



中国科学院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

Robust photocathodes for CW XFEL

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Shanghai Advanced Research Institute, CAS

Photocathodes for Accelerator Science in Europe
(PhASE 2026), September 21-23, 2026 Orsay-IJCLAB-France

<http://www.sari.cas.cn>

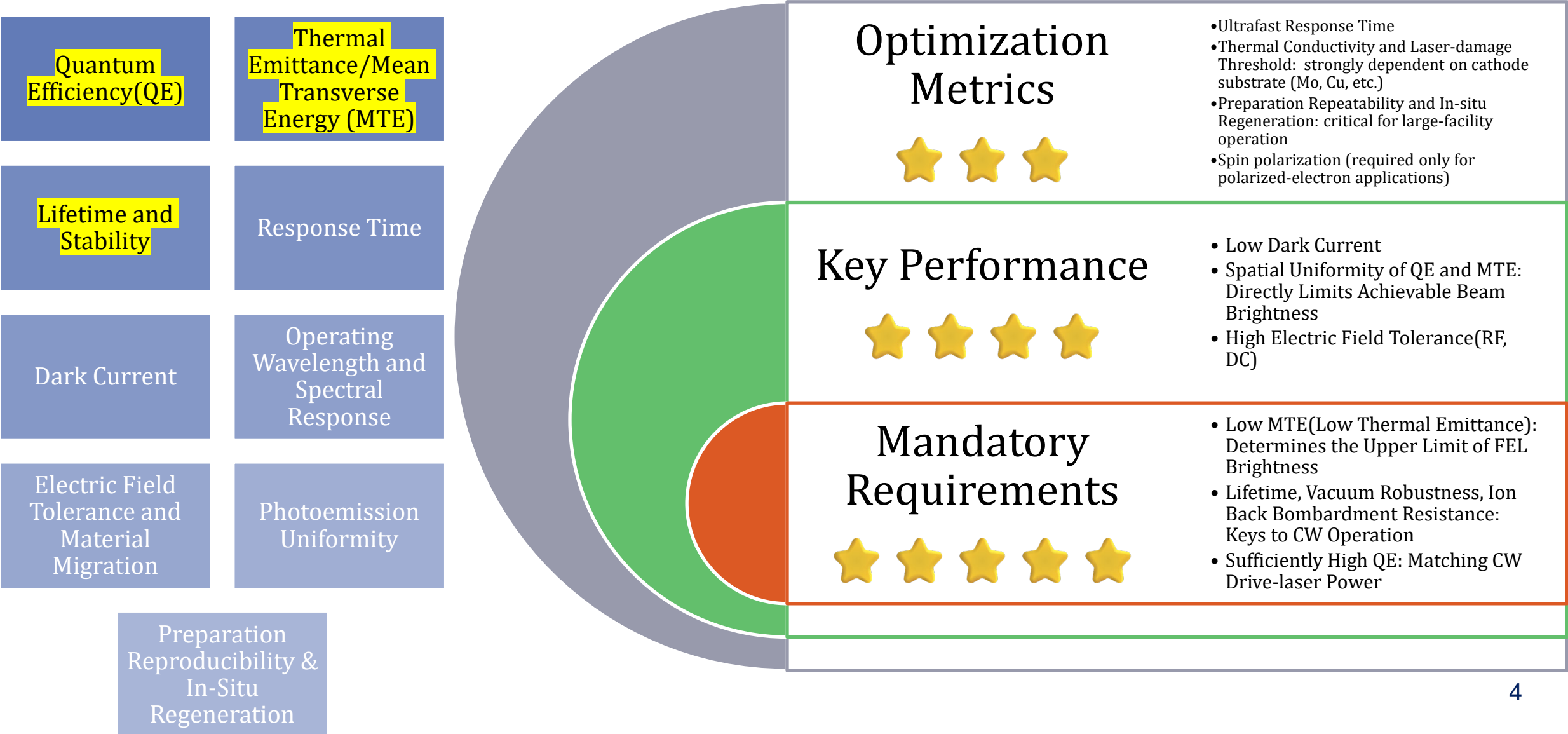
Groups

- Shanghai Advanced Research Institute, Chinese Academy of Sciences (SARI, CAS):
 - Xudong Li, Zenggong Jiang, Hao Meng, Qiang Gu
- Zhangjiang Laboratory (ZJLAB):
 - Qin Zhou, Chen Wang, Zipeng Liu, Guan Shu, Houjun Qian
- Graduate Students, University of Chinese Academy of Sciences (UCAS):
 - Tao Hou, Zehao Tong

