Photocathode Recipes for Bialkali K_2CsSb

Photocathode Physics for Photoinjectors Workshop
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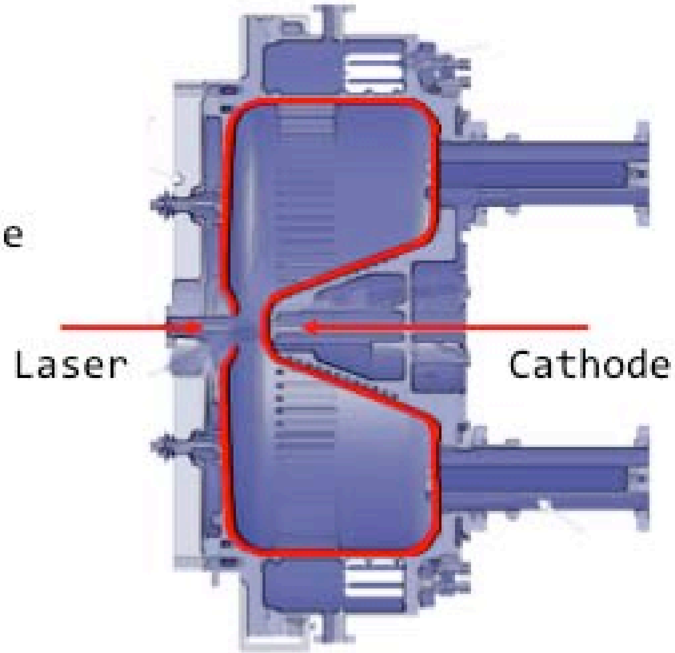
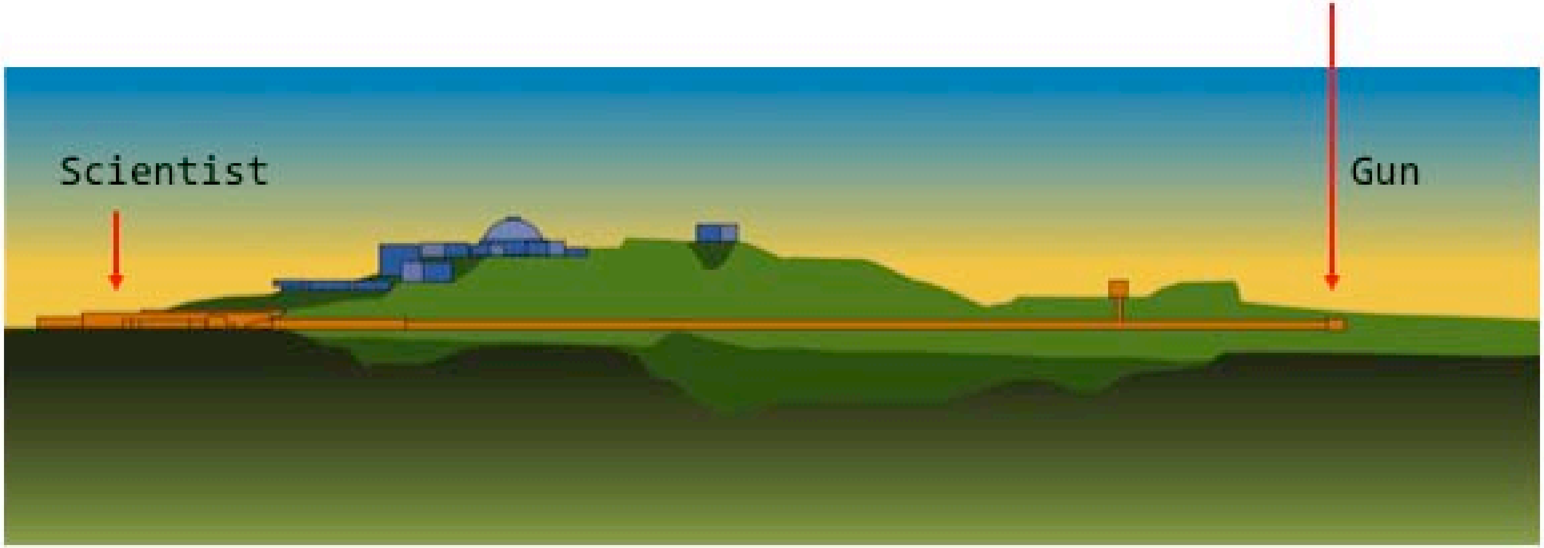
NGLS: Motivation for LBNL Photocathode Research

RF photo-injector for high rep rate X-FEL

- repetition rates up to ~ 1 MHz
- charge per bunch from tens of pC to ~ 1 nC
- < 10^{-7} (low charge) to 10^{-6} m normalized emittance
- beam energy at the gun exit > than 500 keV
- E field at cathode > 10 MV/m
- bunch length from tens of fs to tens of ps

- 10^{-9} - 10^{-11} Torr operation vacuum pressure allows for high QE photo-cathodes!





