PAUL SCHERRER INSTITUT

R. Ganter

Photocathode for electron accelerators

IVeSC and IVEW 25 – 29 Mai 2020

Outline

- Introduction to photocathodes in Accelerators
- Metallic and Semiconductor Photocathodes
- Preparation of Photocathodes
- Photocathode Operation in Accelerators, SwissFEL
- Research trend and Conclusion

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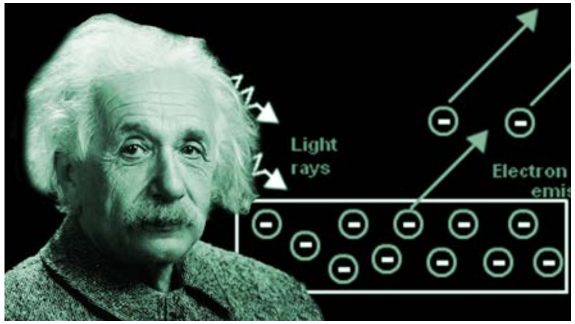
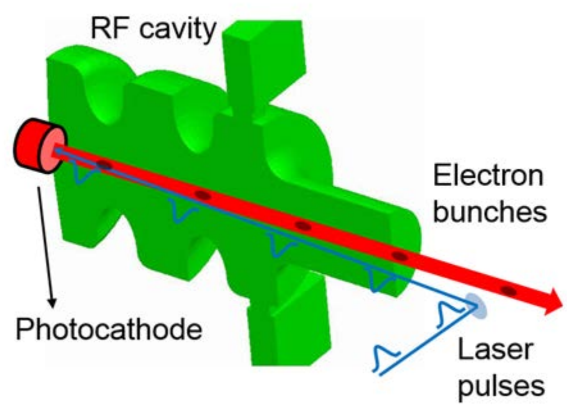
Photocathodes



Ultraviolet light facilitates sparks (H. Hertz, 1887)
Description of Photoelectric Effect (A. Einstein, 1905)

Night googles (e.g. Photonis)

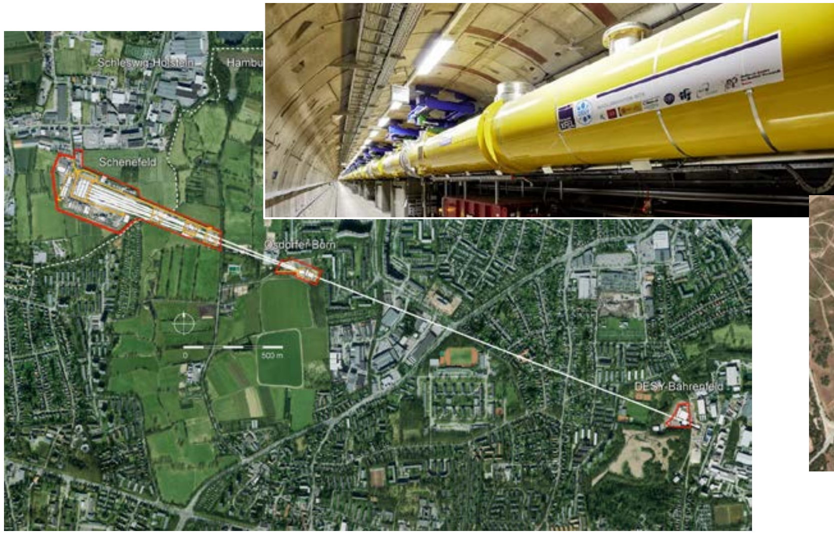
Photomultipliers tubes (e.g. Hamamatsu)



Accelerator Photoinjector

Electron linear accelerators: Linac

Most electron linac, worldwide, are served with photocathodes.



EU-XFEL, 3.4 kms, Hamburg (DE)

SLAC LCLS, 3.2 kms, Menlo Park (USA)

Electron beam brightness is essential for Collider and for Free Electron Laser

$$B = \frac{I}{8\pi^2 \varepsilon_x \varepsilon_y}$$

$$\varepsilon_{x,y} \propto \frac{1}{\gamma}$$

CEBAF, Jefferson Lab (USA)

PAL - XFEL, Pohang Univ., 1.1 kms, (Korea)

SwissFEL, PSI, 0.7 kms, (Switzerland)

Increase brightness in accelerators

$$B = \frac{I}{8\pi^2 \varepsilon_x \varepsilon_y}$$

High Current: Short Electron Bunch with High Charge

- Photoemission current density >> thermionic current density
- Laser is the only way to reach picosecond scale

Photocathode best electron source for high brightness beam

Low Transverse Emittance : electron source intrinsic emittance

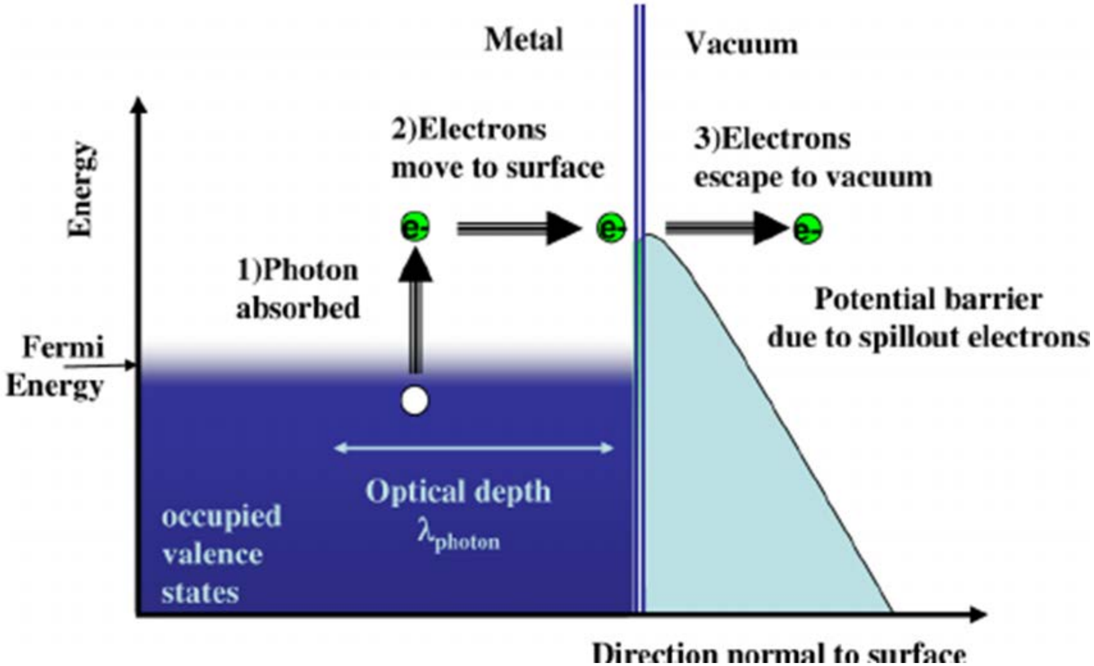
$$\varepsilon_x = \epsilon_{int,x} + \epsilon_{sc,x} + \epsilon_{RF,x} + \cdots$$

$$\varepsilon_{int,x} = \sigma_x \sqrt{\frac{MTE}{mc^2}}$$

$\Rightarrow$ Small source size

$\Rightarrow$ Emitted electrons should have very small mean transverse energy (MTE) => Ideally Field Emission

