C-AD Machine Advisory Committee Meeting (MAC-20), Dec 19-21, 2023

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

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Collider-Accelerator Department, BNL

- Introduction
- Project timeline and task breakdown
- Progress summary
- Experimental results and discussion
- Summary and plan forward

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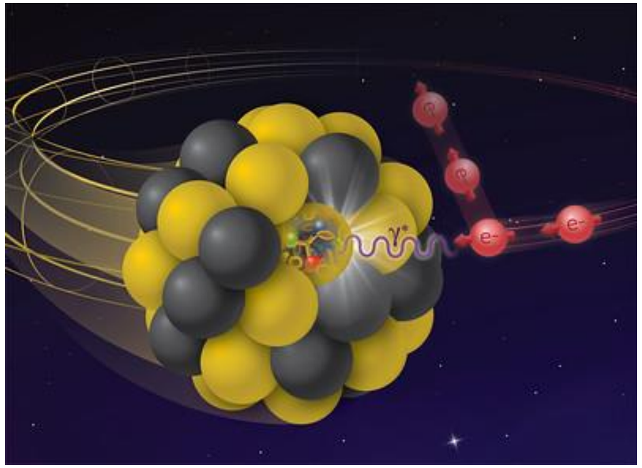
Introduction: Unpolarized high current electron source for EIC

To maintain a luminosity of L= $10^{34} cm^{-2} s^{-1}$ in the Electron Ion Collider (EIC) during long collision runs, it is desirable to maintain hadron emittance by using hadron cooling.



Electron beam for EIC Hadron Cooling

- High average current (100 mA)
- High bunch charge (up to 2nC)
- Long lifetime (>3days)
- Low emittance

Bi-alkali antimonide photocathodes are selected to meeting these requirements, it is also the electron source material currently used at LEReC and CeC.

Current state-of-the-art/practice

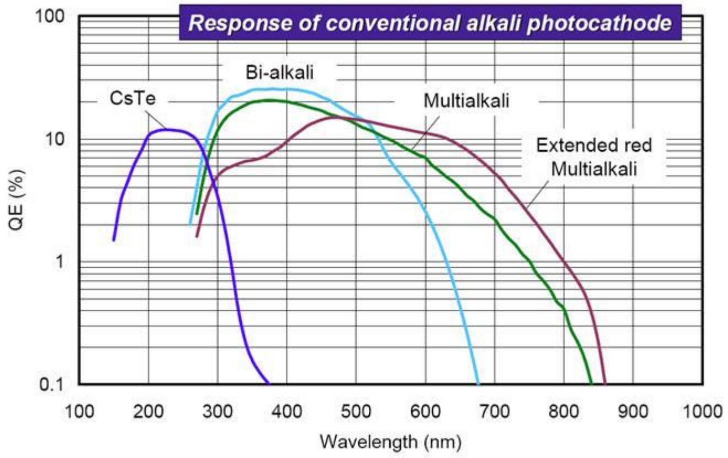
Excellent photocathode for high intensity electron source: good combination of properties

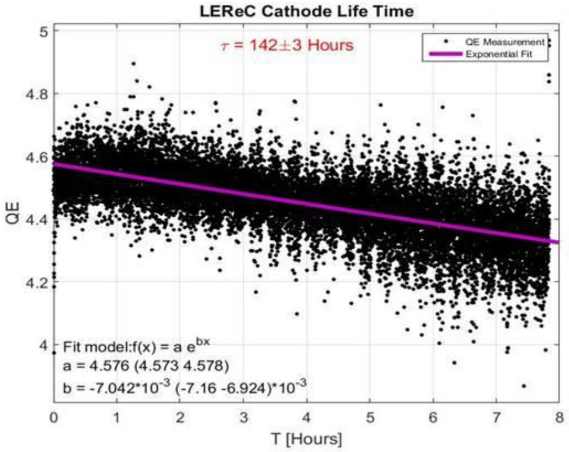
High quantum efficiency in visible light range, low emittance comparing to candidates like Cs_2Te.

Has been demonstrated in practice

Cornell University: 65 mA, 60 pC bunch charge for 2 days
LEReC @ BNL: 55 mA has been reached; 15~20 mA average current for one week of operation, and 20K C charge lifetime

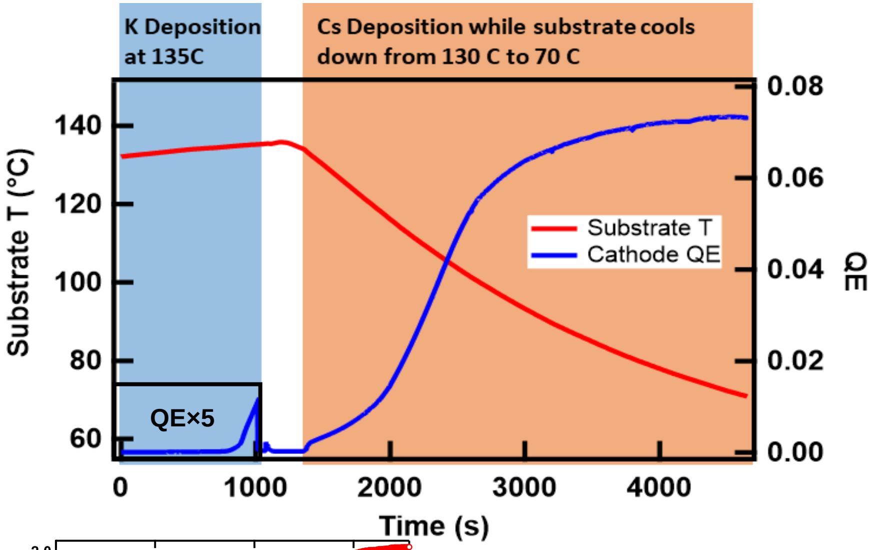
Demonstrated performance doesn't meet the needs for EIC cooling requirements. Photocathode material needs to be improved to achieve higher QE and be more robust for high current operations.

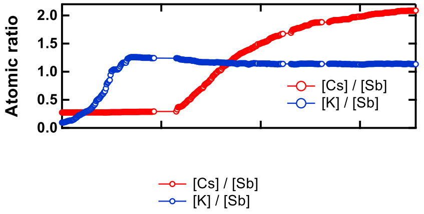


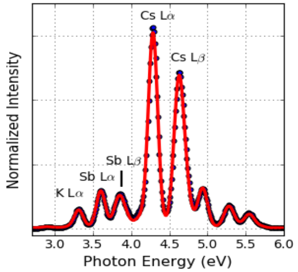


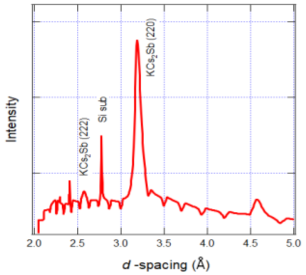
25 mA;
t = 142 h;
QE > 4%

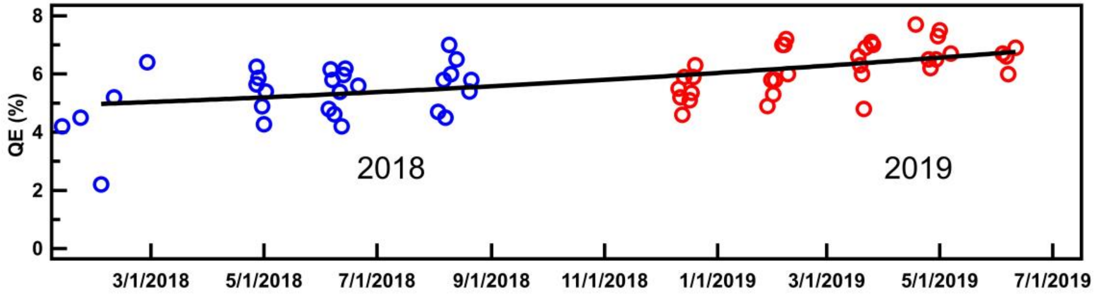
LEReC cathode: characterization of sequential bi alkali antimonides





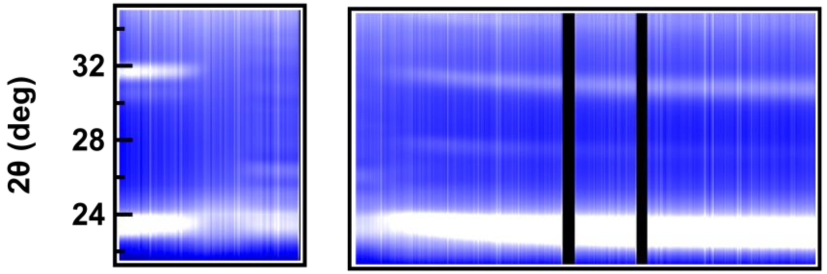






	Run 2018	Run 2019
# of cathodes	28	38
AVG Deposition QE (%)	5.41	6.28
SDEV of QE (%)	0.97	0.85

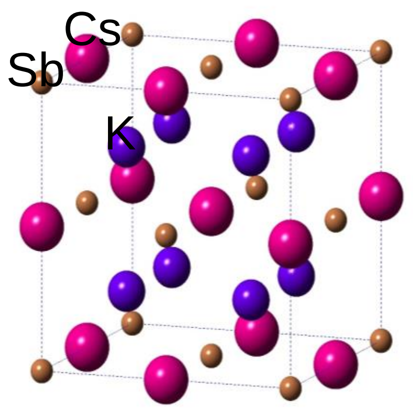
X-ray characterization of the LEReC alkali antimonide photocathode at NSLS-II. Determined the cathode recipe developed for the LEReC project yields the stoichiometry of KCs_2Sb, with a estimated grain size of ~14 nm.