Outline

- Background
 - Photocathodes in CW XFEL
- Photocathode Preparation, Characterization, and Operation Apparatus
- Photocathode Preparation Study
- Photocathode Testing and Commissioning
- Summary and Plans

Photocathode Characterizations in CW XFEL

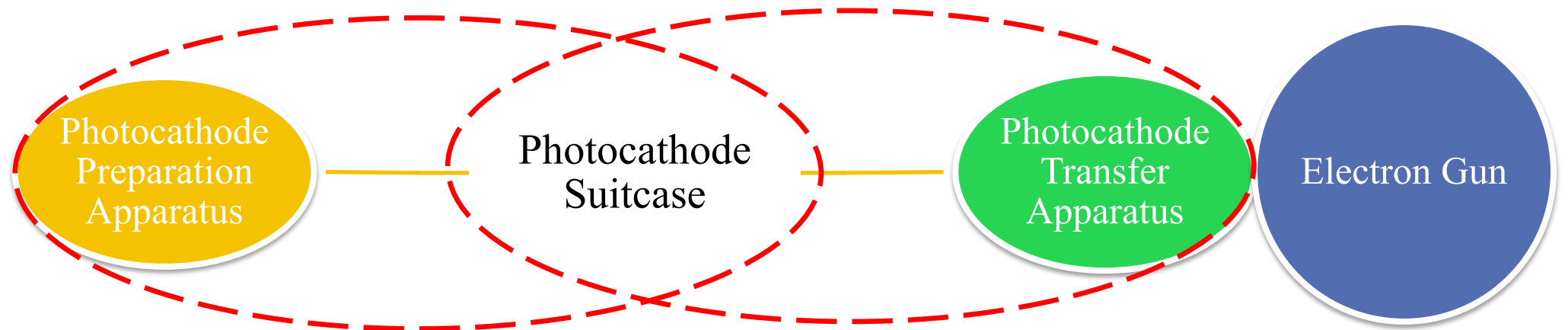
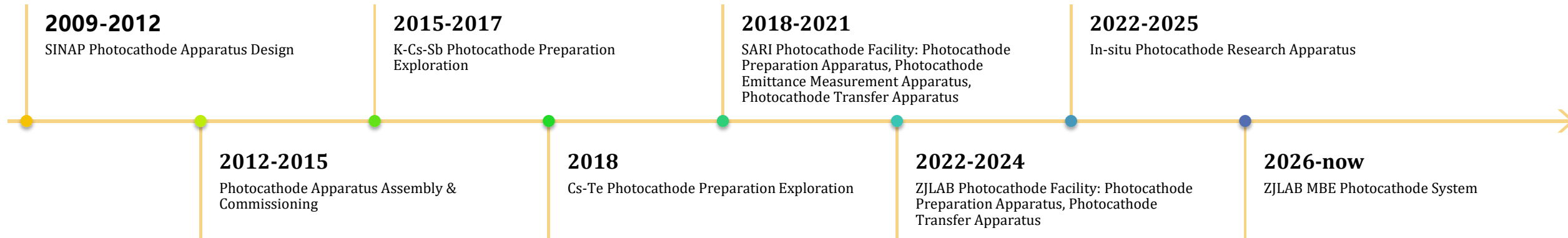


