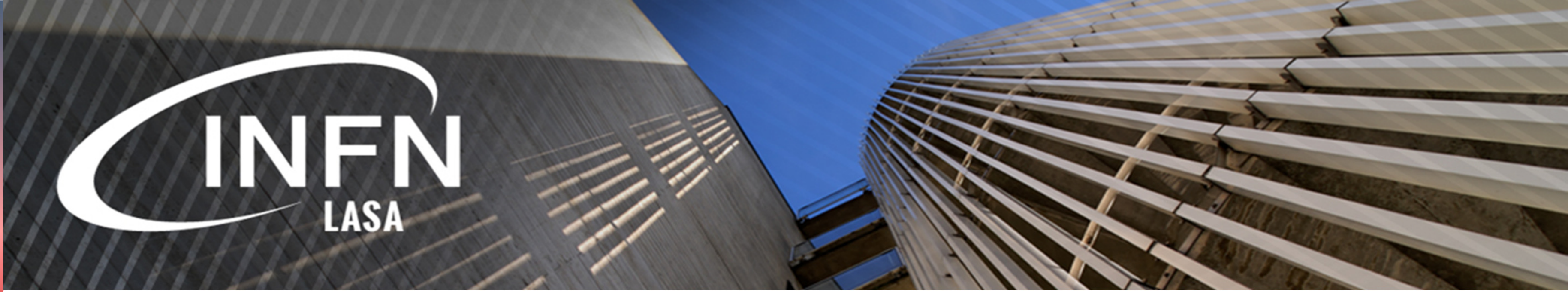


Review of recent photocathode advancements

L. Monaco – INFN LASA

FEL2022 Trieste, Italy 22-26 August 2022

Outline

- Photocathodes required performance
- Metals
- Semiconductors
  - Cs_2Te
  - Alkali antimonide
- Photocathode improvements
- Photocathode diagnostic improvement in production systems for operation
- News on photocathodes test facilities
- The modern approach to photocathode developments and advancements

Photocathodes required performance

Photocathodes principal applications

FEL sources

- Moderate currents
- Low emittance

➢ Semiconductors
➢ Metals

Ultrafast electron diffraction/microscopy

- High brightness
- Very low current
- Short pulse duration

➢ Semiconductors
➢ Metals

Polarized

- High polarization
- High QE

➢ NEA Semiconductors

Electron beam for e-cooling

- High average current (>100mA)
- High bunch charge (1nC)
- Low emittance

➢ Semiconductors

Photocathode Requirements

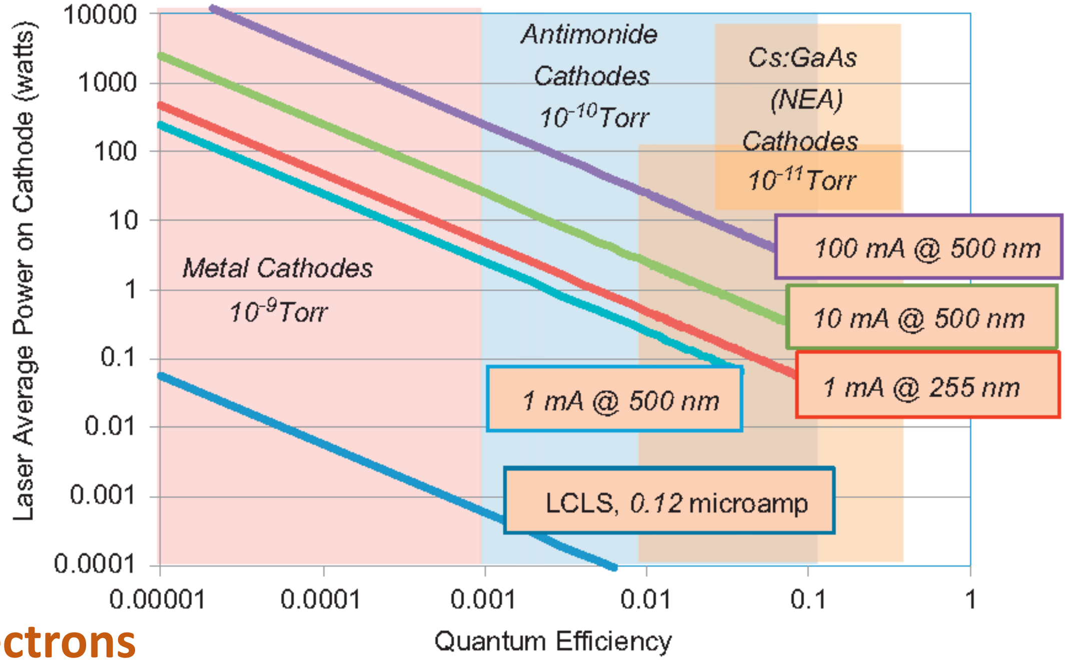
- High QE
  - High QE relaxes requests on laser performance
  - Near threshold operation for thermal emittance reduction may benefit
- Stable QE with good spatial uniformity
  - Reduced inhomogeneities improve photocathode emittance
- Low thermal emittance (or MTE)
  - Brightness improved
- Robustness (vacuum condition)
  - Up-time for machine operation
- Low dark current
  - Clean machine operation and reduce component activation
- Long operative lifetime
  - as long as possible depending on the applications…from wks to months

➢ Reproducible recipe is a must to limit machine parameter changes!!

Photocathode families

- **Metals**
  - Low QE
  - Very fast response time
  - Long lifetime
- **Semiconductor**
  - High QE
  - Fast response time
  - Sensitive to vacuum conditions
- **Photocathode for polarized electrons**
  - Very sensitive to vacuum conditions

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

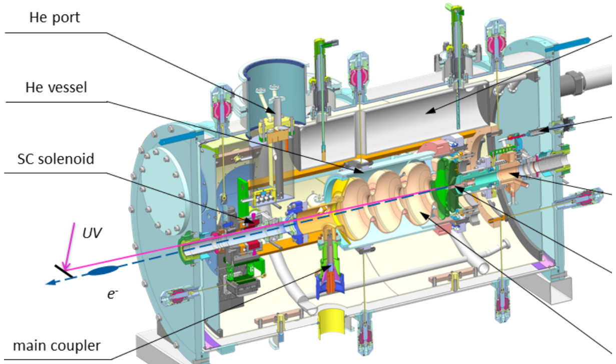


Metal Photocathodes

Metal Photocathode

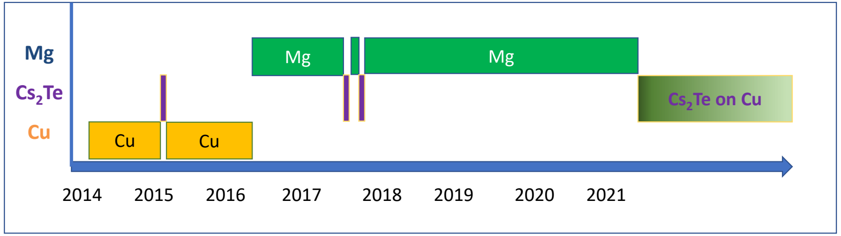
- These cathodes (*Cu, Mg*) are commonly used in normal conducting low repetition rate, high frequency, high gradient RF gun.
- They are the photocathodes of the BNL/SLAC/UCLA S-band RF guns and of the LCLS gun.
- SRF guns use either *Nb* or *Pb* deposited on the RF gun end plate for fixed cathodes. For exchangeble photocathodes, different materials are possible.
- Pros
  - Unlimited lifetime
  - Low sensitivity to vacuum condition
  - Very fast response time
  - Low field emission
  - Low emittance
- Cons
  - High work function
  - Low QEs
  - No polarization possible

Metal photocathodes for HZDR SRF gun



J.Teichert et al. PRAB 24, 033401 (2021)

Parameter	Operation Value
Beam energy	4.5 MeV
Gradient E_{acc}	8 MV/m
Bunch charge	0 - 250 pC
Beam rep. rate	25-250 kHz
Pulse width (rms)	2.3 ps rms in Gauss
Cathode temp.	80 K
Cathode field	14 MV/m
Dark current	60 nA



Highlight:

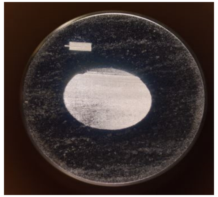
2014 successful commissioning with Cu

2019-2020 stable operation with Mg ~ 1760 h beam time, ~ 57 C charge

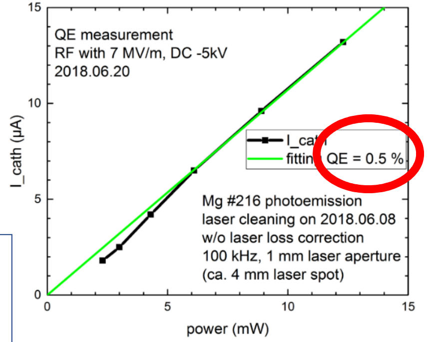
2020-2021 user operation with Cs_2Te (see Cs_2Te section)

Mg cathode status: stable operation

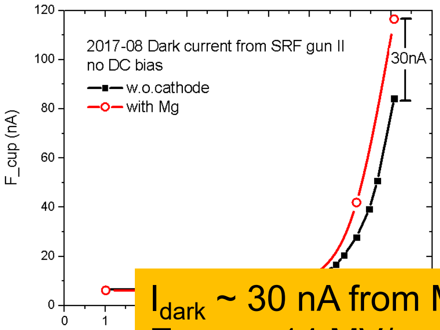
- high QE with UV laser, long life time
- no multipacting problem
- low dark current
- repeatable (can be cleaned several times)