Bialkali Photocathodes in RF Guns Pioneered at LANL

1993

433 MHz RF Gun

26 MV/m E Field

53 psec pulse length

132 A peak current

3-5 mm FWHM cathode spot size

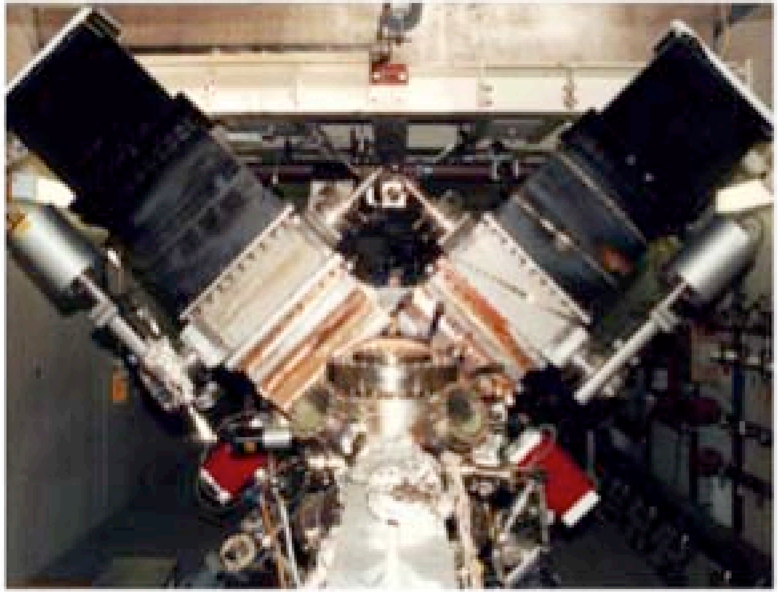
up to 7 nC / pulse

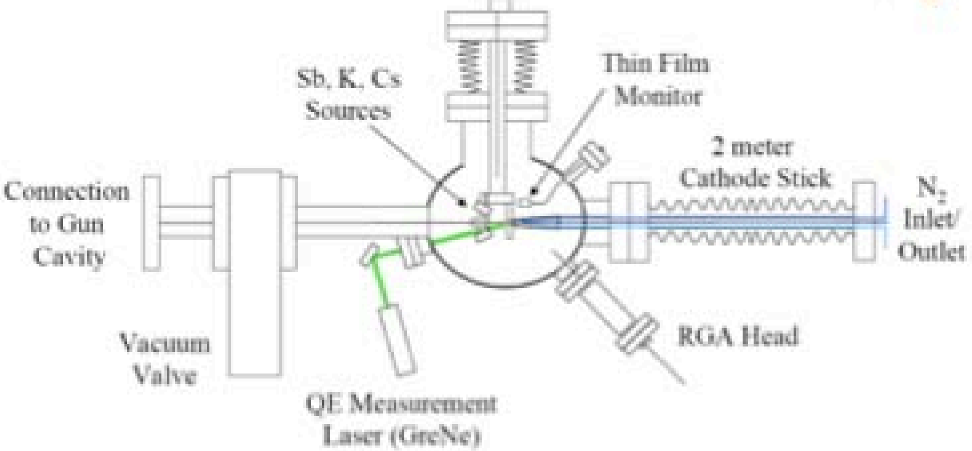
macro rate 30 Hz / micro rate 27 MHz

25% duty factor

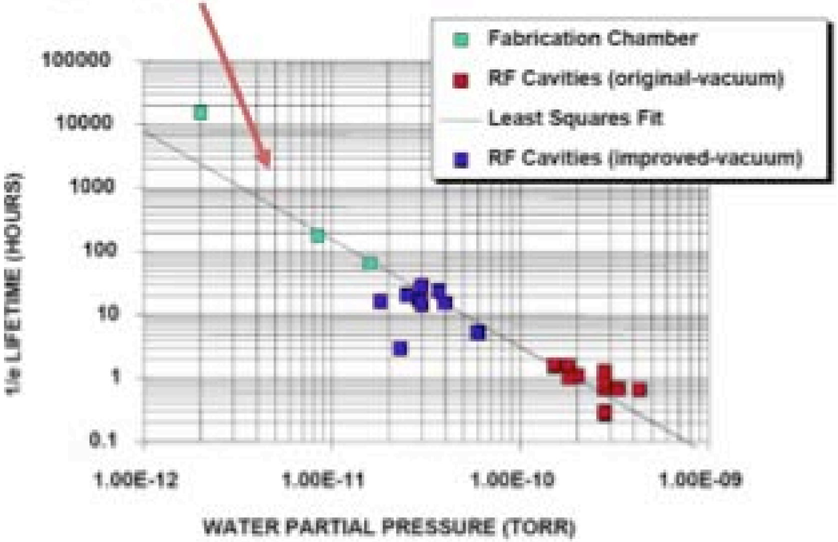
Current record holder?

- 18% QE w/ green laser





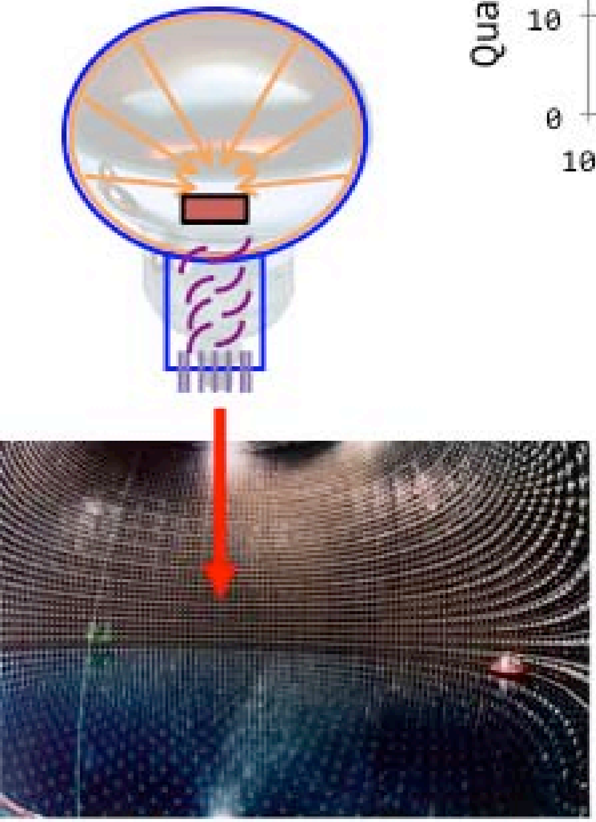
Long Lifetimes



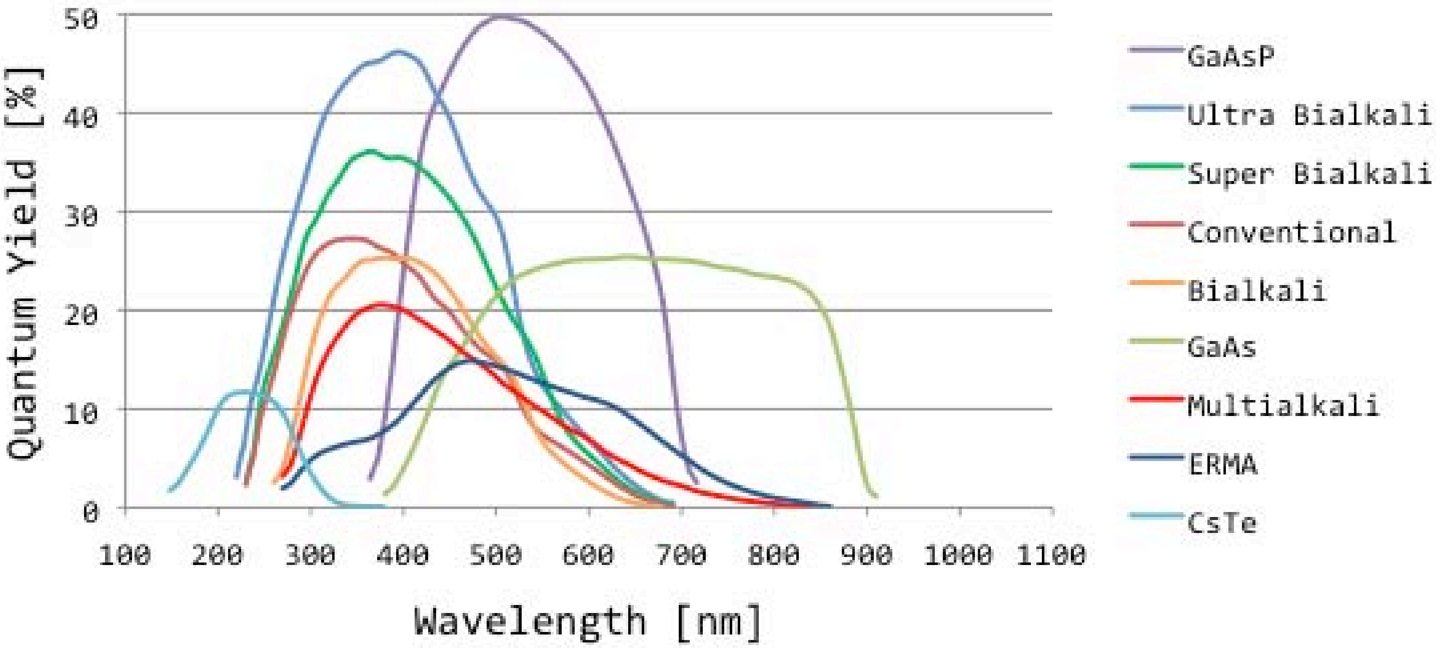
Learning from 60 Year History of Bialkali PMTs