For semiconductor photocathodes, material properties like stoichiometry, crystallinity and surface roughness determines the performance merits such as quantum efficiency and intrinsic emittance. Our studies and experience show that our cathode material has a lot more to improve in terms of these properties.

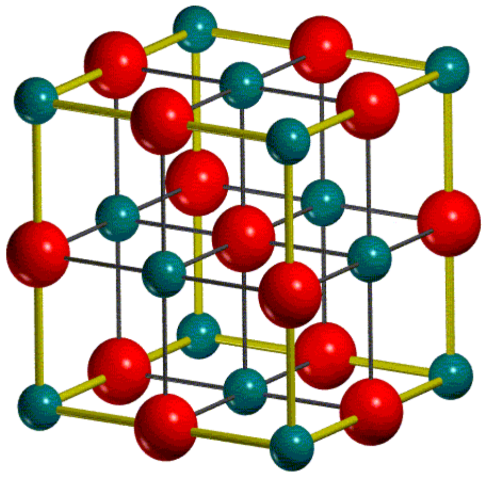
Epitaxial growth of alkali antimonide photocathode

- Epitaxy refers to the growth of a single crystalline film on a single crystalline substrate.
- 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
- 2 key aspects to epitaxial growth: lattice matched substrates and co-evaporation.

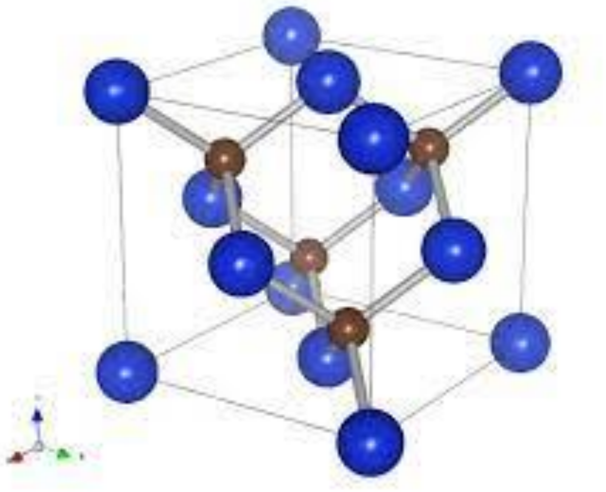


K_2CsSb unit cell

K_2CsSb, Cs_3Sb: b.c.c. crystal structure
Lattice parameter: 8.615 Å, 9.18 Å



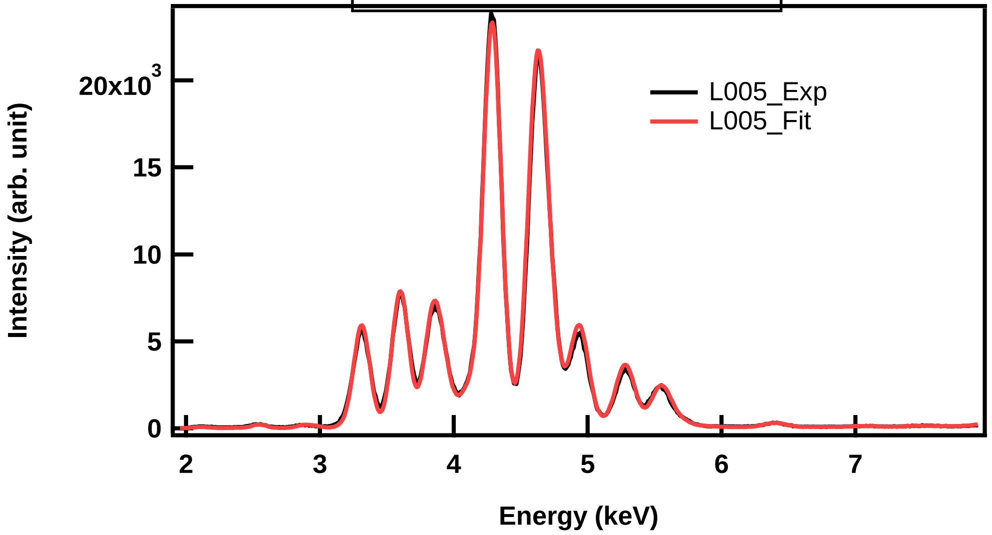
MgO: f.c.c. crystal structure
Lattice parameter: 4.21 Å



3C-SiC: f.c.c. crystal structure
Lattice parameter: 4.35 Å

Co-evaporation for epitaxial growth: stoichiometr
thin film growth in one ste

X-ray fluorescence

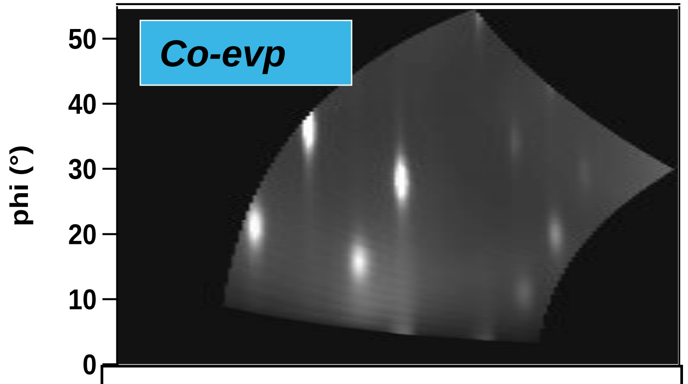


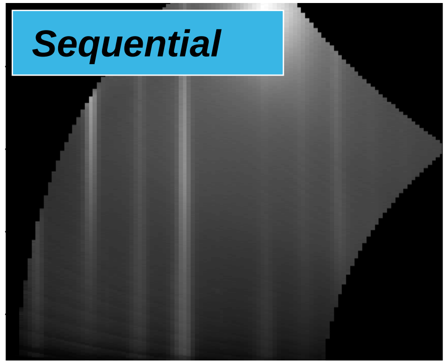
Calculated atomic compositions

	K	Sb	Cs
L005 Si	2.37	1.00	0.91
L006 Si	2.21	1.00	0.95
L011 Si	2.07	1.00	0.94
L012 MgO	1.98	1.00	0.88

Good K/Cs/Sb ratio!