Photocathode Principle



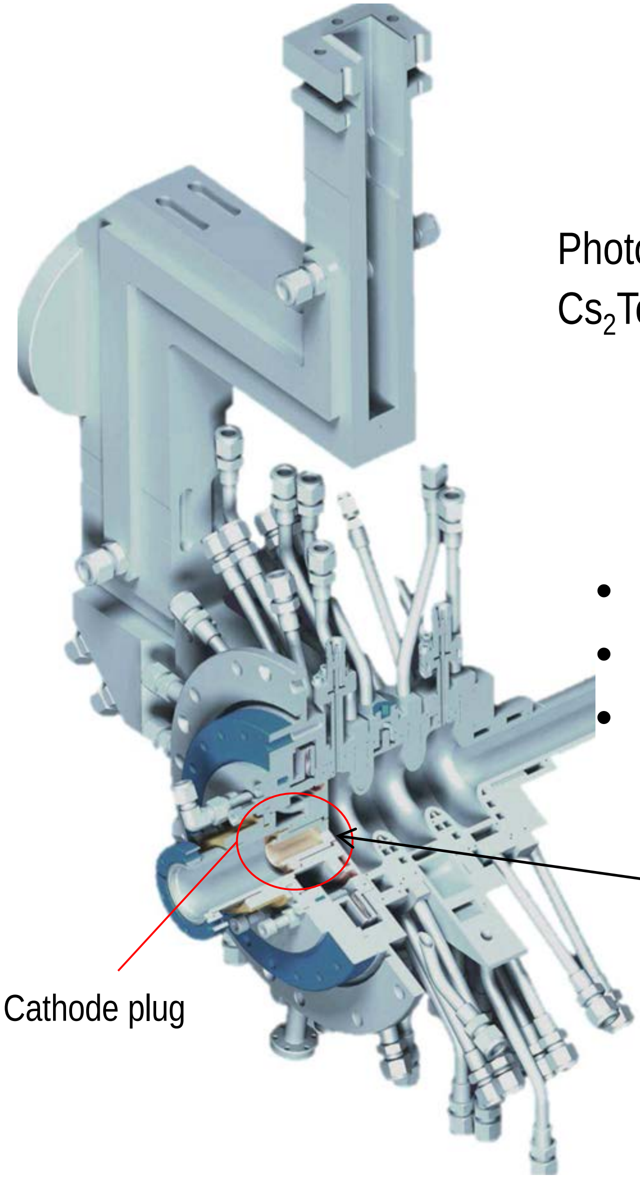
Schematic Courtesy of D. Dowell

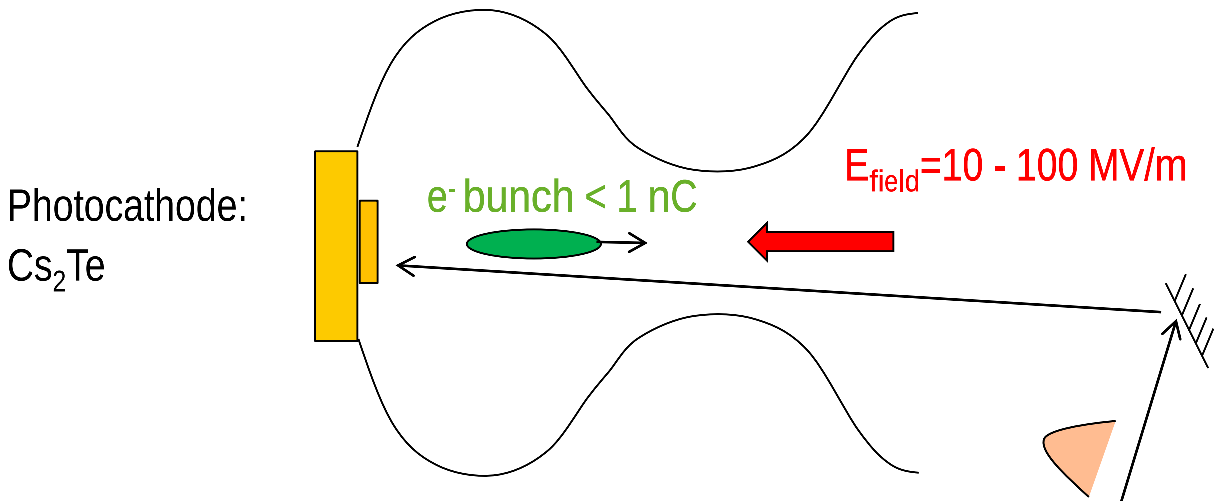
Three-step Model (Spicer, Phys. Rev. 112 (1958)):

1. absorption and excitation
2. transport to surface
3. escape over or through the surface barrier

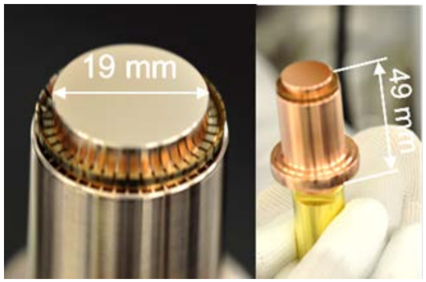
Good to describe practical photocathodes

Photoinjector: electron gun





- **Normal Conducting RF Photoinjector**
- **Supraconducting RF Photoinjector**
- **DC Photoinjector**



Exchangeable cathode plug

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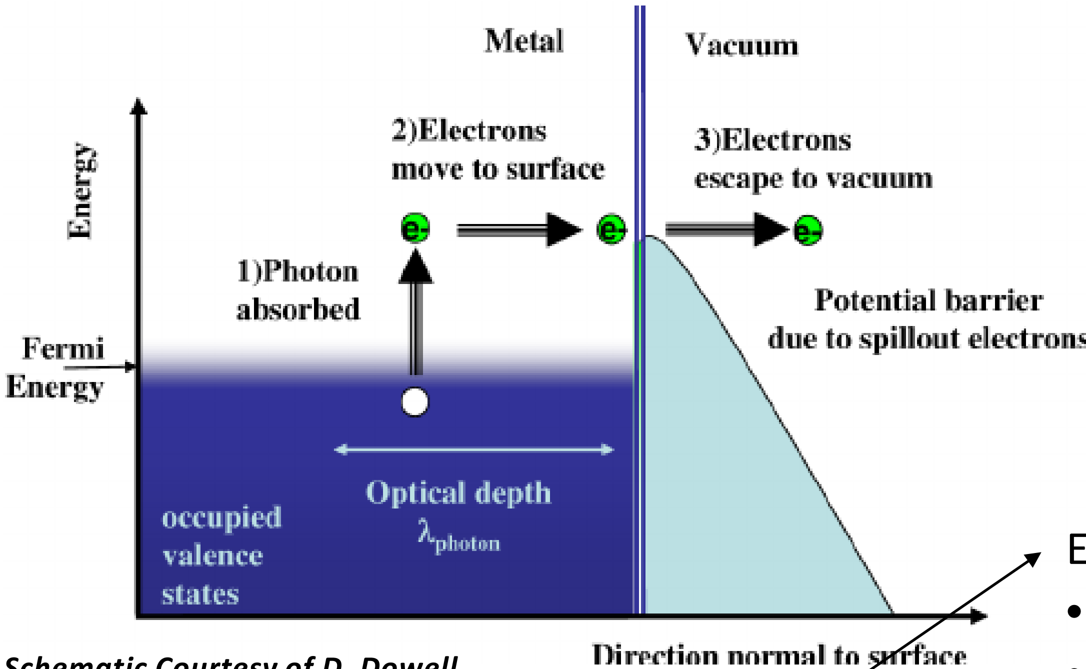
Photocathode Principle: Quantum Efficiency



Schematic Courtesy of D. Dowell

Three-step Model (Spicer, Phys. Rev. 112 (1958)):

1. absorption and excitation
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Good to describe practical photocathodes

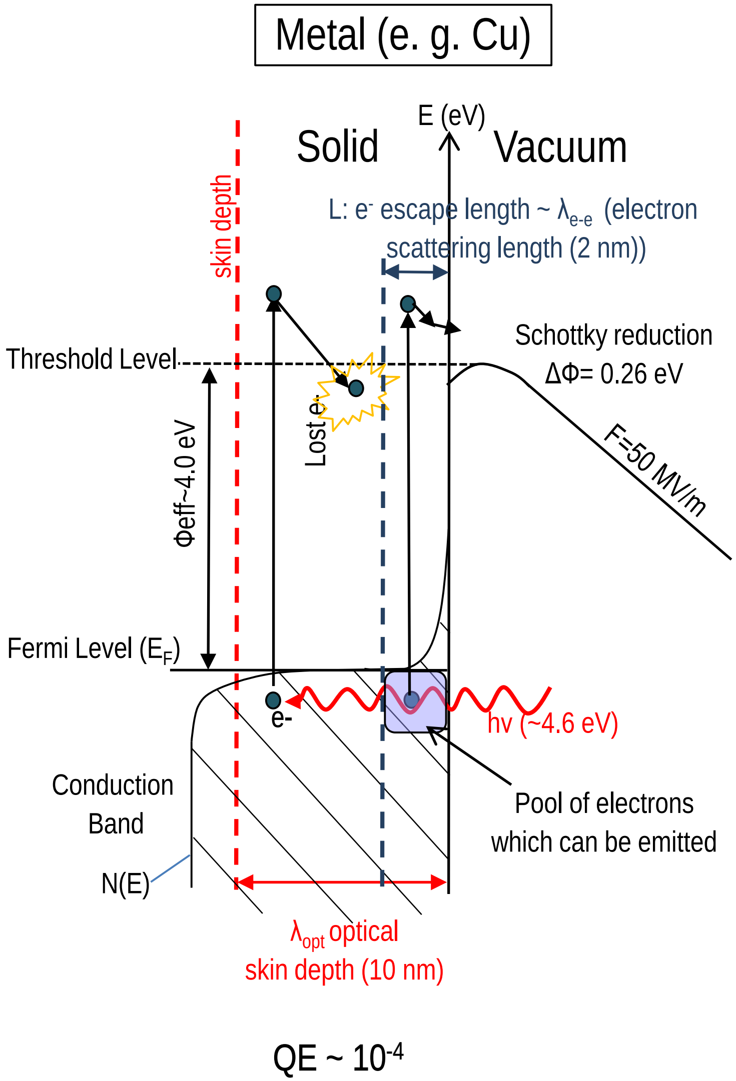
Sum of all Probabilities
$\Rightarrow$ Quantum Efficiency (QE)

