5th International Particle Accelerator Conference
June 15–20, 2014 – Dresden, Germany

Advances in Photocathodes for Accelerators

L. Cultrera, CLASSE - Cornell University

Outline

- **Photocathode requirements and materials:**
  - Quantum Efficiency, Thermal Emittance, Response Time, Lifetime
  - What is new in the field
- **New venues to discuss questions related to photocathodes:**
  - dedicated photocathode workshops
- **Recent results**
  - Metals
    - Plasmonic enhanced emission
    - CsAu
    - CsBr coating on Cu
    - Cs dispenser photocathode
  - Alkali antimonides extensively studied and characterized
  - Engineered structures
    - MBE of epitaxial multilayered structures MgO/Ag(001)
    - GaAs with undoped layer

Properties

$$B_n = \frac{2I}{\varepsilon_{n,x}\varepsilon_{n,y}}$$

- Quantum efficiency => Max achievable currents
- Response time => Temporal profile
- Thermal emittance => Min beam emittance
- Lifetime => Operation time

$$\varepsilon_{n,x} = \sqrt{\varepsilon_{th}{}^2 + \cancel{\varepsilon_{sc}{}^2 + \varepsilon_{trans}{}^2}}$$

The perfect photocathode does not exist yet!

The right choice of the material and operating condition is a tradeoff dependent on the application

Recent workshops

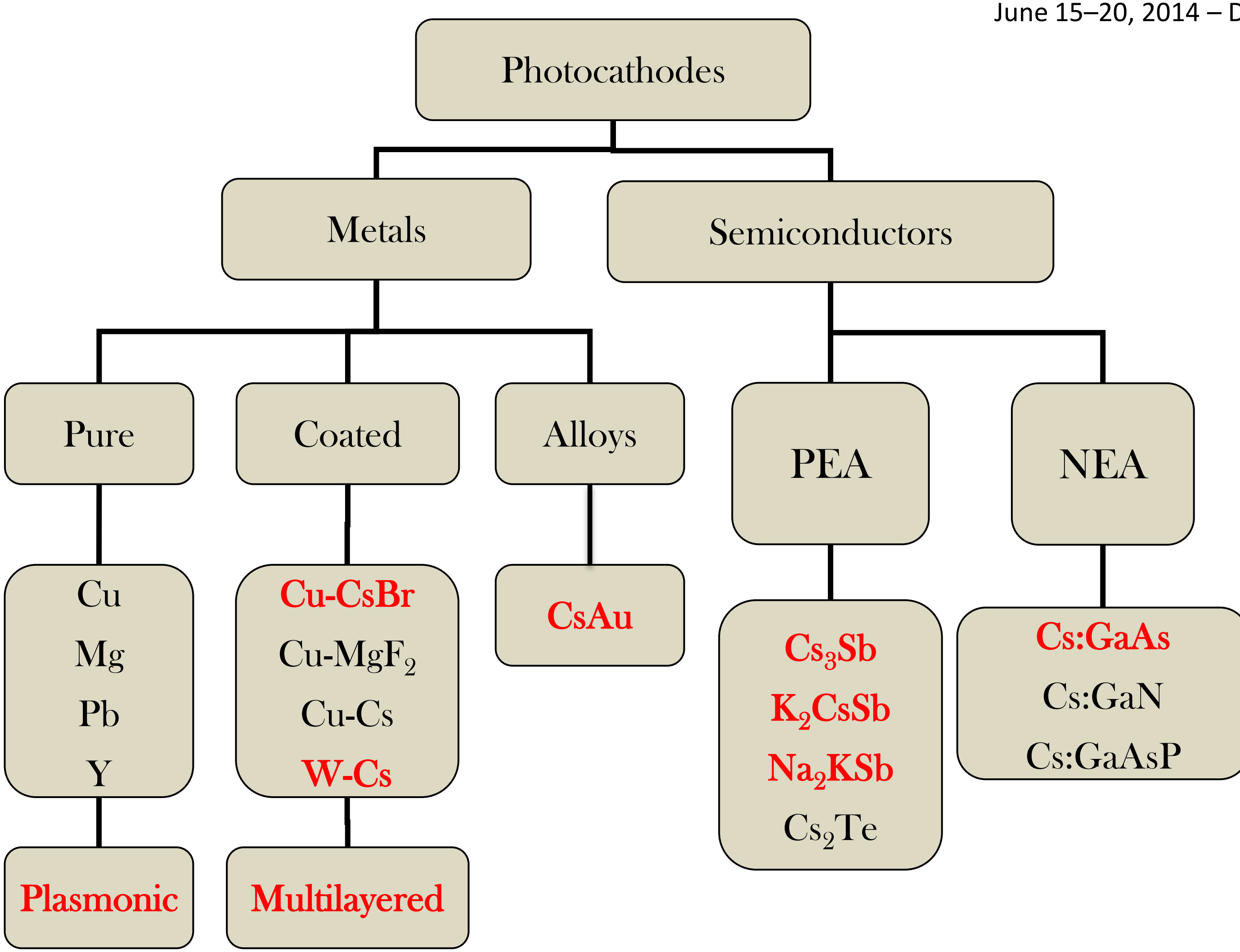
www.lns.cornell.edu/Events/Photocathode2012/

wwwlasa.mi.infn.it/WSPhotocathodes

www.bnl.gov/pppworkshop/

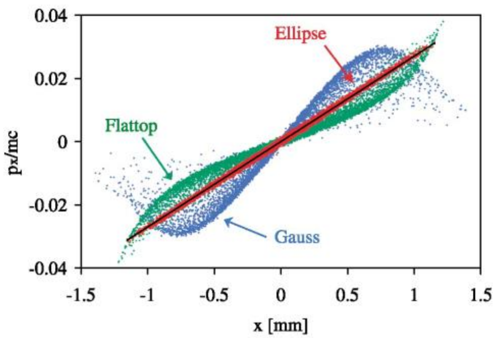
photocathodes2011.eurofel.eu/

Cathode Materials

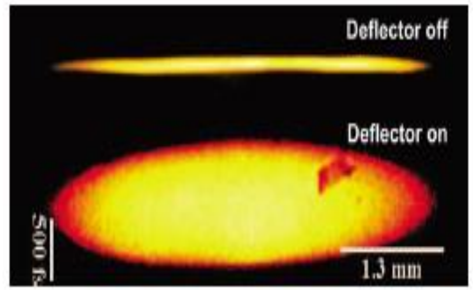


Plasmonic structures (1)

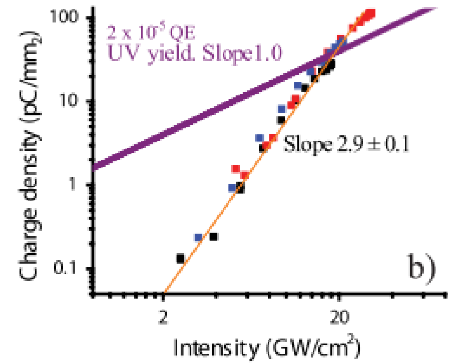
Generation of e-beam in “Blowout” regime is very convenient for RF gun operated at very low charge per bunch because reduced non linearities on the space charge forces



O. J. Luiten et al. , Phys. Rev. Lett. **93** , 094802 (2004)



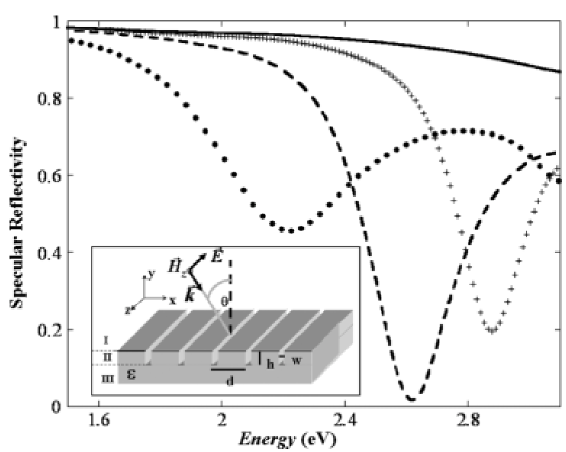
P. Musumeci et al. , Phys. Rev. Lett. **100**, 244801 (2010)



P. Musumeci et al. , Phys. Rev. Lett. **104**, 084801 (2010)

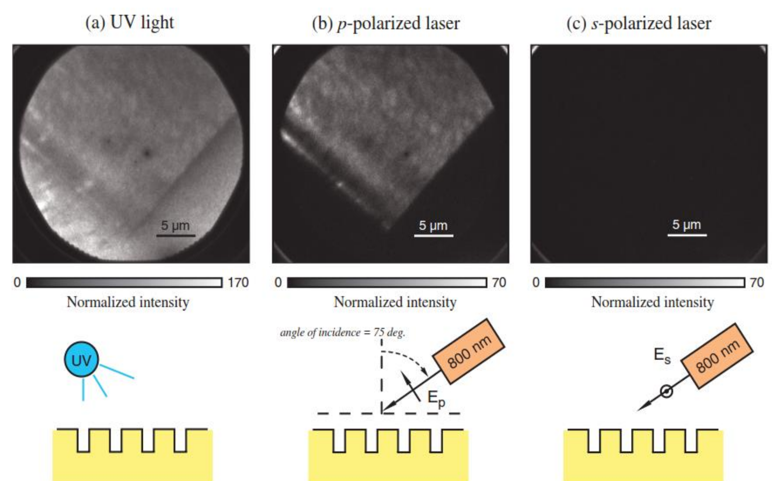
Cu reflectivity with MgF_2 antireflective coating @800 nm ~85%

Need to increase absorption!



J. L. Perchec et al. Phys. Rev. Lett. **100** , 066408 (2008)

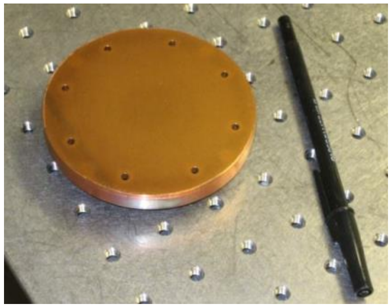
PEEM images of emission from plasmonic structures

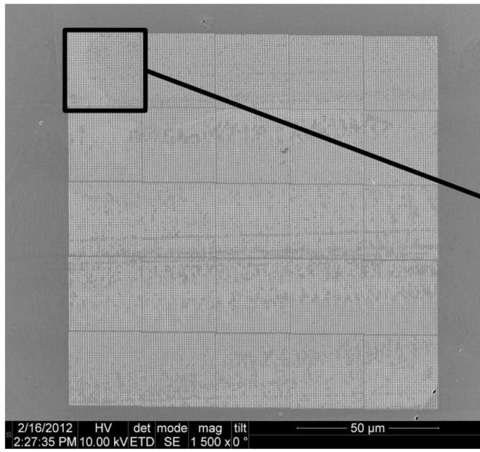


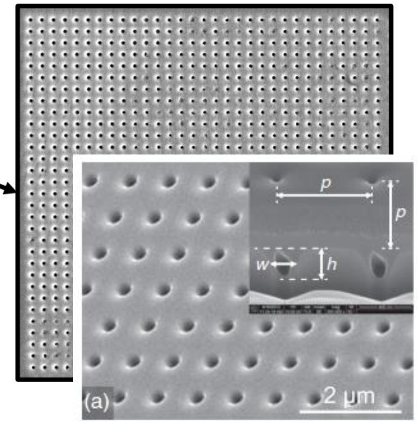
A. Polyakov et al. Phys. Rev. Lett. **110**, 076802 (2013)

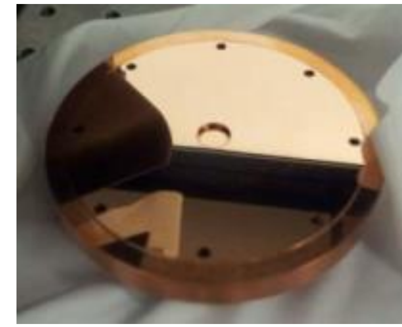
Plasmonic structures (2)

FIB has been used to generate a periodic pattern of nano holes on Copper surface

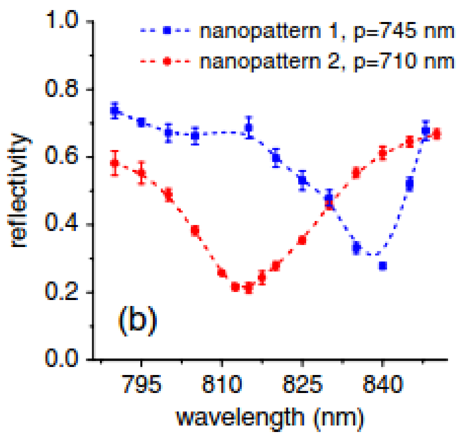


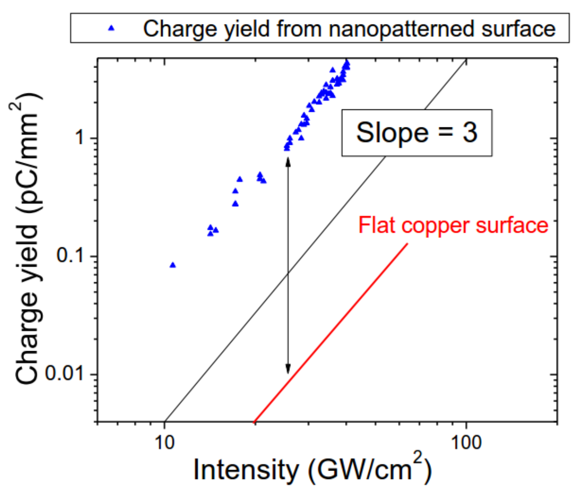






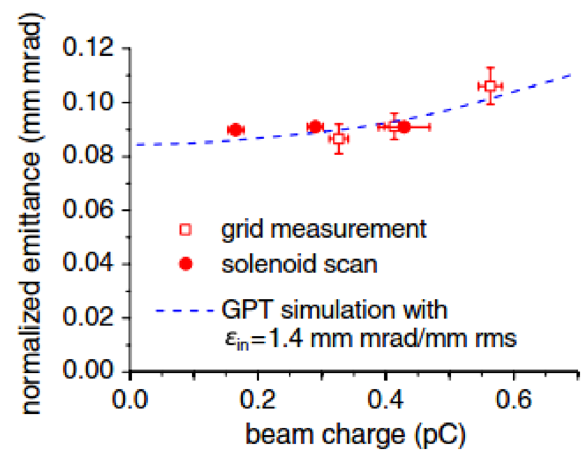
Tunable!