Hamamatsu
PMT leader
4k employees
$200 M PMT sales

Super-Kamiokande
Neutrino Detector
11,200 20”
K_2CsSb PMTs



Spectral Response of Commercial Photocathodes



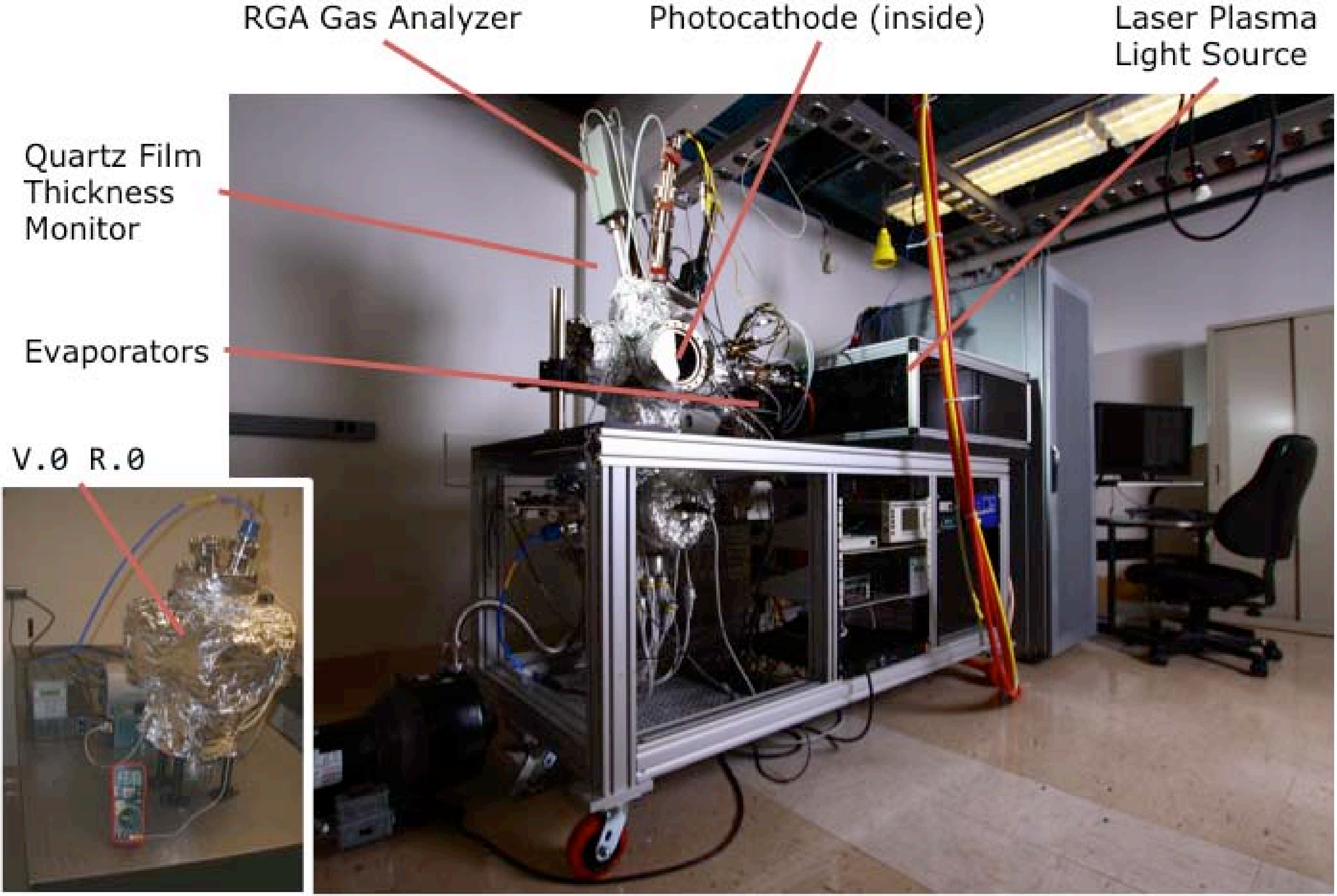
Source: Motohiro Suyama PoS(PD07)018 [Hamamatsu]

[MIRZOYAN R, 2007, NUCL INSTRUM METH PHYS RES A, V572, P449]
ENHANCED QUANTUM EFFICIENCY BIALKALI PHOTO MULTIPLIER TUBES

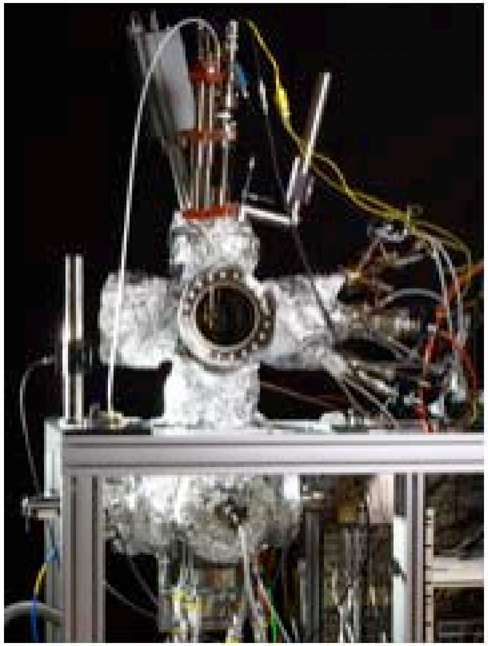
Classical bialkali PMTs peak QE ~ 25-27% (+40 years ago)
New bialkali PMTs with peak QE ~ 30-35%

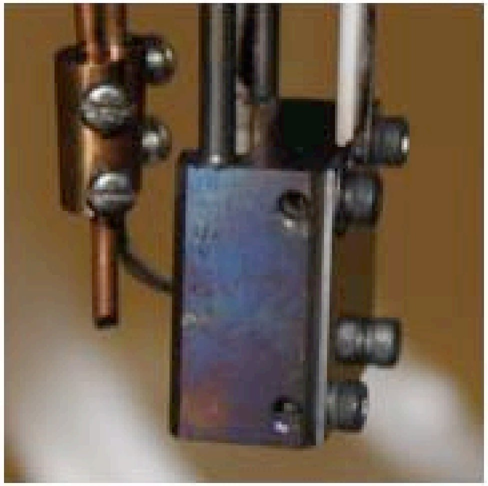
Factors that enhance QE of PMTs:
1) pure materials (e.g. > 99.9999%) provides less e- scattering
   i.e. e^- excited deep in bulk can contribute to emitted current
2) thickness - determines the peak position of max QE
3) composition - provides a wide and high spectral response..

