High QE, Low Emittance, Green Sensitive FEL Photocathodes using K_2CsSb

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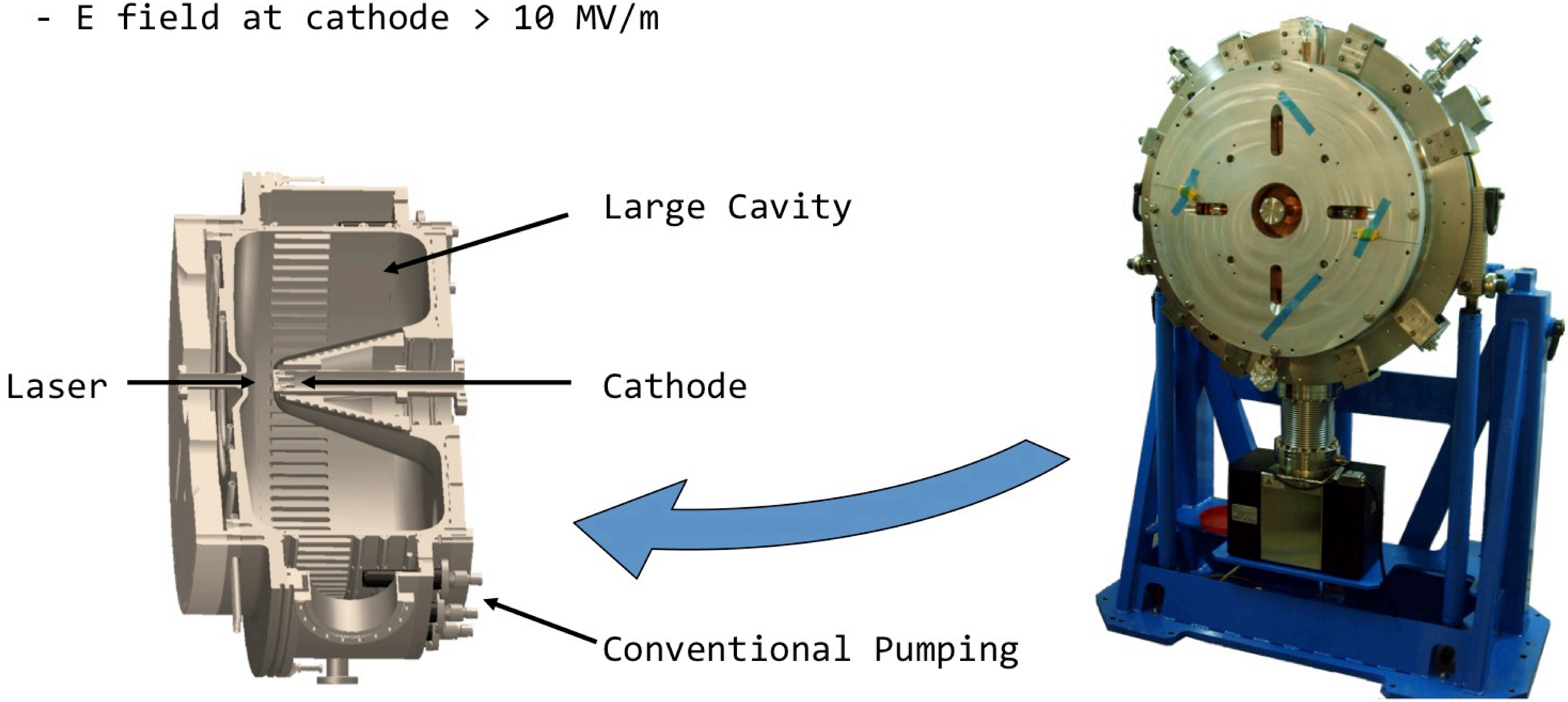
The NGLS (Next Generation Light Source) Injector

- bunch repetition rates up to 1 MHz
  - charge per bunch from tens of pC to 1 nC
  - bunch length from tens of fs to tens of ps

- normal conductive 187 MHz RF photo-injector
  - $< 10^{-11}$ torr vacuum
  - permits surface sensitive high QE photo-cathodes

- normalized transverse emittance < 1 μm / mm-rms beam size
- E field at cathode > 10 MV/m



Photocathode Requirements for the NGLS

1.) Low transverse emittance < 1 μm / mm-rms beam size

2.) High quantum efficiency > 1% in the visible

visible because
- easier transverse and longitudinal pulse shaping
- compact high power light sources – e.g. fiber laser

3.) Long lifetime > 1 week

4.) Robust performance

5.) Ease of production

Photocathodes may be the performance limiting component of 4^{th} gen light sources because emittance can be preserved once the beam leaves the gun

Choosing the Best-Suited Photocathode for the NGLS

Metal (e.g. Copper used at LCLS)
- fast response, < ps pulses
- relatively robust and un-reactive, ok for RF Guns
- typically 5e-5 QE in UV (3rd harmonic Ti:Sapphire)
- 1 nC @ 1 MHz reprate -> ~ KW of IR

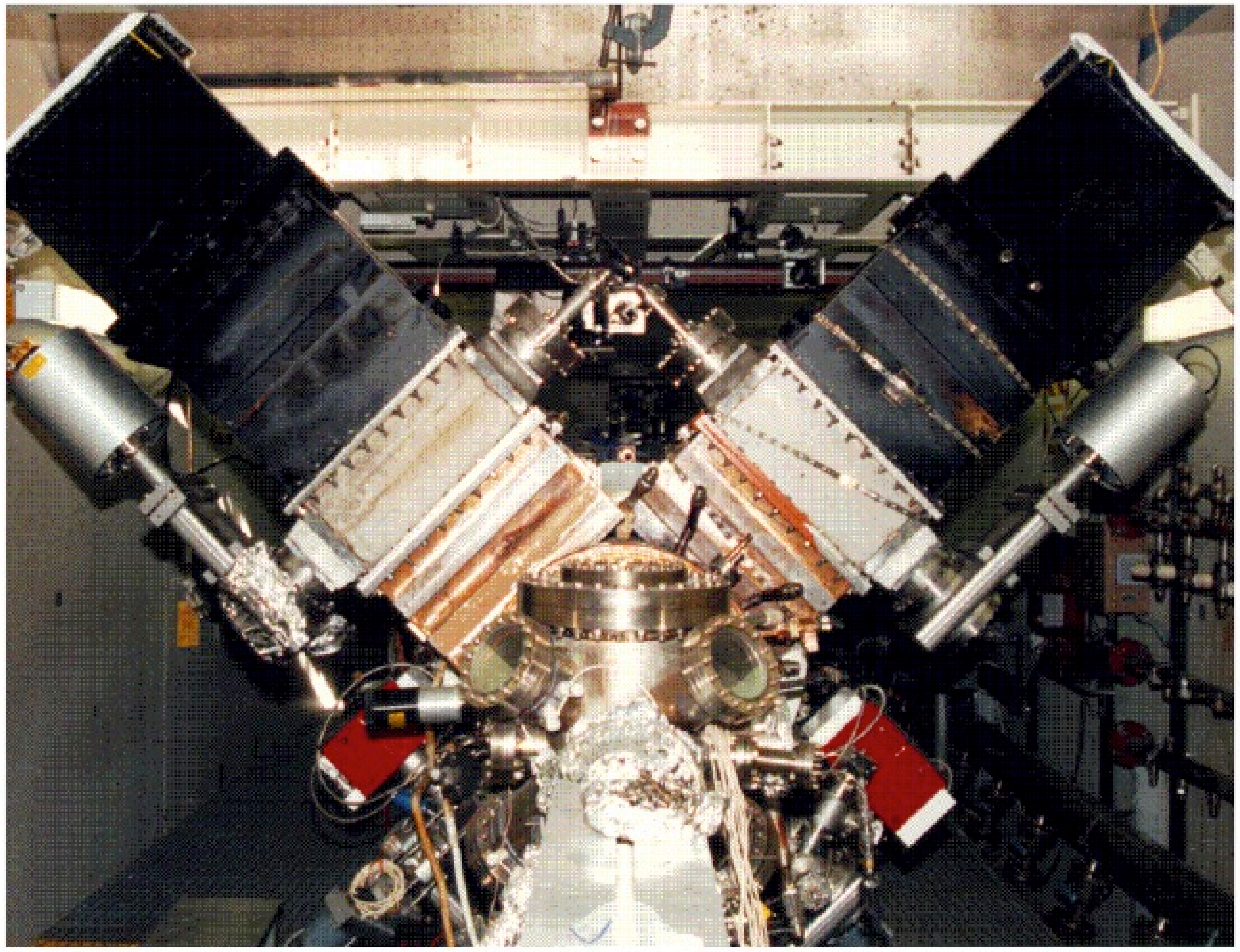
NEA Semiconductor (e.g. Gallium Arsenide GaAs:Cs:O used at Jlab)
- slow response, typically 40 psec for thick films
- extremely reactive, requires < 10^{-12} Torr pressure in DC Gun
- typically 10% QE in visible (frequency doubled Nd:YVO4)
- 1 nC @ 1 MHz reprate -> ~ mW of IR

PEA Semiconductor e.g. Cesium Telluride Cs_2Te used at FLASH
- fast response, < ps pulses
- relatively robust and un-reactive, operates at ~ 10^{-9} Torr
- typically 10% QE in the UV (3rd harmonic Ti:Sapphire)
- 1 nC @ 1 MHz reprate -> ~ W IR

PEA Semiconductor e.g. Alkali Antimonide K_2CsSb used at Boeing
- fast response, < ps pulses
- fairly reactive, requires < 10^{-10} Torr pressure
- QE > 1% in visible (frequency doubled Nd:YVO4)
- 1 nC @ 1 MHz reprate -> ~ mW of IR

Bialkali Photocathodes in RF Guns Pioneered at LANL and Boeing

D. Dowell et al. Nucl. Inst. Meth. **356** (2-3), 167-176 (1995).



433 MHz RF Gun

26 MV/m E Field

53 psec pulse length (long pulses)