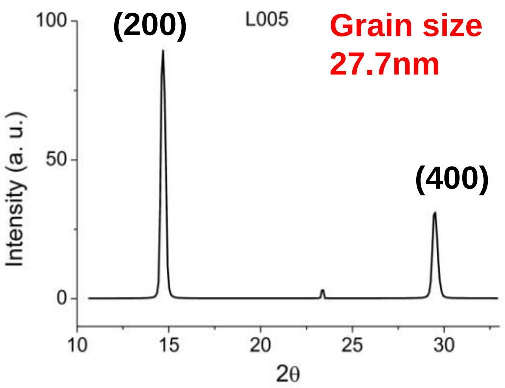
X-ray diffraction: Camera image

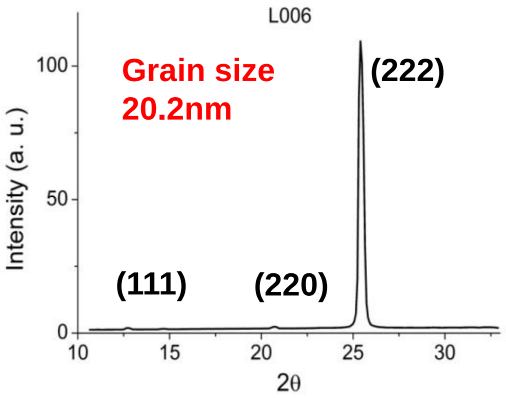




Confined arcs: textured polycrystalline

Continuous lines: polycrystalline

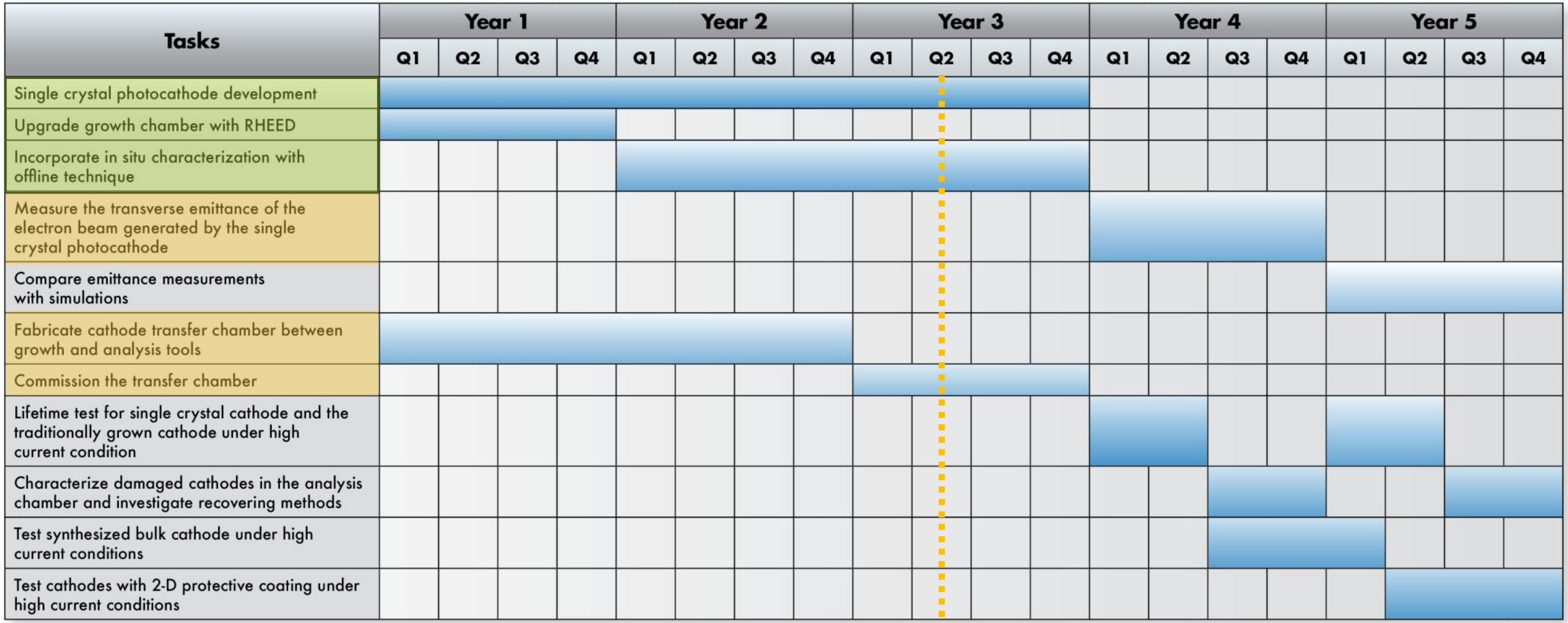




Research approach

Cathode Material development	Transfer system development	High current test
• Epitaxial growth of single crystal cathode material • Upgrade with RHEED • Bulk single crystal growth	• Existing design and experience	• High current test chamber • Gun test in tunnel • Material characterization for degraded cathodes

Project tasks and timeline



- Task breakdown (Y1 ~ Y3)
  - Single crystal photocathode development (90%)
  - Upgrade growth chamber with RHEED (100%)
  - Incorporate in situ x-ray characteristics with offline technique. (100%)
  - Fabricate cathode transfer chamber between growth and analysis tools (50%)
  - Measure transverse emittance of single crystal photocathode (30%)

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Progress summary

Hardware upgrade:

- **RHEED (reflection high energy electron diffraction)** system has been installed, commissioned on the cathode growth chamber. RHEED measurement was successfully performed during the NSLS-II beamline along with the x-ray characterization for the epitaxial growth of the photocathode material.
- Chamber was also upgraded to use **pulsed laser deposition (PLD)** as the growth method. Rotatable PLD target was installed and optics were built to introduce the excimer laser into the chamber.

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.

Development for Epitaxial K_2CsSb photocathode

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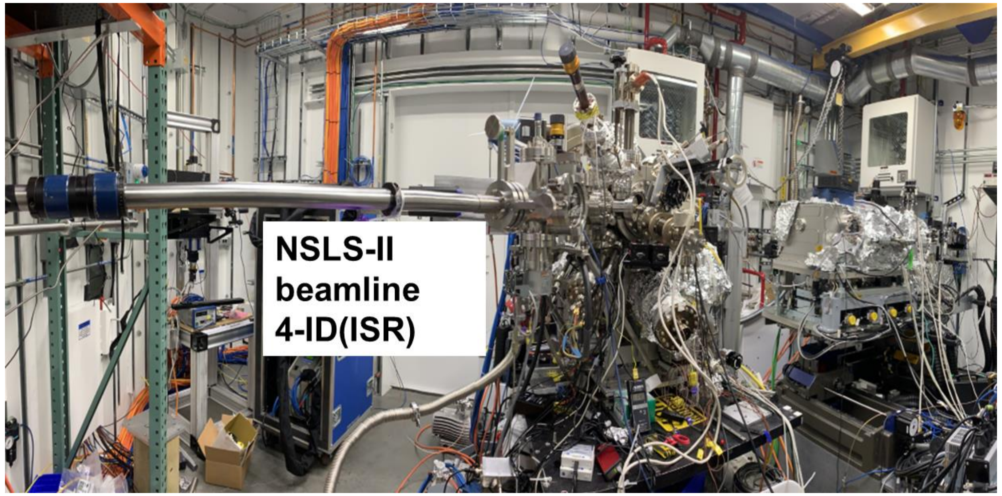
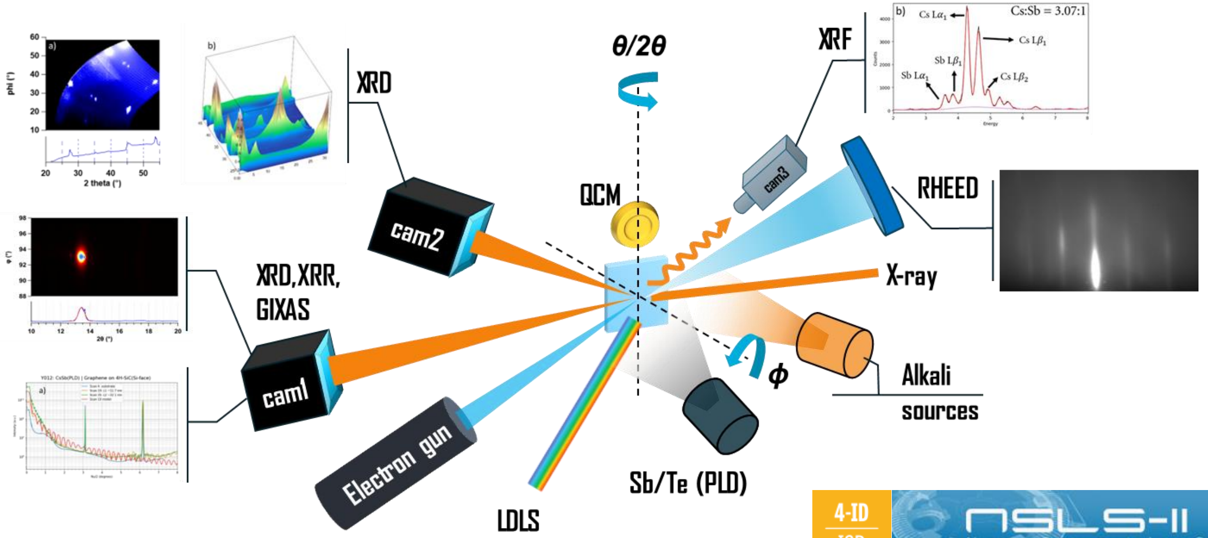
Experimental: characterization





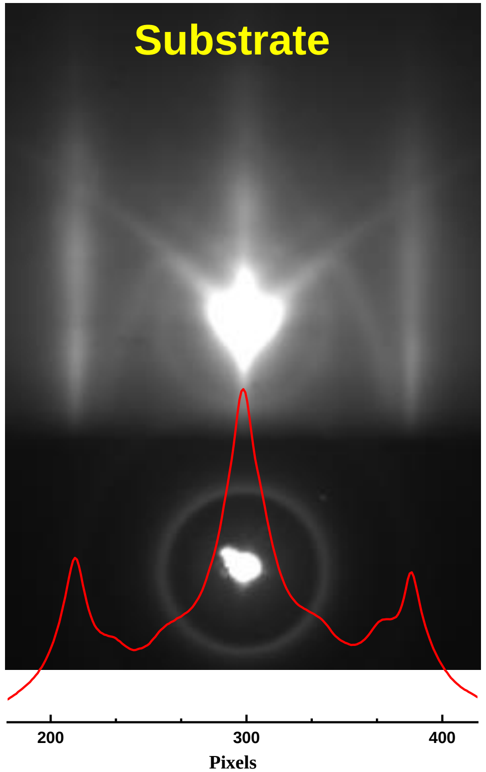
Evaluators:

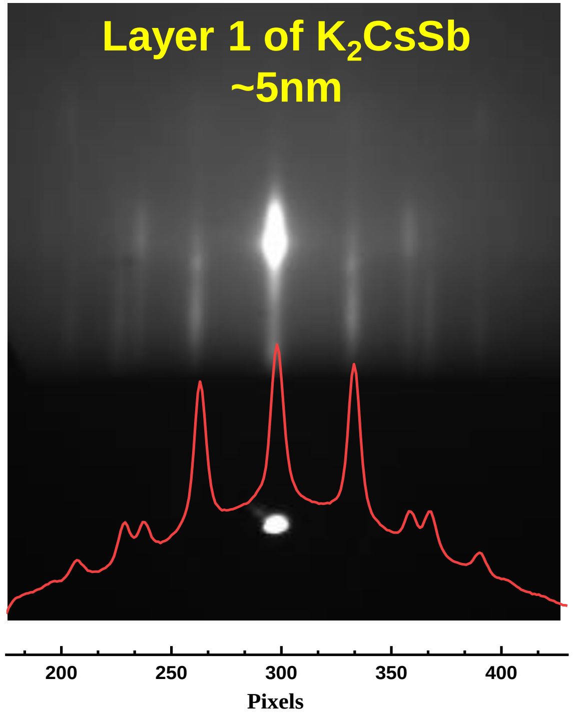
- ❑ **Thermal Sb/Te**
- ❑ **Alkali metals**
- ❑ **PLD Sb/Te (Pulsed laser deposition)**

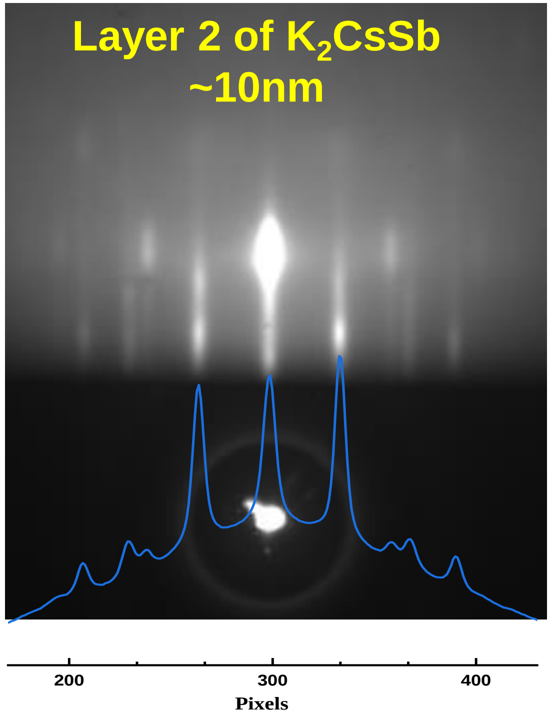
Characterization:

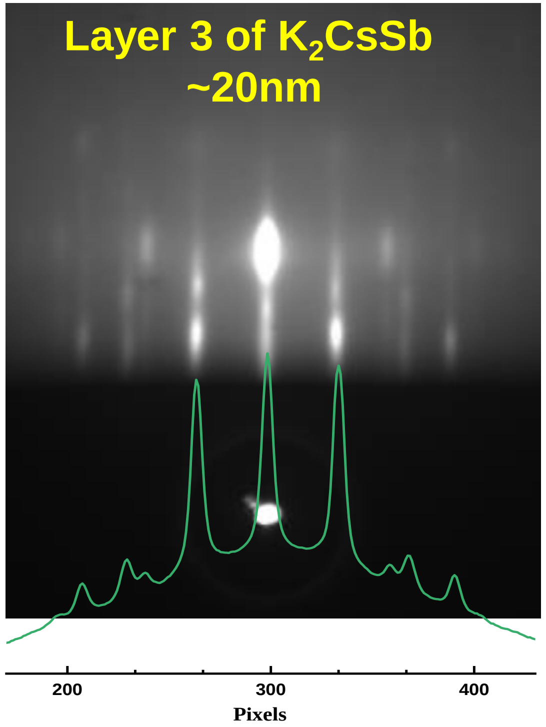
- ❑ Reflection high energy electron diffraction (RHEED): epitaxial growth and crystalline structural details.
- ❑ X-ray diffraction (XRD): crystalline structure.
- ❑ X-ray reflectivity (XRR): thin film thickness, roughness, electron density.
- ❑ Grazing incidence small angle x-ray scattering (GISAXS): Structural details both from surface and interface.
- ❑ X-ray fluorescence (XRF): Stoichiometry of Photocathode
- ❑ Quantum efficiency (QE) measurement: Spectral response of cathode from Laser driven light source (LDLS)
- ❑ Quartz crystal microbalance (QCM): thin film thickness

Epitaxial K_2CsSb: RHEED

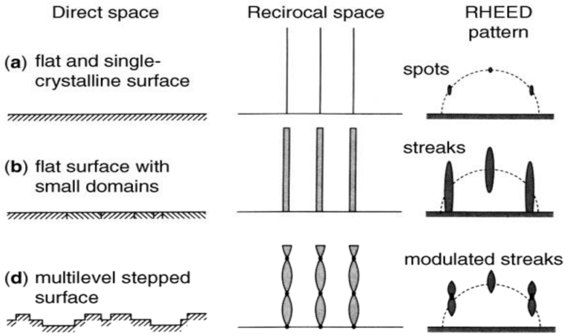




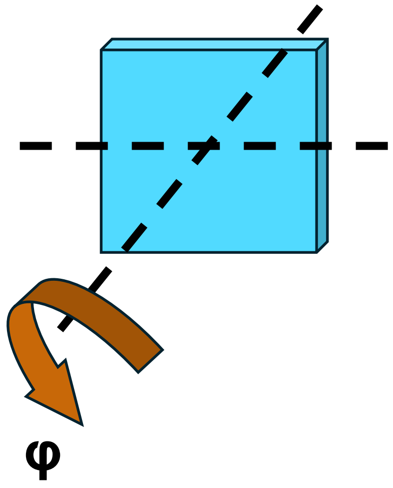




- ❑ Alignment with substrate peaks indicating epitaxy.
- ❑ Streaky pattern represent smooth surfaces with small domains.
- ❑ Multiple sets of streaks visible, indicating multiple epitaxial orientations.
- ❑ Modulated streaks: roughness increases.

