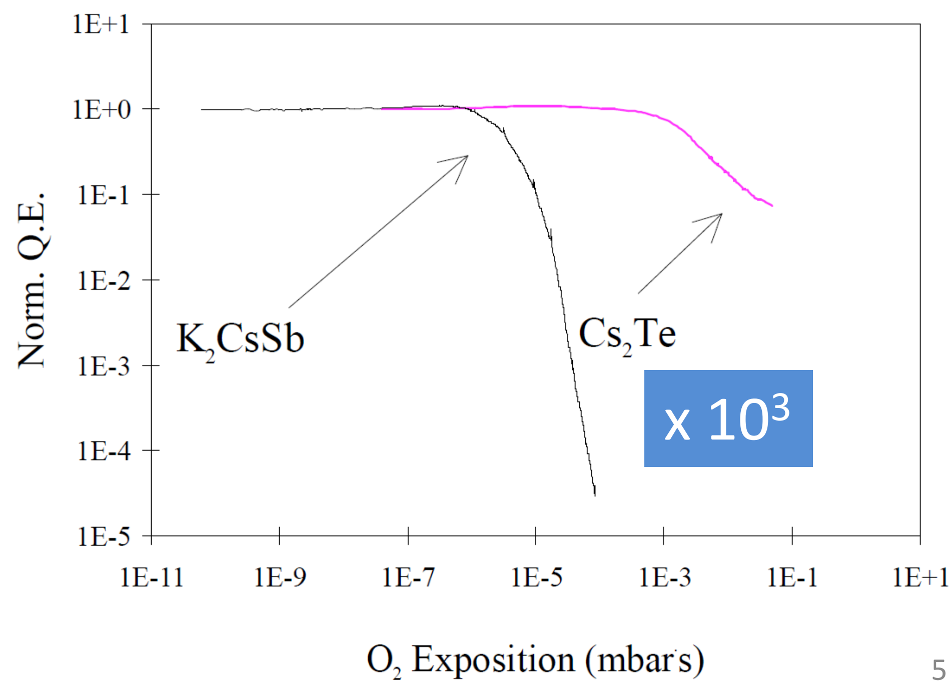

**Very Sensitive To Pollution**

1 Langmuir = $10^{-6}$ mbar s

# Multi Alkali Telluride

- Given the good results obtained at LANL, we started studying cesium telluride (**$Cs_2Te$**) and later cesium potassium telluride (**$K_2CsTe$**).
- The large photoemission threshold (≈ 3.5 eV) forced to use UV light but these cathodes showed to be more robust.



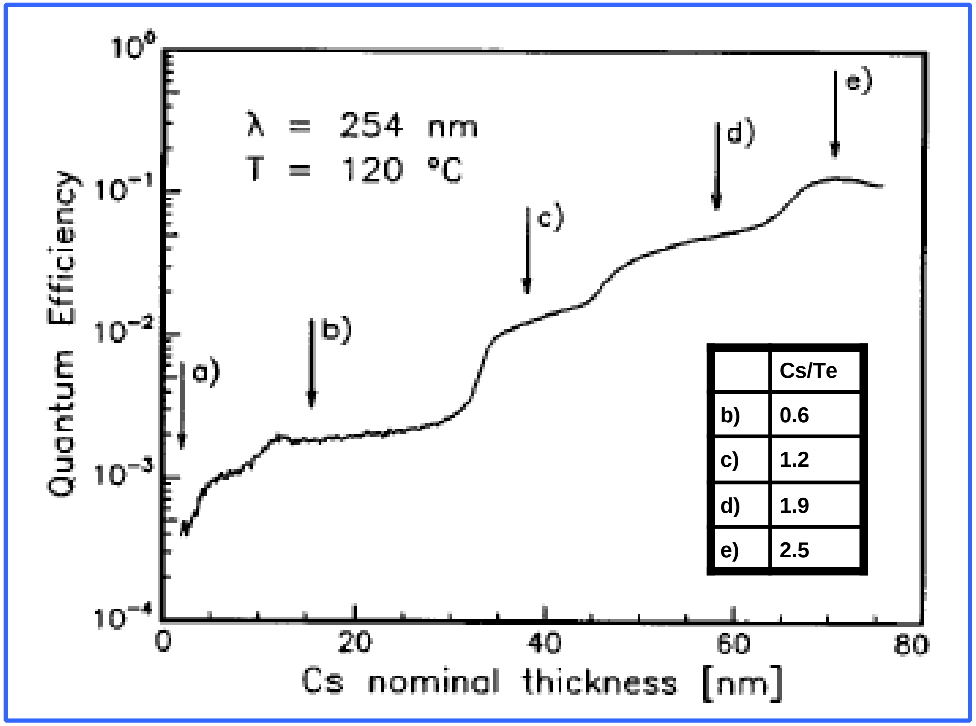




1 Langmuir = $10^{-6}$ mbar s

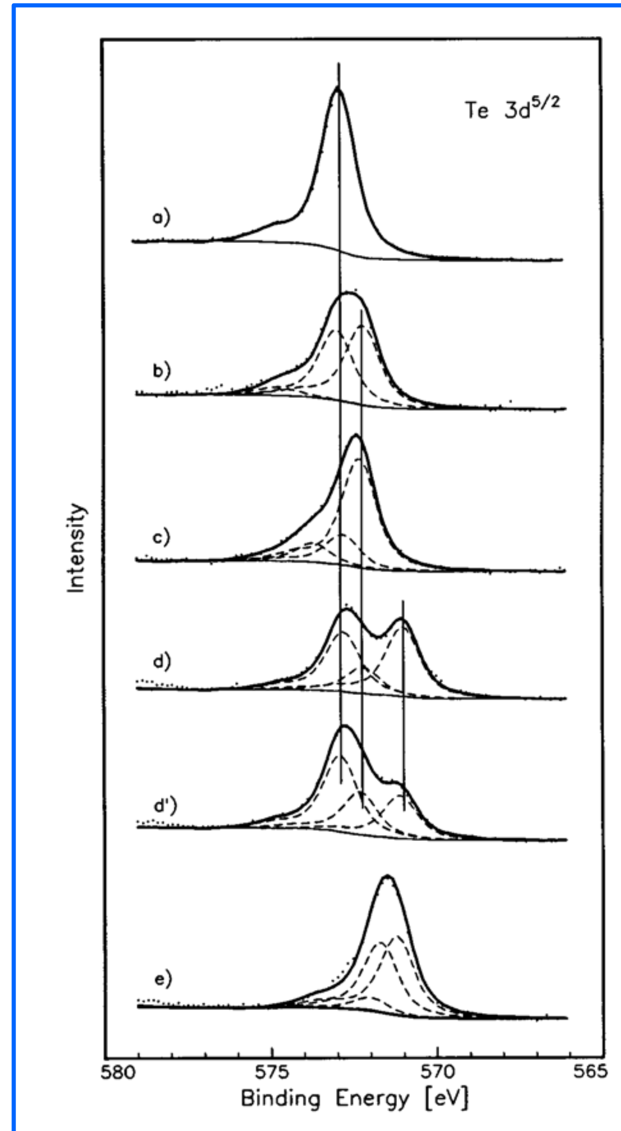
# $Cs_2Te$ GROWTH INVESTIGATIONS



# $Cs_2Te$ Recipe Investigation




A. di Bona et al., JAP80(1996)3024

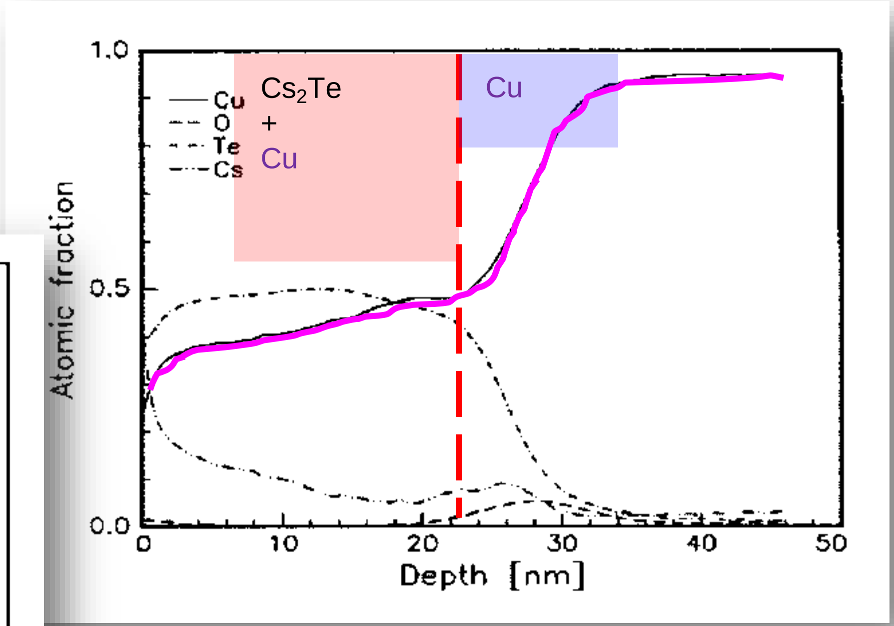


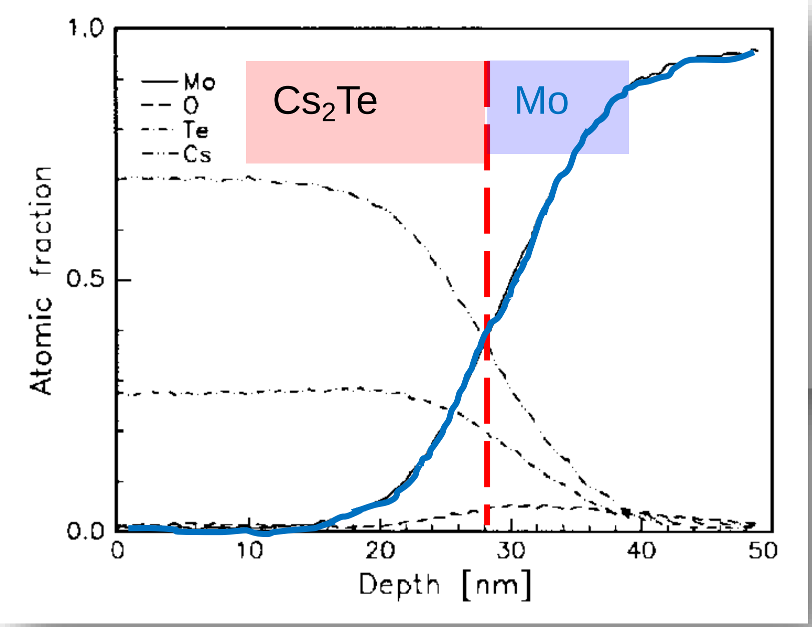

## Cathode growth

- The recipe was developed in Milano and as a "process" transfer to Modena for analysis.
- Auger Electron Spectroscopy shows formation of different stoichiometric compounds during Cs deposition. The "correct" Cs/Te ratio is reached at QE maximum.