132 A peak current (high current density)

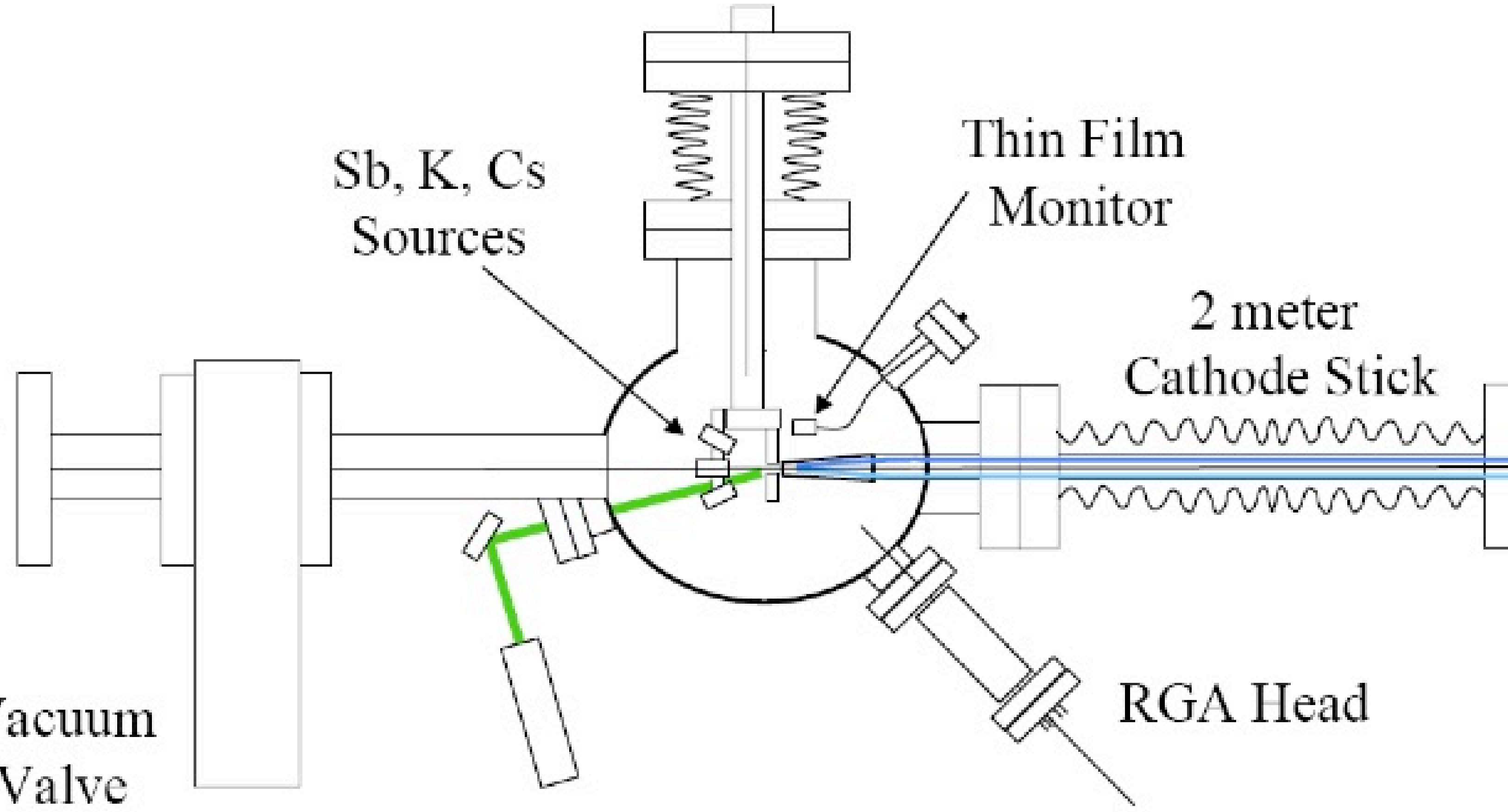
3-5 mm FWHM cathode spot size

up to 7 nC / pulse

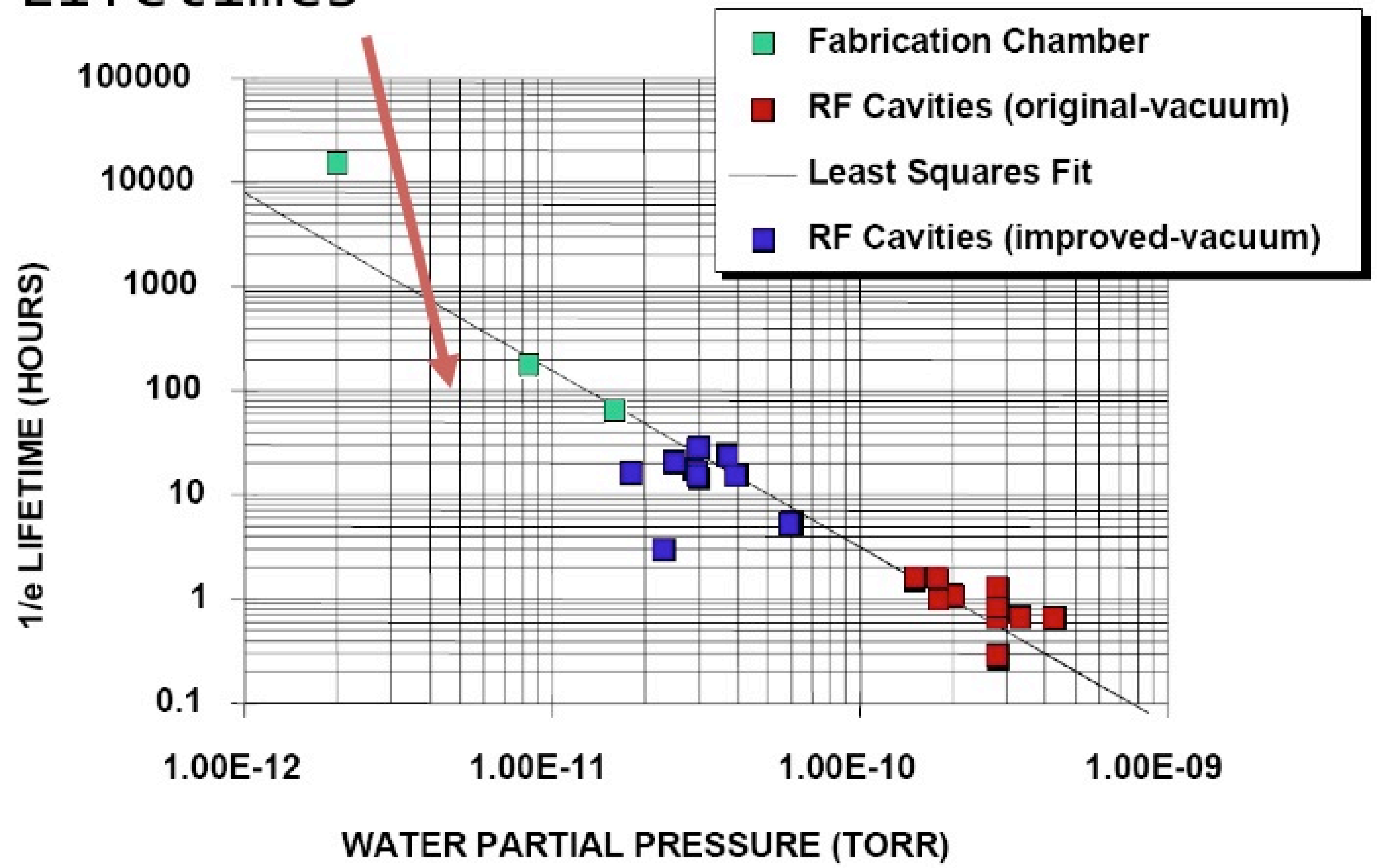
macro rate 30 Hz / micro rate 27 MHz

25% duty factor

Current record holder?
- 18% QE w/ green laser



Long Lifetimes



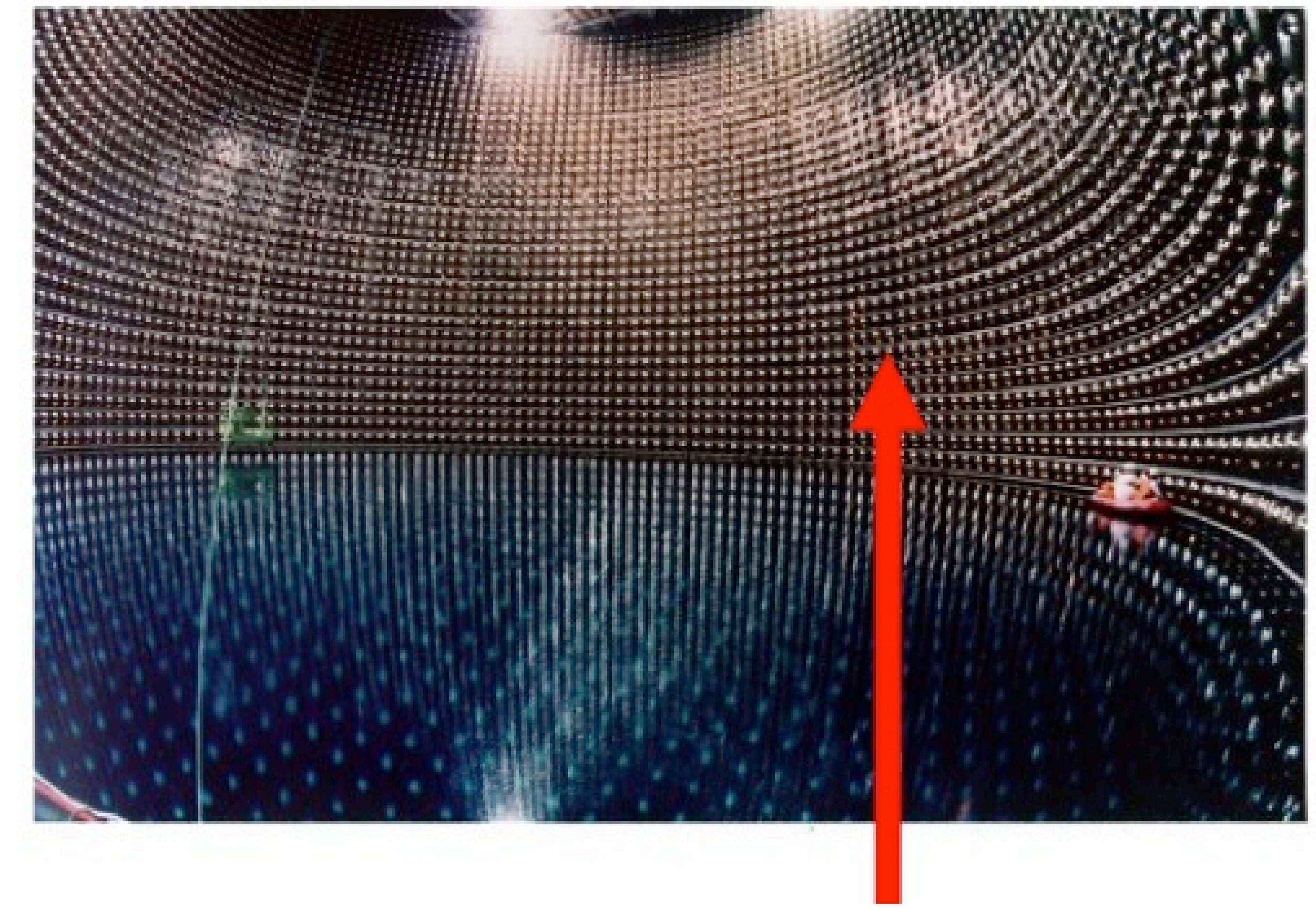
Most importantly: already used in RF photoinjector!