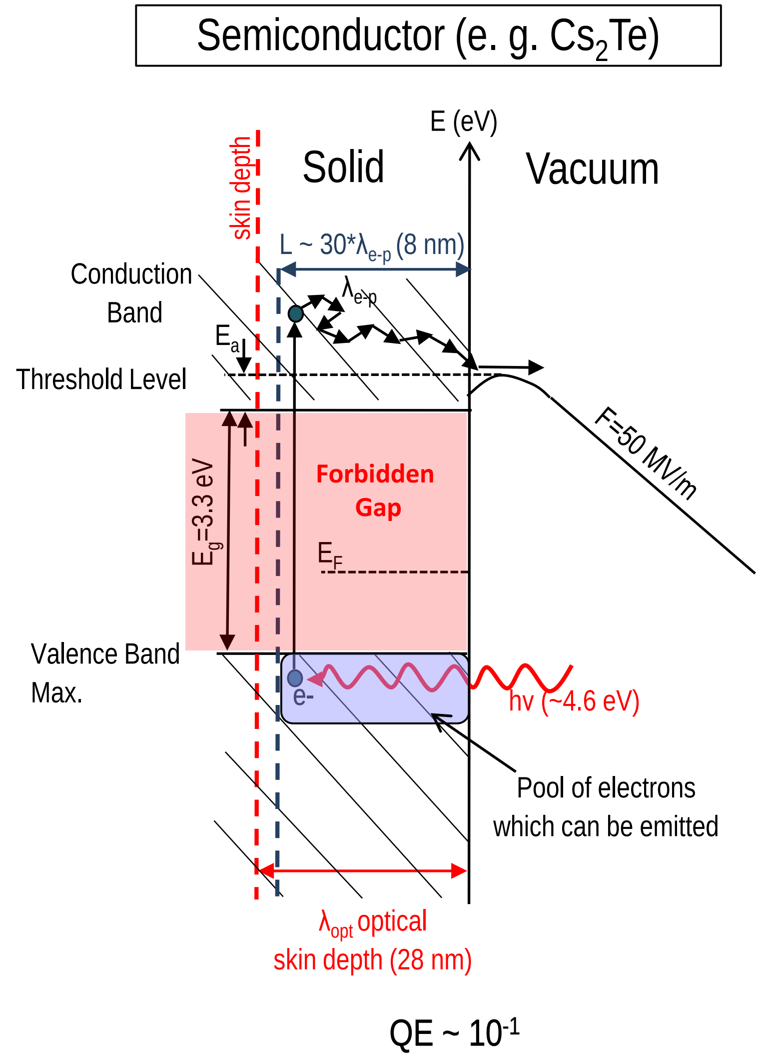
$$QE = \frac{N_{e-}}{N_{photons}}$$

Efficiency Loss due to:
- Reflected photons
- Density of States (excitation below vacuum level)

Efficiency Loss due to:
- Electrons scattering
  => energy loss

Efficiency Loss due to:
- Momentum normal to the surface is too low


Metal (e. g. Cu)
Solid
E (eV)
Vacuum
skin depth
L: e- escape length ~ λe-e (electron scattering length (2 nm))
Threshold Level
Schottky reduction
ΔΦ= 0.26 eV
Lost e-
Φeff~4.0 eV
F=50 MV/m
Fermi Level (EF)
e-
hv (~4.6 eV)
Conduction Band
Pool of electrons which can be emitted
N(E)
λopt optical skin depth (10 nm)
QE ~ 10-4


Semiconductor (e. g. Cs2Te)
E (eV)
skin depth
Solid
Vacuum
L ~ 30*λe-p (8 nm)
Conduction Band
λe-p
Ea
Threshold Level
Forbidden Gap
Eg=3.3 eV
EF
F=50 MV/m
Valence Band Max.
e-
hv (~4.6 eV)
Pool of electrons which can be emitted
λopt optical skin depth (28 nm)
QE ~ 10-1

Metallic versus Semiconductor Photocathodes

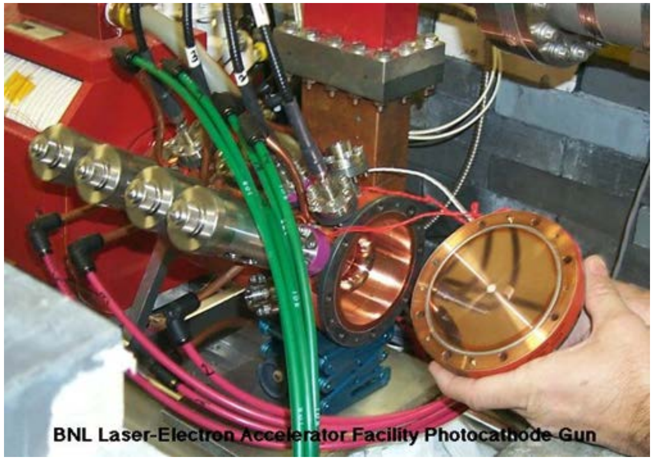
Metallic

+

- Photoinjector **without Loadlock**
- Modest Vacuum Conditions ($P > 10^{-9}$mbar)
- More **robust**
- Lifetime: **> years**
- Response Time: $\mathbf{t_{response\ time}}$ **~ few fs**

-

- Requires **UV illumination** (e.g. 260 nm)
- **Poor QE** (QE ~ 10^{-5} – 10^{-3})



BNL Gun with Mg insert

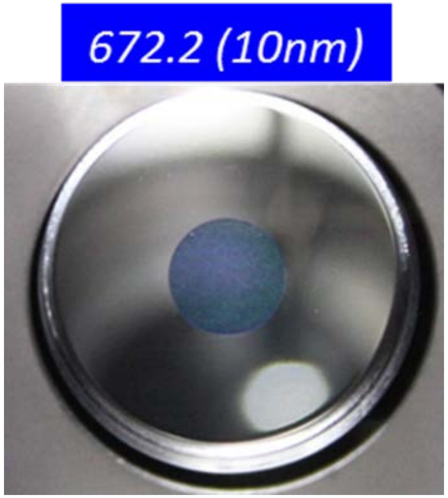
Semiconductor

+

- **Visible light to IR** illumination
- **High QE** (25% < QE < 1%)

-

- Very good Vacuum Conditions
  e.g. $\mathbf{P_{H2O} < 10^{-12}}$ **mbar** for Cs_2KSb
- **Loadlock** mandatory
- Lifetime: hours (GaAs) to years (Cs_2Te)
- Response Time: $\mathbf{t_{response\ time}}$ **~ ps**



Cs_2Te on Mo plug, INFN LASA

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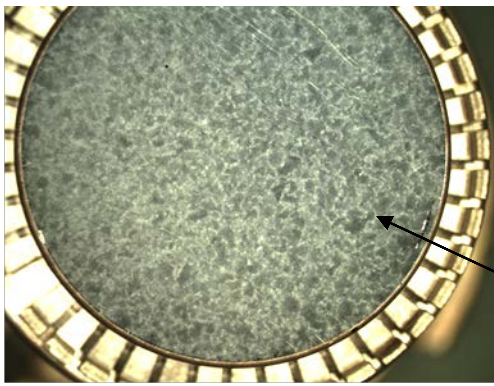
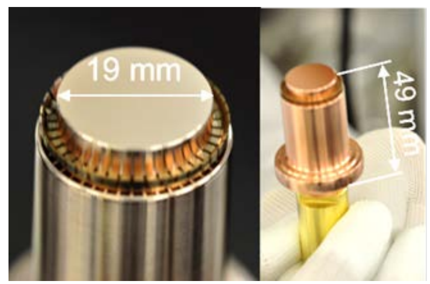
Preparation Metallic Photocathodes

