Summary of the 2nd PPP Workshop

Photocathode Physics for Photoinjectors (P3) Workshop

Cornell University (October, 2012)

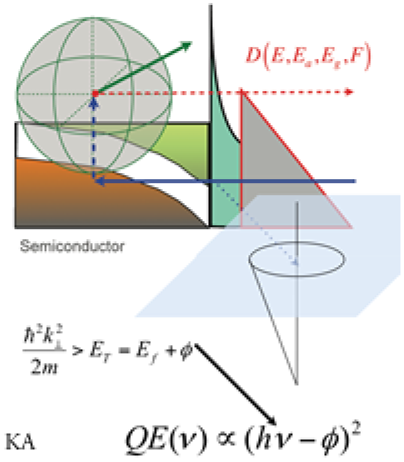
http://edms.classe.cornell.edu/agenda/conferenceOtherViews.py?view=standard&confId=15

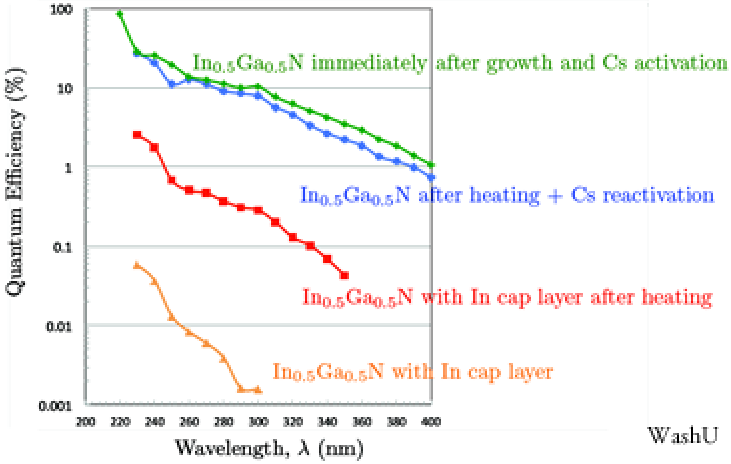
Major Developments

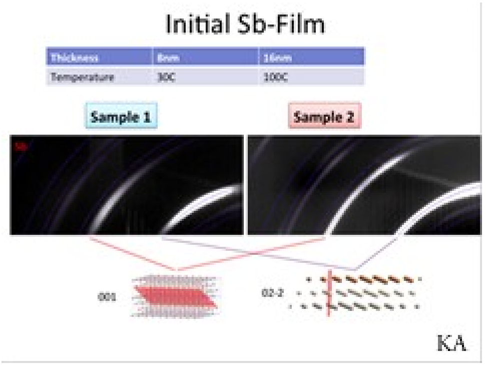
- This was a very interesting Workshop = 40 talks + discussions in 5 sessions:
  - Session 1: Workshop Welcome, Reviews
  - Session 2: New significant developments and relevant measurements
  - Session 3: Photocathode physics I: new insights in theory and modeling
  - Session 4: Photocathode physics II: towards photocathode material engineering
  - Session 5: Future outlook and collaborations
- Impressive photocathode development laboratories have been established in several laboratories
- There are many new results on high average current beam delivery, low intrinsic emittance, very good cathode operational lifetimes…….
- There is much broader use of surface and bulk analytical tools to analyze both cathode formation and degradation
- Aggressive and detailed cathode models are being developed and improved

Reviews

- D. Dowell ”2011 EuroFEL Cathode Workshop”, March,2012, Lecce, Italy
- J. Smedley ” Review of recent U Chicago photocathode/detector workshop” (June 29-30, 2012 University of Chicago), http://psec.uchicago.edu/workshops/2nd_photocathode_conference/talks.php

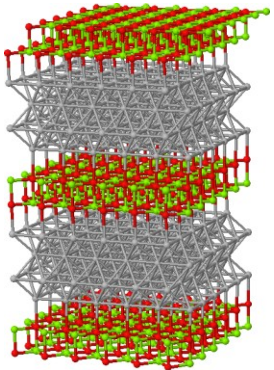






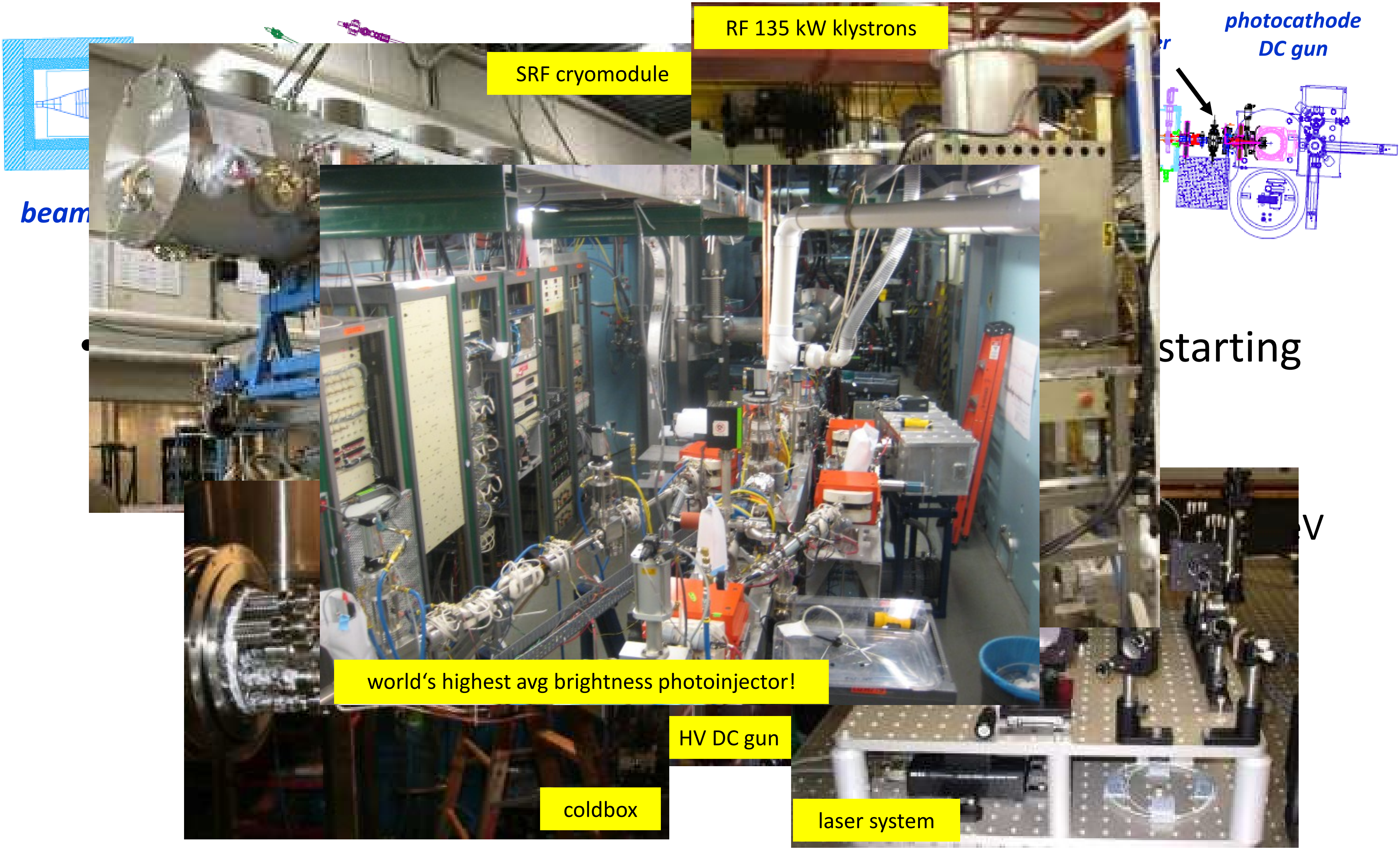
- T. Rao “Memories of the previous P3 workshop ” (2010 P3 Workshop: Recap), Oct 12-14, 2010 At BNL

Engineered Cathode: Mg, O, Ag



MgO(100)2L-Ag(100)4L-MgO(100)2L; DFT(PW91)
Work function reduced by ~1 eV relative to Ag(001)
Normalized emittance 0.05 mm-mr/mm

Cornell photoinjector for Energy Recovery Linac x-ray source



RF 135 kW klystrons

SRF cryomodule

world's highest avg brightness photoinjector!

HV DC gun

coldbox

laser system

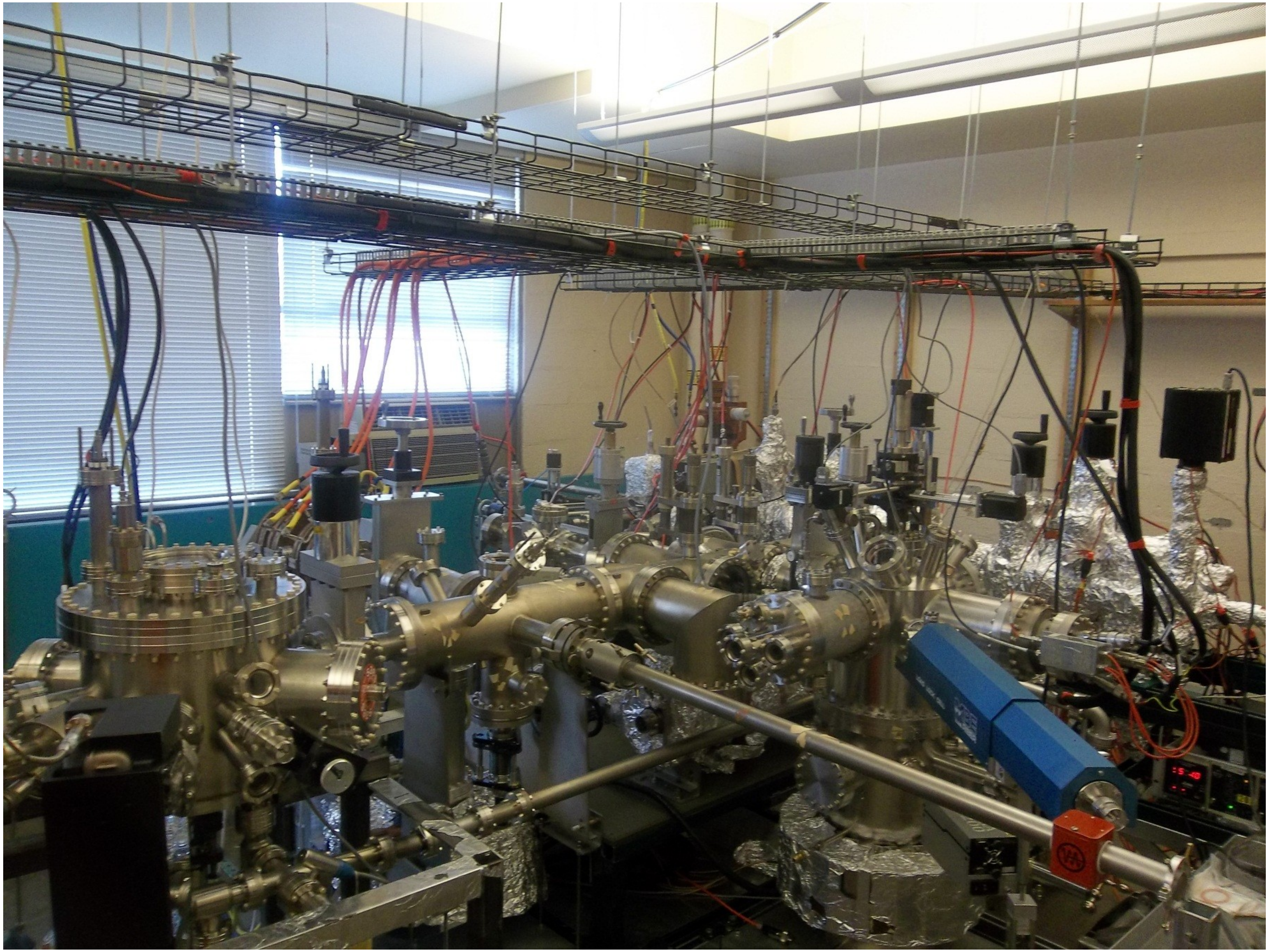
• starting

eV

Cornell photoinjector achievements (so far!)

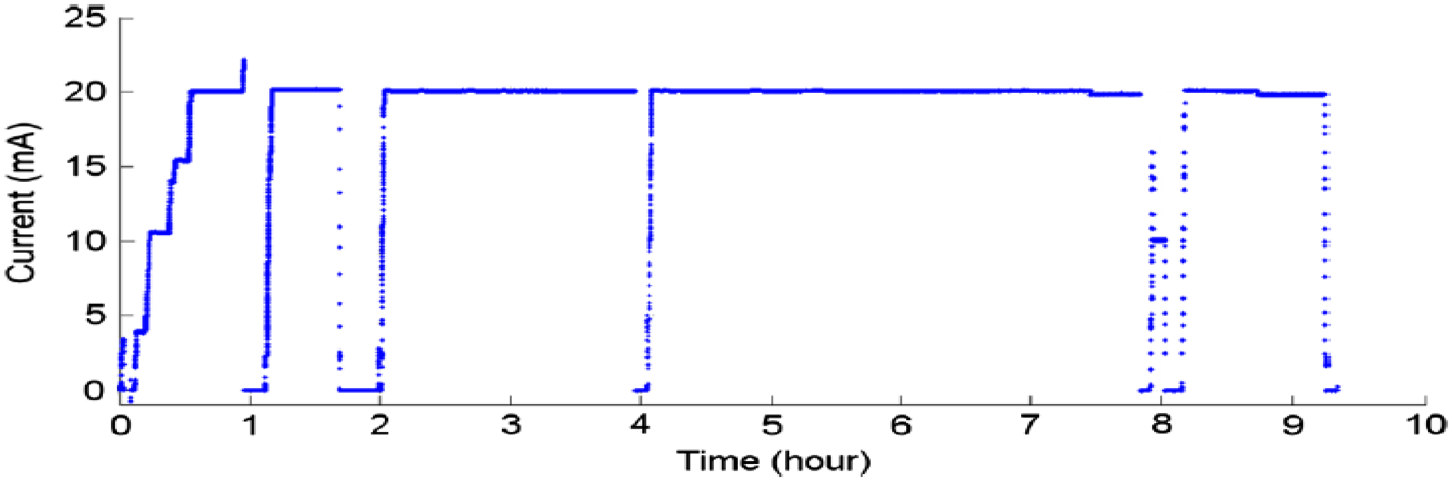
- Maximum average current of 52 mA achieved
  - Previous record from LANL/BOEING RF gun 32 mA (avg. over pulses), JLAB DC photoinjector 9.2 mA (CW);
- Proved practicality of high current operation (~ kiloCoulomb extracted with no noticeable QE degradation from a single laser spot)
- Original emittance spec. achieved:
  - $\varepsilon_{n,90\%} = 0.5\ \mu\mathrm{m}$ at 80pC/bunch (= 100mA at 1.3GHz)
  - $\varepsilon_{n,90\%} = 0.2\ \mu\mathrm{m}$ at 20pC/bunch (= 25 mA)
- Would surpass best of existing storage rings in brightness today if this quality beam were to be accelerated to 5 GeV (~5 better than PETRA3!)