Learning from 60 Year History of Bialkali PMTs

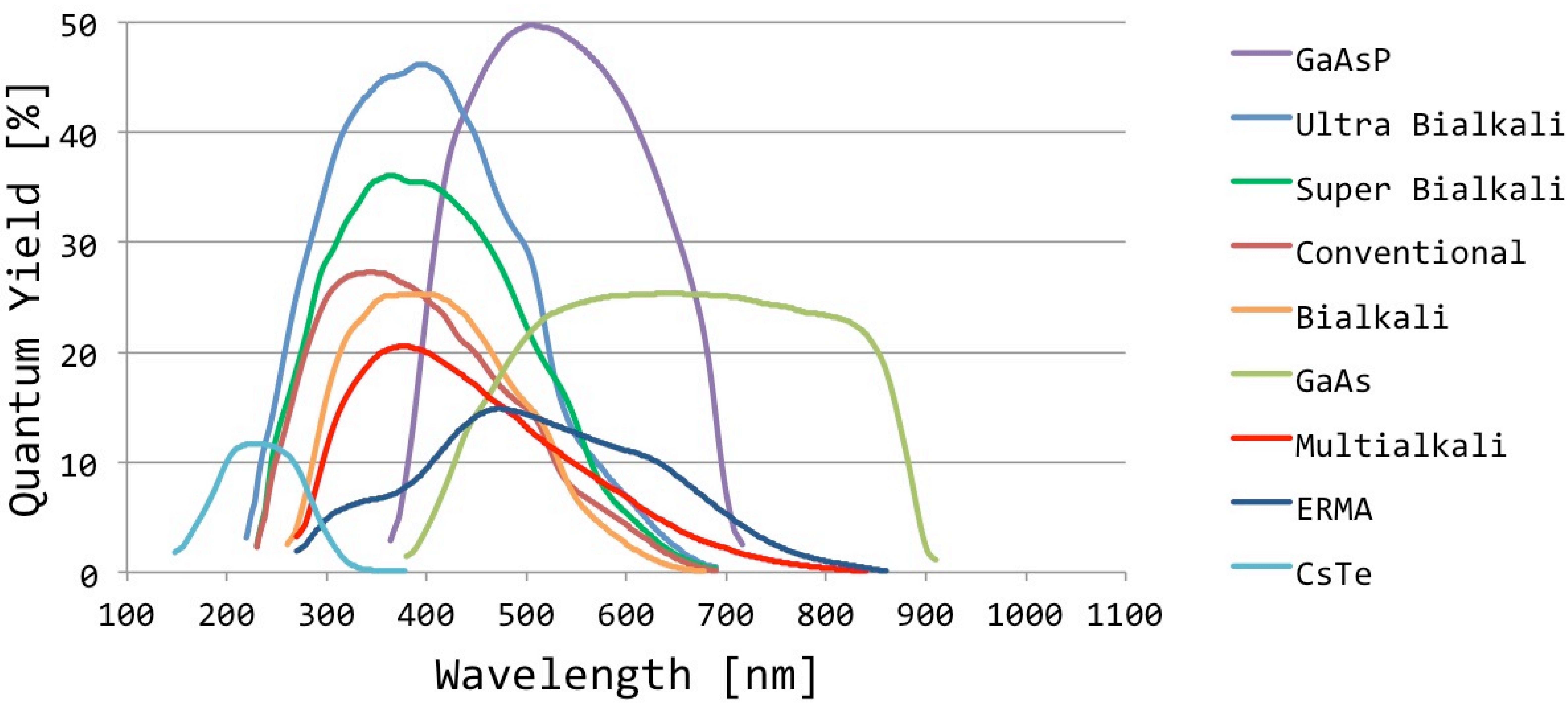
K_2CsSb discovered by Sommer in 1950's

Bialkali PMTs:

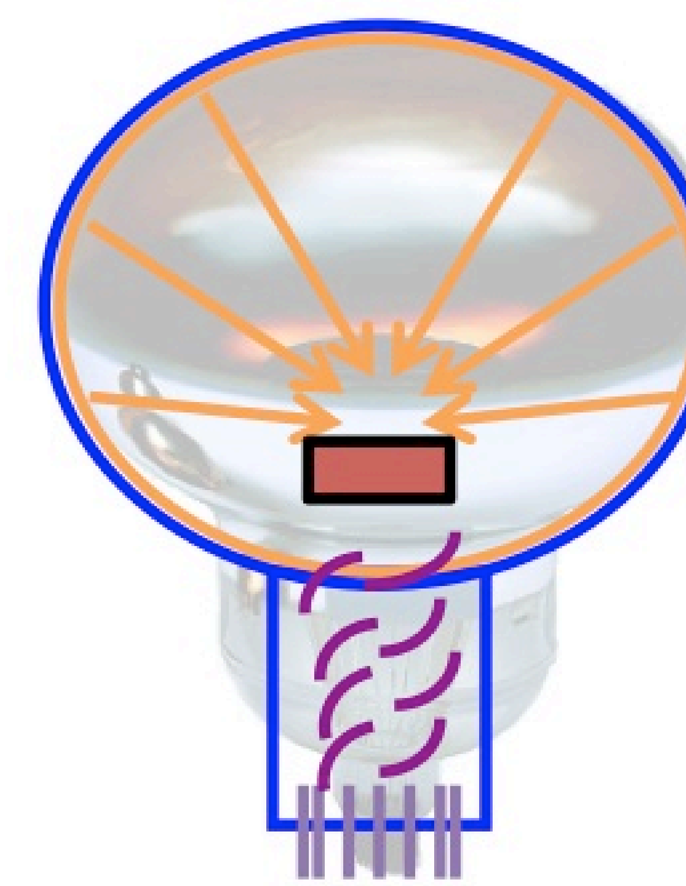
Old peak QE ~ 25-27% (+40 years ago)
New peak QE ~ 30-35%



Spectral Response of Commercial Photocathodes



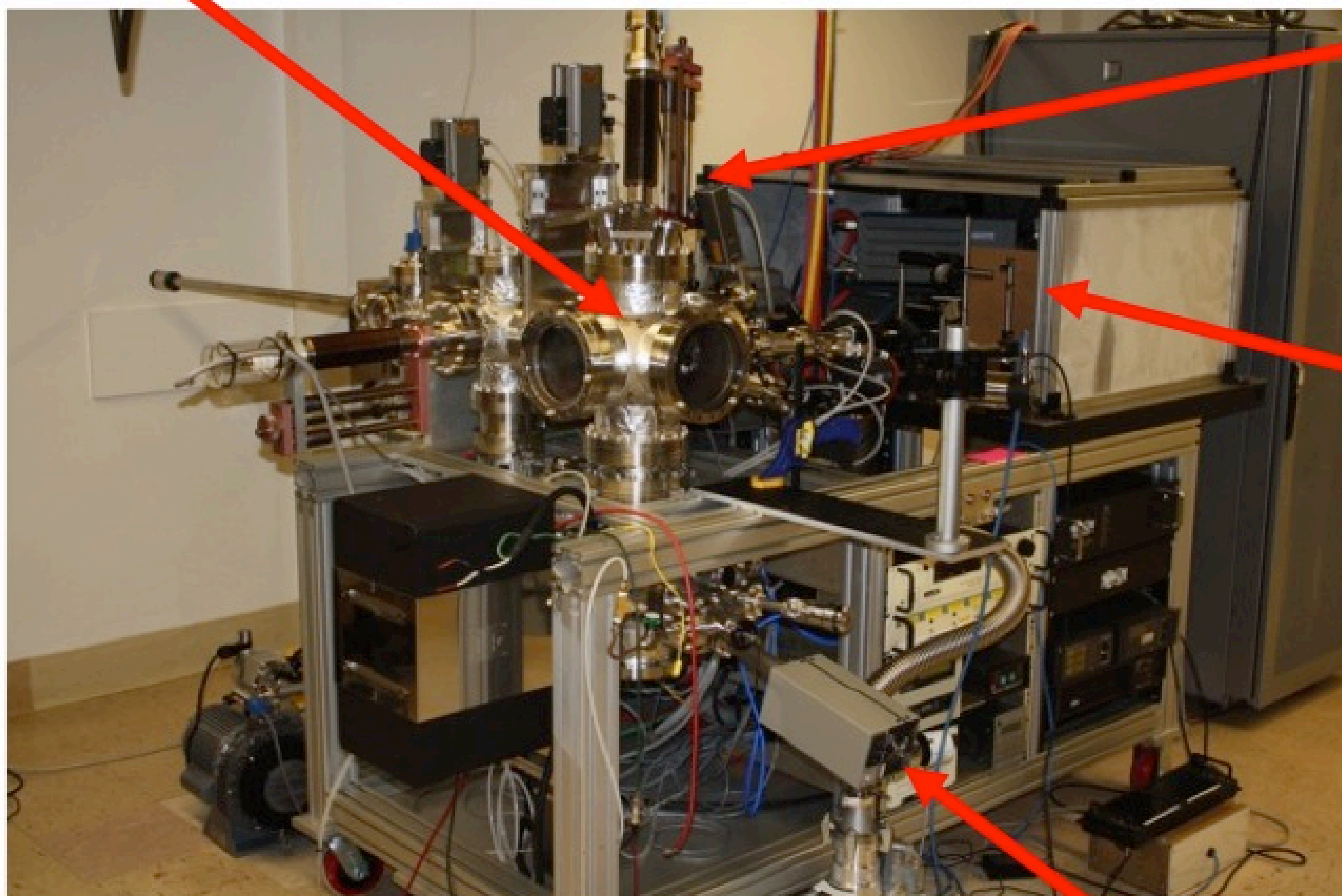
Source: Motohiro Suyama PoS(PD07)018 [Hamamatsu]