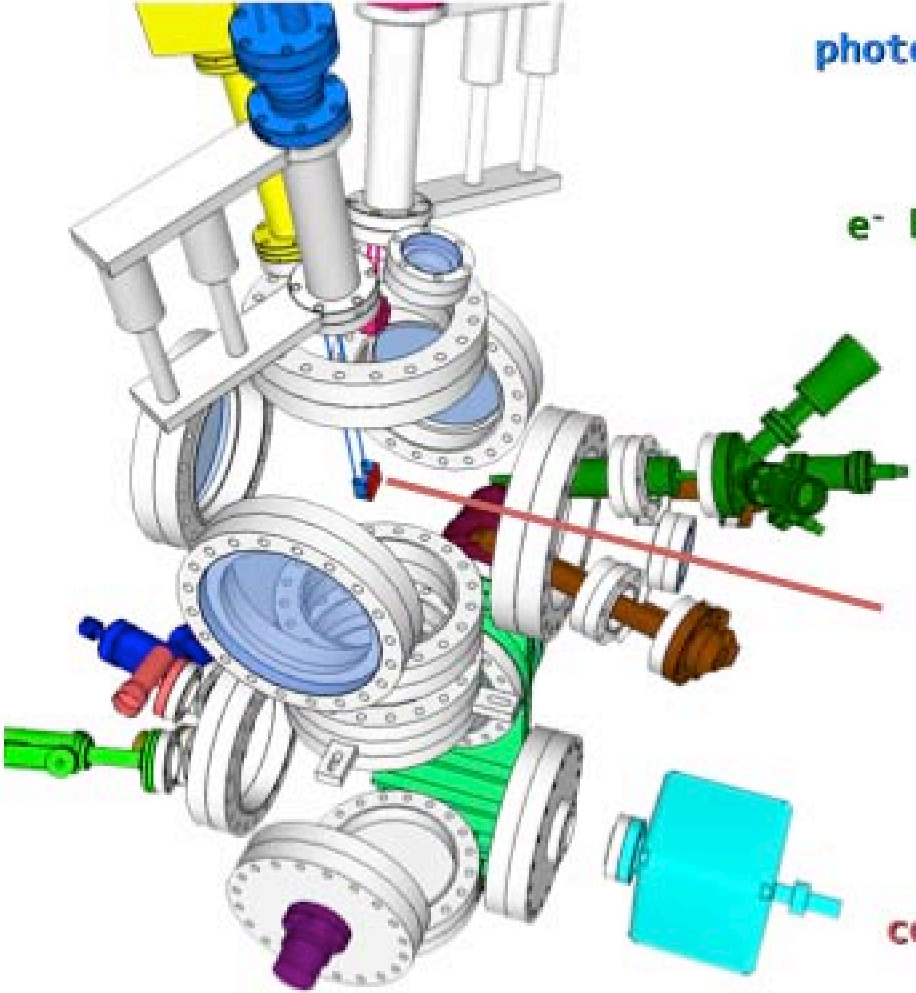
Bialkali Deposition Chamber V.1 R.∞



Deposition Chamber Component Diagram







quartz thickness monitor

photocathode holder

photocathode

e⁻ beam evaporator

effusion cells

turbo pump

gate valve

incident light

ion pump

neg pump

leak valve

convectron gauge

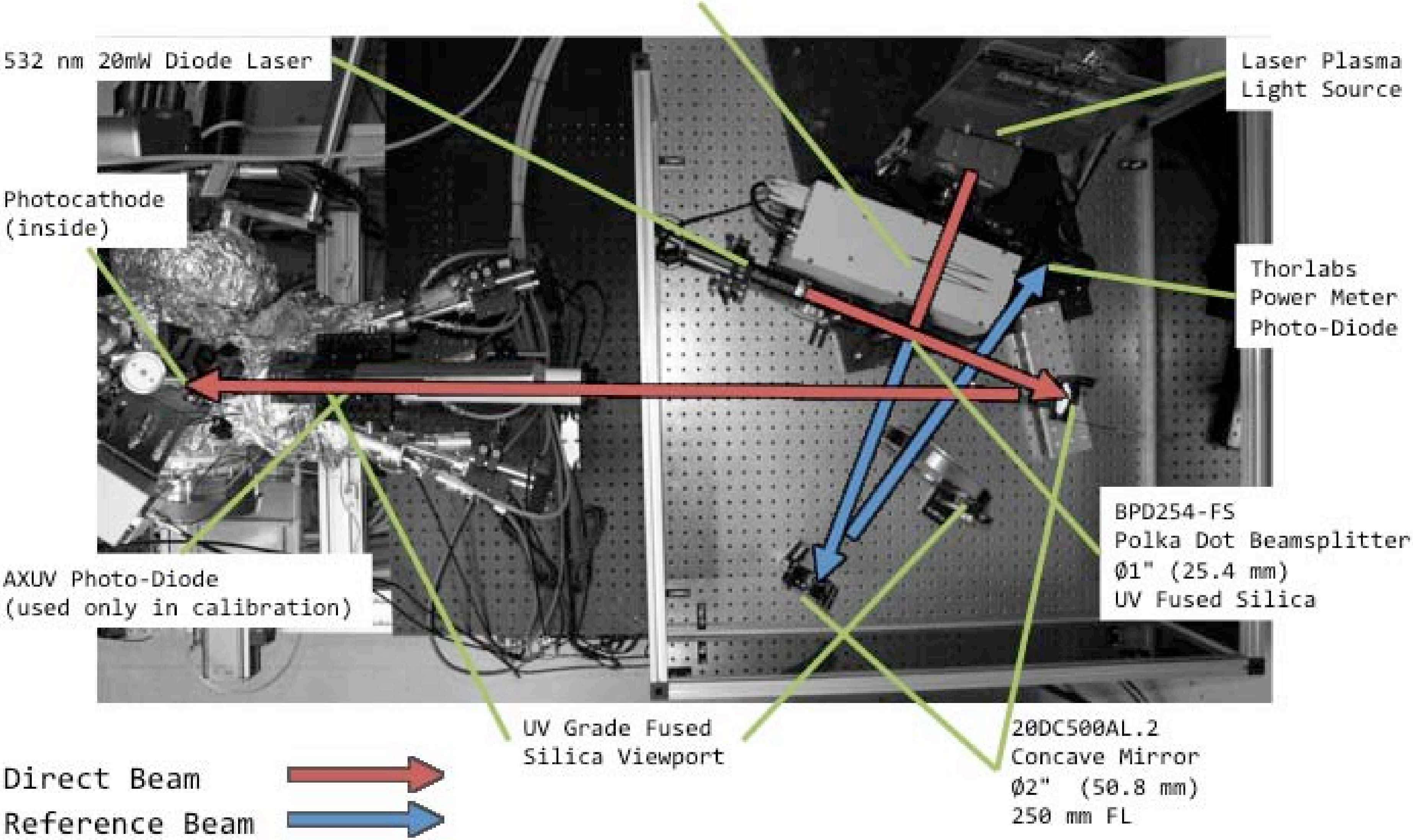
nude gauge

right angle valve

Optics System Used to Monitor QE

Cornerstone Monochromoter, entrance slit 1mm exit slit 0.5 mm

Line Density	Blaze Wave	Type	1/Disp @ Blaze	Peak Eff	Primary Region	Upper Limit	Model
1200 l / mm	350 nm	Ruled	6.6 nm/mm	80 %	200 - 1600 nm	1600 nm	74024