Cornell Photocathode Laboratory

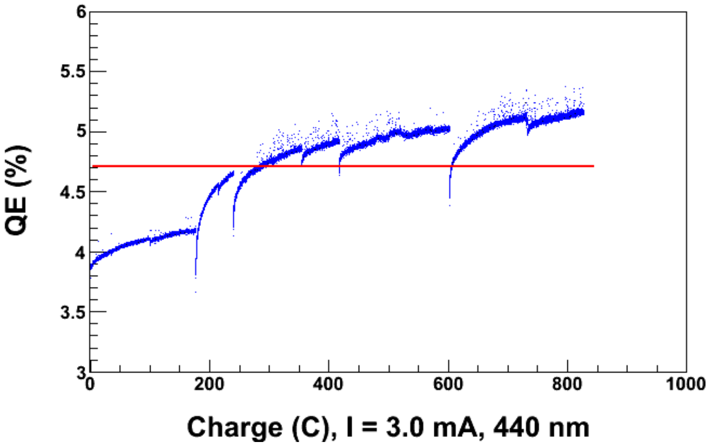


Significant Advances

- High average currents are being achieved – Cornell reached 52 mA average current, and operated at 20 mA average for 8 hours (600 C) from K_2CsSb, stopped by boredom rather than cathode decay. QE dropped from ~11% to ~ 8% during this run. (Cultrera)

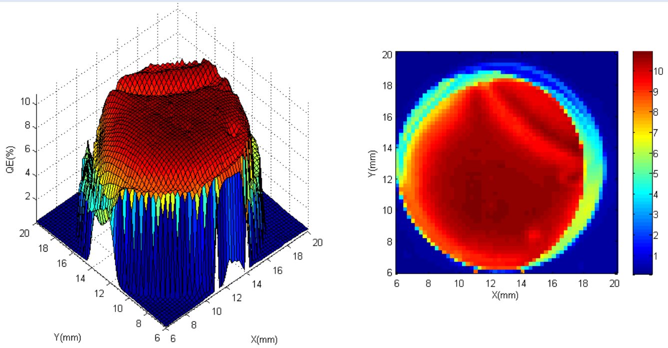


- BNL transported a K_2CsSb cathode to Jlab, where it delivered both high average current and total charge in a test setup, with no decay until reaching ~ 20 mA average current operation



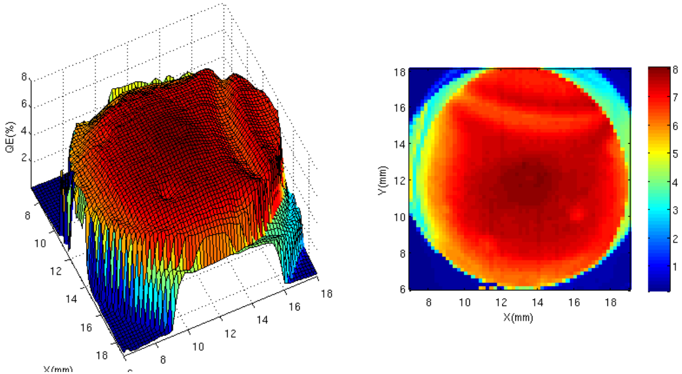
No QE decrease in any of the runs; actually, the QE seems to increase

Cornell Low Average Current Life



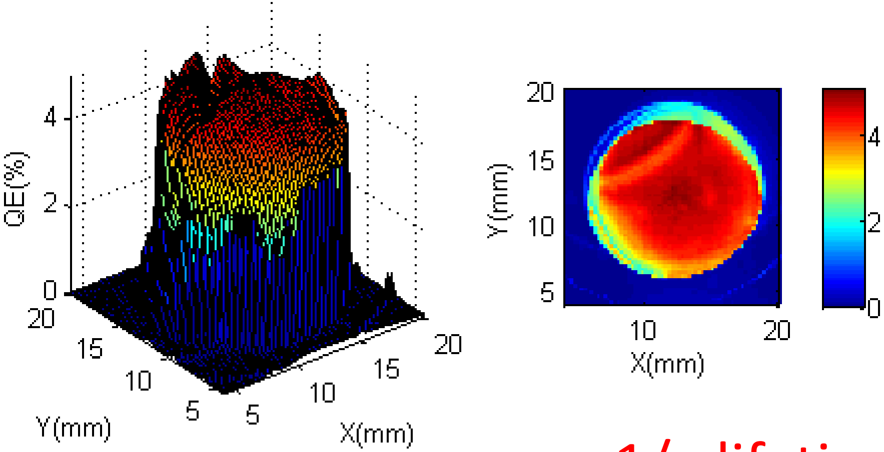
QE map on 03 Feb 2012

~10%



QE map on 03 Apr 2012

~8%



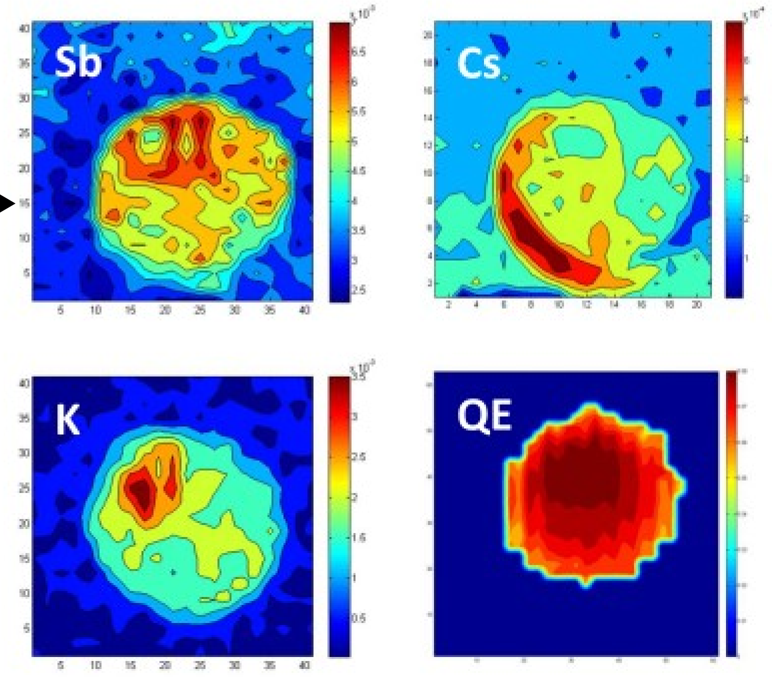
QE map on 02 Oct 2012

~5%

1/e lifetime ~13 months = 9500 hrs

Yet Mysteries Remain……

Cornell measurement
of stoichiometry and
QE of K_2CsSb with 2D scanning Auger
(Cultrera)



And: (Schubert)
“We were not successful in growing a stoichiometric CsK2Sb cathode.”

We are working towards the measure of the stoichiometry of our photocathodes

T. Vecchione (LBNL, Berkeley) “QE and Emittance from Free Electron Metals”

- Bi-Alkali Antimonide → K_2CsSb

Vecchione, T. et al. A low emittance and high efficiency visible light photocathode for high brightness accelerator-based X-ray light sources. Applied Physics Letters 99, 034103 (2011).

Free Electron Model

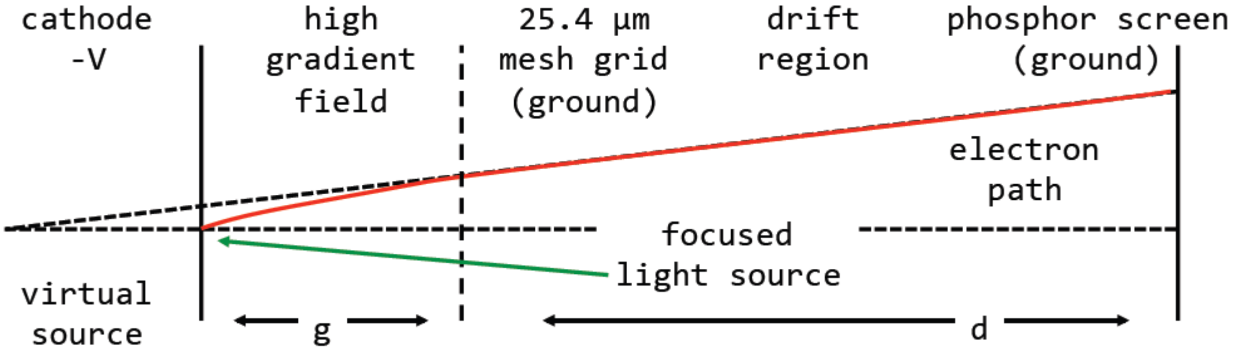
$$\vec{p} = \hbar\vec{k} \qquad E = \frac{\vec{p}^2}{2m} \qquad f[\vec{p}] = \frac{1}{1 + Exp\left[\frac{\vec{p}^2}{2mkT} - \frac{\mu}{kT}\right]}$$

$$QE \propto \frac{Li_2\left[-Exp\left[\frac{\hbar\omega - \phi}{kT}\right]\right]}{Li_2\left[-Exp\left[\frac{\mu}{kT}\right]\right]}$$

Polylogarithm Definition

$$Li_n[z] = \sum_{k=1}^{\infty} \frac{z^k}{k^n} = \frac{z}{\Gamma[n]} \int_0^{\infty} \frac{t^{n-1}}{Exp[t] - z}\,dt$$

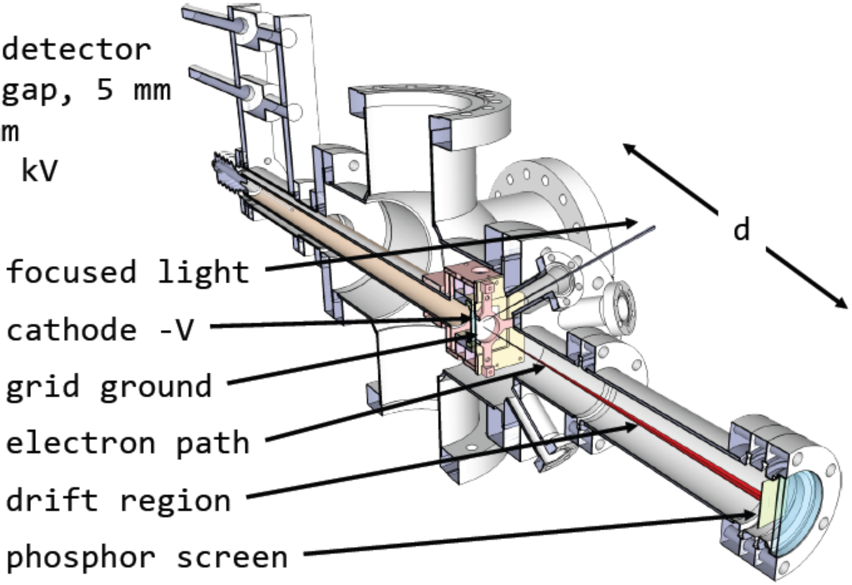
“Momentatron” Apparatus Measuring Transverse Momentum