# Substrate Contribution

- The Mo plug prevents diffusion of the film (AES + $Ar^+$ sputtering study). Estimated photocathode typical thickness is 20-30 nm.

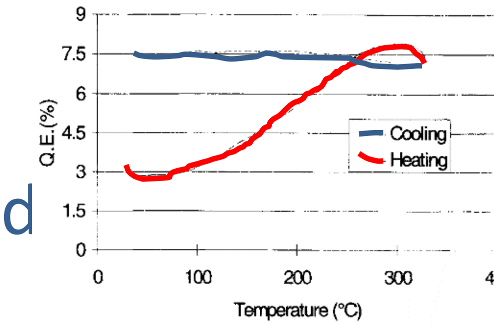


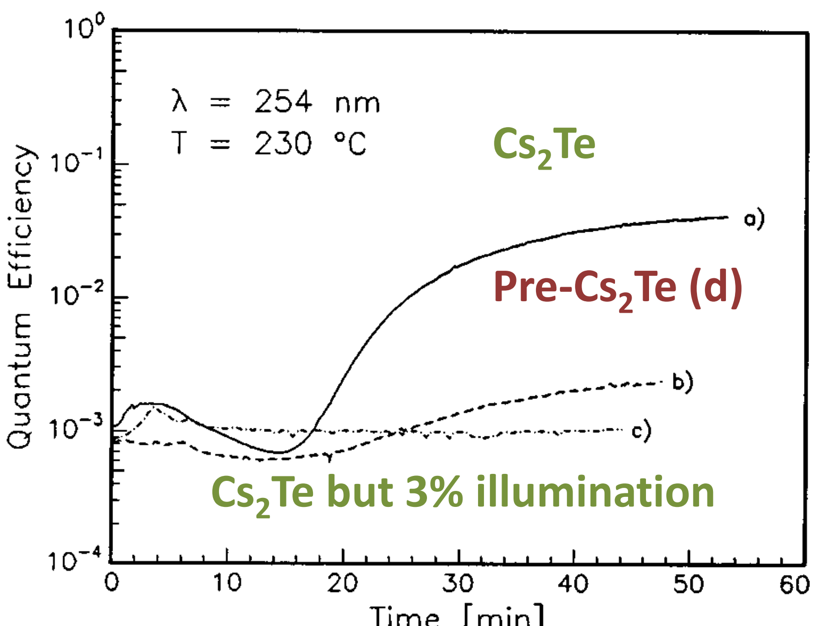



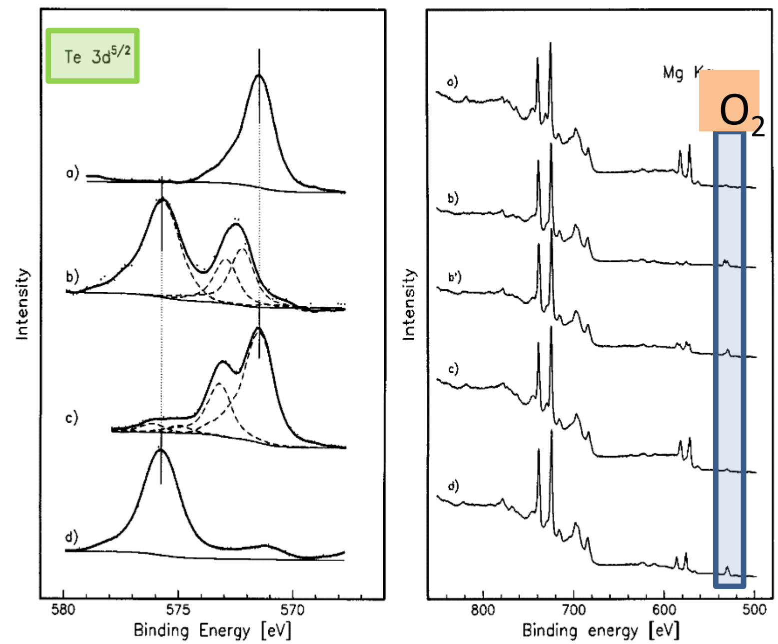


# $Cs_2Te$ Rejuvenation

- $Cs_2Te$ photocathodes can be rejuvenated, i.e. QE can be recovered by heating and illumination.
- Largely used at **FNAL-A0** experiment




a) $Cs_2Te$
b) After 120L $O_2$
c) 230 °C + 254 nm
d) 230 °C only

# Spectral Response and QE maps

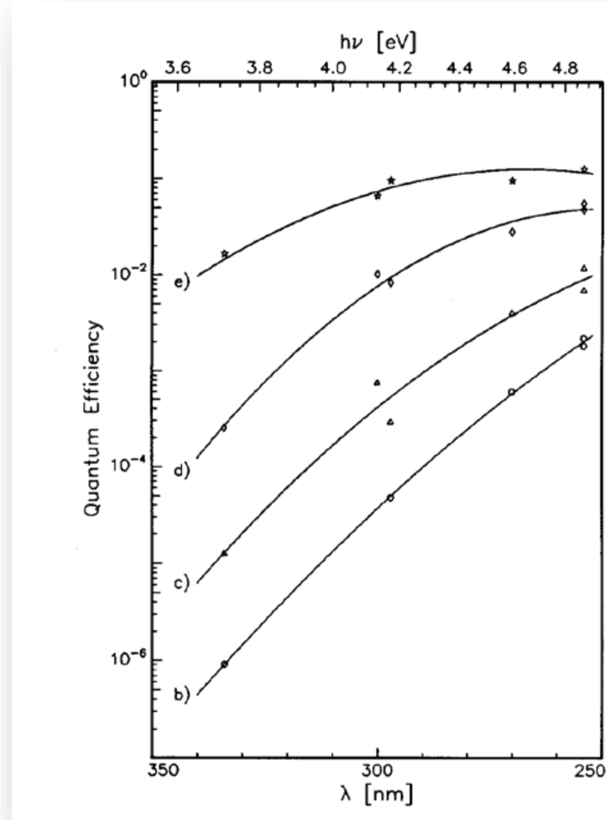
- The **spectral response** analysis provides the **energy threshold** ($E_g+E_a$).
- We fit data with function based on the "Kane" model where $m_i$ depends on the type of transition

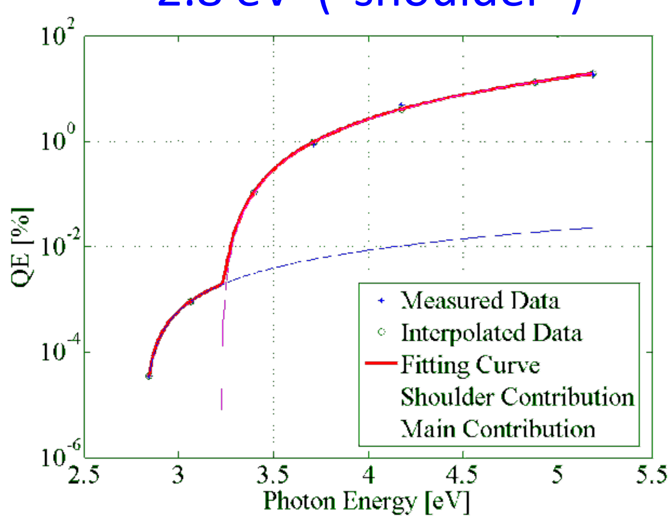
$$QE = \sum_{i=1}^{2} A_i\left[h\nu - \left(E_{g_i} + E_{a_i}\right)\right]^{m_i}$$

- Typical values for thresholds:

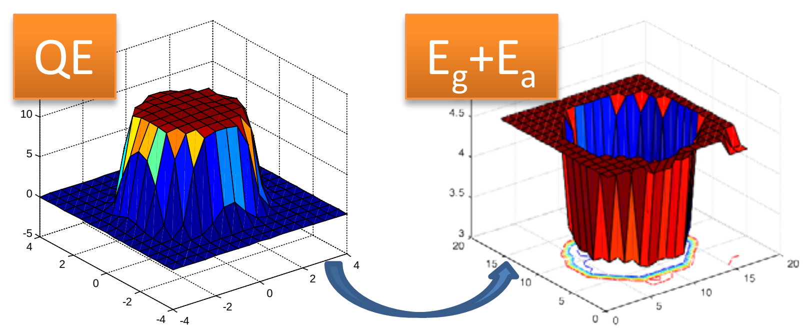
3.3 eV ("high energy")

2.8 eV ("shoulder")




Analisys applied to QE maps



# PHOTOCATHODE SYSTEMS



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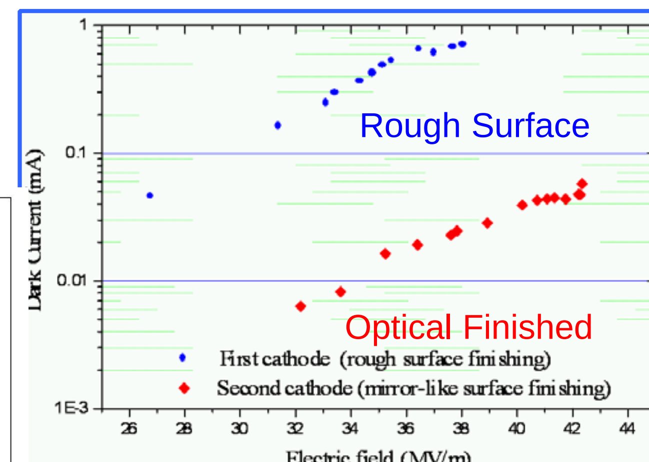
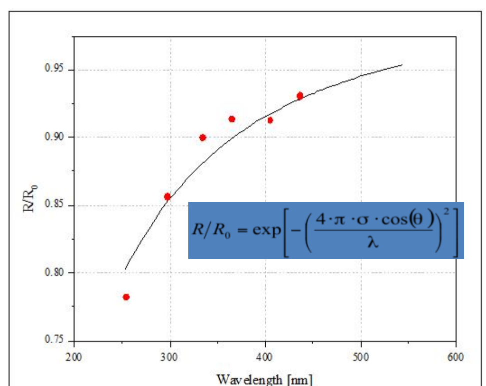
# The $Cs_2Te$ plug