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

Bialkali Deposition Chamber V3, Including Exchange

Photocathode (inside)



Quartz Film Thickness Monitor

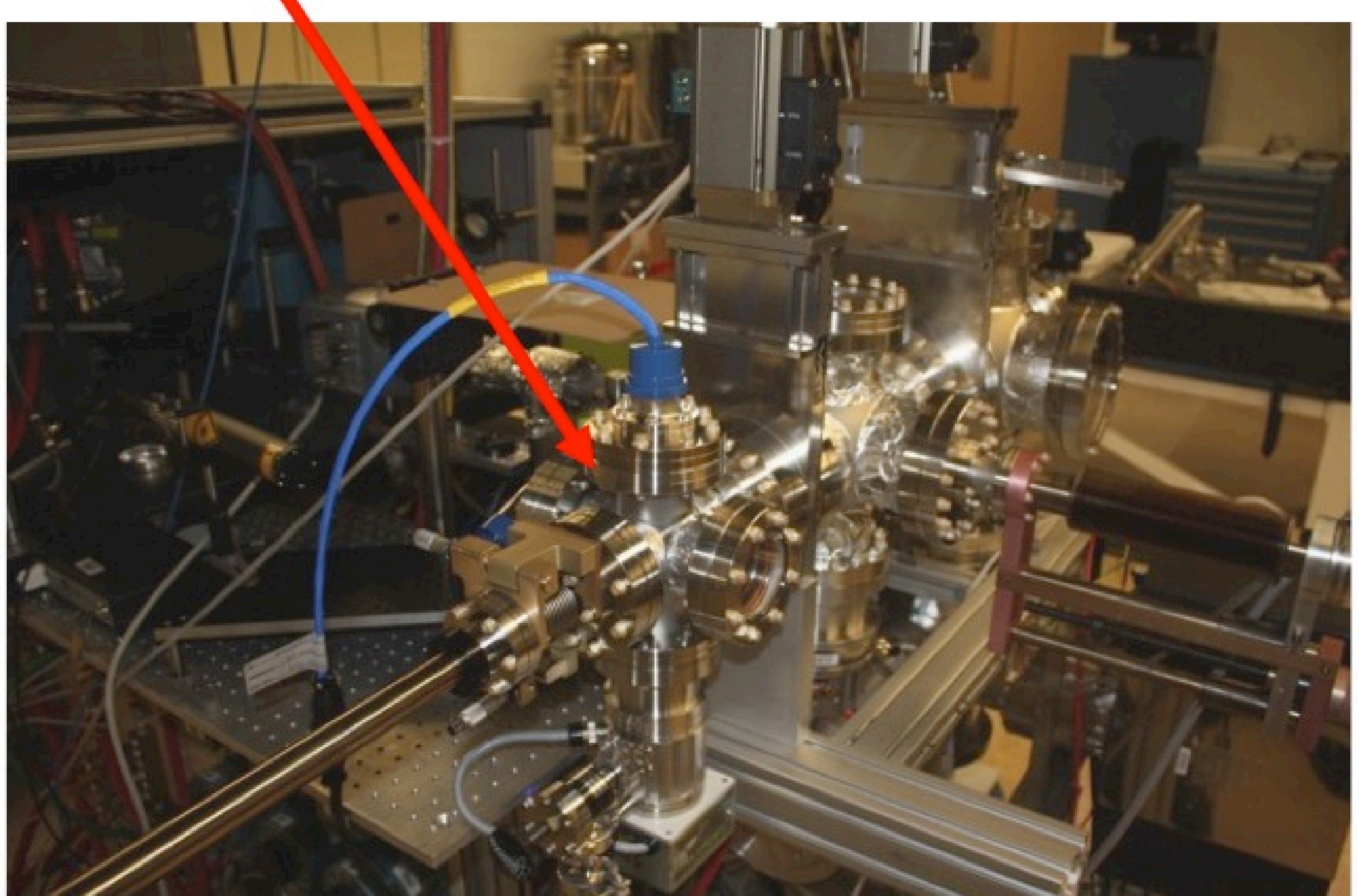
Laser Plasma Light Source

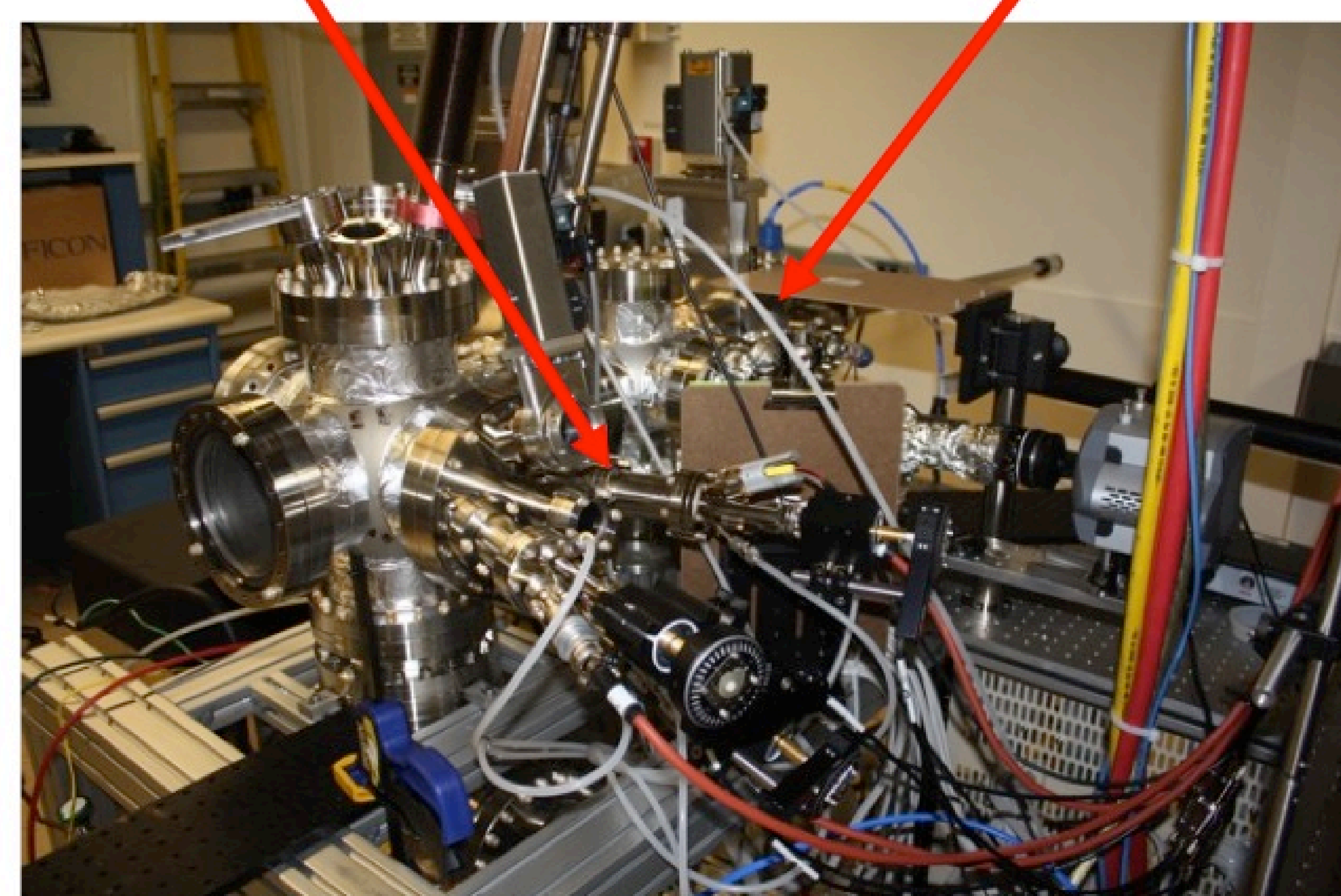
Load lock

RGA Gas Analyzer

MBE Evaporators

Momentum Analyzer





Basic Recipe for Photocathode Production

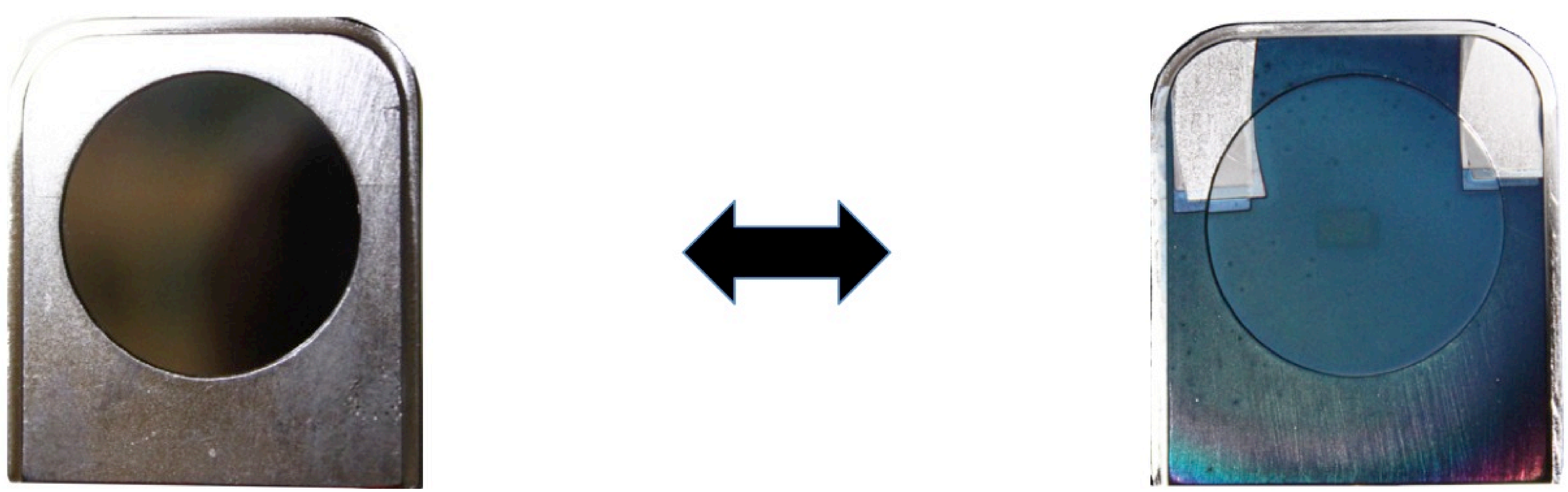
1.) Optically polished Mo substrate heat cleansed at 600° C for 30 min