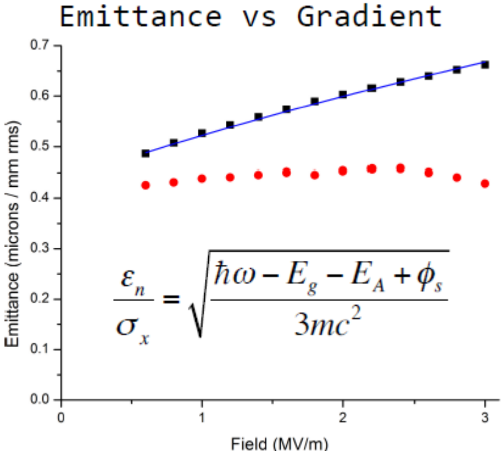


r = radial coordinate on detector
g = cathode-grid (anode) gap, 5 mm
d = drift distance, 244 mm
V = applied voltage, 1-15 kV

$$r = \sqrt{\frac{mc^2}{2eV}}\,(2g + d)\left(\frac{p_x}{mc}\right)$$

$$\sigma_x = \frac{\langle p_x^2 \rangle^{1/2}}{mc}$$





$$\frac{\varepsilon_n}{\sigma_x} = \sqrt{\frac{\hbar\omega - E_g - E_A + \phi_s}{3mc^2}}$$

red dots = thin and smooth cathode

black squares = thicker cathode consisting of several layers

blue line = fit to a model of field dependent emittance growth

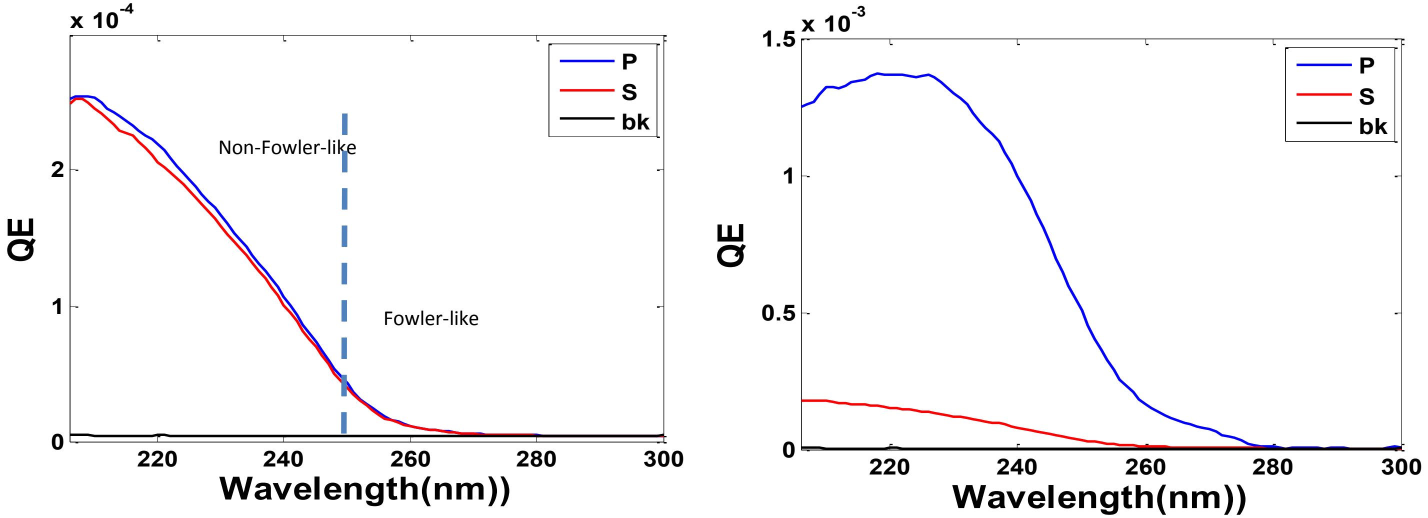
cathode roughness studies

Metal Cathode Developments

Jun Feng (LBNL, Berkeley) **“Reduction of emittance from metals to less than thermal”**

- Emission from metallic surface states by p-polarized light at large incidence angle gives a very large increase in QE, and a large reduction in the mean transverse energy, compared to emission with normal incidence light
- In accord with previous observations of large QE increase from Copper at large incidence angle
- Photoemitted electrons from surface states

Wavelength dependent QE measurement for Ag(111)



Normal incidence

70 degree incidence

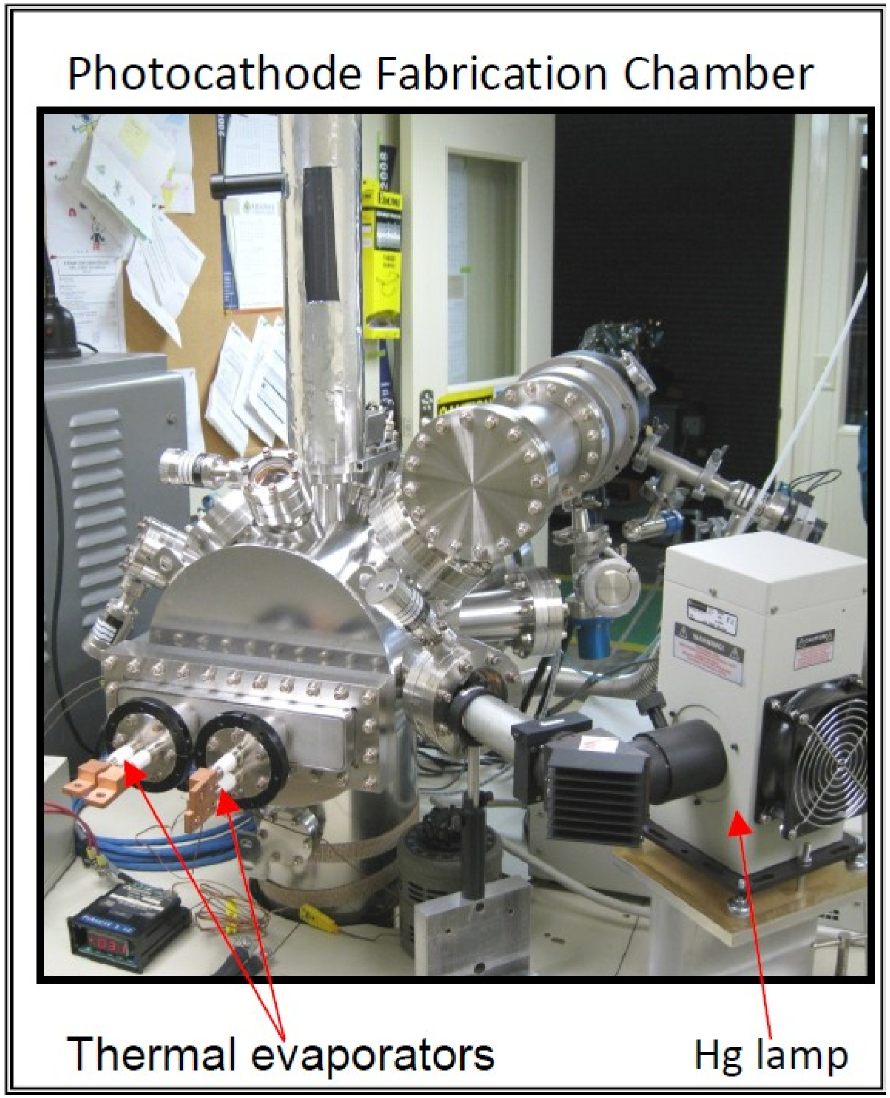
- **S polarized**
  - Fowler like behavior to ~ 250 nm (5 eV)
- **P polarized**
  - Large QE enhancement, particularly close to threshold
  - Non-Fowler like behavior close to threshold

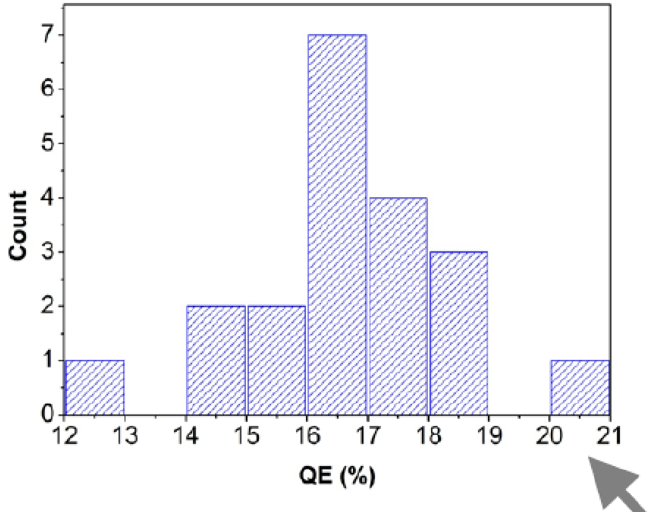
Quantitative Analytical Tools are Being More Widely Employed

- Two Camera XRD (X-Ray Diffraction) and X-Ray reflectivity to observe formation and growth of K_3Sb and K_2CsSb cathode (Ruiz Oses, Stony Brook University)
- XPS (X-ray photo-electron spectroscopy) analysis of growth and stochiometry (stoichiometric ratio) of K_2CsSb cathodes (Schubert, HZB)
- AFM (Atomic Force Microscopy) for observation of cathode roughness → topography of the sample (many labs)
- Study heavily used GaAs cathodes (several thousand Coulombs) from Jlab FEL (Jlab/PNNL, published)

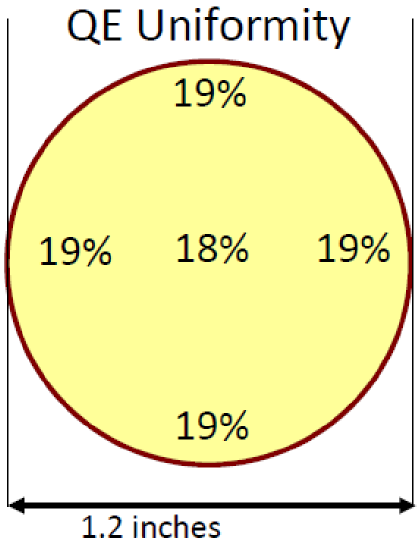
K. Harkay (ANL): “Work Function and Quantum Efficiency Studies on Cesium Telluride”

Argonne Wakefield Accelerator (AWA) upgrade requires production of electron bunch train consisting of 20 bunches, at 40 nC per bunch!





Peak QE histogram of photocathodes produced since 2010.



QE uniformity across the photocathode surface deposited on Mo plug. QE measurement error is ±1% absolute.

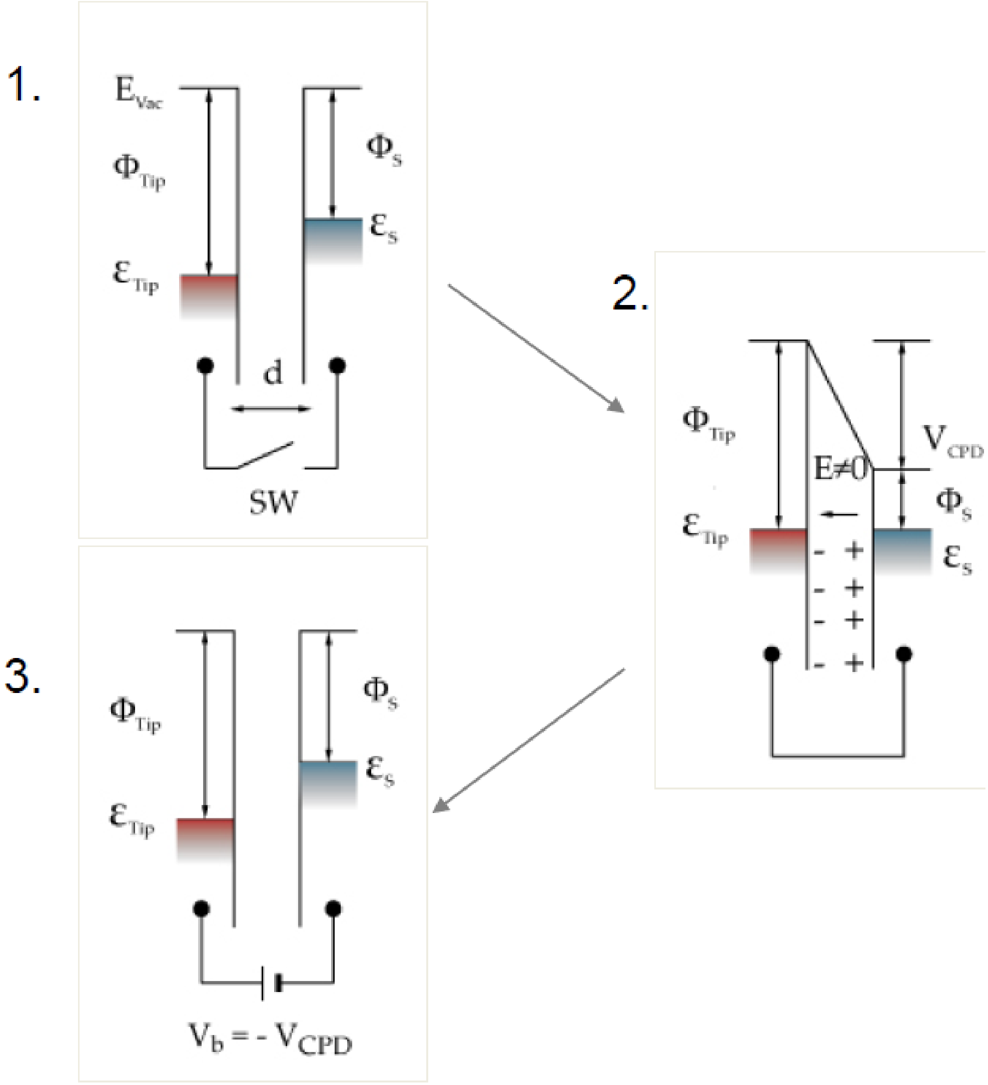
Work Function Measurement Using the Kelvin Probe

1. Two metal plates, different work functions ϕ_1 and ϕ_2
2. Upon contact, charge transfers and Fermi levels align:

   $$\Delta\phi = |\phi_1 - \phi_2| = eV_{CPD}$$

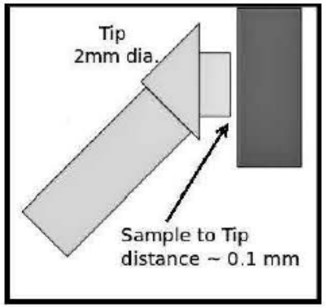
3. Apply a *backing* potential V_b. Vary until there is no electric field between plates
   - Null point-zero current crossing corresponds to the contact potential difference (CPD)

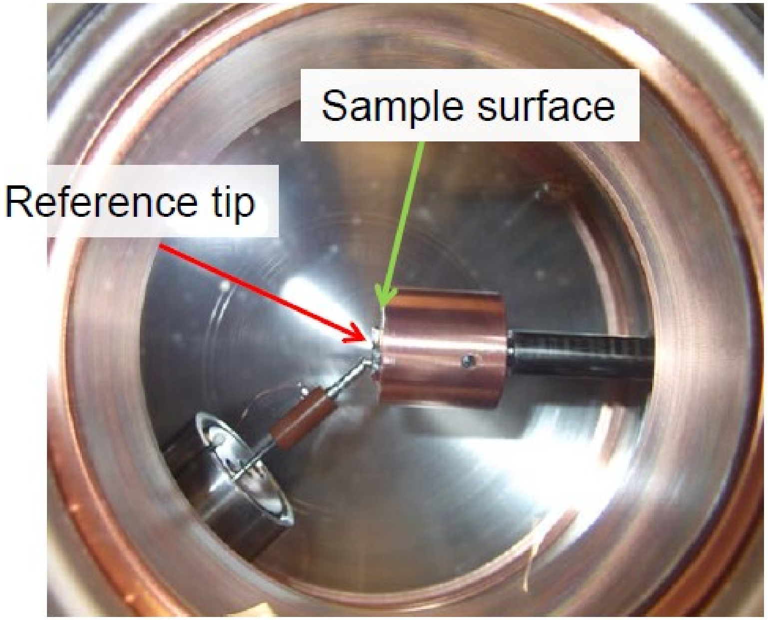
Important Note: For a semiconductor, the Kelvin probe method measures the Fermi Level with respect to the vacuum level, not the photoemission threshold. This is what we define as the “work function” for a semiconductor.



