Brookhaven National Laboratory

C-AD Machine Advisory Committee Meeting (MAC-22), Dec 17-19, 2025

U.S. DEPARTMENT OF ENERGY

R&D for high intensity electron sources in support of EIC (ECA FOA)

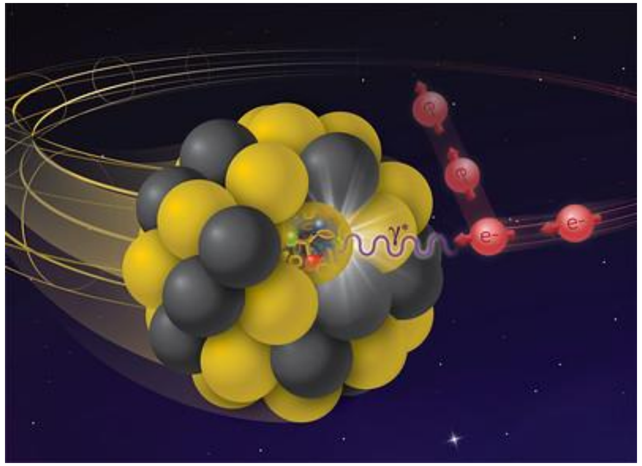
Mengjia Gaowei on behalf of the team
Collider-Accelerator Department, BNL

@BrookhavenLab

- Introduction
- Project timeline and task breakdown
- Progress summary
- Experimental results and discussion
- Future plan for cathode R&D

Introduction

It is desirable to have flat hadron beam achieved by the hadron cooling. And may upgrade to maintain hadron emittance by using high energy hadron cooling.



Electron beam for EIC Hadron Cooling

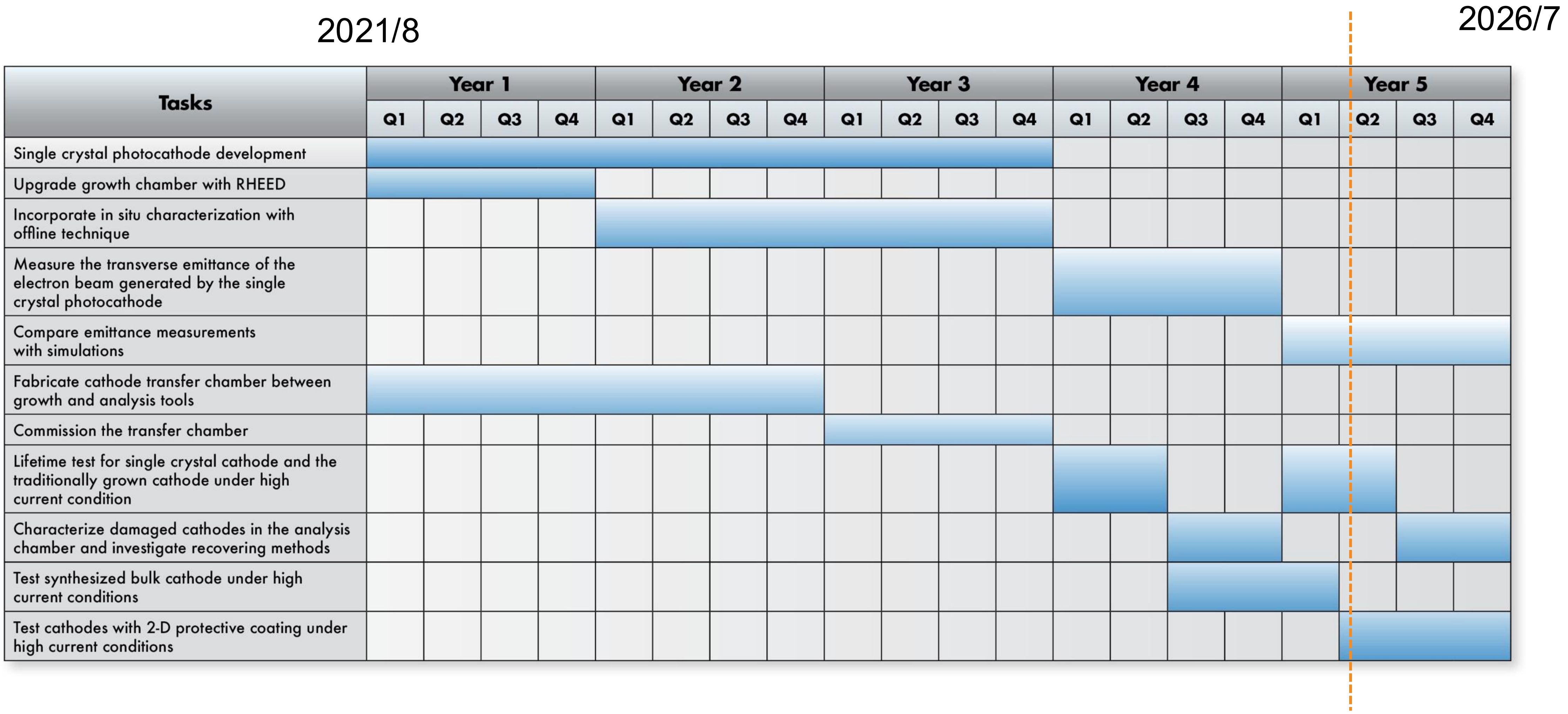
- High average current
- High bunch charge
- Long lifetime
- Low emittance

Our focus: High intensity electron source for EIC with epitaxial photocathodes.

Through epitaxial growth of photocathode, we are looking to achieve photocathode with ordered surface and low physical roughness; large grain or single crystal photocathodes with reduced grain boundaries→ low emittance and high QE.

Brookhaven National Laboratory

Project timeline



Brookhaven National Laboratory

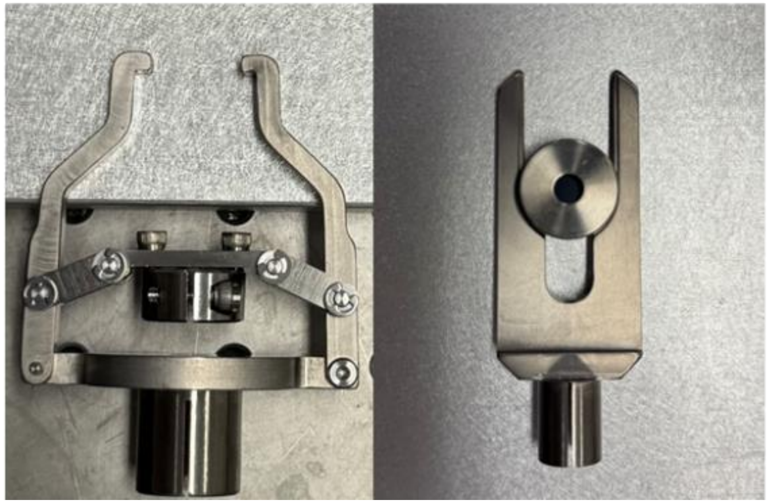
Project tasks breakdown

- ✓ Single crystal photocathode development
  - ✓ K_2CsSb (year 3)
  - ✓ Na_2KSb (year 4)
- ✓ Upgrade growth chamber with RHEED (Year 2)
- ✓ Incorporate in situ x-ray characteristics with offline technique (year 1 & 2)
- Fabricate cathode transfer chamber between growth and analysis tools
  - ✓ Design
  - ✓ Procurement
  - ✓ Modification and Fabrication
  - Assembly
  - Commission
- High current test (in line with gun schedule)
  - Lifetime test for single crystal K_2CsSb
  - Measure transverse emittance of the electron beam generated by the single crystal K_2CsSb
  - Characterize damaged cathodes and investigate recovering methods

Progress summary – hardware development

- Custom modifications are made to the transfer chamber parts. Leak check is performed for the main compartment of the transfer chamber. Custom connections for transfer chamber are fabricated. (Figure. 1a)
- Equipped the experimental chamber with **new evaporator design same as the EIC HC cathode growth system** (Figure. 1b), to grow the cathode material in the same deposition conditions as will be used for EIC. New evaporators are conditioned and tested, with successful growth demonstrated.
- Design new sample pucks which will incorporate the mounting of lattice matched single crystal wafers.

a)



b)

Progress summary - software development

- Simulation work continues for emittance measurement.
- Labview based control and data requisition for emittance measurement is developed.