- The recipe was then transfer to a plug compatible with gun operation
- The Mo plugs, either from sintered or arc-cast material, are cleaned with a BCP after machining and polished to optical finishing to reduce dark current
- Reflectivity measured the quality of the optical finishing and it provides also information on surface roughness, typically ≈ 10 nm
- New technique promises ≈ 1 nm

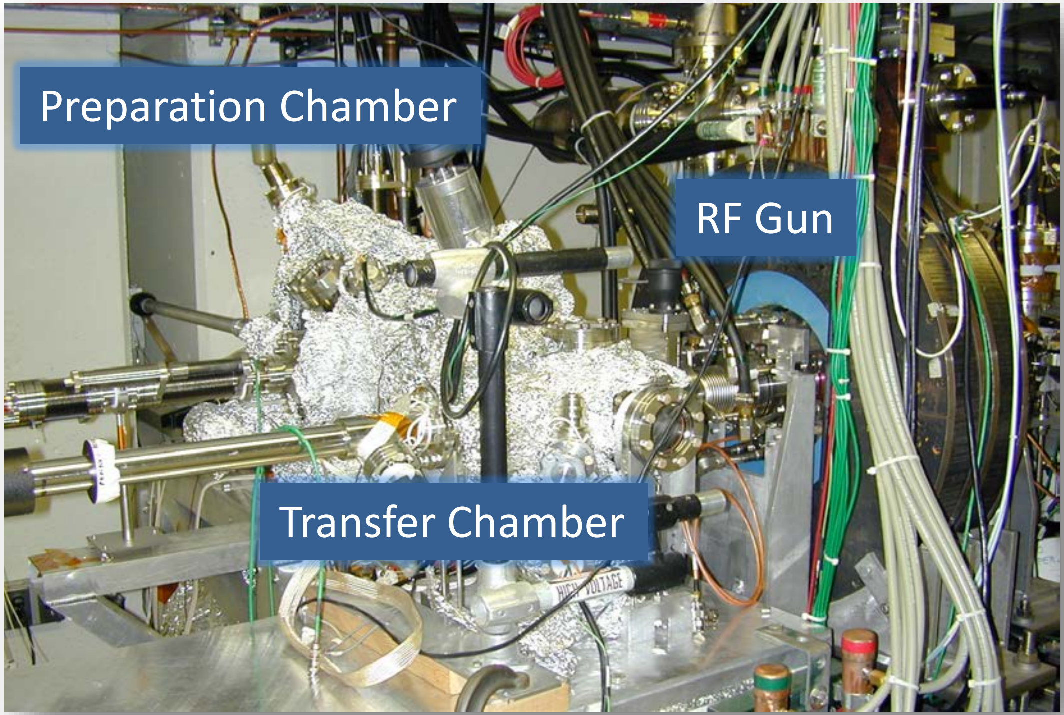




# $Cs_2Te$ PhotoCathode in RF Guns

- In the '90s we start studying the application of $Cs_2Te$ in RF Guns.
- We tested our cathodes in an RF Gun at FNAL-A0 in 1996 with our own preparation and transfer systems.



# The INFN – DESY Cathode System

- In 1998, a split INFN – DESY preparation-transfer system was designed and built. The preparation chamber in Milano and the transfer to the gun at DESY Hamburg.

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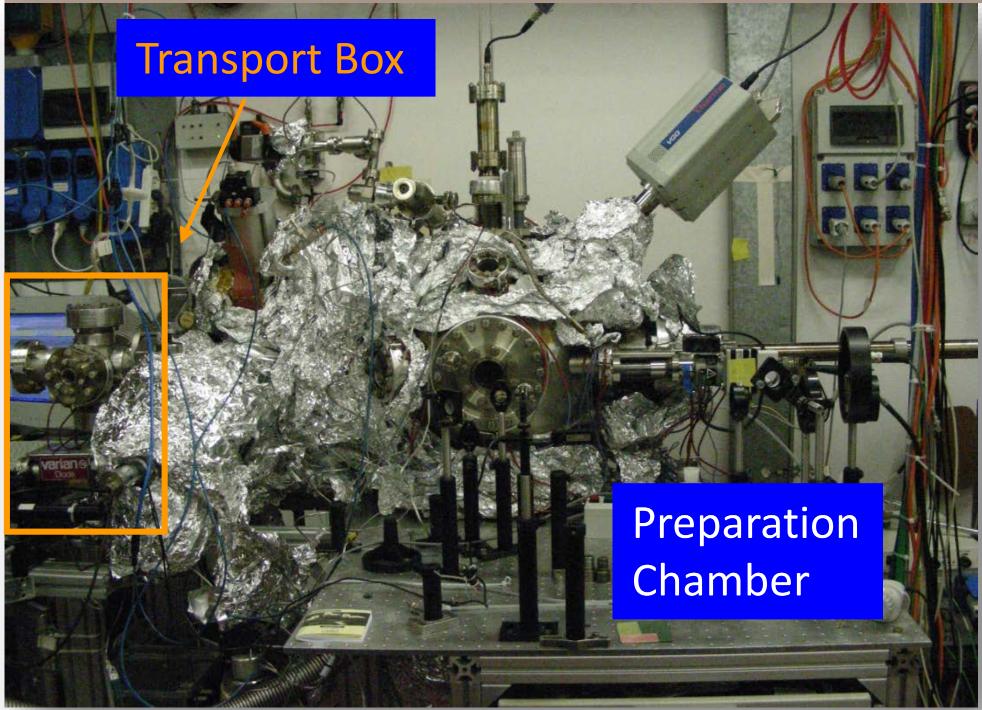
# Preparation System

- UHV Vacuum System (base pressure $10^{-10}$ mbar)
- 6 source slots available
- Te sources out of 99.9999 % pure element
- Cs sources from SAES®
- Masking system ($\phi$ = 5 mm Tungsten Foil)
- High pressure Hg lamp and interference filter for online monitoring of QE during production
- UHV transport boxes

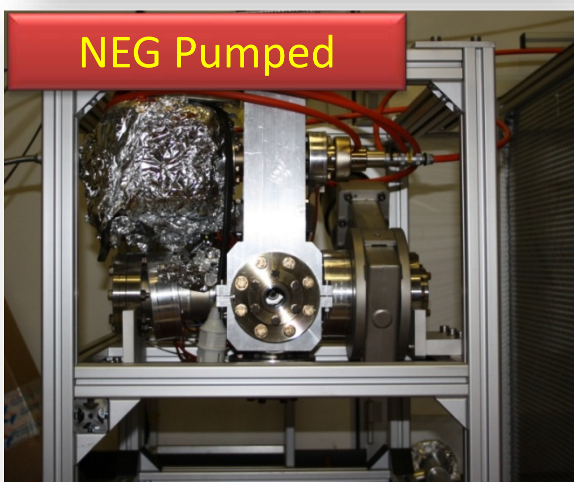






# Transport System

- Cathodes are transported under UHV condition from INFN Milano to the Labs.