Mg plug after laser cleaning



QE_{258nm}~0.2%-0.5%



I_{dark} ~ 30 nA from Mg
$E_{cathode}$=14 MV/m

R. Xiang, Snowmass2021 Electron Source Workshop, Feb 2022

Study activities

MgO on polycrystalline Cu cathode

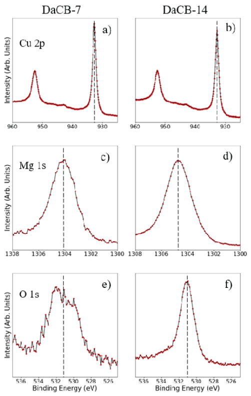
- work function lowering (increase of QE)
- increase of robustness
- measured MTE with TESS

QE @ λ = 266nm (4.7 eV)

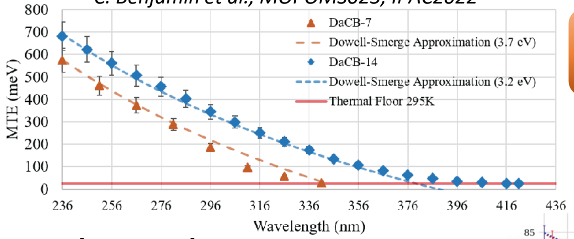
Sample	Substrate WF (eV)	QE	MgO Film WF (eV)	QE
DaCB–7	4.9	1×10^{-6}	3.7	7.0×10^{-5}
DaCB–14	5.0	8×10^{-7}	3.2	4.5×10^{-5}

C. Benjamin et al., MOPOMS025, IPAC2022

XPS



TESS

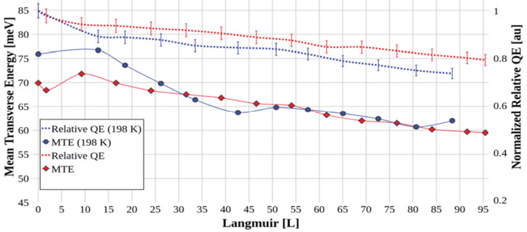


Ag - Polycrystalline vs single crystal

- Ag polycrystalline shows a lower QE degradation w.r.t. single crystal Ag
- QE degrades faster under cryogenic condition -> at cold, higher sticking of O_2 to the surface

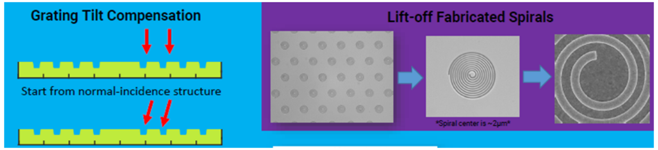
TESS

L. A .J. Soomary et al., THPOPT034, IPAC2022

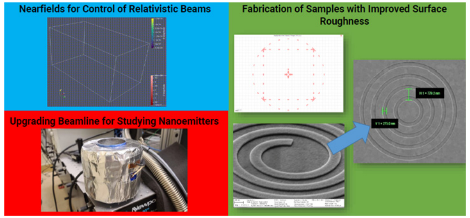


Femtosecond beam from flat surface

- Combine benefit of tip and flat emitters to get femtosecond, few electrons beam with high brightness.



C. M. Pierce et al., P3 workshop, November 2021



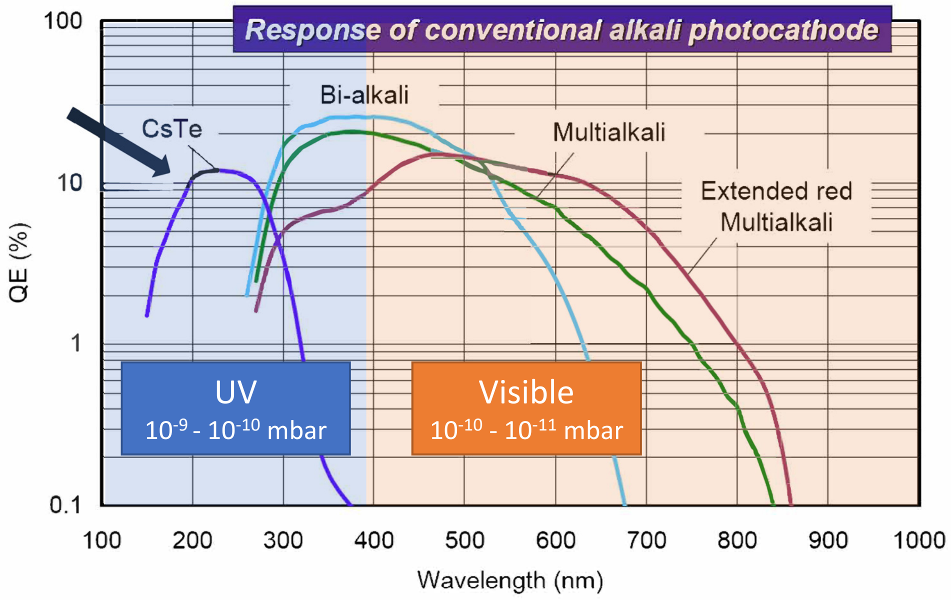
Semiconductor Photocathodes

Introduction

- High charge, long pulses and high repetition rate machines require high QE photocathodes given the limited average laser power to some tens of Watts.
- ***Semiconductor*** photocathodes have high QE, but they are sensitive to gas exposition and require UHV conditions.

Their use in Gun requires also:

- QE uniformity
- Low dark current
- Long operative lifetime
- Stable operation along the train
- Fast response time
- Low thermal emittance



J. Smedley, Snowmass2021 Electron Source Workshop, Feb 2022

Alkali Telluride

C_2Te

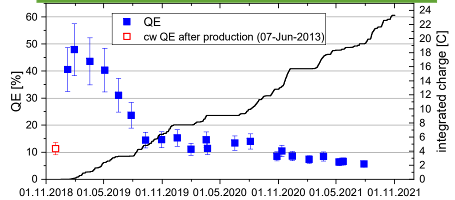
INFN LASA Cs_2Te Photocathodes

INFN LASA
Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

- INFN LASA produce Cs_2Te photocathode since 90s and it's a reference lab for this activity
- With a continuos interplay between collaborators and R&D, we today growth cathodes that have few years of operative lifetime and are a reference for many accelerator complex for users.
- More than 150 photocathodes delivered up to now!
- Cs_2Te photocathodes have been demonstrated usable also for CW operation.

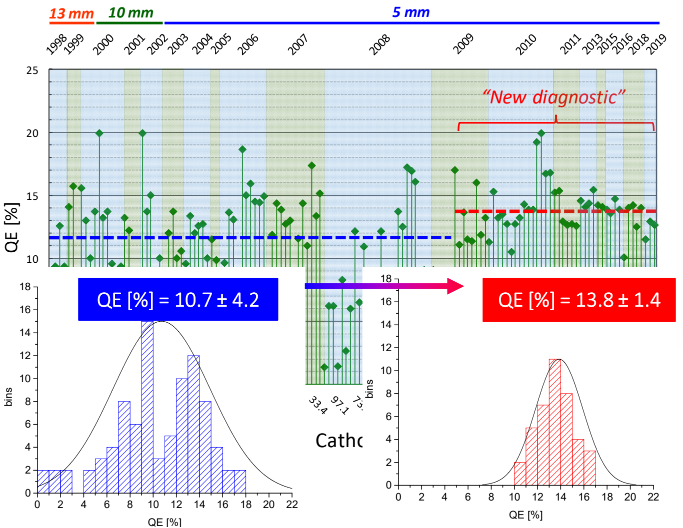
FLASH. Free-Electron Laser FLASH

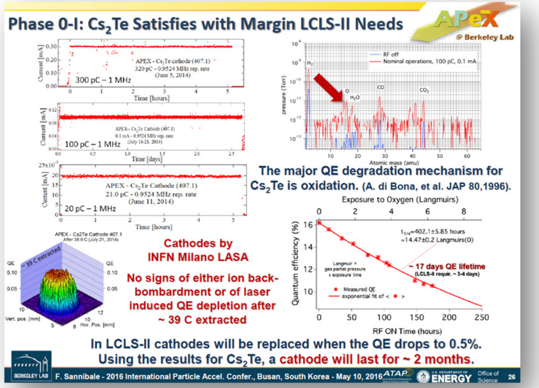
Extracted charge: ~ 23 C
1063 days of oper. until now



QE and integrated charge for cathode #105.2, cw QE measured by Hg-lamp at 254 nm after production June 2013 at LASA..

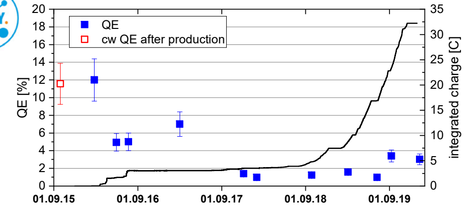
See TUP07 poster (FEL2022)





European XFEL
DESY.