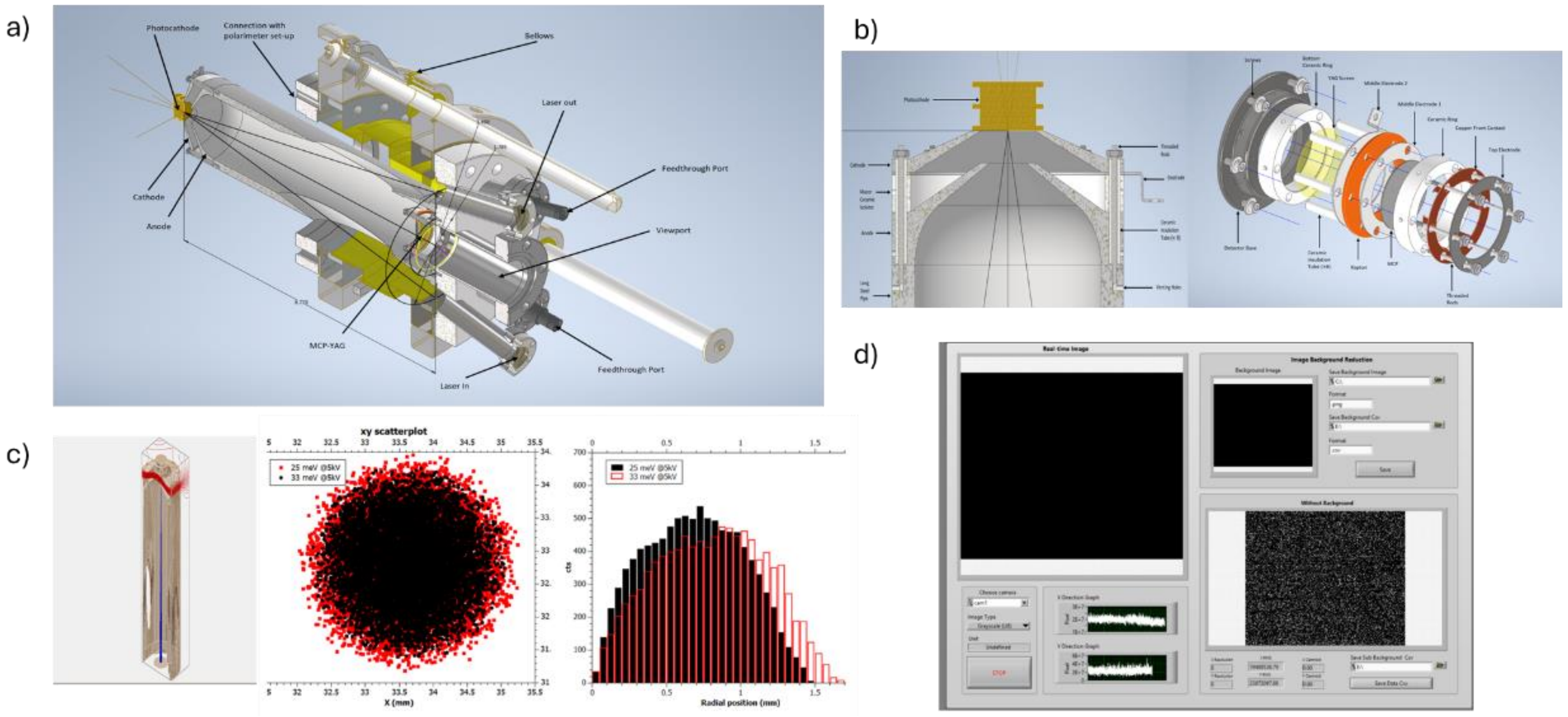


Figure. 2 a) Schematic of cathode emittance measurement chamber **b)** Schematic details of cathode-anode connection and the MCP-YAG detector **c)** Scatter plot and histogram of electron distribution on MCP at 5kV with MTE of 25 and 33 meV, respectively. The rms beam size on the MCP screen with respect to its beam energy for its initial MTE is obtained from Simion simulations. The rms beam size on the cathode (σx) is 60 μm. **d)** Interface of the Labview based control and data requisition program for photocathode emittance measurement.

Progress summary - Material development

- **Epitaxial growth** of **Cs_3Sb, K_2CsSb and Cs_2Te** were performed on various lattice matched substrates. High quantum efficiency, ultrasmooth and epitaxial thin film photocathodes are achieved.

- Epitaxial growth of **Na_2KSb** with ultrasmooth surface (with EIC cathode evaporator configuration) is successfully realized.

APL Materials

RESEARCH ARTICLE | JUNE 12 2024

Growth of ultra-flat ultra-thin alkali antimonide photocathode films

W. G. Stam; M. Gaowei; E. M. Echeverria; Kenneth Evans-Lutterodt; Jean Jordan-Sweet; T. Juffmann; S. Karkare; J. Maxson; S. J. van der Molen; C. Pennington; P. Saha; J. Smedley; R. M. Tromp

Check for updates

APL Mater. 12, 061114 (2024)
https://doi.org/10.1063/5.0213461
CHORUS

APL Materials

RESEARCH ARTICLE | JANUARY 22 2025

A structural analysis of ordered Cs_3Sb films grown on single crystal graphene and silicon carbide substrates

C. A. Pennington; M. Gaowei; E. M. Echeverria; K. Evans-Lutterodt; A. Galdi; T. Juffmann; S. Karkare; J. Maxson; S. J. van der Molen; P. Saha; J. Smedley; W. G. Stam; R. M. Tromp

Check for updates

APL Mater. 13, 011120 (2025)
https://doi.org/10.1063/5.0229850
CHORUS

scientific reports

Check for updates

OPEN

Pulsed laser deposition assisted epitaxial growth of cesium telluride photocathodes for high brightness electron sources

Kali Prasanna Mondal[1], Mengjia Gaowei[1], Elena Echeverria[2], Kenneth Evans-Lutterodt[1], Jean Jordan-Sweet[1,3], Thomas Juffmann[4,5], Siddharth Karkare[6], Jared Maxson[2], S. J. van der Molen[7], Chad Pennington[2], Pallavi Saha[1,6], John Smedley[1,8], W. G. Stam[7] & Rudolf M. Tromp[3,7]

The development of high-brightness electron sources is critical to state-of-the-art electron accelerator applications like X-ray free electron laser (XFEL) and ultra-fast electron microscopy. Cesium telluride is chosen as the electron source material for multiple cutting-edge XFEL facilities worldwide. This manuscript presents the first demonstration of the growth of highly crystalized and epitaxial cesium telluride thin films on 4H-SiC and graphene/4H-SiC substrates with ultrasmooth film surfaces. The ordering of the film was characterized by in situ reflection high energy electron diffraction and multiple X-ray diagnostics. The results of the quantum efficiency performance for epitaxial cesium telluride photocathodes are also reported.

Brookhaven National Laboratory

Na-K-Sb photocathode

Motivation: High current, high charge

- Cathode overheating form high power laser is a concern
- Possible use of NaKSb cathode is introduced as candidate that has better temperature resistance than K2CsSb.

Sodium potassium antimonide (NaKSb) photocathodes is one of the cathode choices for high-brightness applications. These materials offer high QE, fast response, and good thermal stability, making them viable candidates for high-brightness, high-average-current photoinjectors.