- Very smooth surface because of high electric field (up to 100 MV/m)
- Ultrasound cleaning to remove contaminants & Chemical etching to remove oxyde layer
- Anealing to remove water content => loadlock with cathode plug or Laser Cleaning

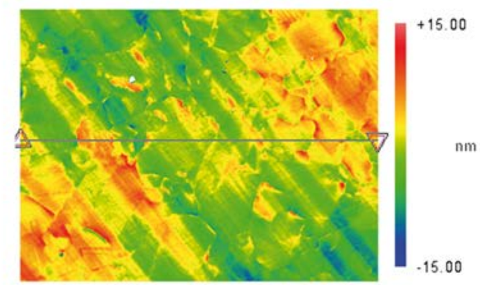




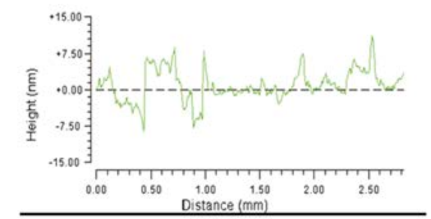
Copper surface after in-vacuum anealing at 250 ° C during 10 hours

=> $QE_{Cu} \sim 10^{-4}$

Grain boundaries more pronounced

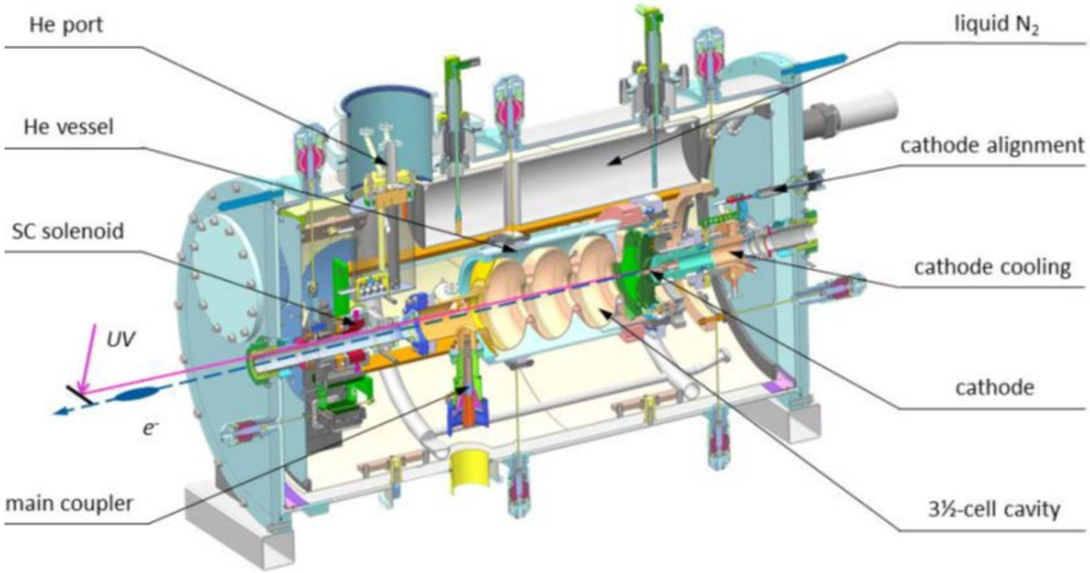


Höhenprofil des Messpunktes 1.



Copper surface
Grain size: 300 µm
Ra ~3 nm
Height Peak to Valley ~ 30 nm

Metallic Photocathodes for superconducting gun

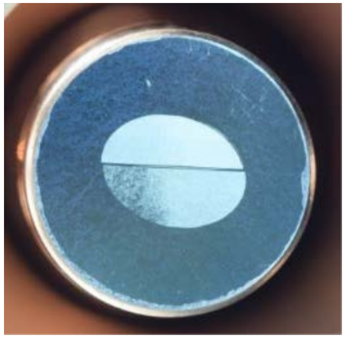


ELBE SRF Gun, Dresden (Courtesy of R. Xiang)

High average photocurrent: ~1 mA

Normal conducting photocathode with thermal insulation: Mg

QE_{Mg}~ 10^{-3} after laser cleaning



Mg photocathode plug

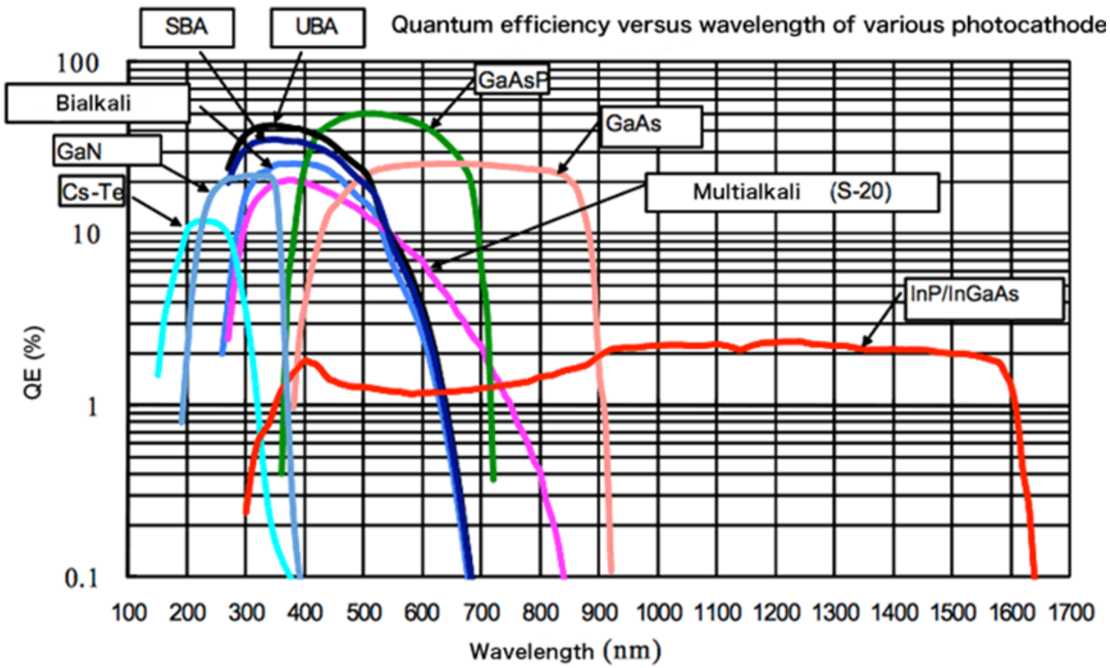
Superconducting Photocathode have too low QE !

e.g. Niobium Photocathode

$QE_{Nb}=10^{-5} – 10^{-4}$ (J. Smedley, LANL, USA)

$QE_{Nb+Pb}=10^{-3}$ is best alternative

Semiconductor Photocathodes



Courtesy of Hamamatsu K. K.

Alkali based materials to cover a large wavelength range !

Some cathodes are multialkali: S-20 ~ K_2CsSb

Most common Semiconductor photocathodes in accelerators:

Material	QE	Lifetime	Response time
Cs_2Te	15% at 262nm	> 1 year	600 fs
K_2CsSb	5 % at 532 nm	weeks	1 ps
Cs:GaAs	0.5 % at 800 nm	days	5 ps

Semiconductor Photocathode Preparation

Successive Deposition:

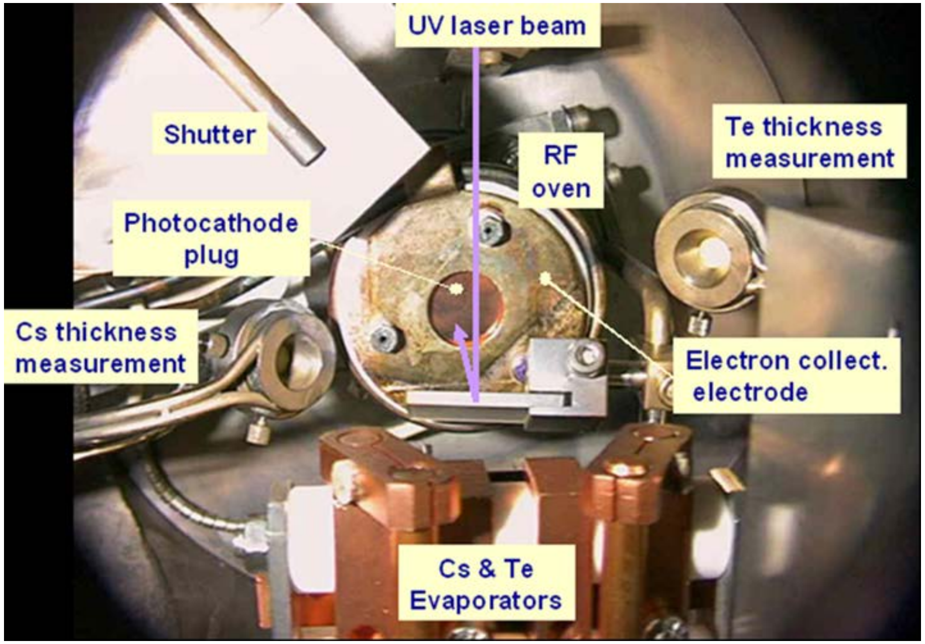
- Evaporation of a first layer of Te, Sb, Ga, As (~10 nm)
- Evaporation of Cs, K, Na from dispenser cathodes (> 20 nm)

Co-deposition:

- Simultaneous Evaporation of Te, Sb, Cs, K, …
- Monitoring of QE

=> Smoother crystalisation, less roughness

SAES alkali metal dispensers



Picture courtesy of E. Chevallay (CERN)

(*) recipe from CERN: CERN - CLIC Note 299 – E. Chevallay

Semiconductor Photocathode: Cs_2Te at SwissFEL

Copper substrate

Forged OFE copper (less inclusions, 10 ppm impurities)
Ultra precision diamond turning (Ra ~ 3 nm)

Ultrasonic Cleaning

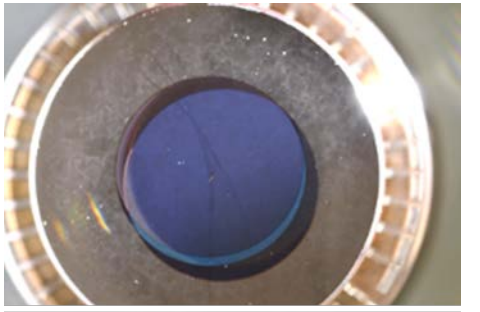
Soap > Water > Acetone > Alcohol

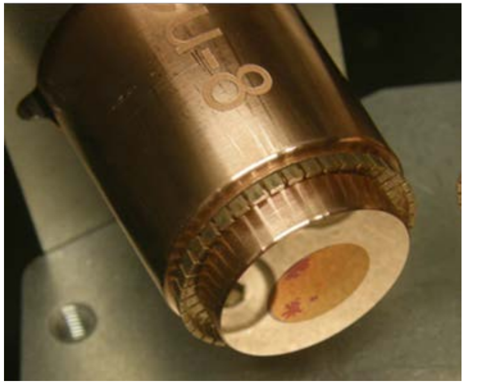
Annealing

10 hours at 250 C
At 1e-9 mbar

→ **Cu Photocathode**

$QE_{initial} \sim 10^{-4}$





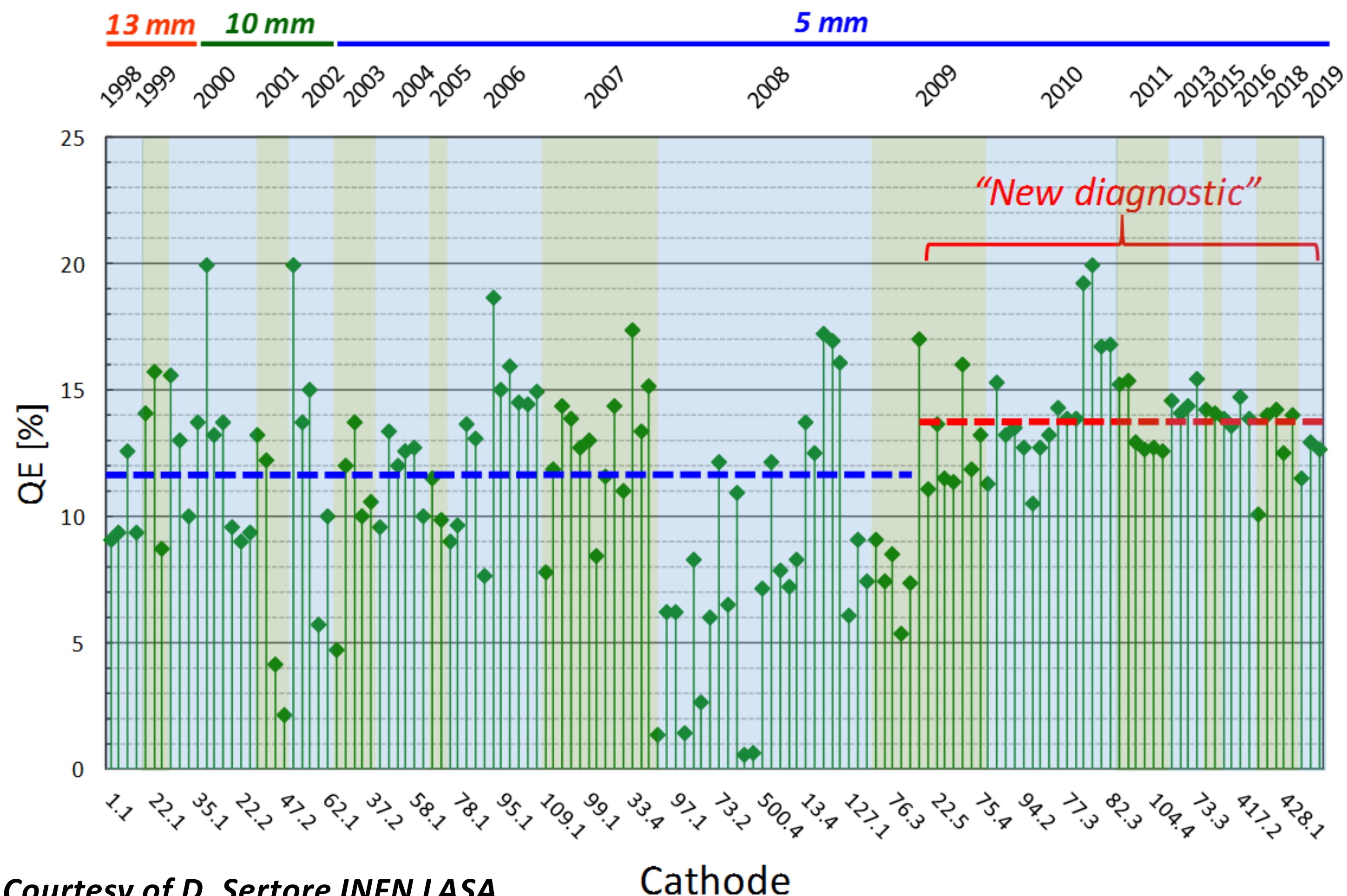
SwissFEL Photocathodes

Cs_2Te Deposition (*):

- cathode plug heated to 110 deg C
- Evaporation of 15 nm Te
- Evaporation of 25 nm Cs
- pressure stays below 1e-8 mbar during evaporation
  - $QE_{initial} \sim 1$ %

(*) recipe from CERN: CERN - CLIC Note 299 – E. Chevallay

Many groups expert in cathode preparation



Courtesy of D. Sertore INFN LASA

> 150 Cs_2Te Cathodes over 20 years
operated in several facilites FLASH, EU-XFEL, …