100x better QE!

Worse MTE !



R.K. Li, Phys. Rev. Lett. ***110****, 074801 (2013)*

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Coated Metals

IPAC14

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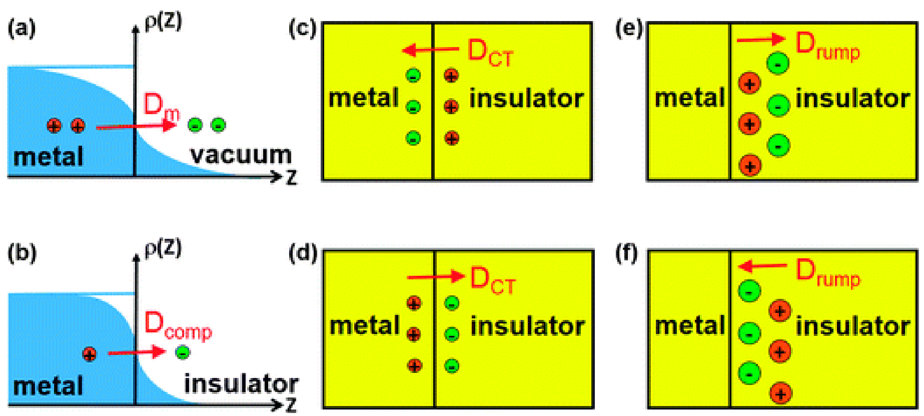
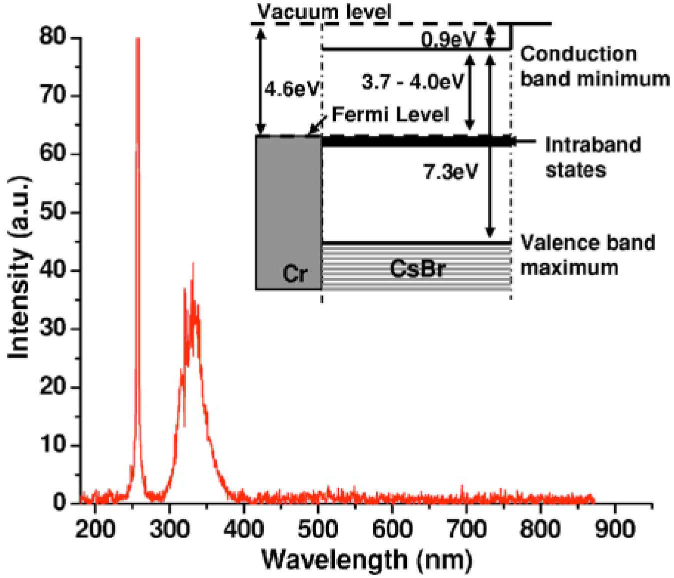
Possible way to enhance QE of metals:

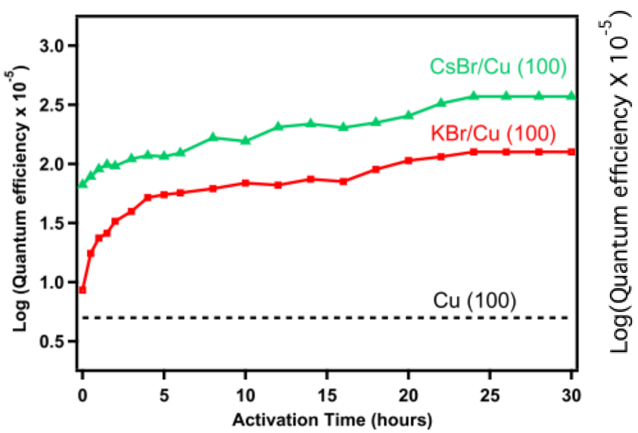
- Reduction of workfunction
- Emission from intra-band states of insulating coatings



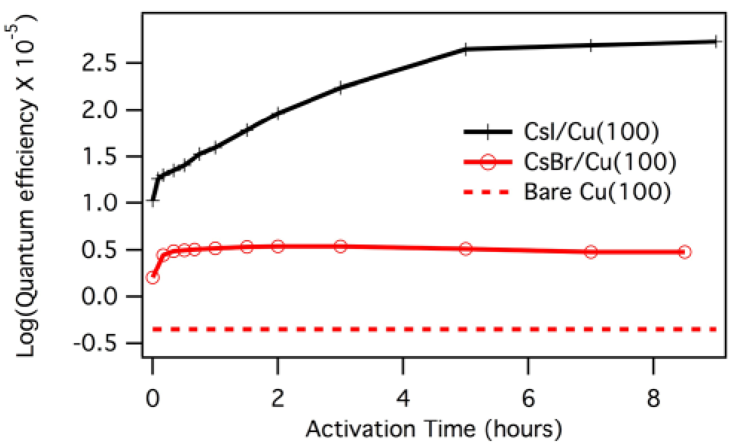
S. Ling et al, *Phys. Chem. Chem. Phys.* **15**, 19615 (2013)



Z. Liu et al., *Appl. Phys. Lett.* **89**, 111114 (2006)



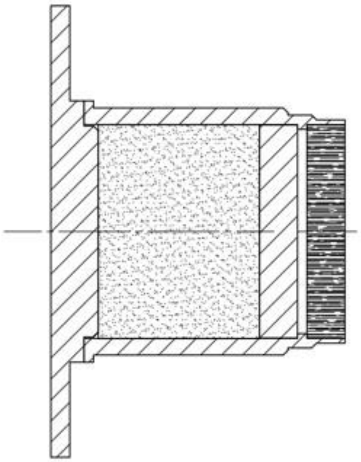
W. He et al, *Appl. Phys. Lett.* **102**, 071604 (2013)

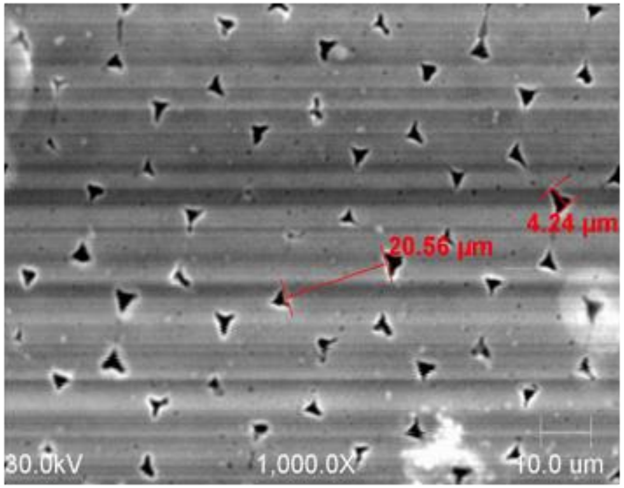


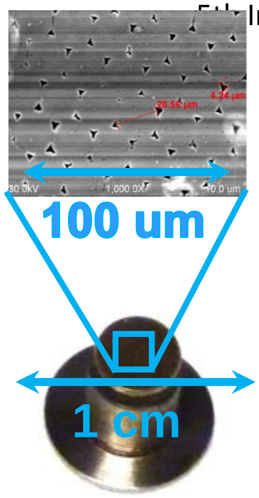
L. Kong et al., *Appl. Phys. Lett.* **104**, 171106 (201 4)

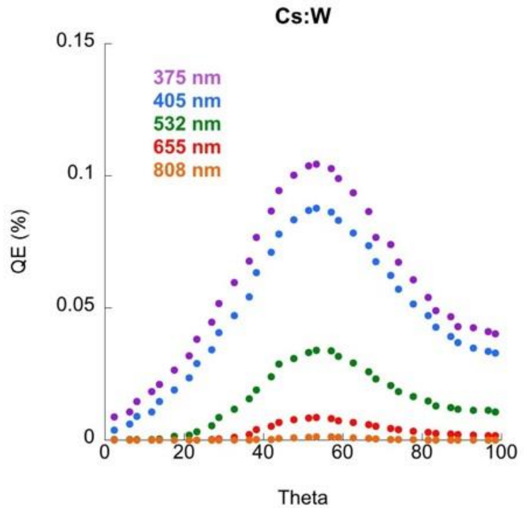
266 nm	KBr	CsBr	CsI
Film thick. (nm)	7	7	8
QE enh. b.a.	1.8	14	18
QE enh. a.a.	2.6	77	2700
WF b.a. (eV)	3.96	3.76	3.68
WF a.a. (eV)	3.66	3.41	1.74

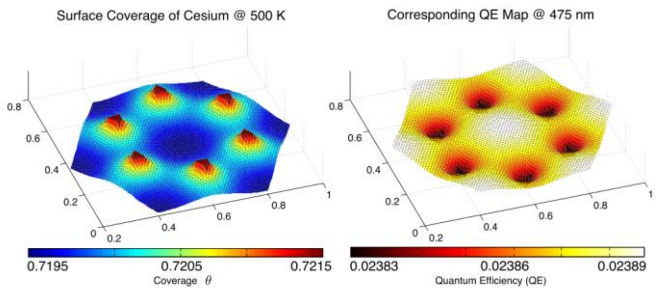
Cs dispenser CPR



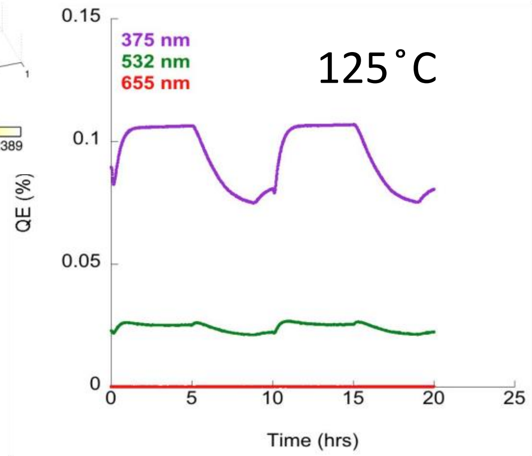








Estimated QE uniformity better than 1%

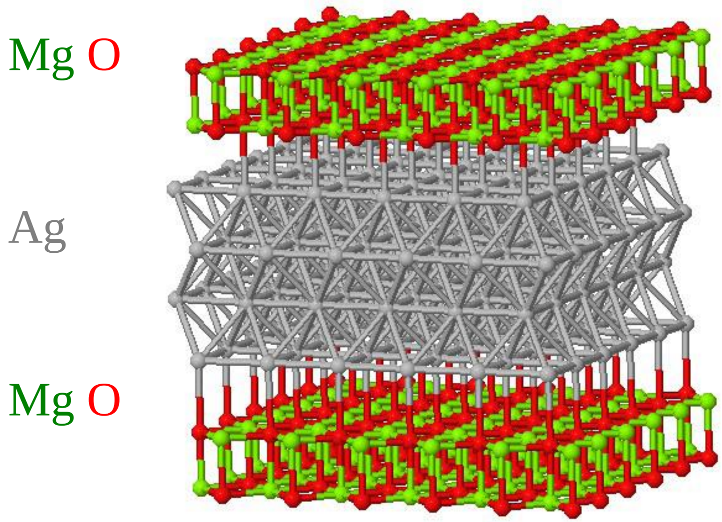


	125ºC
Cs emission ug / cm^2 / hr	0.023
Monolayers per hr	0.34
Conservative reservoir lifetime (hr)	31000

Z. Pan, *J. Appl. Phys.* **114**, 104906 (2013)

Multilayers (1)