- **Thermal robustness**: @100°C showed QE degradation from 7% to ~3% after 90h. QE recoverable by re-evaporating K.
- Lifetime and High Current Operation: 1/e lifetime is 66 h.
- Fit from MTE measurement gives a work function of ~1.95 eV;

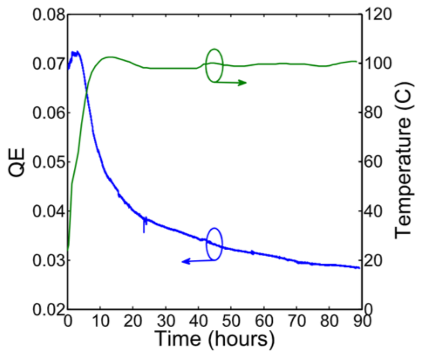


FIG. 2. A NaKSb photocathode is kept at about 100 °C for 90 h. The QE is observed to decrease from the original 7% to slightly less than 3%.

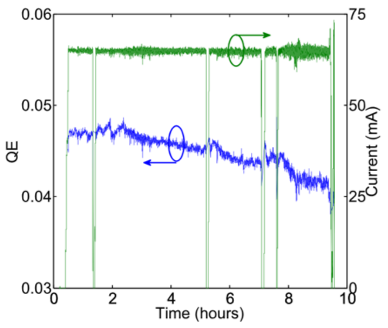


FIG. 8. Photocurrent and QE of a NaKSb photocathode operated in a high average current run of the ERL injector prototype at Cornell University. 65 mA of average current has been delivered for about 9 h. QE degradation with a time constant 1/e of about 66 h has been observed.

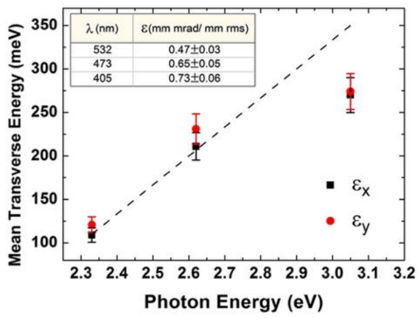
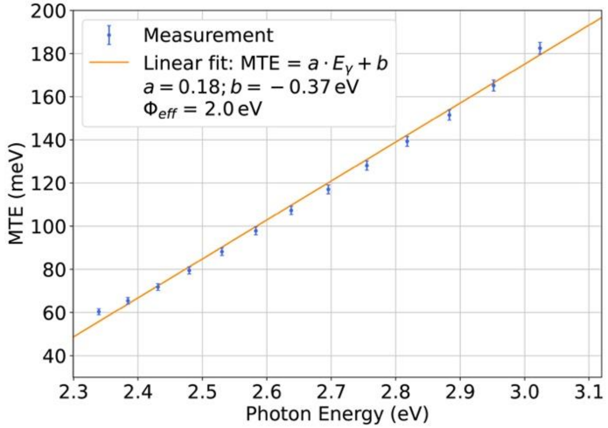


FIG. 6. Intrinsic emittance measurements (ε_x and ε_y stand for along x and y direction, respectively) are reported as a function of the photon energy and laser wavelength. The dashed line is a simple $1/3(E_{ph} - E_{th})$ model, where E_{ph} is the energy of the photons and $E_{th} = 1.95$ eV is the workfunction.

Cultrera, L., et al. "Growth and characterization of rugged sodium potassium antimonide photocathodes for high brilliance photoinjector." Applied Physics Letters 103.10 (2013).

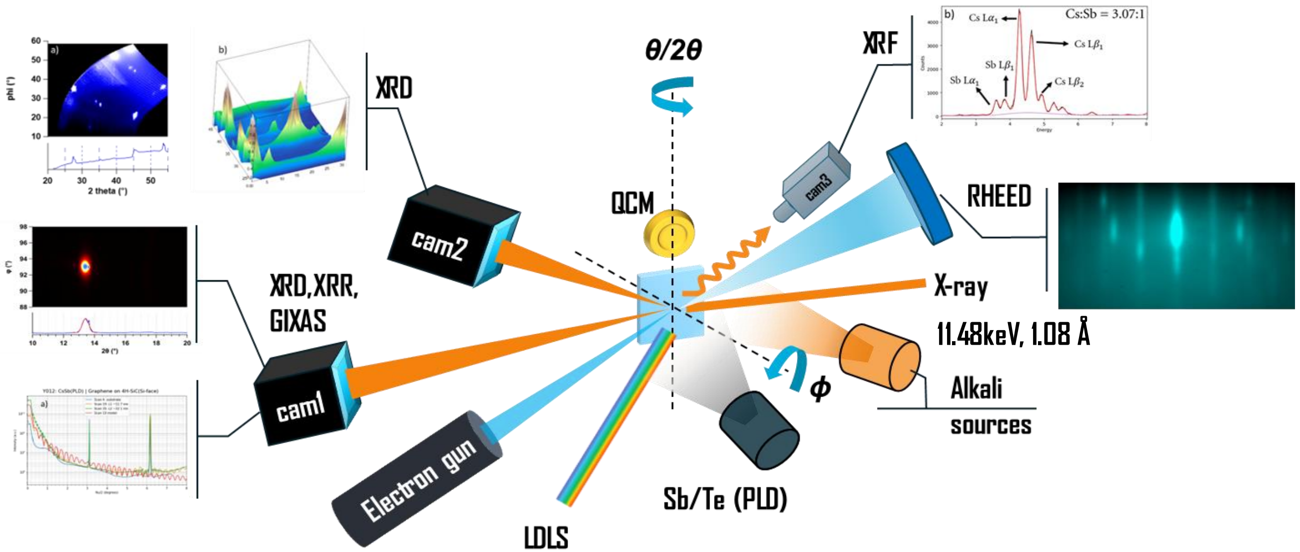
- Fit from MTE measurement gives a work function of ~2 eV.
- 135 meV @ 2.76 eV; 60 meV at 2.33 eV



J. Dube, J. Kühn, C. Wang, S. Mistry, G. Klemz, A. Galdi, T. Kamps; Triple evaporation growth and photoemission characterization of bialkali antimonide photocathodes. *J. Appl. Phys.* 28 July 2025; 138 (4): 045704.

In situ in operando Characterization of photocathodes @ synchrotron light source

- Unique program that interfaces with the beamlines at NSLS-II to study photocathode material with the state-of-the-art synchrotron light source
- Develops new tools and recipes, which benefit the broad photocathode and accelerator community in providing insight into the fundamental material research
- The only active synchrotron research facility for photocathode, attracts collaborators from various Nuclear Physics facilities and from international accelerator facilities.