Typical Candidate Photocathodes for CW XFEL

Materials	Parameters	Advantages	Disadvantages	CW-FEL Suitability
Alkali-metal antimonides K_2CsSb/Na_2KSb	MTE: 0.10–0.25 eV Drive laser: 515 nm Green QE: 5%-15%	Low MTE, high QE at green light	Moderate lifetime, alkali-metal migration risk, vacuum-sensitive	★★★★ Popular candidate
Alkali-metal tellurides Cs_2Te	MTE: 0.15–0.30 eV Drive laser: 266 nm UV QE: ~10%	Good robustness, long lifetime	Elevated MTE, UV-laser required	★★★ Suitable for Non-Extreme Brightness
Metals Cu/Mg	MTE: 0.40–0.70 eV Drive laser: 266 nm UV QE: $\sim 10^{-5}$ – 10^{-3}	Excellent lifetime, high stability	Very low QE, UV-laser required, large MTE	★ Low-Brightness CW Only
III-V semiconductors NEA-GaAs	MTE: 0.10–0.20 eV Drive laser: 532 nm Green QE: ~10%	Low MTE, spin-polarized emission	Extremely residual-gas-sensitive, short lifetime	★ Short-Time Polarized Experiments Only

Photocathode Research Journey

Evolution of Photocathode Facilities and Related Research in the Project Team

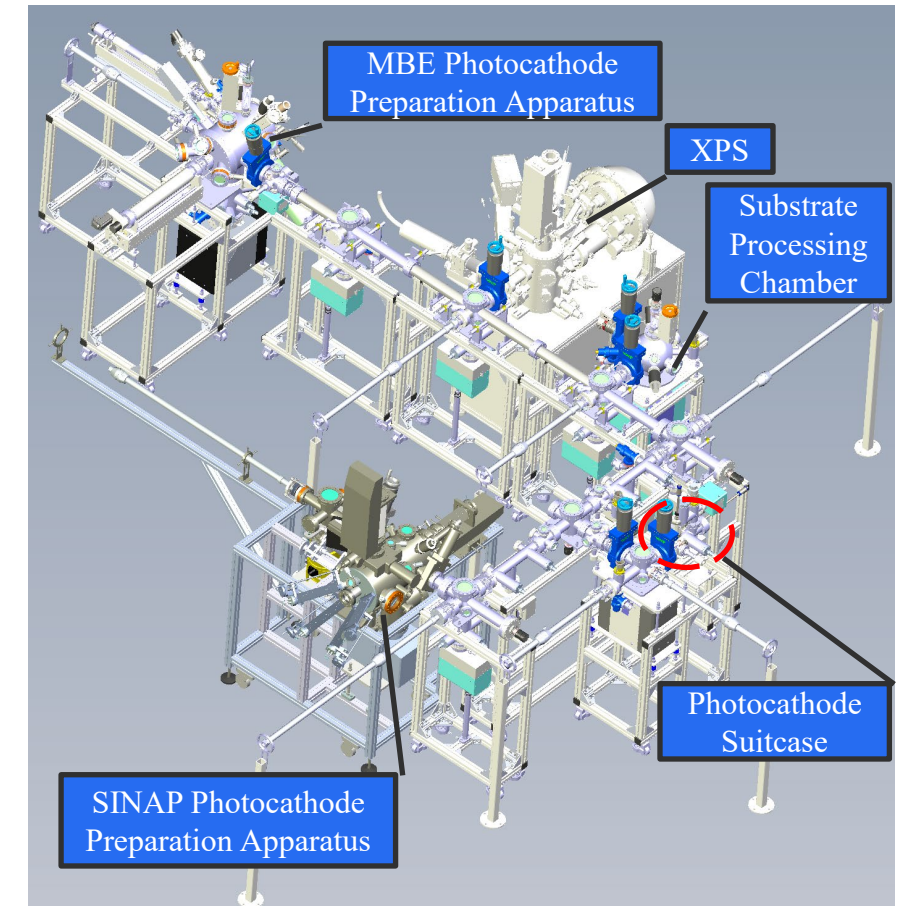
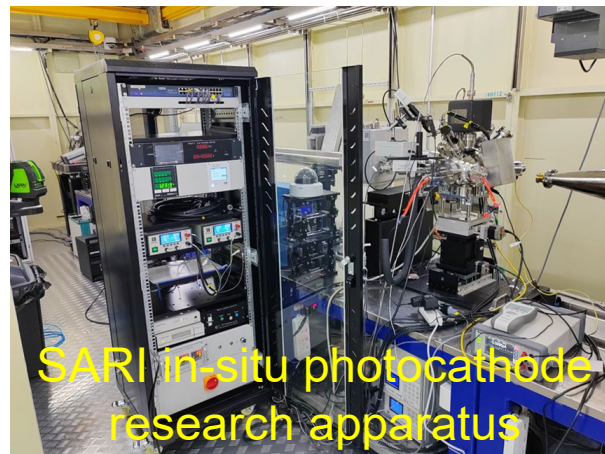
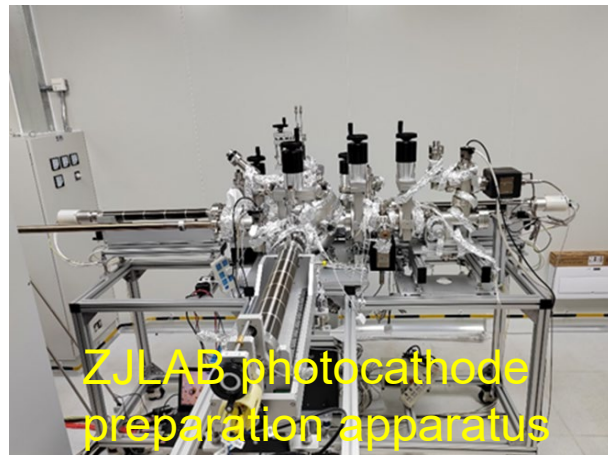
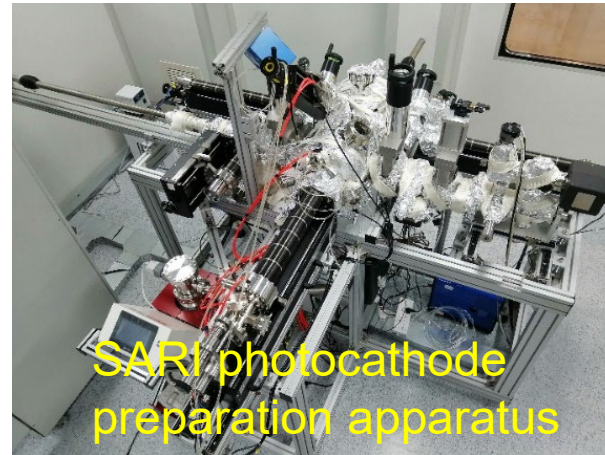