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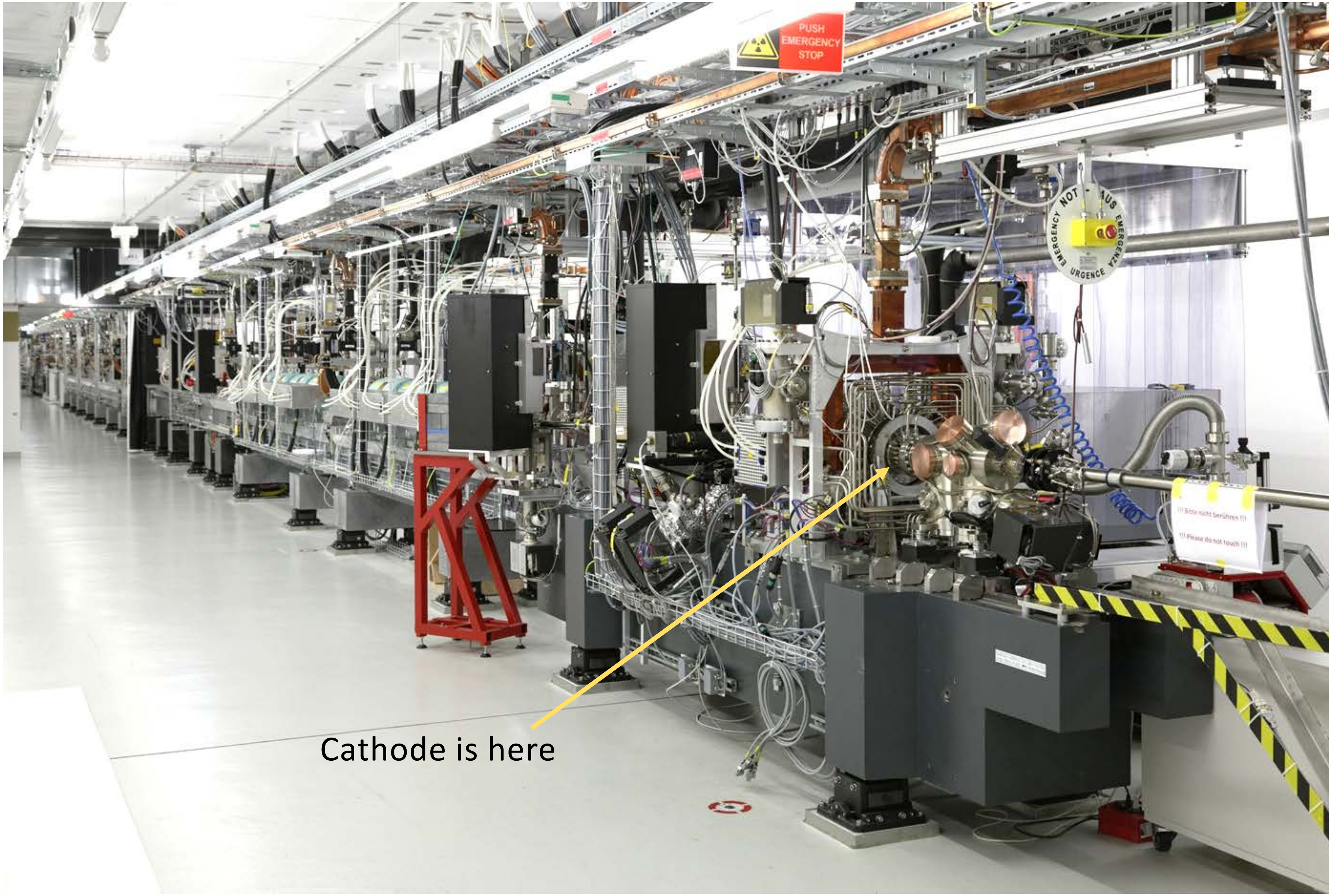
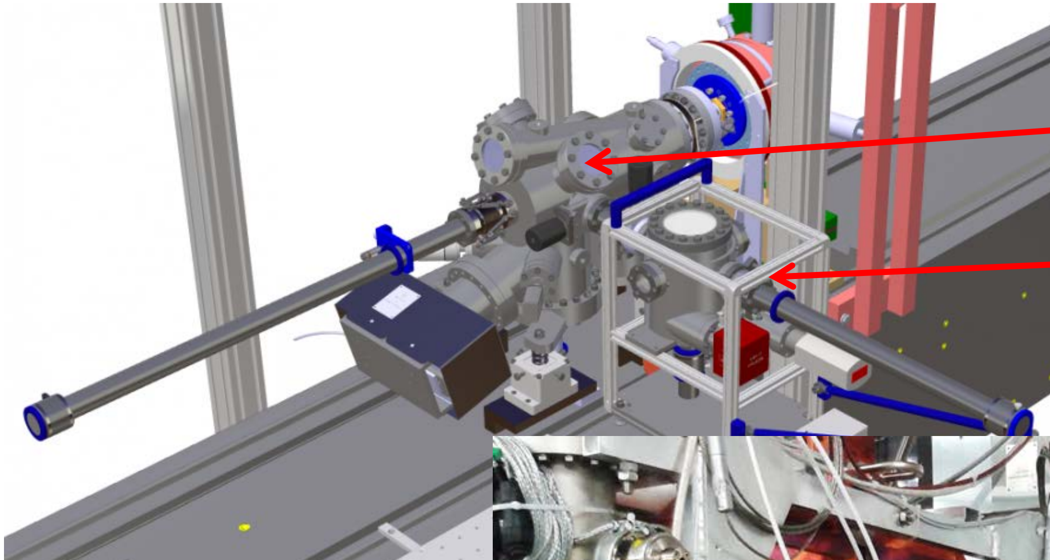
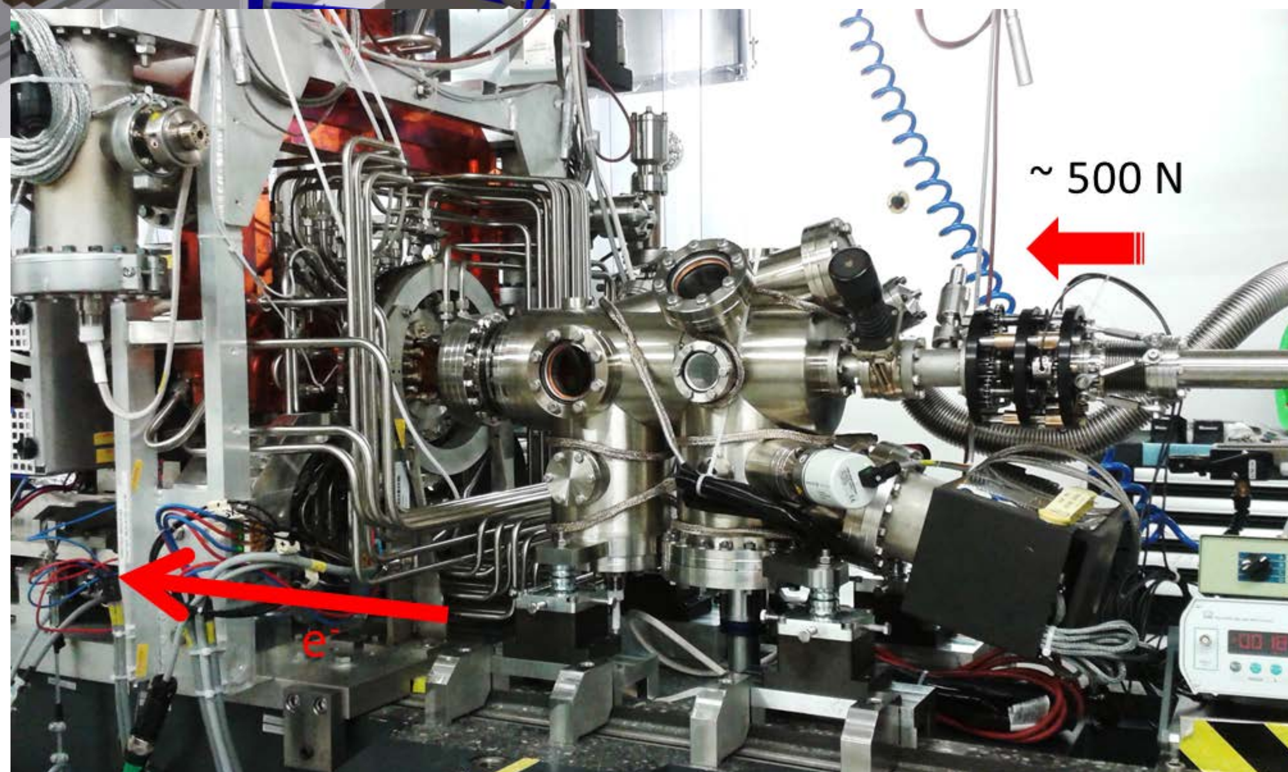
SwissFEL Electron Gun and Loadlock