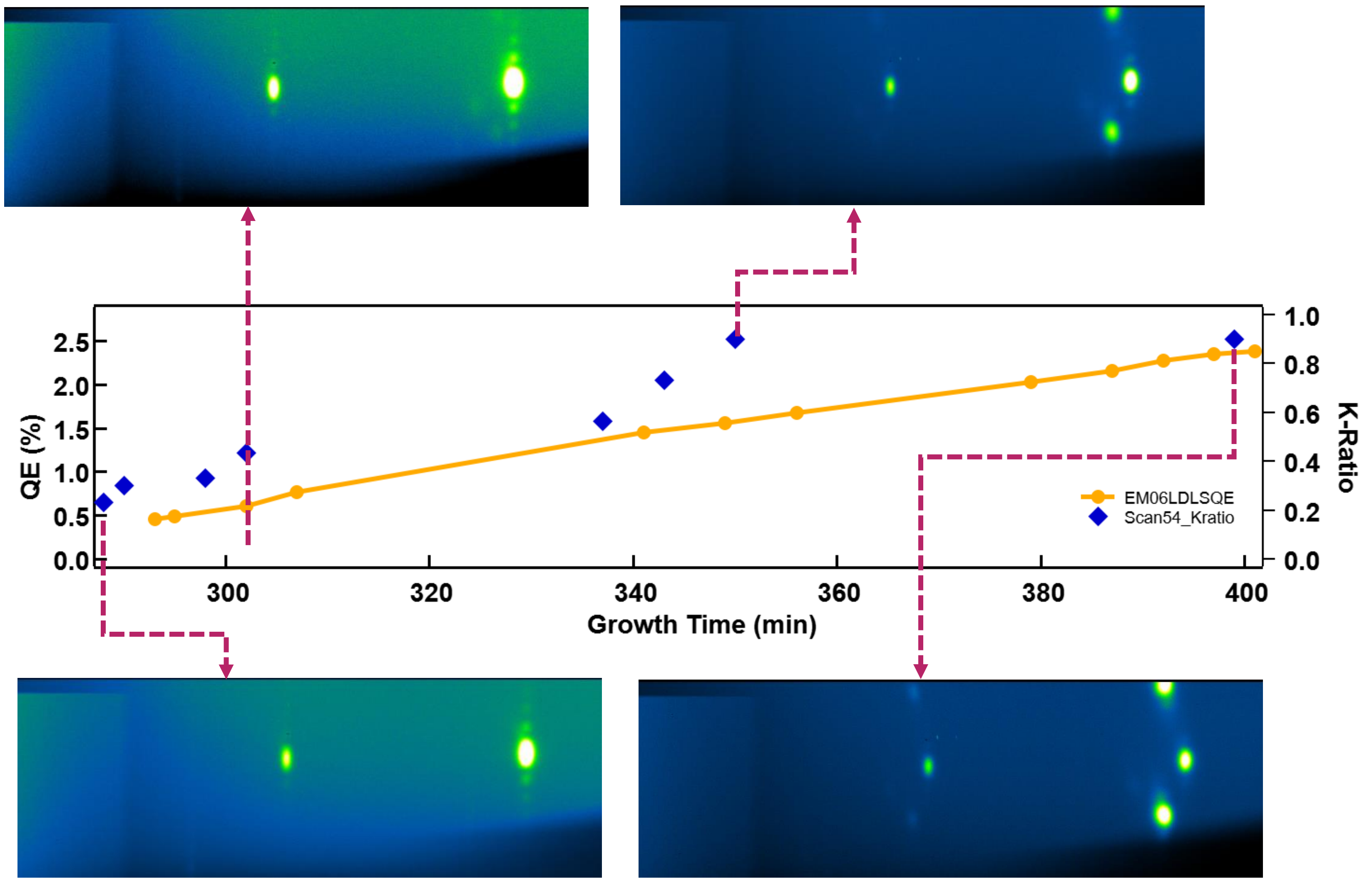


Evaporators:
- ❑ Thermal Sb
- ❑ PLD Sb
- ❑ Alkali effusion cells

Characterization:
- ❑ QCM
- ❑ XRD - crystal structure
- ❑ XRR - surface roughness
- ❑ XRF - stoichiometry
- ❑ QE
- ❑ RHEED

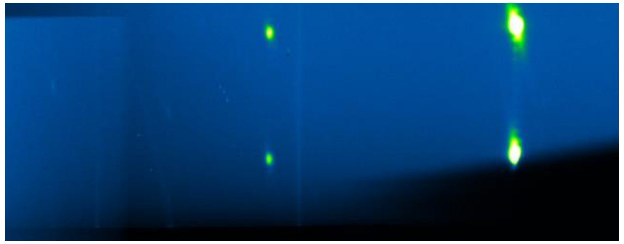
Cathode Candidates:
- ❑ K_2CsSb/KCs_2Sb
- ❑ Cs_3Sb
- ❑ Cs_2Te
- ❑ Na_2KSb

In situ, real time XRD: Structural evolution



Start

Final



Slight annealing

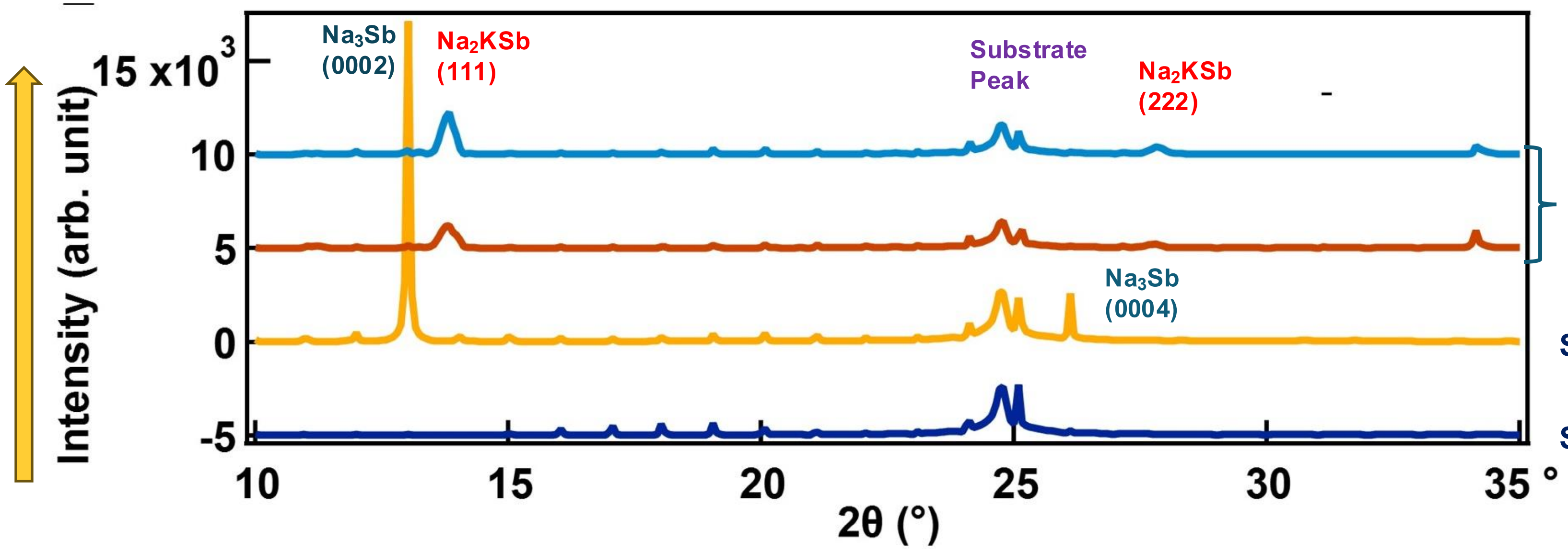
- As K ratio increases, QE is trending up. When K reaches 1 and kept stable, QE continue to rise and eventually saturates.
- At K ratio~0.4 (ideal ratio is 1); QE 0.5% another phase shows up
- When K ratio reaches ~1, new phase intensity is lower than original phase
- As growth continues, new phase switch intensity with original phase, as QE keeps rising and eventually saturates.
- After slight annealing, original phase disappears