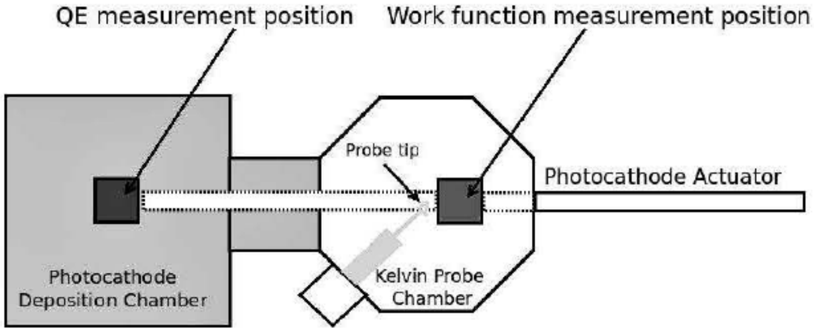
Experimental Setup

- The KP is inserted at a 45° angle with respect to the sample surface
- A customized 45° tip is used
- Tip Work Function calibrated value 4.6 ± 0.1 eV





Top View



- We observed a correlation between Quantum Efficiency and Work Function.
  - Cathode aging – QE and Φ vs. time behaves as expected before rejuvenation by heating.
  - Heating raises the QE without reducing Φ – further study is required.
- 4.9 eV UV light exposure temporarily reduces the work function. This effect is dependent on exposure time and intensity. 3.7 eV UV light did not produce this effect. *Further study is required – similar observation on ITO attributed to either charging effects or photochemistry.*

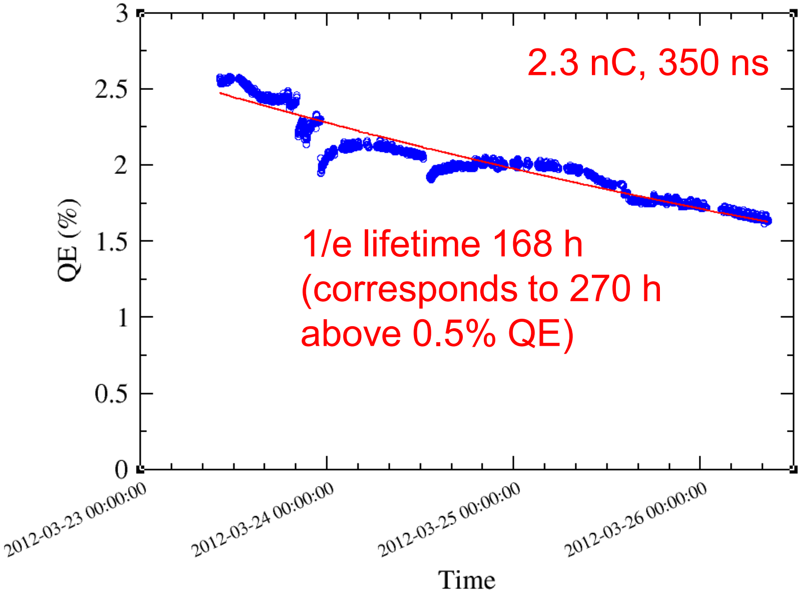
C. Hessler (CERN):” Operation of the High-Charge PHIN RF Photoinjector with Cs_3Sb Cathodes”

Cs_3Sb and Cs_2Te Cathodes Prepared and Evaluated in the Same System for the PHIN Photoinjector

- Photocathode planned to replace the nominal thermionic cathode for the CLIC drive beam
- Conclude that Cs_3Sb is about as good as Cs_2Te for this application. (For Cs_3Sb a factor 6 less of QE is needed as for Cs_2Te cathodes, due to the different wavelength and the absence of 4th harmonics conversion stage)
- Vacuum conditions are very important for lifetime, for either photocathode

Parameter	**PHIN**	**CLIC**
Charge / bunch (nC)	2.3	8.4
Macro pulse length (μs)	1.2	140
Bunch spacing (ns)	0.66	2.0
Bunch rep. rate (GHz)	1.5	0.5
Number of bunches / macro pulse	1800	70000
Macro pulse rep. rate (Hz)	5	50
Charge / macro pulse (μC)	4.1	590
Beam current / macro pulse (A)	3.4	4.2
Bunch length (ps)	10	10
Charge stability	<0.25%	<0.1%
Cathode lifetime (h) at QE > 3% (Cs_2Te)	>50	>150
Norm. emittance (μm)	<25	<100

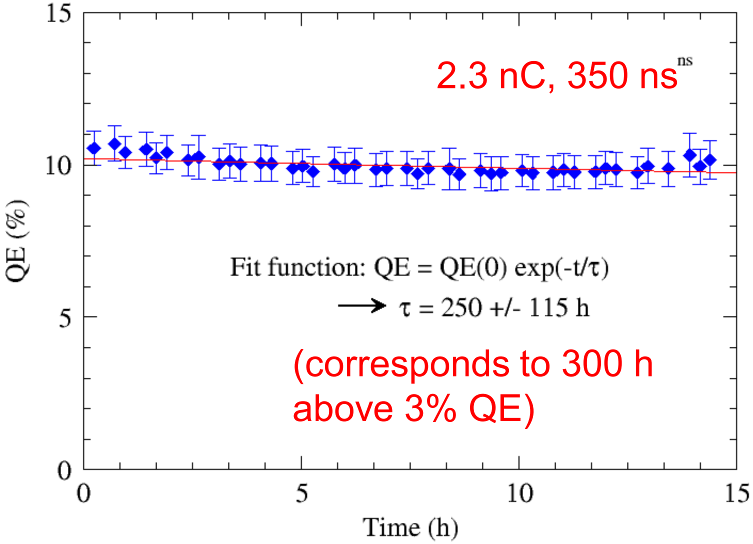
Cathode #189 (Cs_3Sb)



2.3 nC, 350 ns

1/e lifetime 168 h (corresponds to 270 h above 0.5% QE)

Cathode #185 (Cs_2Te)



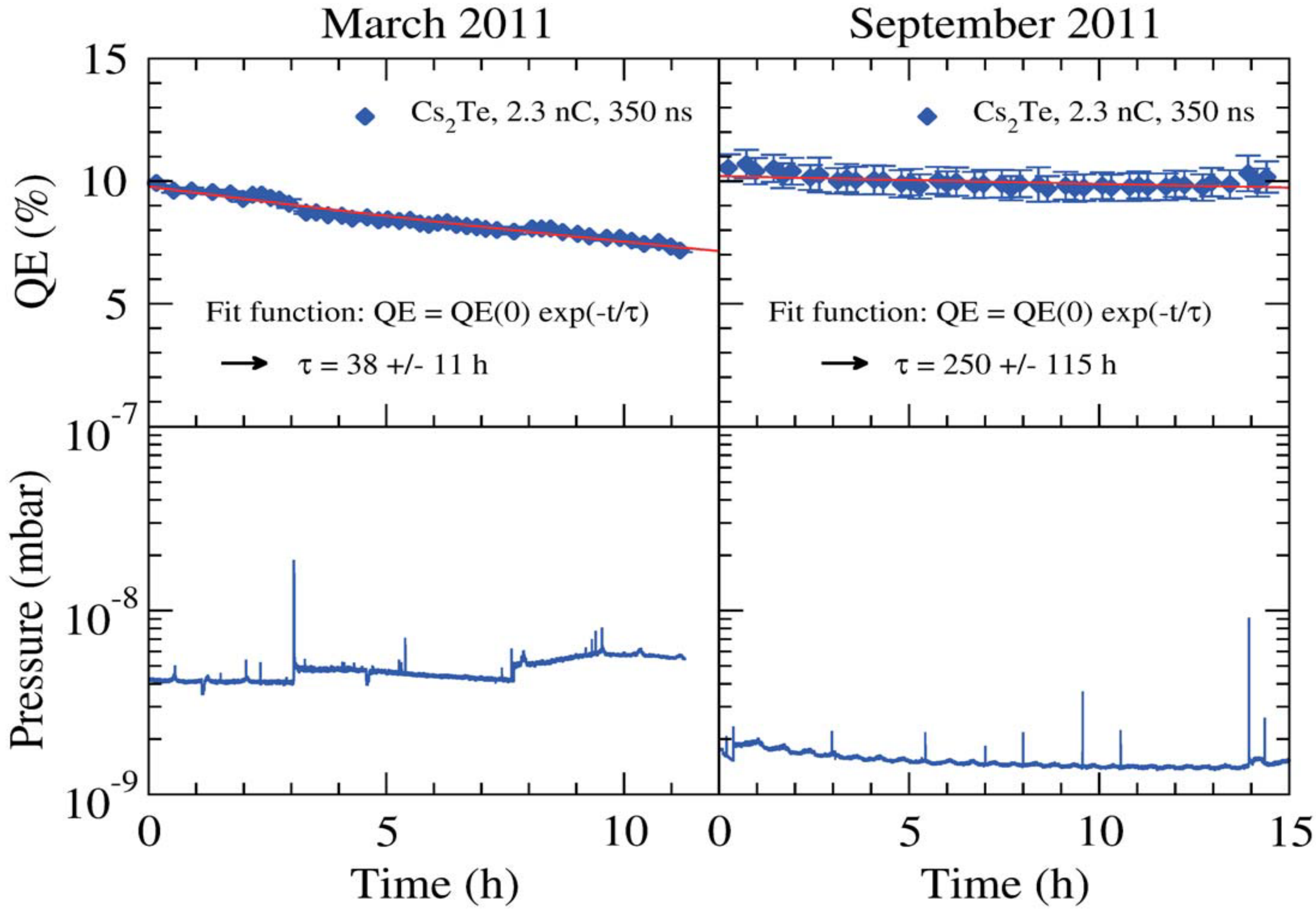
2.3 nC, 350 ns

Fit function: QE = QE(0) exp(-t/τ)

→ τ = 250 +/- 115 h

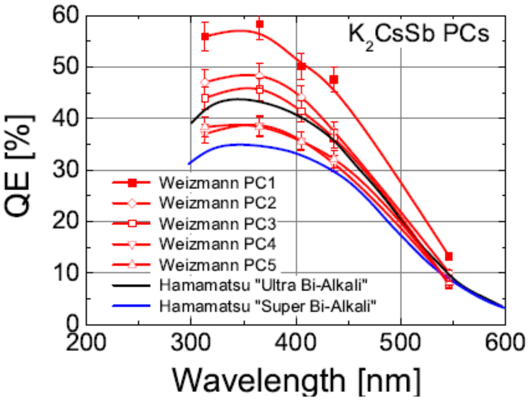
(corresponds to 300 h above 3% QE)

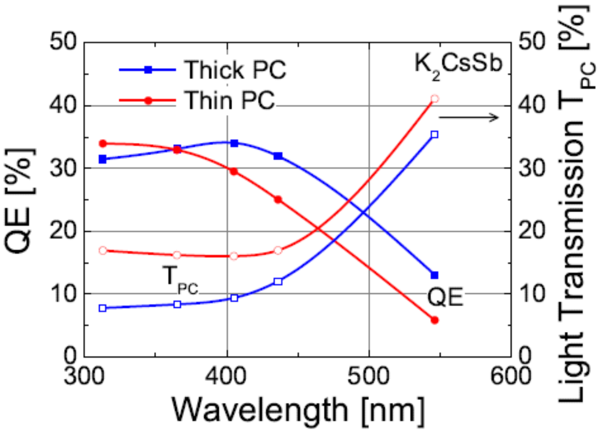
Impact of Vacuum on Cs_2Te Operating Lifetime

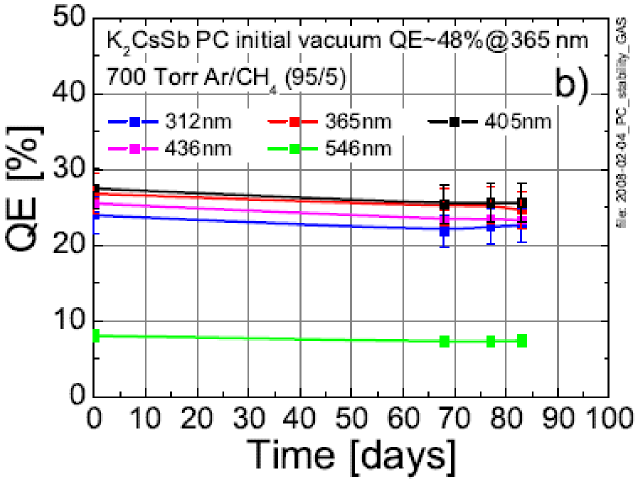


Two possibly unfamiliar K_2CsSb results (C. Sinclair)

- Bob Springer (LANL) reproducibly made ~ 17% QE at 532 nm in a single step taking minutes, using a liquid metal K/Cs source – no separate K or Cs sources
- **Alexey Lyashenko (Ph.D. thesis, Weizmann Institute)** made a large number of K_2CsSb cathodes with very good QE and lifetime
- Thicker cathodes gave better green response.
- Very good lifetime with exceptionally small degradation in a 700 torr Ar/CH_4 mixture.