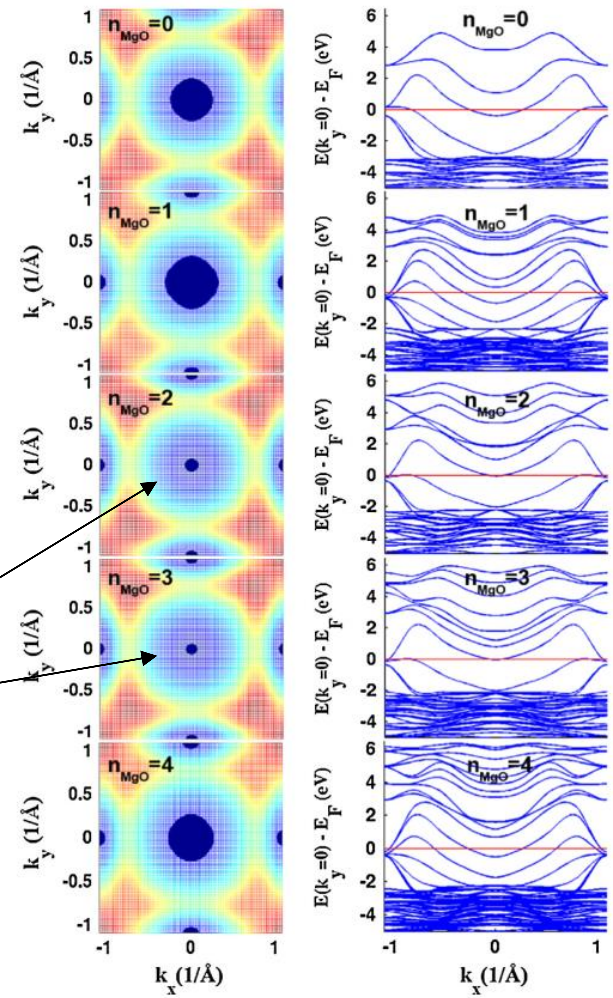
Limiting the emission to a single surface band making k_{max} as small as possible



The transverse intrinsic emittance is a function of the number of MgO layers;

Minimum at n_{MgO} =2,3 with ε_{th} =0.06mm mrad

Maximum sensitivity to n_{MgO} can be achieved with thin Ag (<<8ML) and MgO on both top and bottom surfaces (work function greatly reduces from ~4.6 eV to 2.92eV due to the MgO overlayers)



K. Németh et.al, Phys. Rev. Lett. ***104****, 046801 (2010)*

Multilayers (2)

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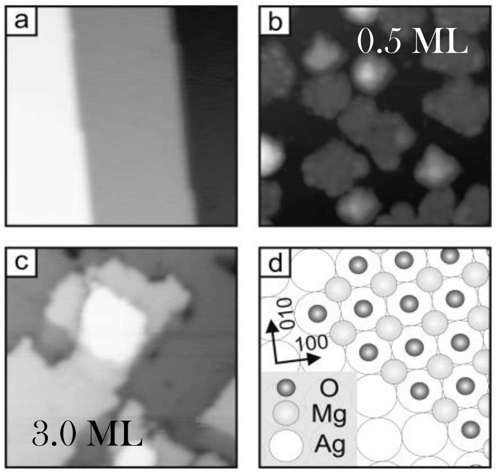
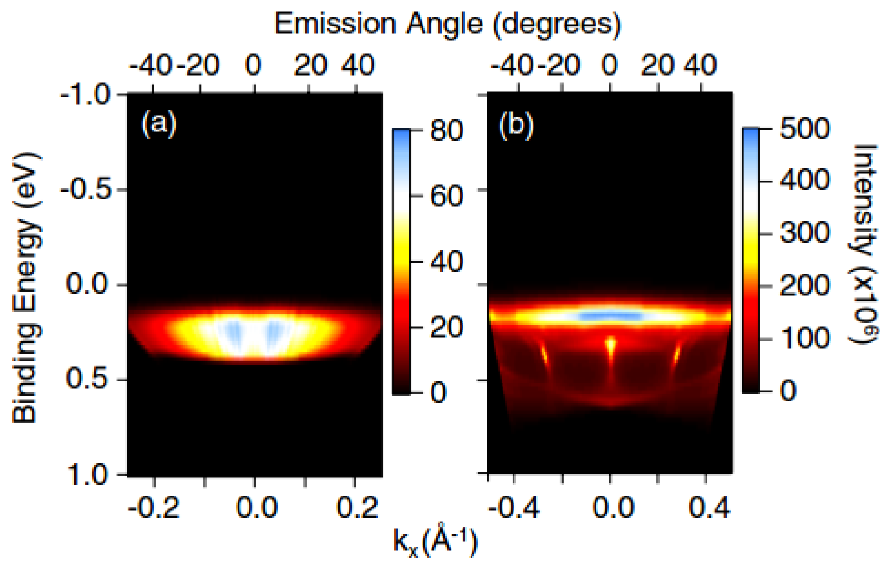
STM of thermal evaporated MgO on Ag(001)

20x20 nm^2 50x50 nm^2

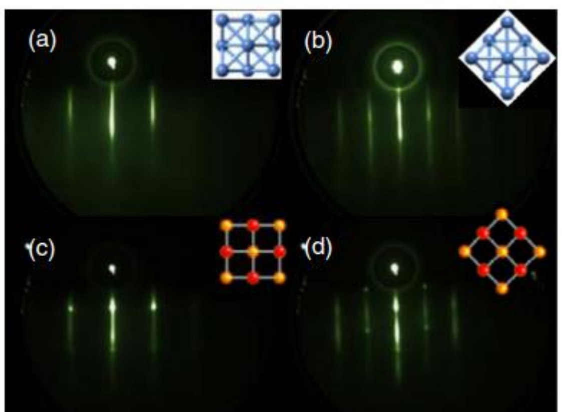


30x30 nm^2 1.5x1.5 nm^2

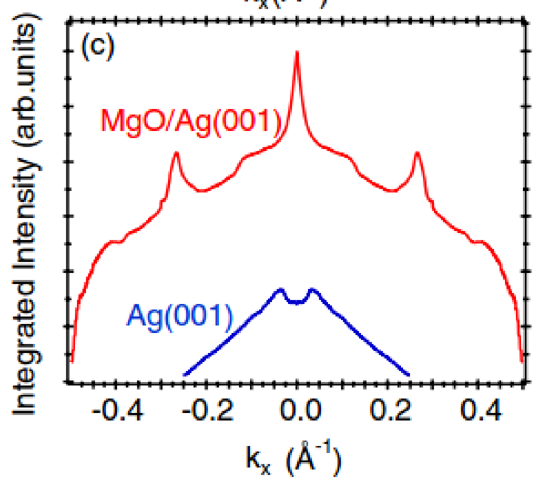


UV ARPES used to study emission properties and band structure

4 ML MBE grown MgO



RHEED indicate a non perfect layer by layer growth



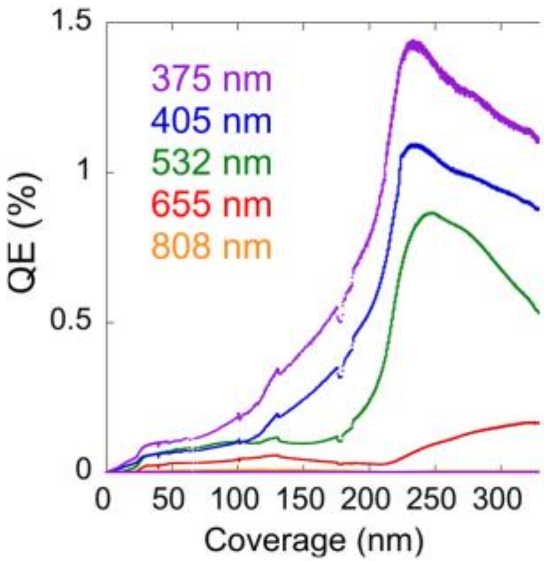
266 nm	Ag(001)	4ML MgO
QE	5×10^{-5}	3.5×10^{-4}
ε_{th} ($\mu m/mm$)	0.42	0.97

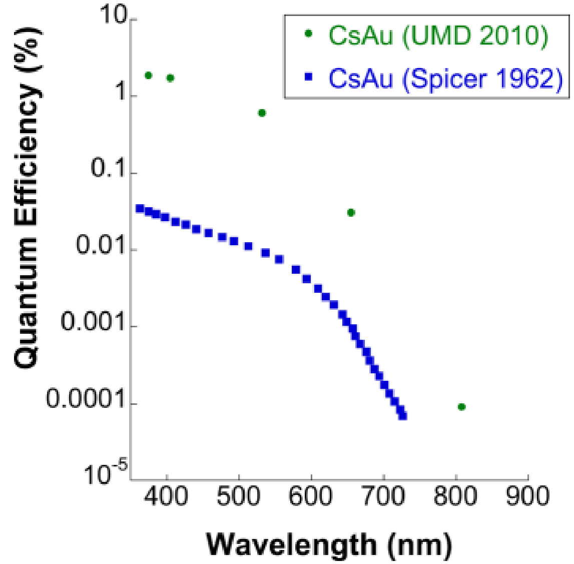
Timothy C. Droubay, Phys. Rev. Lett. ***112****, 067601 (2014)*

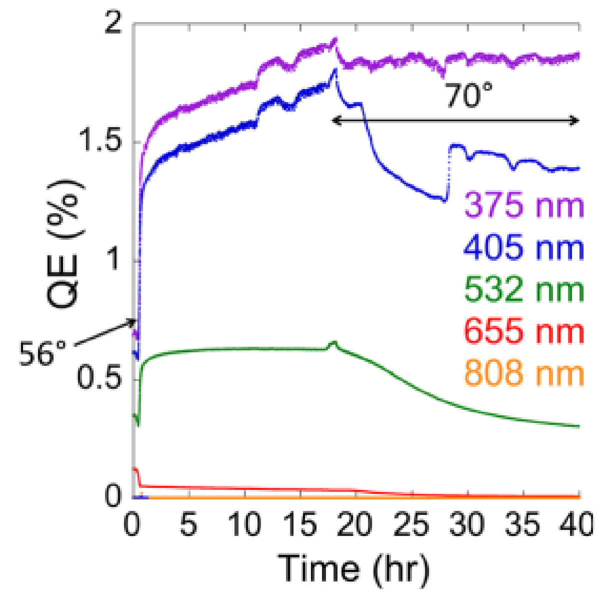
CsAu

As was to be expected, the alloys of the Au*M* type are photo-electrically sensitive, but the sensitivity is too low to be of practical importance. An

A. Sommer, Nature **152**, 215 (1943)



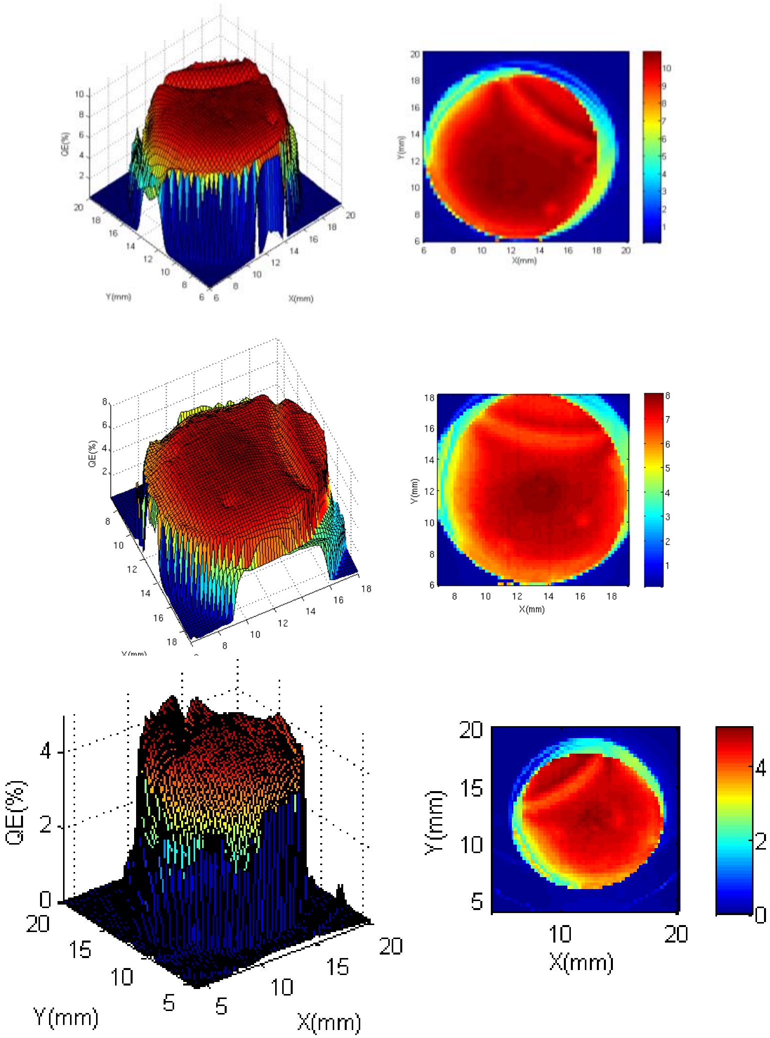




- These results **reopen** the question of AuM semiconductors
- QEs in the range of few % can be achieved in the visible
- Lifetime properties at room and moderate temperature are encouraging
- MTE, Response Time yet to be characterized