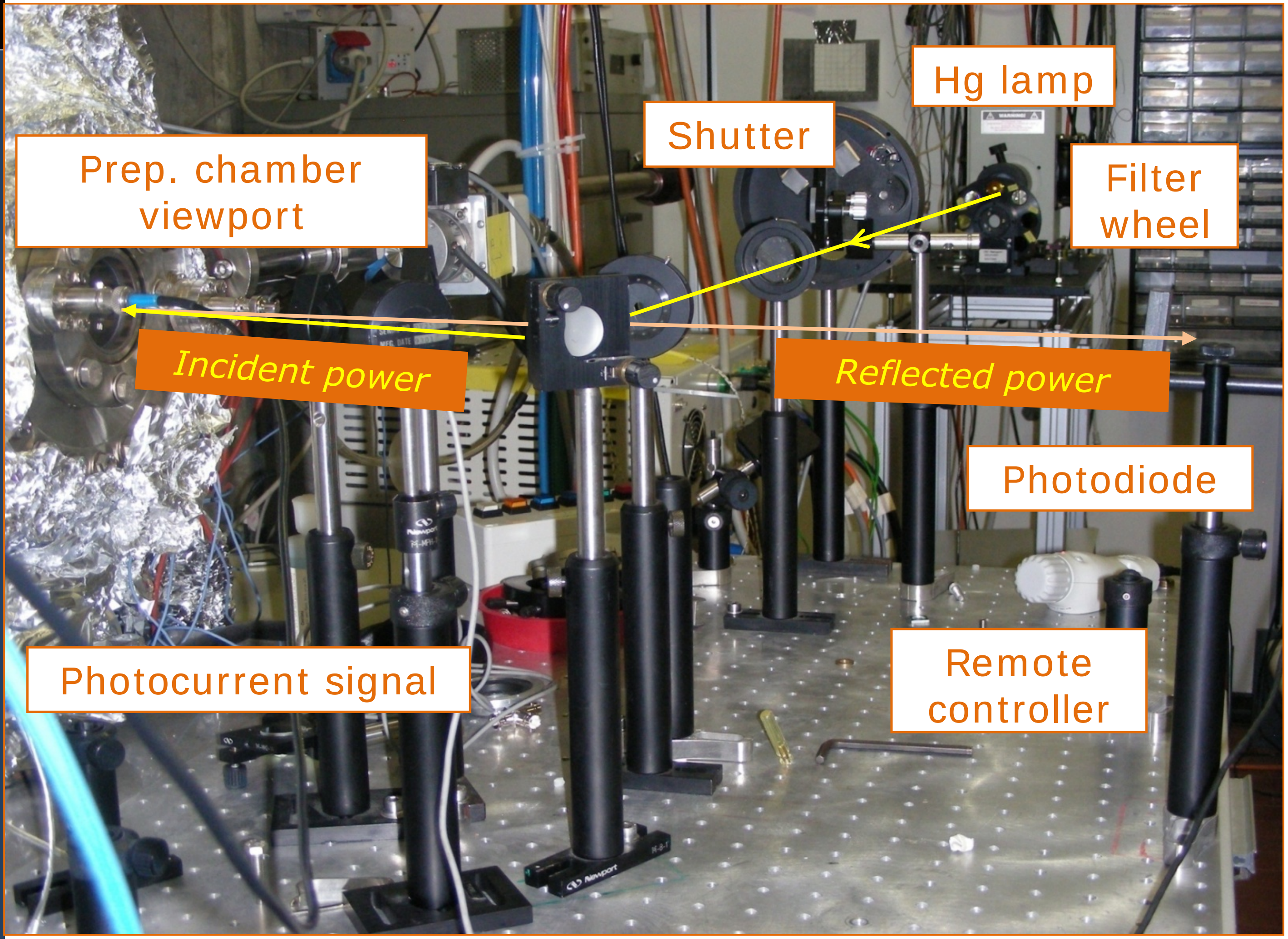





Total number of deliveries between labs ~ 130

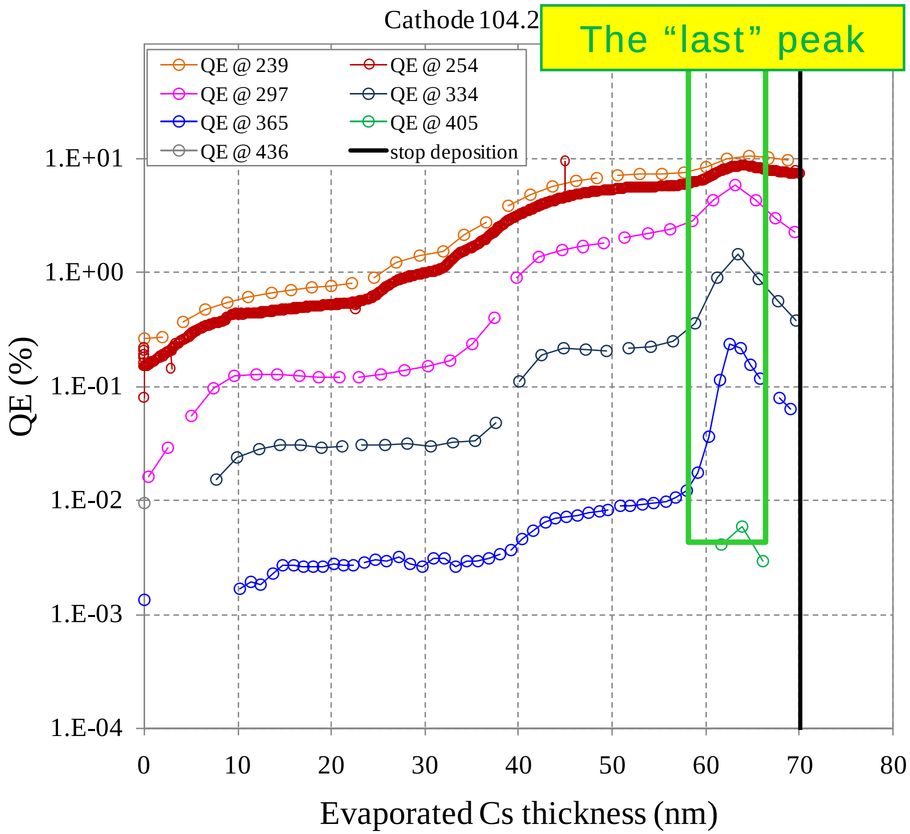
# PRODUCTION IMPROVEMENTS

# New online diagnostic set-up




- ***Calibrated photodiode*** for reflected light power from the film
- *A* ***motorized*** and remotely controlled ***filter wheel*** with interference filters (239 nm, 254 nm, 334 nm, 365 nm, 405 nm, 436 nm)
- ***Picoammeter*** for photocurrent measurement

# $Cs_2Te$ QEs during deposition




- Te thickness 10nm
- Cs evaporated thickness 70nm
- Last peak @ 64nm of evaporated Cs
- Final QE @ 254nm 10.9%

- At wavelengths longer than 254 nm, the typical growth steps are no more clearly visible except at 40 nm and the last one at 64 nm of evaporated Cs thickness.
- The **last peak** corresponds to the complete formation of the $Cs_2Te$ and it is more evident at longer wavelengths.
- "Last" peak position, in term of the evaporated Cs amount, is related to the Te thickness deposited.
- A stop of Cs evaporation before it produces a not totally finished cathode that might be less stable, while a stop after it leads to a cathode with a Cs excess

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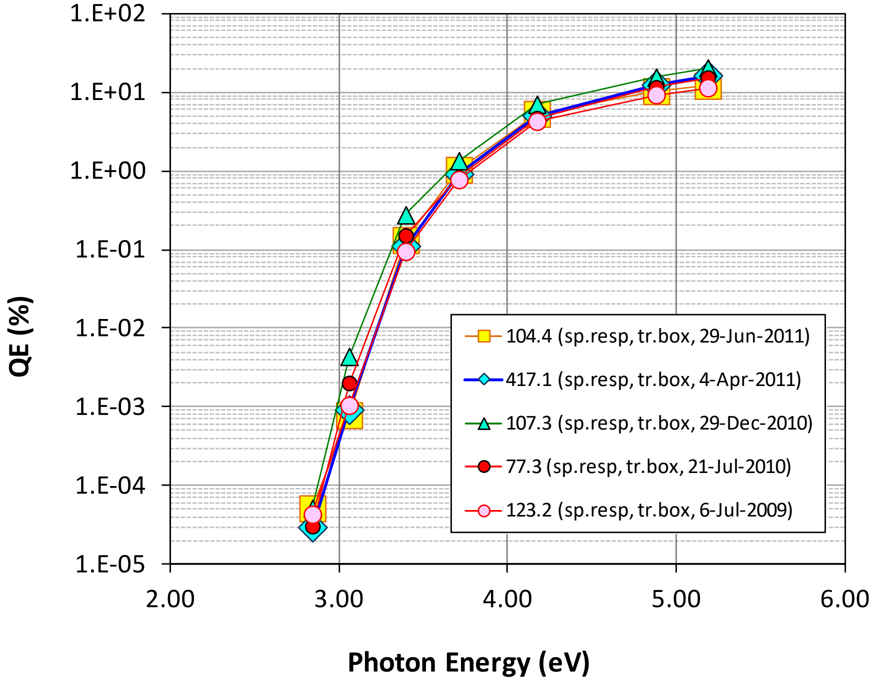
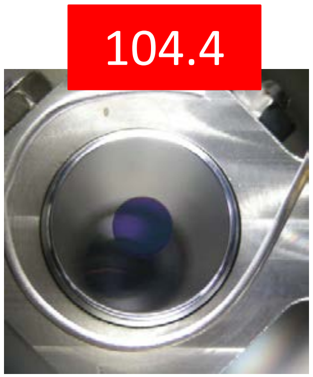
# Spectral response reproducibility

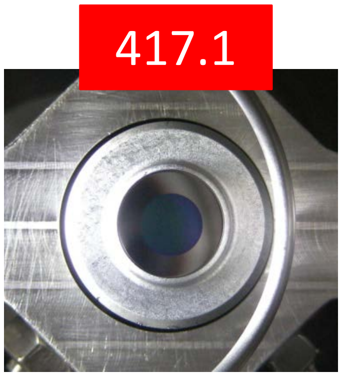


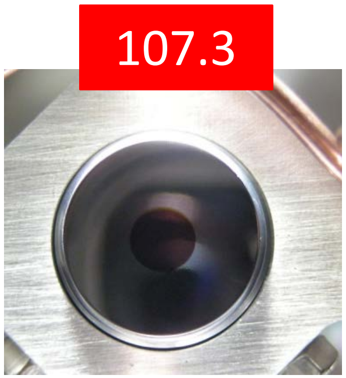

The on-line diagnostic allows better control of the cathode growing.

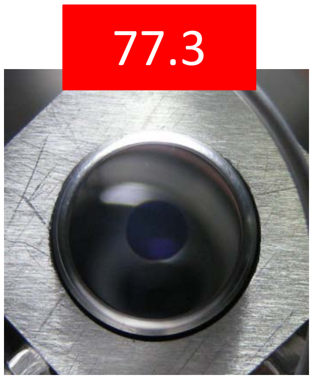
The reproducibility of produced cathode spectral responses is largely improved.

The Cs excess is under control. No more low energy shoulder.