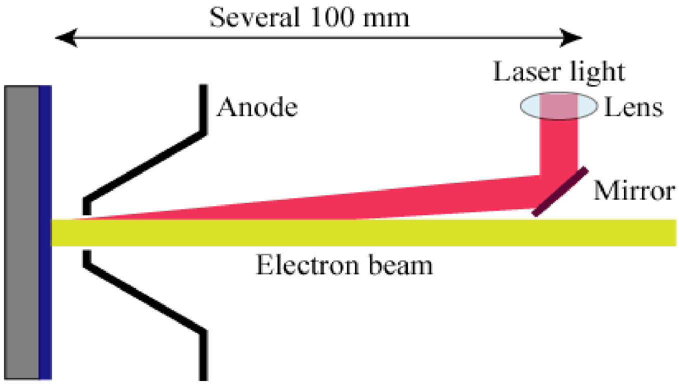






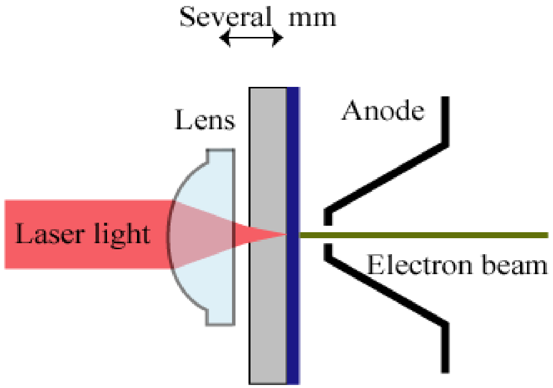
X.G. Jin: "Innovations from Nagoya University"

- Use GaAs/GaAsP transmission cathodes on GaP substrates to achieve small emitting area and thus higher brightness with high (~90%) beam polarization
- Grow $Ga_{0.52}In_{0.48}P$, (1.9 eV bandgap) lattice matched to GaAs, to achieve a high QE (~ 14%), fast time response (~ 6 ps) cathode with a small mean transverse energy under 532 nm illumination



Transmission geometry allows smaller cathode spots

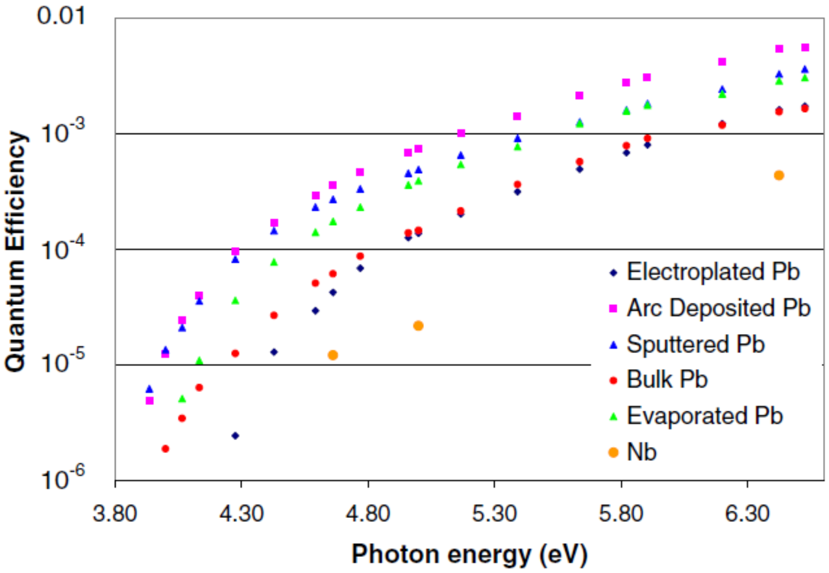
Conventional geometry – cathode spot size limited by the diffraction limit



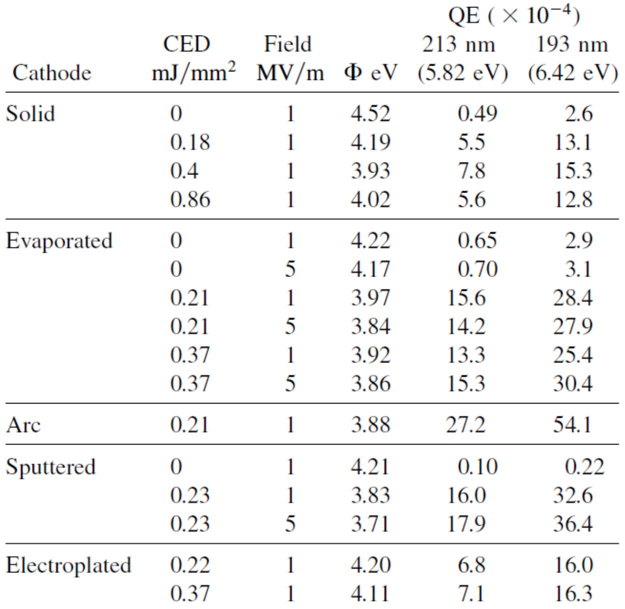
S.Schubert (HZB): “Growth and Operation of Pb/Nb photocathodes in SRF gun”

QE enhancement through laser cleaning

QE of Pb films prepared by various deposition techniques

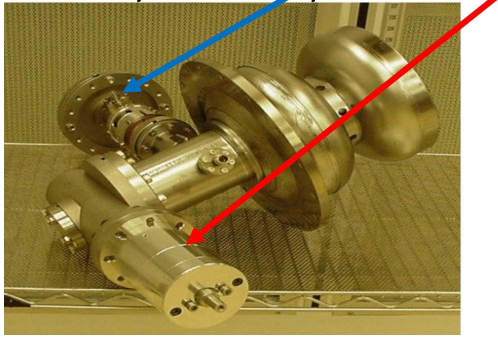


QE values before and after irradiation

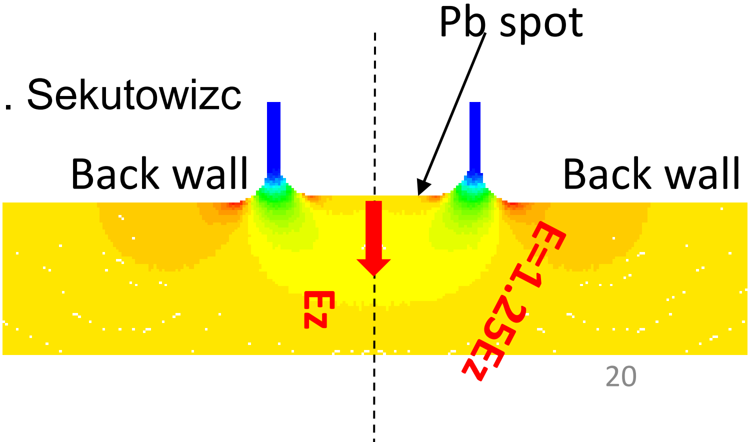


Cathode	CED mJ/mm^2	Field MV/m	Φ eV	QE ($\times 10^{-4}$) 213 nm (5.82 eV)	QE ($\times 10^{-4}$) 193 nm (6.42 eV)
Solid	0	1	4.52	0.49	2.6
	0.18	1	4.19	5.5	13.1
	0.4	1	3.93	7.8	15.3
	0.86	1	4.02	5.6	12.8
Evaporated	0	1	4.22	0.65	2.9
	0	5	4.17	0.70	3.1
	0.21	1	3.97	15.6	28.4
	0.21	5	3.84	14.2	27.9
	0.37	1	3.92	13.3	25.4
	0.37	5	3.86	15.3	30.4
Arc	0.21	1	3.88	27.2	54.1
Sputtered	0	1	4.21	0.10	0.22
	0.23	1	3.83	16.0	32.6
	0.23	5	3.71	17.9	36.4
Electroplated	0.22	1	4.20	6.8	16.0
	0.37	1	4.11	7.1	16.3

Cavity is equipped with input coupler and valve and is now installed in the Bessy test facility.



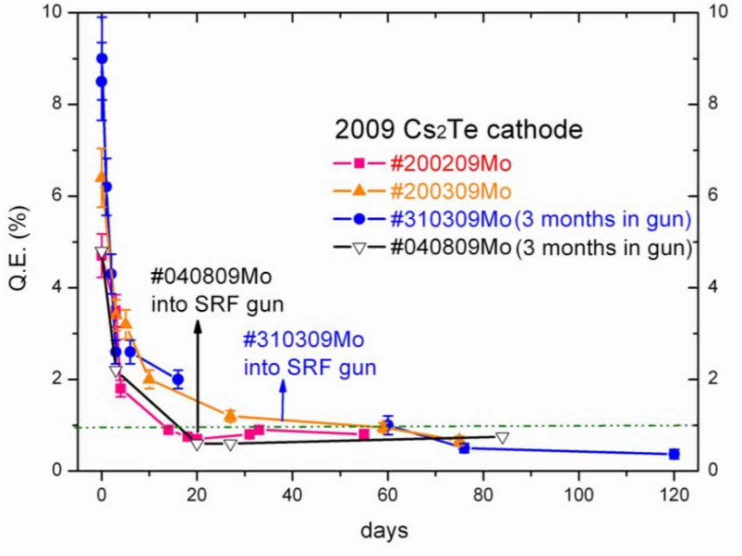
courtesy of J. Sekutowizc



R. Xiang (HZDR): “Photocathodes for Rossendorf SRF gun”

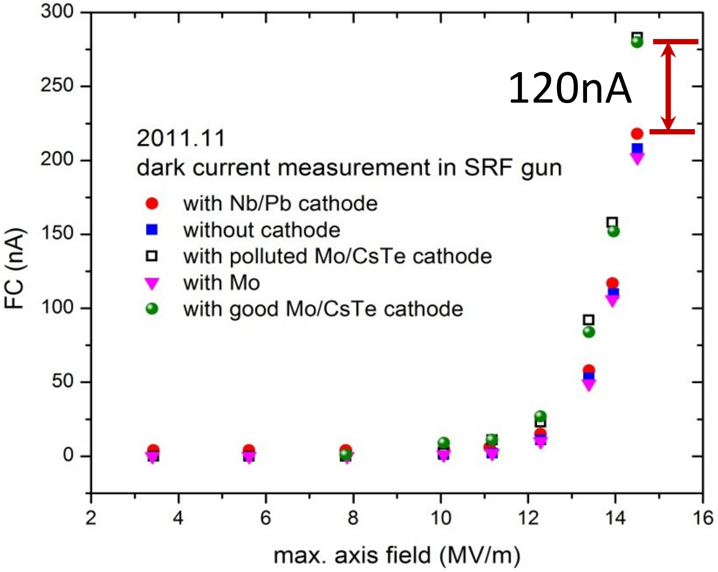
Cs_2Te photocathodes for SRF gun

- 8 cathodes tested in gun
- QE ~1 % in months
- I_{dark} ~ 120 nA @ 15 MV/m
- $\varepsilon_{thermal}$ ~ 0.7 mm·mrad/r(mm)



Open questions:

- QE decrease during transport
- Strong multipacting around cathode plug
- Dark current
- layer destroyed during operation



1. #170412Mo(TiN) after preparation 23.04.2012

2. #170412Mo(TiN) in cavity, 07.06.2012

3. #170412Mo(TiN) in cavity, 23.08.2012

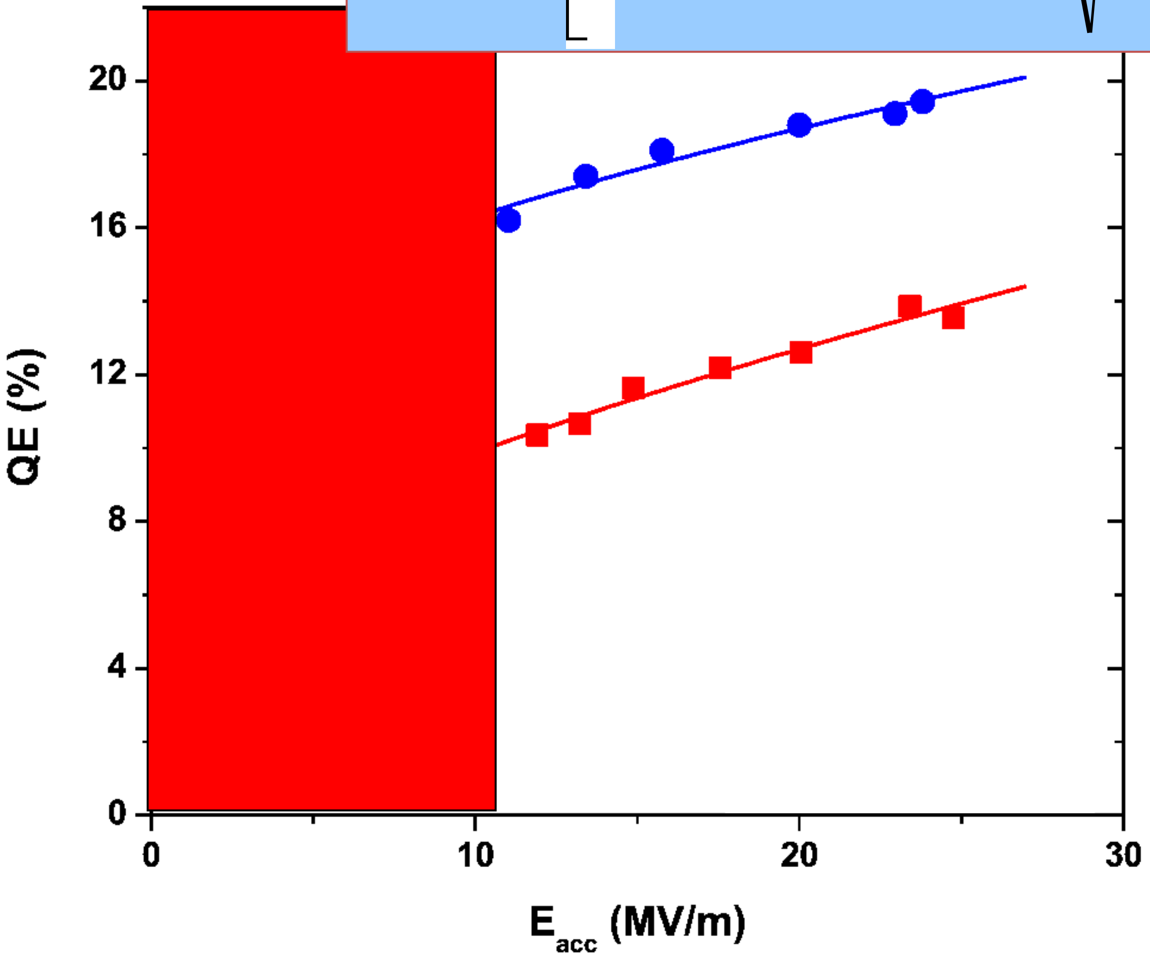
Test new photocathode candidates :