S. A. Khan, *J. Vac. Sci. Tech B* 30, 031207 (2012)

Alklai antimonides promise of high QE and long lifetime



QE map on 03 Feb 2012 ~10%

QE map on 03 Apr 2012 ~8%

QE map on 02 Oct 2012 ~5%

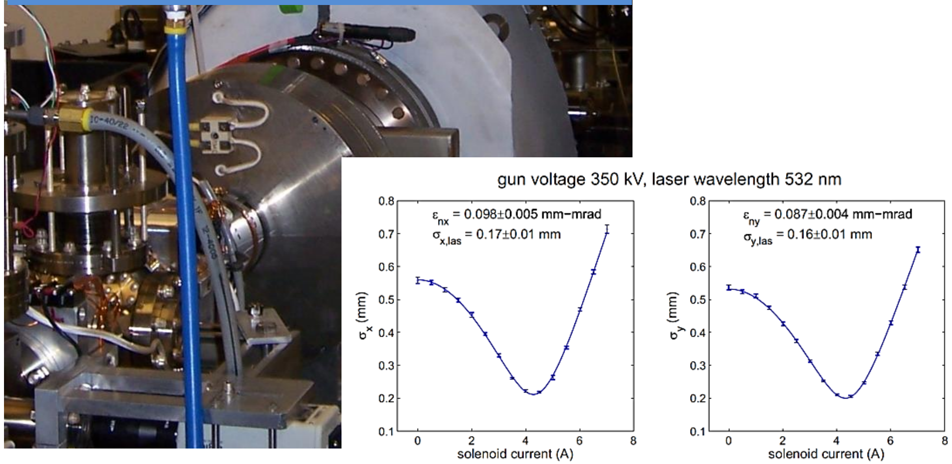
QE 1/e lifetime ~13 months

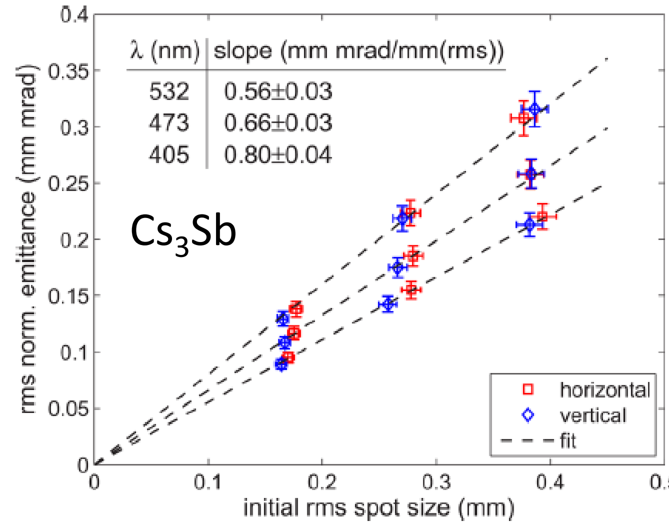
Non continuous low current (<mA) operation

Antimonides MTEs

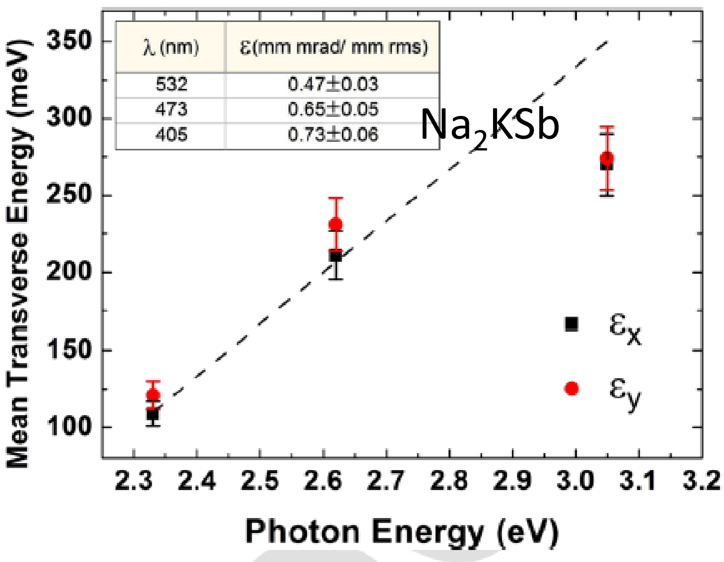
onference
, Germany

Measured in HV DC gun using solenoid scan

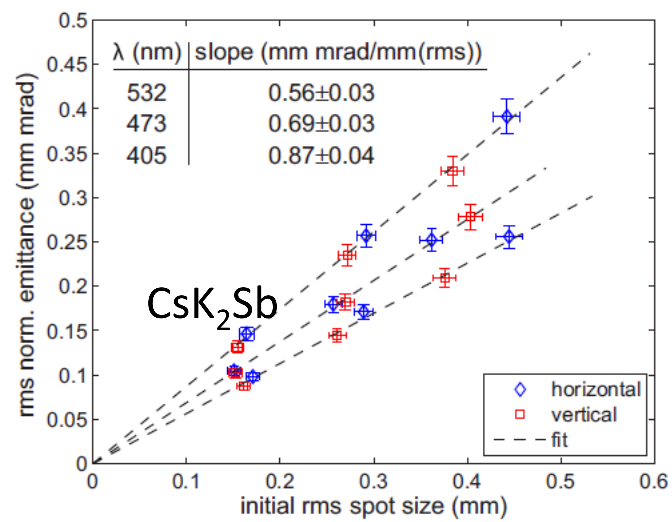




L. Cultrera et al., *Appl. Phys. Lett.* 99 (2011) 152110



L. Cultrera et al., *Appl. Phys. Lett.* 103 (2013) 103504



I. Bazarov et al., *Appl. Phys. Lett.* 98 (2011) 224101

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High current lifetime

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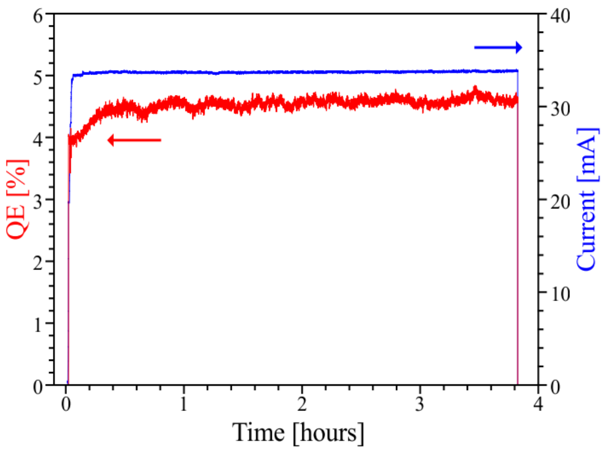
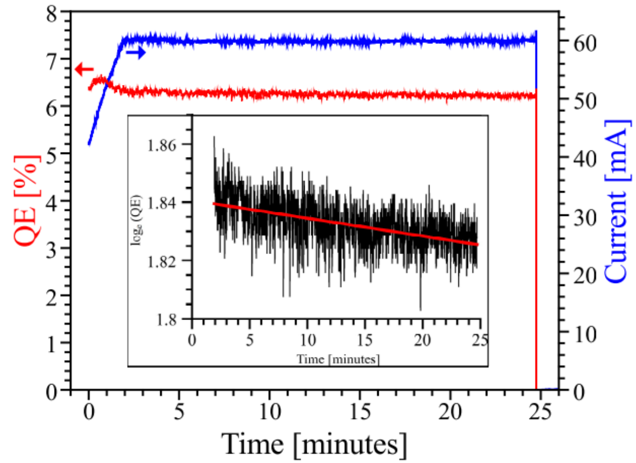
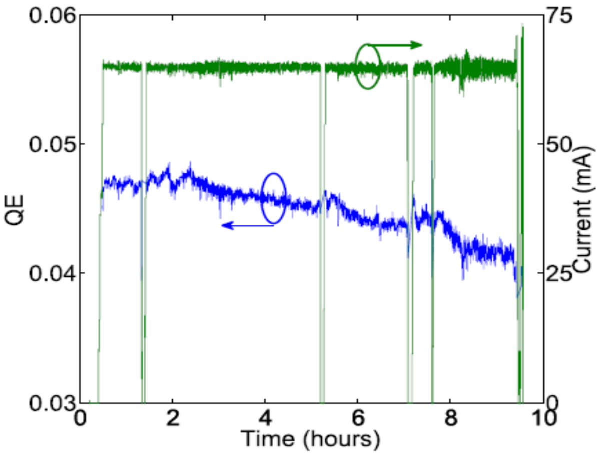






Cs_3Sb
QE @ 520 nm 4%
Max AVG current **33 mA**
Lifetime >> 500 C
NO QE DECAY

Cs_2KSb
QE @ 520 nm 6.5%
Max AVG current **60 mA**
Lifetime >> 2000 C
1/e QE 30 hr

Na_2KSb
QE @ 520 nm 4.5%
Max AVG current **65 mA**
Lifetime >> 2000 C
1/e QE 66 hr

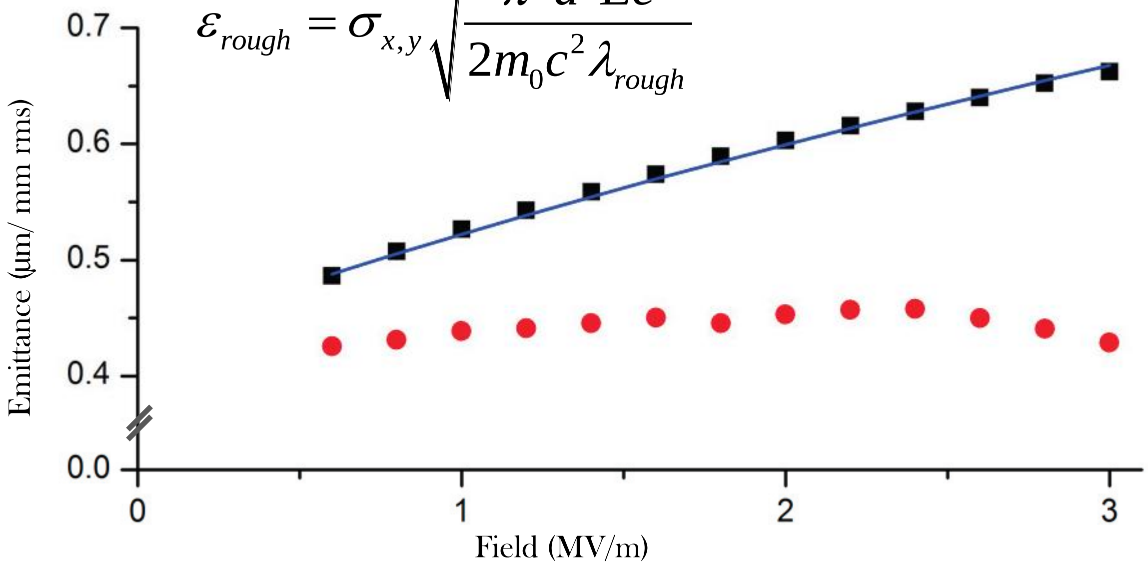
Alklai antimonide based photocathode have been extensively tested in DC gun of the ERL injector prototype at Cornell University. MTEs, response time, QEs and lifetimes at high current are **compatible with the operation of an ERL user facility.**

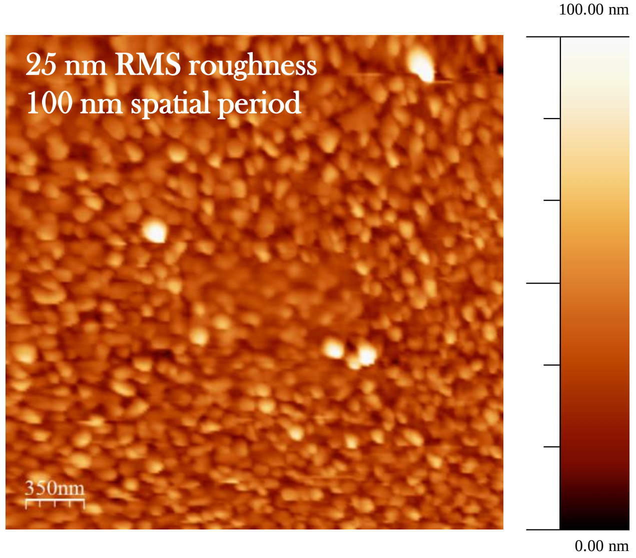
B. Dunham et al., *Appl. Phys. Lett.* 102 (2013) 034105

L. Cultrera et al., *Appl. Phys. Lett.* 103 (2013) 103504

Roughness and emittance

$$\varepsilon_{rough} = \sigma_{x,y}\sqrt{\frac{\pi^2 a^2 Ee}{2m_0c^2\lambda_{rough}}}$$





Films grown at high rate give expected emittance (very low field dependence)

Films grown in a multilayered manner were shown to give higher QE but showed marked emittance growth with field

Can be explained by invoking a simple roughness model.

