Laser Applications at Accelerators Conference 2015

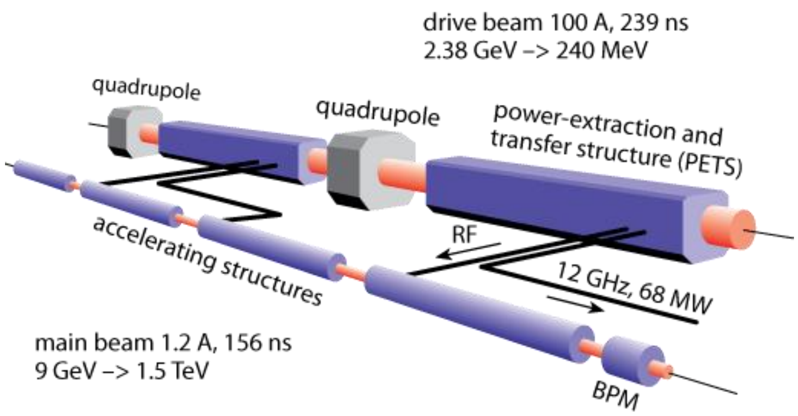
Research and development of photocathodes sensitive to visible laser beam for photoinjector applications.

Irene Martini

Mallorca, 25.03.2015

CLIC at CERN

- **CLIC (Compact Linear Collider)** is a study for a future electron-positron room temperature linear collider (~50 km long) at CERN.
- Linear leptons collider for a fine characterization of LHC (Large Hadron Collider) discoveries.
- Two beam-acceleration method: a **drive beam** to supply with the RF power the **main beam** accelerating structures.

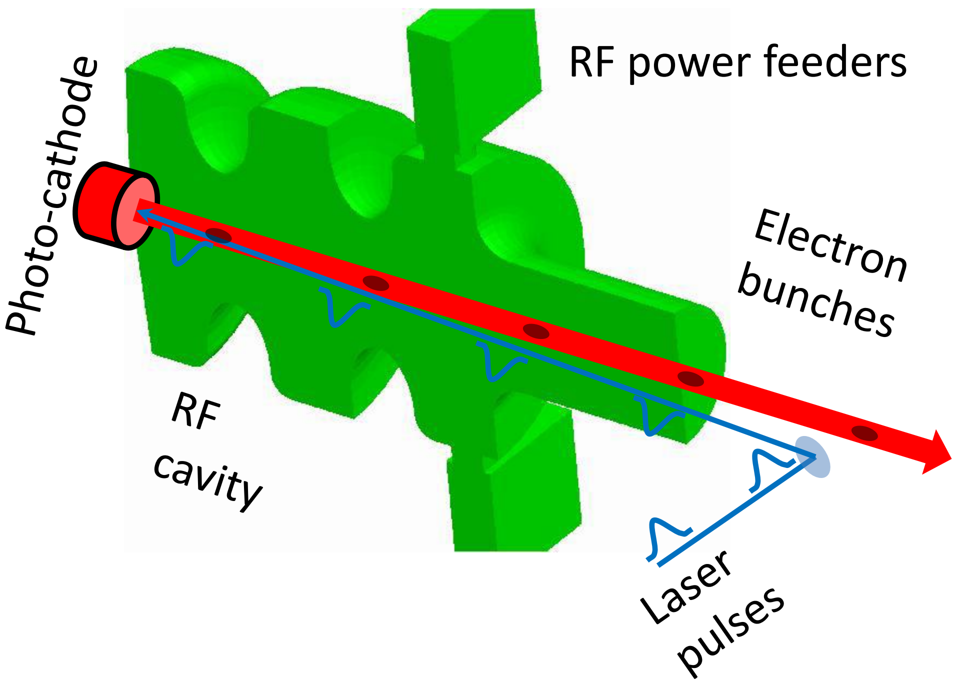


http://clic-study.org/

- Drive beam: high peak and average current ⇨ challenging requirements to the source of electrons.

Photoinjector Option

- The **PHIN RF photoinjector** is used at CERN for R&D in the framework of feasibility studies of the photoinjector option for the **CLIC drive beam**.



Parameter	CLIC	PHIN
Charge/bunch (nC)	**8.4**	**2.3**
Bunch length (ps)	10	10
Bunch rep. rate (GHz)	0.5	1.5
Number of bunches	70000	1800
Train length (μs)	**140**	**1.2**
Charge/train (μC)	590	4.1
Macro pulse rep. rate (Hz)	50	5
Beam current/train (A)	4.2	3.4
Cathode lifetime (h) at QE>3% (Cs_2Te)	**>150**	**>50**
QE>0.5% (Cs_3Sb)		

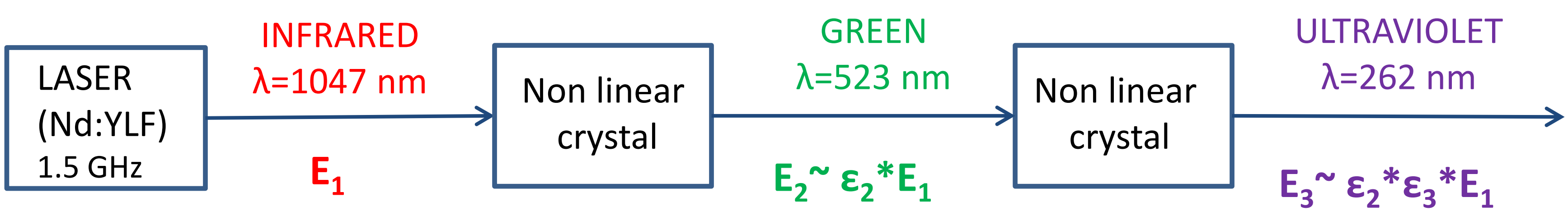
- **Long cathode lifetimes with high bunch charge, long trains and high rep rate.**

Motivation

- In parallel to the the development of a laser system for the CLIC paramenters, photocathode R&D studies are on-going.
- Photocathodes sensitive to ultra-violet **UV light** (such Cs_2Te) are used in many photoinjector facilities.
- The available laser pulse energy in UV for 0.14 ms long pulse trains is currently limited due to a degradation of the beam quality during the 4th harmonics frequency conversion process. Using **visible laser beams** would overcome this limitation.

→ NEED of PHOTOCATHODE with high QE for green laser light.

Cs_3Sb



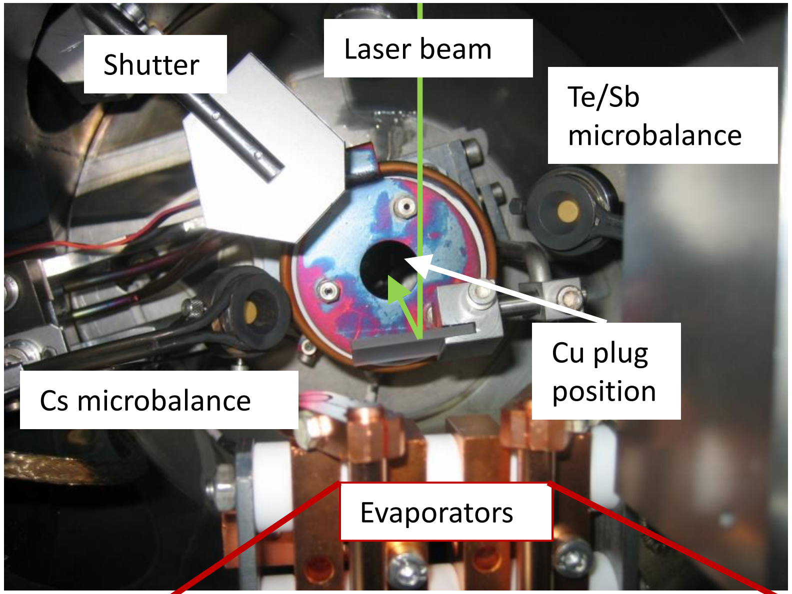
2nd harmonic generation
Conversion efficiency ε_2~0.5

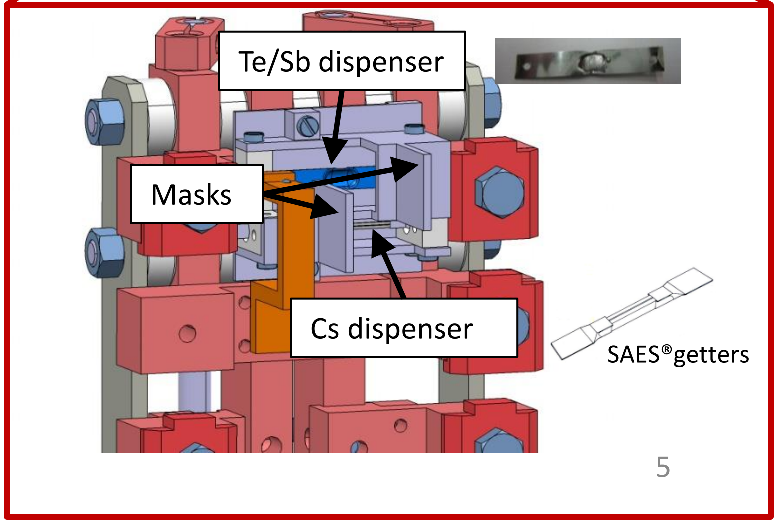
"4th harmonic generation"
Conversion efficiency ε_3~0.3

Photocathodes Production

- **CO-DEPOSITION:**
  Cs and Te or Sb evaporated at the same time: the metallic elements can mix together in the vapour phase.

- The **Copper** substrate is **heated** up to 125° C. ⇨





- **On-line QE measurement** shooting with laser: the evaporators power is controlled in order to reach a maximum in the QE.

R&D on Photocathodes

Cathodes feasibility studies:

- Testing the material performance in a real photoinjector setup.
- Understanding the main factor affecting cathode performance (production/operation).
- Improve the cathode performance acting on both the setup or the cathode itself.

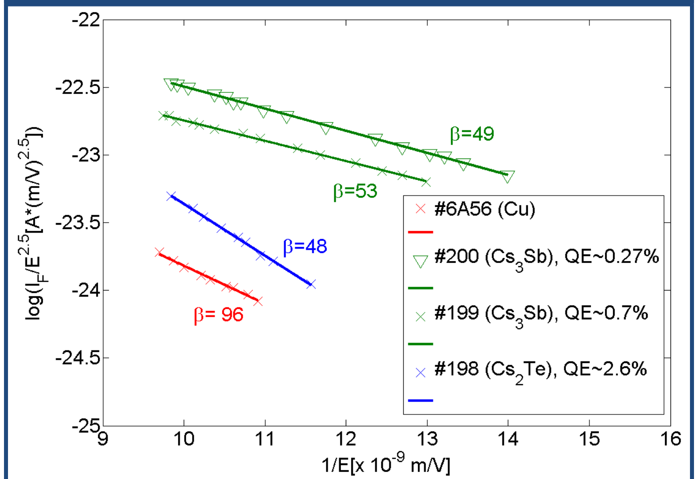
R&D on Photocathodes

Cathodes feasibility studies:

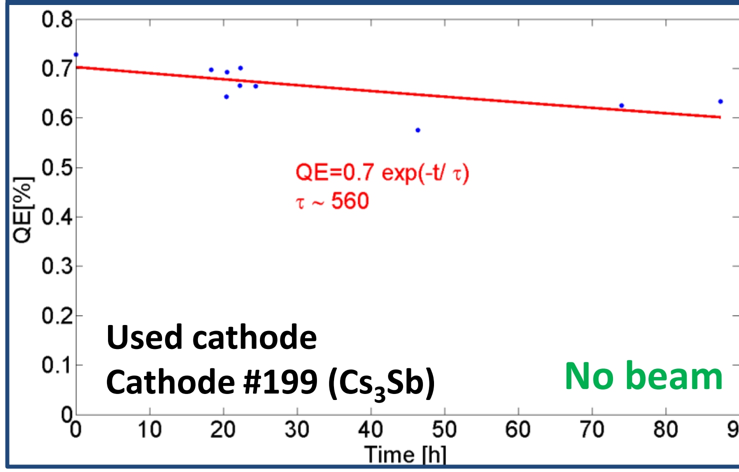
- **Testing the material performance in a real photoinjector setup.**
- Understanding the main factor affecting cathode performance.
- Improve the cathode performance.

Test in the PHIN RF Photoinjector

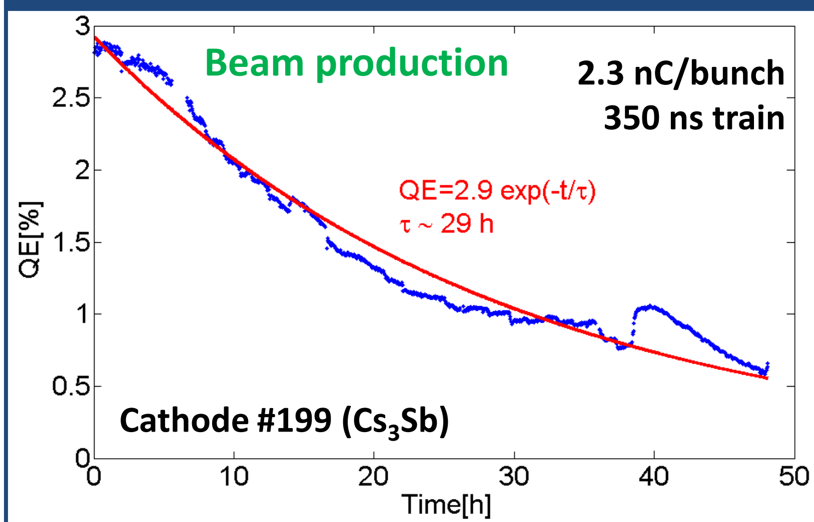
Dark current measurements

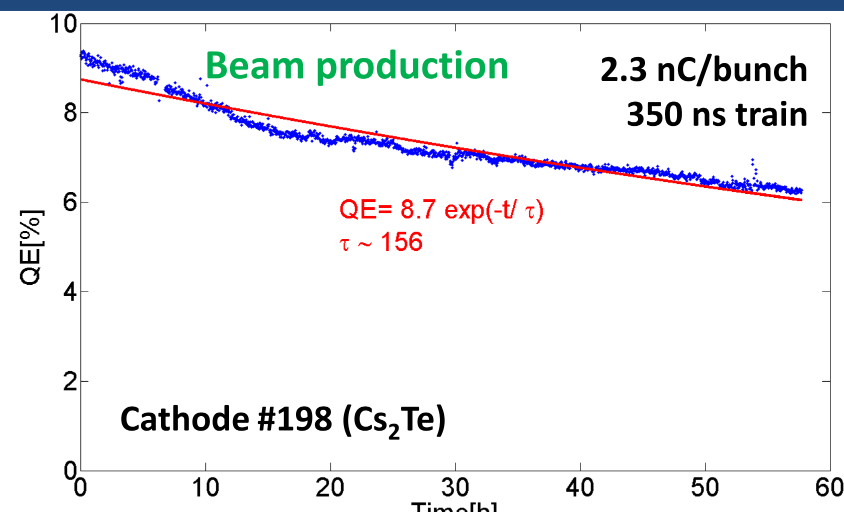


RF lifetime measurements



Operational lifetime measurements





R&D on Photocathodes

Cathodes feasibility studies:

- Testing the material performance in a real photoinjector setup.
- **Understanding the main factor affecting cathode performance.**
- Improve the cathode performance.

Cathode Deterioration Processes

CHEMICAL POISONING (Residual Gas Contamination, mainly oxidation)

Static vacuum level (Residual gases)

Electrons (from Beam Losses) Stimulated Desorption (**Dynamic vacuum level**)

Electrons (from Field Emission) Stimulated Desorption (**Dynamic vacuum level**)

Cathode Deterioration Processes

CHEMICAL POISONING (Residual Gas Contamination, mainly oxidation)

Static vacuum level (Residual gases)

Electrons (from Beam Losses) Stimulated Desorption (**Dynamic vacuum level**)

RADIATION DAMAGE

Electrons (from Field Emission) Stimulated Desorption (**Dynamic vacuum level**)

Ions (from beam interaction with residual gases) **Back Bombardment**

Cathode Deterioration Processes

Independent of beam current

Static vacuum level (Residual gases)

Electrons (from Field Emission) Stimulated Desorption (**Dynamic vacuum level**)

Electrons (from Beam Losses) Stimulated Desorption (**Dynamic vacuum level**)

Ions (from beam interaction with residual gases) **Back Bombardment**

Cathode Deterioration Processes

Independent of beam current

Static vacuum level (Residual gases)

Electrons (from Field Emission) Stimulated Desorption (**Dynamic vacuum level**)

Proportional to beam current

Electrons (from Beam Losses) Stimulated Desorption (**Dynamic vacuum level**)

Ions (from beam interaction with residual gases) **Back Bombardment**

R&D on Photocathodes

Cathodes feasibility studies:

- Testing the material performance in a real photoinjector setup.
- Understanding the main factor affecting cathode performance.
- **Improve the cathode performance acting on the setup or on the cathode itself.**

Cathode Deterioration Processes

Independent of beam current

Static vacuum level (Residual gases) → **Vacuum system upgrade.**

Electrons (from Field Emission) Stimulated Desorption (**Dynamic vacuum level**) →

Fowler-Nordheim for RF field
($\bar{I}_F$: Average field emitted current, A_e:Emitting Area)

$$\bar{I}_F = \frac{5.7 * 10^{-12} * 10^{4.52\phi^{-0.5}} * A_e(\beta E)^{2.5}}{\phi^{1.75}} * \exp\left(-\frac{6.53 * 10^9 * \phi^{1.5}}{\beta E}\right)$$

- Work Function → **CATHODE MATERIAL**
- Field Enhancement Factor → **SURFACE MORPHOLOGY**
- Electric field at the cathode → **OPERATING CONDITION**

Cathode Deterioration Processes

Independent of beam current

Static vacuum level (Residual gases)

Electrons (from Field Emission)
Stimulated Desorption (**Dynamic vacuum level**)

Proportional to beam current

Electrons (from Beam Losses)
Stimulated Desorption (**Dy**
vacuum le

DEPENDENT ON DESIGN PARAMETERS

Ions (from beam interaction with residual gases) **Back Bombardment**

R&D on Photocathodes

Cathodes feasibility studies:

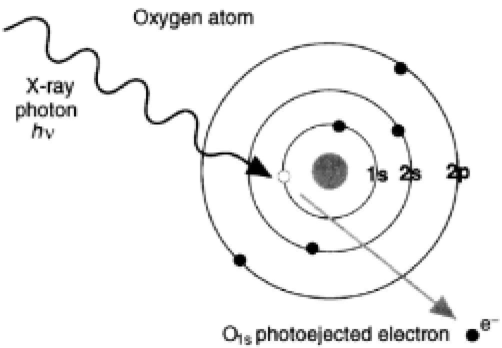
- Testing the material performance in a real photoinjector setup.
- **Understanding the main factor affecting cathode performance.** ⇦ MATERIAL CHARATERIZATION
- Improve the cathode performance.

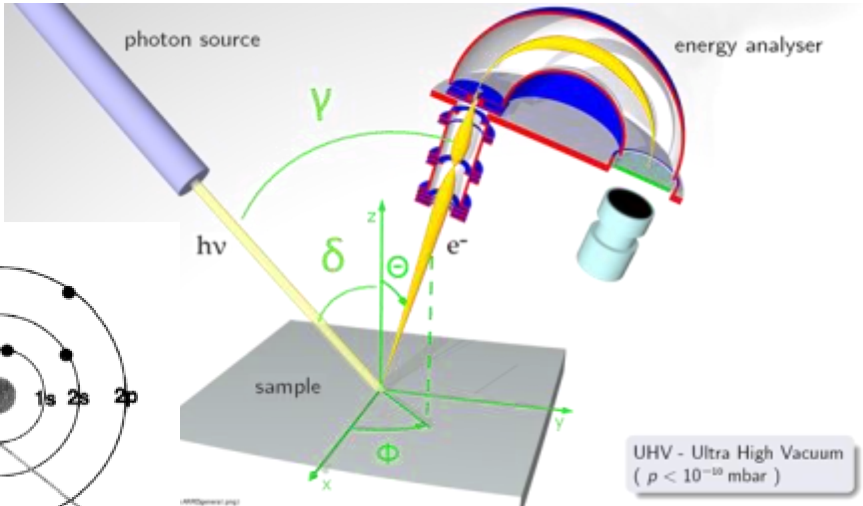
Surface Analysis: X-Rays Photoemission Spectroscopy (XPS)

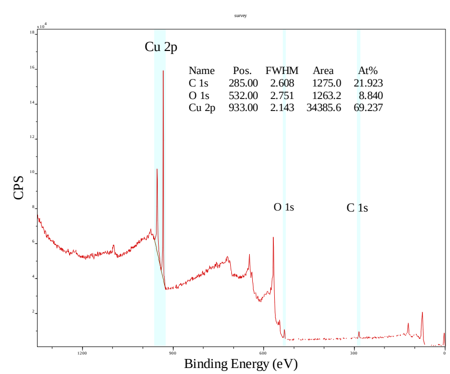
- XPS is a surface analysis technique (~ nm) able to detect all elements (except H, He) and to distinguish different chemical bonding states.