- Cs_3Sb
- GaN (Cs)
- GaAs (Cs,O)

S. Lederer (DESY): “Photocathode analysis and characterization at DESY”

Standard Cathode analysis: QE vs. field

$$QE = \cdot \left[\nu - (E_G + E_A) + e \cdot \sqrt{\frac{q_e \cdot \beta \; E \cdot \sin \phi}{4 \cdot \pi \; \varepsilon}} \right]$$



cathode #77.2
QE @ zero gradient = 11.2 %
W = E_G+E_A = 3.5 eV
β = 4.7

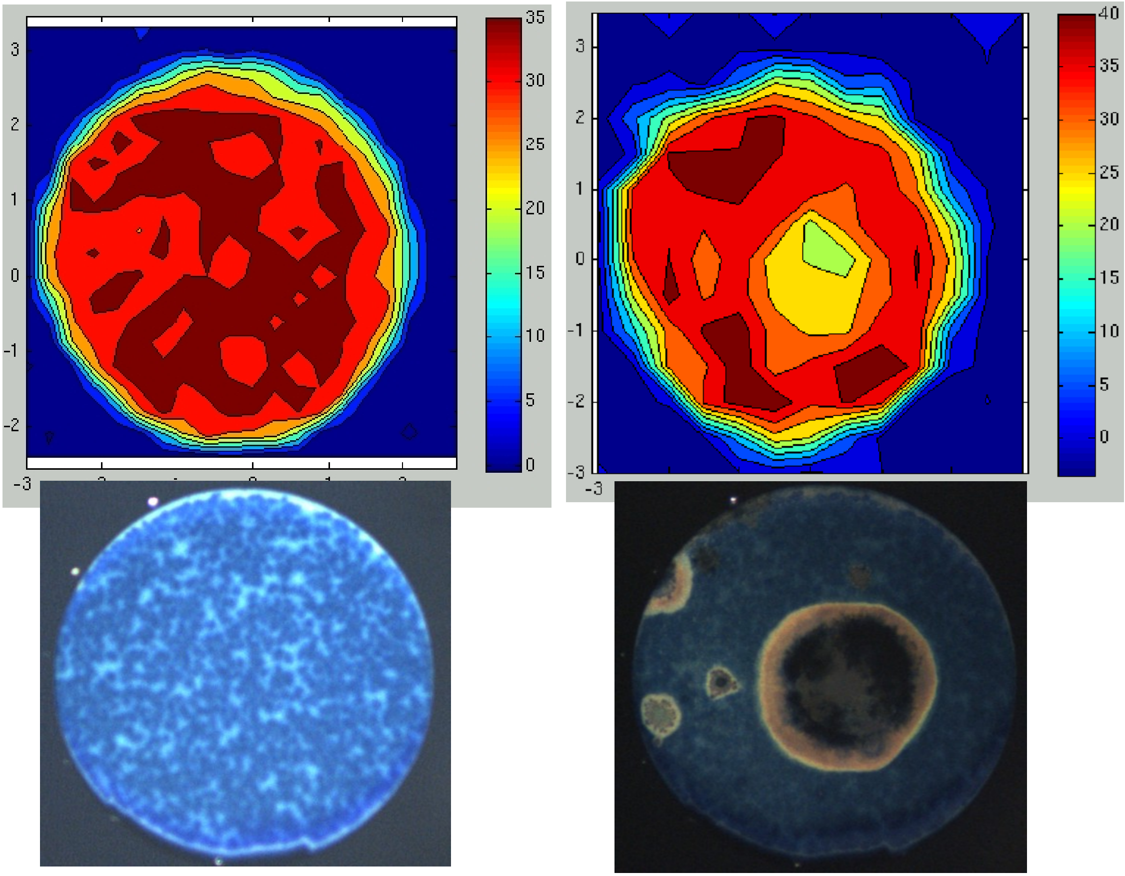
56 days of operation
@ FLASH

cathode #77.2
QE @ zero gradient = 4.5 %
W = E_G+E_A = 3.8 eV
β= 12.7

- → **QE decreased**
- → **E_G+E_A increased**
- → **field enhancement increased**

Standard Cathode analysis: QE-maps

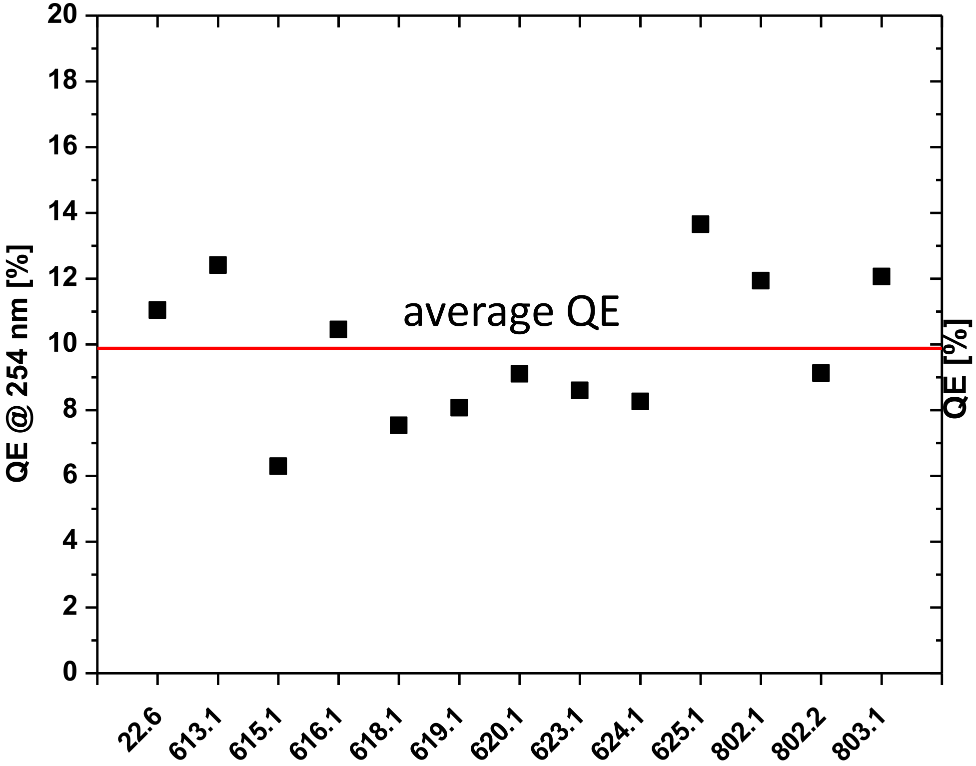
- Investigations on homogeneity of electron emission

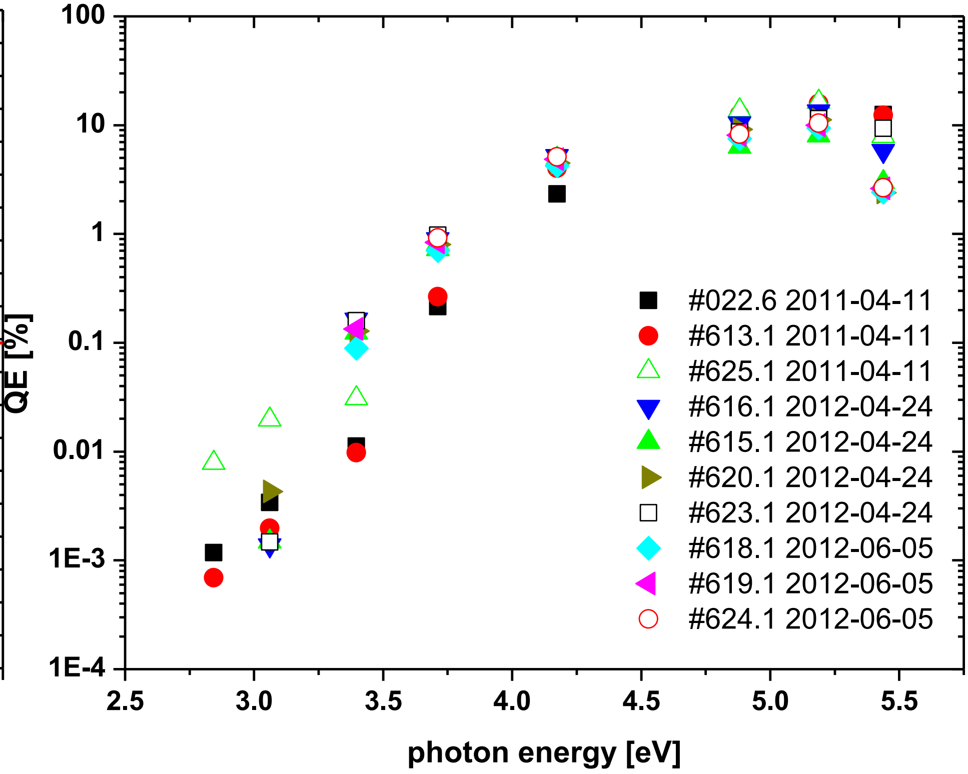


#613.1 operated (week 12/2012) at PITZ 60 MV/m, 600 bunches approx. 1 nC, 10 Hz – less than a week – possible life time problem!!

Cathode preparation @ DESY

- After commissioning and training - system and operator now in production mode
- 10 cathodes produced for FLASH and PITZ





Photocathode physics I: new insights in theory and modeling

- S. Karkare (Cornell) “Monte-Carlo simulations of Charge transport and photoemission from GaAs photcathodes”
  - 3-step model for GaAs(Cs/O) photoemission (NEA)
  - Need for a Monte-Carlo simulation (Diffusion model (IR) fails for the case of visible excitation)
  - Photoemission step 1 – Excitation (3-valley model for GaAs, absorption length)
  - Photoemission step 2 – Transport and scattering (Scattering processes: impurity, phonon, carrier)
  - Photoemission step 3 – emission and surface effects (surface barrieer, roughness)

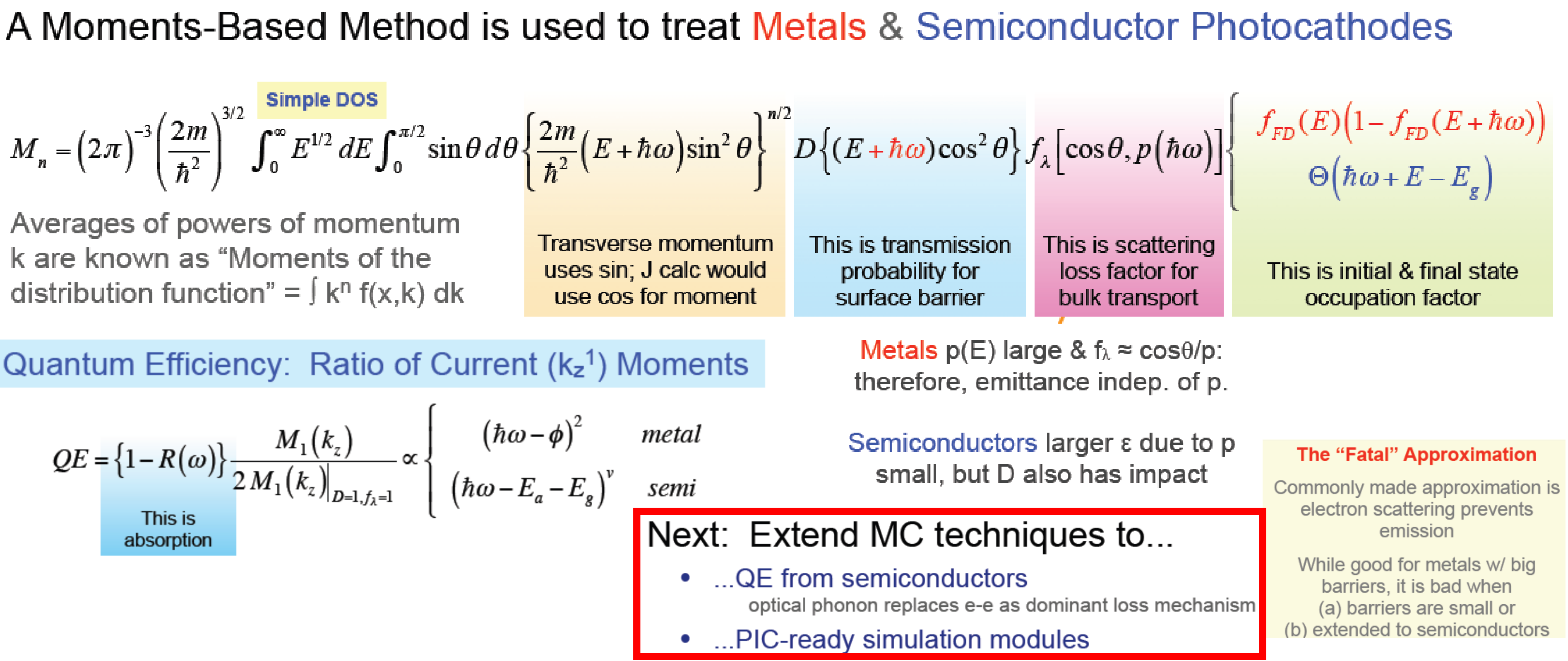
- D. A. Dimitrov (Tech-X Corporation+ BNL coll.) “Modeling Electron Emission From Diamond-Amplified Cathodes”
  - The simulations consist of modeling three main parts (3-step model) VORPAL
  - The new emission models included effects due to the external field
  - The models calculate the probability for both tunneling and over-the-barrier emission

Photocathode physics I: new insights in theory and modeling

E. Montgomery (UMD, Maryland +NavalRL) "Monte Carlo Scattering Corrections to Moments-Based Emission Models"

Monte Carlo based models developed to augment emission modules for the beam simulation particle-in-cell (PIC) code MICHELLE.