Fitting gave reasonable roughness parameters, confirmed by in vacuum AFM

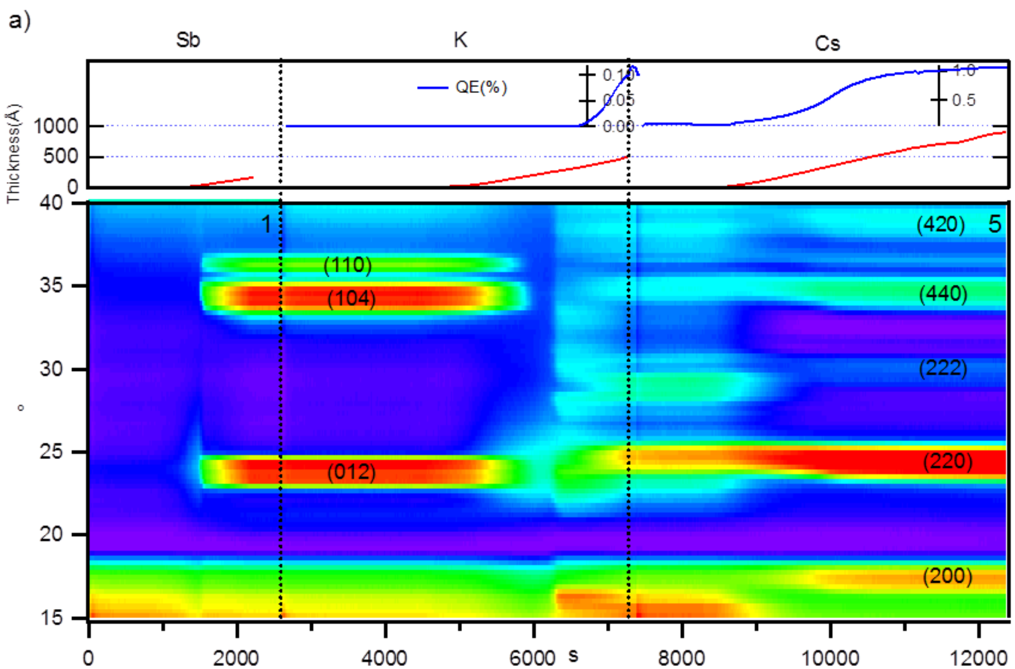
Roughness in high gradient guns looks to be an issue based on current in-situ measurements of cathode surfaces

T. Vecchione et al., Proceedings of IPAC2012, 655 (2012)

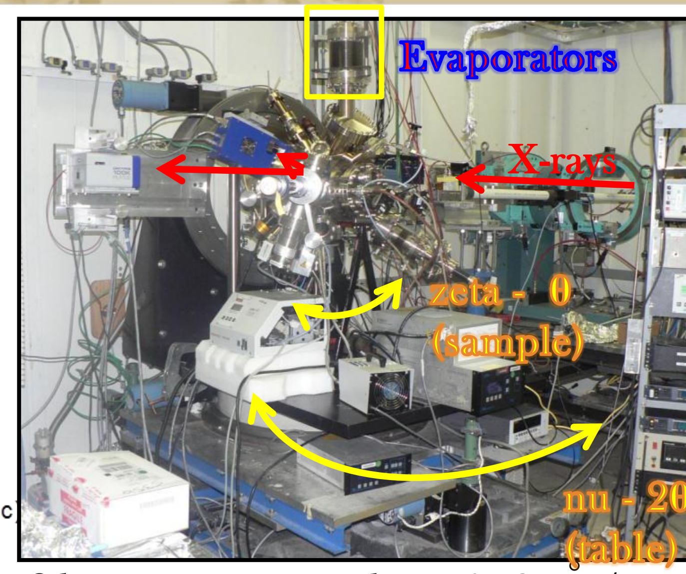
S. G. Schubert et al., *APL Mater.* **1**, 032119 (2013)

Reaction Dynamics

4 axis diffractometer UHV chamber
NSLS & CHESS compatible
XRD and GISAXS during growth
High resolution XRD and XRR
between growth steps
XRD gives reaction chemistry
GISAXS and XRR give roughness



c)



Sb evaporated at 0.2 Å/s
- Room temp,
- Crystallize at 4nm

K deposition dissolves Sb layer
- Film goes amphorus

QE increase corresponds with
- K_3Sb crystallization

Cs increases lattice constant and
- reduces defects

J. Smedley et al., Proceedings of IPAC2013, 464 (2013)

New recipes and sources

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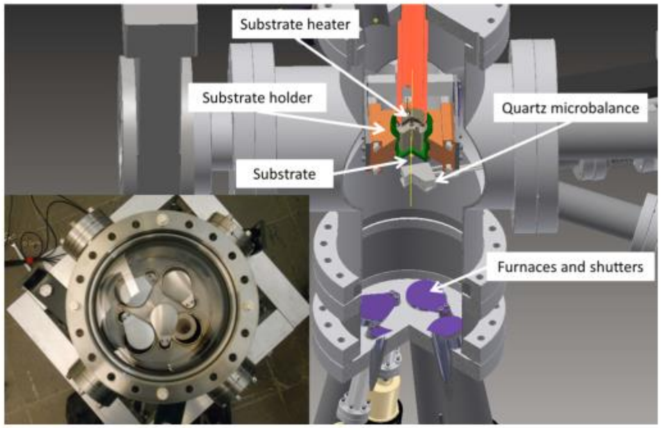
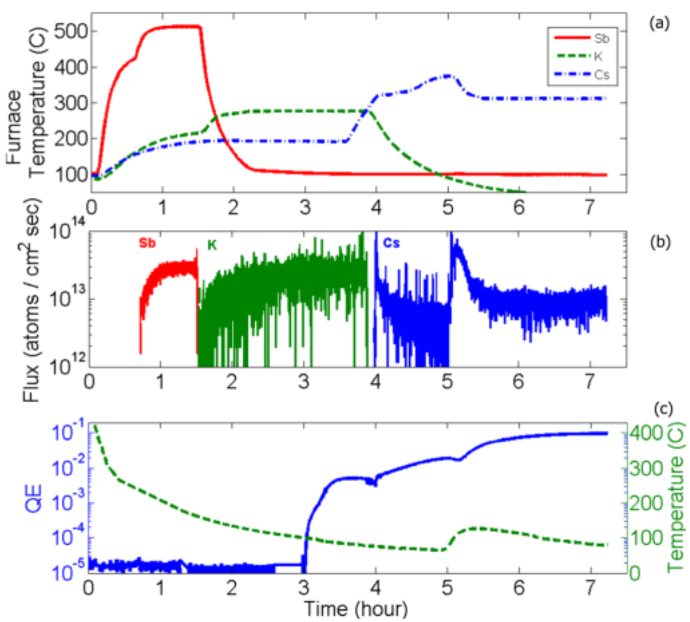
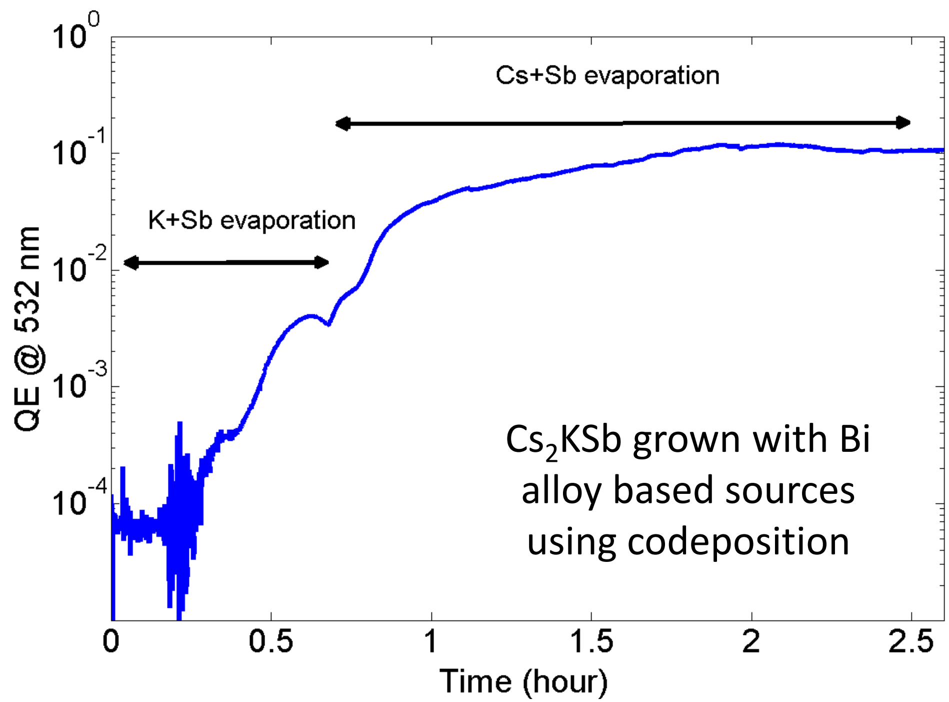


Alkali Azide (AN_3)

Pure alkali metal





Cs_2KSb grown with Bi alloy based sources using codeposition

L. Cultrera et al., J. Vac. Sci. Tech. B **32**, 031211 (2014)

MTE and Temperature

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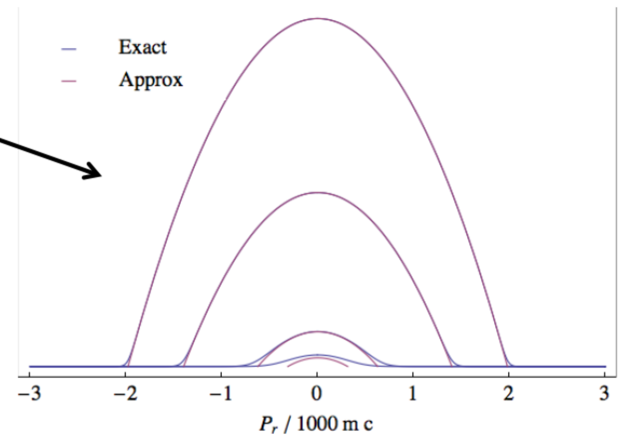
Theoretical Transverse Emittance, Free Electron Model

Radial Momentum Distribution

$$dJ = \frac{ekT}{4\pi^3\hbar^3} Log\left[1 + Exp\left[\frac{\hbar\omega - \phi}{kT} - \frac{p_r^2}{2mkT}\right]\right] p_r dp_r d\theta$$

Approx: $dJ \approx \frac{e}{4\pi^3\hbar^3}\left(\hbar\omega - \phi - \frac{p_r^2}{2m}\right) p_r dp_r d\theta$

Transverse Momentum Distribution

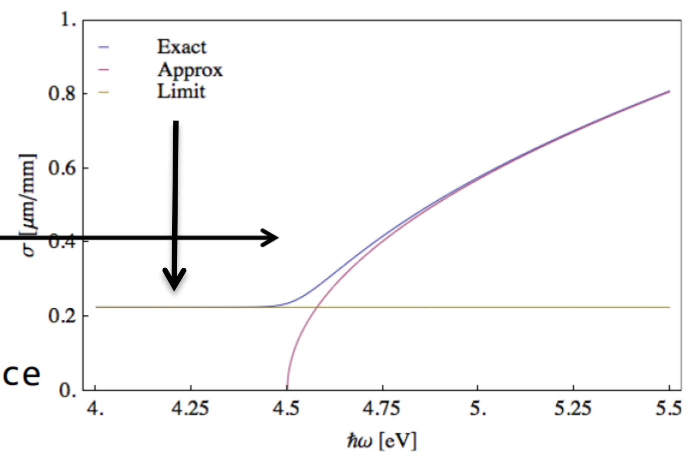


RMS Radial Momentum

$$P_{r,rms} = \sqrt{\frac{\frac{ekT}{4\pi^3\hbar^3}\int_0^\infty \int_0^{2\pi} Log\left[1 + Exp\left[\frac{\hbar\omega - \varphi}{kT} - \frac{p_r^2}{2mkT}\right]\right] p_r^3 d\theta\, dp_r}{\frac{ekT}{4\pi^3\hbar^3}\int_0^\infty \int_0^{2\pi} Log\left[1 + Exp\left[\frac{\hbar\omega - \varphi}{kT} - \frac{p_r^2}{2mkT}\right]\right] p_r d\theta\, dp_r}}$$

$$P_{r,rms} = \sqrt{2mkT}\sqrt{\frac{Li_3\left[-Exp\left[\frac{\hbar\omega - \varphi}{kT}\right]\right]}{Li_2\left[-Exp\left[\frac{\hbar\omega - \varphi}{kT}\right]\right]}}$$

Transverse Emittance



Normalized Emittance Definition

$$\sigma_x = \left(\frac{1}{mc}\right)\sqrt{\langle P_x^2\rangle - \langle P_x\rangle^2}$$

$$\sigma_{x,rms} = \left(\frac{1000}{\sqrt{2}}\right)\frac{P_{r,rms}}{mc}$$

$$\sigma_{x,rms} = 1000\sqrt{\frac{kT}{mc^2}}\sqrt{\frac{Li_3\left[-Exp\left[\frac{\hbar\omega - \phi}{kT}\right]\right]}{Li_2\left[-Exp\left[\frac{\hbar\omega - \phi}{kT}\right]\right]}}$$