FUNDAMENTALS OF THE XPS:

- Photons (from **x-rays gun**) interact with the core electrons of the sample atoms creating ionized states.
- The Kinetic Energy of the subsequently photoemitted electrons is measured thanks to the **Energy Analyser .**
- The measured spectrum is a direct indication of the Binding Energy of the different atomic levels.

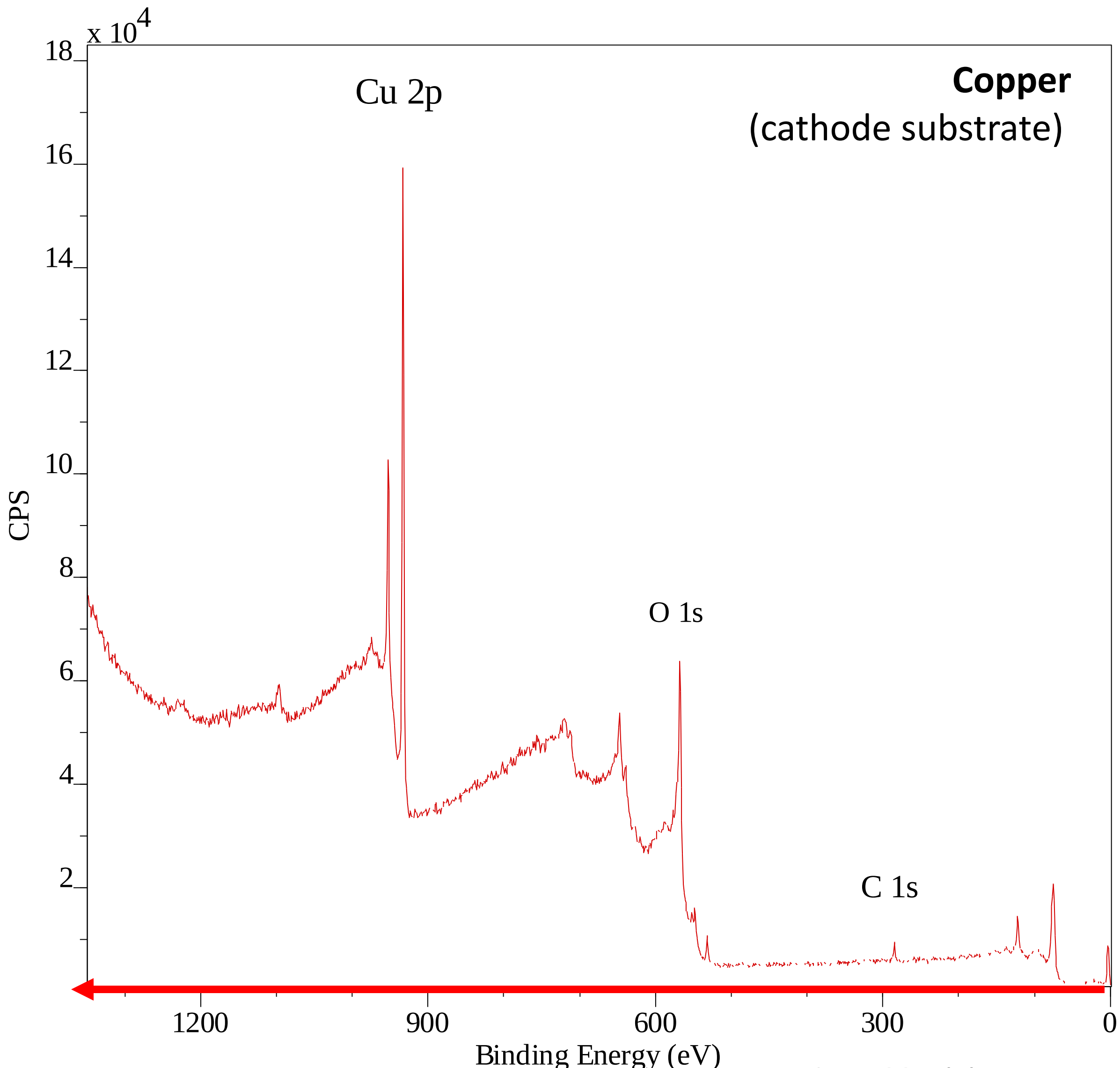






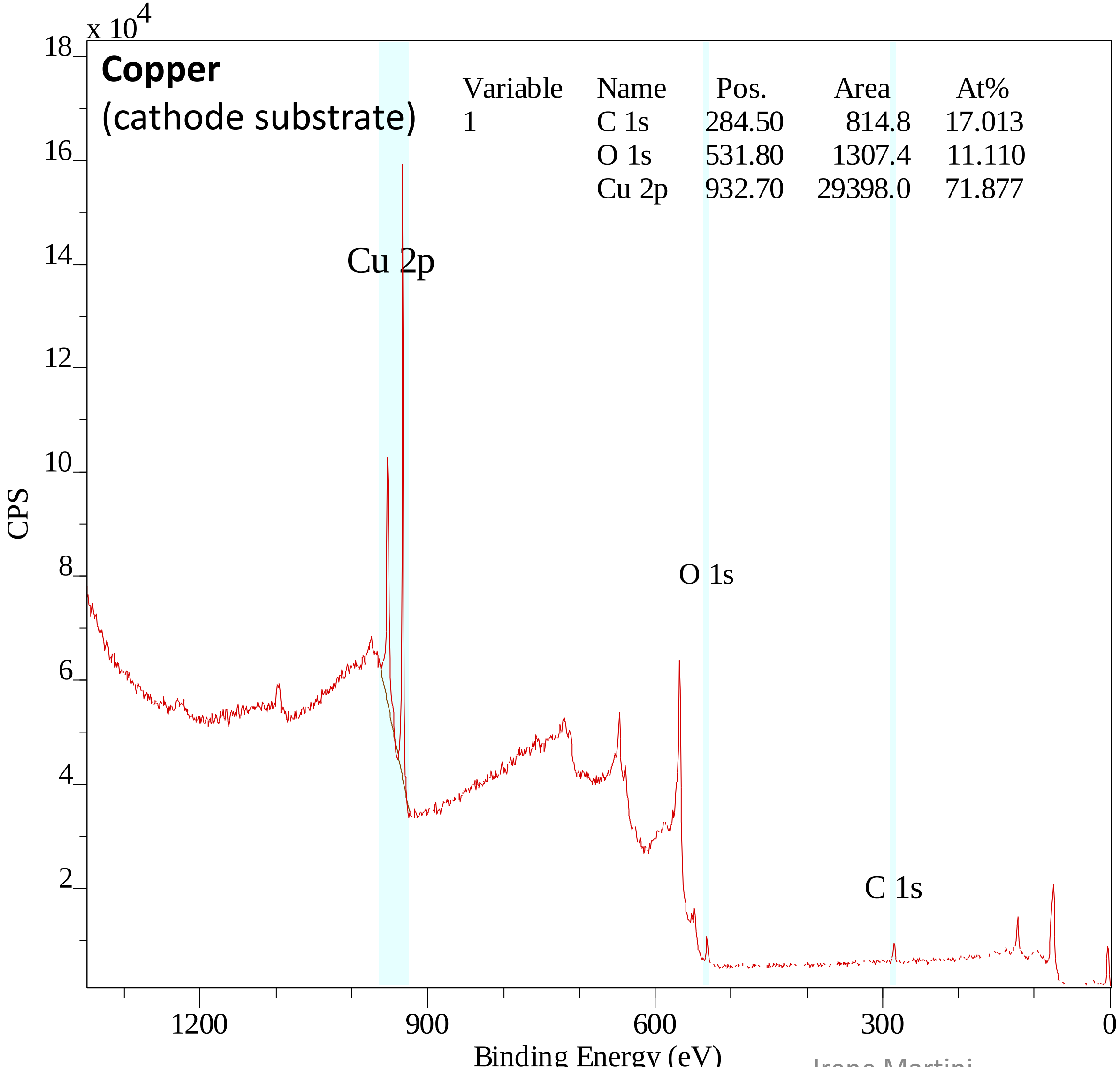
The spectrum is the FINGER PRINT of the material in that specific chemical environment!

XPS: What information?



Qualitative analysis:
ELEMENTAL IDENTIFICATION

XPS: What information?



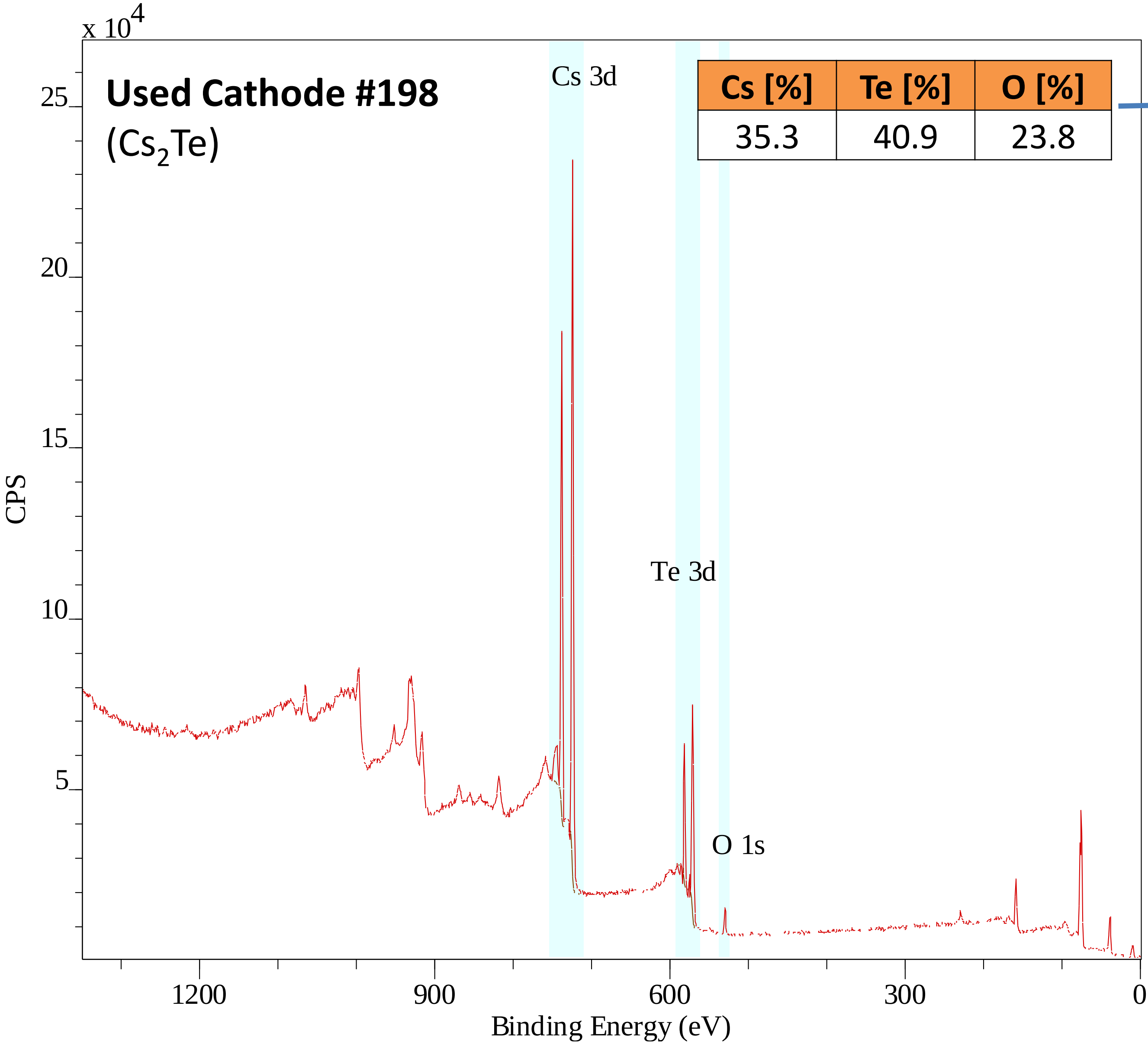
Qualitative analysis:
ELEMENTAL IDENTIFICATION

Quantitative analysis:
RELATIVE COMPOSITION of the surface.

$$I_A = N_A * \sigma_A * \lambda_A * K$$

I_A: peak intensity
N_A: concentration of element A
σ_A: photoionization cross-section
λ_A: mean free path
K: all setup related factors

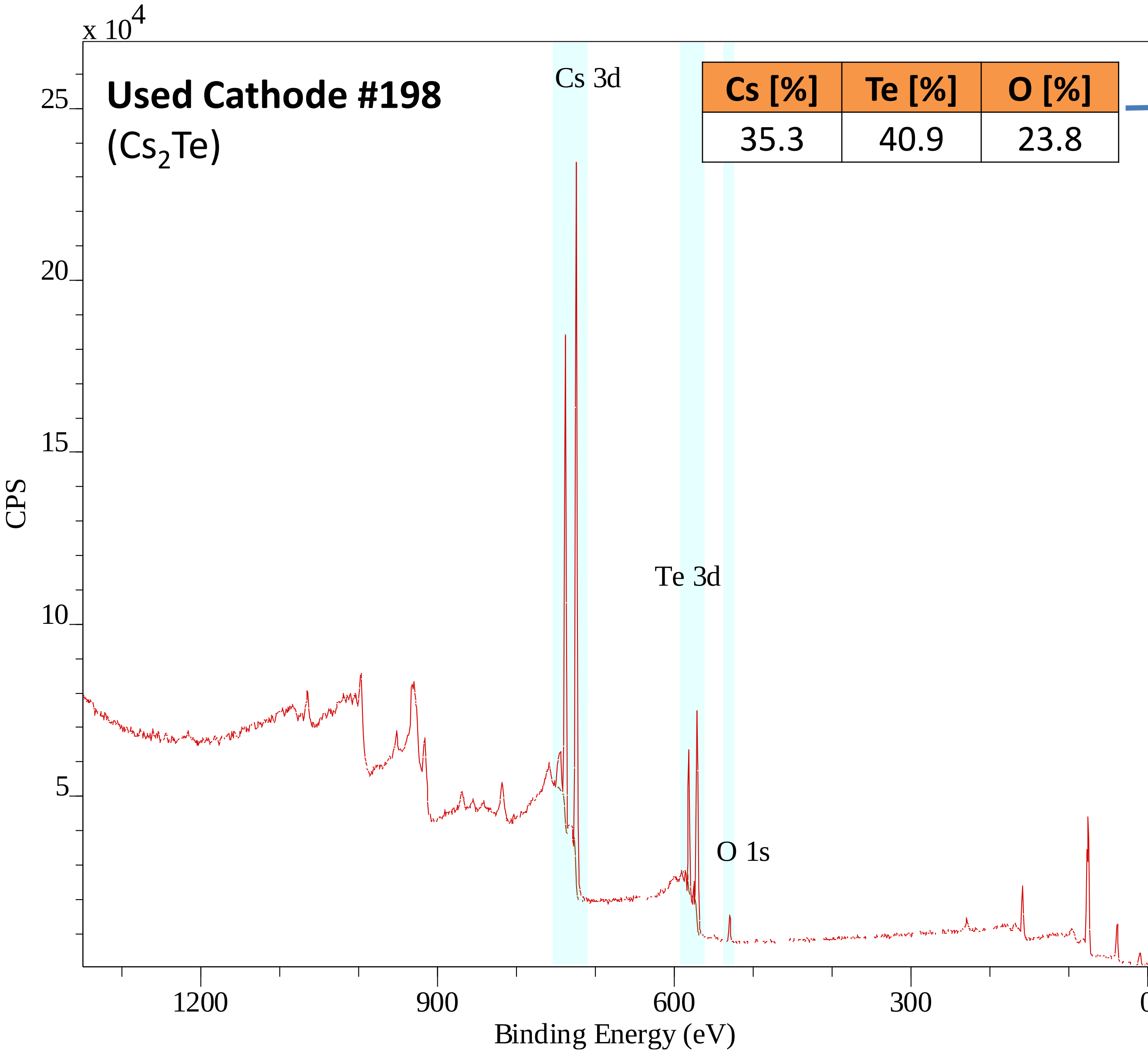
XPS Studies of Cathode #198 (Cs_2Te)



Cs [%]	Te [%]	O [%]
35.3	40.9	23.8

Elemental composition of the surface: lack of Cs compared to the compound Cs_2Te.

XPS Studies of Cathode #198 (Cs_2Te)



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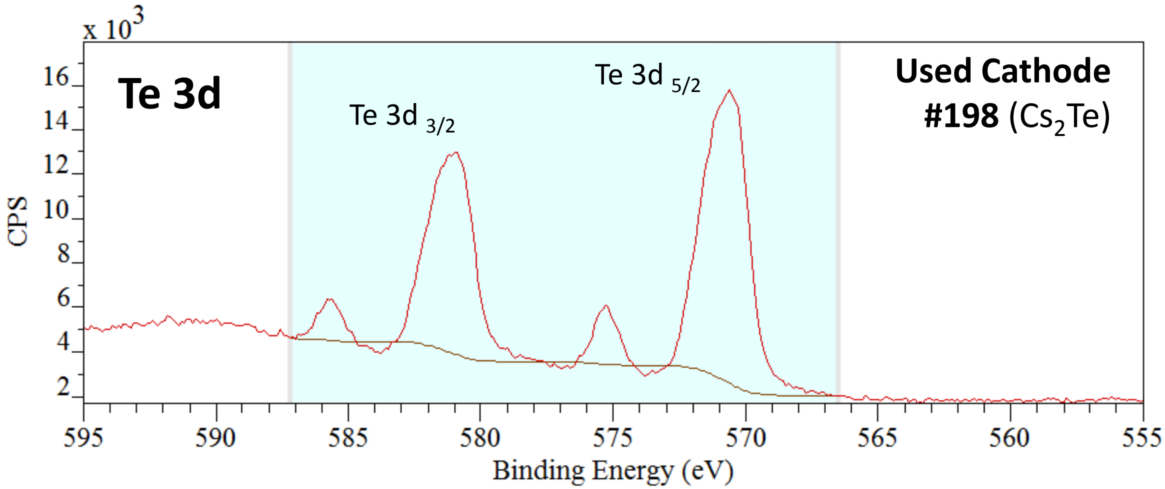
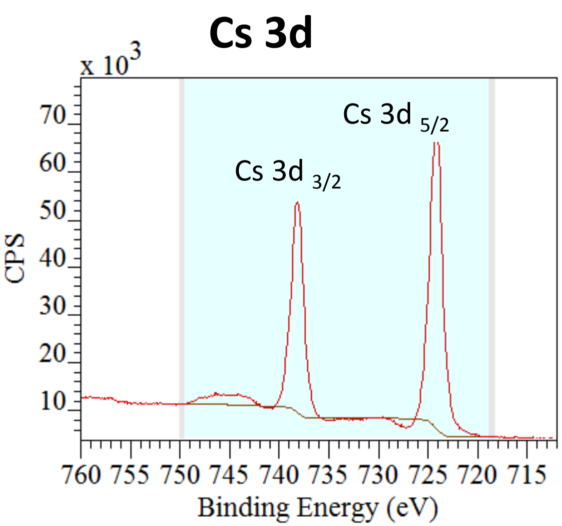
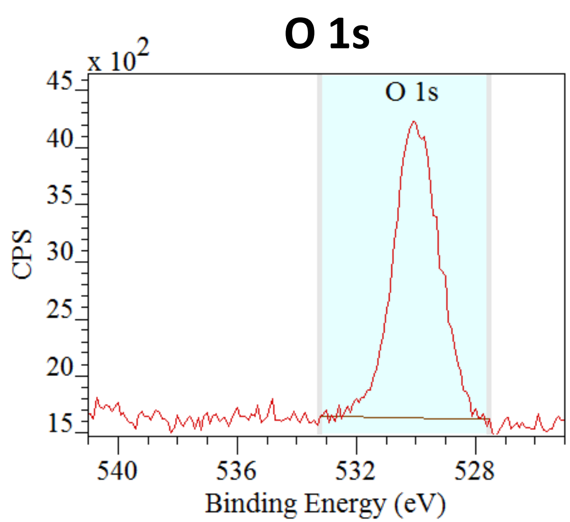
CHEMICAL STATES
IDENTIFICATION

XPS Studies of Cathode #198 (Cs_2Te)