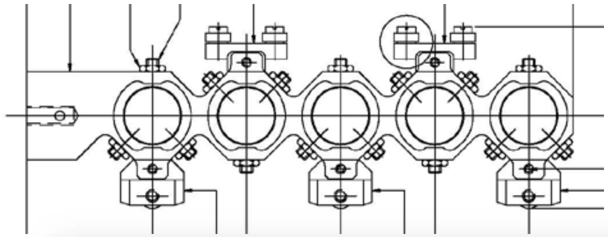


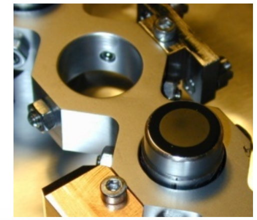



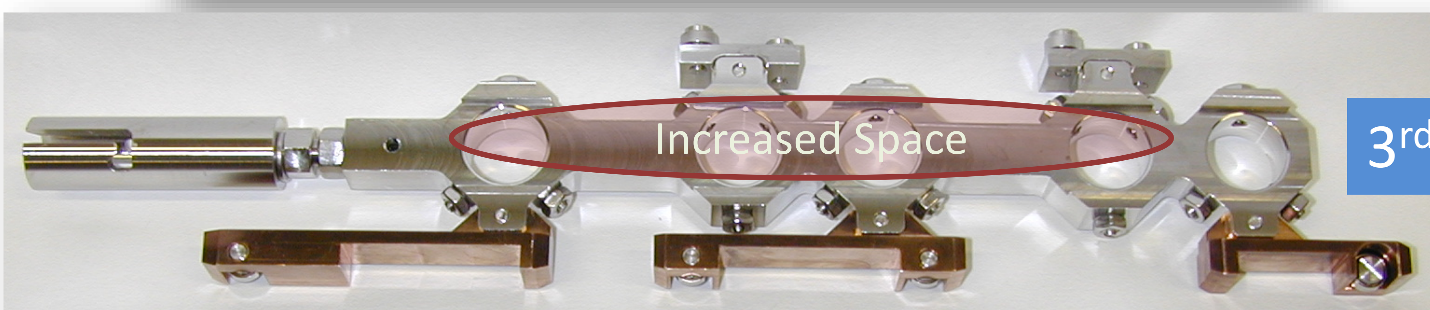

# Carriage Evolution



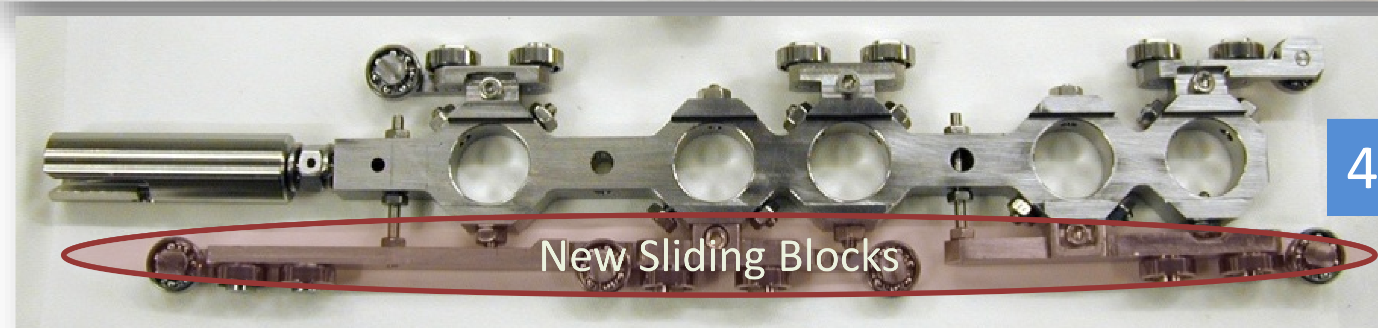


A0 Carrier


2nd gen.




3rd gen.




4th gen.

# New NEG Based UHV Vacuum Transport System

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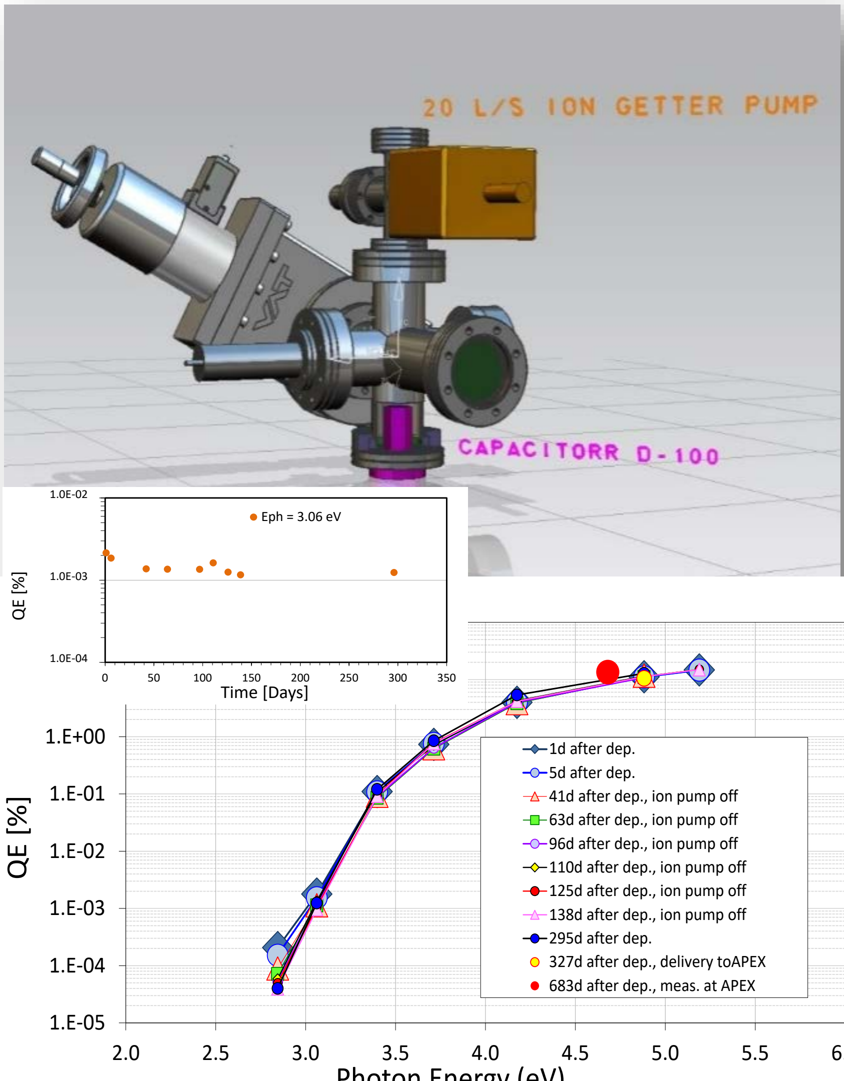
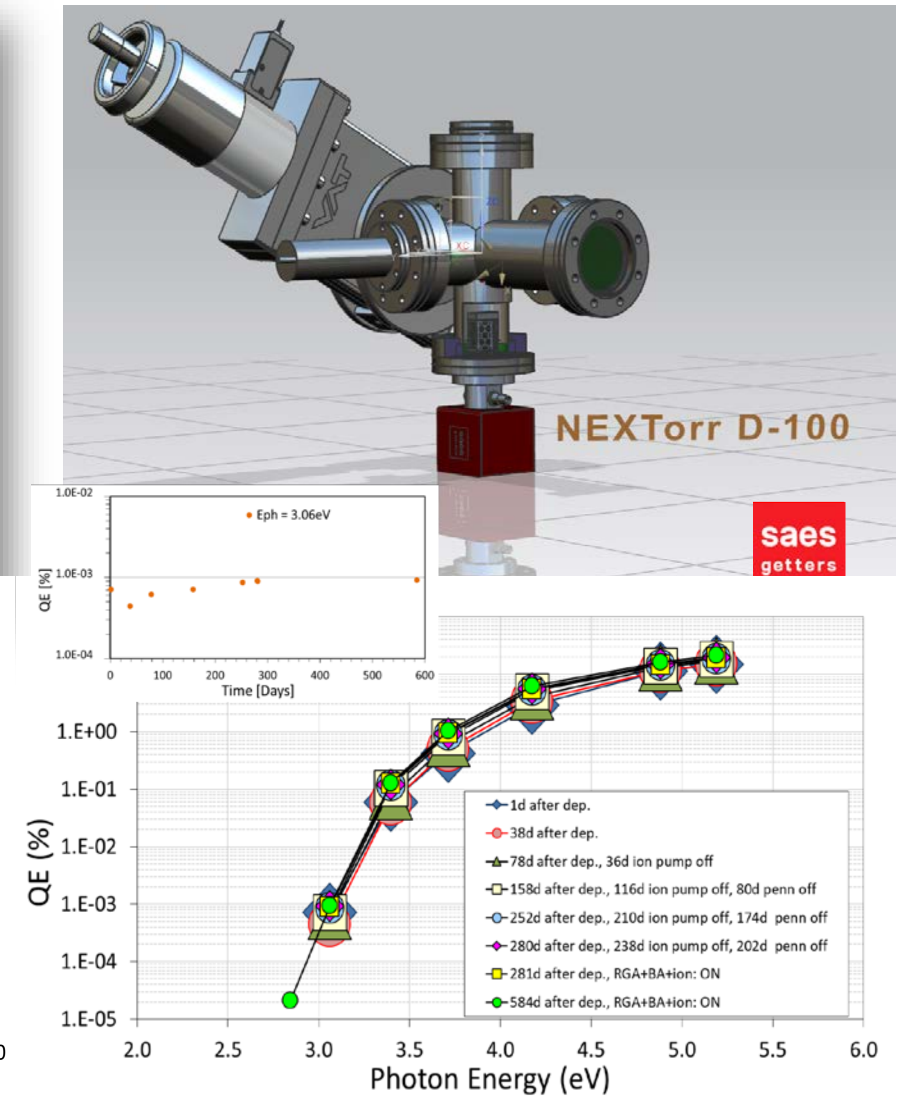






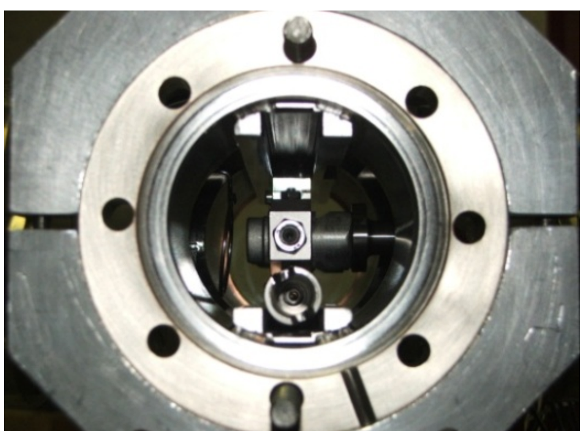
# Photocathode handling system

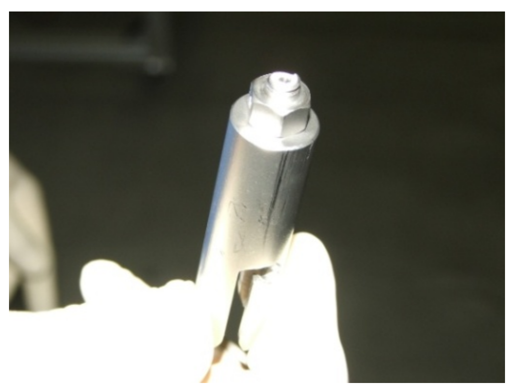
Analysis of accident during cathode operation:

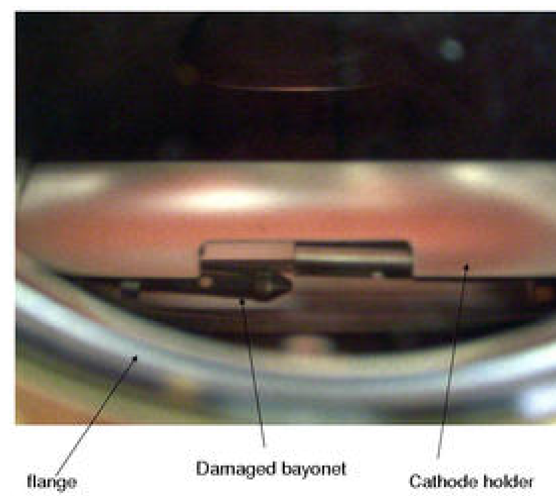
- Only three significant accidents have occurred after about 17 years of operation

Damages on the connection system:

- due to a not correct parking of the carrier in the transport box and then closing of the valve
- due to the manipulator magnet uncoupling from its vacuum counterpart

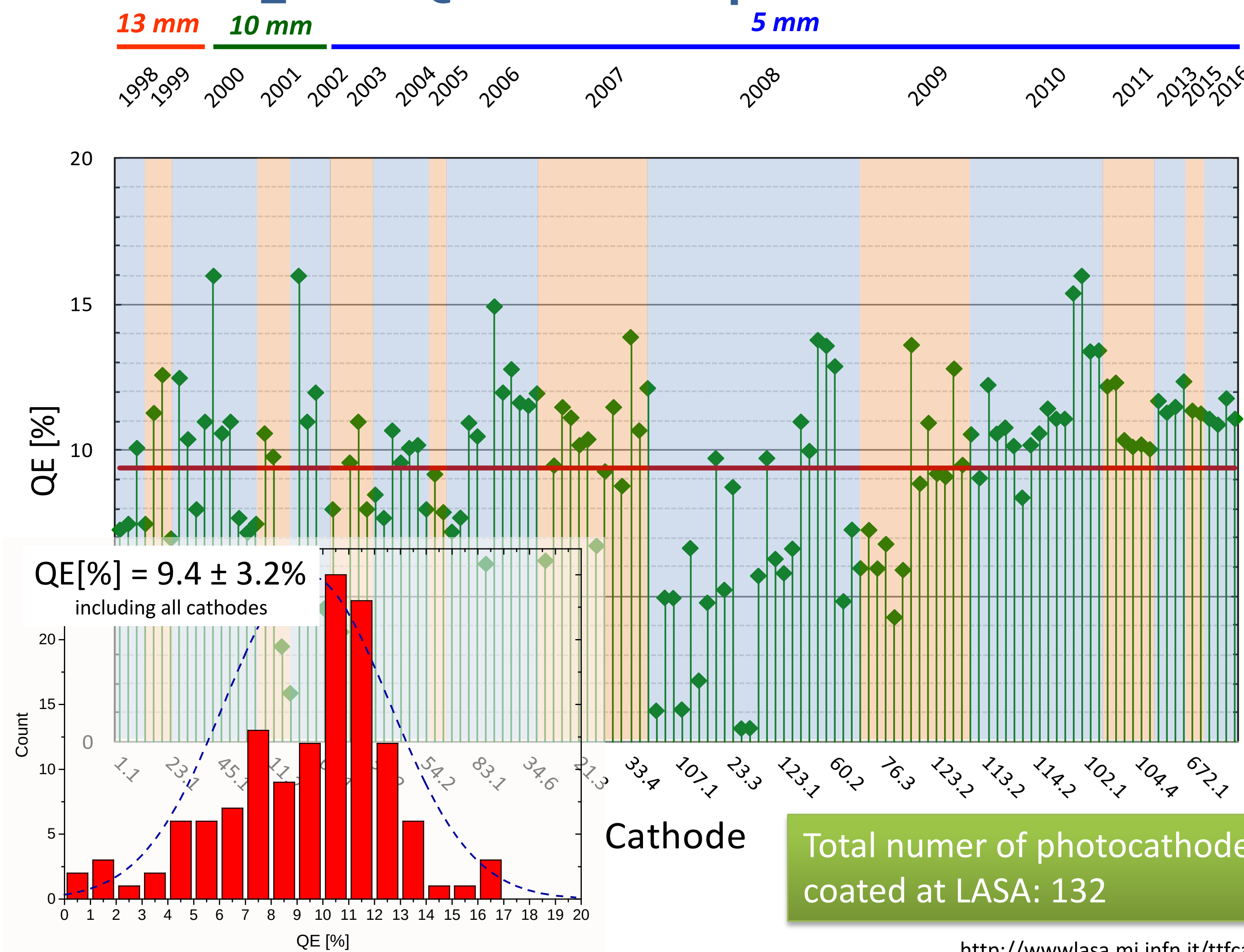






# PERFORMANCE

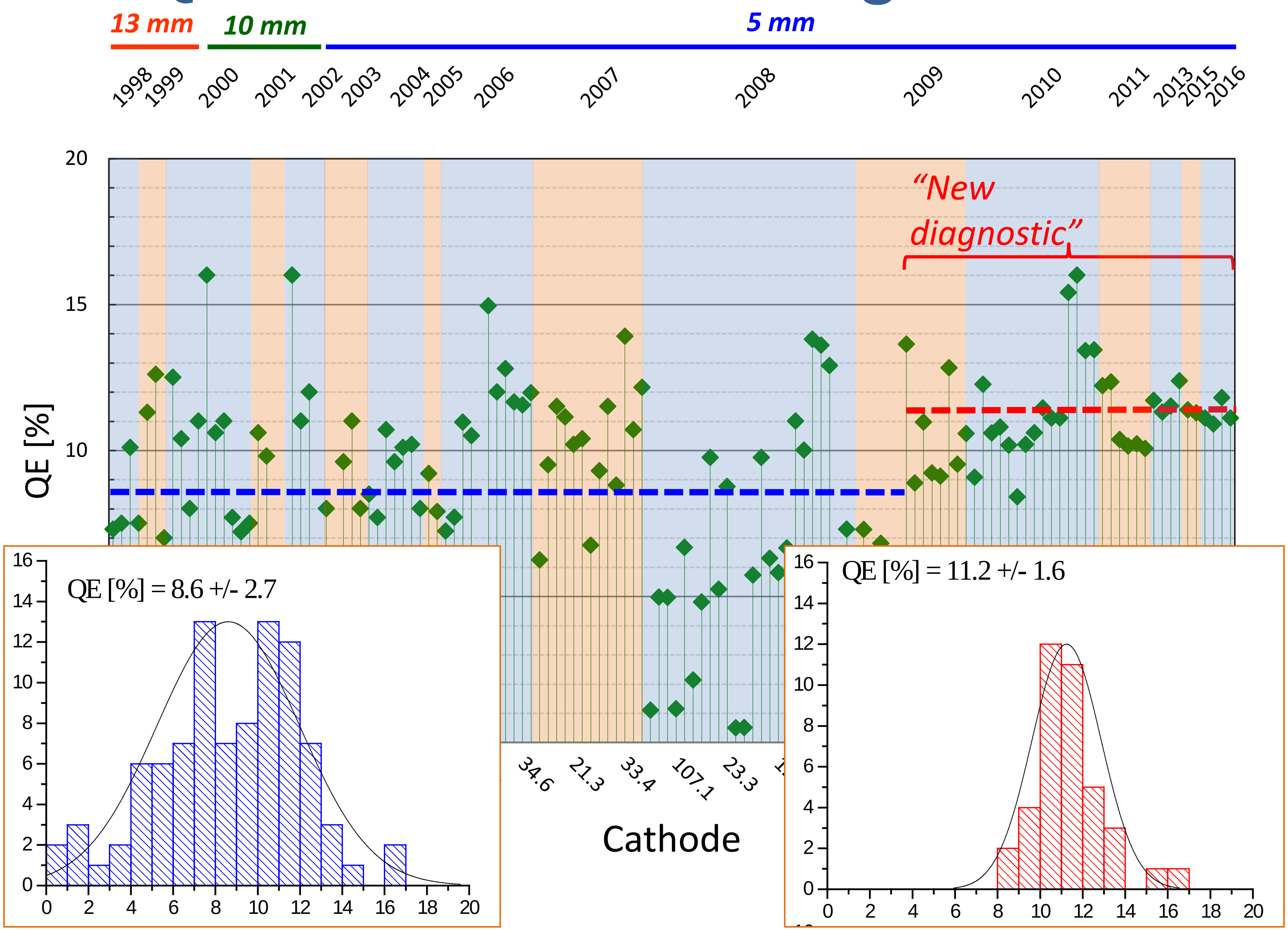
# $Cs_2Te$ QE after production




Total numer of photocathodes coated at LASA: 132

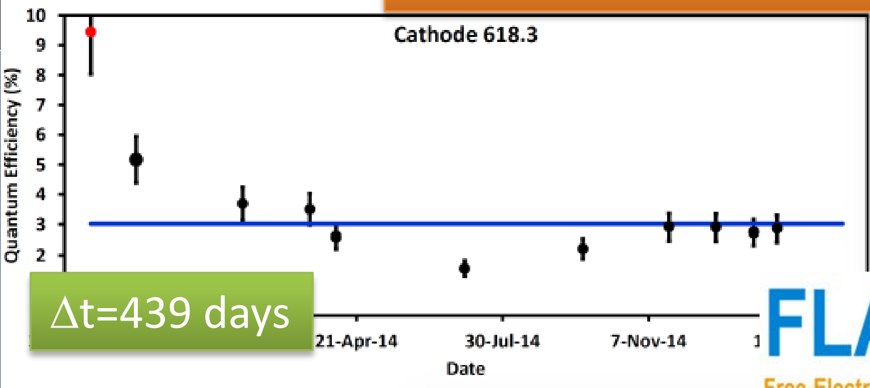
http://wwwlasa.mi.infn.it/ttfcathodes/

# QE old and new diagnostic



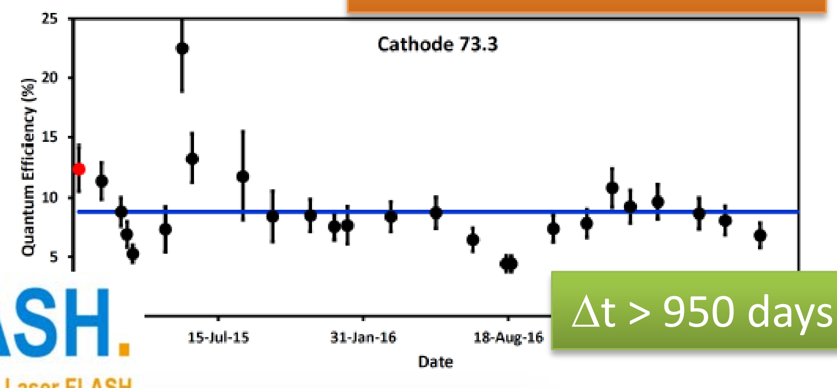
# Lifetime and extracted charge

Extracted charge: 3.1 C



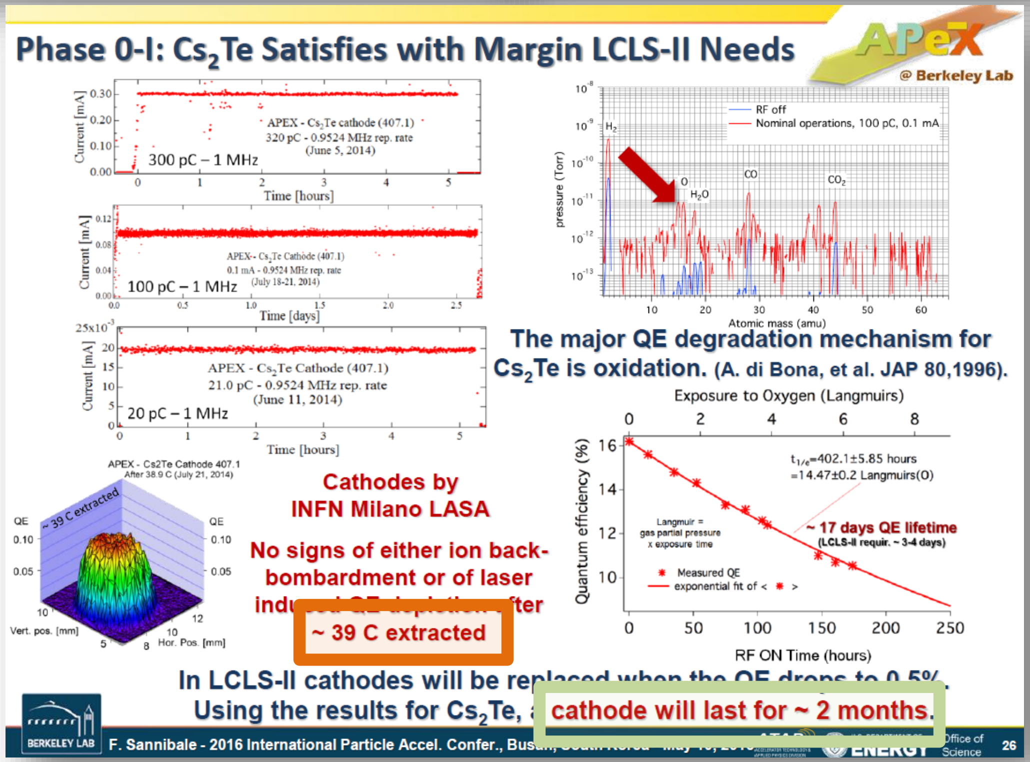

Δt=439 days

Extracted charge: 18 C




Δt > 950 days

FLASH. Free-Electron Laser FLASH



# Conclusions

- Surface science tecniques essential in understanding the cathode properties
- Once the growth process is stable and reproducible, it might be moved to the production