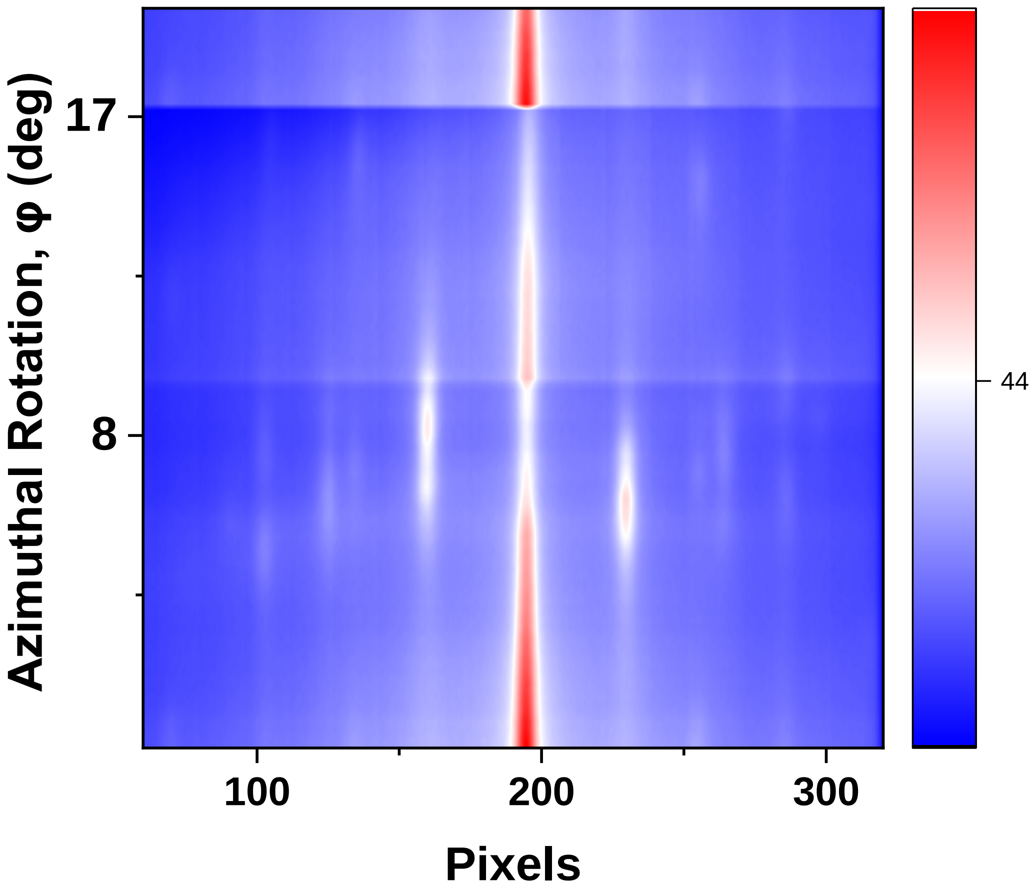


Epitaxial K_2CsSb: RHEED

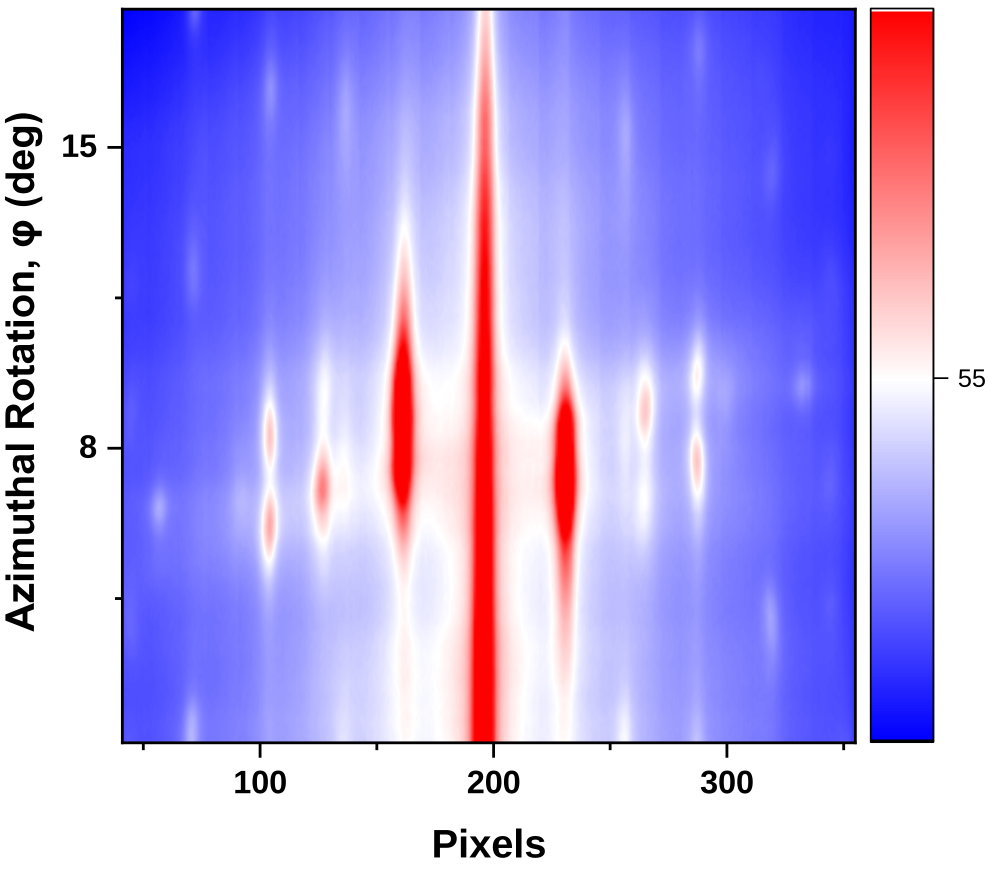


Schematic of azimuthal sample rotation

Layer 1 of K_2CsSb

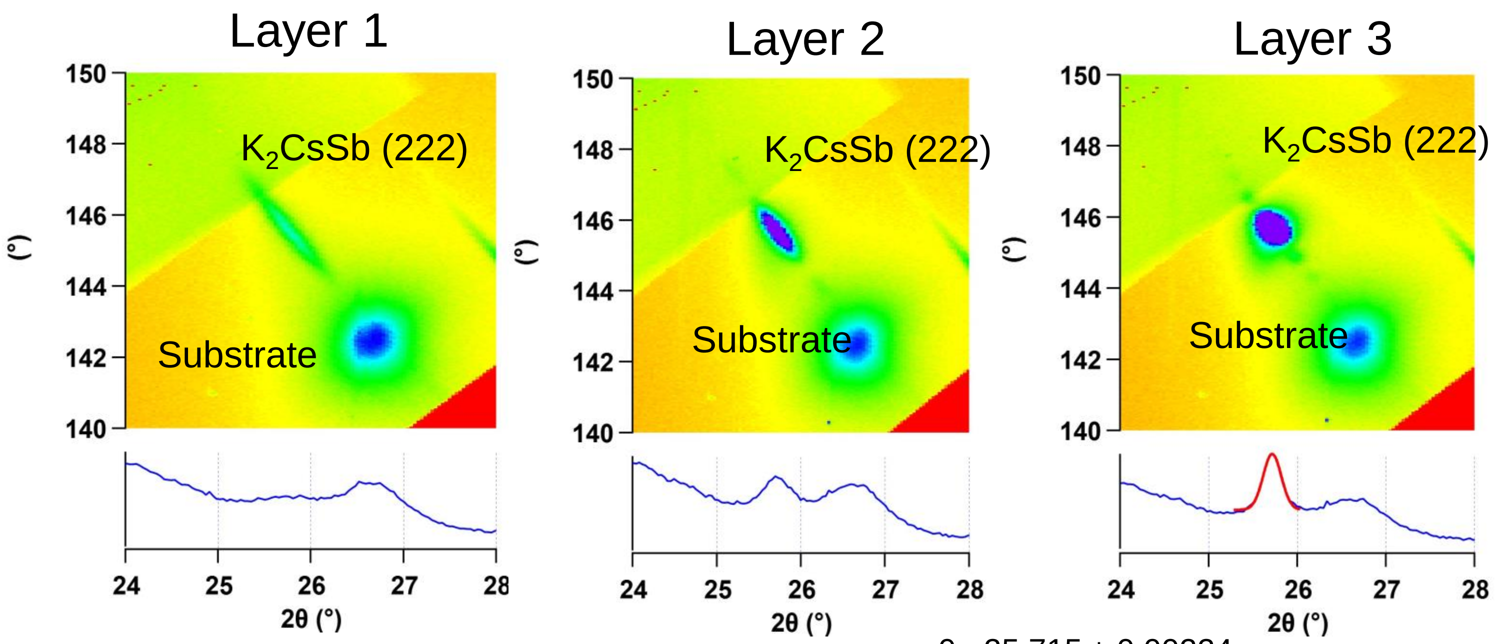


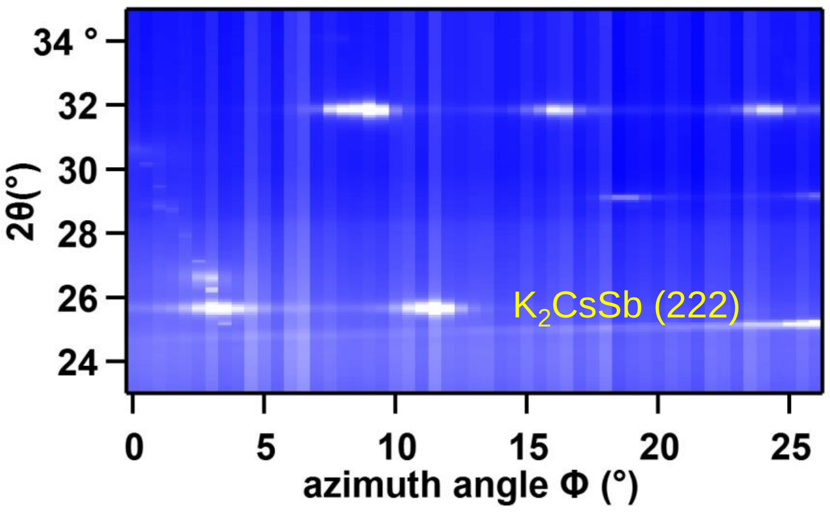
Layer 3 of K_2CsSb



Azimuthal angular dependence in RHEED pattern are observed, indicating aligned crystalline domains are formed in the cathode film.