High Resolution Spectra of the highest peak







CHEMICAL STATES
IDENTIFICATION

High Resolution Spectra

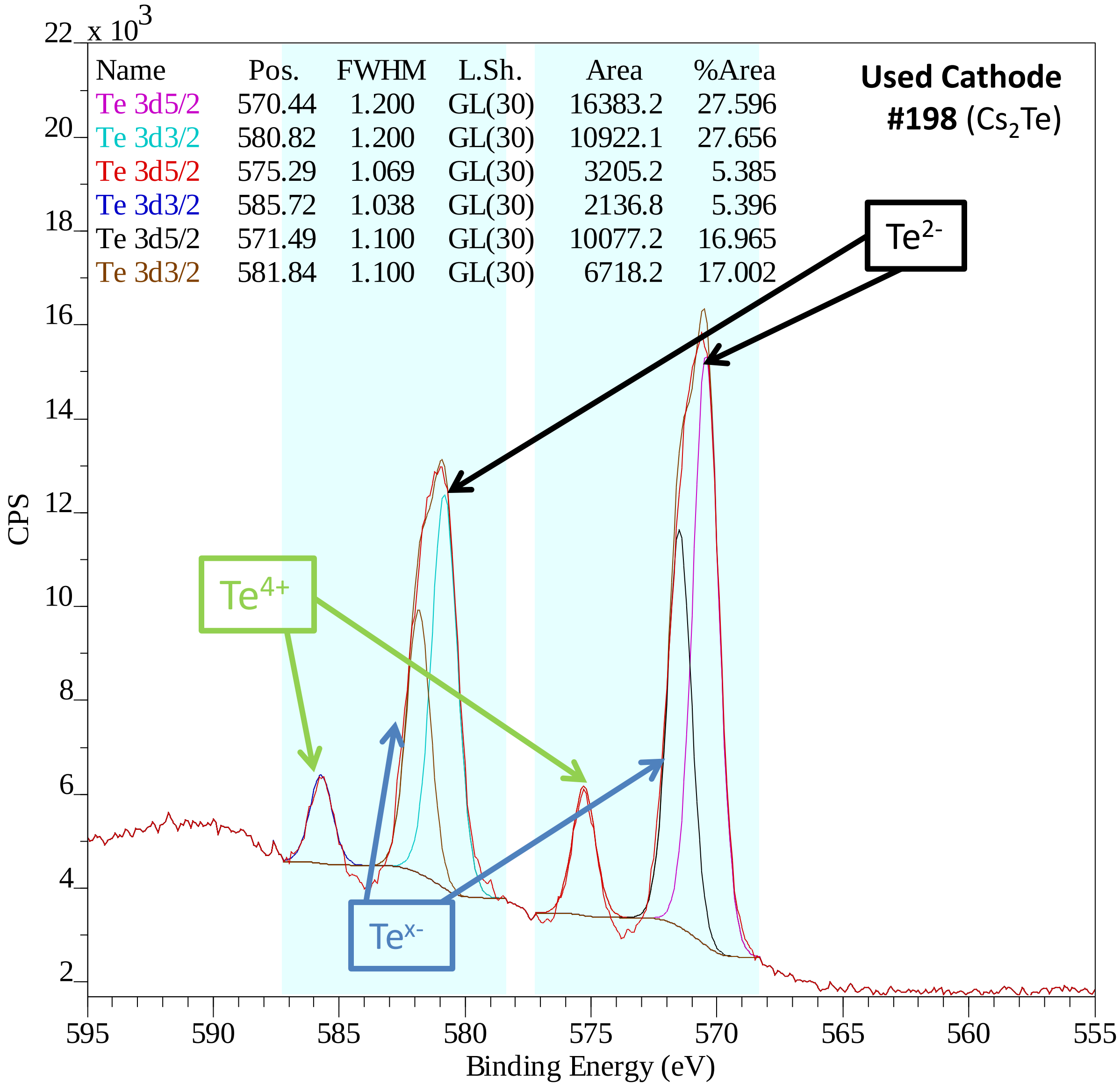
CHEMICAL SHIFT
The peak energy position is related to the chemical state of the element.

PEAKS FITTING: different compounds of the same element

Peak position (slightly) and FWHM depends on the measurement setup

LITERATURE +
STANDARD SAMPLES

XPS Studies of Cathode #198 (Cs_2Te)



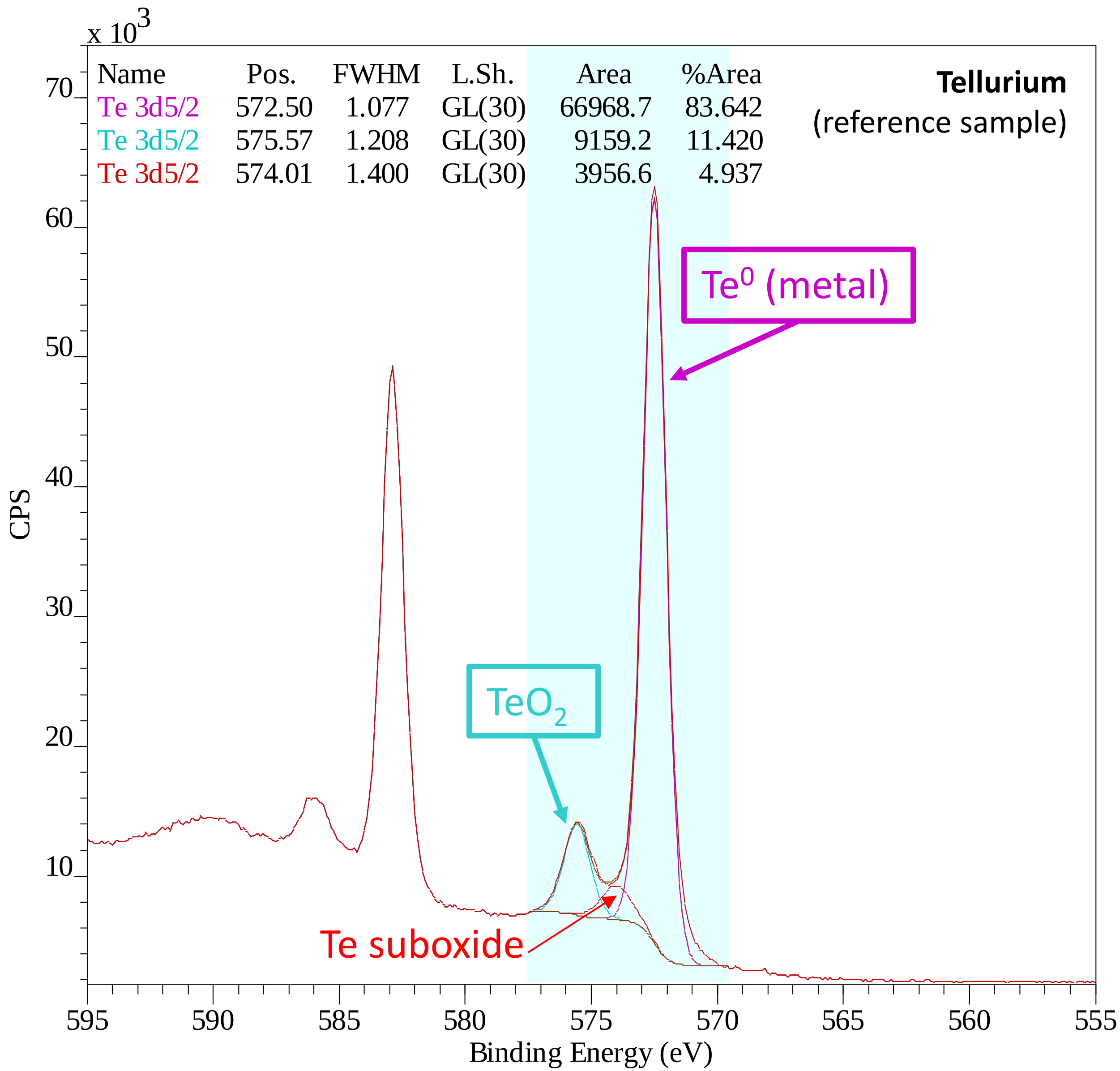
Te 3d region

PEAKS MODEL MUST HAVE PHYSICAL REASON.

Possible explanation:

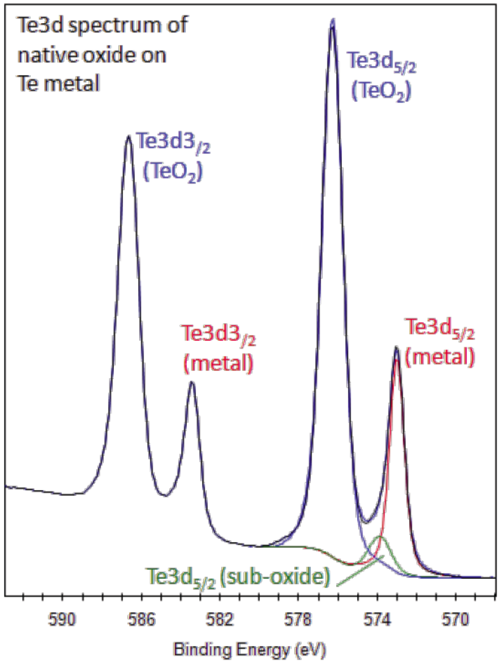
- Cs_2Te (Te^{2-})
- Cs_xTe (Te-rich phase)
- TeO_2 (Te^{4+})

Tellurium Reference Sample



Te 3d region

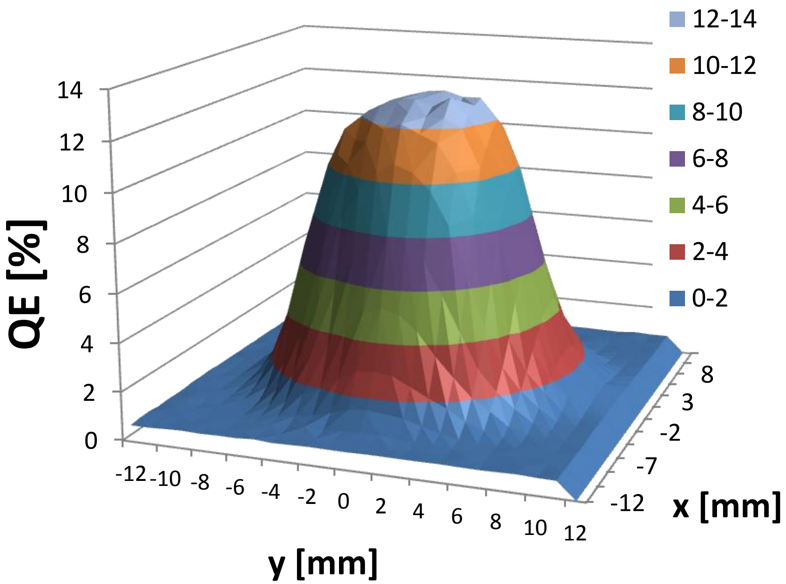
Literature:



http://xpssimplified.com/elements/tellurium.php

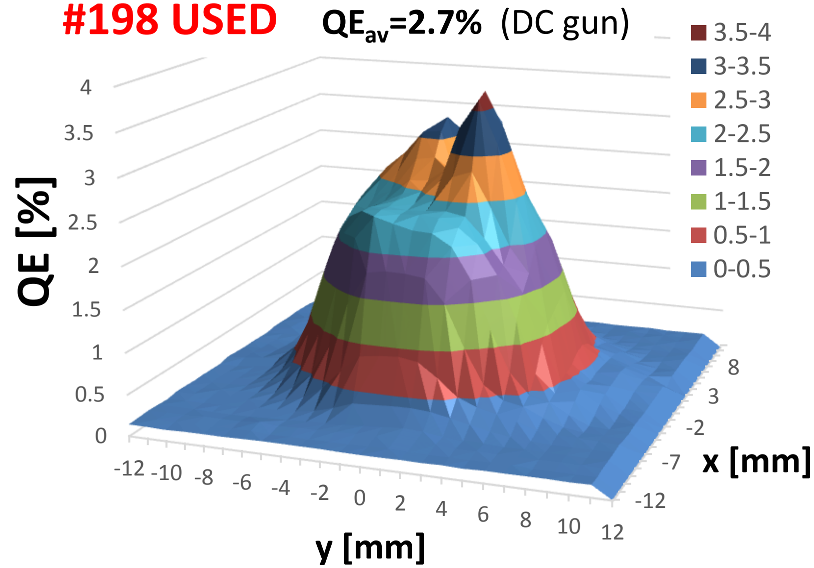
Cathode # 198 (Cs_2Te)

 # 198 NEWLY PRODUCED **QE_{av}=14%** (DC gun)

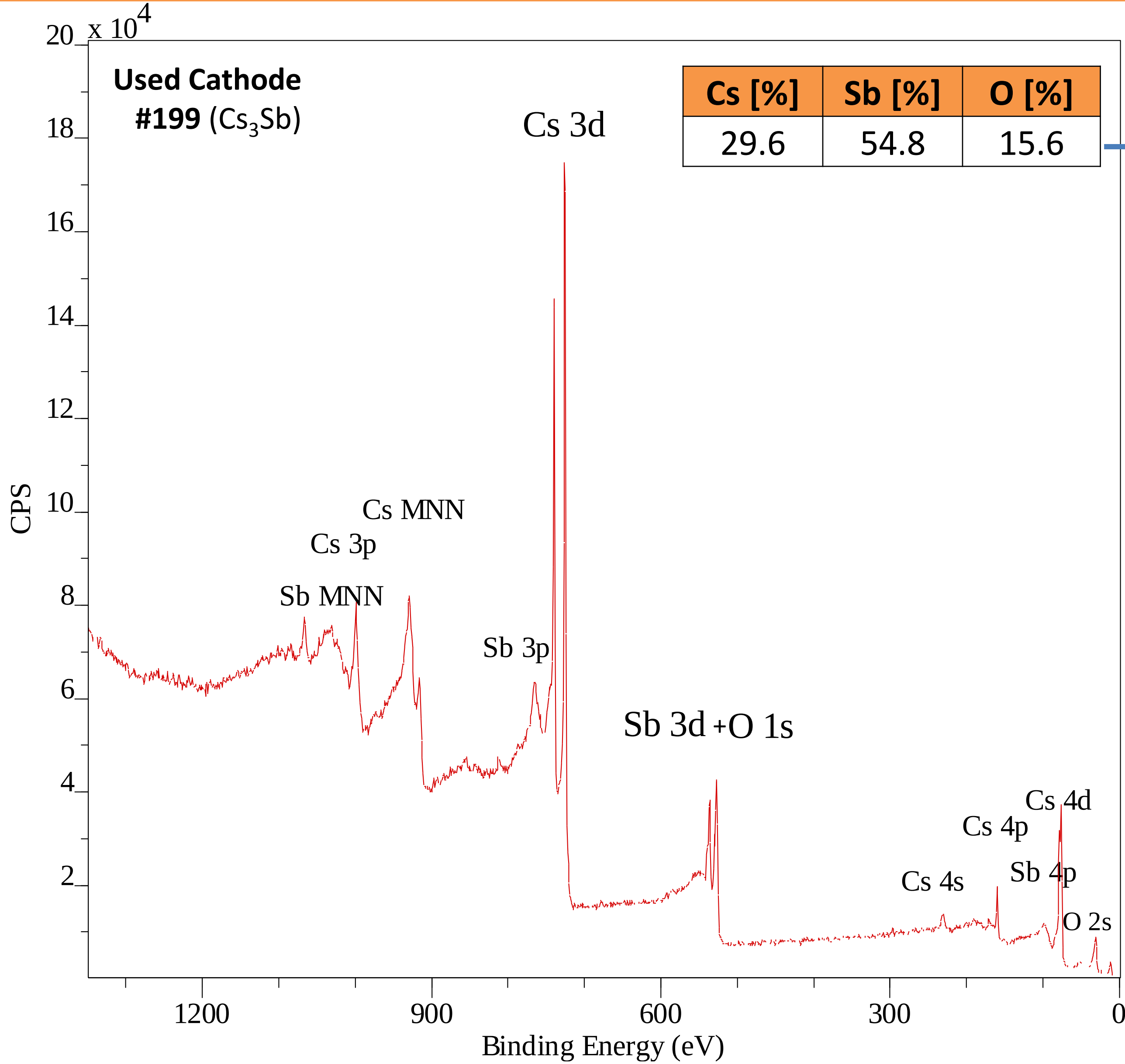


PHIN photoinjector run

#198 USED **QE_{av}=2.7%** (DC gun)



XPS Studies of Cathode #199 (Cs_3Sb)



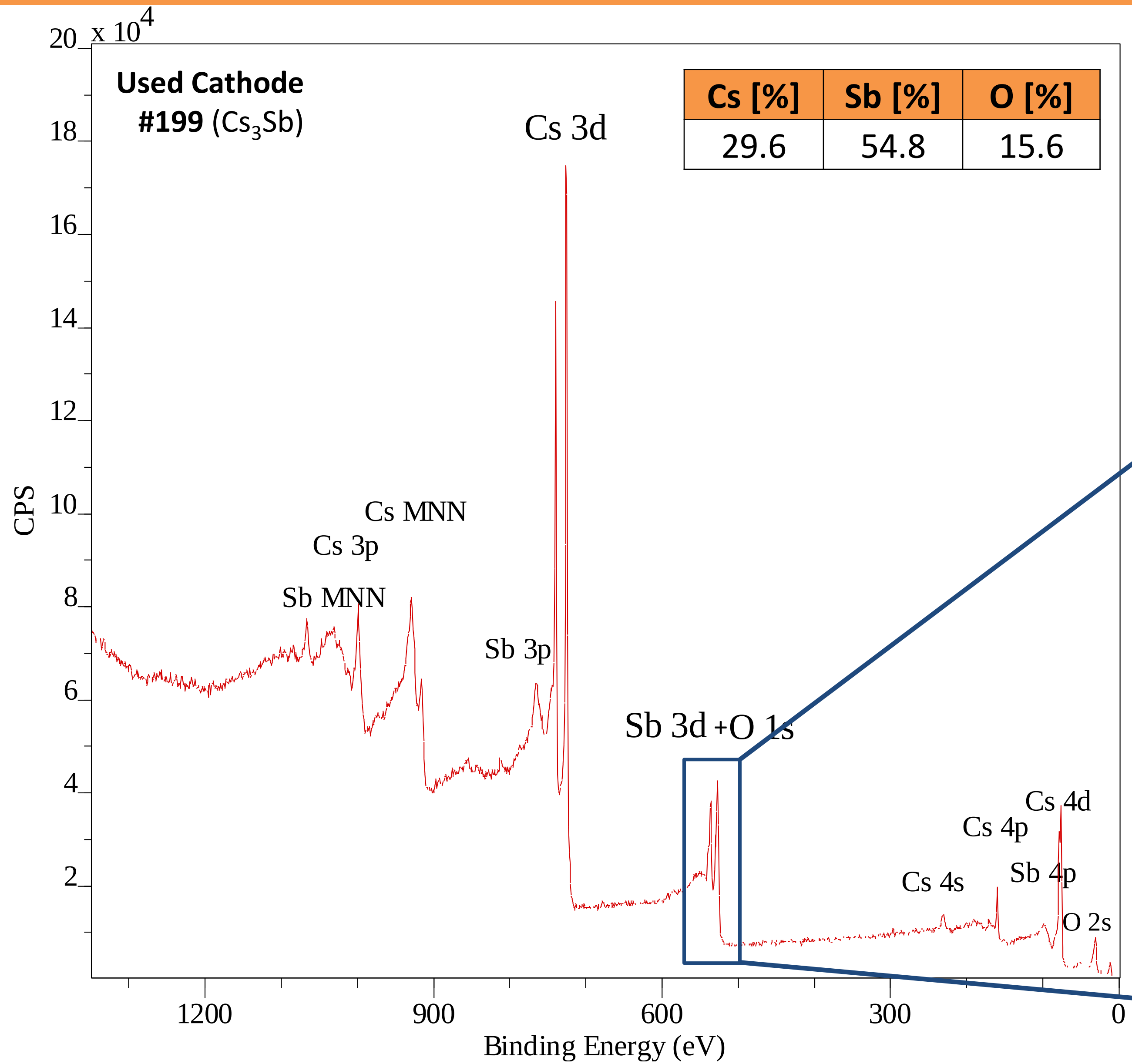
Cs [%]	Sb [%]	O [%]
29.6	54.8	15.6

Elemental composition of the surface: lack of Cs in comparison with Cs_3Sb.