- Transport of charge through semiconductor materials followed by emission into vacuum - Augments Moments-based models of QE (photocathodes)
- Scattering determines how bunches evolve under band bending, temporal characteristics, and phase space distribution
- Revised code: faster, 10x more electrons than previous, more accurate



A Moments-Based Method is used to treat Metals & Semiconductor Photocathodes

Simple DOS

$$M_n = (2\pi)^{-3}\left(\frac{2m}{\hbar^2}\right)^{3/2} \int_0^\infty E^{1/2}\,dE \int_0^{\pi/2} \sin\theta\,d\theta \left\{\frac{2m}{\hbar^2}(E+\hbar\omega)\sin^2\theta\right\}^{n/2} D\left\{(E+\hbar\omega)\cos^2\theta\right\} f_\lambda\left[\cos\theta, p(\hbar\omega)\right] \begin{cases} f_{FD}(E)\left(1-f_{FD}(E+\hbar\omega)\right) \\ \Theta\left(\hbar\omega+E-E_g\right) \end{cases}$$

Averages of powers of momentum k are known as "Moments of the distribution function" = ∫ k^n f(x,k) dk

Transverse momentum uses sin; J calc would use cos for moment

This is transmission probability for surface barrier

This is scattering loss factor for bulk transport

This is initial & final state occupation factor

Quantum Efficiency: Ratio of Current (k_z^1) Moments

$$QE = \{1-R(\omega)\}\frac{M_1(k_z)}{2\,M_1(k_z)\big|_{D=1,f_\lambda=1}} \propto \begin{cases} (\hbar\omega-\phi)^2 & metal \\ (\hbar\omega-E_a-E_g)^\nu & semi \end{cases}$$

This is absorption

Metals p(E) large & $f_\lambda \approx \cos\theta/p$: therefore, emittance indep. of p.

Semiconductors larger ε due to p small, but D also has impact

The "Fatal" Approximation

Commonly made approximation is electron scattering prevents emission

While good for metals w/ big barriers, it is bad when
(a) barriers are small or
(b) extended to semiconductors

Next: Extend MC techniques to...

- ...QE from semiconductors
  optical phonon replaces e-e as dominant loss mechanism
- ...PIC-ready simulation modules

Photocathode physics I: new insights in theory and modeling

- **D. Dowell (SLAC): “Models of effect of roughness on emittance ”**

Intrinsic (aka Thermal) Emittance, $\varepsilon_{intrinsic}$:

Cathode’s material properties (E_F, ,E_G ,E_A , m^* ,…)
Cathode temperature, phonon spectrum
Laser photon energy, angle of incidence and polarization

Bunch Space Charge Emittance:

Large scale space charge forces across diameter and length of bunch
Image charge (cathode complex dielectric constant) effects space charge limit
Emittance compensation
Bunch shaping (beer-can, ellipsoid) to give linear sc-forces

Rough Surface Emittance:

Electron and electric field boundary conditions important
Surface angles washout the exit cone
Coherent surface modulations enhances surface plasmons
Three principle emittance effects:

- Surface tilt washes out intrinsic transverse momentum > escape angle increases
- Applied field near surface has transverse component due to surface tilt
- Space charge from charge density modulation due to E_x surface modulation

$$\varepsilon_{intrinsic+tilt+field} = \sigma_x \sqrt{\frac{(\hbar\omega - \phi_{eff})}{3mc^2}\left[1+\frac{(a_n k_n)^2}{2}\right]+\frac{\pi e E_0}{2k_n mc^2}\frac{(a_n k_n)^2}{2}}$$

Conclusions

-The electric field term dominates the roughness emittance. Surface roughness most important at high fields.

-The term given by the product of the excess energy and roughness shows that decreasing the intrinsic emittance will relax the roughness required to achieve a desired emittance (Karkare & Bazarov).

-The 2D emittance is approximately 40% higher than the 3D emittance for a surface with the same roughness parameters for Krasilnikov.

-The surface field enhancement can strongly focus the beam to modulate the charge density with high spatial frequency. This can generate geometric and space charge emittance as well as slice emittance. The size of these emittances and the downstream effects requires further study.

Photocathode physics I: new insights in theory and modeling

- W. Wan (LBNL) Metal Photocathodes: “One-step model of photoemission and extensions to the three-step model ” (Three-Step Model and Beyond)
  - Including temperature in the simplified 3-step model reveals the lower limit of the emittance of normal metals, which is 0.23 µm/mm
  - Surface state on the (111) plane of noble metals, esp., Ag, offers a way of reducing the emittance pass the limit for the normal metals, which is 0.16 µm/mm at LN2 temperature
  - One-step model has the potential of quantitatively describing the great enhancement of QE from (111) surface states at grazing angle and predicting the increase of interested metals

- Z. Pan (NRL) “Modeling the Resupply, Diffusion, and Evaporation of Cesium Based Dispenser Photocathodes”
  - Controlled Porosity Dispenser(CPD) Photocathodes

- M. Krasilnikov (DESY) “Measurements and modeling of space charge assisted photoemission at PITZ”➔

Photocathode physics II: towards photocathode material engineering

- K. Harkay (ANL) “Redesigning Cs2Te: Workfunction Lowering and Quantum-Efficiency Preservation via Acetylation”
  - O2, CO2, CO, N2 and CH4 were investigated in order to simulate practical vacuum conditions.
  - However, acetylene gas, **C2H2** was not investigated.
  - **What about reacting Cs2Te with acetylene?**
  - Acetylene is fairly reactive, easily losing its hydrogens, which captures electrons from the material in contact. This forms “acetylides,” containing the acetylide anion [:C:::C:]2-, commonly denoted as C22.
  - “Designer” acetylated Cs2Te – Cs2TeC2 – and other systems in this class are predicted to have low work functions. The QE of Cs2TeC2 is predicted to be comparable to Cs2Te. The rod-perpendicular orientation may exhibit low emittance. Robustness in imperfect vacuum also predicted.
  - Preliminary synthesis is ongoing through collaboration at IIT/ANL; results are encouraging.

- W. Hess (PNNL - Pacific Northwest National Laboratory): “Surface science techniques ”
  - Thin film (CsBr, KBr) coated metals have highly modified optical/chemical properties

    - QE is dramatically increased

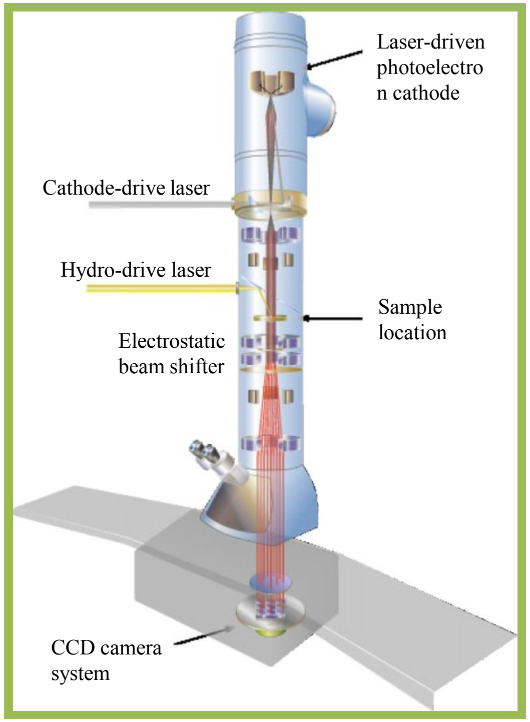
    - Work function is reduced

    - Studies of photoreaction of CsBr and alkali halides on metals and QE enhancement mechanism ongoing

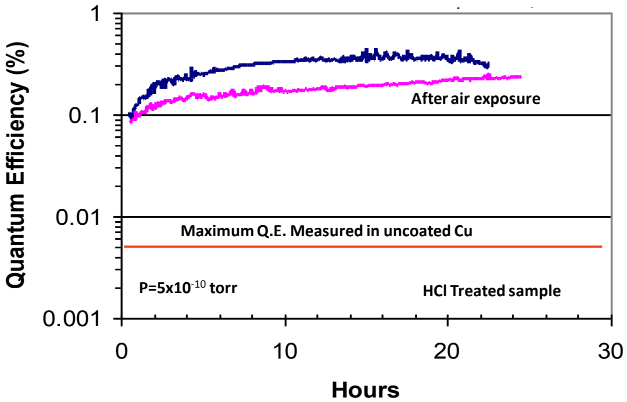
Photocathode physics II: towards photocathode material engineering

W. A. Schroeder (University of Illinois at Chicago) “Electron Effective Mass: Emittance and Efficiency”

- Dynamic transmission electron microscopy (DTEM)
  - Time-resolved diffraction and imaging examples
  - Electron source requirements for ultrafast (sub-ns) regime
  - ⇒ Spatial emittance reduction
- Experiment: ***Direct*** transverse rms momentum measurement
  - Two-photon thermionic emission (**2ωTE**) from Au ($2\hbar\omega < \phi$)
- GaSb and InSb photocathodes
  - Excited state thermionic emission (**ESTE**); $\hbar\omega < \phi$
  - Electron effective mass (m^*) effects …
- Metal photocathodes (Ag, Ta, Mo, and W)
  - Single-photon photoemission (**1ωPE**); $\hbar\omega > \phi$
  - Preliminary results analysis (incl. Cu and Mg)

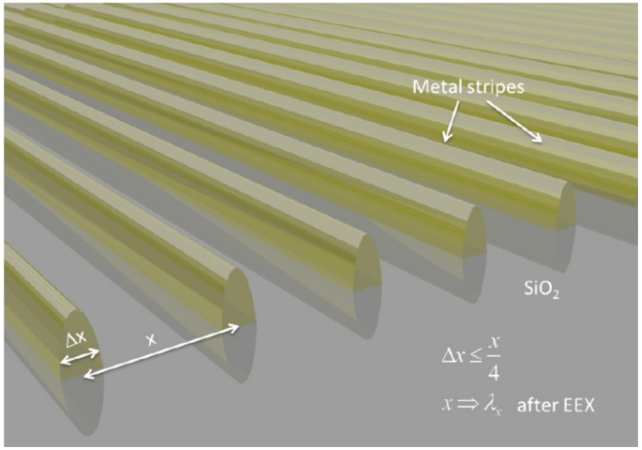


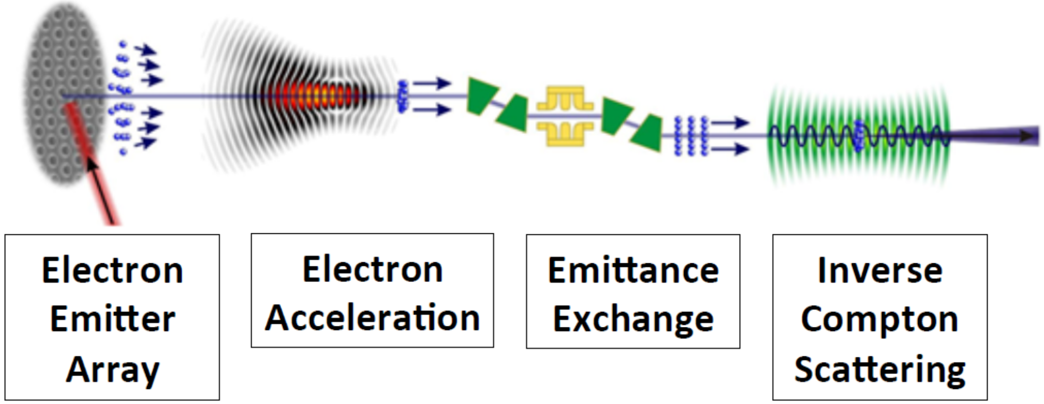
- Juan Maldonado (SLAC): “Status of CsBr Photocathodes ”
  - CW Performance of CsBr photocathodes
  - Energy Spread/Emittance Measurements
  - Pulsed Behavior



Photocathode physics II: towards photocathode material engineering

- R. Hobbs (MIT) “Nanostructured Photoelectron Emitters for Electron Beamlet Array Generation”





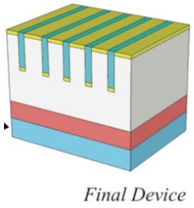
Electron Emitter Array

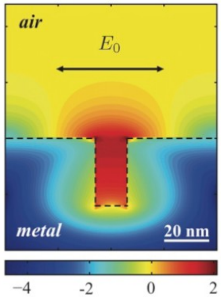
Electron Acceleration

Emittance Exchange

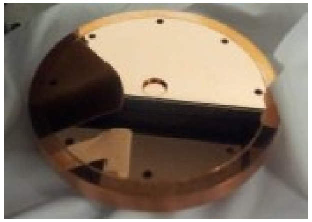
Inverse Compton Scattering

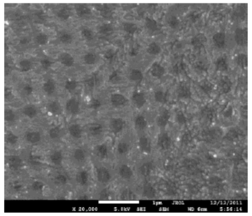
- D. Keathley (MIT) “High Aspect Ratio Si Photoelectron Emitter Arrays ”
- A. Polyakov (LBNL) “Nano-cavity plasmonic photocathodes ”
  - Nanogroove grating





- P. Musumeci (UCLA) “Grating based plasmonic photocathodes ”
  - First RF photoinjector test successful





Future outlook and collaborations

- D. Sertore (INFN) “Cathode production and supply, useful things to track, photocathode website ”
  - In the last 15 years we have delivered about 120 cathodes mainly to DESY-FLASH and DESY-PITZ
  - We have a mean operative lifetime of the cathode (24/24h 7/7d) of about 3 months with FLASH parameter (1 nC, 800 ms, 10 Hz, 42 MV/m)
  - Mean QE at delivery is about 10 % (l=254 nm)
  - Cathode systems: carriage evolution, transport system (+LBNL box)
  - The Photocathode Database