Extracted charge: 32.2 C
1452 days of operation



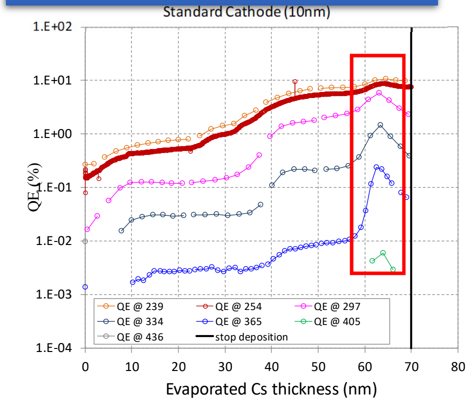
QE and integrated charge for cathode #680.1, cw QE measured by Hg-lamp @ 254 nm after production September 2015 at DESY

D. Sertore, Snowmass2021 Electron Source Workshop, Feb 2022
F. Sannibale, TUOCA02, IPAC2016
S. Schreiber et al., TUP07, FEL2022

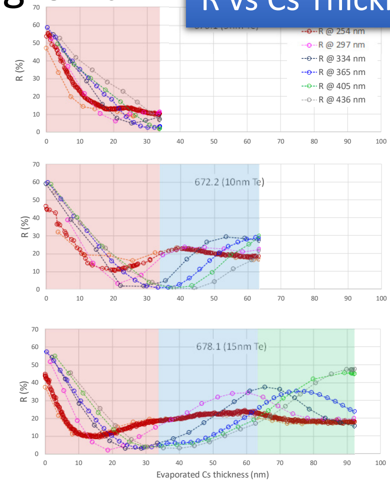
Photocathode Fundamental R&D

Deposition system is equipped with a "multiwave" diagnostics for the monitoring of optical parameters and QE during cathode growth

QE vs Cs Thickness and λ

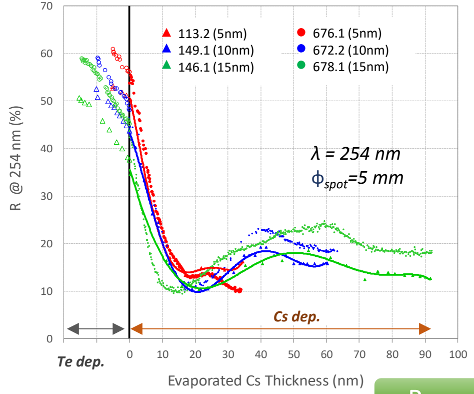


R vs Cs Thickness



L. Monaco et al., WEA04, FEL2019

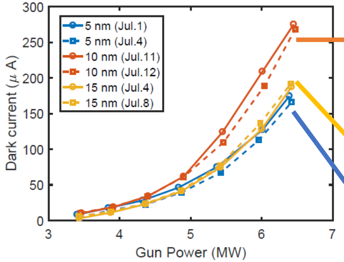
Reflectivity during production



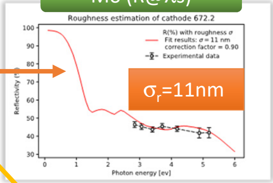
Response time

Measurements at PITZ and FLASH RF gun provide feedback to production process

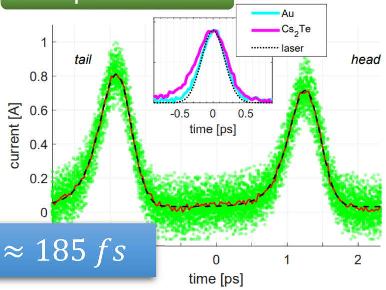
D. Sertore et al., THPOPT027, IPAC2022



Mo (R@λs)

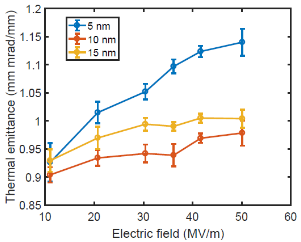


Response time

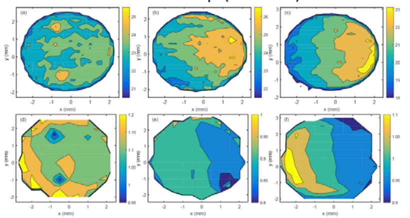


G. Loisch et al., Appl. Phys. Lett. 120, 104102 (2022)

✓ Thermal emittance vs E



✓ QE map (1st row) and thermal emittance map (2nd row)



P. Huang et al., WEP062, FEL2019

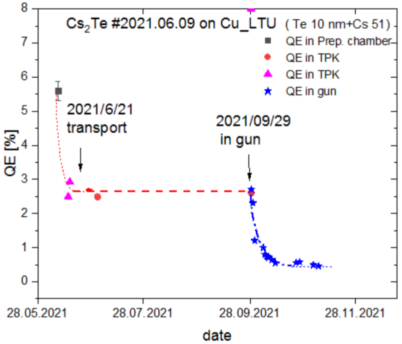
HZDR SRF Gun Cs_2Te on Cu operation

- ✓ **Switch from Mo substrate to copper substrate for improving thermal contact**
- ✓ 2020.06-2022.02 extracted **91.3 C** for **3064 h user beam** (7 Cs_2Te)
- ✓ Providing 200pC/2.3ps, 50-100kHz (CW)
- ✓ 2-3 months lifetime with QE 0.5%-1%
- ? QE drops down due to transport, multipacting and beam operation

Cs_2Te on Cu plug

Up to now, 7 Cs_2Te cathodes have been operated in the SRF gun

Status: stable operation



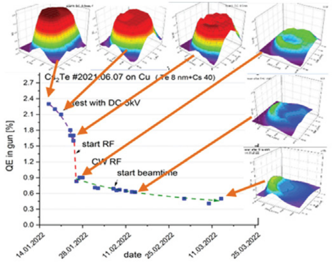
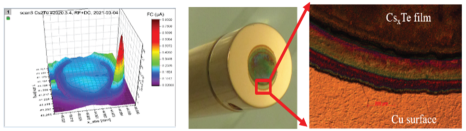
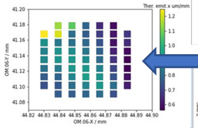
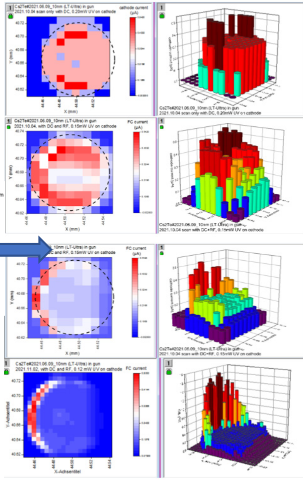


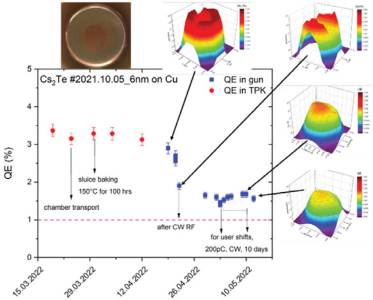
Figure 2: QE tracking of Cs_2Te #2021.06.07 with the QE mappings in different stages during operation in SRF gun.



thermal emittance 0.6-1.2 µm







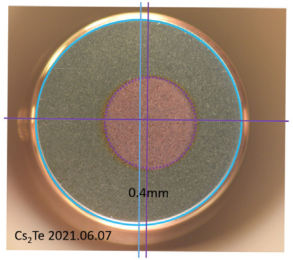
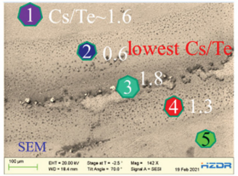
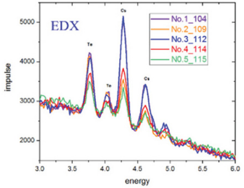


Figure 3: Photograph of the Cs_2Te cathode #2021.06.07 with 8 nm Te and 40 nm Cs, but 0.4 mm off centre.

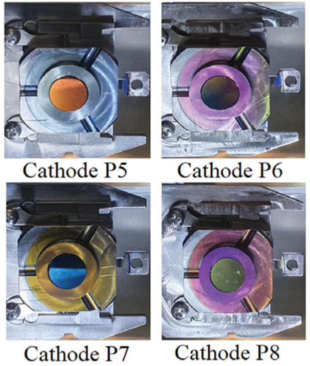
SEM and EDX analysis after usage





R. Xiang et al., THPOPT022, IPAC2022
R. Xiang, Snowmass2021 Electron Source Workshop, Feb 2022

Cs_2Te co-evaporation towards production



Cs_2Te history:
- Cu substrates prepared at Daresbury
- Co-deposition at CERN
- Delivery in UHV ($1{\cdot}10^{-10}$mbar)
- Transfer in PPF (XHV $5{\cdot}10^{-12}$ mbar, p_{max} $1{\cdot}10^{-9}$ mbar in transfer)

Cs_2Te diagnostic:
- TEDC (Transverse Energy Distribution Curve) in TESS
- λ = 236÷436nm (10nm step), T @ RT & cryogenic T
- QE determined in TESS
- XPS analysis -> evaluation of Cs/Te ratio, main peaks

TEDCs & XPS results
- Films behave differently and this is confirmed by XPS results.
- P6: large TEDC @ λs> 400nm, probably due to oxygen peak (XPS) that reduces the work function increasing MTE

L. A. J. Soomary et al., THPOPT033, IPAC2022

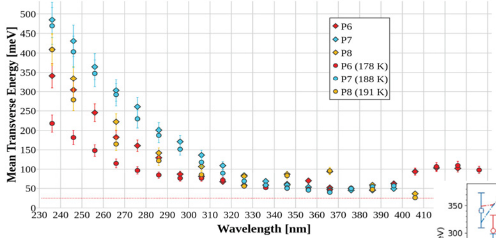
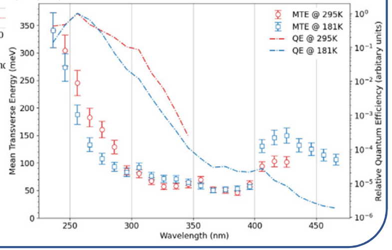