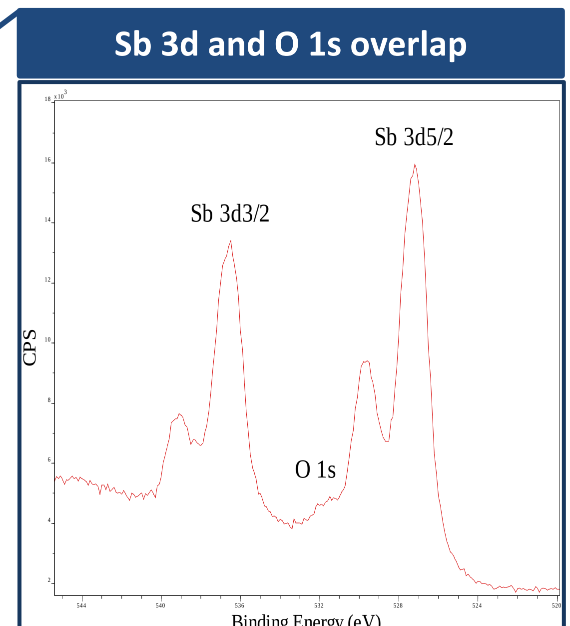
XPS Studies of Cathode #199 (Cs_3Sb)

Used Cathode #199 (Cs_3Sb)

Cs [%]	Sb [%]	O [%]
29.6	54.8	15.6

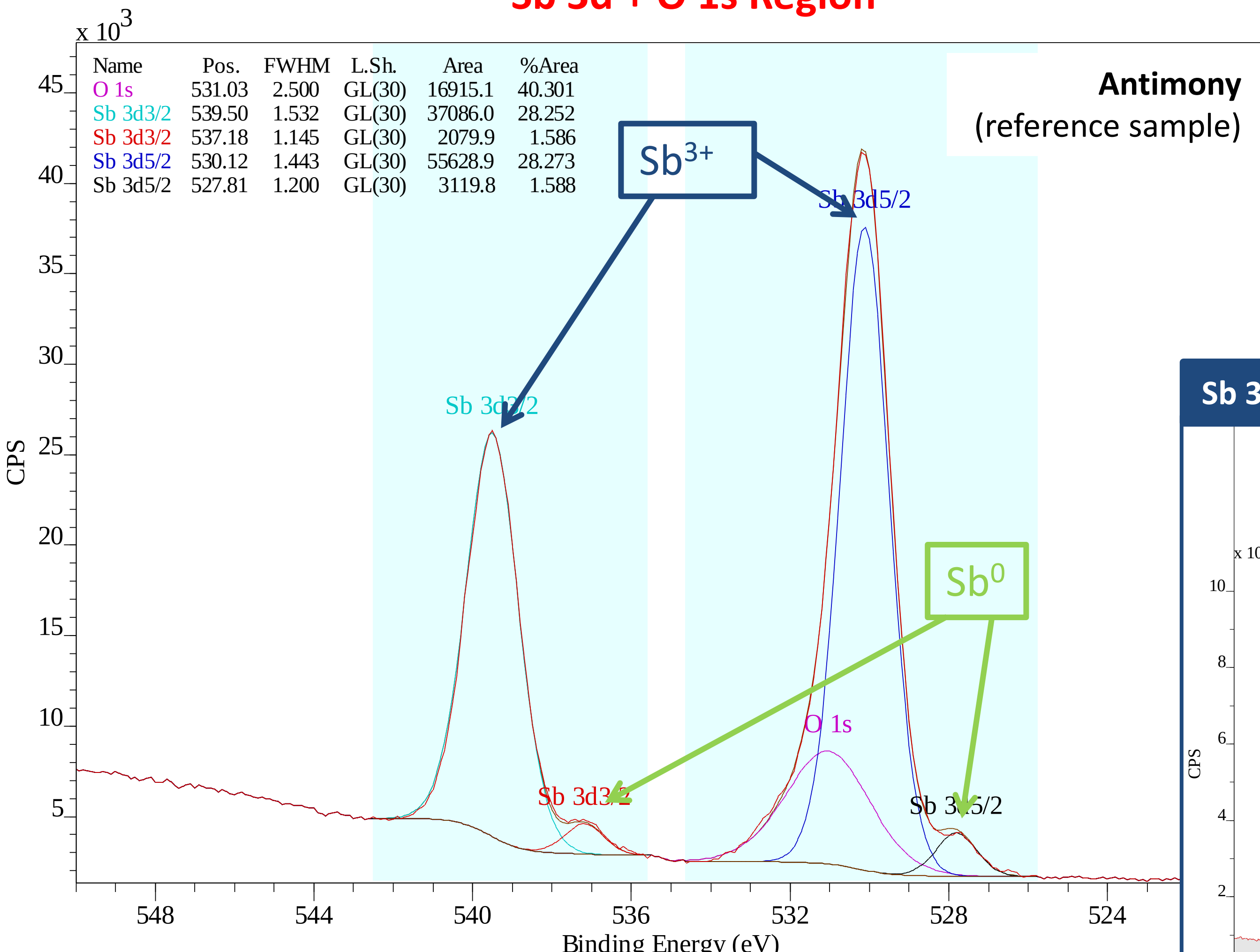


Chemical states identification: O 1s and Sb 3d are overlapping!



Antimony Reference Sample

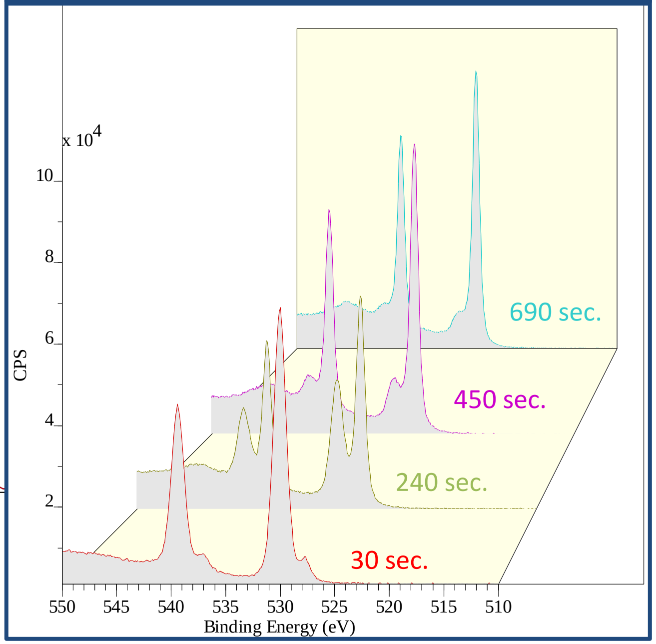
Sb 3d + O 1s Region



Native oxide layer on top of Sb metallic:

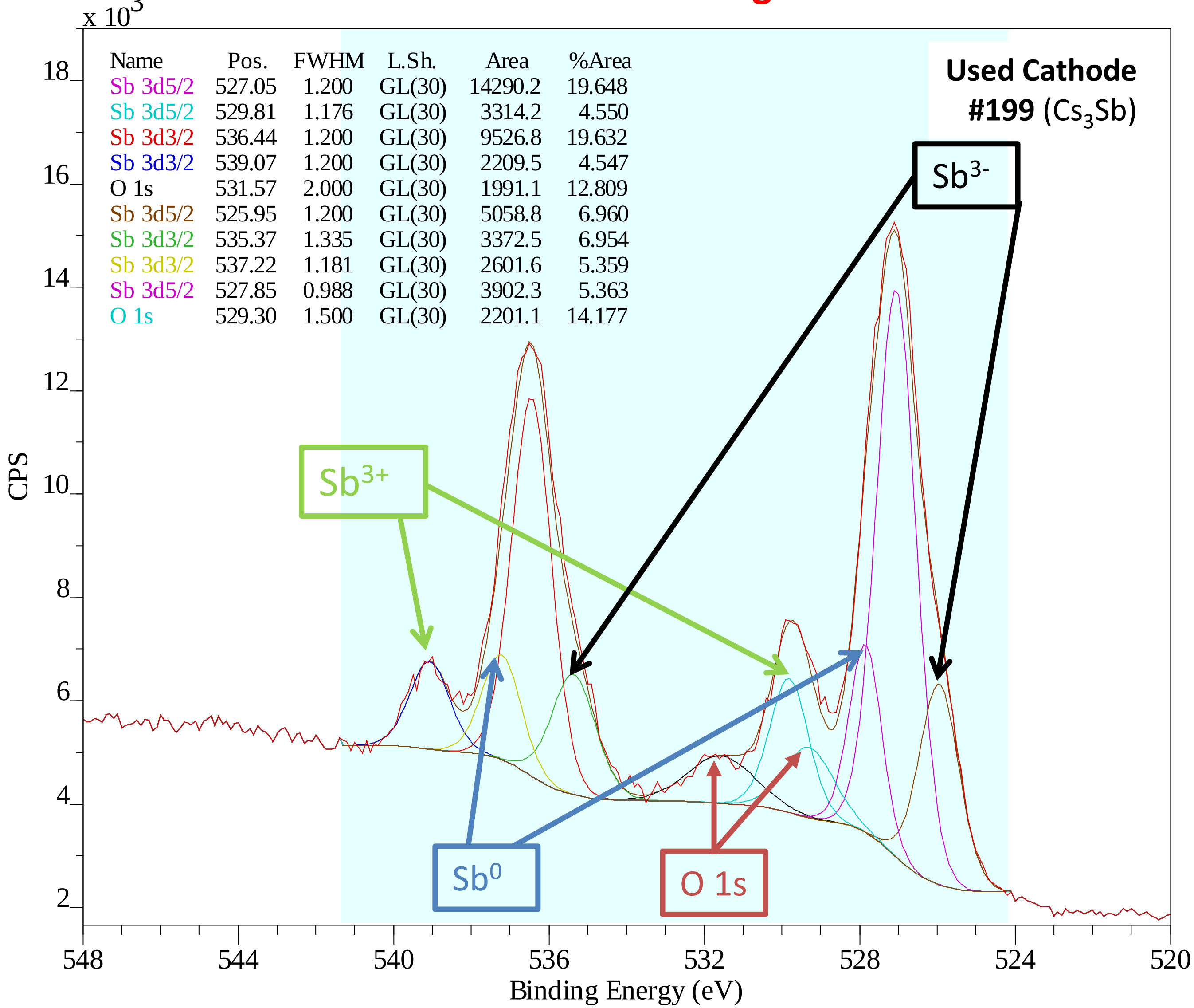
- Sb^{3+}: Sb_2O_3
- Sb^0: Sb metallic

Sb 3d+O1s during Ar ions sputtering



XPS Studies of Cathode #199 (Cs_3Sb)

Sb 3d + O 1s Region



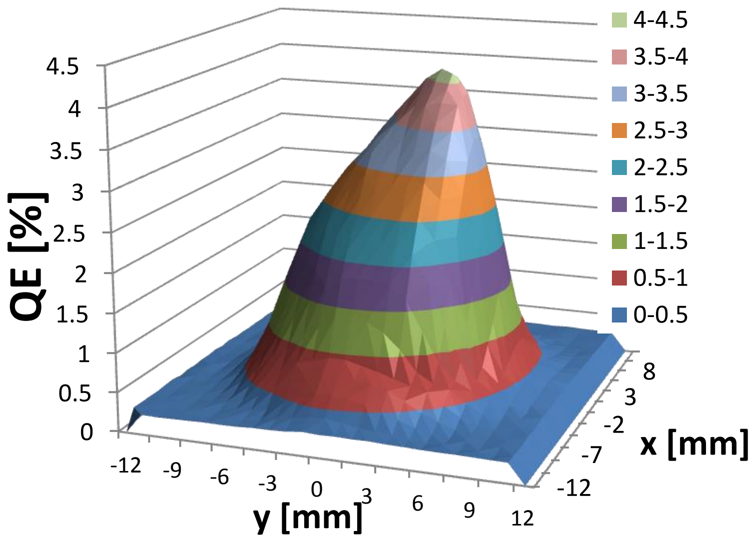
PEAKS MODEL MUST HAVE PHYSICAL REASON.

Possible explanation:

- Sb^{-3}: Cs_3Sb
- Cs_xSb (Sb-rich phase)
- Sb^0 metal
- Sb^{3+}: Sb_2O_3
- 2 OXYGEN peaks:
  - Sb_2O_3
  - Cs oxide

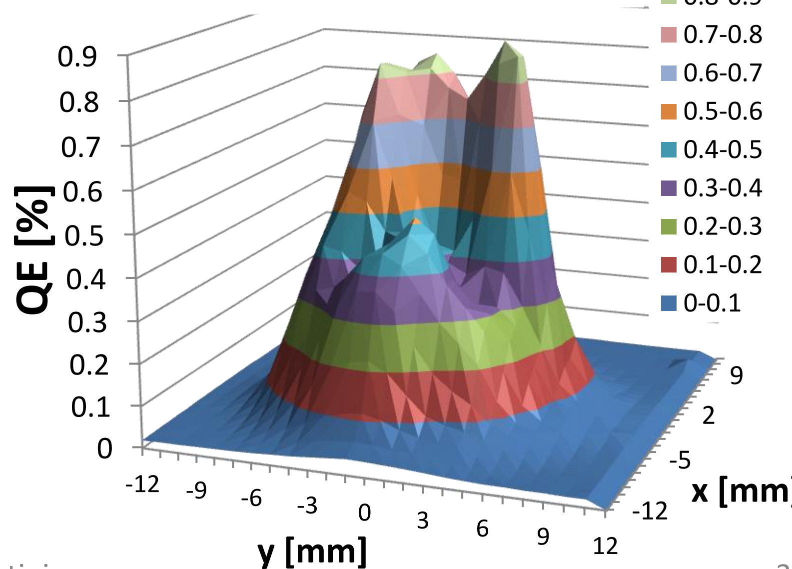
Cathode # 199 (Cs_3Sb)

#199 NEWLY PRODUCED Max **QE_{av}=5.2%** (DC gun)



PHIN photoinjector run

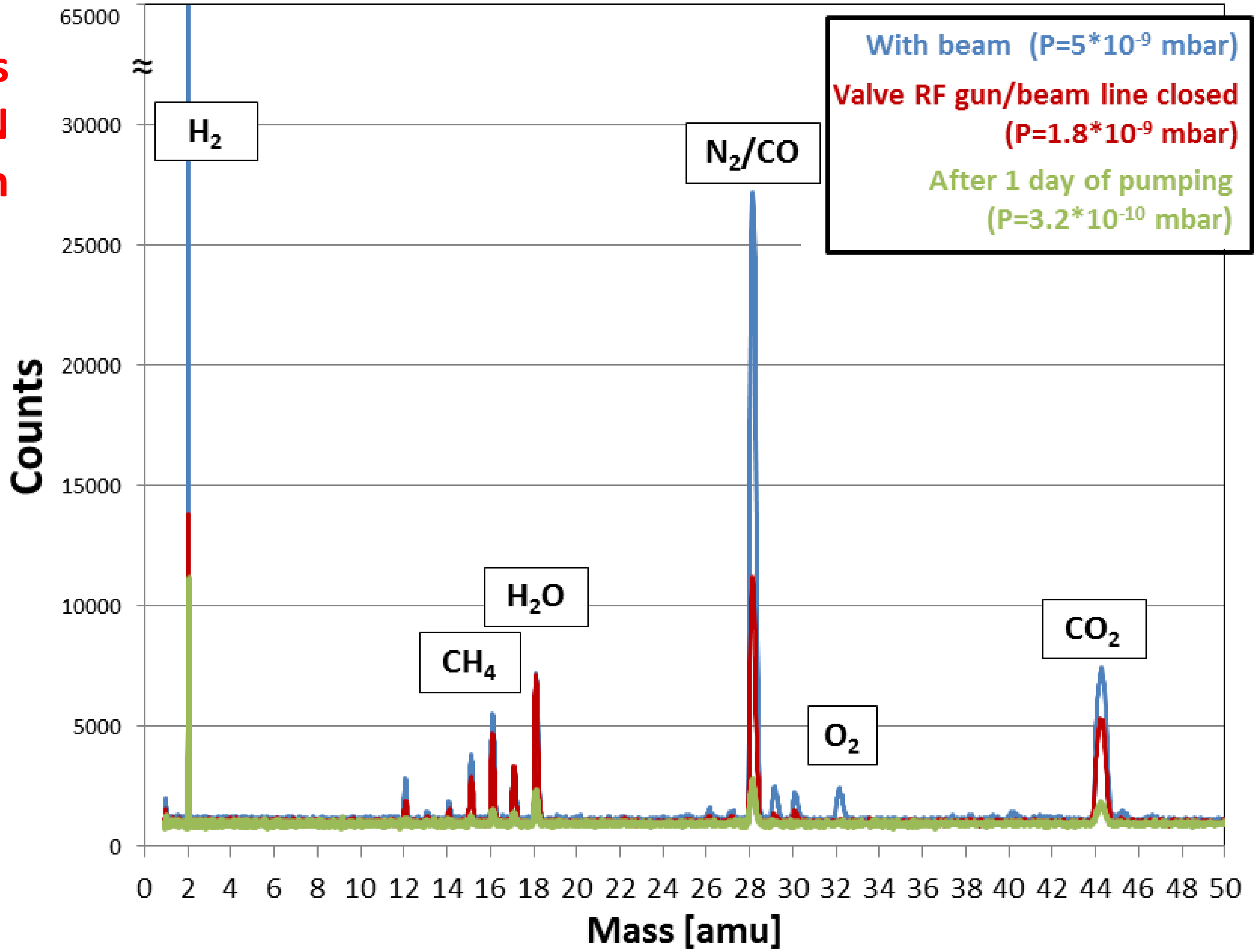
#199 USED **QE_{av}=0.7 %** (DC gun)



Conclusions

- Both used cathodes (Cs_3Sb and Cs_2Te) are slightly oxidized, most probably during photoinjector operation (Dynamic Vacuum is worse than Static Vacuum):

Residual gases spectrum in PHIN photoinjector gun



Conclusions/Outlook

- **Cathode #198**: more than 50% of Te found on the surface is bound to Cs as Cs_2Te ⟺ The measured QE for the used cathode is still good QE~3% .
- **Cathode #199**: the Sb-rich phase is the main component ⟺ The used cathode shows strongly degraded photoemissive properties (QE~0.7 %).
- The low QE phases could be produced during the test in the RF photoinjector (i.e. ions back scattering) or be already there in the deposited layer of the newly produced cathode.

⇓

XPS studies on newly produced cathodes are called:

- Comparison with measurement on used cathodes
- Understanding and improving production process

Aknowledgements

Thank you all for your attention!

- Eric Chevallay, Christoph Hessler, Mikhail Martyanov, Valentin Fedosseev (CERN, EN/STI-LP)
- Holger Neupert, Valentin Nistor, Mauro Taborelli (CERN, TE/VSC-SCC)