Brookhaven National Laboratory

XRD: Structural evolution

Cam 1

Growth



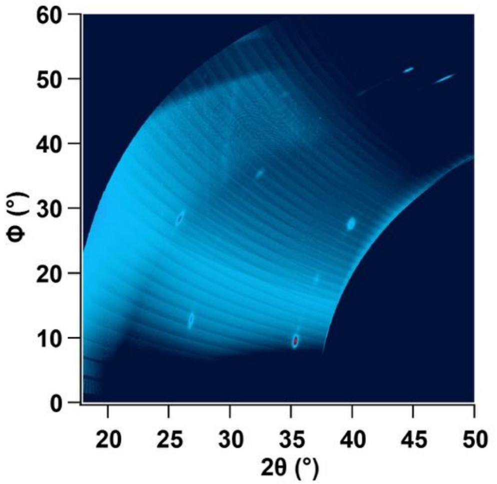
Slight annealing

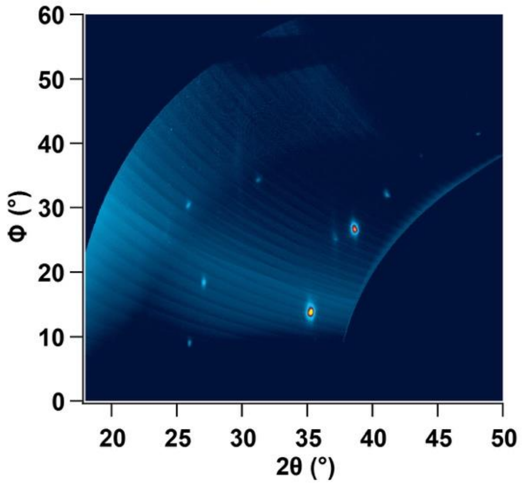
Single phase of Na2KSb

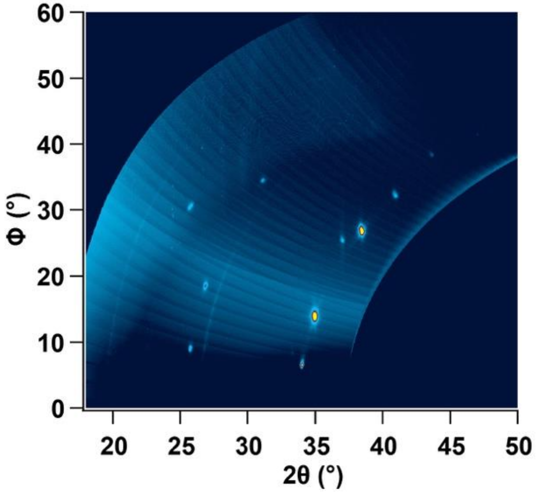
Single phase of Na3Sb

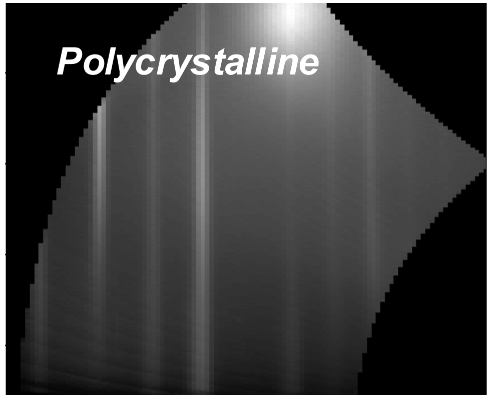
Substrate

Cam 2



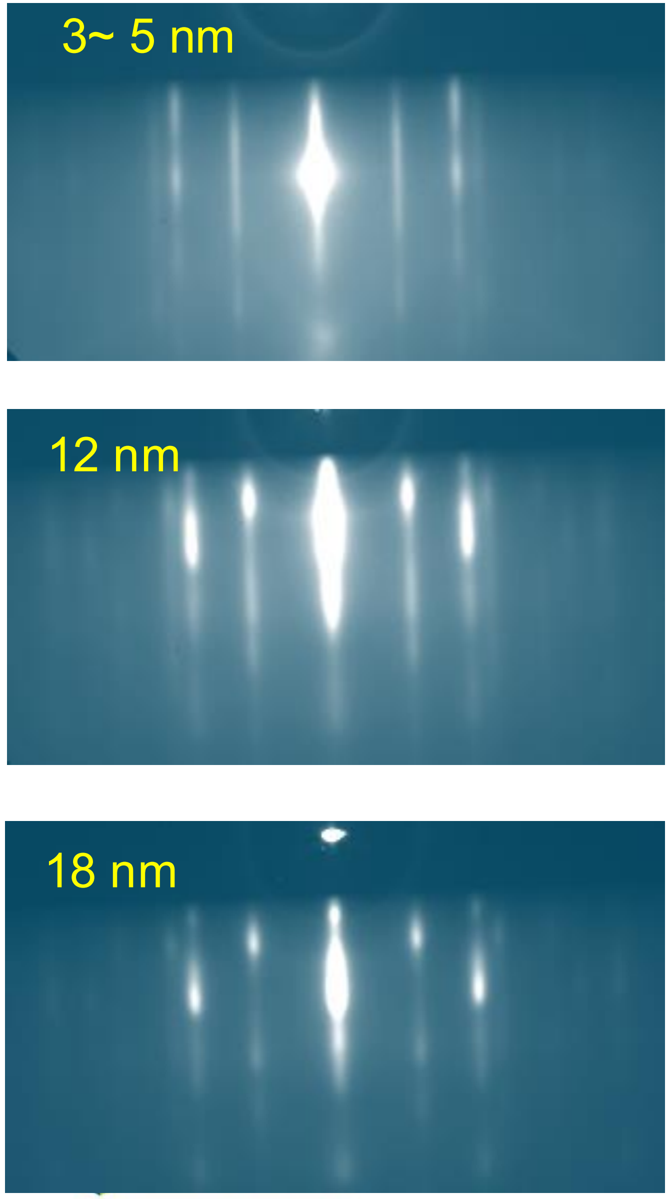


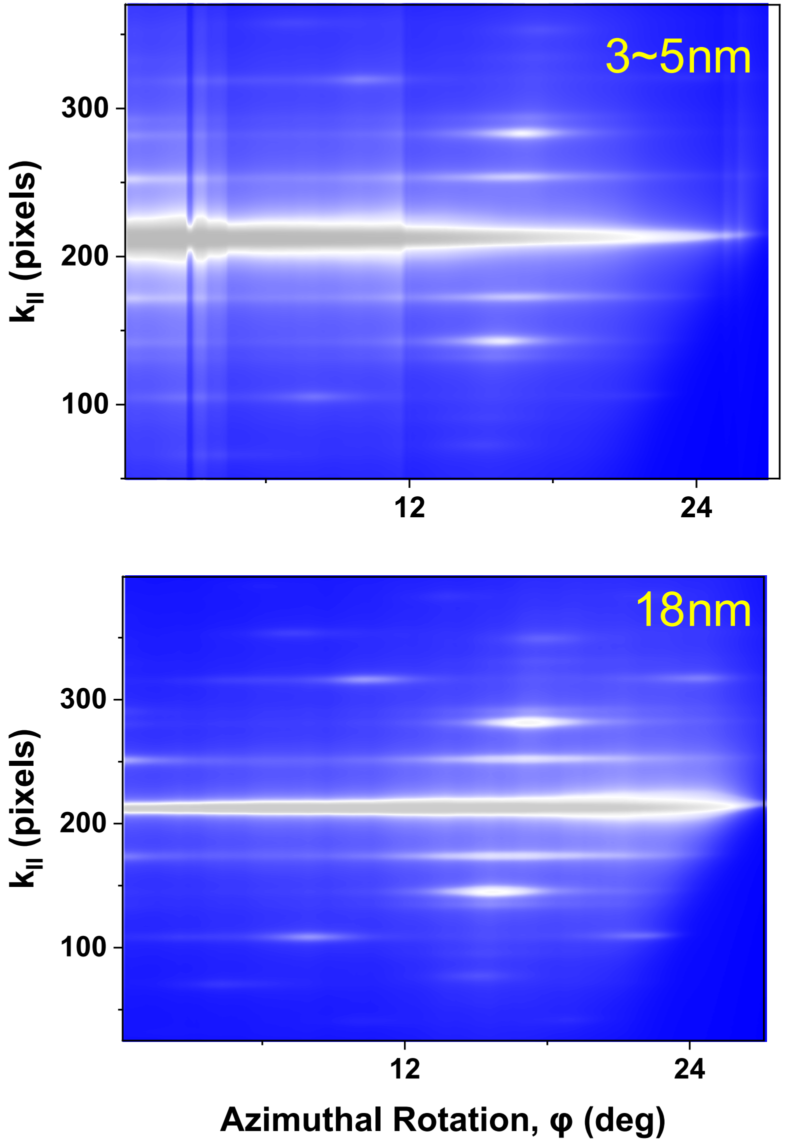


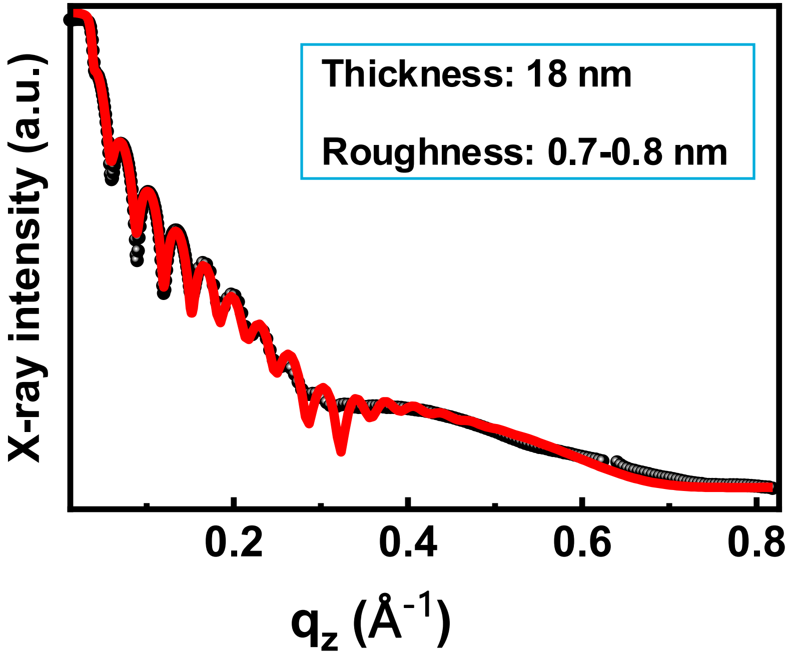


Brookhaven National Laboratory

Na-K-Sb photocathode – RHEED, XRR

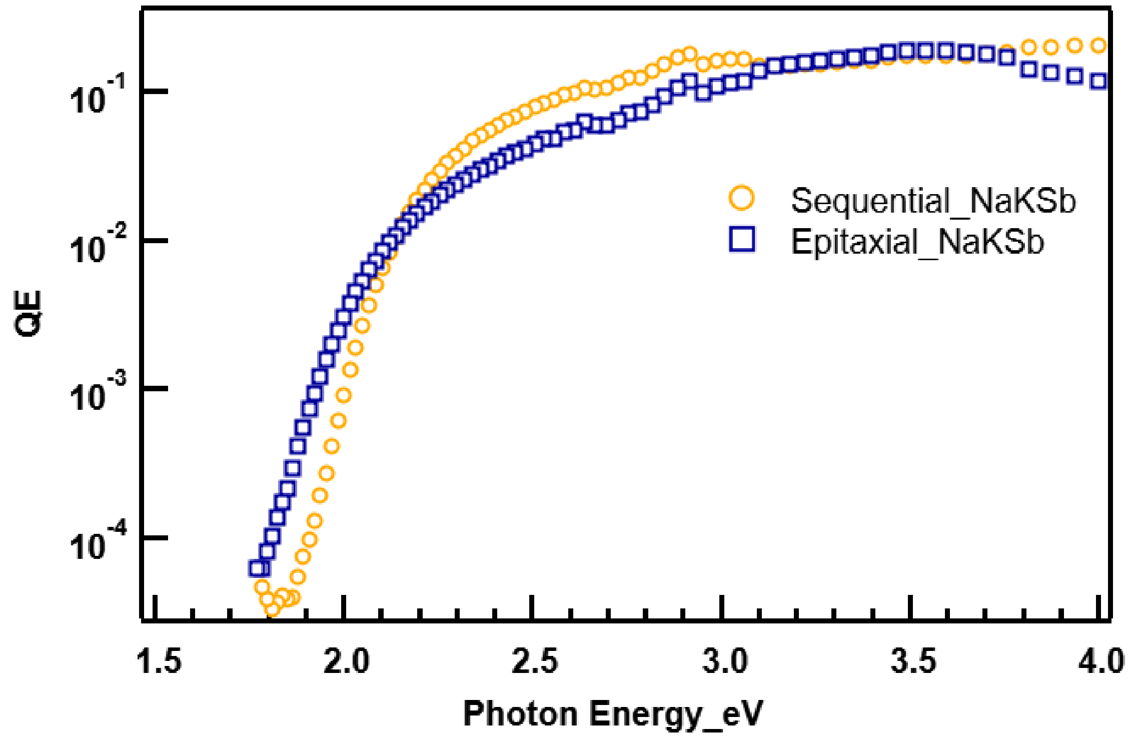






- ✓ **RHEED streaks**
- ✓ **Azimuthal dependence**
- ✓ **Ultrasmooth**

Results- QE



Sequential+ K-Sb yoyo

- Spectral response gives a work function of ~1.9 eV.
- 530nm- QE 4.6%
- 450nm- QE 12.3%

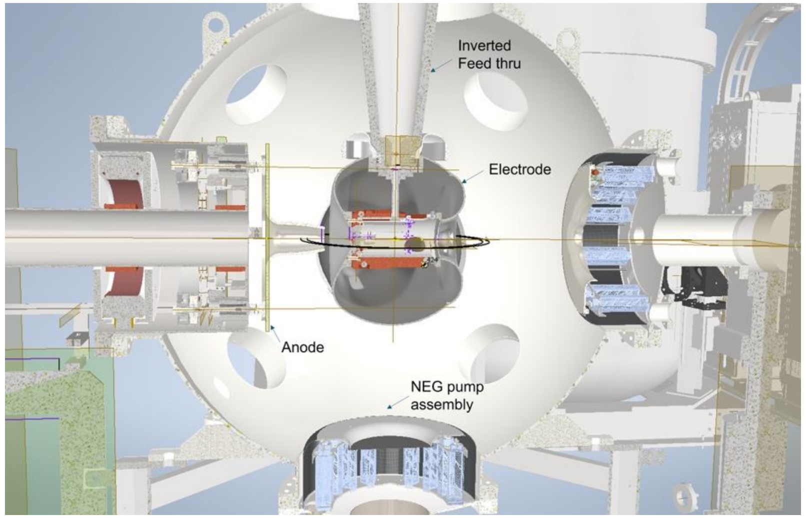
Epitaxial growth

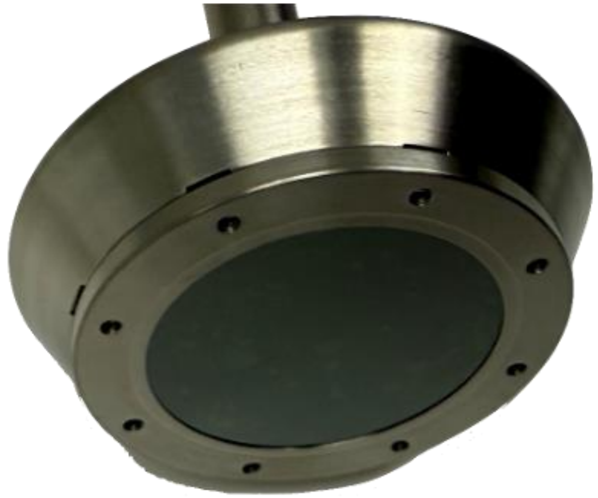
- Work function estimated ~ 1.8eV
- 530nm- QE 2.8%
- 450nm- QE 7.1%

Brookhaven National Laboratory

High current test (On schedule 2026~2027)

@High-Average-Current, High-Brightness HVDC Electron Gun for EIC Hadron Cooling at Stony Brook University





- Lifetime test for single crystal K_2CsSb
- Measure transverse emittance of the electron beam generated by the single crystal K_2CsSb
- Characterize damaged cathodes and investigate recovering methods

Potential Future work for cathode R&D (long term)