Figure 2: Measured MTE values for the P6, P7 and P8 Cs-Te cathodes at room temperature (diamo
temperatures (circles) under illumination wavelengths between 236 nm and 436 nm

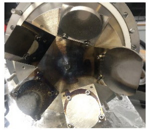


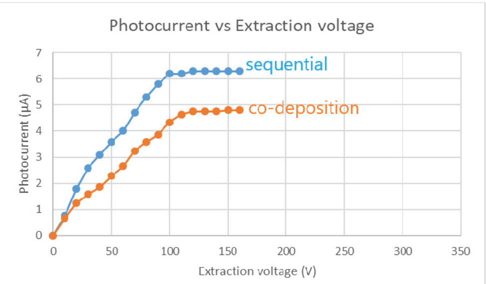
CLARA injector at STFC: S-band RF Gun, successfully operated with Cu cathodes

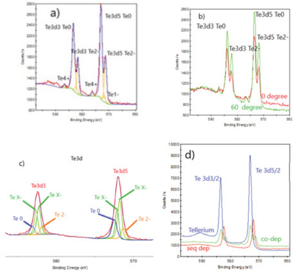
For FEL application, Alkali telluride (Cs_2Te) is chosen (Mo substrate)

Design of a new preparation facility for(also by ion beam deposition/implantation):
- metal, metal/oxide, caesium implanted on metal
- Alkali-Telluride and Alkali-Antimonide

Cs_2Te history:
- Mo substrates (0.5mm thick)
- Cleaning: acetone, methanol, deionized water in US bath, baking (p 10^{-9} mbar), ion beam spattering
- **Sequential deposition** (1h for each) **and Co-deposition** (1h in total)
- T 120 °C, 20nm Te (ion beam sputtering), Cs (source)
- QE after deposition, XPS analysis







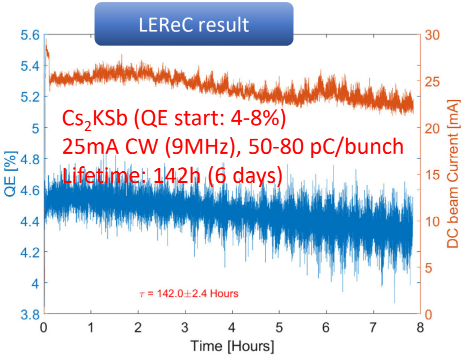
R. Valizadeh et al., MOPOMS027, IPAC2022

Alkali antimonide

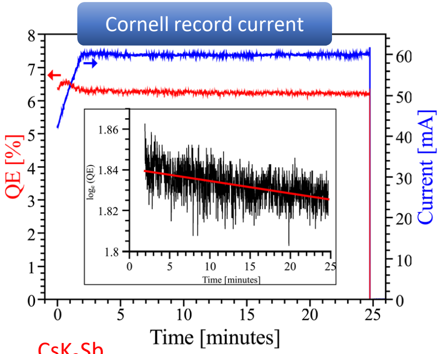
Lifetime at high average current operation

Demanding EIC requests for Electron beam e-cooling:

- >100 mA, 1.5 nC bunch charge, 1.5 mm·mrad, > 3 days lifetime



X. Gu et al., PRAB 23, 013401 (2020)

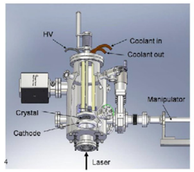


CsK_2Sb
65mA CW, lifetime: 30h 1/e (1d)

B. Dunham et al., Appl. Phys. Lett. 102, 034105 (2013)

Drawback (not only for High Average current):

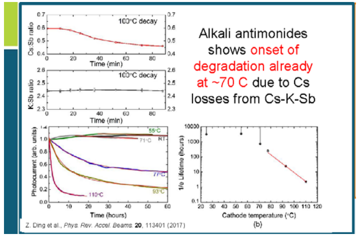
- Cs-K-Sb QE drop ~ 70 °C (Cs losses)
- Cs-K-Sb QE drop P_{laser} >5W
- Ion back bombardment



Cooling of the cathode also present in other DC gun (Cornell, SBU-BNL) and in SRF gun (HZDR)

H. Lee et al., Rev. Sci. Instr. 89 (2018) 083303
E. Wang et al., arXiv.2112.03042
J. Teichert et al., Phys. Rev. Accel. Beams 24, 033401 (2021)

Up to 40 W of laser power

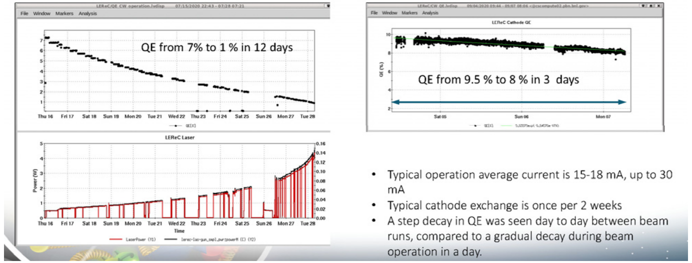


Alkali antimonides shows onset of degradation already at ~70 C due to Cs losses from Cs-K-Sb

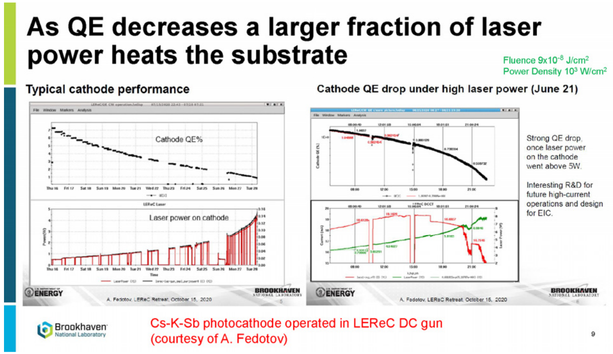
L. Cultrera, Snowmass2021 Electron Source Workshop, Feb 2022

Solutions

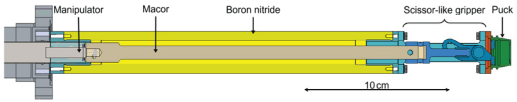
- ➢ new robust cathodes: multi-alkali (Na), coating, epitaxial growth, graphene, etc.
- ➢ cathode cooling
- ➢ anode bias voltage/coating off-centered



E. Wang et al., Snowmass2021 Electron Source Workshop, Feb 2022



MIST: K_2CsSb in puck, heating trasnferred by BN



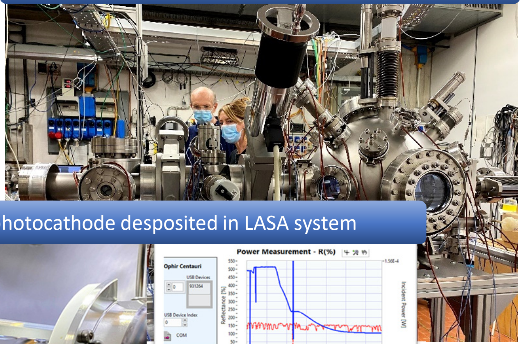
D. Filippetto et al., arXiv:2207.08875v1 [physics.acc-ph] 18 Jul 2022

M. A. Dehn et al., THPOPT024, IPAC2022

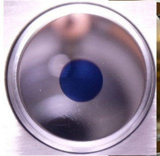
“Green” Photocathodes INFN - DESY

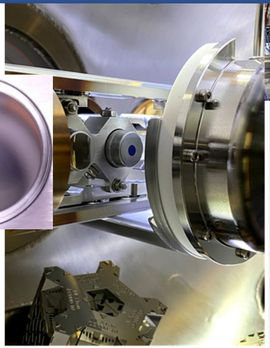
- CW machine operation requests photocathode:
  - sensitive to visible light to relax requests on lasers.
  - smaller thermal emittances $\epsilon_{th} \approx$ 0.3 mm mrad to improve machine performances.
- However, these materials requires XUHV (≈ 10^{-11} mbar) being more sensitive than Cs_2Te
- In collaboration with DESY PITZ:
  - we have developed a new deposition system suitable for «green» photocathodes.

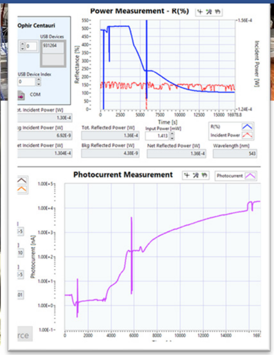
New deposition system for «green» cathodes



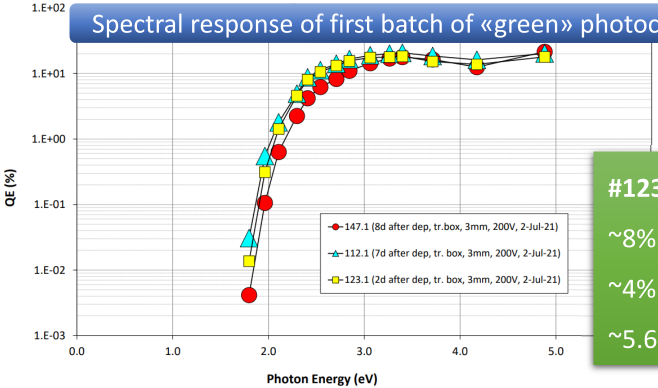
First photocathode desposited in LASA system







Spectral response of first batch of «green» photocathodes



#123.1 QE@2.4 eV

~8% (At INFN)

~4% (In PITZ loadlock)

~5.6% (In PITZ gun)