Functions:



Photocathode Apparatus

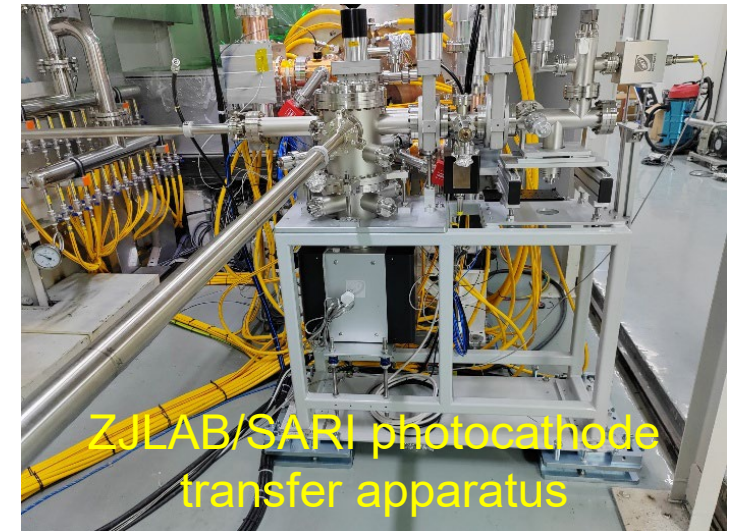
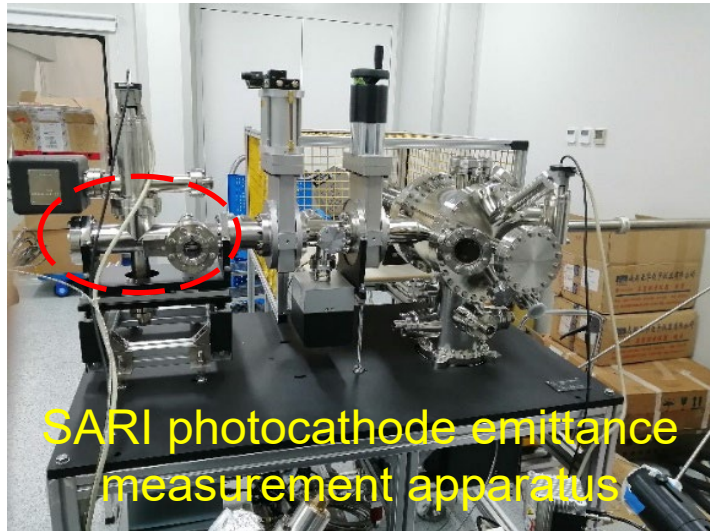
- Photocathode Preparation Apparatus