Approx: $\sigma_{x,rms} \approx 1000\sqrt{\frac{kT}{mc^2}}$ Thermionic Emittance

$\sigma_{x,rms} \approx 1000\sqrt{\frac{\hbar\omega - \phi}{3mc^2}}$ Dowell Emittance

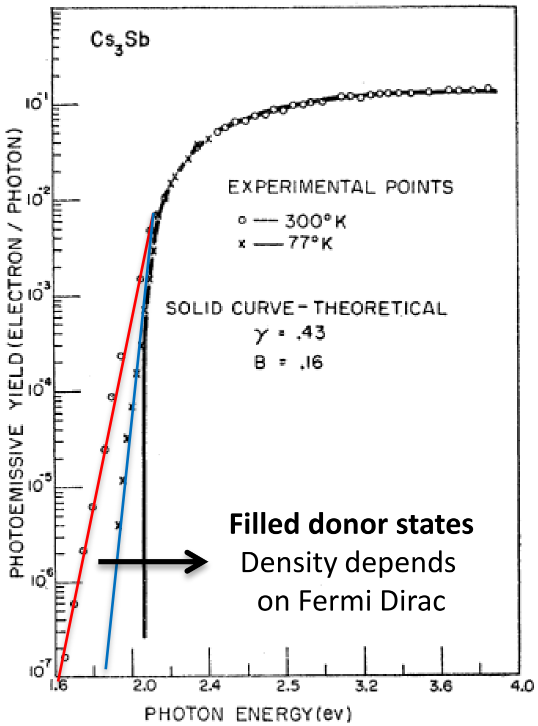
T. Vecchione et al., Proceedings of FEL2013, 424 (2013)

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

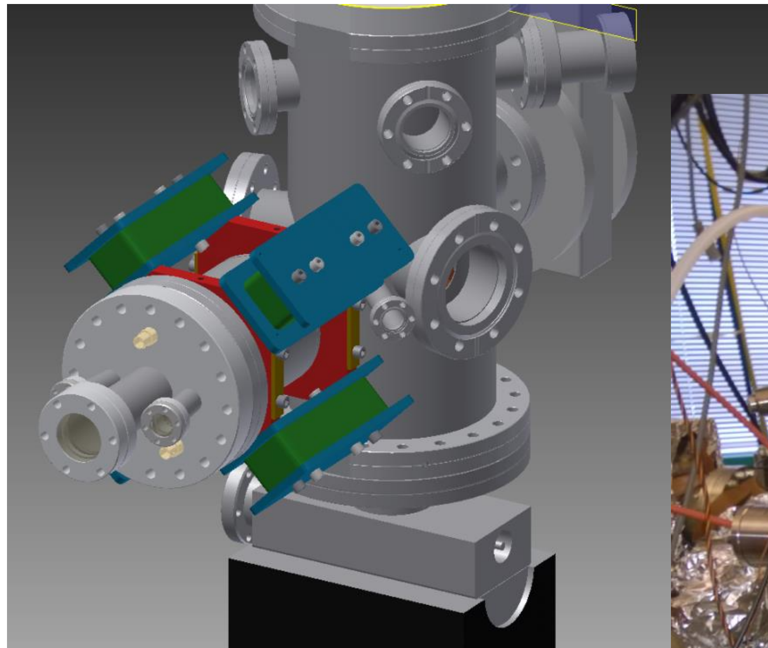
Cold beam generation (1)

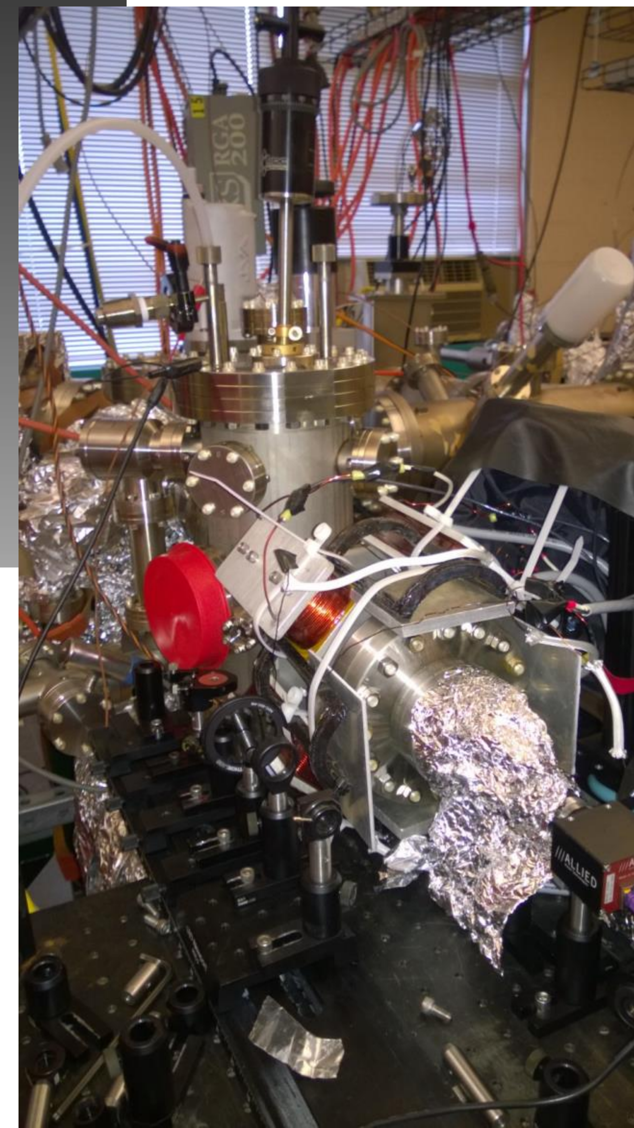
IPAC14

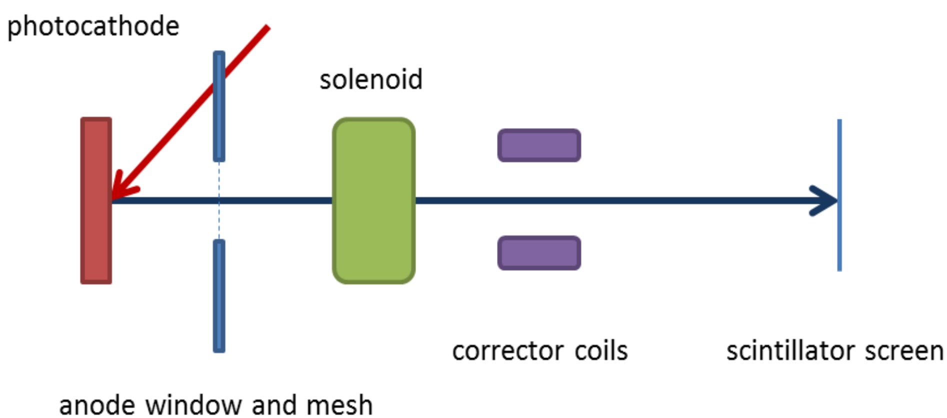
5th International Particle Accelerator Conference
June 15–20, 2014 – Dresden, Germany



W.E. Spicer, *Phys. Rev.* **112**, 114 (1958)

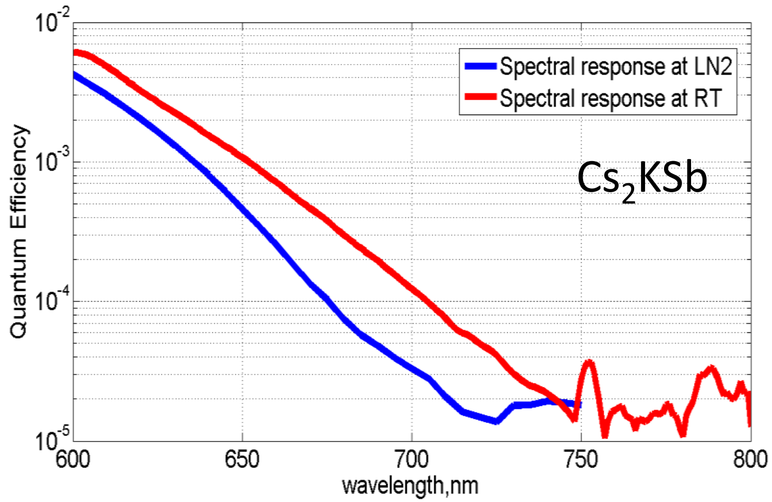


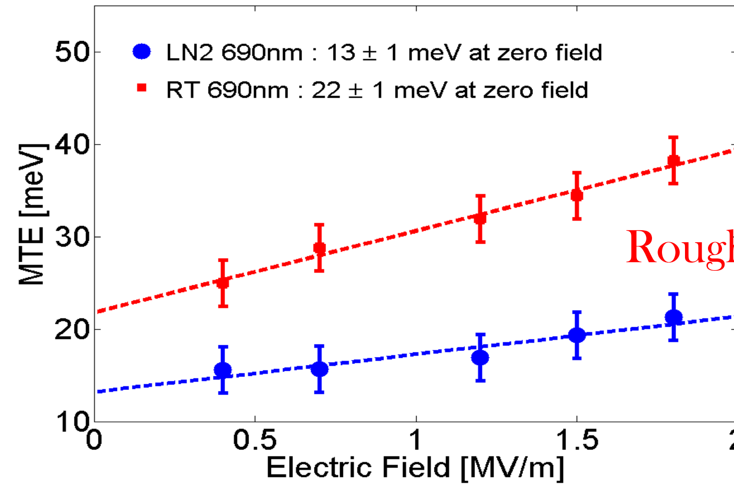




Cold beam generation (2)

ference
ermany





Roughness?

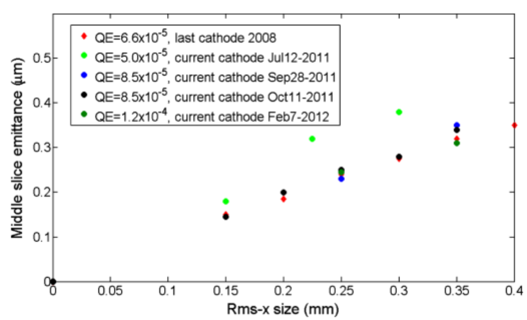
690 nm	300 K	90 K
QE	$2x10^{-4}$	$5x10^{-5}$
MTEs (meV)	22 (25)	13 (9)
ε (μm/mm)	0.21 (0.22)	0.16 (0.13)

Sub-thermal electron beam generation with a "standard" bialklai photocathode

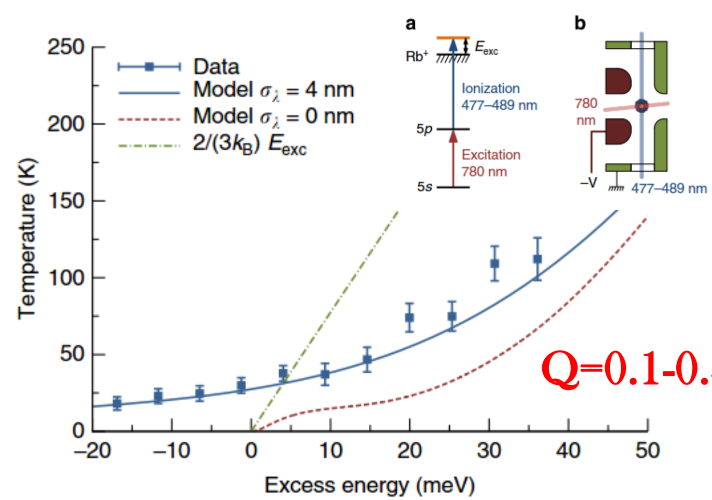
L. Cultrera et al., *Phys. Rev. Lett. , submitted*