532 nm 20mW Diode Laser

Laser Plasma
Light Source

Photocathode
(inside)

Thorlabs
Power Meter
Photo-Diode

BPD254-FS
Polka Dot Beamsplitter
Ø1" (25.4 mm)
UV Fused Silica

AXUV Photo-Diode
(used only in calibration)

UV Grade Fused
Silica Viewport

20DC500AL.2
Concave Mirror
Ø2" (50.8 mm)
250 mm FL

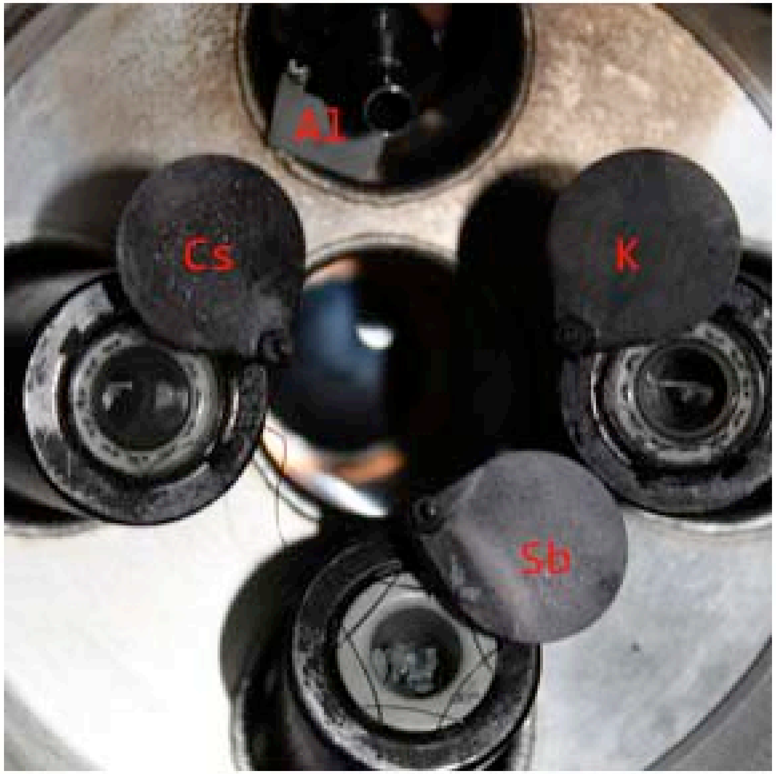
Direct Beam

Reference Beam

Low Temperature Effusion Cells for Sb, Cs and K

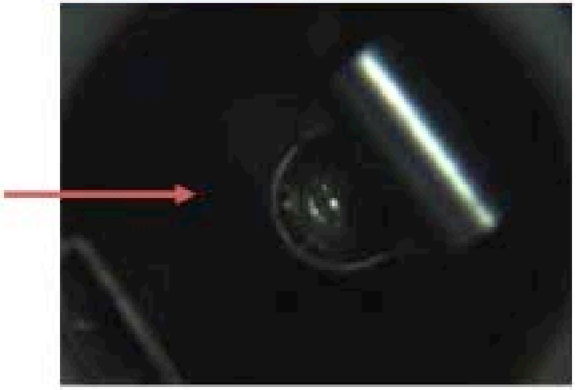
Dr. Eberl MBE-Komponenten GmbH

Alvatec Alkali Sources

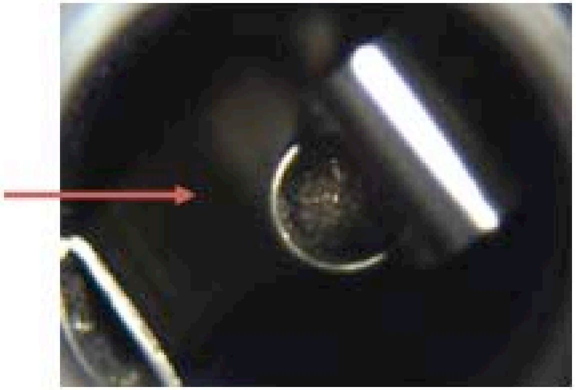


the last thing a new cathode ever sees…

After 24 h @ 200 °C there is still indium at the entrance of the source



Increasing temperature to 300 °C and the indium appears to disappear in 10-15 min



Conventional Bialkali Recipes from the Literature

[GHOSH C, 1978, J APPL PHYS, V49, P4549]
PREPARATION AND STUDY OF PROPERTIES OF A FEW ALKALI ANTIMONIDE PHOTO CATHODES

First K_3Sb is made, then cesiated to form K_2CsSb
1) K is deposited on a phototube at 180 °C till a very small photosensitivity is registered
2) Sb is deposited until peak photosensitivity is reached
3) if terminal step: while cooling K is deposited at a slower rate to compensate for losses
   otherwise: Cs and Sb are deposited at a rate adjusted to maintain a steady rise in photosensitivity
   (temp unclear, either 180 or 160 °C)

[TERNES RL, 1992, NUCL INSTRUM METH PHYS RES A, V318, P401]
A STATISTICALLY DESIGNED EXPERIMENT FOR ASSESSING CESIUM POTASSIUM ANTIMONIDE PHOTOCATHODE FABRICATION PARAMETERS

5 variables: Sb thickness, K thickness, source temp, Cs temp rampdown, substrate temp
Tests seem to be sequentially applied to the same substrate with new alkali materials switched midway
Total of 47 photocathodes: 24 initial combinations, 11 replicates, 12 complementary tests
Deposition Order = Sb -> K -> Cs; Substrate ramping = 140°C Sb -> 130°C K -> 130°C Cs deposition
Sb and K depositions performed to predetermined thickness
Cs deposition allowed to proceed such that the QE of the photocathode was maximized
Photocathodes were cooled to 70°C and QE was measured (130°C to 70°C required ~ 40 min)
160°C substrate temperature without ramping setting resulted in **negligible QE**
140°C substrate temperature with ramping resulted in **6.1% average QE**
100°C substrate temperature without ramping setting resulted in **1.8% average QE**

[DIBONA A, 1997, NUCL INSTRUM METH PHYS RES A, V385, P385]
DEVELOPMENT OPERATION AND ANALYSIS OF BIALKALI ANTIMONIDE PHOTOCATHODES FOR HIGH BRIGHTNESS PHOTO INJECTORS

Recipe for 2.5% QE at 532
1) The MO substrate is baked at 450°C for several hours
2) 5 nm of Sb are deposited at 0.1 nm/s at 110°C
3) K is deposited at 0.1 nm/s till photocurrent maximized, typically after 20 nm of deposition
4) Cs is deposited in same manner as 3)