Cathode	Sb evaporation	K evaporation	Cs evaporation	QE @ 515 nm
147.1	120 °C, 10 nm	150 °C, 62.4 nm	135 °C, 178.2 nm	5.3 %
112.1	120 °C, 5 nm	constant power, 44.6 nm	constant power, 153.6 nm	7.87 %
123.1	120 °C, 5 nm	constant power, 153.6 nm	constant power, 156.6 nm	7.58 %

- A deposition process was studied in the R&D system and transfer to growing these cathodes.
- The first K_2CsSb photocathodes have been produced in June ’21 and tested in July in the PITZ RF Gun.
- Successful transfer of the photocathodes to PITZ with limited QE degradation

D Setore et al., THPOPT027, IPAC2022

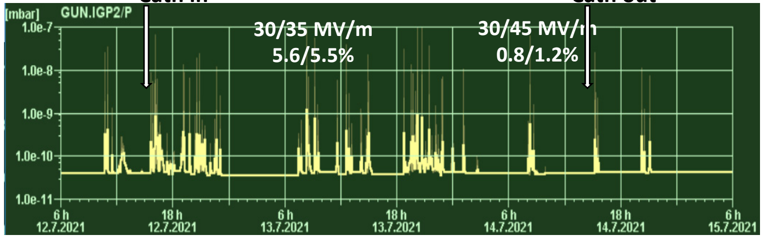
S. Mohanty et al., TUP04, FEL2022

K_2CsSb photocathode in high gradients RF Gun

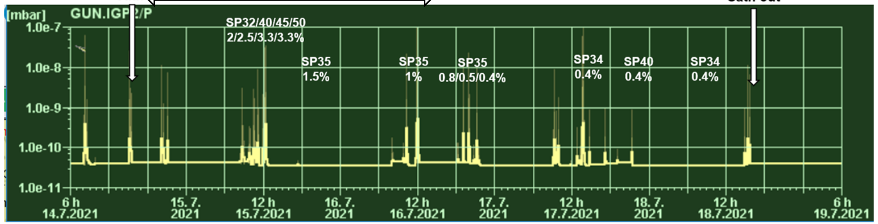
Cathode RF conditioning, QE, lifetime, vacuum

- Cathode RF conditioning
  - Below 30 MV/m, almost not necessary, up to 400 µs was tested without vac events
  - Above 30-40 MV/m, much more vac events than Cs_2Te conditioning, degrades QE significantly
- Cathode QE
  - Fresh QE in gun is consistent with lab measurements
  - QE decrease dominated by vac events during conditioning, QE also slowly decreases w/o vac events.

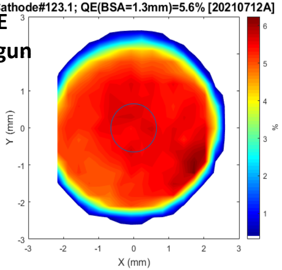
2 days <1% QE (T_{cath}~70℃ #123.1)

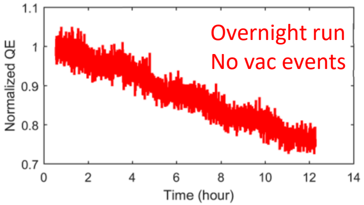


2 days <1% QE (T_{cath} ~50℃ #147.1)

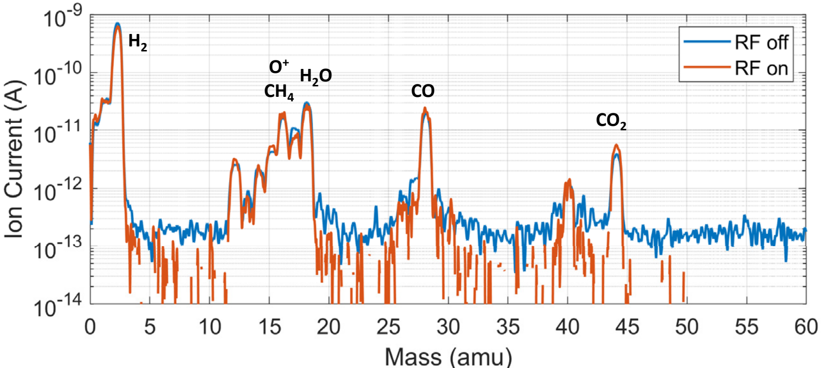


Fresh QE map in gun





QE slowly drops by 20% in 12 hours



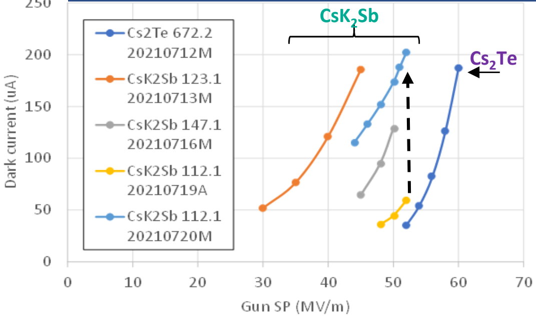
S. Mohanty et al., TUP04, FEL2022

K_2CsSb photocathode in high gradient RF Gun

Dark current, cathode response time

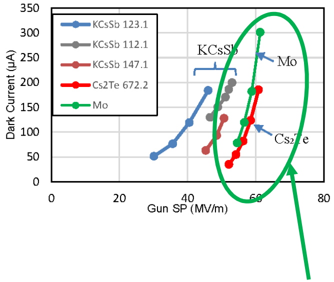
- Dark current vs gun gradient

Max dark current @ 0.8 m from cathode



All cathodes have **higher dark current than Cs_2Te one**.

#112.1 dark current increased during cathode conditioning.



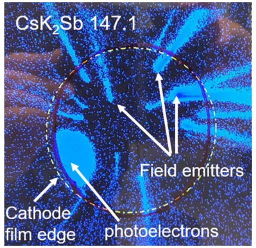
Higher dark current can be due to the different energy threshold of films:

E_{th} (KCsSb) = 1.9 eV < E_{th} (Cs_2Te) = 3.5 eV

F-N analysis, high dark current due to low emission threshold, not due to surface quality

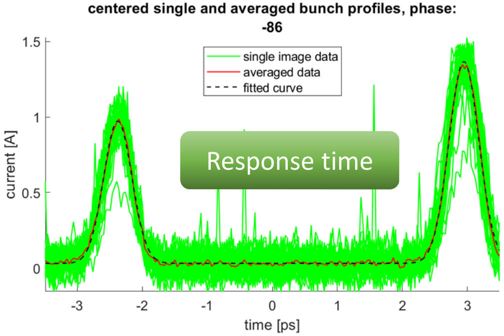
	beta	A (nm²)
Cs_2Te 672.2	126	15212
123.1	462	0.002
147.1	97	0.98
147.1	102	1.1
112.1	99	0.3
112.1	246	0.013

Dark current imaging



Mo dark current similar to Cs_2Te one confirm that the **major contribution** of dark current comes **from the film** itself

- Cathode response time measurement
  - #147.1 CsK_2Sb, **measured in green when QE dropped to 0.4%**
  - Two laser pulses with known optical delays shine the cathode to calibrate the beam temporal response at photoemission
  - Preliminary data show that response time is **below the resolution of 100 fs!** Much shorter than high QE Cs_2Te cathode response time in UV (~200 fs)
    -> but…measurement to be repeated on a fresh cathode since QE degradation could indicate possibly changes in the surface chemistry of the film

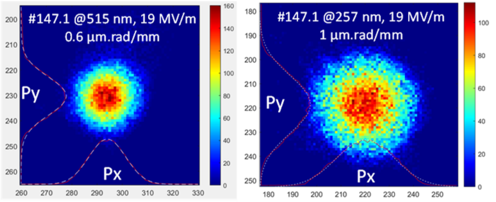


S. Mohanty et al., TUP04, FEL2022

K_2CsSb photocathode in high gradients RF Gun

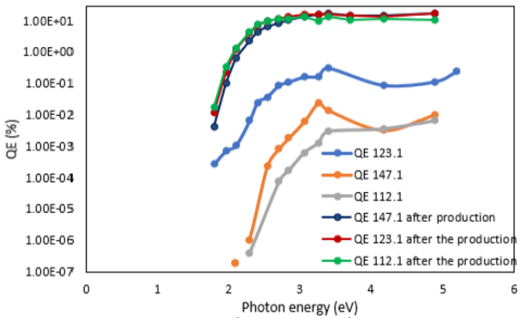
Thermal emittance and 100 pC emittance

- **Thermal emittance** vs QE & laser λ
  - **515 nm:** 19 MV/m, 0.6 µm.rad/mm (2%, 0.8%, 1.5%)
    -> Consistent with APEX gun results
  - **515 nm:** 29 MV/m, 0.7 µm.rad/mm (1.5%)
    -> limited at 30MV/m since high dark current
  - **257 nm:** 19 MV/m, 1 µm.rad/mm (2.5%)
    -> Very similar to Cs_2Te cathode



2D distribution of photoemission transverse momentum

Spectral responses of KCsSb cthodes

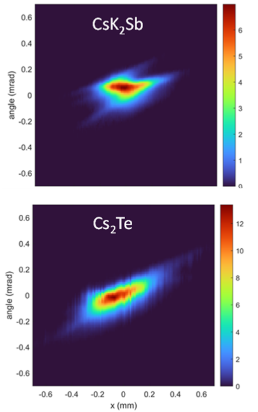


S. Mohanty et al., TUP04, FEL2022

- **100 pC emittance, CsK_2Sb vs Cs_2Te**
  - **40 MV/m** 1.6 cell L-band gun, ~20 MeV linac
  - Emittance reduced by **~23%**,
    4D brightness increased by **~60%**