Comparison with LCLS Cu cathode and MOT

Drive Laser Wavelenght 253 nm
QE $1x10^{-4}$
MTE (meV) 413
ε (μm/mm) 0.9



F. Zhou, *Phys. Rev. Spec. Top.-Accel. Beams* **15**, 090703 (2012)

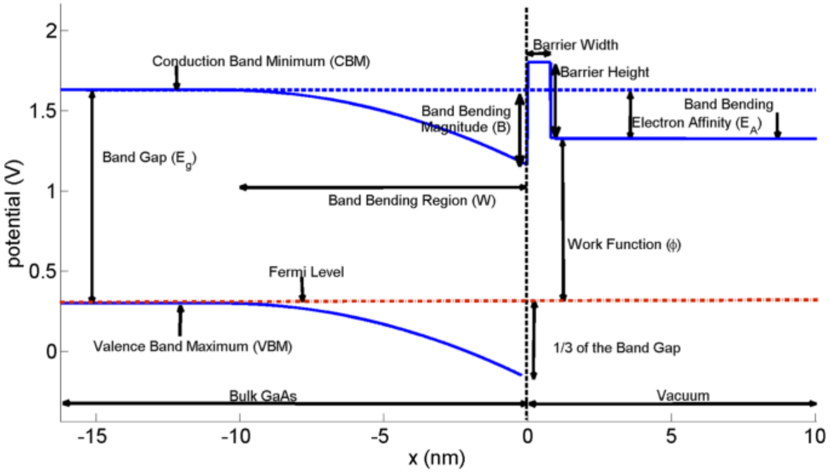


Q=0.1-0.4 fC

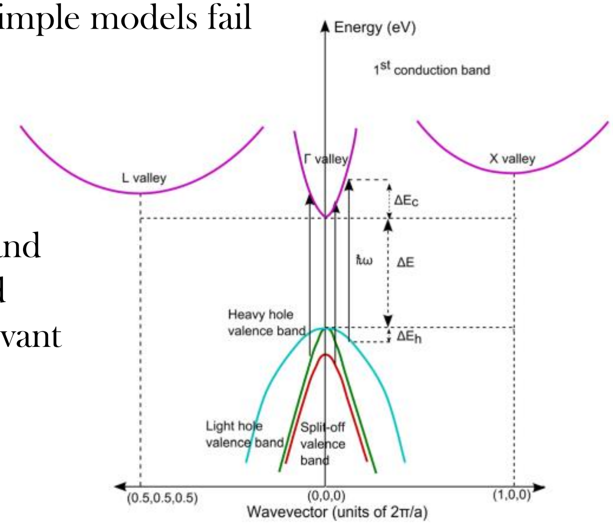
W. J. Engelen et al., *Nature Communications* **4**, 1693 (2013)

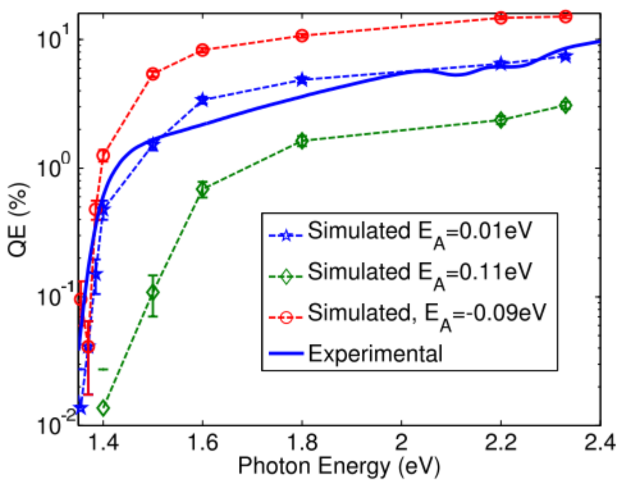
GaAs Montecarlo

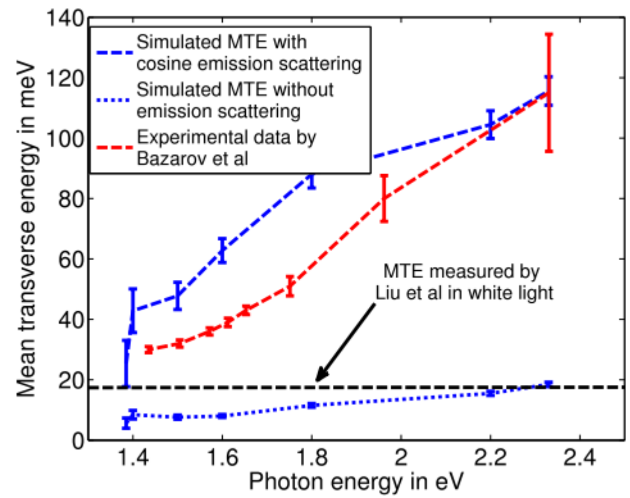
Need to better understand the physics to explain the experimental results where simple models fail



Excitation, relaxation and transport are simulated considering all the relevant physical processes





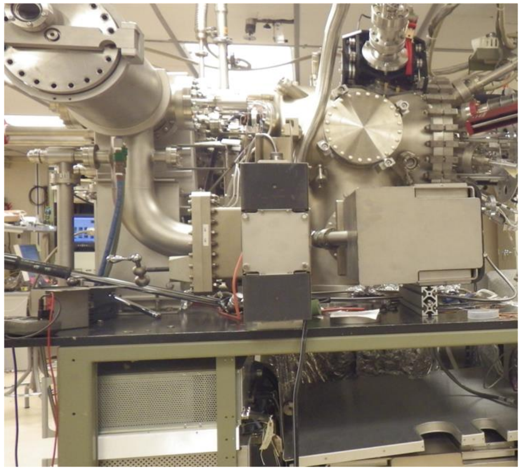


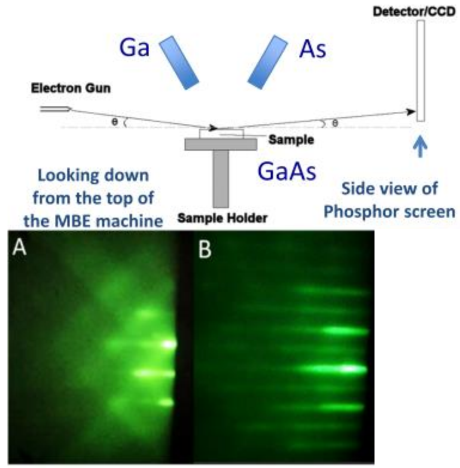
The only free parameter is the *electron affinity*

S. Karkare et al., J. Appl. Phys. **113**, 104904 (2013)

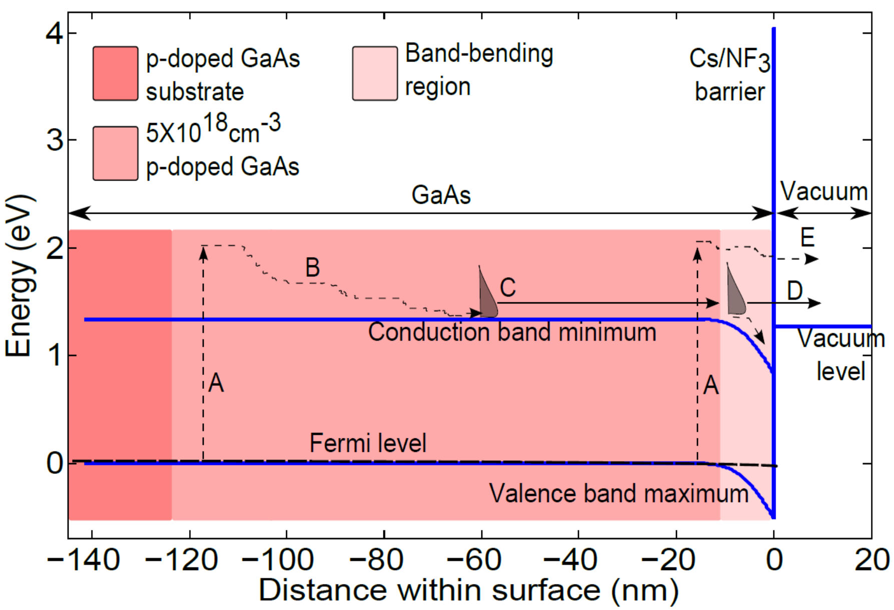
GaAs MBE (1)

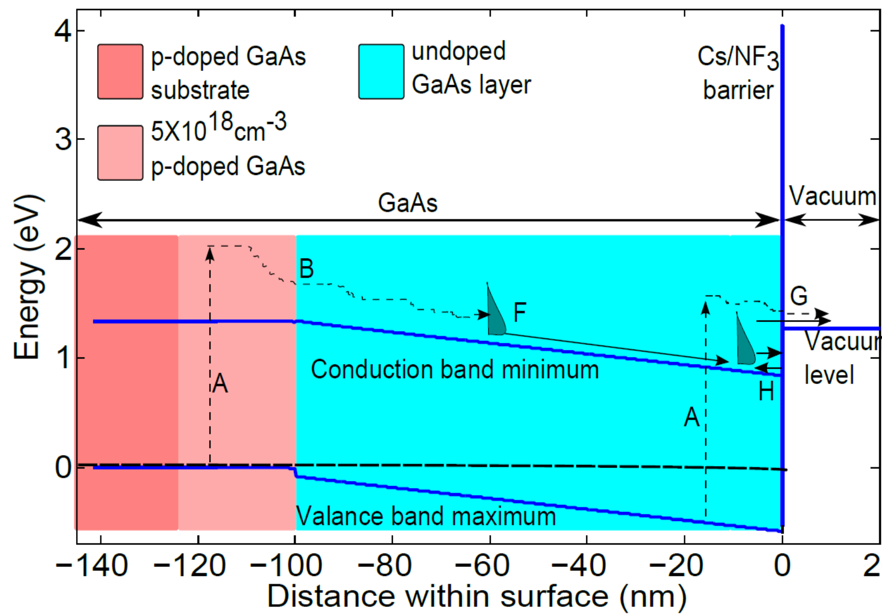
5th International Particle Accelerator Conference
June 15–20, 2014 – Dresden, Germany





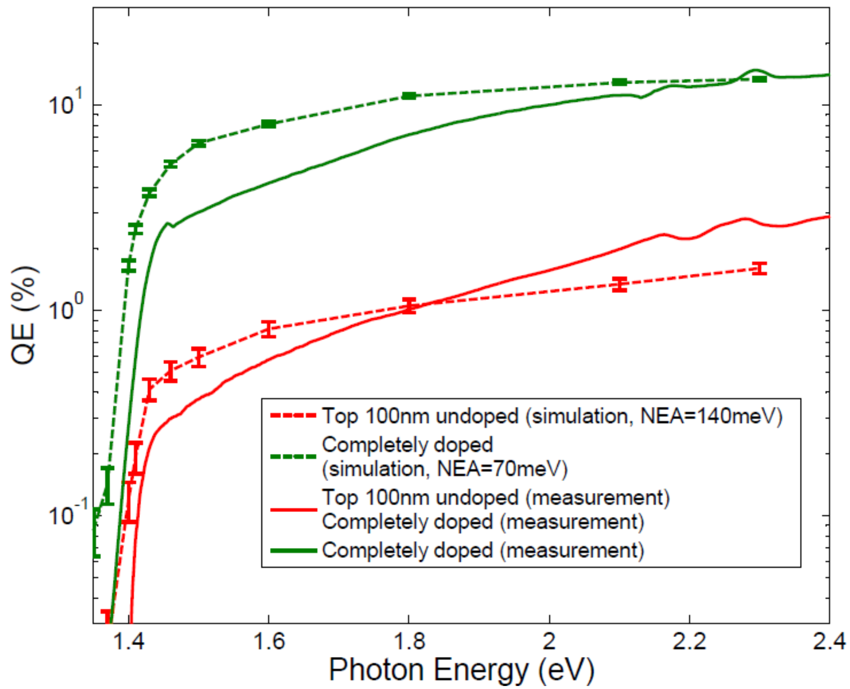
- MBE: ultimate tool for photocathodes
  - Atomically flat GaAs photocathodes with customized doping
  - Routinely used in photoinjector for smallest emittance
- Now “engineering” new types of MBE photocathode structures





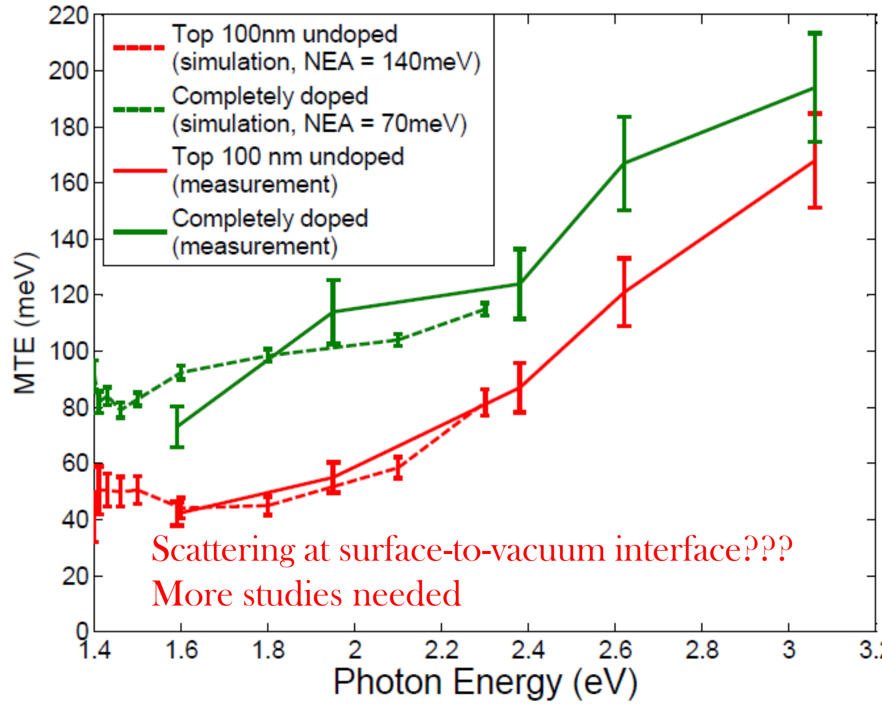
S. Karkare et al., Phys. Rev. Lett. ***112*** *(2014) 097601*

GaAs MBE (2)



MBE samples with As cap to prevent contamination and preserve surface flatness

- Control sample $5x10^{18}$ cm^{-3} doping
- Test sample with 100 nm intrinsic layer



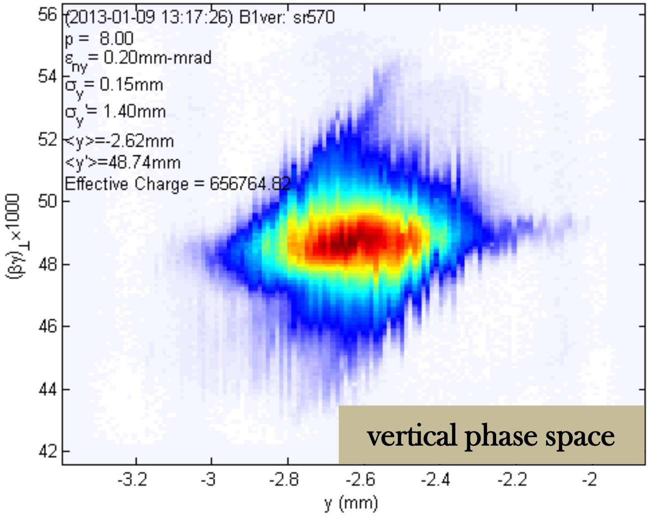
The sample with intrinsic layer shows as expected a smaller QE and MTE.