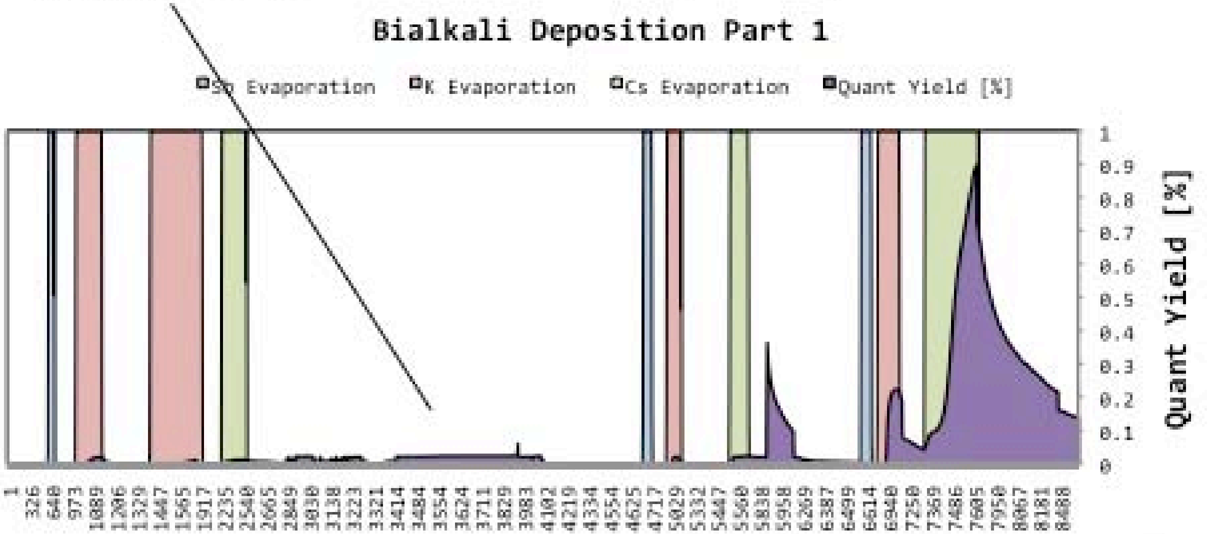
Recipe for 5% QE at 532
1) Mo substrate baked at 450°C for several hours, cooled, then bombarded w/ 3 kV Ar^+ ions (2 A/cm^2)
2) 5 nm of Sb is deposited at 0.5 nm/min at 120°C
3) 3 nm of K is deposited at 1 nm/min
4) Cs is deposited at 2 nm/min till photocurrent maximized
5) Substrate is heated to 230°C for 1 h then lowered to 120°C
6) K is evaporated at 1 nm/min till photocurrent maximized

A Complex Recipe to Produce Bialkali Photocathodes

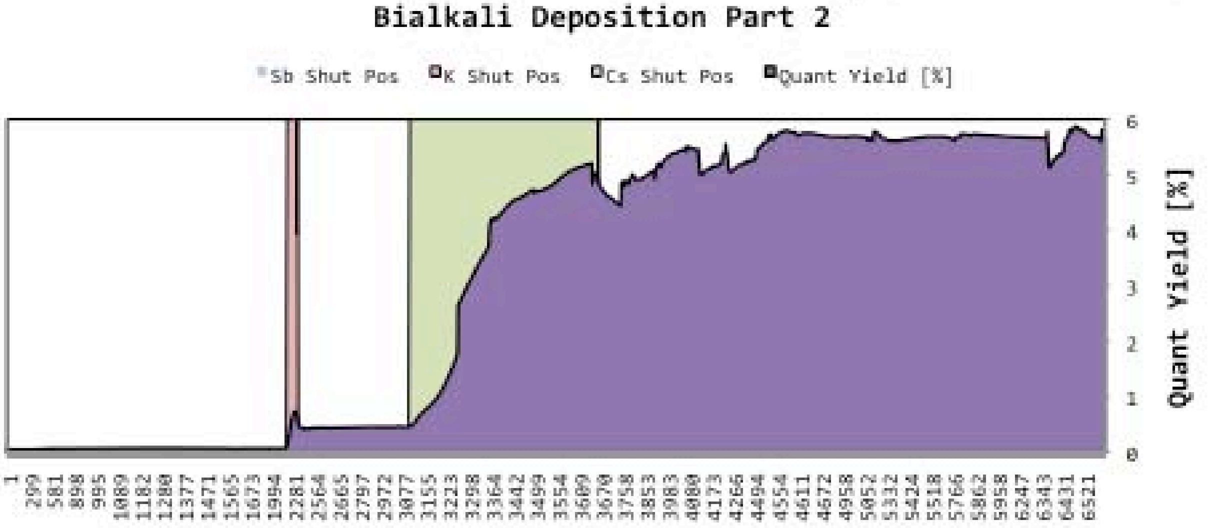
1st 50 Å deposition of Sb
1st deposition of K
QE increases to max value, then decreases
QE doesn't return, so 2nd deposition of K
QE increases, then decreases (again)
QE doesn't return, so 1st deposition of Cs
QE increases, then saturates at low value
Deposition stopped, cathode heated to 550 °C
2nd 50 Å deposition of Sb
2nd deposition of K
QE increases to max value, then decreases
QE doesn't return, so 2nd deposition of Cs
QE increases, then saturates at low value
Deposition stopped
3rd 50 Å deposition of Sb
4th deposition of K
QE increases to max value, then decreases
QE doesn't return, so 3rd deposition of Cs
QE increases to max value, then decreases
Deposition stopped
Next Day…
5th deposition of K
QE increases to max value, then decreases
QE doesn't return, so 4th deposition of Cs
QE increases, then saturates at high value
Deposition completed

Notes:
1: Cathode held at ~ 150 °C unless otherwise indicate
2: Choppy regions of data are actually missing data
from when spectral response scans are taken.