- Continous improvements during the cathode production are essential to guarantee reliable photocathode properties.
- Important is the interplay between cathode improvement and gun development

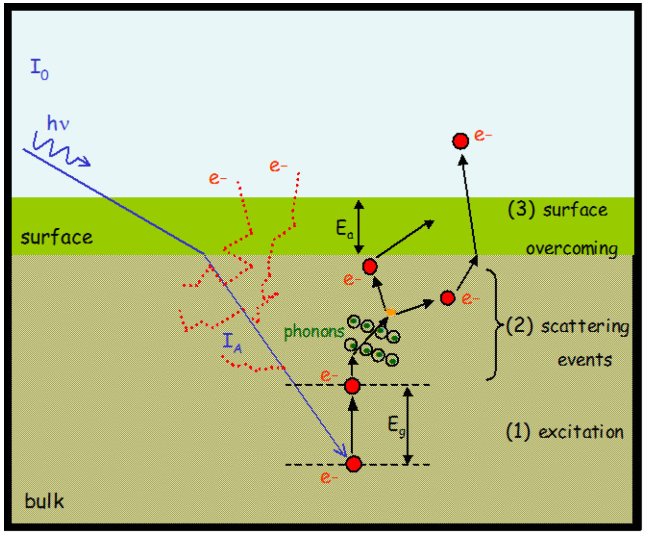
# INFN systems around the world


Thank you!

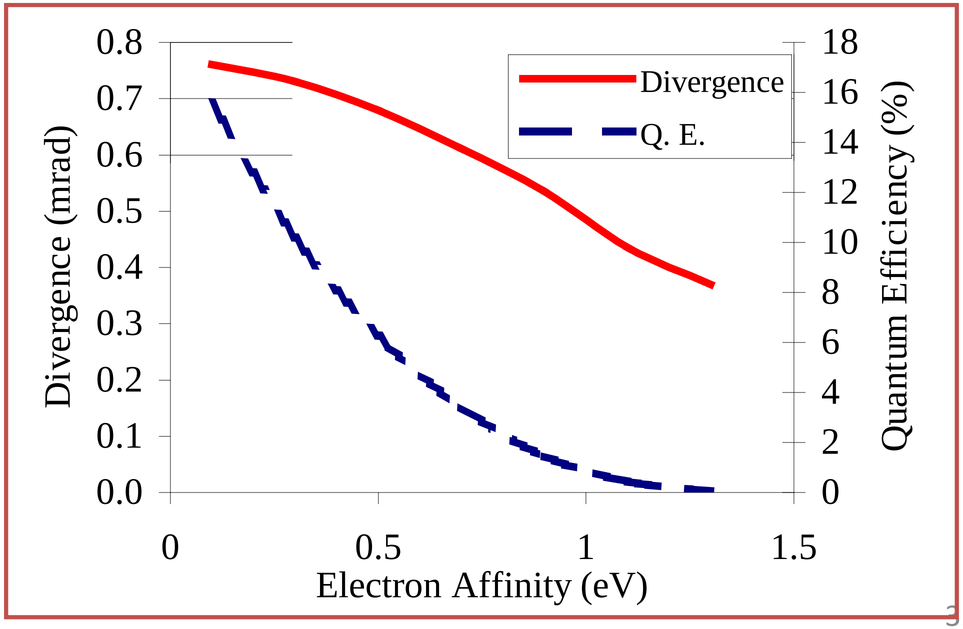
# Back Up Slides

# The $Cs_2Te$ Photoemission Model

- Given the information on optical properties and energy bands of $Cs_2Te$, we develop a simple Monte Carlo model of the photoemission from $Cs_2Te$ photocathodes based on Spicer's "Three Steps" model.

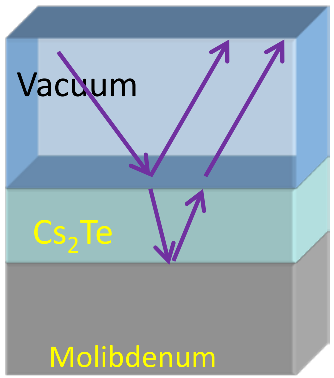


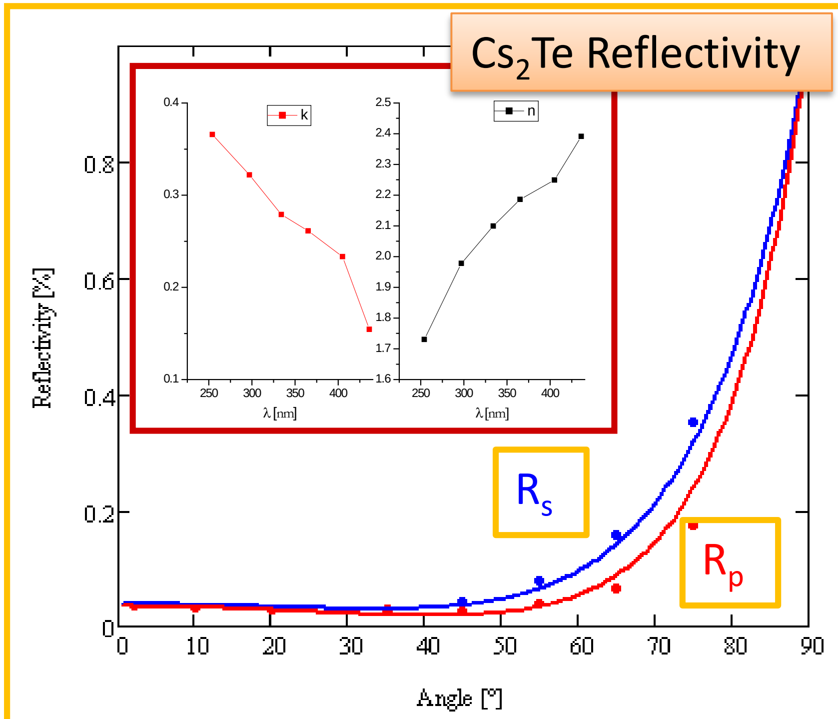

- As an example we correlate QE and electron divergence at the photocathode changing the electron affinity.



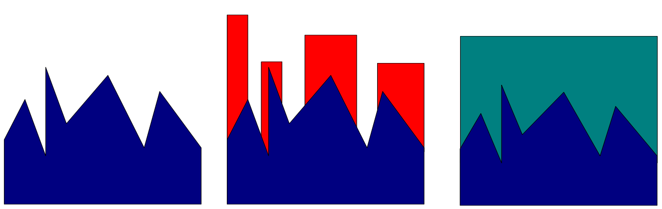
# $Cs_2Te$ Optical Properties

- $Cs_2Te$ are thins film deposited on a Mo substrate. There is a key role played by the substrate in the interpretation of the optical data.