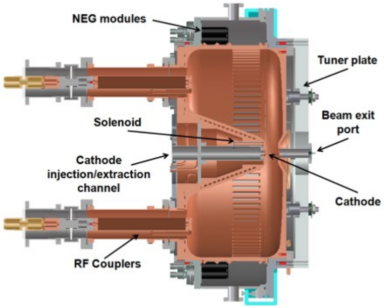
- S. Karkare (Cornell) “Update on the photocathode wiki-project ”
  - Photocathode look-up table
  - Photocathode preparation details
  - Photocathode theory
  - Photocathode diagnostics and surface characterization
  - Collaboration portal

  URL - http://photocathodes.chess.cornell.edu

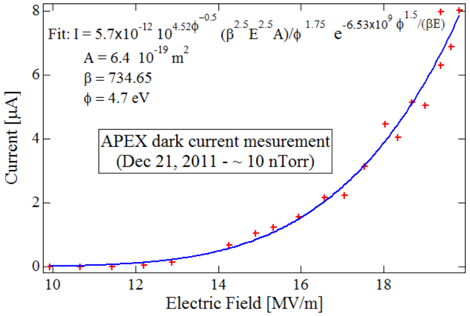
Future outlook and collaborations

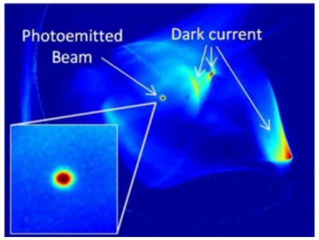
F. Sannibale (LBNL) “LBNL gun as a test venue for various cathodes ” (APEX at LBNL as a Photocathode Test Facility)

Gun technology fully demonstrated!
F. Sannibale, *et al.*, PRST-AB 15, 103501 (2012)



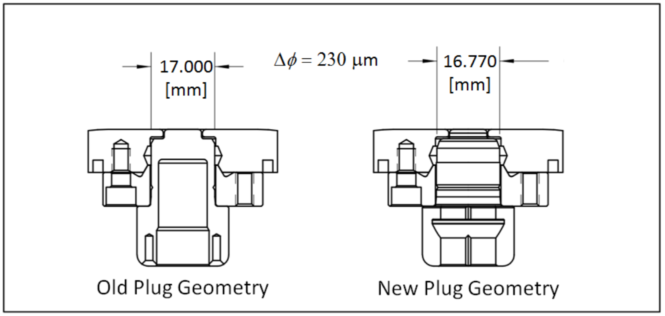
Frequency	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0 (ideal copper)	30887
Shunt impedance	6.5 MΩ
RF Power @ Q_0	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm²
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-10}-10^{-9} Torr



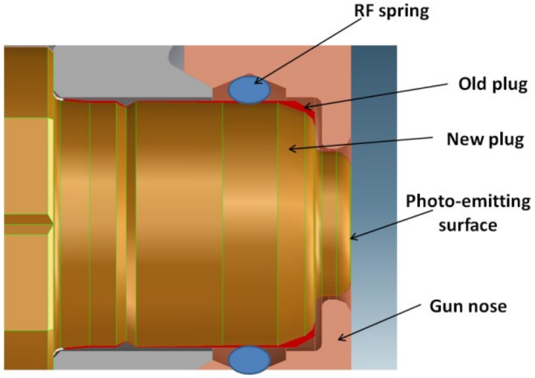


2nd generation: modified version of the INFN/FLASH plug for reducing field emission (used by FNAL and others).

Problems with the insertion/extraction operation damaging the RF spring pushed us to modify the cathode plug



3rd GENERATION CATHODE PLUG (PUCK)

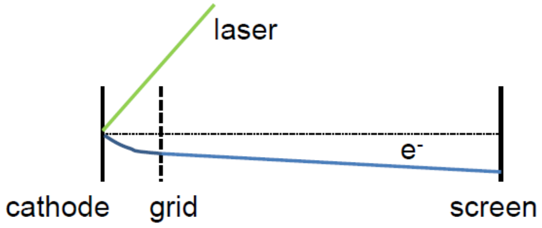


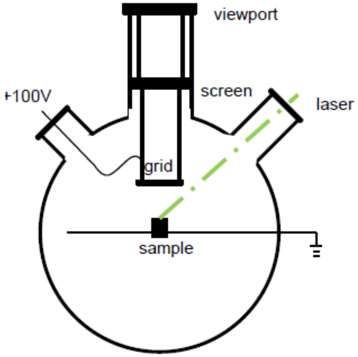
- **Smaller spring “invitation” angle: 20º instead than 30º**
- **Slightly smaller diameter (-230 μm) at the RF spring contact**
- **Gold plated stainless steel RF spring with no discontinuity**

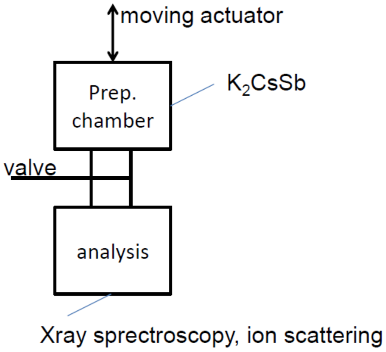
Future outlook and collaborations

- M. Schmeißer (HZB) „German-Russian collaboration on high-brightness photocathodes“
  - emittance measurements → slit method
  - in-situ QE and emittance measurements of the prepared cathodes

Idea:
Emittance measurement similar to Theo Vecchione‘s work



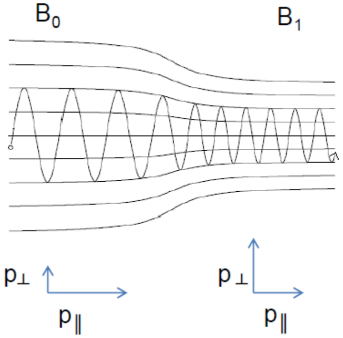


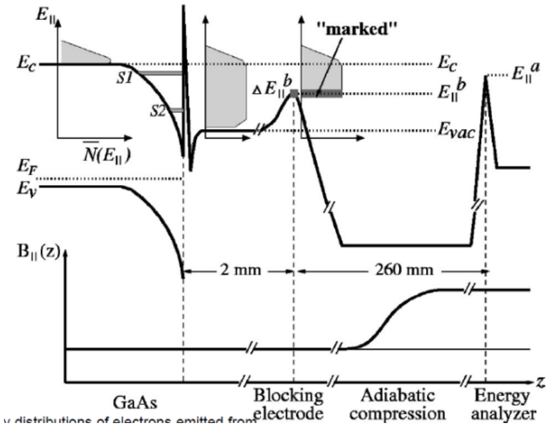


- German-Russian Collaboration involves:
  - Helmholtz Centres Berlin and Dresden-Rossendorf
  - Mainz University
  - Inst. for nuclear physics at Lomonossov University, Moskow
  - Polytechnical University St. Petersburg

Work Items:
- Modeling and initial measurements of K2CsSb emission, retarding field energy analyzer
- Operational testing in DC and SRF gun, response time measurements, cathode transport system

- Magnetic mirror based emittance meter: Concept:
  - e- bunch in a magnetic guiding field compresses if field strength increases (and vice versa)
  - measure shift in longitudinal energy in retarding
  - field analyzer





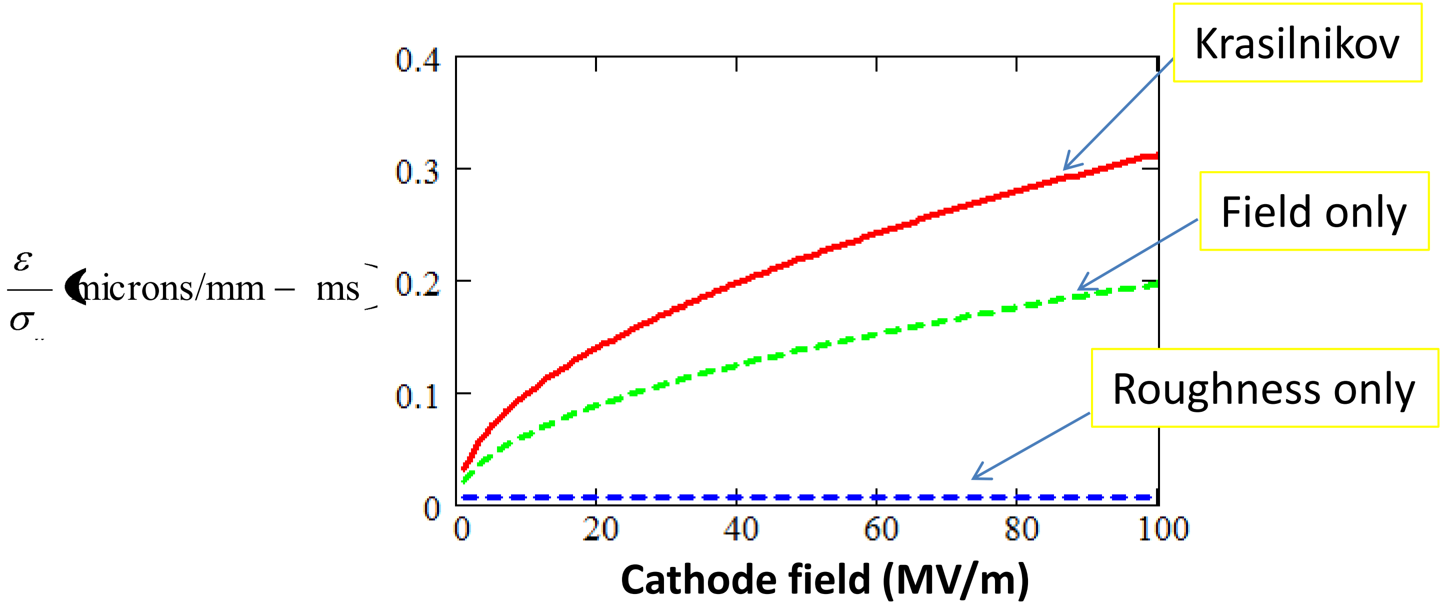
Unresolved Questions

- What is the role of dopant(s) for NEA and PEA cathodes?
- How important is band bending in NEA cathodes?
- Reconcile non-uniform stiochiometry with uniform, and high, QE of antimonides
- “Prescriptions” for alkali antimonide cathode formation – how do we understand the differences, and which is best?
- The “payoff” from developing NEA III-V cathodes to what we believe their potential to be is ENORMOUS – a truly COLD emitter
- …

Conclusions

- Photocathode/emission is one of key studies at PITZ
  - available
  - rel. not expensive
  - BUT still not in comprehensive use
- QE, QE-maps, life time as functions of many PI parameters!
- Photo emission vs. machine parameters
- New photocathode types?
- Field enhancement in semiconductor photocathode?

Comparison of Roughness Models



Krasilnikov model

$$\varepsilon_x^{D} \approx 2\sigma_x \sqrt{\frac{eE_0}{mc^2} h \left(1-\frac{1}{\sqrt{1+\xi}}\right)}$$

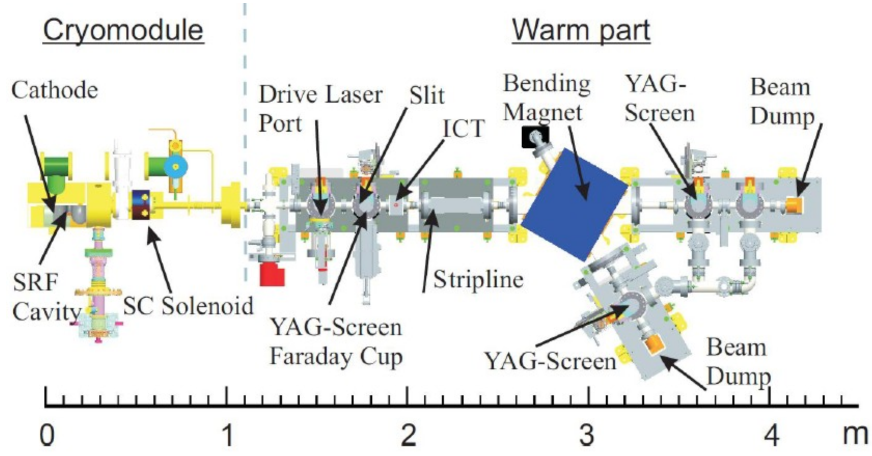
Current model

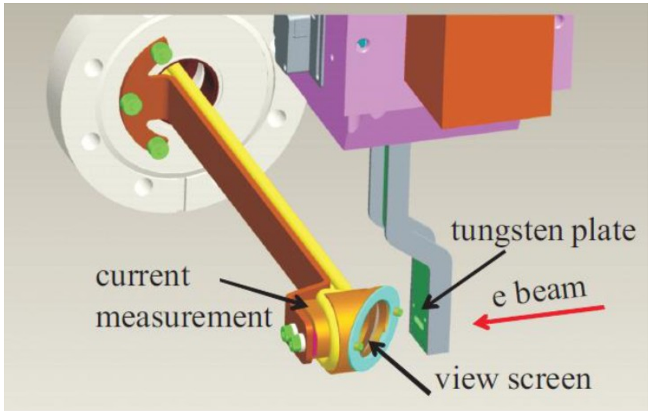
$$\frac{\varepsilon_{\text{intrinsic}+\text{tilt}+\text{field}}}{\sigma} = \sqrt{\frac{(\hbar\omega - \phi)}{3mc^2}\left[1 + \frac{(a_n k_n)^2}{2}\right] + \frac{\pi E_0}{4k_n mc^2}(a_n k_n)^2}$$

The Krasilnikov model because of it’s assumptions it doesn’t give the roughness/tilted surface emittance, instead it is more like the field emittance.

Future outlook and collaborations

- M. Schmeißer (HZB) „German-Russian collaboration on high-brightness photocathodes“
  - Emittance measurements





- Magnetic mirror based emittance meter