PhD School on Materials Engineering

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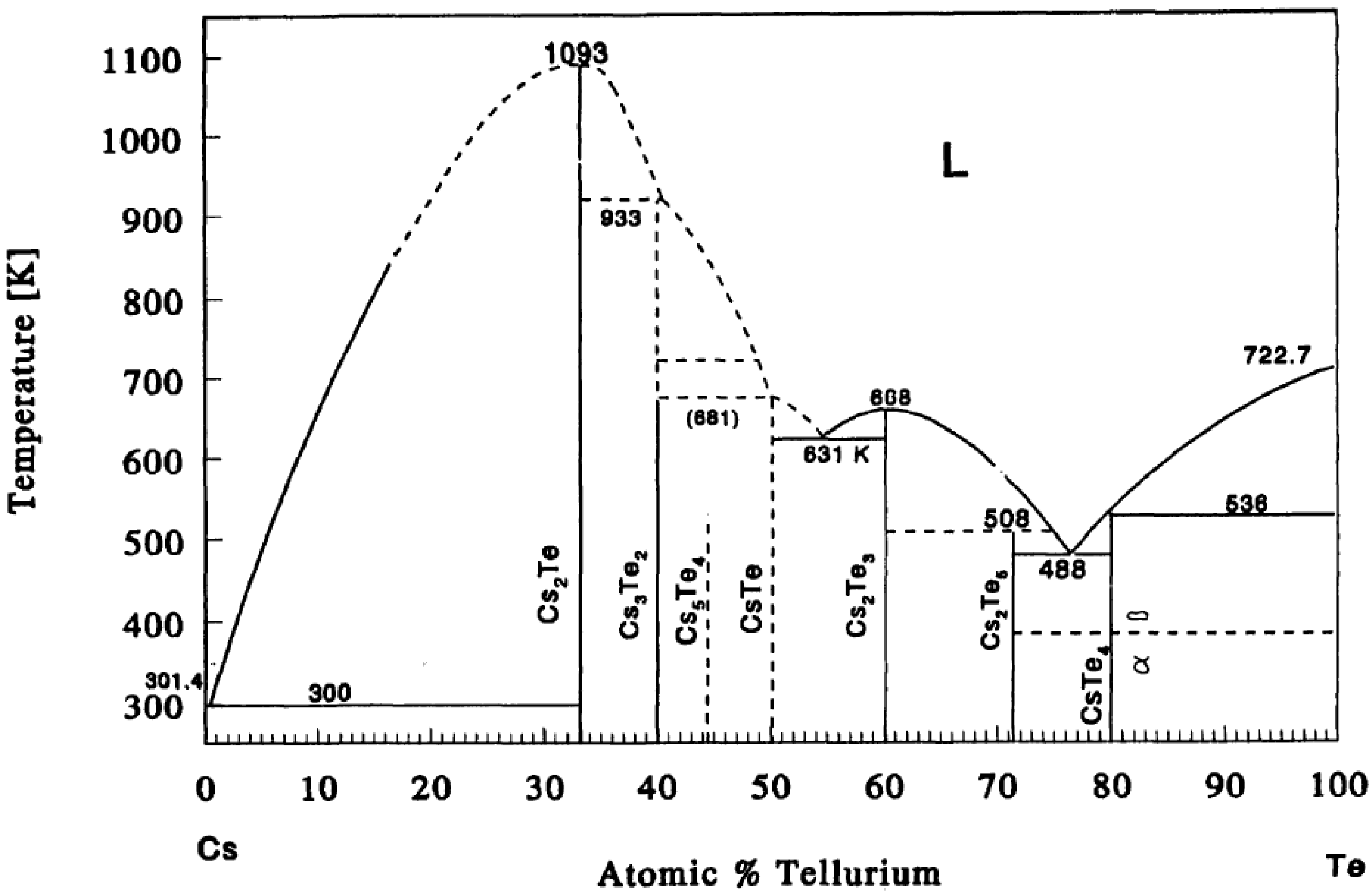
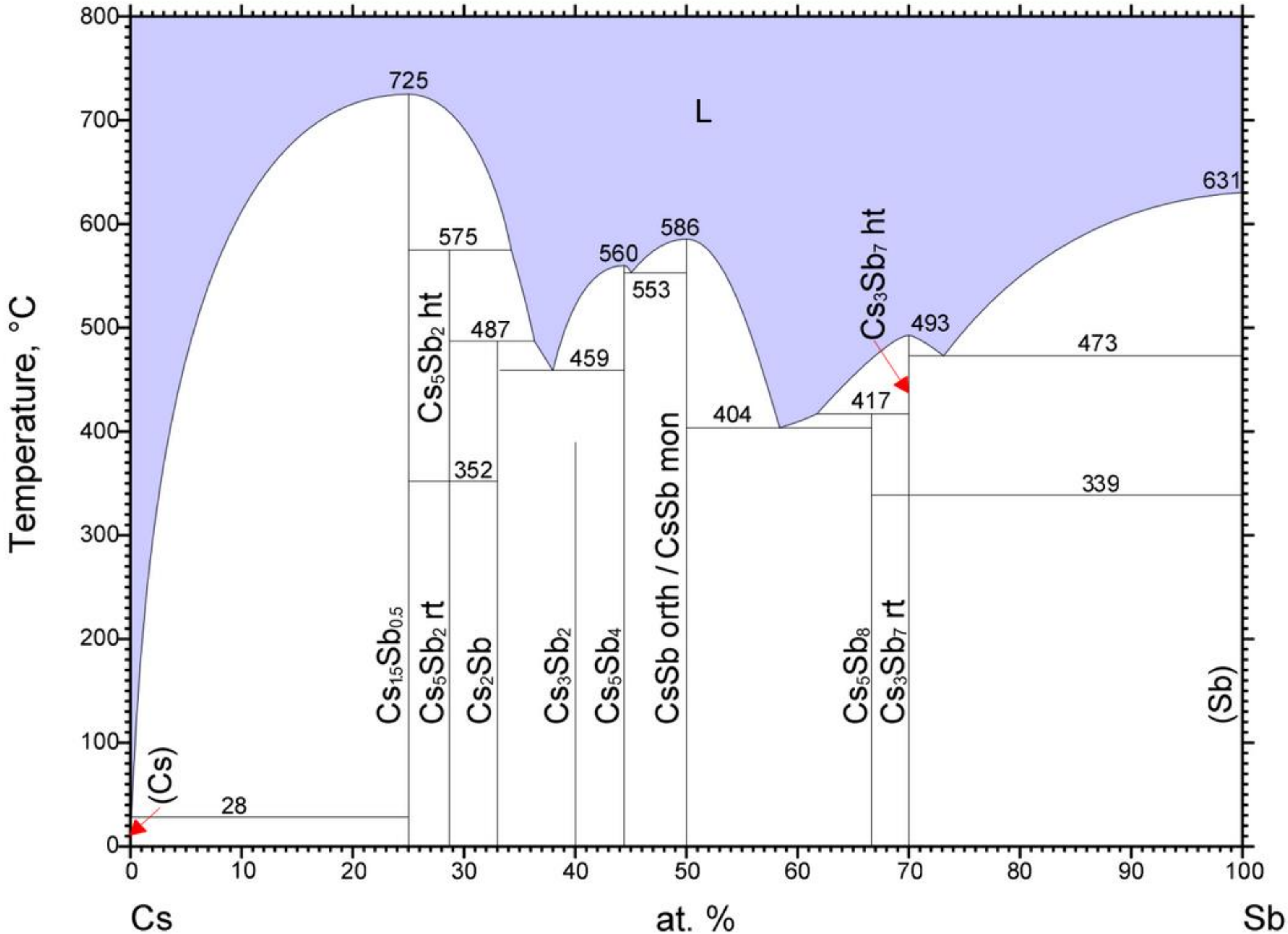
SPARE SLIDES

Cs – Te phase diagram



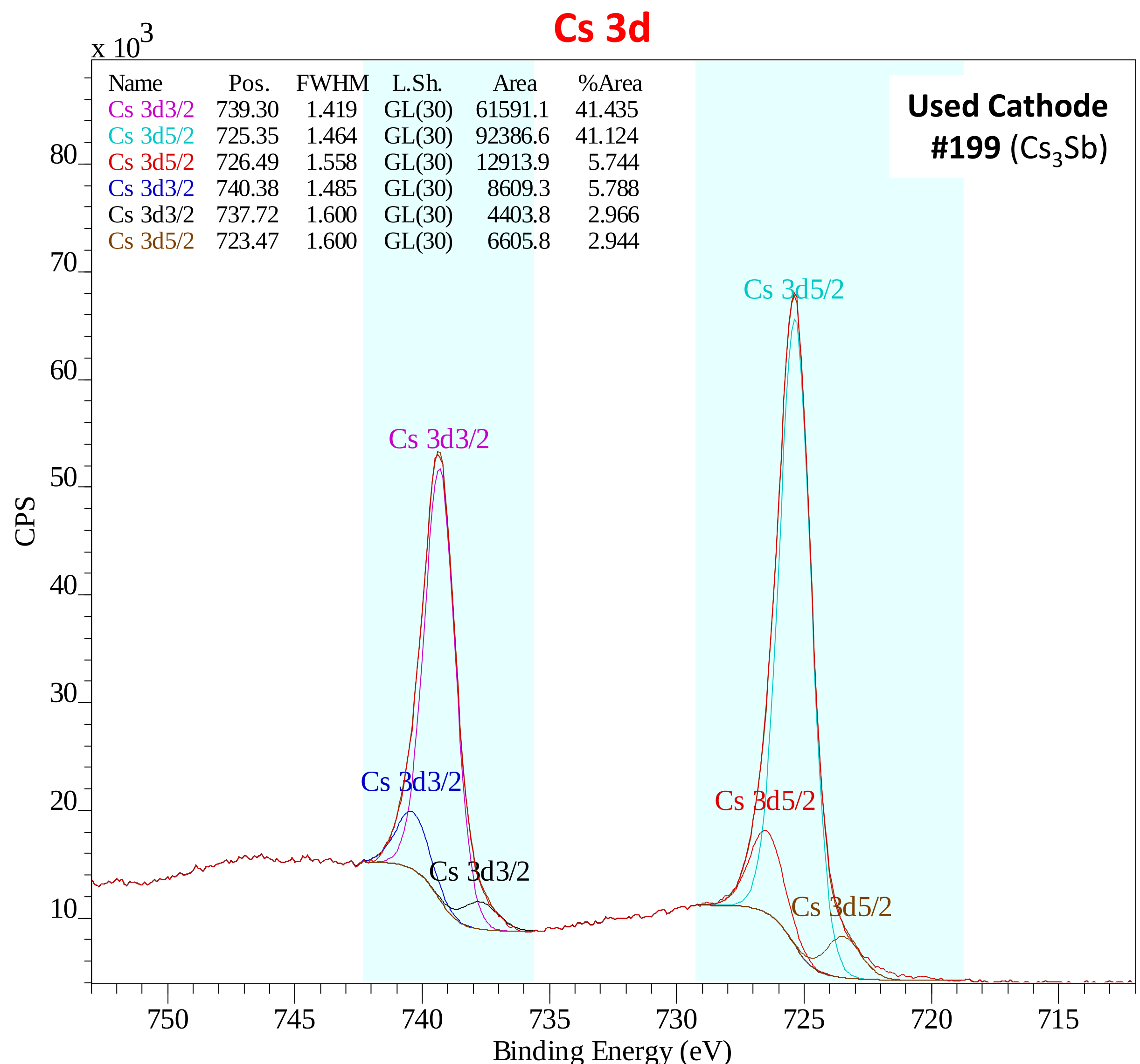
http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/27/010/27010183.pdf

Cs – Sb phase diagram



http://materials.springer.com/isp/phase-diagram/docs/c_0900841

XPS on used cathode #199 (Cs_3Sb)



Possible explanation (to be consistent with Sb region fitting):

- Cs_3Sb
- Cs_xSb (Sb-rich phase)
- Cs oxide

Surface Analysis: X-rays Photoemission spectroscopy

- Surface analysis of photocathode materials with XPS and their impact on the cathode performance in collaboration with the CERN Vacuum Group has started.

XPS SET UP

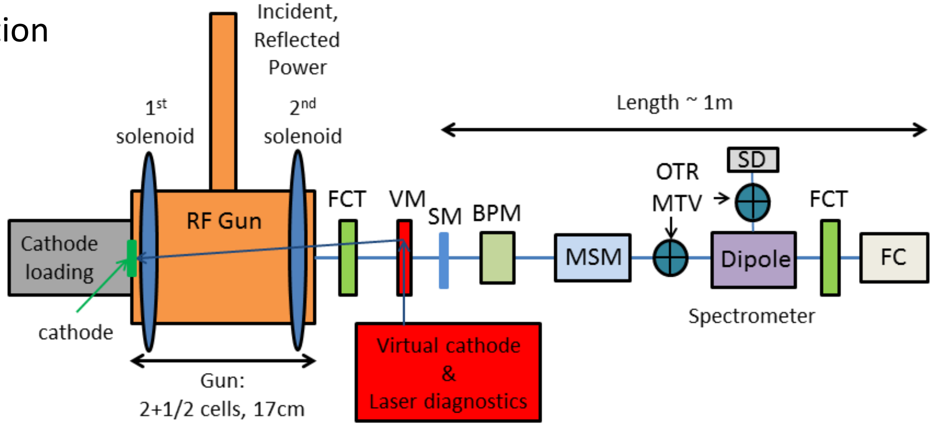
UHV carrier vessel to transfer cathode from production laboratory to the XPS set-up.

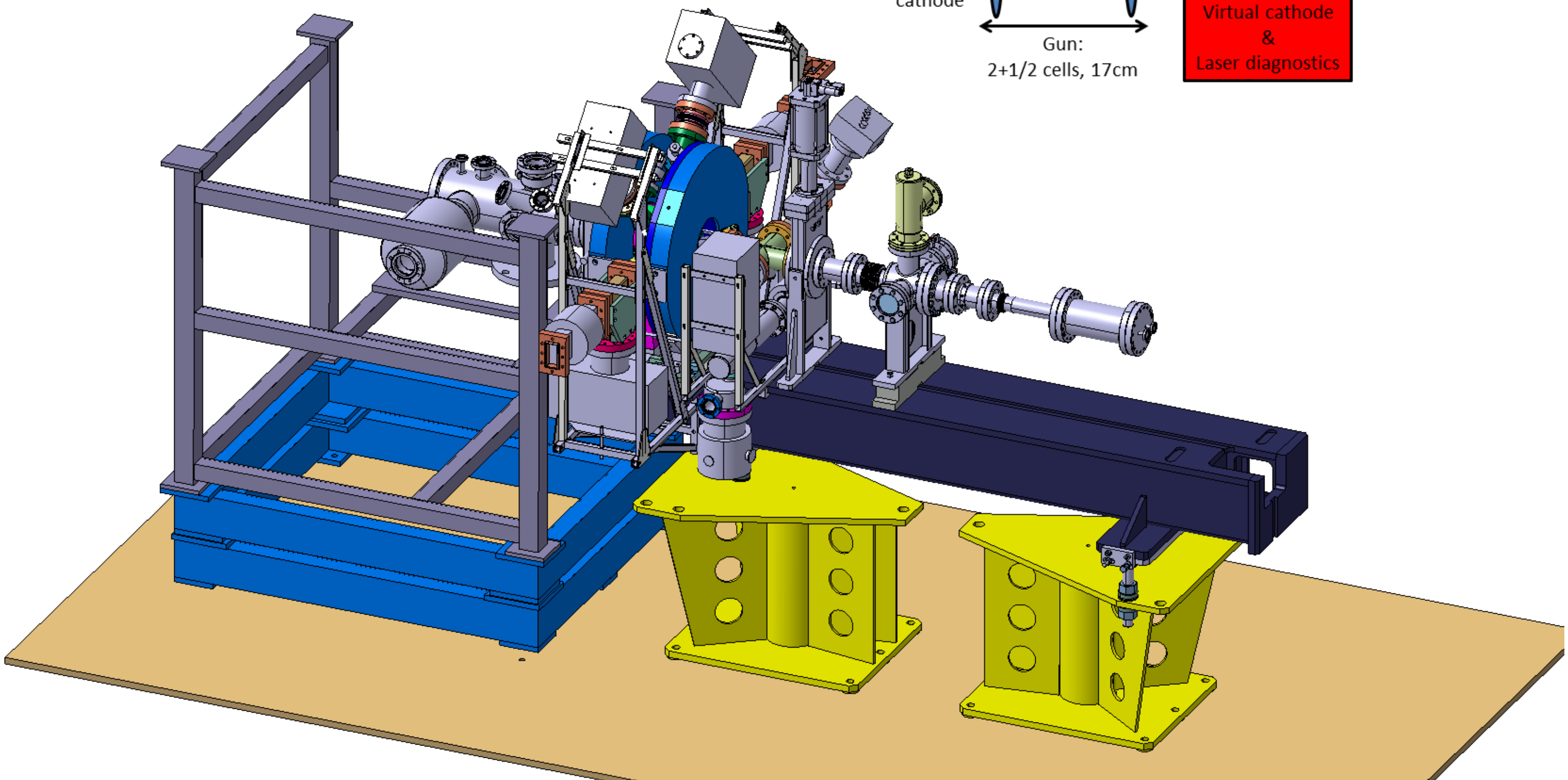
2 WEEKS NEEDED EACH TIME FOR 1 CATHODE TRANSFER (included baking of the SAS at the Photemission Lab and at the XPS set up lab)

PHIN RF photoinjector

FCT: Fast current transformer
VM: Vacuum mirror
SM: Steering magnet
BPM: Beam position monitor
MSM: Multi-slit Mask

OTR: Optical transition radiation screen
MTV: Gated cameras
SD: Segmented dump
FC: Faraday cup



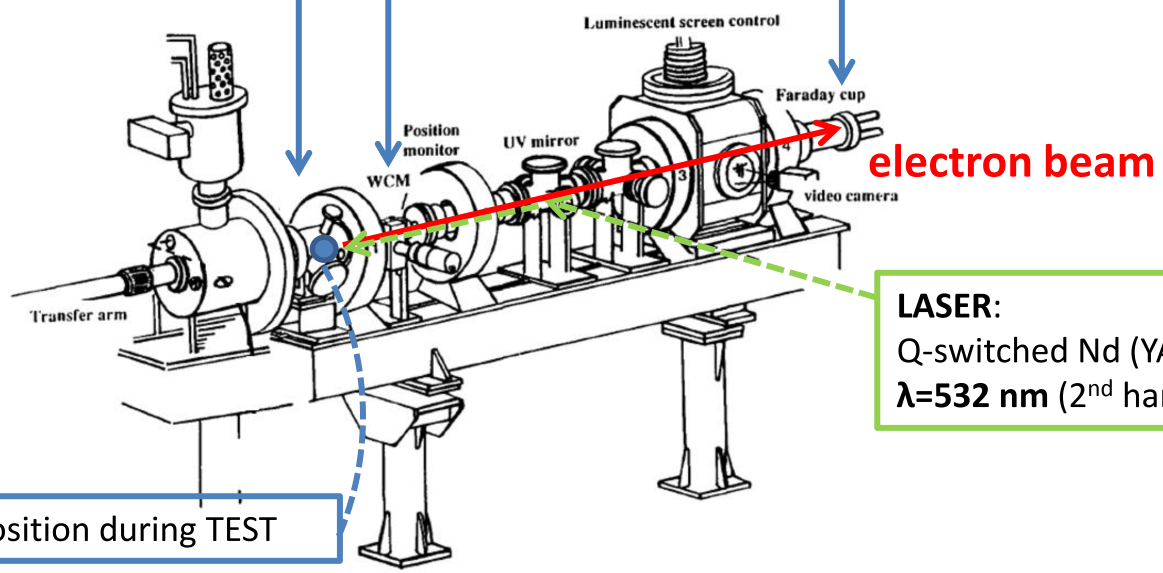


PREPARATION CHAMBER

BEAM LINE

DC GUN:
70 kV supplied voltage
(7 MV/m electric field)

Bunch charge measured by:
Wall Current Monitor (**WCM**)
Faraday Cup (**FC**)



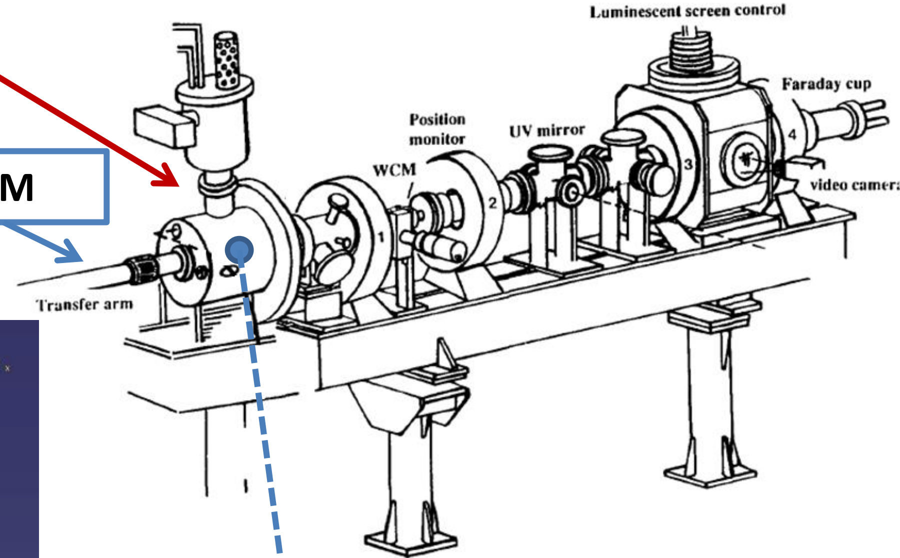
LASER:
Q-switched Nd (YAG)
λ=532 nm (2^{nd} harmonic)

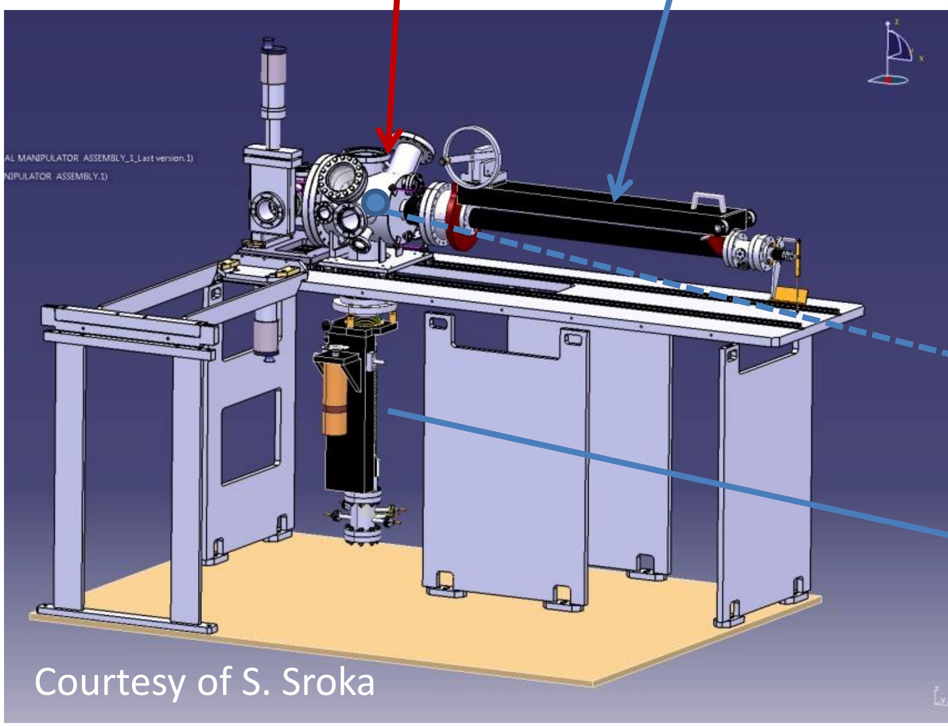
CATHODE position during TEST

PHOTOEMISSION LABORATORY

PREPARATION CHAMBER

TRANSFER ARM





CATHODE position during PREPARATION

EVAPORATORS ARM

Photocathodes for photoinjectors: Requirements

- High QE (Quantum Efficiency) at a convenient laser wavelength λ

$$QE(\%) = \frac{\#\,emitted\ electrons}{\#\,incident\ photons} \sim \frac{Q}{\lambda * E}$$

- Low dark current

- Long lifetime in challenging environment

$$\mathbf{QE(t)} = QE_{max} * e^{-\frac{t}{\tau}}, \qquad \tau\!: \frac{1}{e}\, lifetime$$

Introduction

Photocathodes requirements:

- **High QE at a convenient laser wavelength λ**
- Low dark current
- Long lifetime in challenging environment

Factor Affecting QE

Photoemission process: absorption, electron scattering, escape over surface barrier	Depending on the material (metals, semiconductors,..) and laser
Deposition process	Substrate material, Layer thickness, substrate temperature,..
Vacuum environment	Residual gas composition, Electron stimulated desorption, ..
Operating environment	Space charge,..