- **Hardware & Infrastructure Development**
  - Incorporate PLD laser for PLD growth.
  - Upgrade growth chamber with Energy-Dispersive X-ray Spectroscopy (EDX), sharing the same electron source with RHEED.
  - Design sample holders and transfer forks for the transfer chamber to interface with multiple characterization tools : XPS, ARPES.
- **Engineering for heterostructure photocathodes**
  - Grow and characterize known heterostructure systems for multialkali photocathodes: S20 and alike
  - Use *in situ* XRR/XRF/XRD to monitor and characterize material interface
  - Optimize band alignment using DFT and experimental validation
- **Surface engineering for enhanced stability**
  - DFT modelling of cathode surface + capping layer
  - Evaluate protective layers (2D materials, oxide capping)
- **Continued High current test for cathode materials**
  - Lifetime test for single-crystal K_2CsSb and Na_2KSb
    - QE decay
    - QE mapping before/after test
    - Thermal load vs QE degradation
  - Transverse emittance measurement
    - MTE measurement at high charge
    - Correlate emittance with cathode material properties

Summary

- High QE, ultrasmooth (sub-nm roughness) and epitaxial photocathodes of **Cs_3Sb, K_2CsSb, Cs_2Te and Na_2KSb** are achieved. The epitaxial growth of **K_2CsSb, Cs_2Te and Na_2KSb** are the *first demonstration* in the field.