Epitaxial K_2CsSb: bulk crystallinity



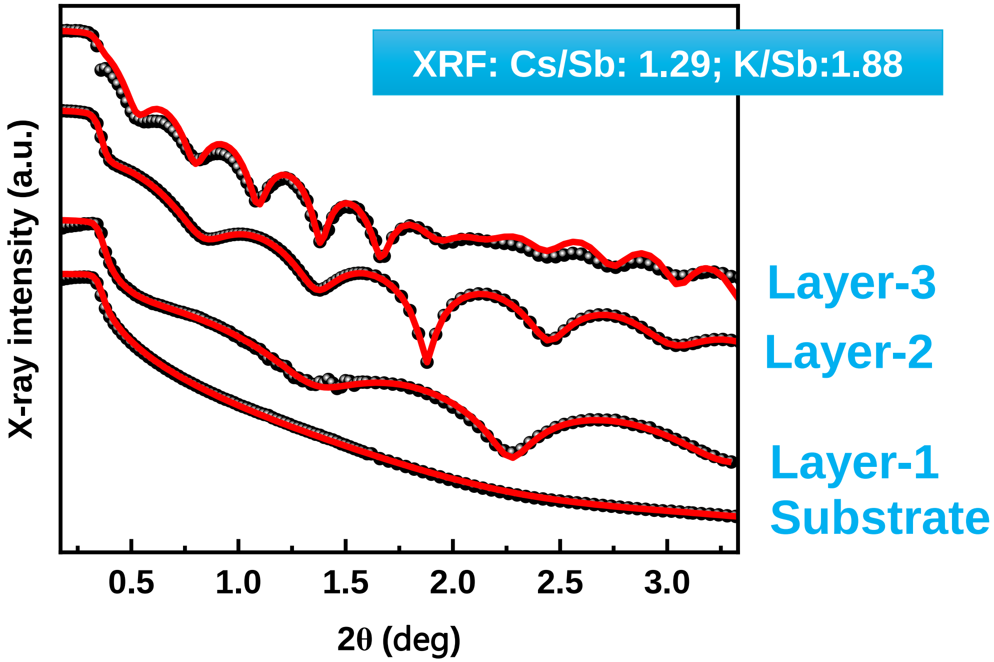


x0 =25.715 ± 0.00224
width =0.14515 ± 0.00415
Grain size: 411.30 nm, comparing to typical polycrystalline film grain size of 10 ~ 30 nm.
Film thickness Layer 3 : 20 nm

- **Diffraction image at Brag condition (222)**
- **Elongation structure is from Mosaicity and strain of the film.**
- **Grain size is >> film thickness; indicating the formation of large crystal domains.**

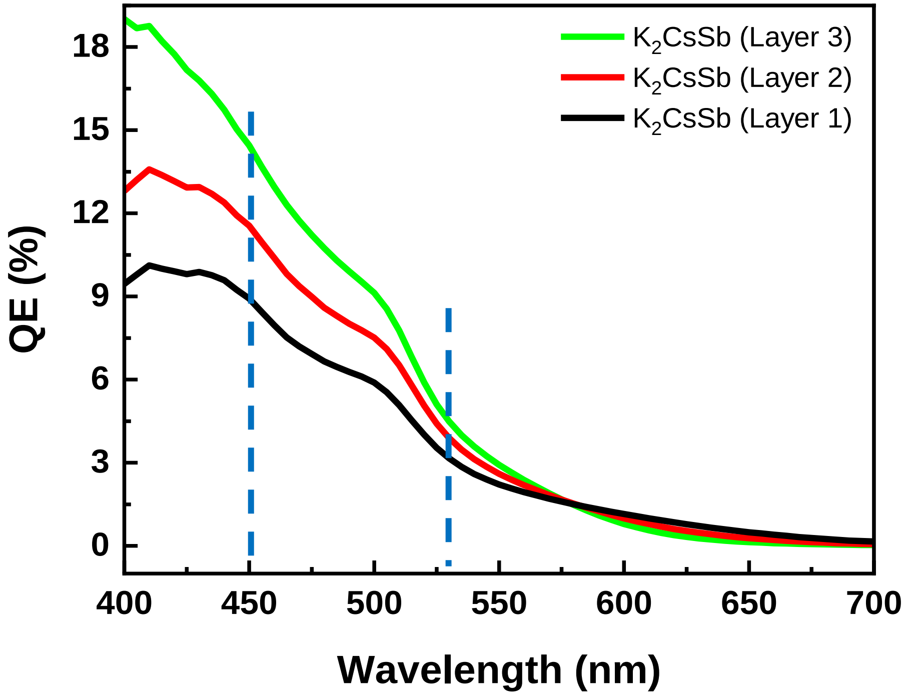
Azimuthal angular dependence from XRD is observed, agrees with RHEED. Indicating the crystalline grains are aligned in orientation.

Film roughness and QE



XRR	Thickness (nm)	Roughness (nm)
Substrate	NA	0.40
Layer 1	6	0.60
Layer 1+2	11	0.65
Layer 1+2+3	20	0.75

XRR of K_2CsSb Roughness increased with increasing thickness of photocathode thin film.



Wavelength (nm)	QE (%)		
	L1	L2	L3
450 (Blue)	8.9	11.6	14.5
530 (Green)	3.2	3.9	4.5

Offline development: K_2CsSb growth on doped 4H/SiC

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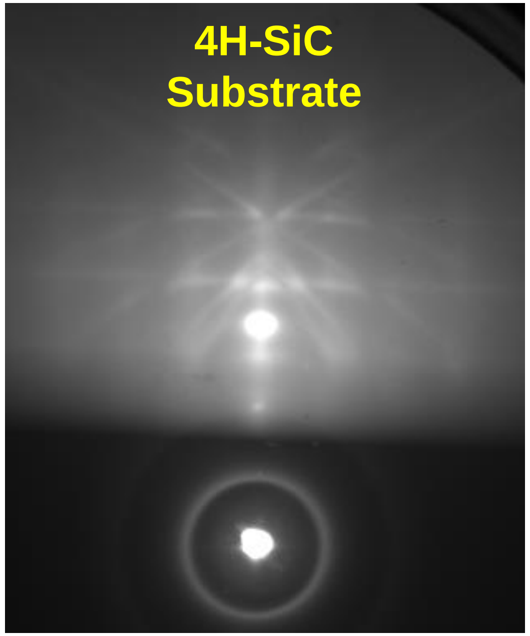
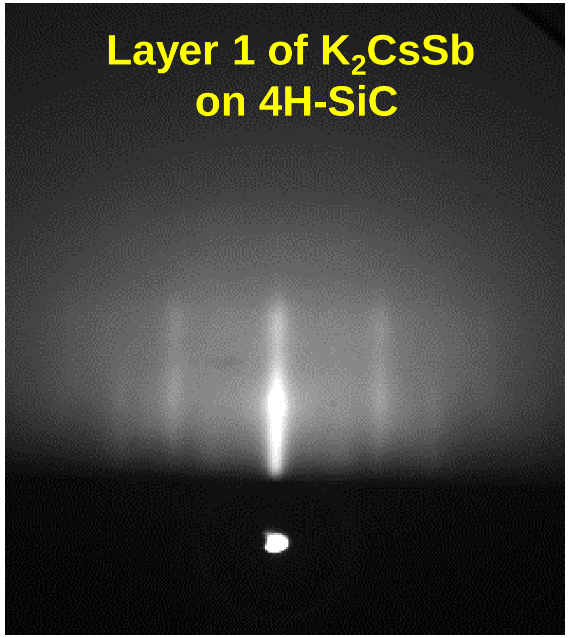
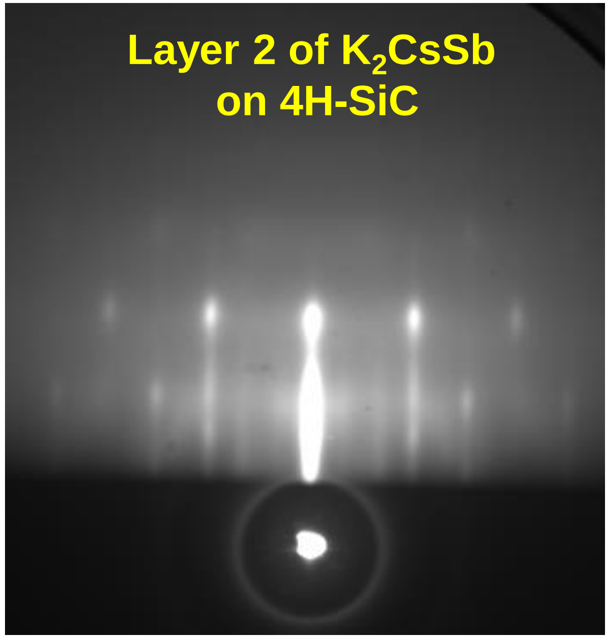
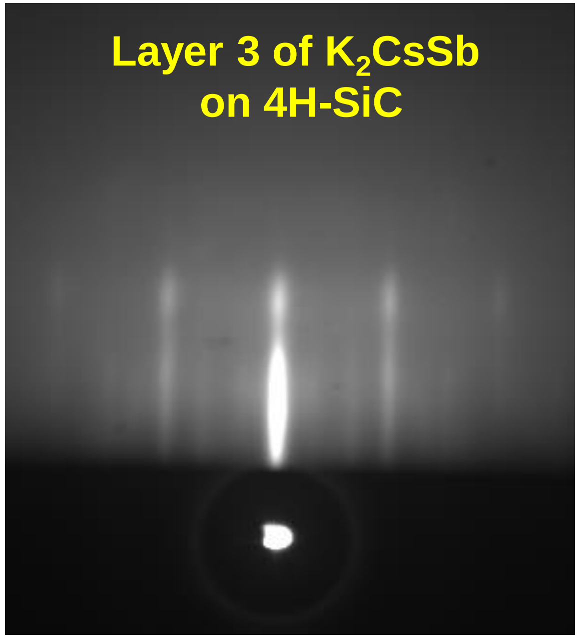
K_2CsSb/4H-SiC: RHEED