2.) 50 Å Sb evaporated from pellets while substrate is at 160° C

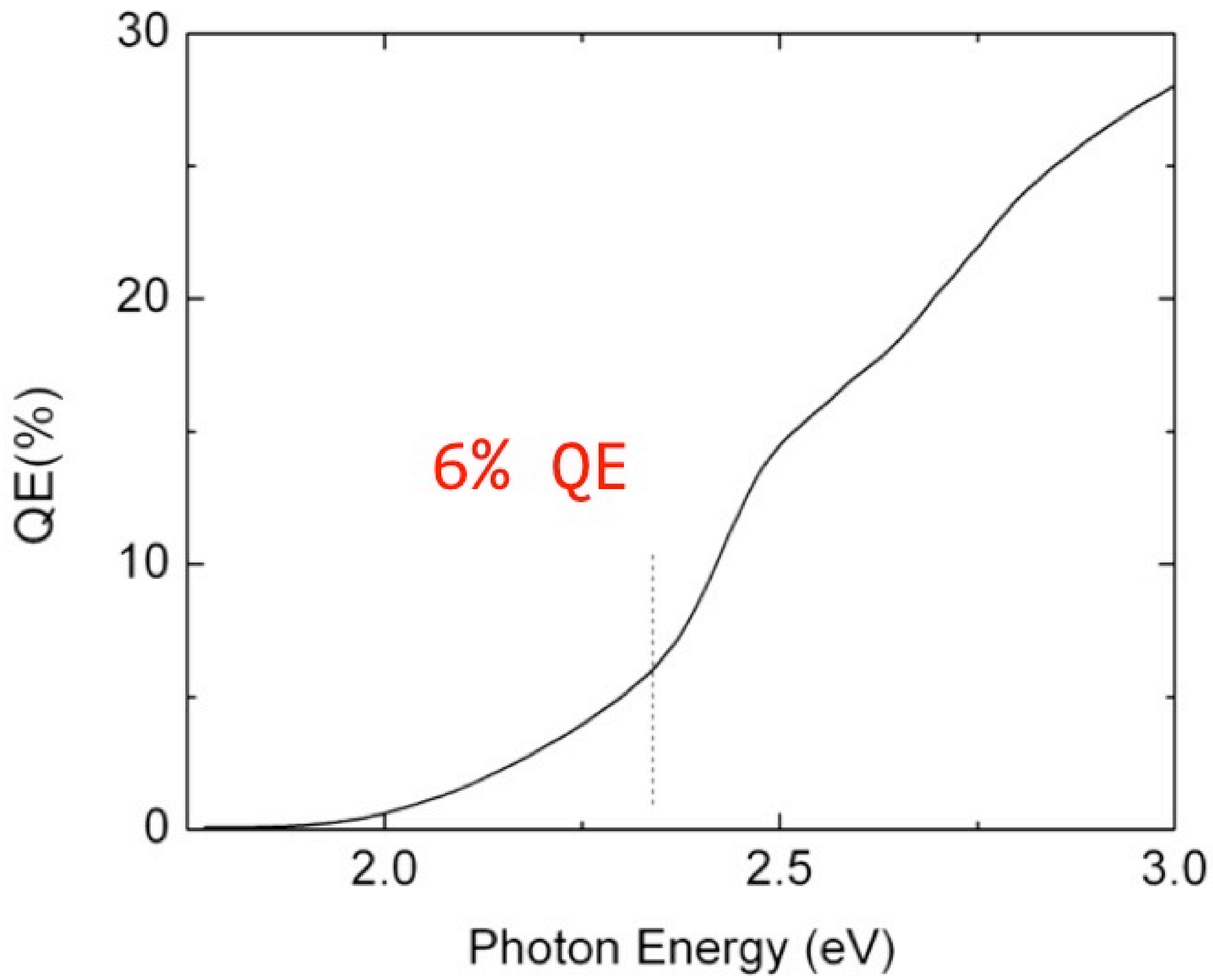
3.) K and Cs evaporated sequentially from de-alloying sources (Bi-Cs and Bi-K) while substrate is at temperatures lower then 160° C. Evaporation continues as needed until maximum QE is achieved in each case.

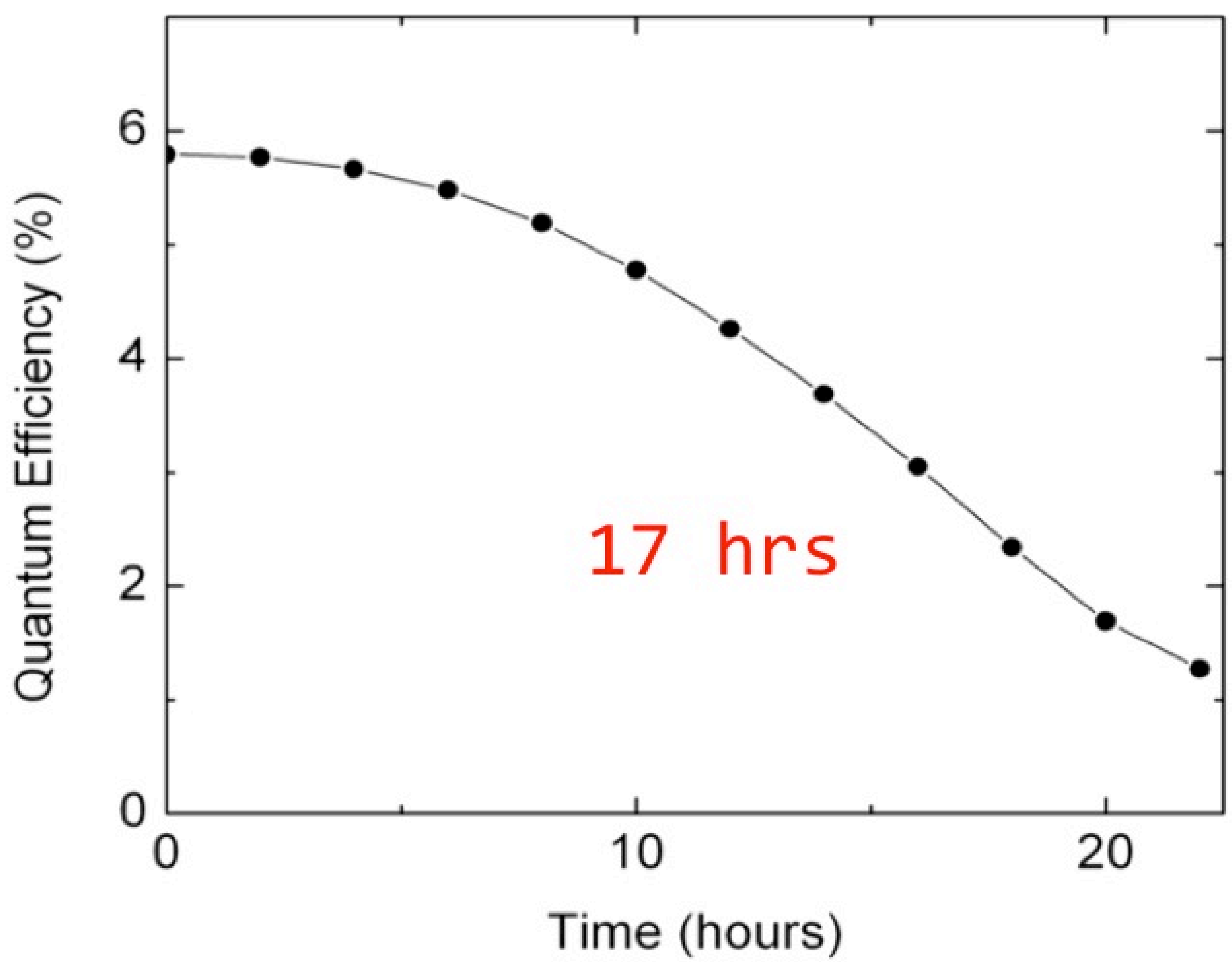
Different recipes (temps, order) are observed to produce similar results