Measurement	Cs_2Te **1 µm.rad/mm**	CsK_2Sb **0.7 µm.rad/mm**	Unit
95% rms emit.	0.36	0.28	µm.rad
Gauss emit.	0.33	0.25	µm.rad
4D brightness	760	1209	pC/(µm.rad)^2

100 pC beam phase space



Post-usage analysis and future plan

- **Photocathode spectral responses after RF gun operation**
  - Lower QE at all λs for the three cathodes. Cathode 123.1 show a higher QEs w.r.t. cathode 147.1 and 112.1
  - Low energy (photoemission threshold): E_{th} (147.1 and 112.1) **increased** from **1.79 eV to 2.08 eV;** a **shoulder appeared at the low photon energy** for cathode 123.1 **-> potential oxidation of cathode films**

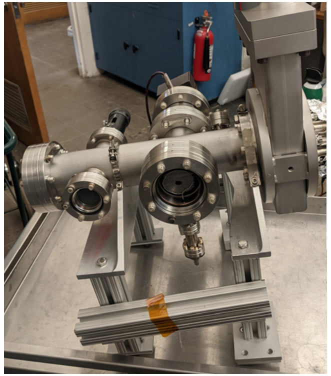
Next steps will be:

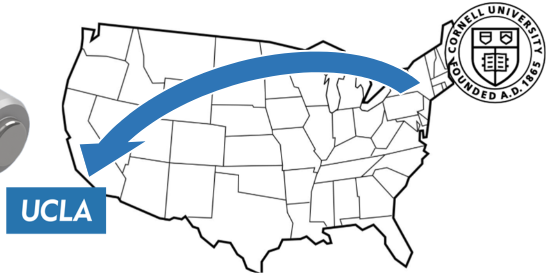
- CsK_2Sb recipe improvement and development of multi-alkali (Na)
- New tests at PITZ

See TUP04 poster (FEL2022)

Testing Alkali Antimonide Photocathodes in High Gradient RF Injector

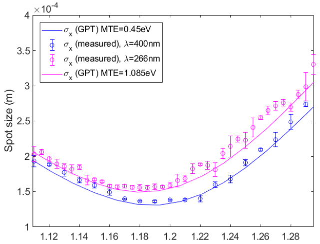
- Na-K-Sb grown on molybdenum plug surface at Cornell University



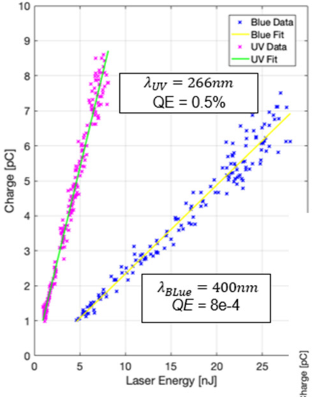


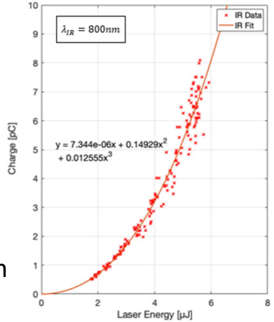
- Initial QE of **Na-K-Sb** after growth: **~1.5% at 532nm**. (10/8/21)
- QE upon arriving at UCLA: **~8e-4 at 405nm**. (10/20/2021)
- Previous testing verified transportation by car, yet the cathodes experienced QE degradation during delayed transport.
- **QE remains** above 0.2% at 266 nm and **greater than 5e-4** at **400 nm** for **multiple weeks of operation**.
- Negligible change in QE after transfer from vacuum suitcase to the gun.
- Maximum single shot bunch charge extracted: ~ 600pC.
- Schottky scan fits for 400 nm and 266 nm yield a work function of $2.2\ eV$ for Na-K-Sb.
- Difference in MTE between 266 nm and 400 nm agrees with workfunction and excess energy measurement from Schottky scans.

$$MTE = E_{exc} / 3$$



C. Pennington, P3 Workshop, November 2021





2 and 3 photon photoemission @ 800 nm

Multi-alkali antimonide development

Na-K-Sb as alternative to Cs-K-Sb photocathode, since more robust at high temperature to be used in Sealab/bERLinPro SRF gun.

HZB Helmholtz Zentrum Berlin

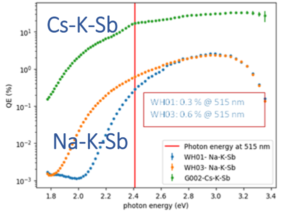
6 Na-K-Sb produced and analyzed:
- 5 with Sb + co-deposition of alkali
- 1 with sequential deposition (WH04)

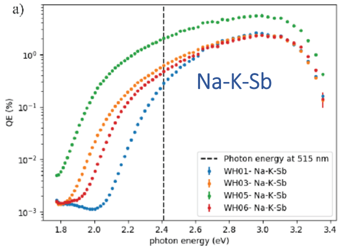
QE @ 515nm between 0.3 and 2.0%

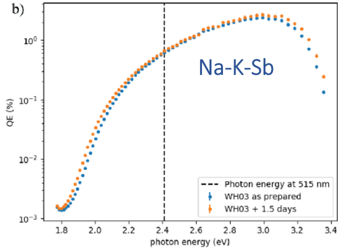
QE stability of co-dep: film WH05 showed a fast decrease (Na excess?) while WH03 was stable after 1.5d

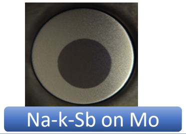
XPS (WP04 & WP05)

S. Mistry et al., THPOPT019, IPAC2022









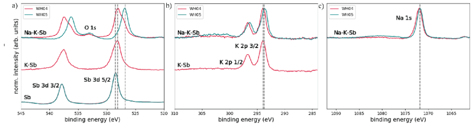


Figure 3: XPS spectra of two Na-K-Sb samples: WH04 was grown by sequential deposition and WH05 by alkali metal co-evaporation. Comparison of a) Sb 3d spectra, b) K 2p spectra and c) Na 1 s spectra.

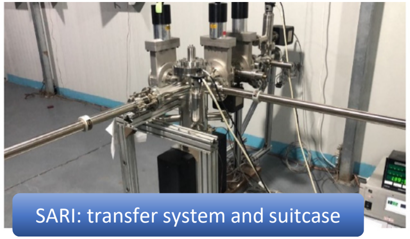
Different Chinese laboratories are making progress on developing new production system for telluride and alkali antimonies.

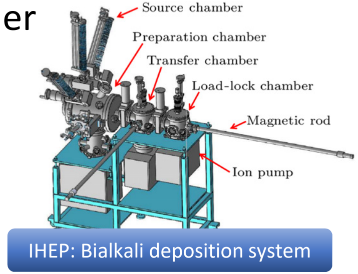
Institute of High Energy Physics, Chinese Academy of Sciences; PEKING UNIVERSITY

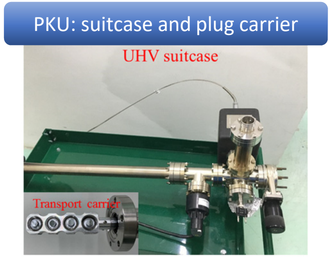
H. Xie, Micromachines 2021, 12, 1376

They are exploring both sequential and co-evaporation.

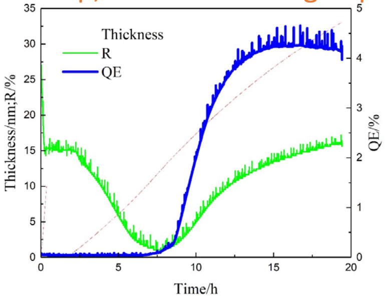
For co-evaporation recipe, Sb is deposited in advance and then alkali metals are evaporated together







SARI first results: K_2CsSb (Mo plug) : co-dep, QE and R during dep

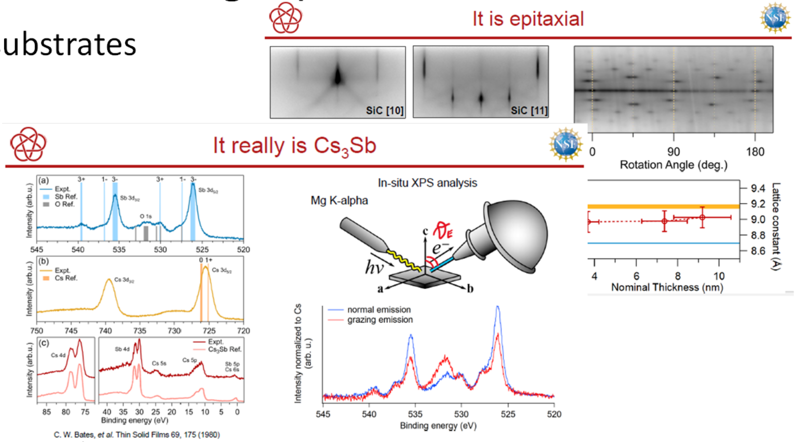


Trieste, Italy 22-26 August 2022

FEL2022

Multi-alkali brightness improvement

- Molecular beam epitaxy of Cs_3Sb: a single crystalline visible light photocathode
- Successfully deposited epitaxial Cs_3Sb (100) films on 3C SiC (100) substrates
- XPS measurements well reproduce literature data on Cs_3Sb
- Ultrathin samples (<10 nm) have >2% QE at 532 nm
- We observe enhnaced QE at 650 nm on our best epitaxial sample
- ARPES measurements unveil for the first time the Cs_3Sb band structure
- DFT band strucure calculations show good agreement with measurements , but significant bandwidth discrepancy indicates that strain and intrinsic instabilities of the Cs_3Sb structure may play a role.