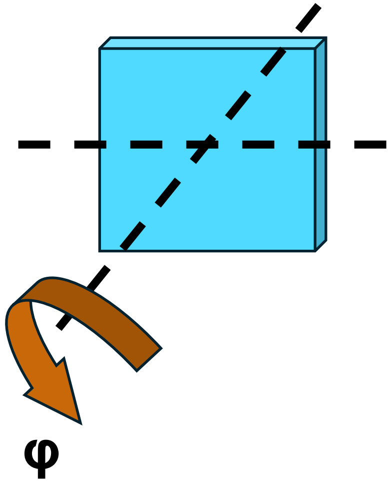




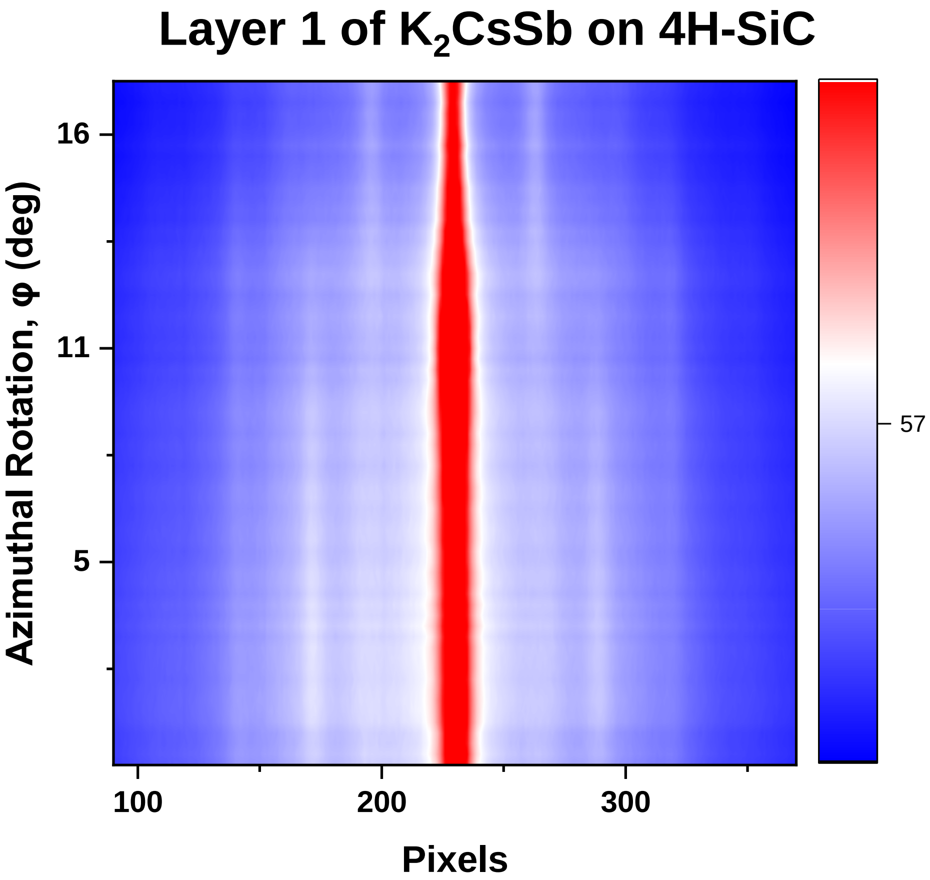


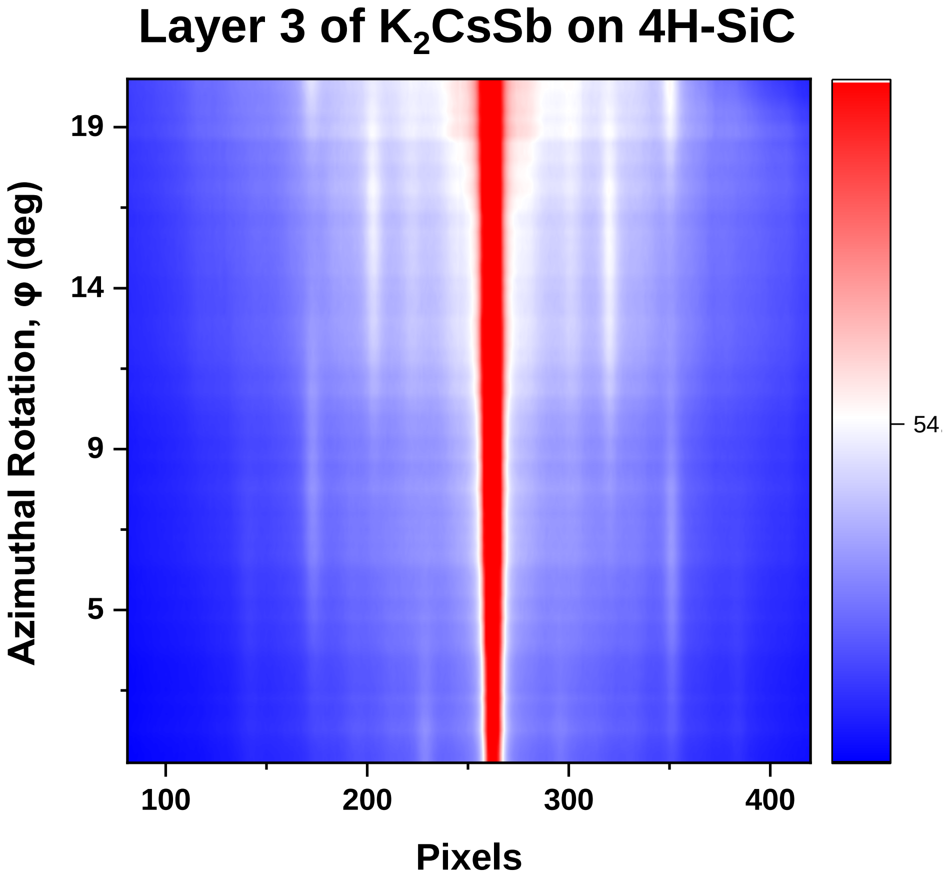
- ❑ Similar streaks to film in the x-ray experiment
- ❑ Streaky pattern represent smooth surfaces with small domains.
- ❑ Modulated streaks: roughness increases.