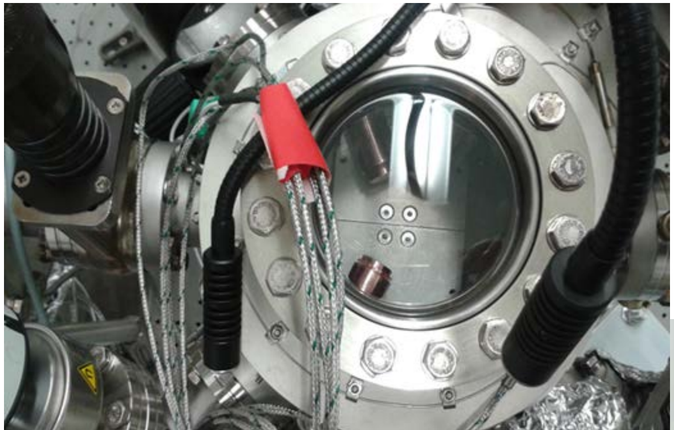


Loadlock chamber behind RF gun



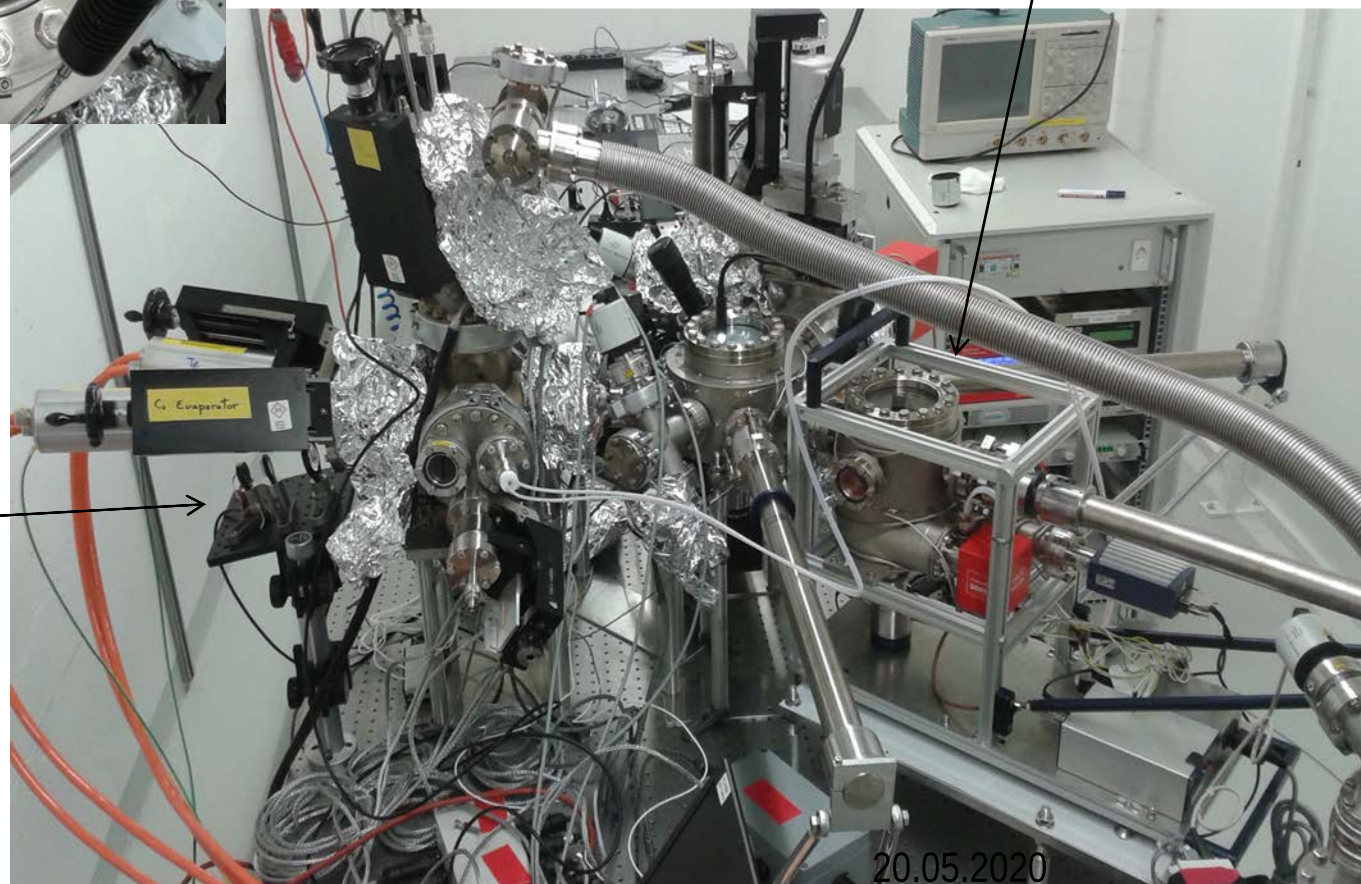


SwissFEL Cathode Preparation system



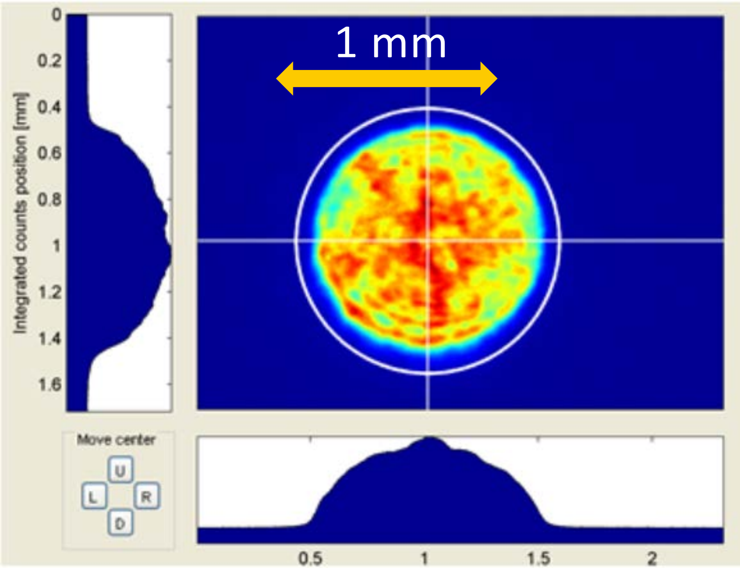
Vacuum Suitcase

266nm LED
for QE monitoring

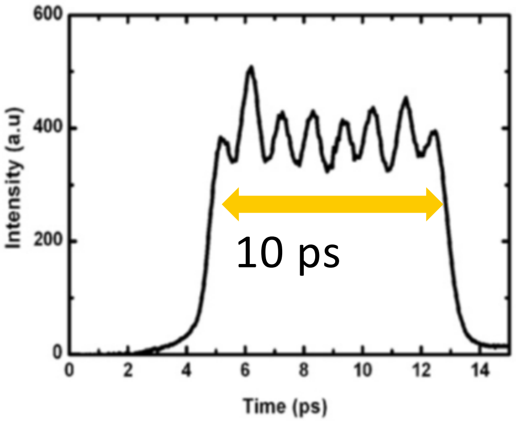


Laser illumination

Laser Transverse Profile (263 nm)