C. T. Parzyck and A. Galdi et al., PRL 128, 114801 (2022)

P. Saha et al., Appl. Phys. Lett. 120, 194102 (2022)

Applied Physics Letters ARTICLE scitation.org/journal/apl

Physically and chemically smooth cesium-antimonide photocathodes on single crystal strontium titanate substrates

Cite as: Appl. Phys. Lett. 120, 194102 (2022); doi: 10.1063/5.0088306
Submitted: 15 February 2022 · Accepted: 29 April 2022 ·
Published Online: 10 May 2022

Pallavi Saha,[1,a] Oksana Chubenko,[1] Gevork S. Gevorkyan,[1] Alimohammed Kachwala,[1] Chri Carlos Sarabia-Cardenas,[1] Eric Montgomery,[2] Shashi Poddar,[2] Joshua T. Paul,[3] Richard Howard A. Padmore,[4] and Siddharth Karkare[1,a]

ASU Department of Physics · euclid BEAMLABS · UF University of Florida · Berkeley Lab

ABSTRACT

The performance of x-ray free electron lasers and ultrafast electron diffraction experiments is largely dependent on the brightness of electron sources from photoinjectors. The maximum brightness from photoinjectors at a particular accelerating gradient is limited by the mean transverse energy (MTE) of electrons emitted from photocathodes. For high quantum efficiency (QE) cathodes like alkali-antimonide thin films, which are essential to mitigate the effects of non-linear photoemission on MTE, the smallest possible MTE and, hence, the highest possible brightness are limited by the nanoscale surface roughness and chemical inhomogeneity. In this work, we show that high QE Cs_3Sb films grown on lattice-matched strontium titanate (STO) substrates have a factor of 4 smoother, chemically uniform surfaces compared to those traditionally grown on disordered Si surfaces. We perform simulations to calculate roughness induced MTE based on measured topographical and surface-potential variations on the Cs_3Sb films grown on STO and show that these variations are small enough to have no consequential impact on the MTE and, hence, the brightness.

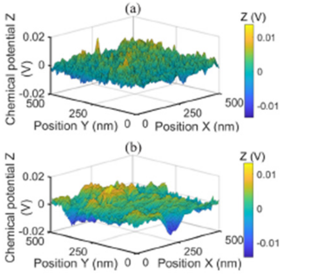
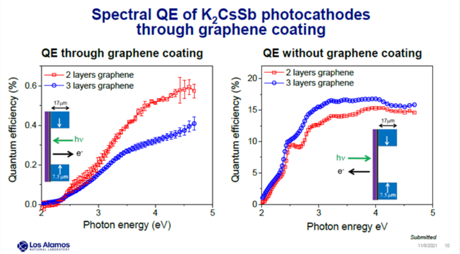
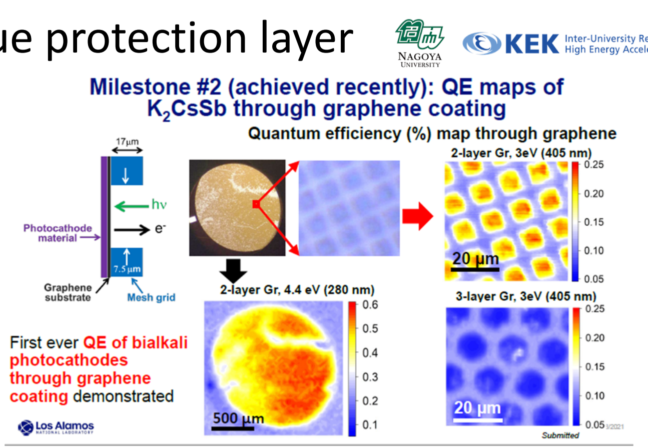


FIG. 3. 3D chemical potential maps of (a) the thin Cs_3Sb film on STO and (b) the thick Cs_3Sb film on STO.

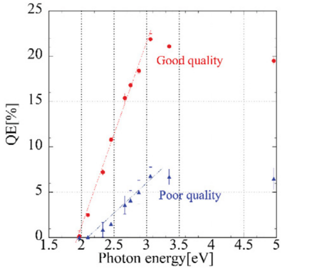
Multi-alkali improvement - Graphene

- Towards the use of 2D materials as unique protection layer for bialkali photocathodes
- Cs_2KSb grown on graphene layers deposited on grid/substrate
- Good quality graphene is important for optimal result
- Achieved good QE through graphene layer





H. Yamaguchi, P3 Workshop, November 2021



L. Guo et al., THPOPT028, IPAC2022

Unexpected findings

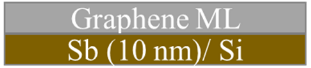
- QE enhancement of bialkali photocathodes by coating metal substrates with graphene
- Graphene as reusable substrate for bialkali photocathodes

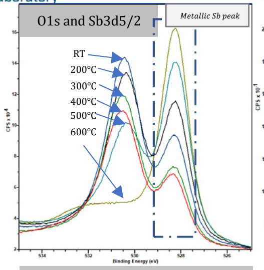
- Progress towards long lifetime photocathodes with protective layer

Brookhaven National Laboratory

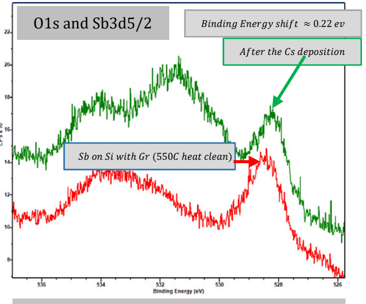
J. K. Biswas, P3 Workshop, November 2021

- Cs_3Sb grown on Sb (10 nm)/Si substrate coated with graphene ML
- Graphene layer prevent Sb to evaporate during thermal cycle
- Successfully grown Cs_3Sb on this support





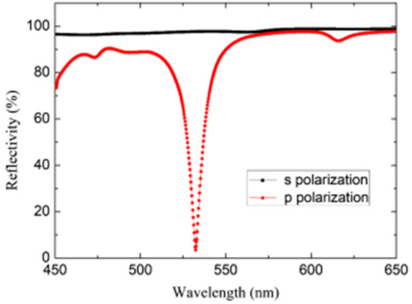
Sb on Si substrate with Graphene layer

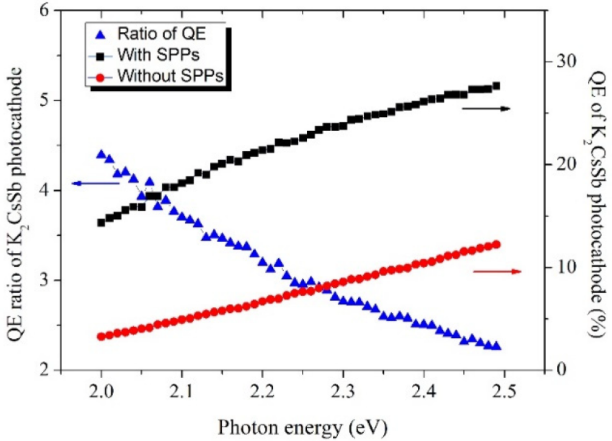


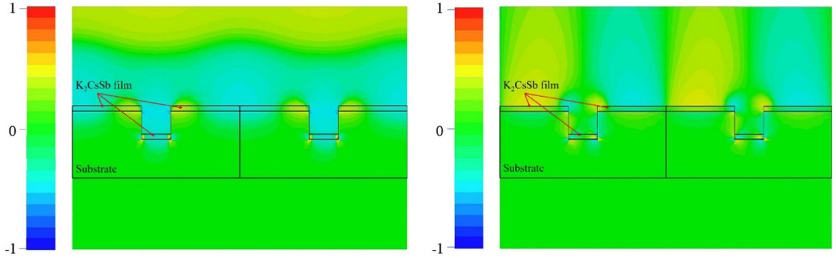
Sb on Si substrate with Graphene layer

Multi-alkali improvement – Surface Plasmon

- The maximum efficiency of the typical K2CsSb film photocathode in absorbing the incident laser is approximately 30%
- To improve absorption, it is proposed to use Surface Plasmon Polaritons (SPP)
- This structure produces a peak in laser light absorption
- The SPP are introduced into a Monte Carlo model by proper modification of the absorption process







H. Xie, Micromachines 2021, 12, 1376

Z. Jiang et al., PRAB 24, 033402 (2021)

Photocathode diagnostics in production systems for operation

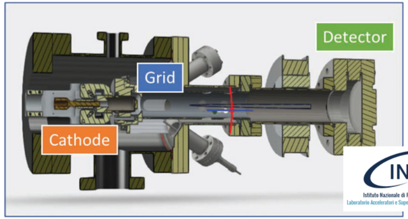
Importance of photocathode diagnostics in production system for operation

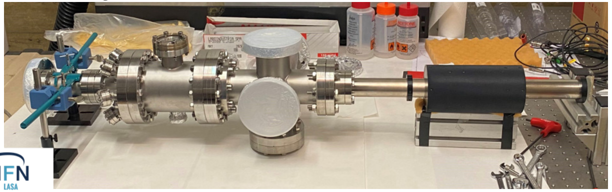
Diagnostics in system for photocathode production will provide:

- Feedback on the quality of produced photocathodes -> possibility to improve films reliability
- Post-usage analysis on photocathodes after operation in guns -> correlation between performance and photoemissive properties of films
- Continuous improvement of recipes -> hints for corrections and new solutions
- R&D activities….but done on real photocathodes to be used in operation (and not samples!)