Introduction

Photocathodes requirements:

- High QE at a convenient laser wavelength λ
- **Low dark current**
- Long lifetime in challenging environment

Factor Affecting Dark Current (Field Emission)

$$\bar{I}_F = \frac{5.7 * 10^{-12} * 10^{4.52\phi^{-0.5}} * A_e(\beta E)^{2.5}}{\phi^{1.75}} * \exp\left(-\frac{6.53 * 10^{9} * \phi^{1.5}}{\beta E}\right)$$

Fowler-Nordheim for RF field ($\bar{I}_F$: Average field emitted current, A_e:Emitting Area)

Work Function → **CATHODE MATERIAL**

Field Enhancement Factor → **SURFACE MORPHOLOGY**

Electric field at the cathode → **OPERATING CONDITION**

Introduction

Photocathodes requirements:

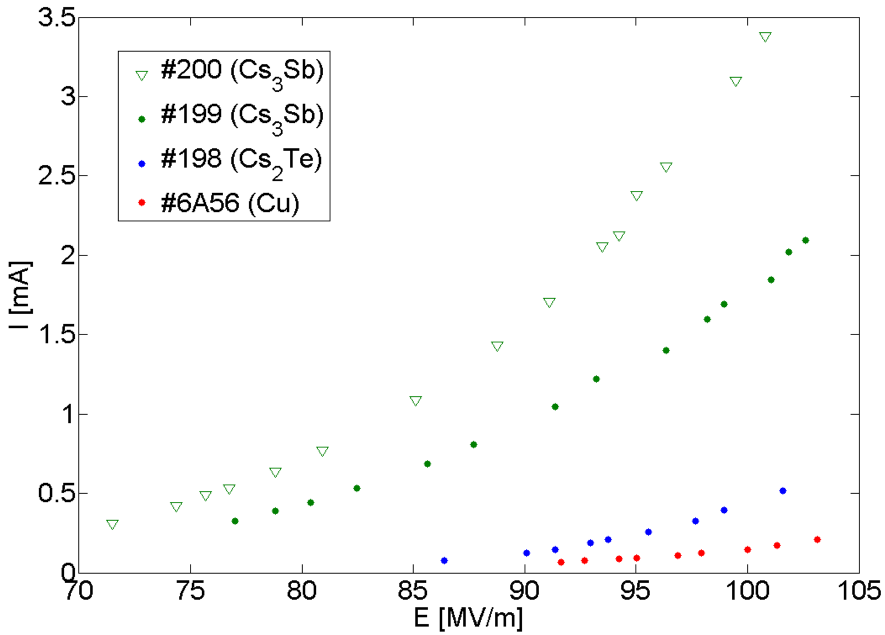
- High QE at a convenient laser wavelength λ
- Low dark current
- **Long lifetime in challenging environment**

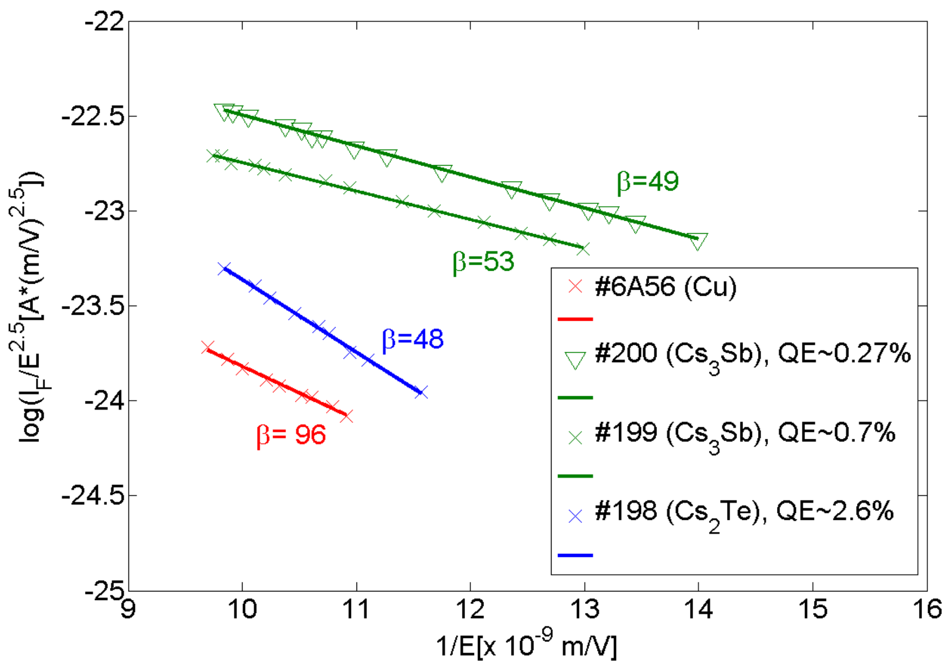
Factor Affecting Lifetime

Chemical poisoning	Static and Dynamic Vacuum condition
Radiation damage	Electron and Ion Bombardment on the cathode surface

The dynamic vacuum and the ion back bombardment depend on the <u>beam properties</u>: charge/bunch, rep rate, beam transmission,..

Dark Current Measurements



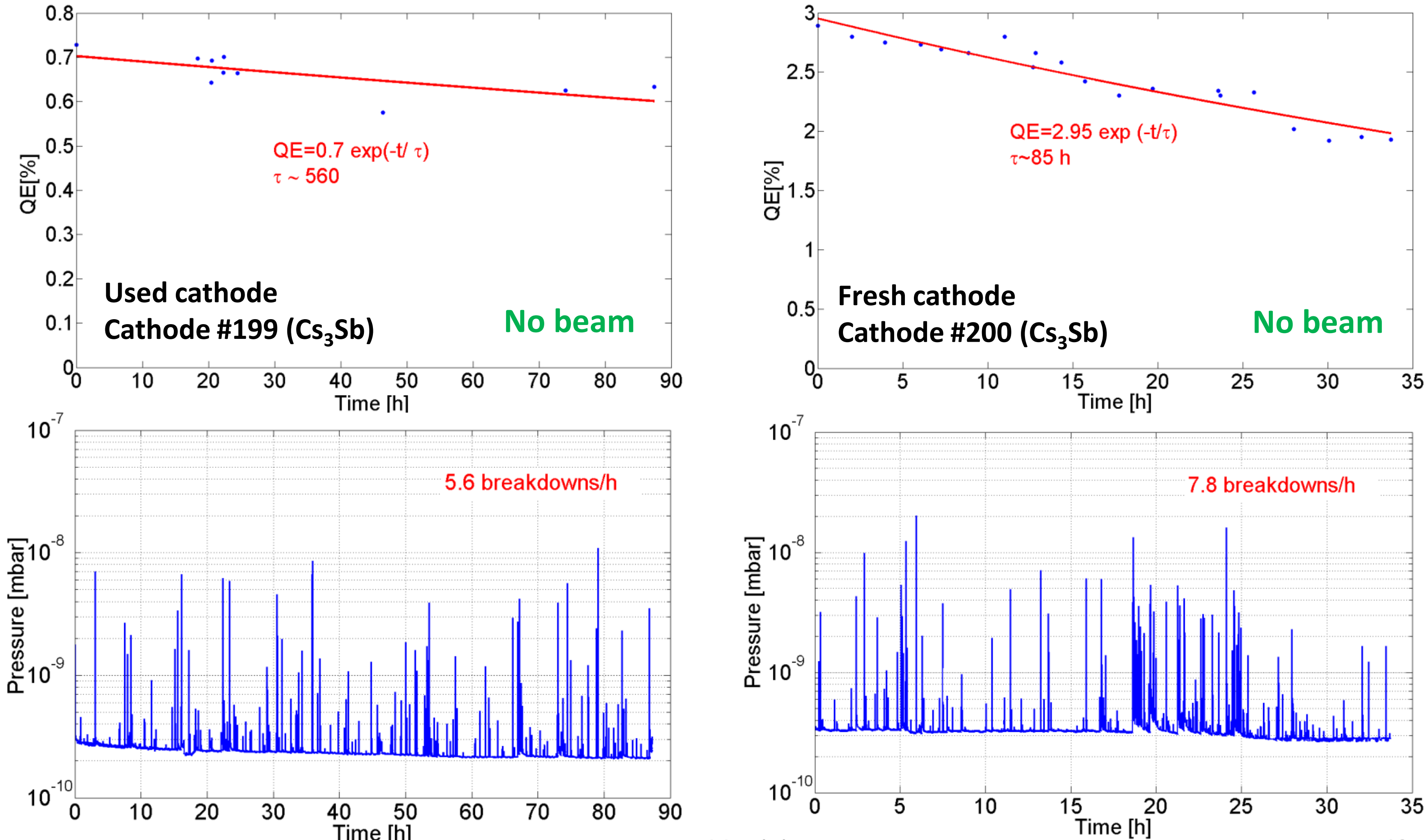


- Non desirable effect: **affecting negatively the beam dynamics** and possibly **originating RF breakdowns** (high voltage discharge inside the gun resulting in pressure sparks).

- Field emission contribution from RF gun walls (copper made) and from the cathode.
- The low dark current measured with copper confirmed the **major contribution is coming for the cathode**.
- Cs_3Sb cathodes (ϕ~2 eV) produce higher dark current than Cs_2Te (ϕ~3.5 eV).

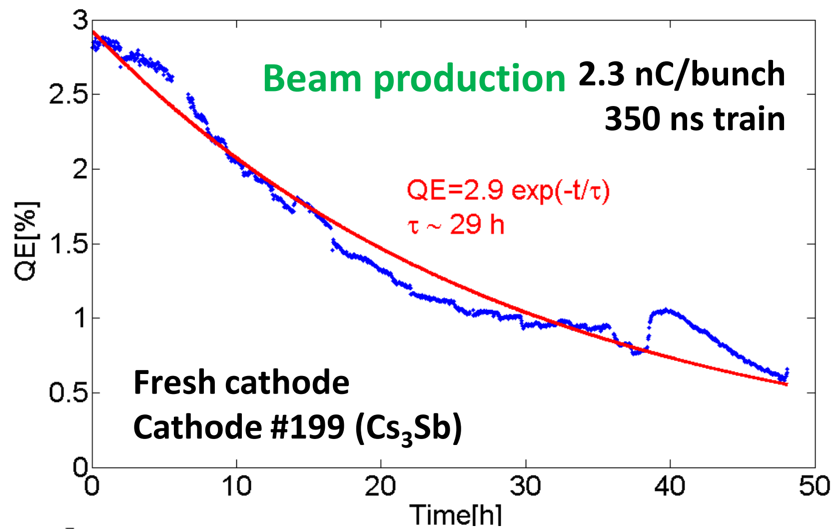
RF Lifetime Measurements

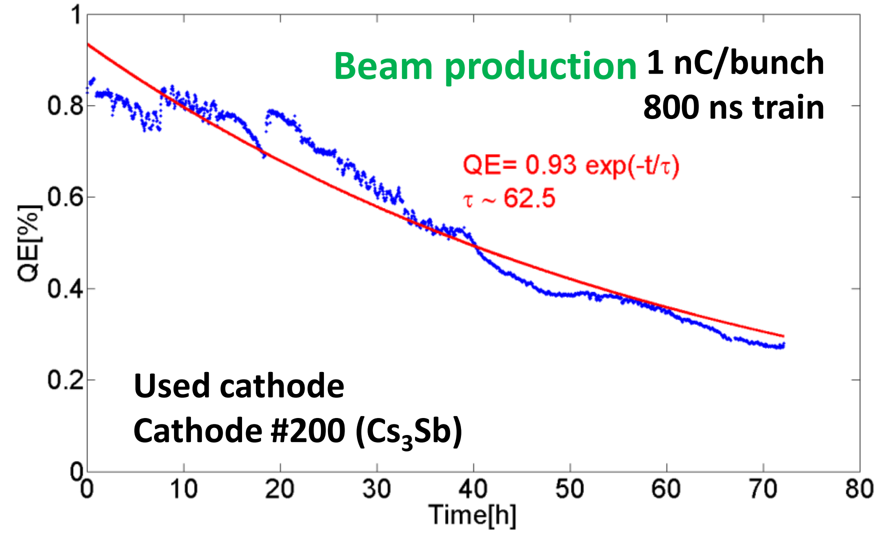
- QE deterioration under the influence of **high electric gradient (100 MV/m)** – no continuous beam production.

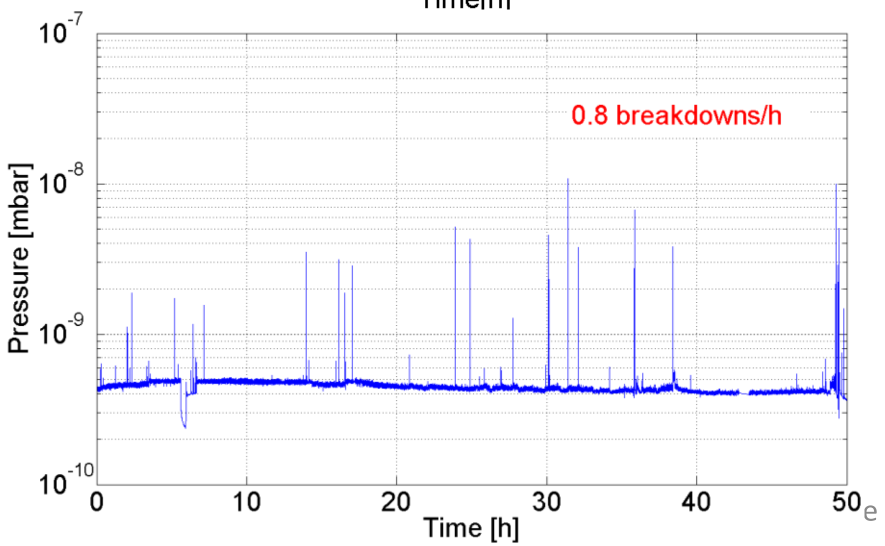


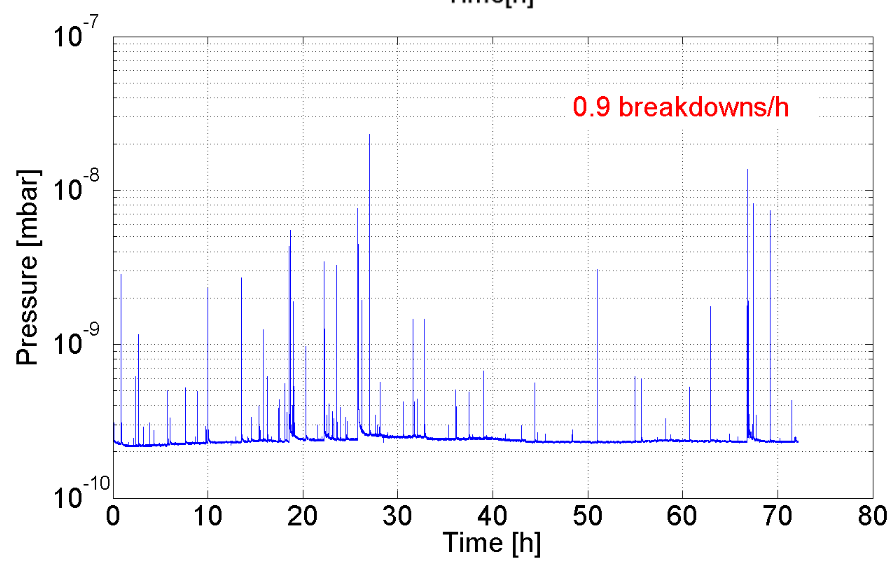
Operational Lifetime Measureme

- QE deterioration during beam production.
- The laser power was adjusted for keeping the produced charge constant: 1200 nC/train.









Operational Lifetime Measureme

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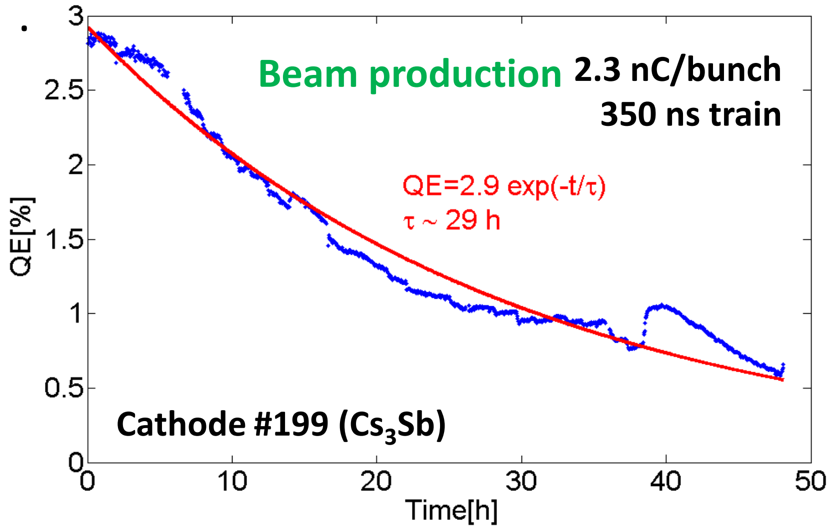
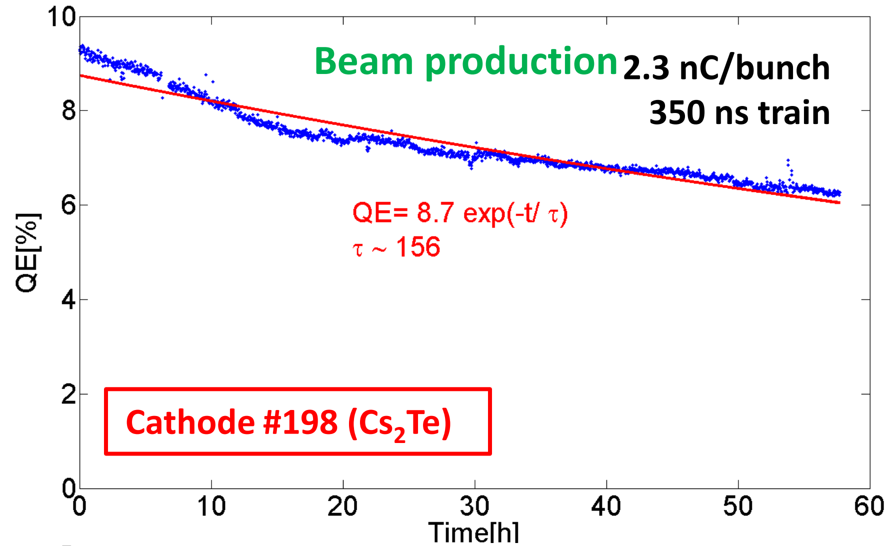
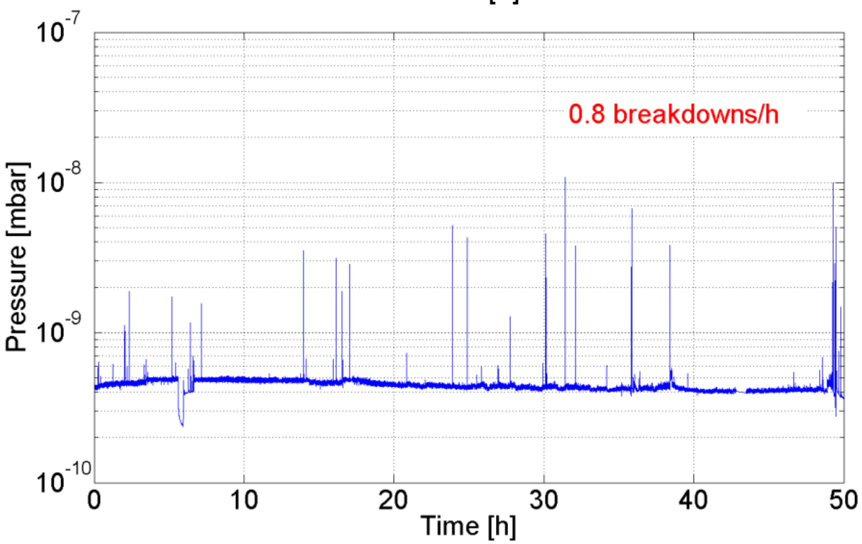
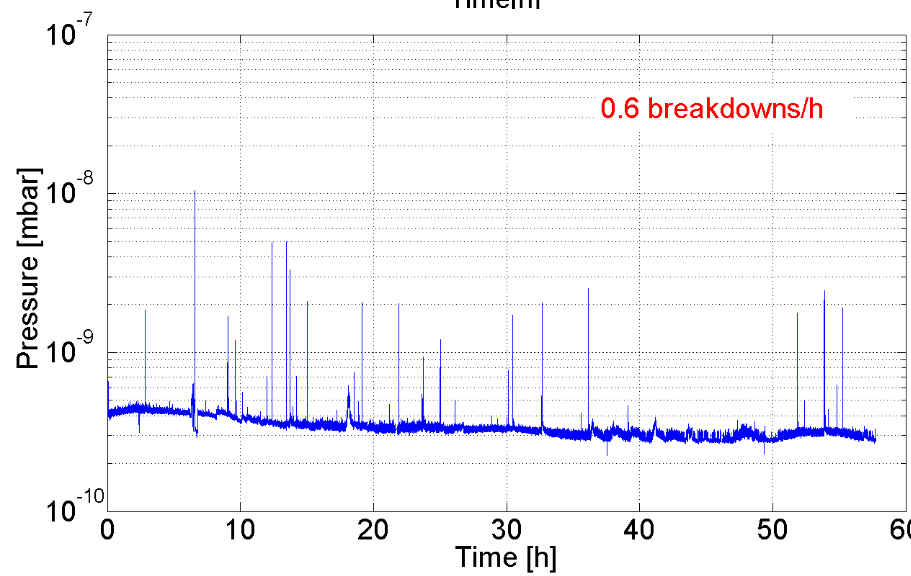