Flash to 550 °C

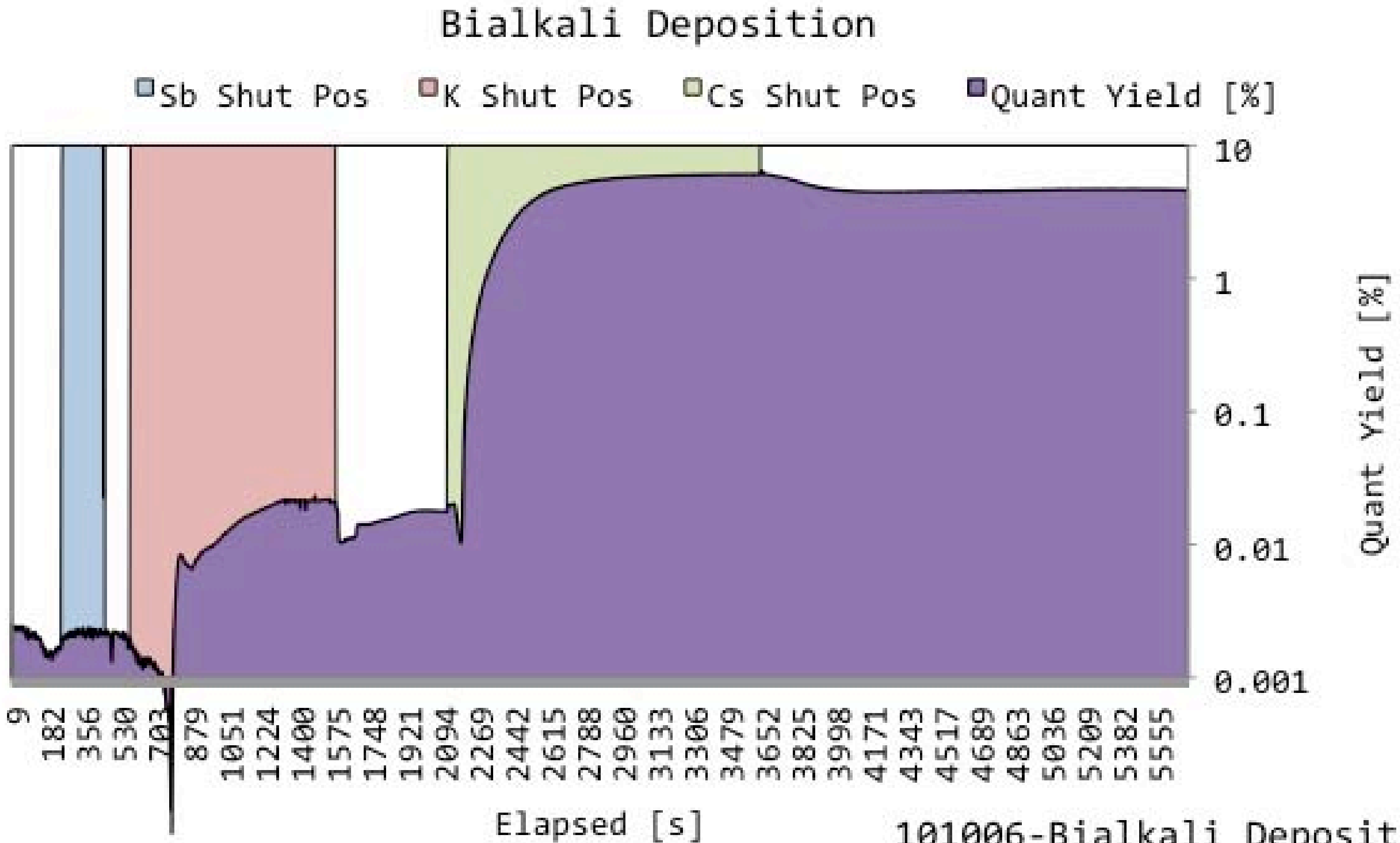


100404-Bialkali Deposition Part 1.xlsx



100404-Bialkali Deposition Part 2.xlsx

Much More Simple Recipe Yields Same Result



101006-Bialkali Deposition.XLSX

Initially cathode cleansed at 600 °C

200 Å deposition of Sb at 190 °C

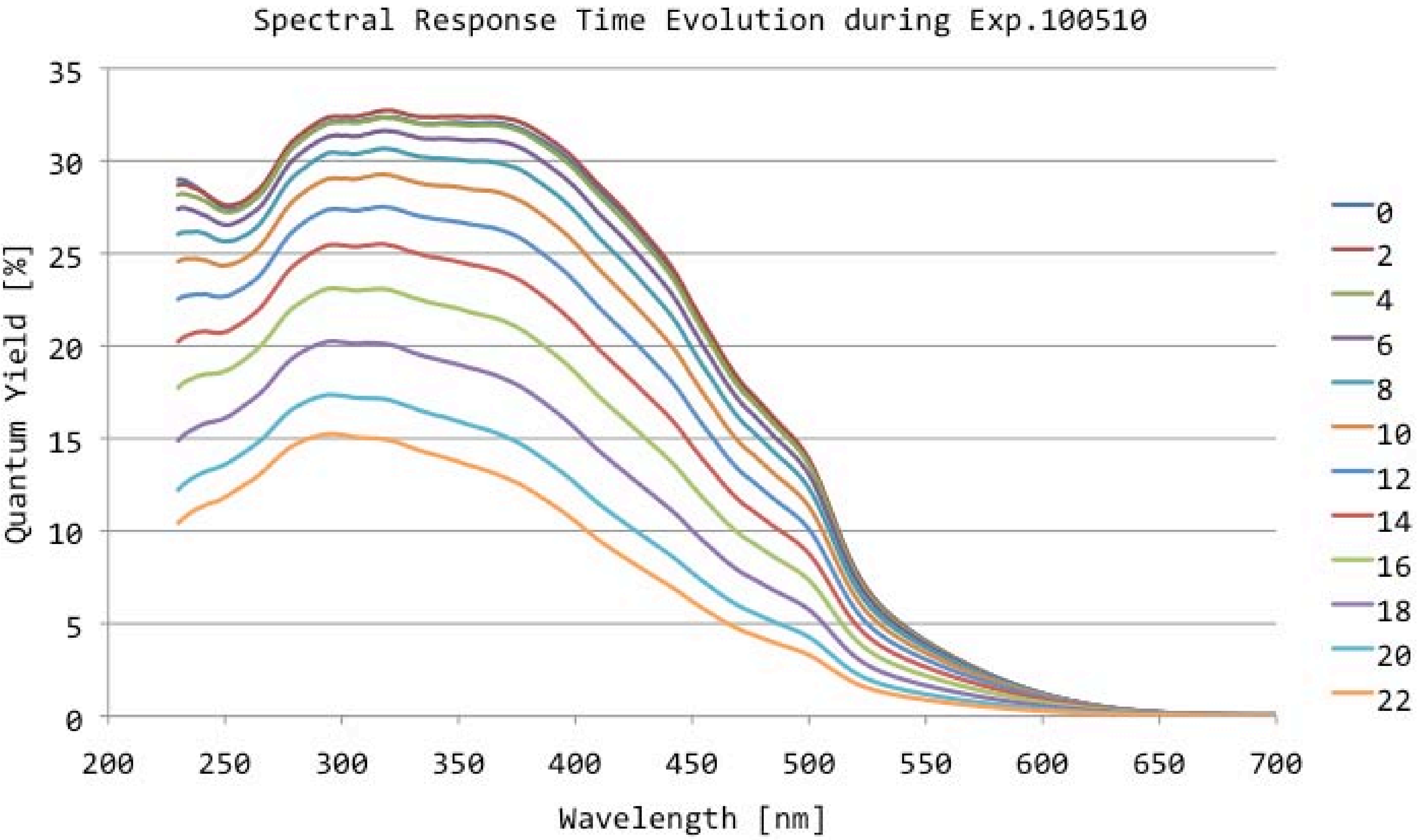
Deposition of K at 140 °C

Deposition of Cs at 120 °C

Max QE reached 6%, stabalized after cooling to r.t. at 4.5%

Typical time-evolution of QE curves

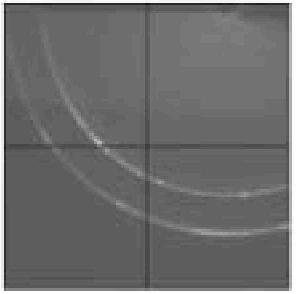
Approximately 20h for QE to fall by ½ at 5×10^{-9} torr H_20