Photocathode material	Preparation method	QE	Roughness(nm)
Cs_3Sb	PLD	3% @ 532 nm, thin	0.3 @11 nm thickness
K_2CsSb	PLD; Co-dep	>9% @ 532 nm	0.6 @ 11 nm thickness
Cs_2Te	PLD	17~20%@270nm	0.8 @ 22 nm thickness
Na_2KSb	Co-dep	2.8% @ 532 nm	0.8 @ 20 nm thickness

Match or exceed the best reported results in the field!

- Emittance measurement is in progress.
- High current test is scheduled 2026-2027.

Acknowledgement

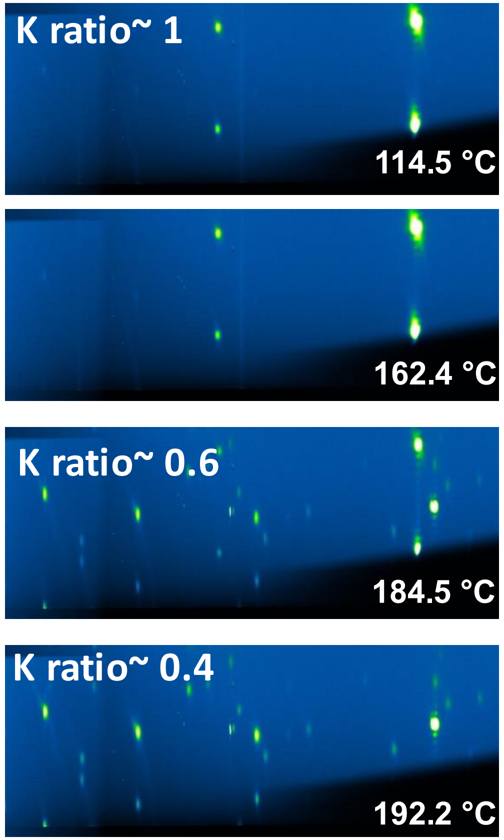
Many thanks goes to the contributors: Kali Prasanna Mondal, Elena Maria Echeverria Mora, Yilin Yang, John Smedley, Jared Maxson, Kenneth Evans-Lutterodt, Raul Acevedo-Esteves, John Walsh, Rudy Begay

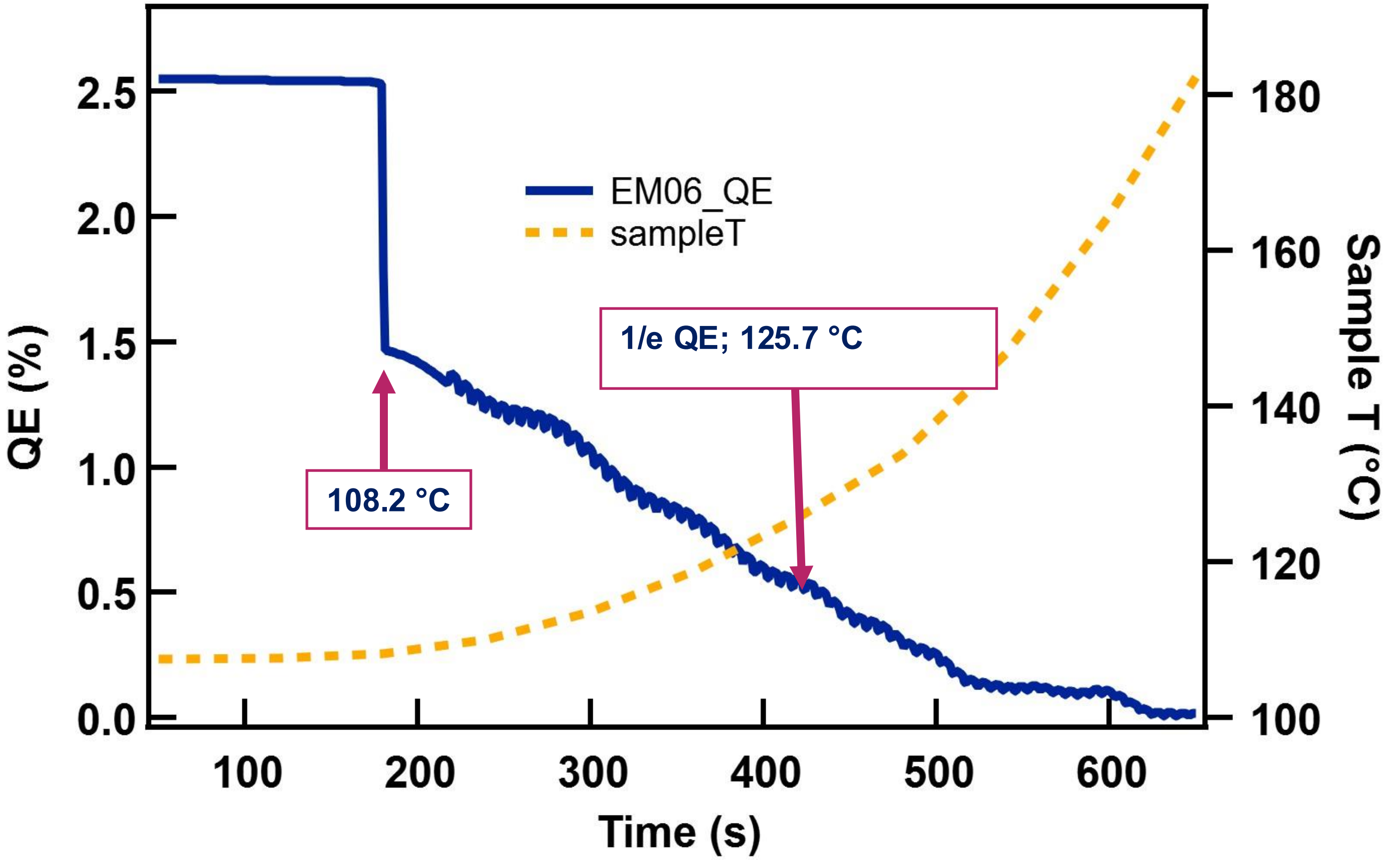
U.S. DEPARTMENT OF ENERGY

Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704. This research used resources 4-ID (ISR) of the National Synchrotron Light Source II, a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Brookhaven National Laboratory under Contract No. DE-SC0012704.

Thank you very much! Suggestions and comments are appreciated!

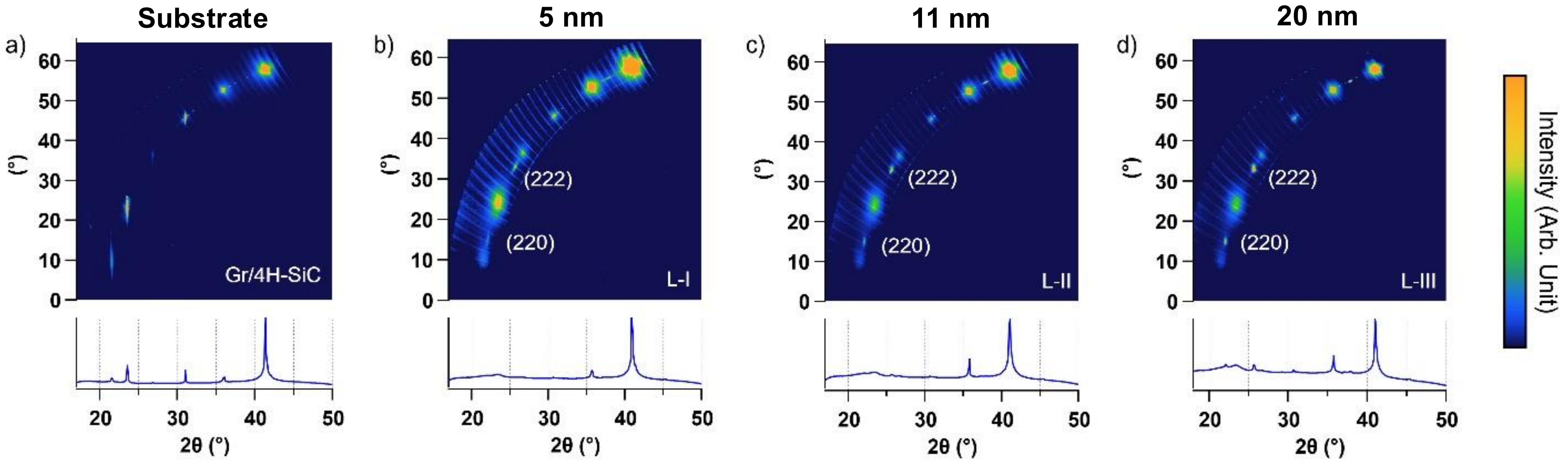
(Back up slides) XRD: Heat decomposition: Na_2KSb