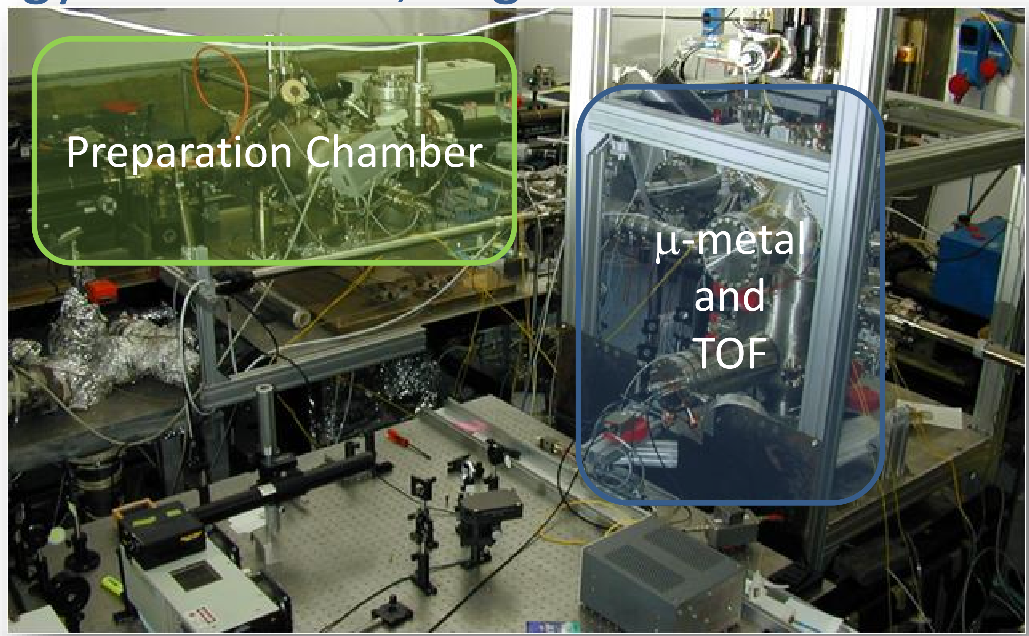

**A possible mechanism for $Cs_2Te$ growth**

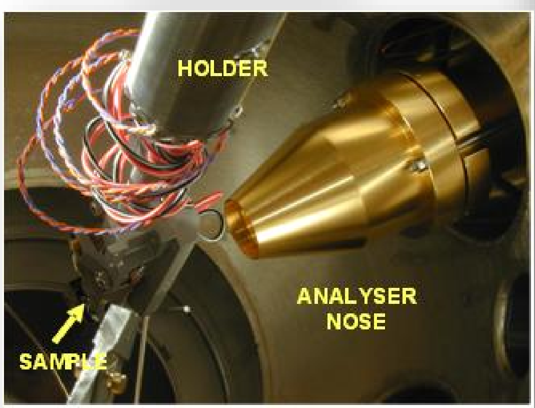


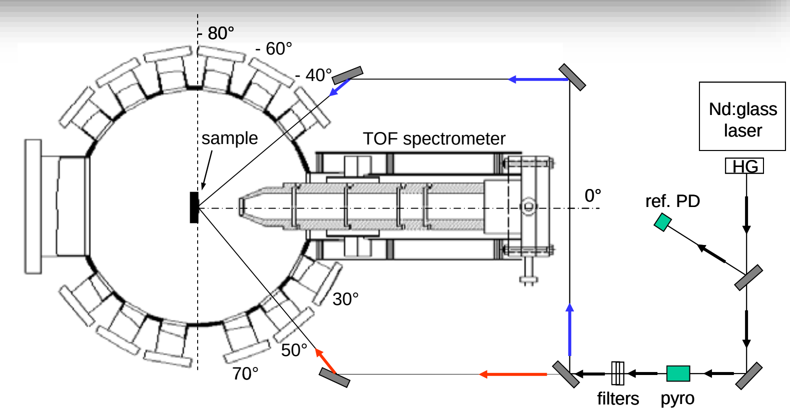

| n | k | σ [nm] | thickness [nm] |
|---|---|---|---|
| 1.75 | 0.356 | 0 | 38.5 |

# Thermal Emittance

- We developed a Time of Flight detector for measuring the photoelectron energy distribution, angle resolved.



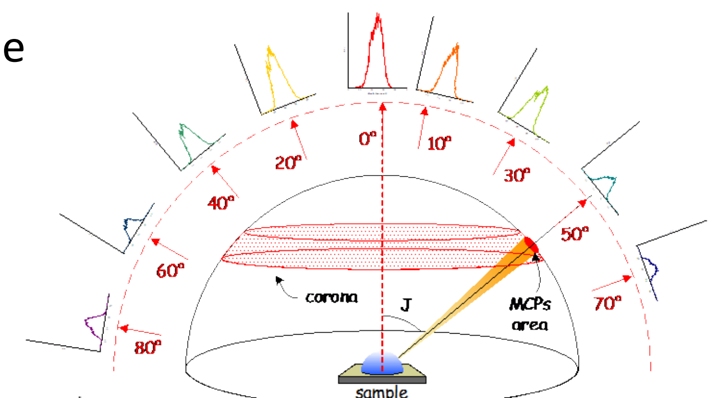
# Reconstruction

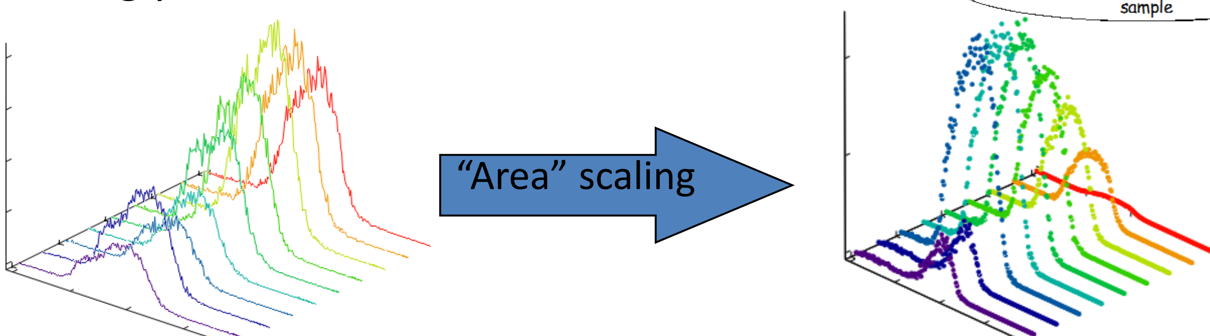
- We use the following definition for the normalized emittance

$$\varepsilon_x = \frac{1}{2 \cdot c} \cdot \sqrt{\left\langle r^2 \right\rangle \cdot \left\langle \frac{2 \cdot E_{Kin}}{m_0} \cdot \cos^2(\theta) \right\rangle} \qquad E_{Kin} = \frac{1}{2} \cdot m_0 \cdot \left( \frac{L_{TOF}}{t} \right)^2$$

where we assume cylindrical symmetry and no correlation position-velocity. The average appearing inside the square root is performed over the distribution in energy and angle of the emitted electrons.

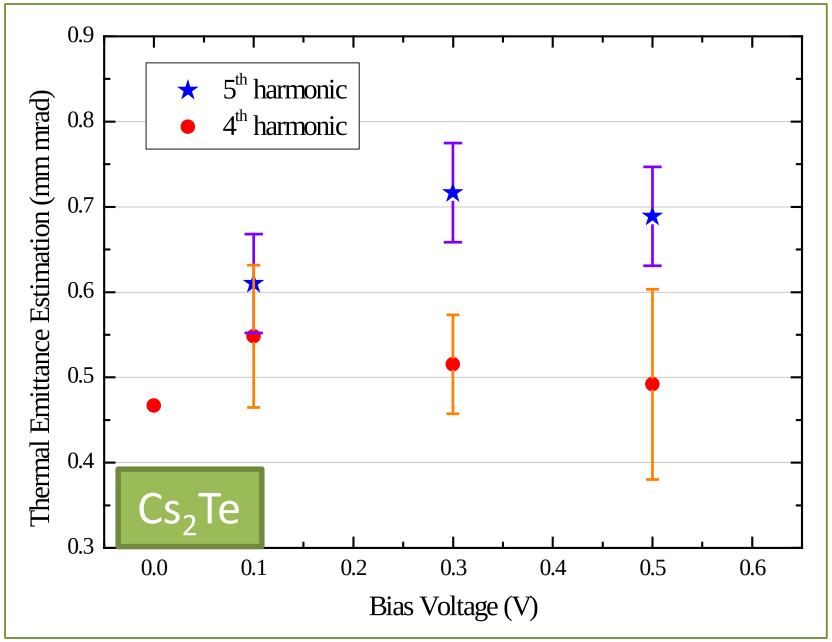
- The energy distribution measured at each angle $\theta_n$ at the MCP area is representative of the emission within the solid angle underlying the spherical corona separating two successive angles, and the total number of counts is correspondingly scaled.



European Workshop on Photocathodes for Particle Accelerator Applications

# $Cs_2Te$ Thermal Emittance




*$5^{th}$ harmonic ($\lambda$ = 211 nm)*
$\varepsilon_{th}$ = 0.7 ± 0.1 mm mrad
for 1 mm rms spot radius

*$4^{th}$ harmonic ($\lambda$ = 264 nm)*
$\varepsilon_{th}$ = 0.5 ± 0.1 mm mrad
for 1 mm rms spot radius

Assuming, that the thermal emittance scales as the square root of the most probable energy, the ratio between the estimated thermal emittances at the $4^{th}$ and $5^{th}$ harmonic varies according to this simple scaling.

$$\sqrt{\frac{E_{MP}^{4^{th}}}{E_{MP}^{5^{th}}}} \simeq \frac{\varepsilon_{th}^{4^{th}}}{\varepsilon_{th}^{5^{th}}}$$