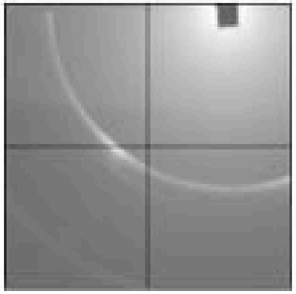
Characterization of K_2CsSb using X-Ray Techniques

- mixture of Mo substrate (continuous) and antimonide diffraction (discontinuous rings)
- dots in rings are individual single grain reflections
- indicates grainy thin film (see AFM)
- radial integration with Mo subtracted
- double peaks indicate 2 phase material

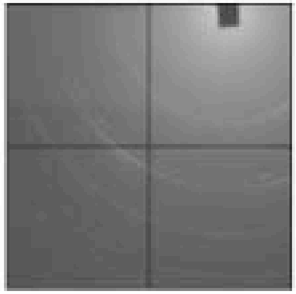
Aluminum



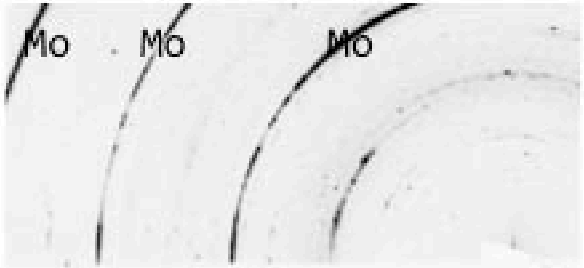
Mo



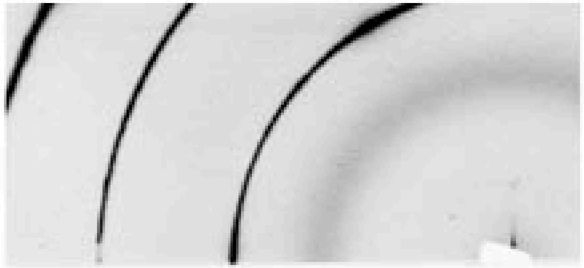
Alkali



XRD - 0.7° grazing incidence

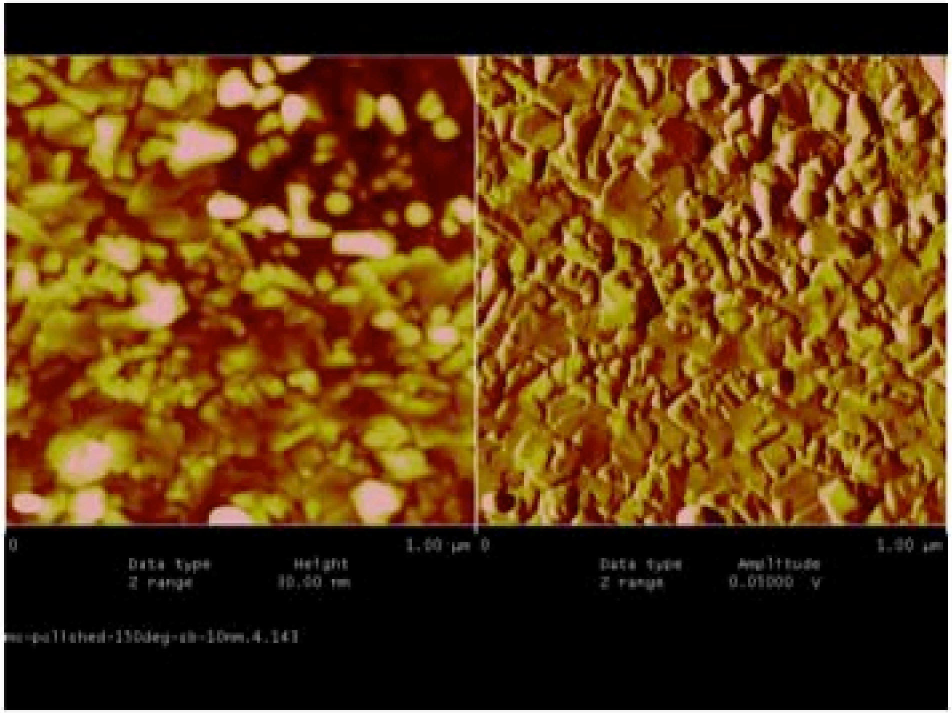


On large K,Cs-rich particle

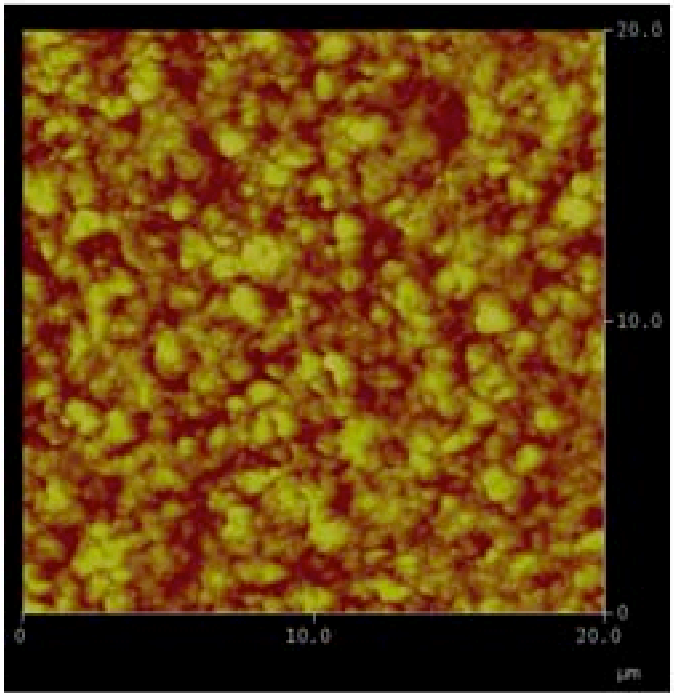


Off large particle

Characterization of Surface Roughness Using AFM



AFM of 20 nm Sb deposited on Mo at 150C
- average grain size ~ 50 nm
- average grain height ~ 20 nm



AFM of K_2CsSb reacted on Mo at 150C
- average grain size ~ 1 micron
- average grain height ~ 100 nm

will roughness increase transverse momentum?

Conclusions

1.) The recipe: Sb -> K -> Cs can succeed on 1st iteration
High temp intermediate steps work but are not necessary

2.) Rapid cooling to room temperature may still be important
Slower cooling produces useable cathodes with reduced QE
Thought to be due to cesium losses

3.) Different recipes appear to produce similar results

4.) QE results so far are independent of substrate

5.) Surface roughness appears to be a problem
Effects on transverse emittance need to be quantified

6.) Cathode turn-around time is limiting our rate of progress
Each cathode requires a 2 week process
Rectifying this by implementing a load-lock system

*** Most Important ***

7.) We still don't know what we need to know…

In-situ characterization of surface morphology, crystal structure and chemical stoichiometry will be essential for properly understanding how these materials work and how to reliably produce them.