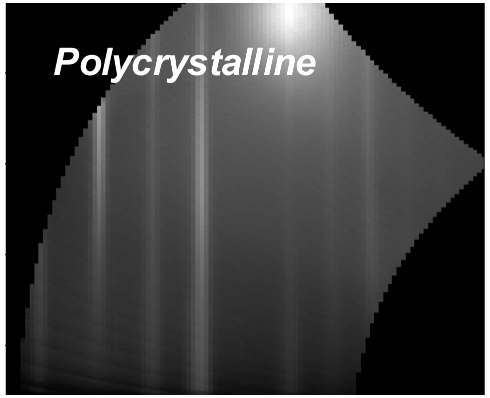


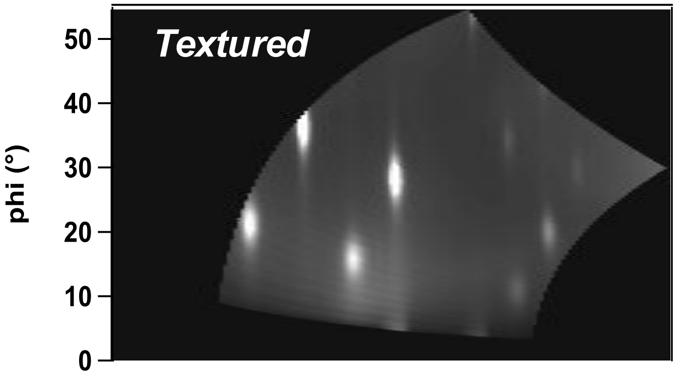


Brookhaven National Laboratory

XRD of epitaxial K_2CsSb cathode





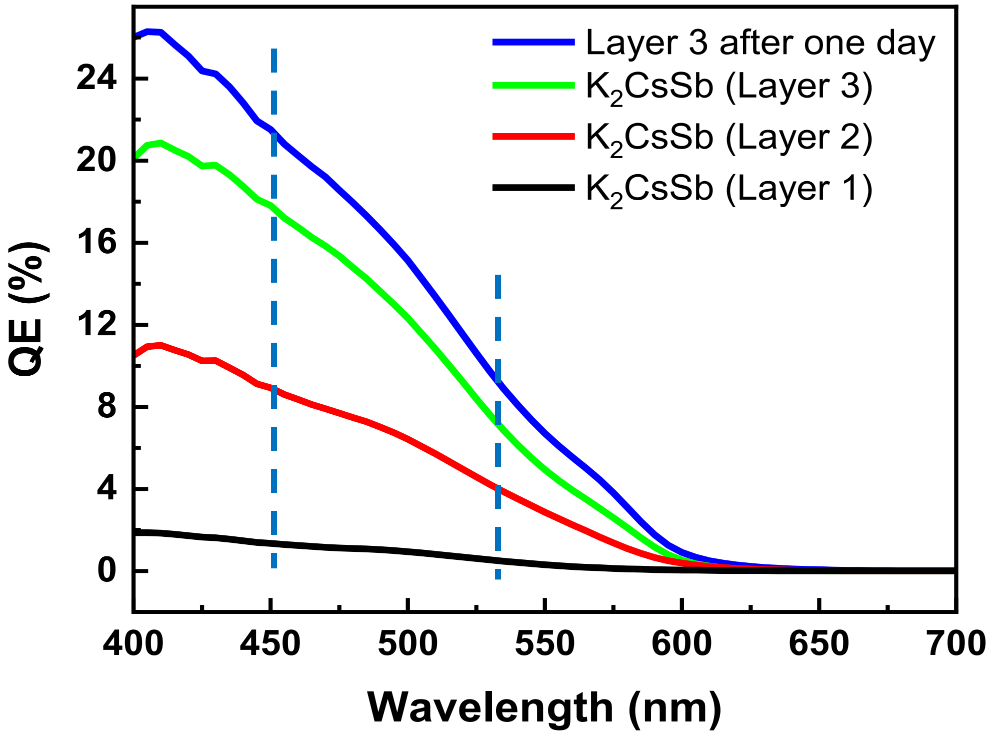


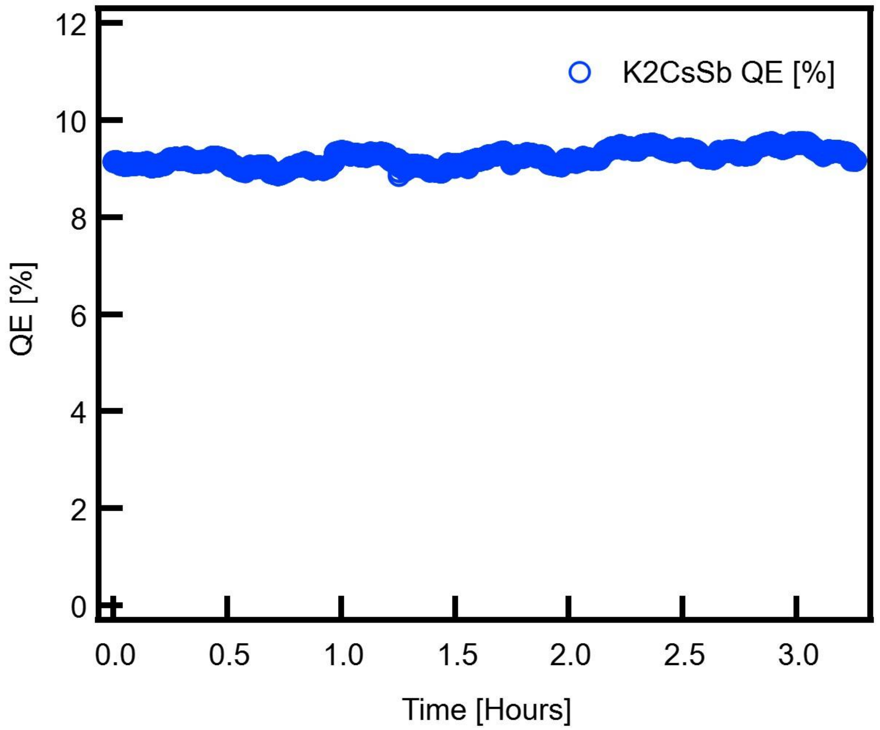
- Sequential growth → Polycrystalline
- Co-evaporation → fiber-textured
- Epitaxial growth → ordered grains/single crystal

Crystallinity

Brookhaven National Laboratory

QE of epitaxial K_2CsSb cathode





Wavelength (nm)		Sample-3 QE (%)			
		L1	L2	L3	L3 after 1 day
Green laser		0.5	4.6	9.2	--
LDLS source	450	1.3	8.9	17.8	21.5
	530	0.5	4.2	7.6	9.7

- ❑ Green QE is > 9% !
- ❑ Measured QE after 3-4 days of growth, no decay
- ❑ Current draw is about 25 uA
- ❑ Fluctuations are likely from laser power