News on diagnostics in production systems

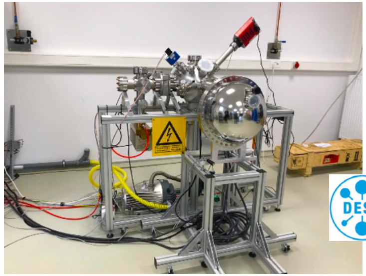
- INFN LASA - TRAMM
  - A TRAnsverse Momentum Measurement device is being developed and it will be installed on the production systems

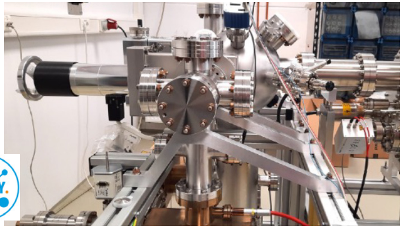




D. Sertore et al., THPOPT026, IPAC2022

- DESY - Blue Lab
  - Build a characterization system based on AES and XPS
  - Build on electron momentum spectrometer

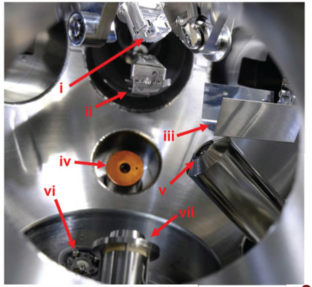


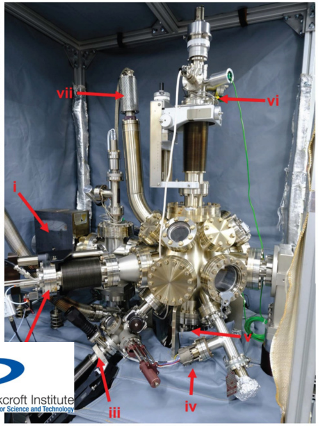


P. Juarez, P3 Workshop, November 2021

- ASTeC - Alkali-metal Photocathode Preparation Facility (APPF)
  - This facility will produce photocathodes for Gun (CLARA)
  - Multiprobe system (for QE and work function measurements) and in the Transverse Energy Spread Spectrometer (TESS) for MTE (or TEDC), CMA for AES.
  - The system can use R&D sample (Omicron) and INFN Mo plug (for production)

H. M. Churn et al., THPOPT044, IPAC2022





Science & Technology Facilities Council ASTeC

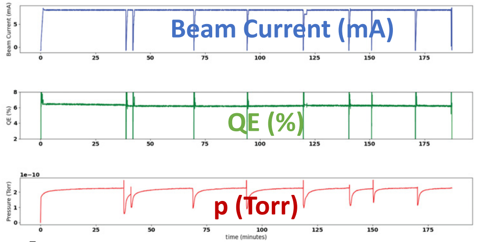
WARWICK

The Cockcroft Institute of Accelerator Science and Technology

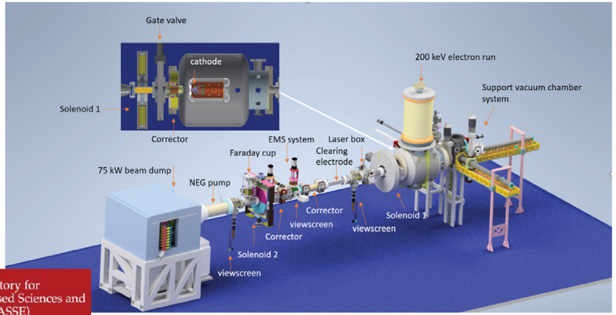
News on
Photocathode test facilities

News on Photocathode test facilities

- Cornell - High ElectrRon Average Current for Lifetime ExperimentS (HERACLES)
  - Dedicated beamline for robustness improvement of photocathodes at high current
  - Photocathode produced at Cornell are transported by a UHV suitcase
  - DC Gun: commissioned at 200 keV, 10 mA
  - Cs_3Sb (first test): 8mA (av. curr.), no QE decrease (3hs run)



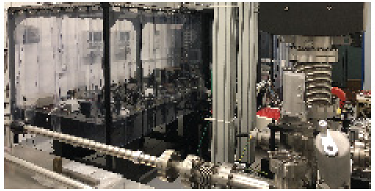
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)



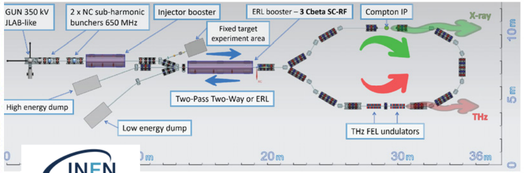
M. B. Andorf et al., THPOMS036, IPAC2022

- INFN LASA – Photocathode Stress Test Bench (BriXSinO)
  - Dedicated system for Cs_2Te operative lifetime studies at High rep rate & current (in construction)
  - LASA photocathode transported by UHV suitcase
  - DC Gun: 100 kV, 5 mA; Laser system: 92.857 MHz (IR=1035nm, 4^{th}=258.75nm), P (4^{th}) 700mW

D. Sertore et al., THPOPT025, IPAC2022



Overview of StressTestBench



BriXSinO layout (TDR)

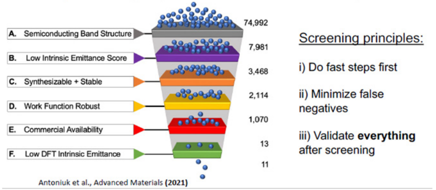
- DESY PITZ – Test of "green" photocathodes in high gradient RF Gun
  - PITZ upgrade for "green" photocathodes test in RF gun (new tests foreseen)

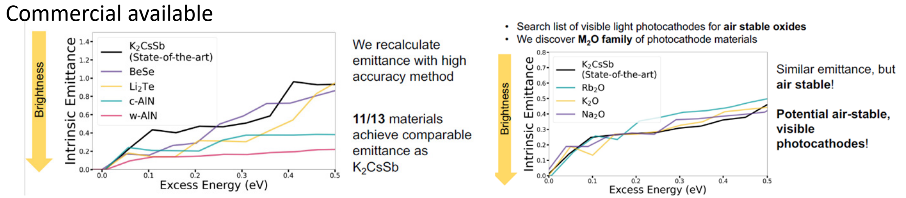
The modern approach to photocathode developments and advancements

Machine learning and AI

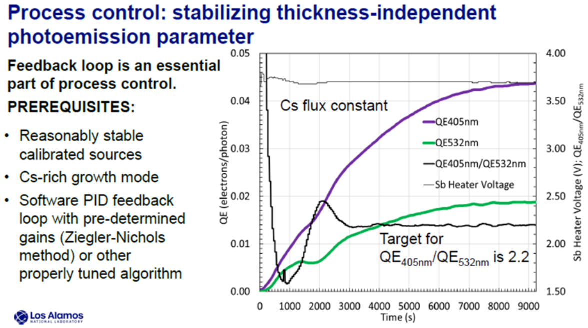
- Novel Ultrabright Photocathodes Discovered from Machine Learning and Density Functional Theory Driven Screening (32)
  - Development of a generalizable photoemission model
  - Machine learning for predicting the work function of photocathodes
  - Screening for novel photocathode materials

E. R. Antoniuk, P3 Workshop, November 2021





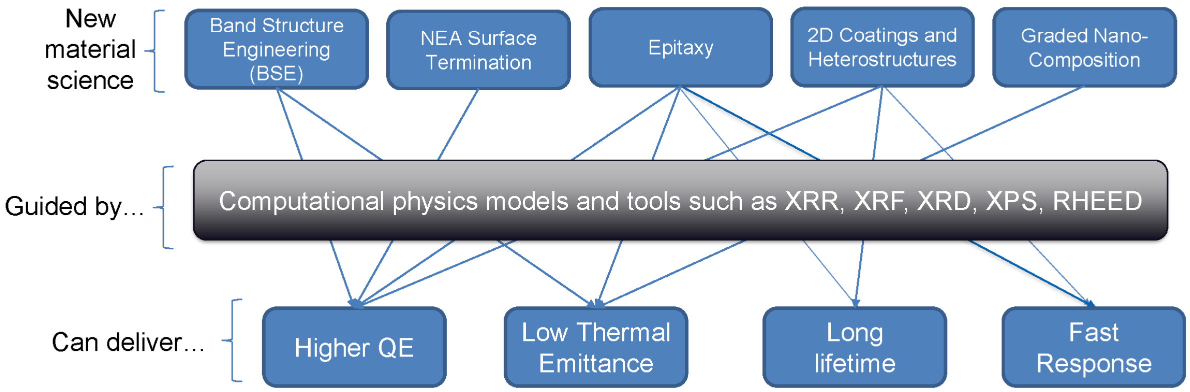
- Automated growth of photocathode films: from the basics of process control towards artificial intelligence
  - First implementation of automatic film growth process on Cs_3Sb
  - Positive first results
  - Extension to further materials (Cs_2Te)
  - Implementation of AI instead of standard feedback on ratio QEs



V. Pavlenko, P3 Workshop, November 2021

How to improve photocathode performances

New fabrication techniques are developed and applied to photocathodes motivated by theory and guided by real-time *in situ* x-ray analysis



- ***In Situ*** **or rapid feedback is required to optimize for material properties other than QE**
- **Modeling is needed to guide growth and understand properties**

J. Smedley, Snowmass2021 Electron Source Workshop, Feb 2022

One example: Sealab- bERLinPro

Thanks for your attention!

For an update on the most recent R&D in Europe,
you are invited to

EWPAA 2022: European Workshop on Photocathodes for Particle Accelerator Applications

in Milano, 20-22 September 2022.

http://agenda.infn.it/e/ewpaa2022

INFN

Trieste, Italy 22-26 August 2022

FEL2022

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