QE @532 nm is still on the range of few %

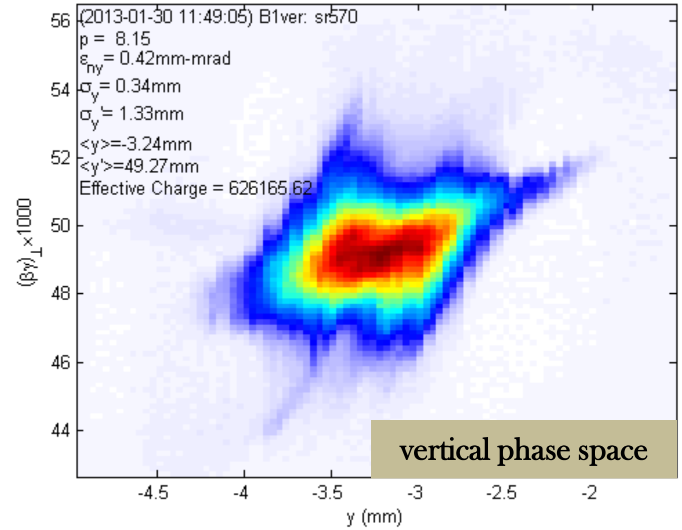
S. Karkare et al., Phys. Rev. Lett. ***112*** *(2014) 097601*

Improved beam brightness

20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps rms

20 pC/bunch	80 pC/bunch
0.22/0.15 mm-mrad	0.49/0.29 mm-mrad

Normalized rms core emittance (horizontal/vertical) @ core fraction (%)

20 pC/bunch	80 pC/bunch
0.14/0.09 mm-mrad @ 68%	0.24/0.18 mm-mrad @ 61%

20x the brightness at 5 GeV of the best storage ring (1nm-rad hor. emittance 100 mA)!
Similar to the best NCRF guns emittance but with > 10^6 repetition rate (duty factor = 1)

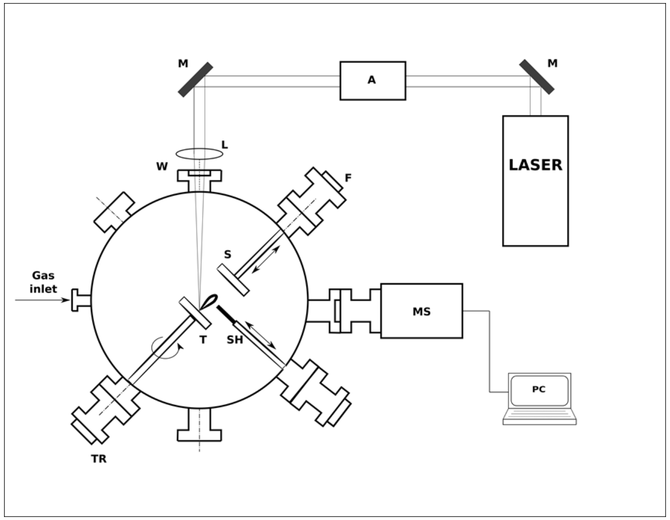
C. Gulliford, *Phys. Rev. Spec. Top.-Accel. Beams* 16 (2013) 073401

Conclusions

- Lots of new results during last 3 years
  - Sub thermal emittance
  - World record average current
  - Improved beam brightness
  - Better understanding of growth dynamics
  - DFT and Montecarlo applied to photoemission
  - New materials and new structures

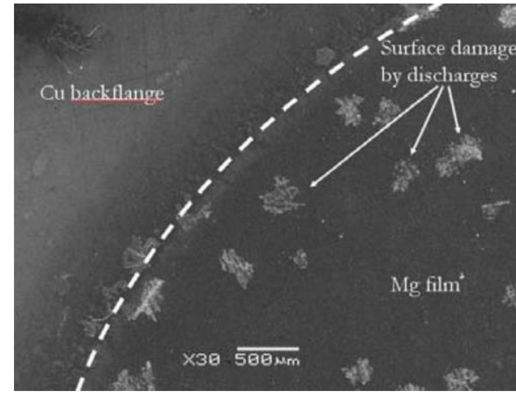
Thank you!

PLD metal film



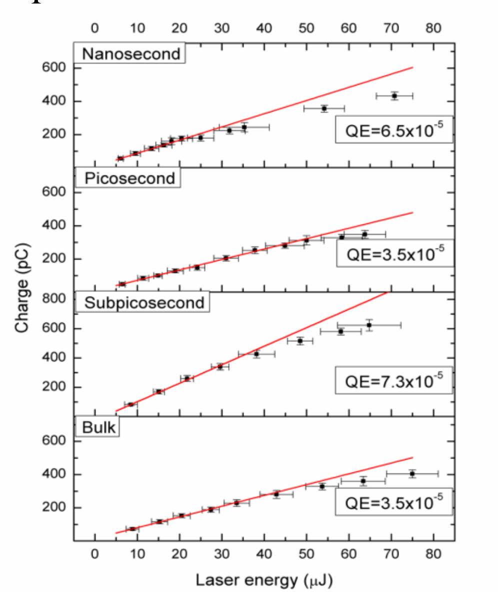
Successful RF testing of Mg on Cu

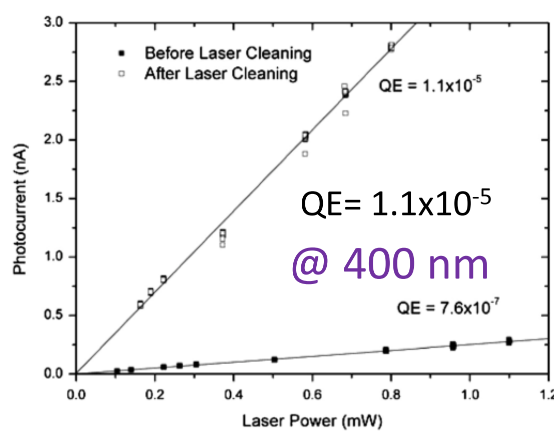
*L. Cultrera et al., Phys. Rev. ST Accel. Beams **12**, 043502 (2009)*



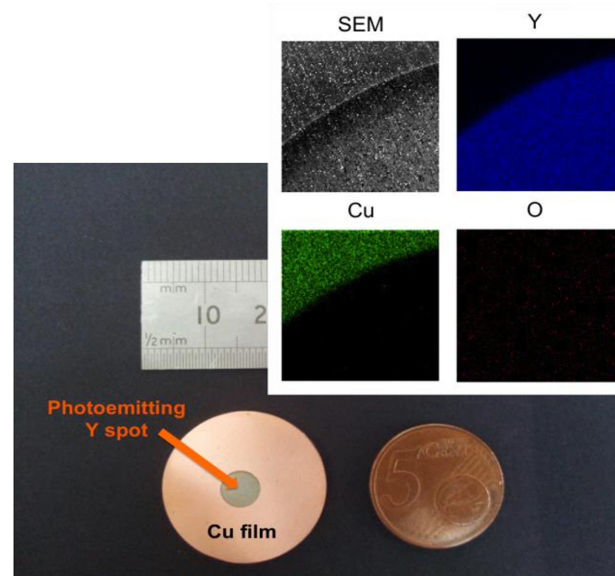
Extensive exploration of growth parameters space have been performed for Mg, Y and Pb

Deposition of Pb on Nb for SRF gun





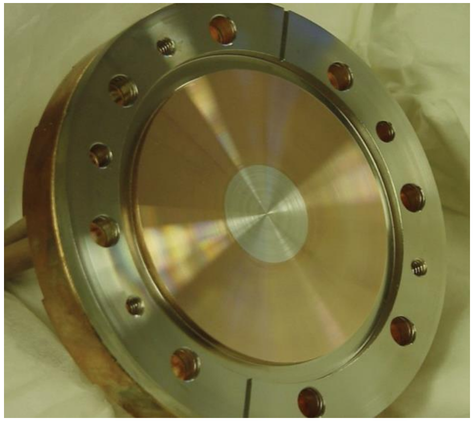
*F. Gontad and A. Perrone, NIMA **747** 1 (2014)*

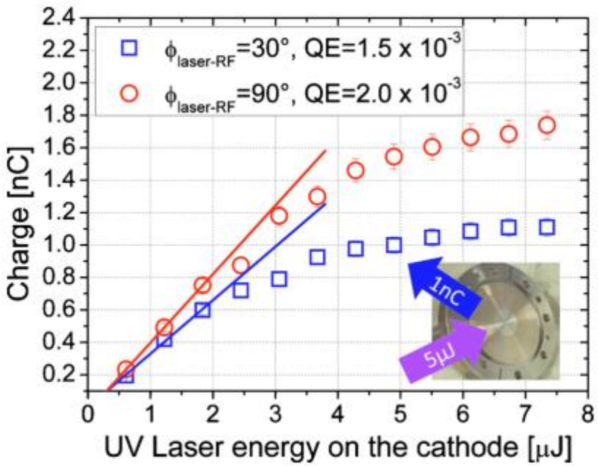


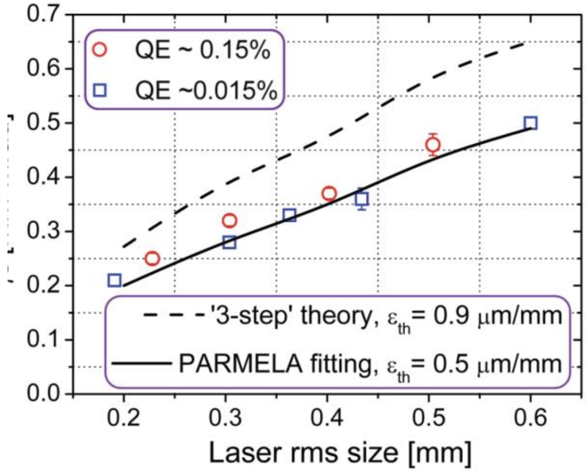
*A. Lorusso et al., Phys. Rev. ST Accel. Beams **12**, 043502 (2009)*

Metals – bulk Mg

5th International Particle Accelerator Conference
June 15–20, 2014 – Dresden, Germany





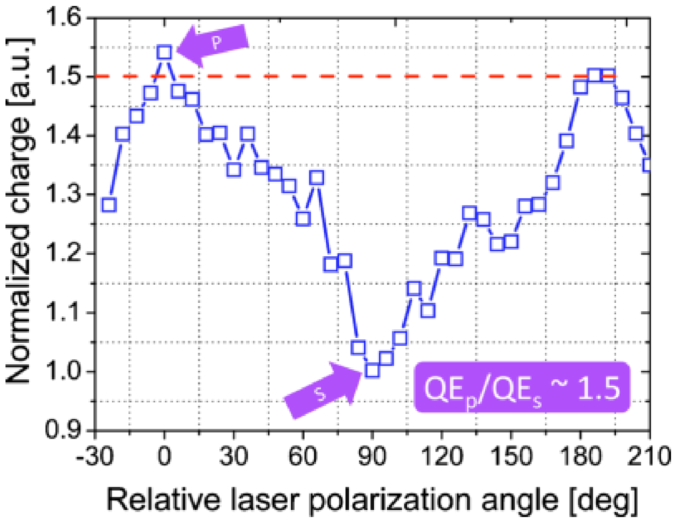


UV photons needed (hν>3.6 eV)

Laser cleaning procedure

QE is higher compared to Cu

ε_{th} is smaller than predicted



QEp/Qes under this condition was reported to be 5 for a flat surface film:

- *Plasmon enhancement* due to residual roughness after cleaning?

Mg bulk is a reliable alternative to Cu!

H. J. Qian, Appl. Phys. Lett. **97**, 253504 (2010)