Substrate   Cathode



Performance and Robustness of K_2CsSb at 532 nm





1.) Nominally 6% QE at 532

2.) When illuminated with a 100 µm focused green laser, a current density of 100 mA/cm^2 has been maintained over several days

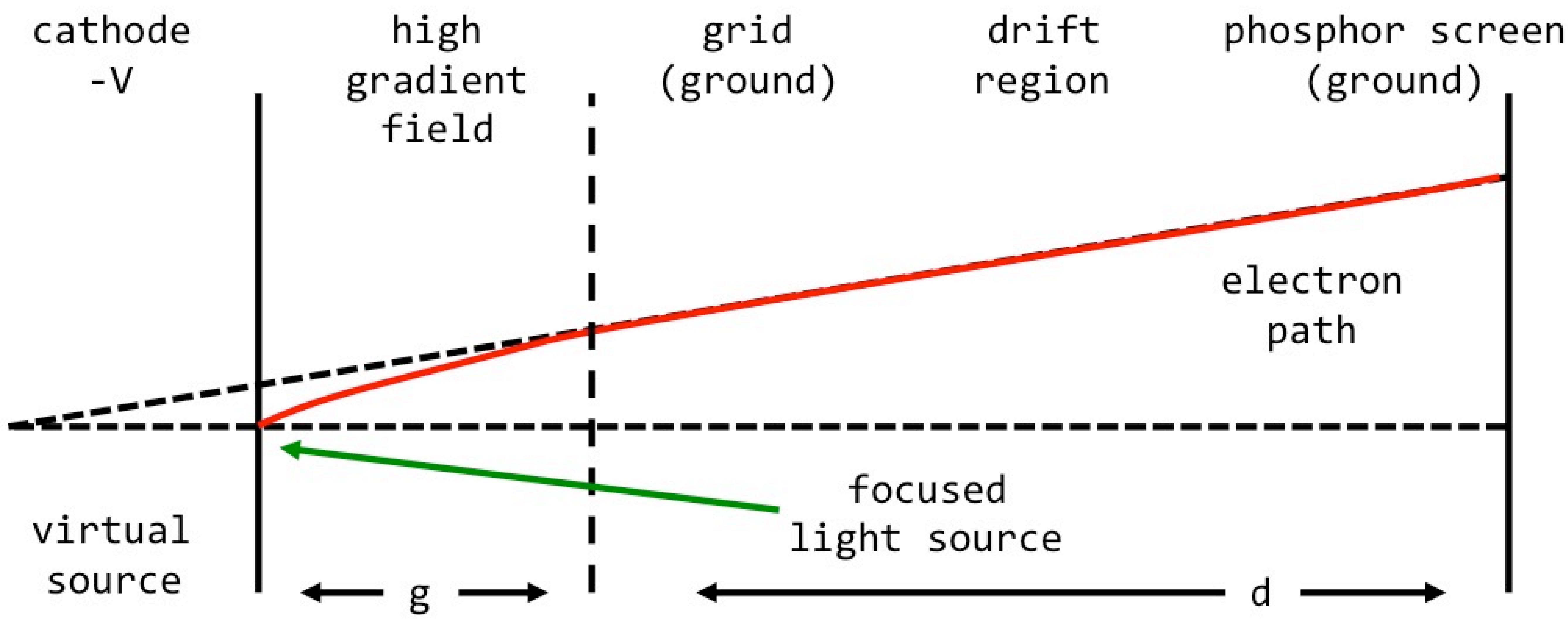
3.) Damage to cathode has been observed from UV radiation however not seen so far at 532 nm

4.) QE vs time at 5e-9 torr pp H20
- 50% decay time of around 17 h
- Stable to relatively high partial pressures of water
- pp in DC, RF and SRF photo-guns is better than this

5.) Known to be stable over months when stored in UHV. However, robustness may be dependent on actual details of the deposition

Setup for Measurement of Transverse Momentum

Electrons accelerated in a high gradient field, 0.4 - 3 MV/m
Anode is a mesh grid, 25 μm mesh pitch
Laser focused onto cathode at 30° through grid, 543 nm typical
Laser spot size is ~ 200 μm FWHM
Imaging done on a phosphor screen
Imaged by a lens coupled CCD camera using msec exposure times
Instrumental resolution is less than kT
System tested and calibrated on metals, Sb and Mo