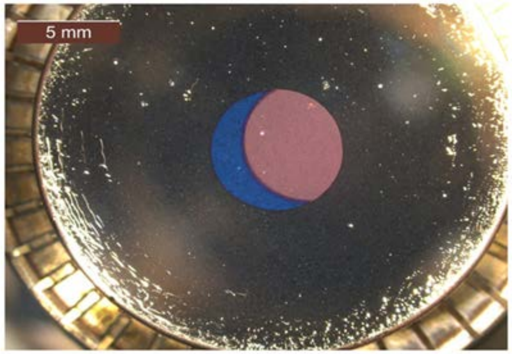


Laser Longitudinal Profile



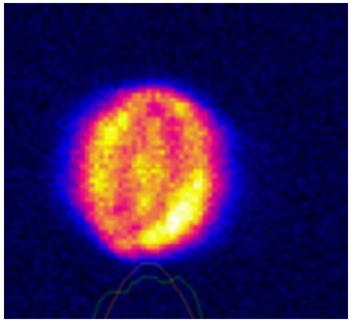
Truncated Gaussian or pulse stacking

+



Photocathode Uniformity

Ref. C.P. Hauri – FEL2011



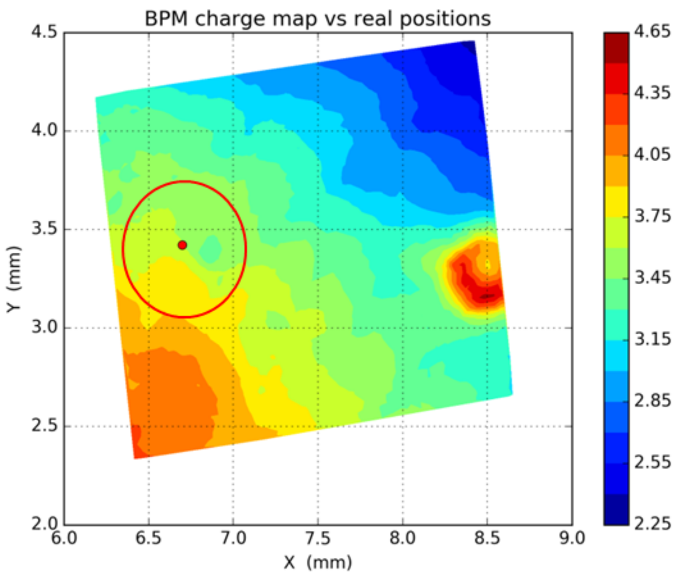
Electron Beam Profile

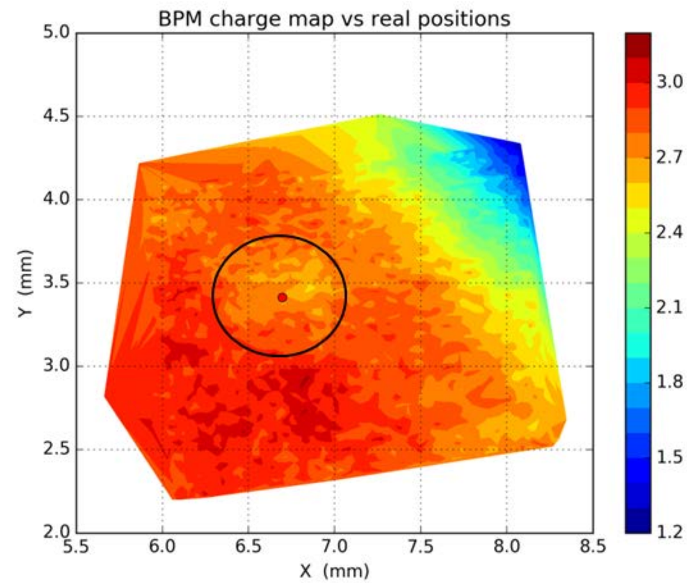
ε_{slice}= 155 nm.rad

Charge 200 pC; 300 MeV

SwissFEL - PSI

Cathode emission uniformity





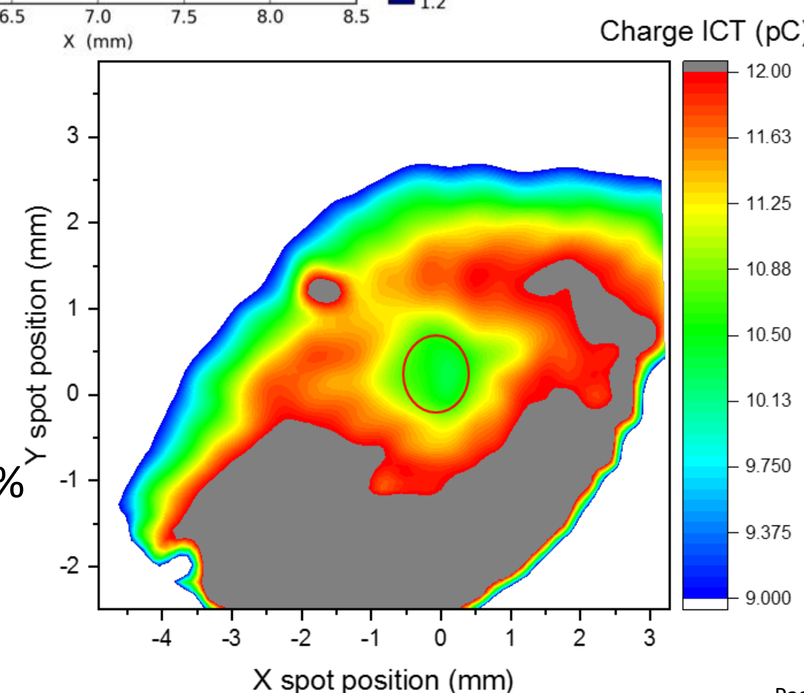
22 Dec. 2017

Uniformity

δ_{QE}/QE ~13 %

02 Sept. 2017:

Uniformity δ_{QE}/QE ~15 %



Cathode started to develop a **QE hole** after few months !

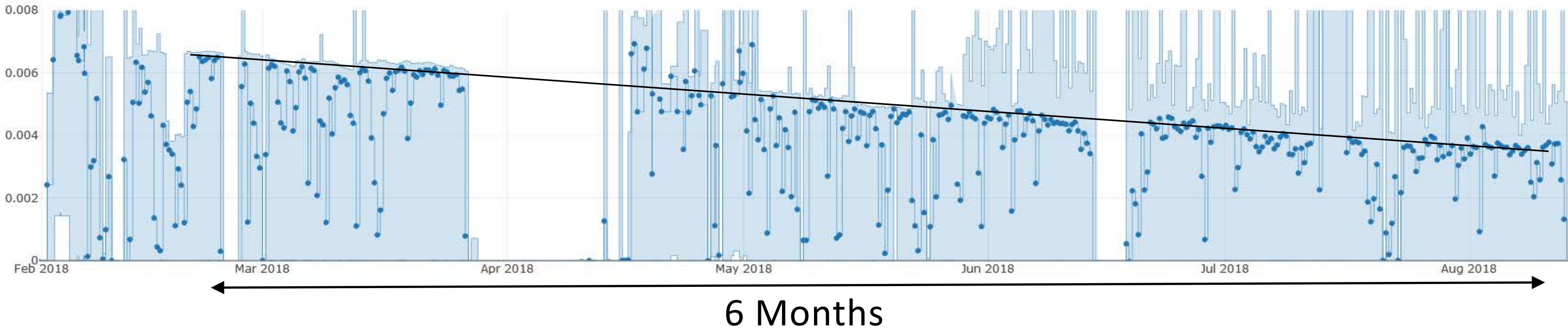
31 Jul. 2018

Uniformity

δ_{QE}/QE ~10 %

SwissFEL Cs_2Te Cathode #31

QE evolution in SwissFEL Gun



Averaged QE dropped by 40% after 6 Months (~ 15 mC charge)

Lifetime until QE~0.1% > 1 year

Cathode #31 (Cs_2Te)
10 Hz; 200 pC
100 MV/m
$P_{cathode} < 1.10^{-9}$ mbar
(1.1e-11 mbar at the pump)

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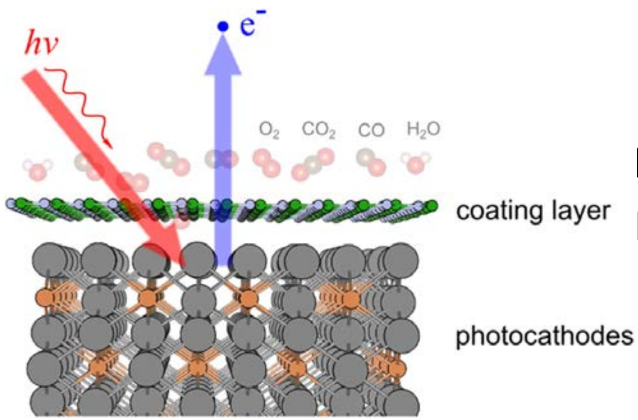
Recent developments: few examples

Photocathode in a sealed can:
- no need of vacuum suitcase and cathode can be produced in large series by **plasma sputtering**

J. Smedley et. al. – PAC2013



Protective Layer: few atomic layer of BN to increase lifetime

E. Batista – LANL – npj 2D materials and applications 2018

Cool down photocathode to reduce mean transverse energy MTE and improve emittance (50% smaller)
MTE ~ 25 meV at 90K for Cs_3Sb

$$\varepsilon_{i,x} = \sigma_x \sqrt{\frac{MTE}{mc^2}}$$

*L. Cultrera et al., Phys. Rev. ST Accel. Beams **18**, 113401 (2015).*

Conclusion

- Photocathode research for accelerator is an **active field**:

  Photocathode Workshop every year alternating USA / Europe

  => P3 Workshop – SLAC 2020

  => EWPAA Workshop – INFN Milano – 2021

- Photocathode has still a **large impact on Electron beam quality** and cost (length) of accelerators

- Large know how exists in **engineering photocathodes** (multilayers, growth control, …)

- Major recent developments were in Semiconductor Photocathodes but metallic photocathodes with development of Superconducting guns should get new interest.

- Many thanks for your attention

- Thanks to my colleagues for the slide material