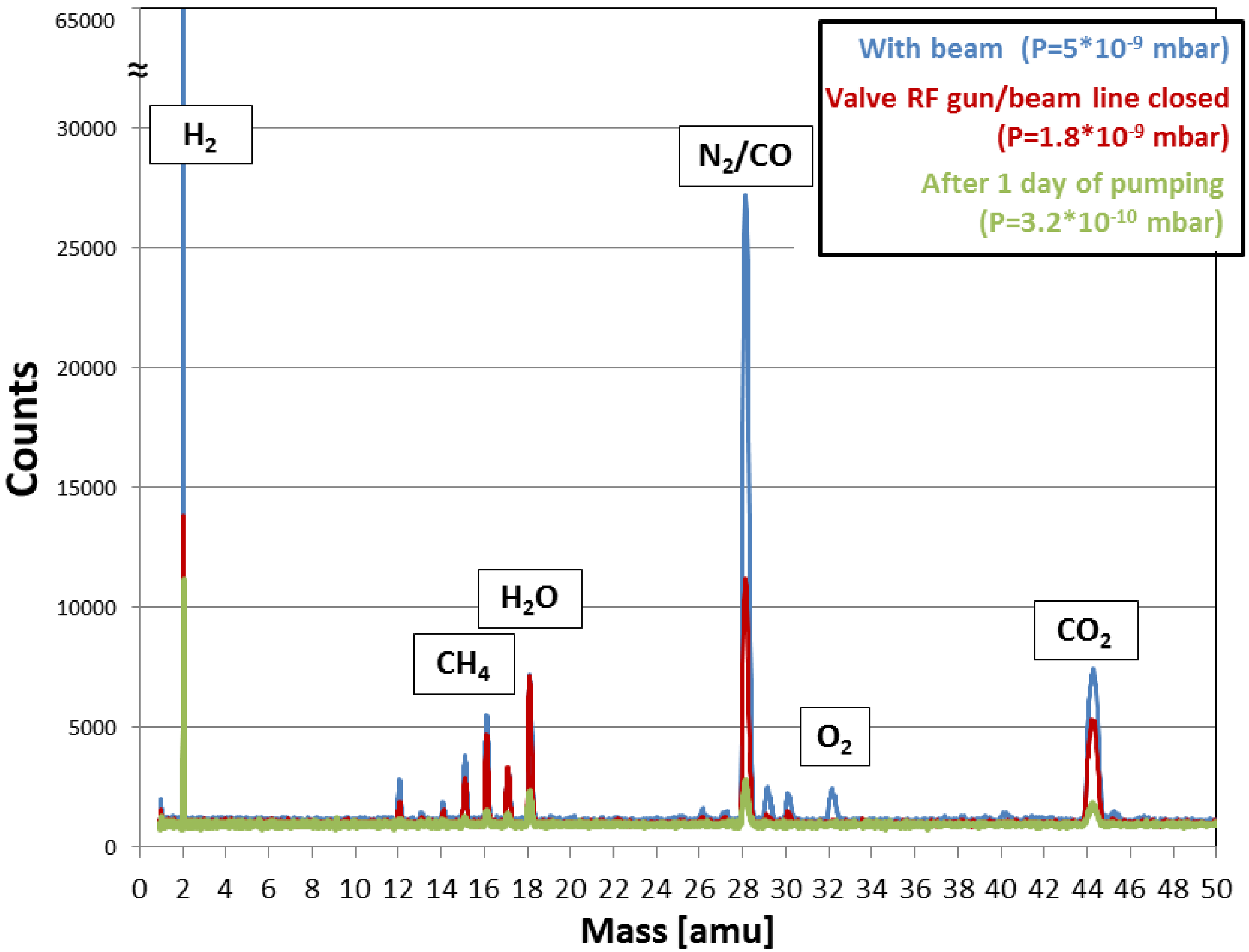




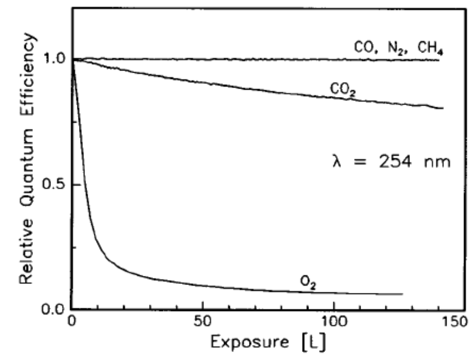


Irene

QE degradation: Residual Gas Spectr

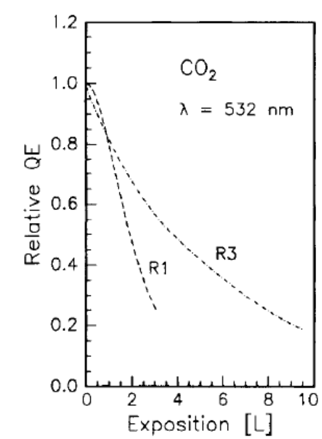


Cs_2Te cathode



A. Di Bona et al., J. Appl. Phys. 80, 3024 (1996)

K_2CsSb cathode

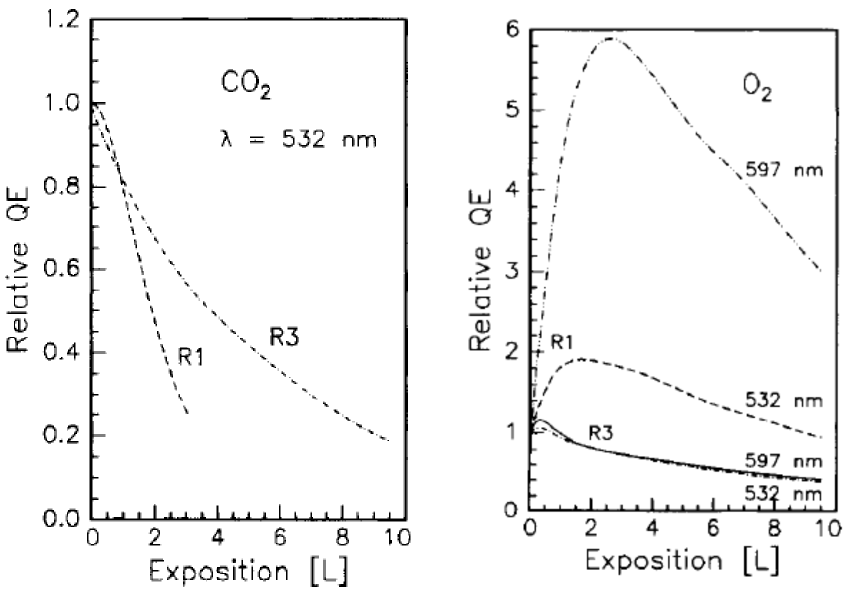


A. Di Bona et al., Nucl. Instr. Met. In Phy. Res. A 385 (1997) 385-390

Chemical poisoning

QE drop after exposure to different gas species

K_2CsSb



A. Di Bona et al., Nucl. Instr. Met. In Phy. Res. A 385 (1997) 385-390

K_2CsSb

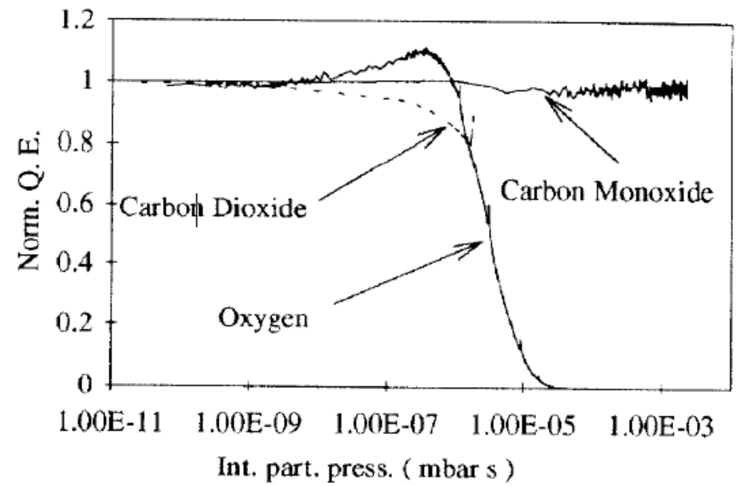


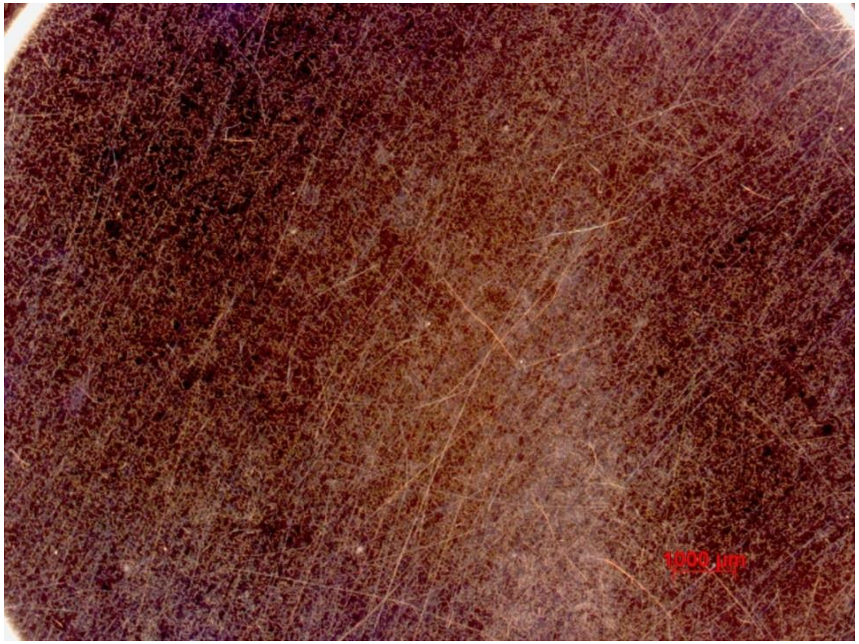
Fig. 6. Poisoning of KCsSb cathode with different gases.

P. Michelato et al., "*Multialkali Thin Photocathodes fir High Brightness guns*", Proc. of EPAC '94

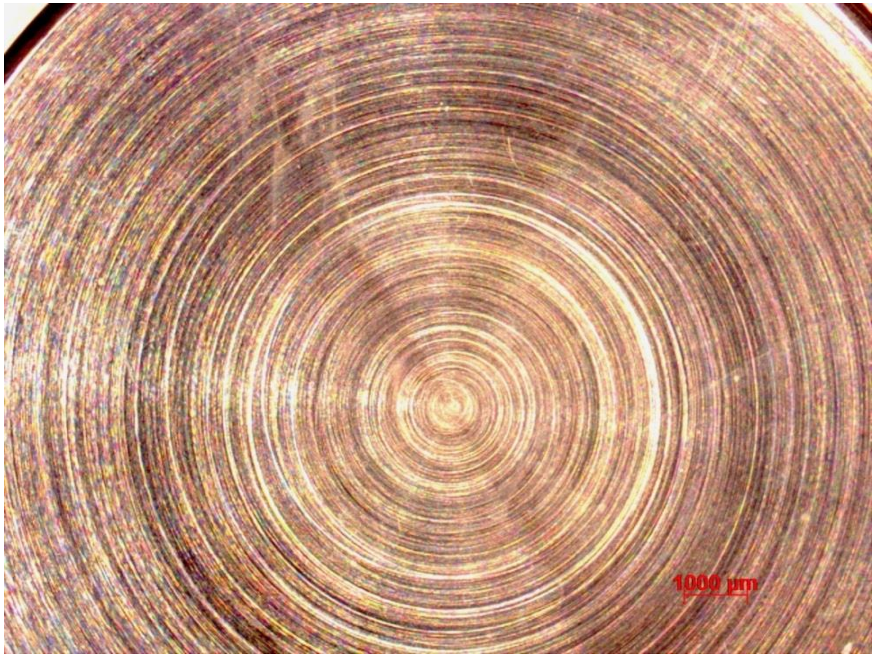
Surface morphology

COPPER SUBSTRATE MACHINING

1) Diamond powder polished.

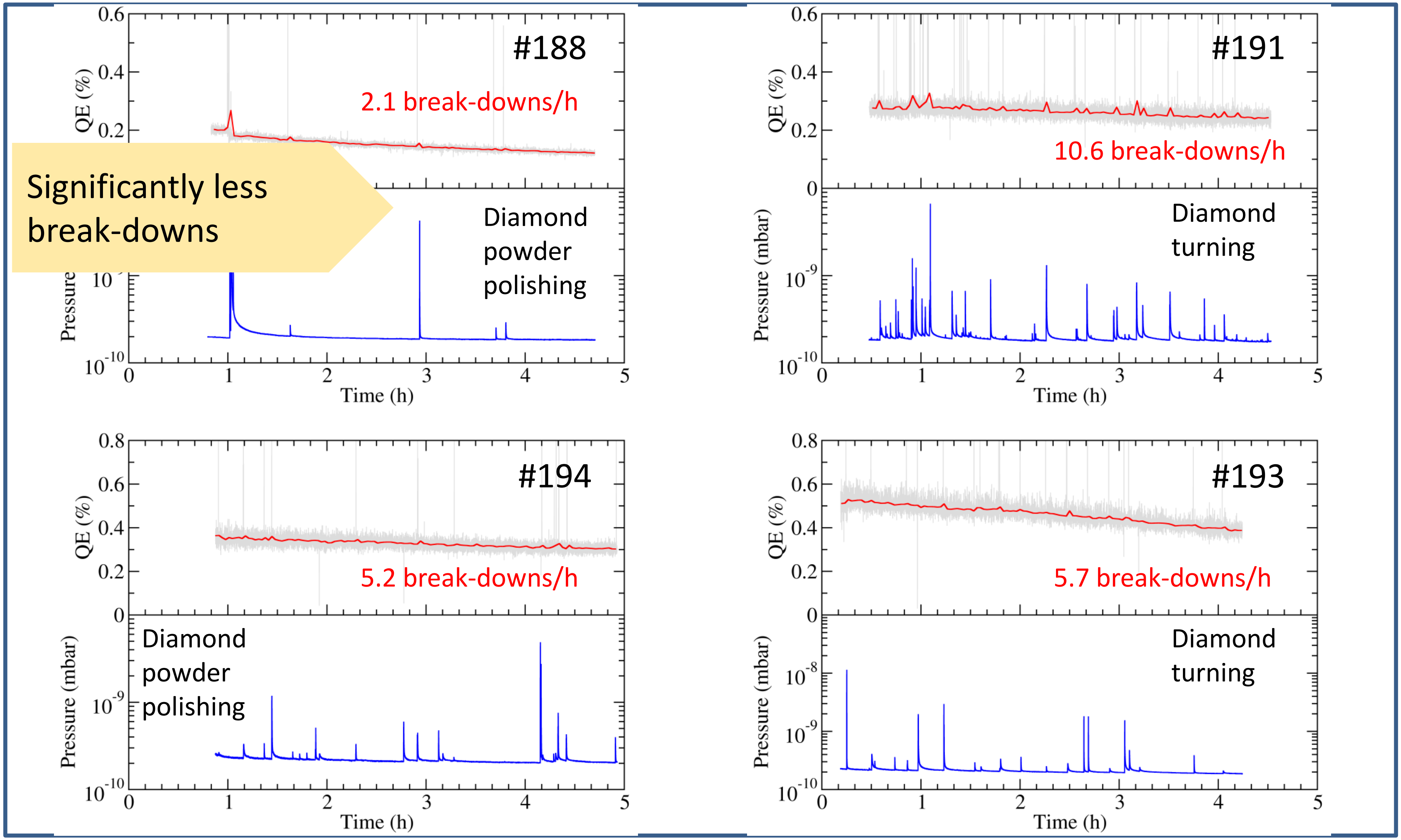


2) Diamond turned.



- Assumption: The thin deposited Cs_3Sb layer (<100 nm) is reproducing the roughness profile of the substrate (determining the β field enhancement factor).
- Future studies in collaboration with Daresbury Laboratory (ASTeC, U.K.) for **reducing roughness** and **improving cleaning** of the copper substrate surface.

Surface morphology and RF breakdowns



COURTESY OF C.HESSLER

Collaborative work

Studies of clean OFE Copper for photoinjector applications

MOTIVATION: The roughness and cleaniness of Cu substrate influence the photocathode performance.

Test 2 different cleaning procedures on diamond powder polished Cu (XPS, Roughness):

- Oxygen plasma cleaning+ annealing (250°C,1h)
- CERN chemical treatment + annealing (250°C,1h)

#003	Cu [%]	O [%]	C [%]
as received	3.9	17.4	78.7
O_2 plasma	32.1	47.5	20.4
annealed	72.8	16.5	10.7

#007	Cu [%]	O [%]	C [%]
CERN cleaning	18.4	40.4	41.2
annealed	58.3	22.5	19.2

#001	Cu [%]	O [%]	C [%]	S_A[Å]
as received	3.8	75.9	20.3	78
O_2 plasma	13.9	36.5	49.6*	89
annealed	58.3	16.6	25.1	129

#009	Cu [%]	O [%]	C [%]	S_A[Å]
CERN cleaning	30,1	27,1	42,8	69
annealed (x2)	78,3	16,6	5,1	111

*bad handling of sample

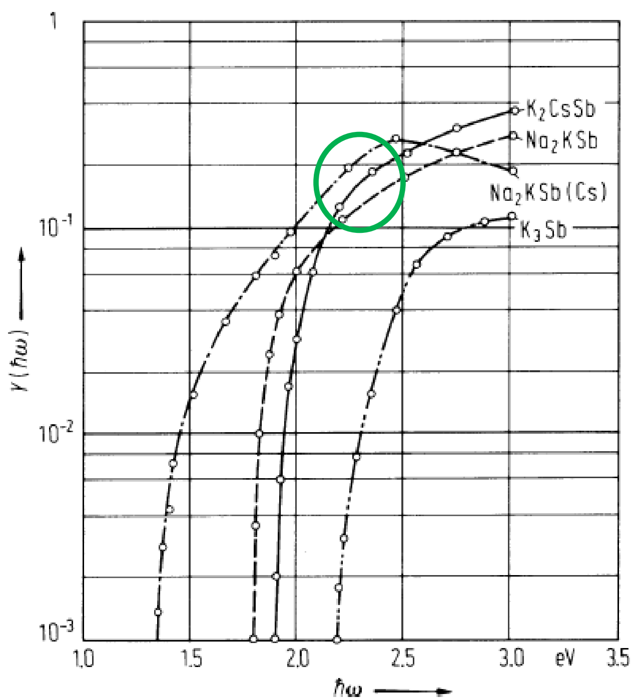
SUMMARY:

- Both cleaning procedure give similar final oxygen content.
- Carbon (from pollution) can be drastically reduced with both procedure (residual C due to embedded diamond particles?)
- Roughness seems to be increased during annealing.