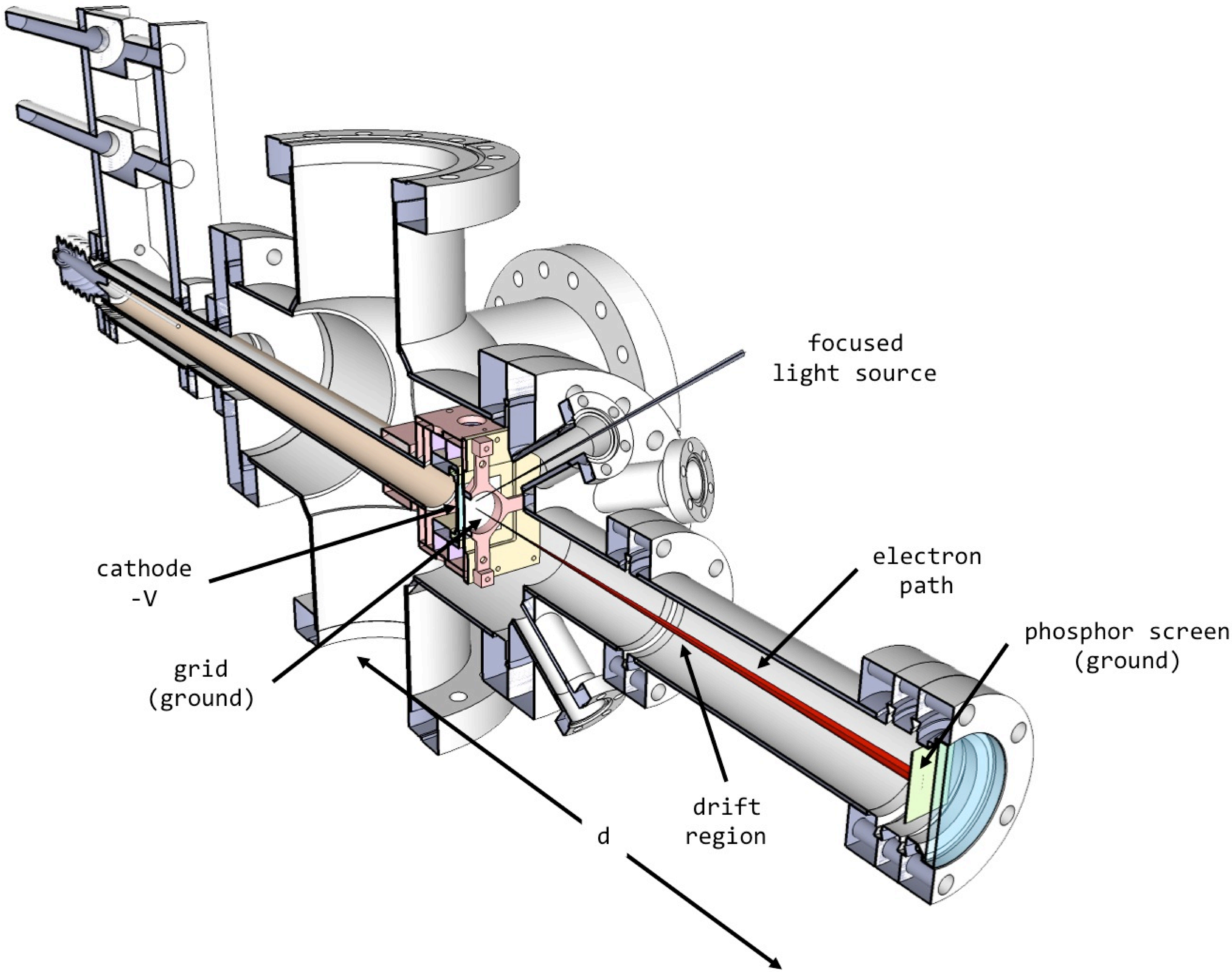


$$r = \sqrt{\frac{mc^2}{2eV}}\,(2g + d)\left(\frac{p_x}{mc}\right)$$

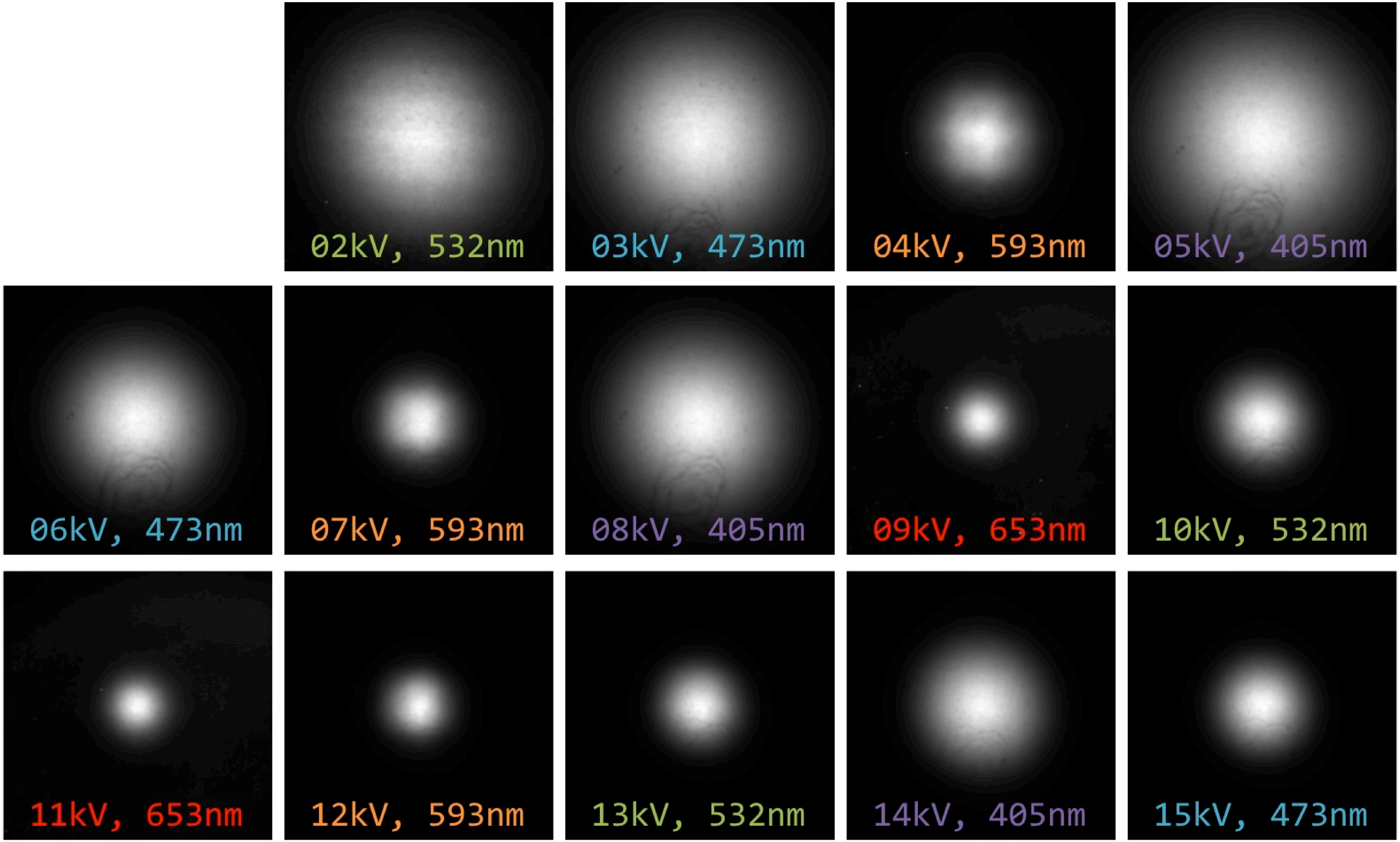
$$\frac{\varepsilon}{\sigma_x} = \frac{\left\langle p_x^2 \right\rangle^{1/2}}{mc}$$

r = radial coordinate on detector
g = cathode to grid (anode) gap, 5 mm
d = drift distance, 252 mm
V = applied voltage, varied from 2 kV - 15 kV

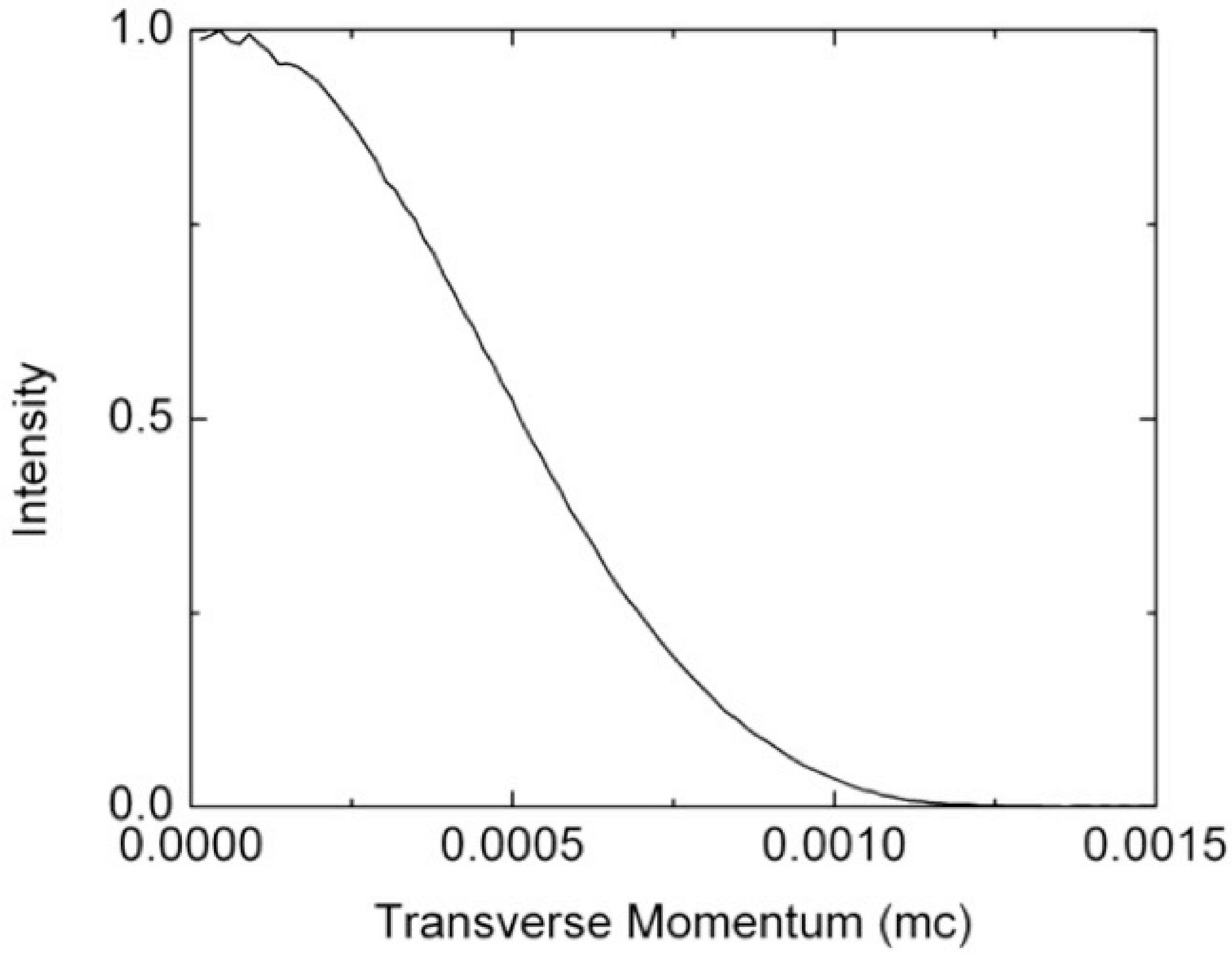
Diagram of the "Momentatron"

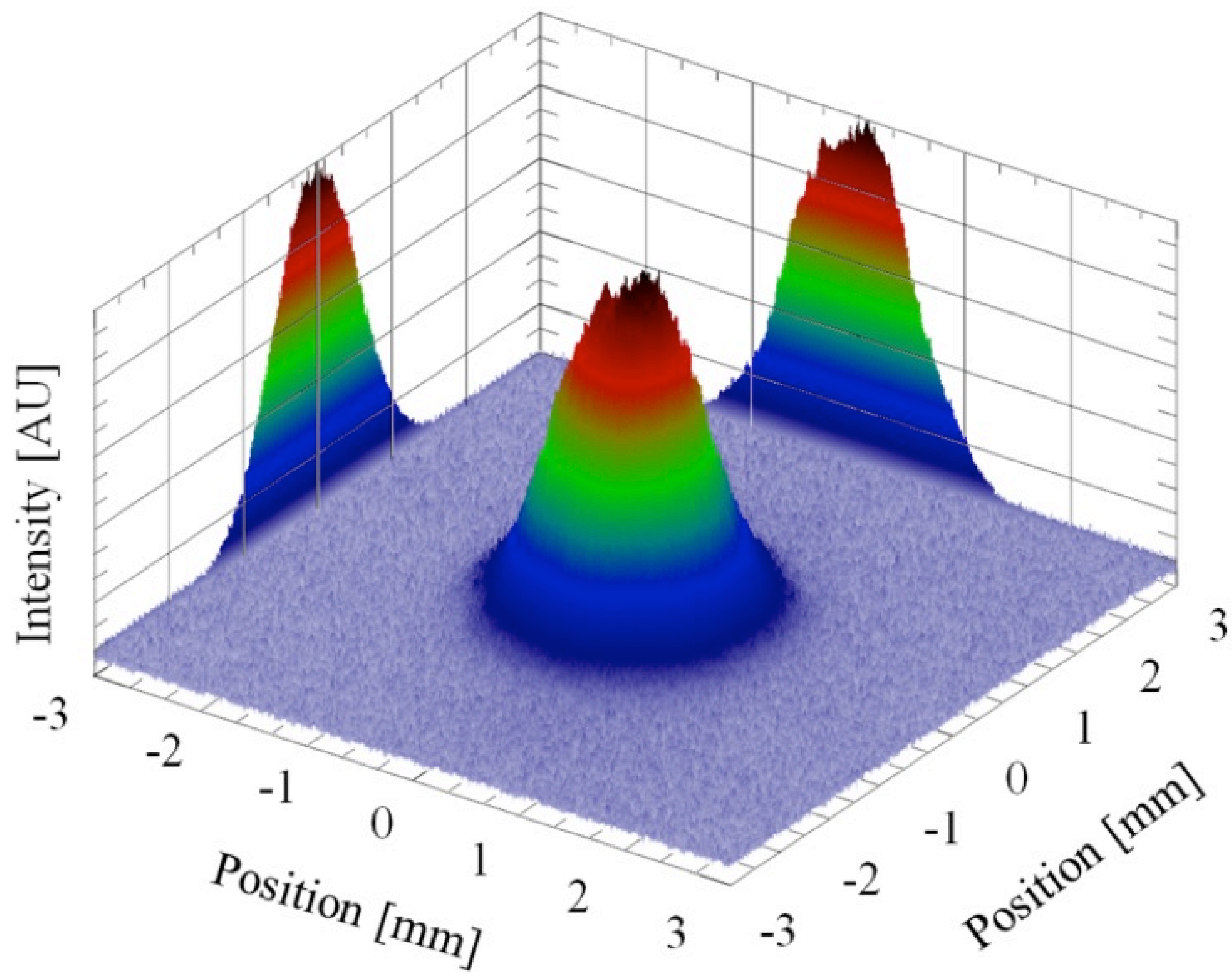


Various Transverse Momentum Measurements on K_2CsSb



Transverse Momentum Measurement on K_2CsSb at 543 nm





Measured ε_n = 0.37 μm / mm rms beam size

Simple model*:

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

Threshold emission = 1.9 eV
Energy Band Gap = 1.2 eV
Electron Affinity = 0.7 eV
Schottky barrier lowering at 2 MV/m = 0.053 eV

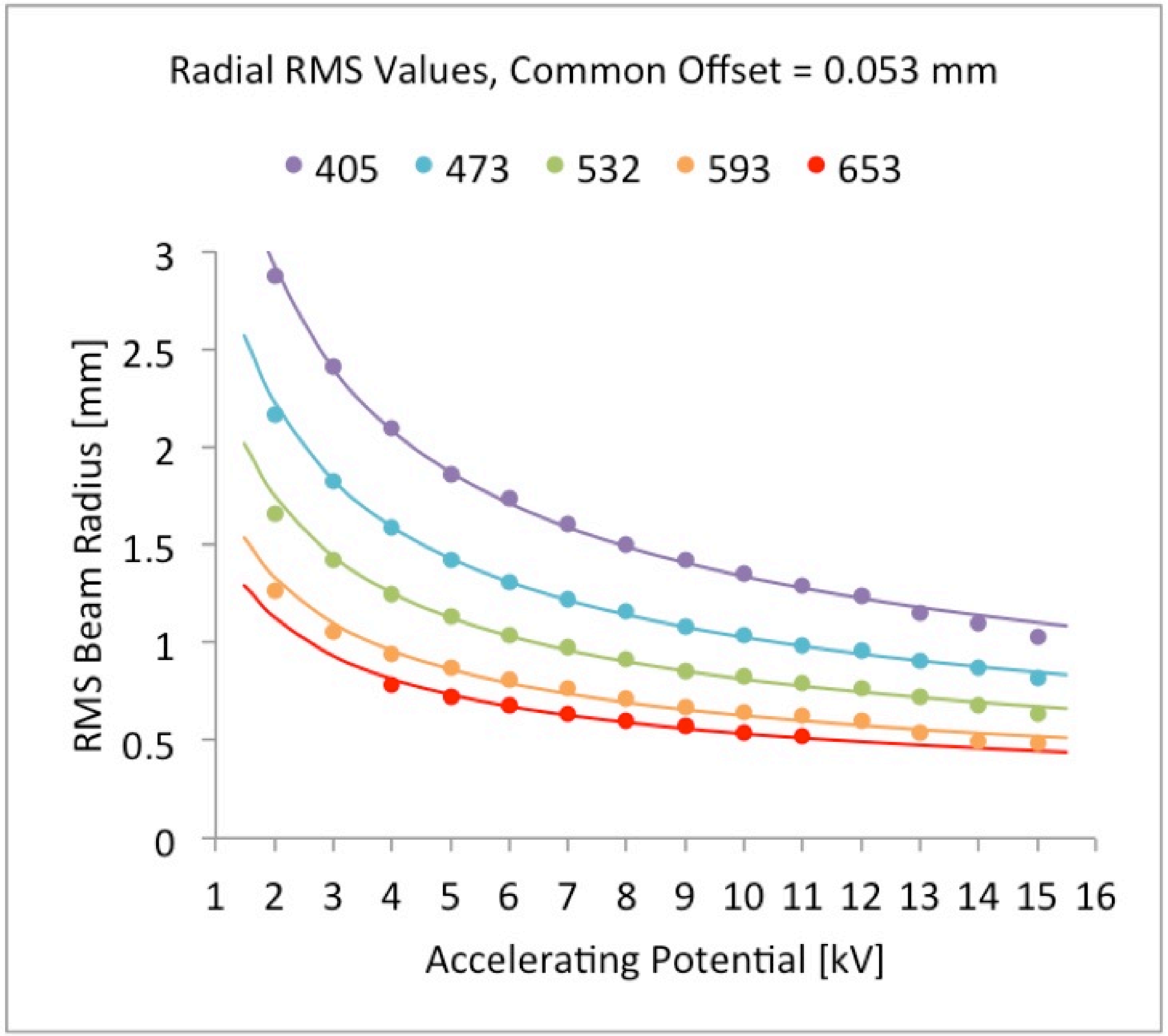
Predict ε_n = 0.39 μm / mm rms beam size

Good agreement with prediction!

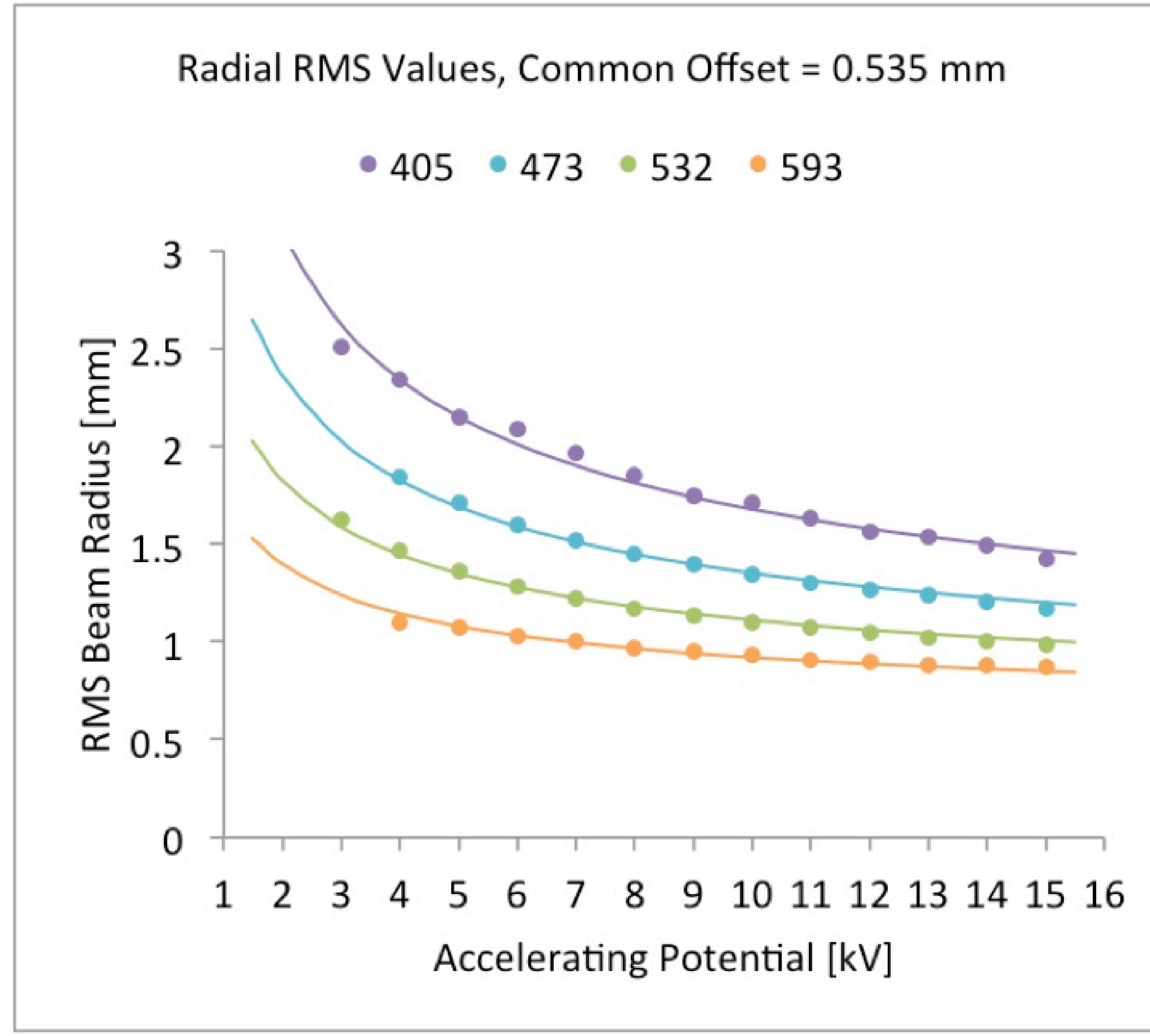
*Dowell et al, Nucl. Instrum. Methods Phys. Res. A 622, 685 (2010).

Emittance Growth due to Cathode Thickness

Thin Cathode (smooth)



Thick Cathode (rough)



ε_{405} = 0.70 µm / mm
ε_{473} = 0.54 µm / mm
ε_{532} = 0.43 µm / mm
ε_{593} = 0.33 µm / mm
ε_{653} = 0.28 µm / mm

E_{405} = 0.89 µm / mm
E_{473} = 0.70 µm / mm
E_{532} = 0.57 µm / mm
E_{593} = 0.48 µm / mm

Note: the unit "/ mm" implies per mm RMS beam size

Next Steps:

1.) Determine the effect of micro-roughness
- emittance is observed to increase for thick films
- in-situ characterization may be possible using SEM

2.) Improve stoichiometry control
- needs real time measurements of elemental composition
- possible using electron induced x-ray fluorescence

3.) Testing with psec fiber laser at 515 nm
- test robustness under high pulse fluence conditions

4.) Transfer cathodes to the VHF gun for testing
- new deposition chamber being commissioned now

Reference

APPLIED PHYSICS LETTERS **99**, 034103 (2011)

A low emittance and high efficiency visible light photocathode for high brightness accelerator-based X-ray light sources

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Free-electron lasers and energy recovery linacs represent a new generation of ultra-high brightness electron accelerator based x-ray sources. Photocathodes are a critical performance-limiting component of these systems. Here, we describe the development of photocathodes based on potassium-cesium-antimonide that satisfy many of the key requirements of future light sources, such as robustness, high quantum efficiency when excited with visible light, and low transverse emittance. [doi:10.1063/1.3612916]

Conclusions

1.) K_2CsSb has excellent properties as a photocathode for accelerator applications

- Very high QE in the green (adjustable)
- Low transverse emittance (adjustable)
- Robust in terms of sensitivity to water contamination

2.) Surface roughness needs to be minimized

- Effects on transverse emittance need to be more carefully studied
- Different recipes produce similar QE results but different values of emittance

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