K_2CsSb/4H-SiC: RHEED



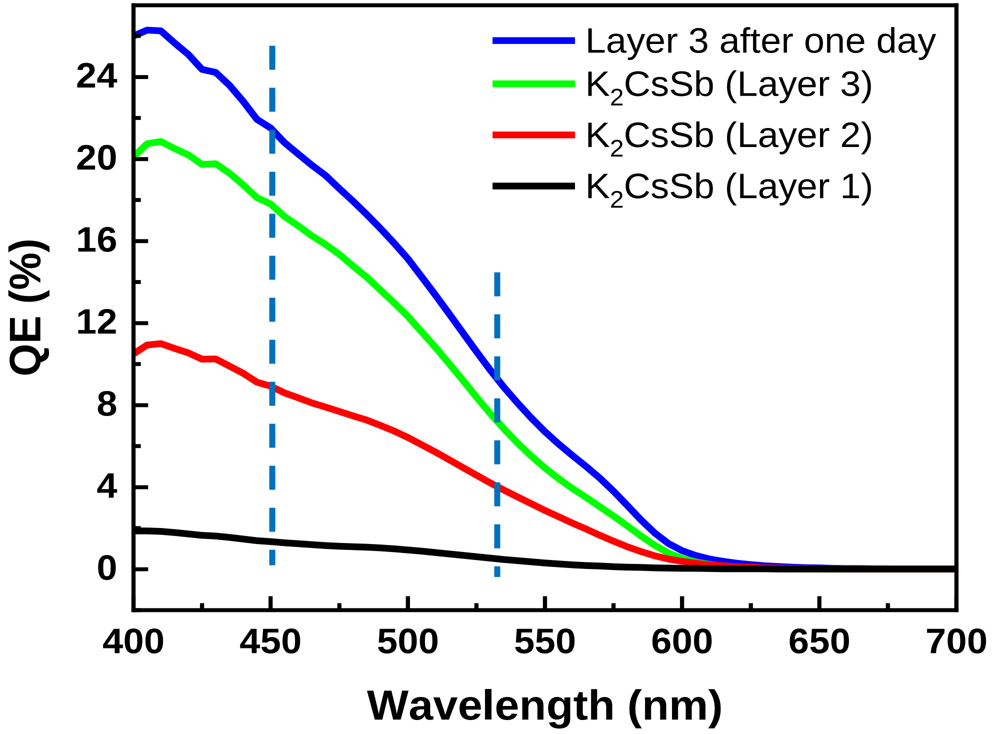
Schematic of azimuthal sample rotation

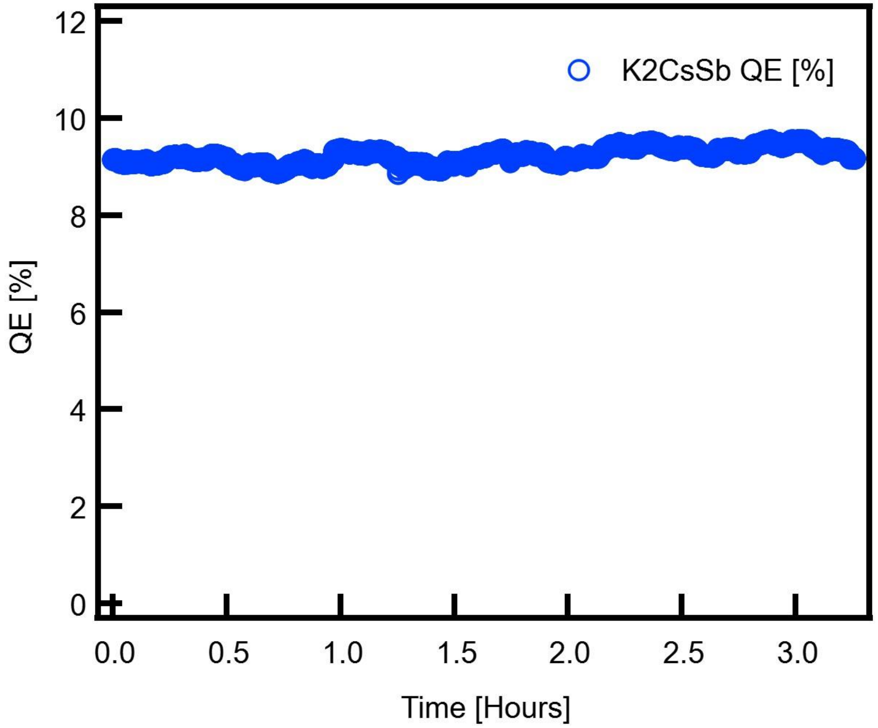




- ❑ Similar azimuthal angular dependence is observed
- ❑ Similar to the previous experiment, multiple grain orientations are observed.

Quantum Efficiency





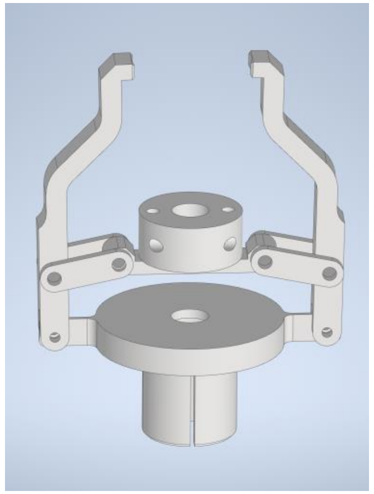
Wavelength (nm)		Sample-3 QE (%)			
		L1	L2	L3	L3 after 1 day
Green laser		0.5	4.6	9.2	--
LDLS source	450	1.3	8.9	17.8	21.5
	530	0.5	4.2	7.6	9.7

- ❑ **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**

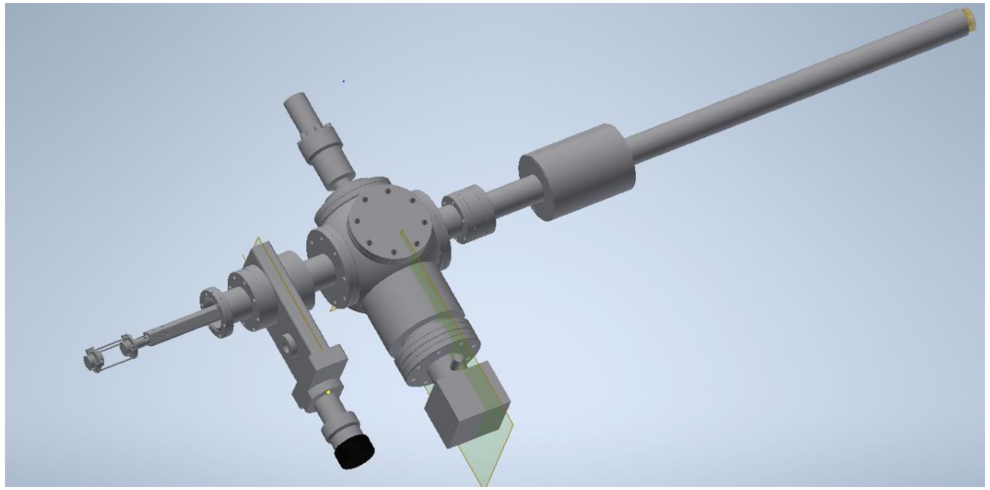
Transfer chamber /emittance measurement progress

- Transfer chamber is designed according existing drawings. Custom connection mechanism is designed and being fabricated.
- Material order in progress
- Emittance chamber is being designed, simulation underway.

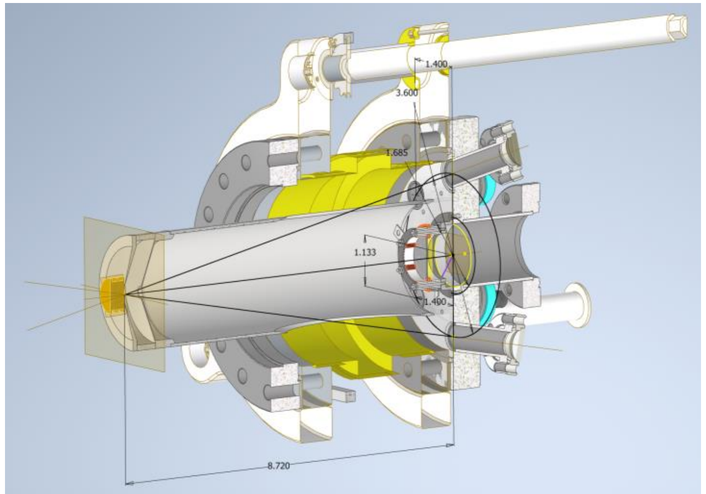
Custom fork design



Transfer chamber design



Emittance measurement



Design curtesy to John Walsh, John Skarica, Yilin Yang

Summary/Plan forward

Epitaxial growth of multiple alkali-based photocathode materials are achieved. The cathode films are showing exceptional performance in crystallinity, surface roughness and QE in a varied thickness range.

The plan forward:

- Complete the transfer chamber and the system for emittance measurement
- Measure the emittance for epitaxial K_2CsSb
- Gun test for high current performance (up to 100 mA avg. current)
- Analysis for damaging mechanism to improve cathode lifetime.

Acknowledgement

Many thanks goes to the contributors: John Smedley, Jared Maxson, Chad Pennington, Elena Maria Echeverria Mora, Kenneth Evans-Lutterodt, Raul Acevedo-Esteves, Siddharth Karkare, Priyadarshini Bhattacharyya, Pallavi Saha, Jean Jordan-Sweet, Guido Stam, Molen S.J. Van der, Thomas Juffmann, Rudolf Tromp, John Walsh, Rudy Begay

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Thank you very much! Suggestions and comments are appreciated!

Back up slides

High current gun test: parallel efforts

EIC cathode R&D

- Cathode puck is designed to adapt epi ready substrate for the SHC gun at SBU.
- Growth system (LEREC-II system) is being reconfigured and upgraded to:
  - perform co-evp from alkali effusion cells and
  - fit the footprint of the SBU gun;
  - address cathode storage and transfer.

High current gun test: parallel efforts

High current test bed in Instrumentation Division, BNL

- Design completed.
- Material ordering in progress.
- Compatible with the puck style and transfer scheme for this project.