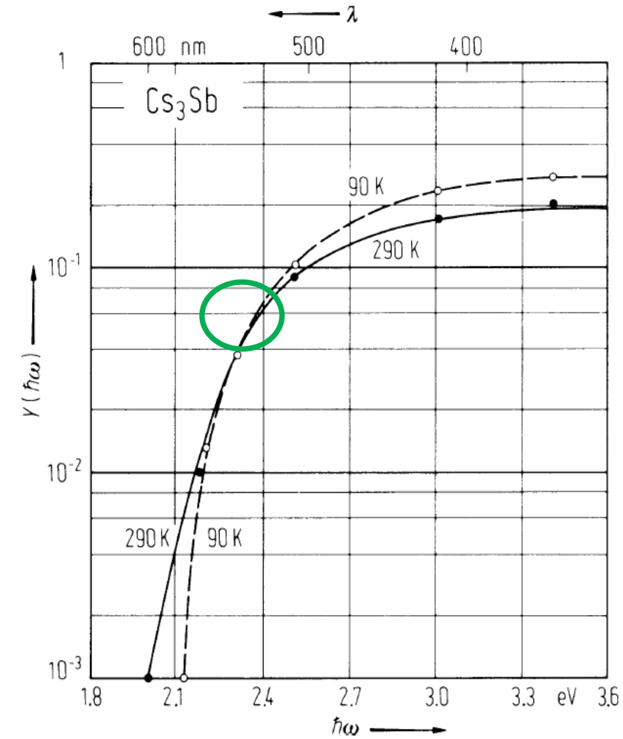
Overview on "green cathodes"

ALKALI-ANTIMONIDE: SPECTRAL RESPONSE

- K_2CsSb
- Cs_3Sb
- K_3Sb
- Na_2KSb
- …



J. Appl. Phys. 49 (8), August 1987.



A.H.Sommer. Photoemissive Materials.
John Wiley and Sons,Inc., New York, 1986.

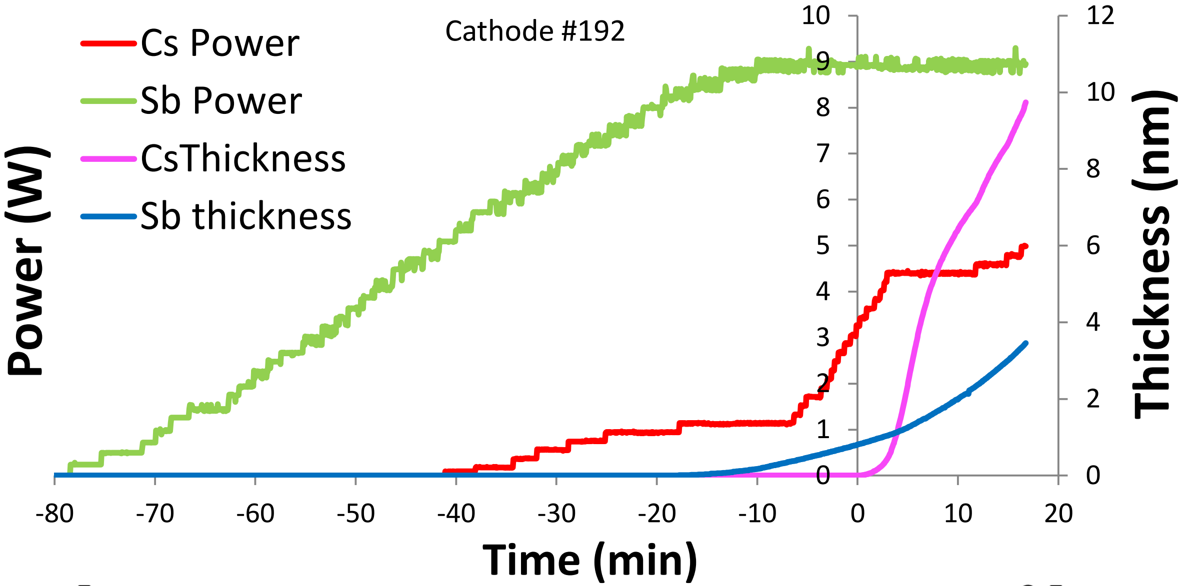
Stable for many years in phototubes!
BUT in a photoinjector??

⇨ Let's start with **Cs_3Sb**!

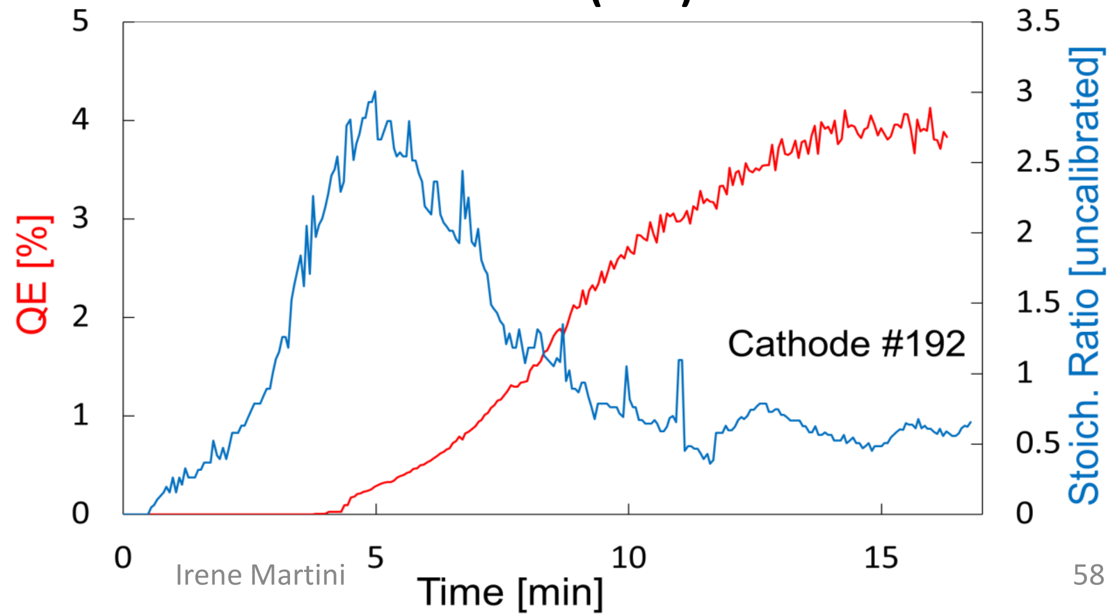
Co-deposition process

- **CO-DEPOSITION**

Cs and or Sb evaporated at the same time: the metallic elements can mix together in the vapour phase.

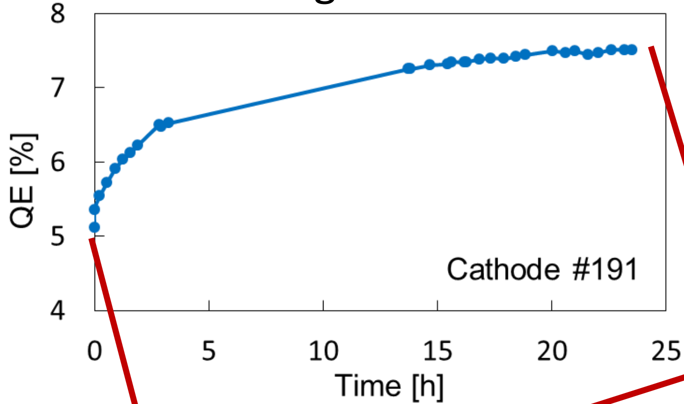


- The evaporators power is tailored in order to reach a maximum value of the QE.

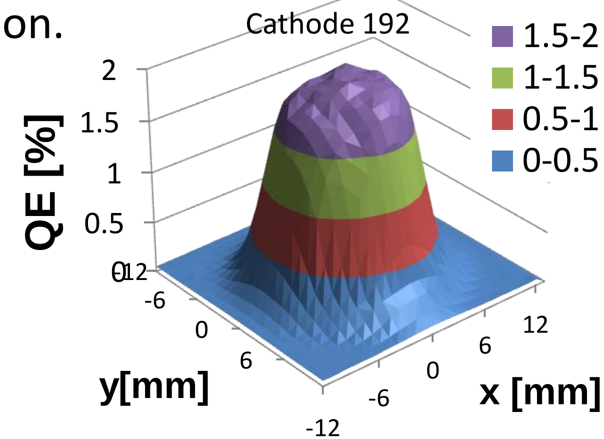


Deposition results

- The QE rise during the first hours of electron beam generation in the DC gun.



- **QE mapping** shows uniform electron photoemission.



No.	Initial QE (%)	Max QE (%)	Evaporated Cs (nm)*	Evaporated Sb (nm)*	Final stoich. ratio*
178	0.3	0.5	120	18.4	2.9
179	1.4	2.3	156	24.5	1.74
180	0.6	1.0	52	14.4	0.82
187	0.3	0.4	67.6	4.7	4.9
188	1.3	2.2	152	17.8	2.3
189	2.3	4.4	64	15	1
191	5.4	7.5	156	14	1.7
192	2.0	2.7	9.7	3.5	0.66
193	4.2	5.8	10.8	7.6	0.66

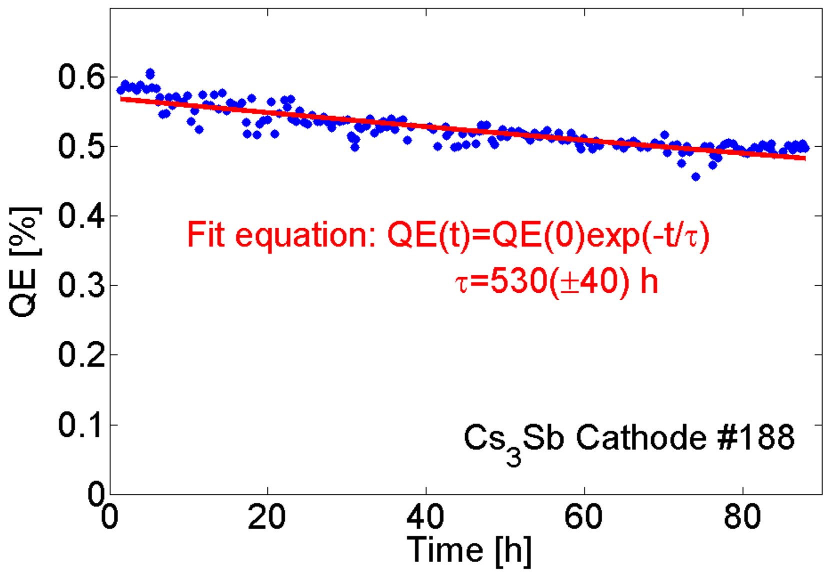
(*)Not calibrated

- Excellent QE values of up to 7%.
- No obvious correlation between QE and the final stoichiometric ratio or the evaporated quantity.

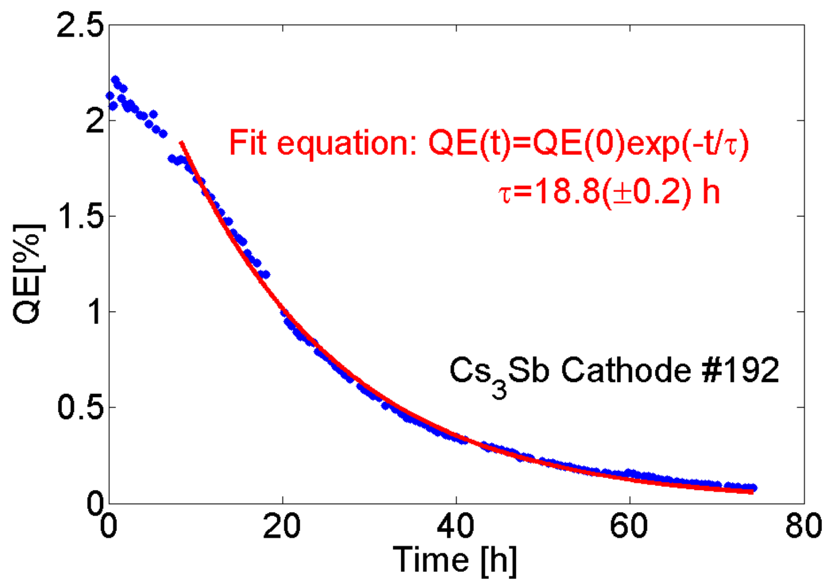
Test in the photoemission lab (DC gun)

Cs_3Sb cathodes lifetime measurements

Low average current measurement (1 μA)



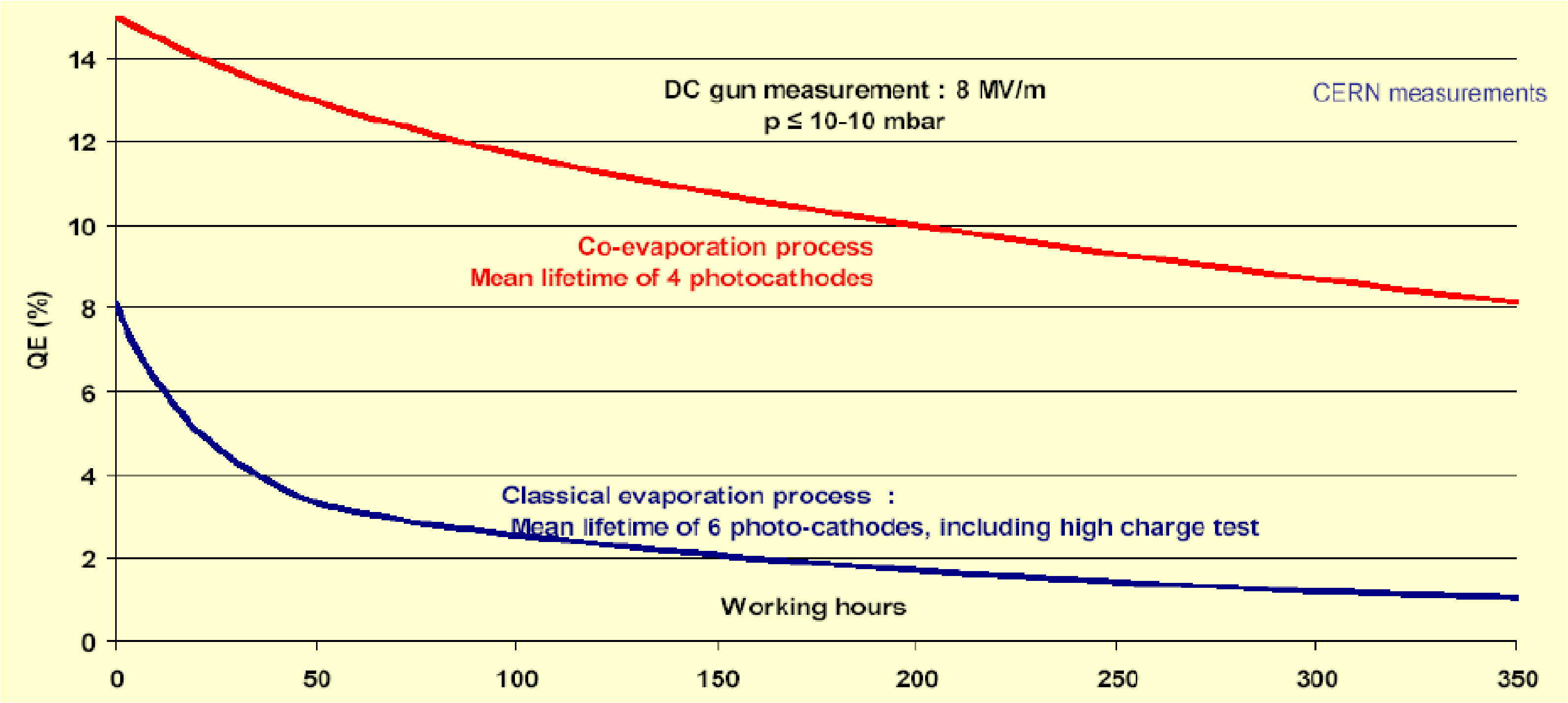
High average current measurement (120 μA)



- Low current measurements: very promising results!
- High current: faster degradation (chemical poisoning related to desorption induced by high current beam losses?)
- Cathode #192 has thin photoemissive layer ⇨ investigate thick photoemissive layer

Co-deposition vs sequentally deposition (Cs_2Te)

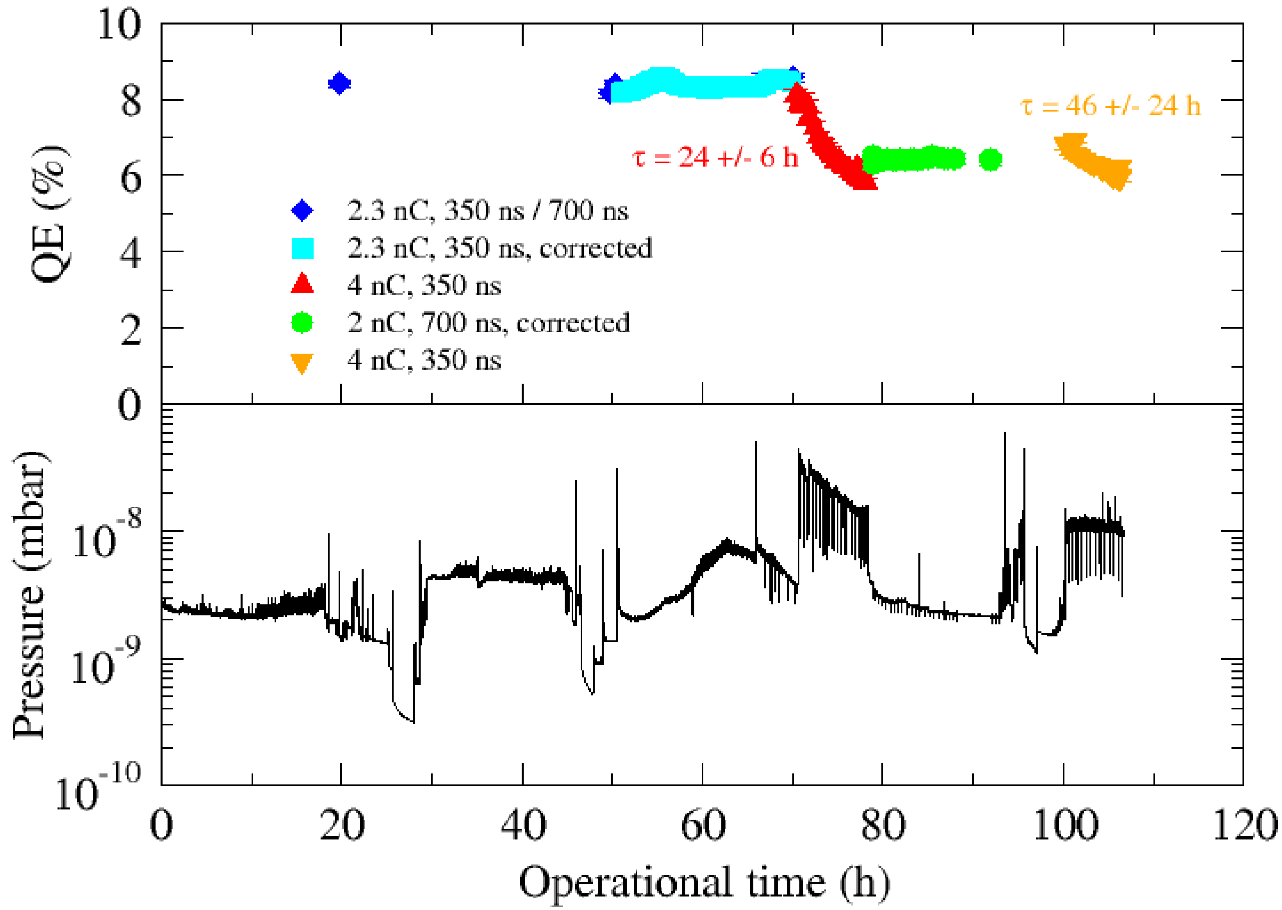
Comparison of lifetime and QE measured on photocathode **produced by co-deposition** and for cathode produced by **sequential deposition**.



R. Xiang et al., "*Report on photocathodes*", CARE Note-2004-033-PHIN

Correlation between lifetime and vacuum.

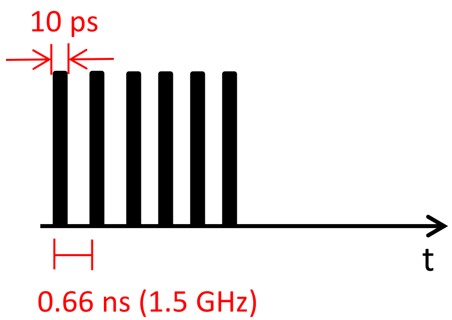
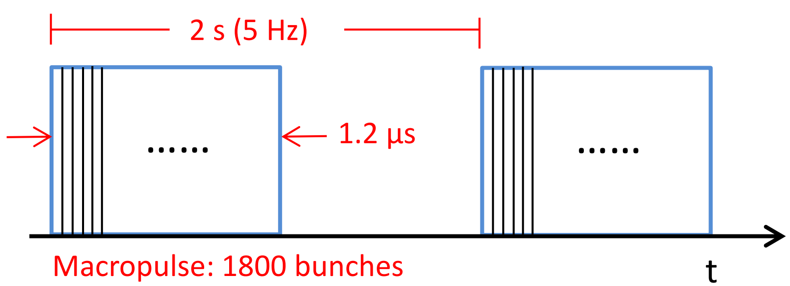
Lifetime Studies of Cs_2Te Cathodes in PHIN photoinjector.



C. Hessler et al., "*Lifetime studies of Cs_2Te cathodes at the PHIN RF photoinjector at CERN*", Proc. of IPAC '12

PHIN laser time profile

Nominal parameters (Phase coding OFF)

Laser beam		Electron beam
	~1 µJ/bunch	2.3 nC/bunch
		4.1 µC/macropulse