ZJLAB MBE Photocathode System

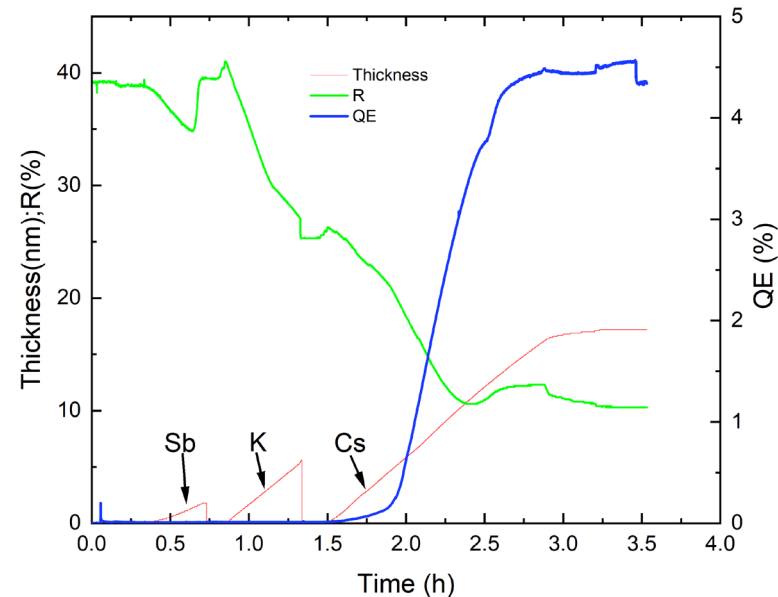
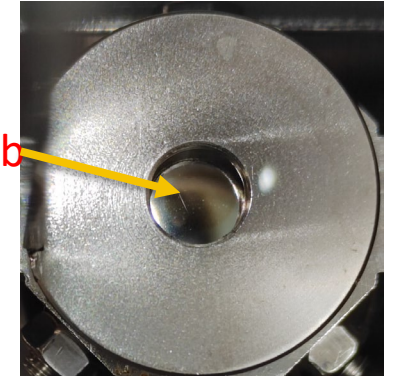
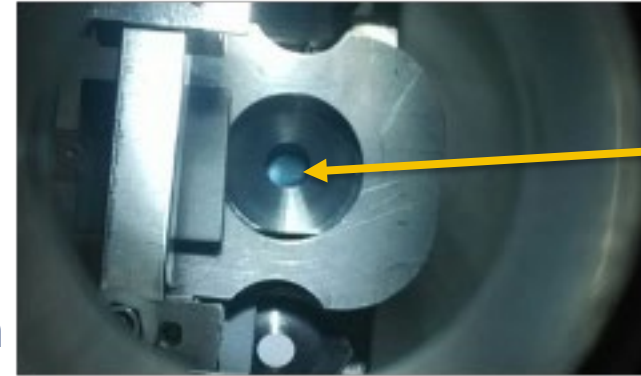
Photocathode Apparatus

- SARI Photocathode Emittance Measurement Apparatus
- Photocathode Transfer Apparatus
 - SHINE photocathode transfer apparatus
 - ZJLAB/SARI photocathode transfer apparatus

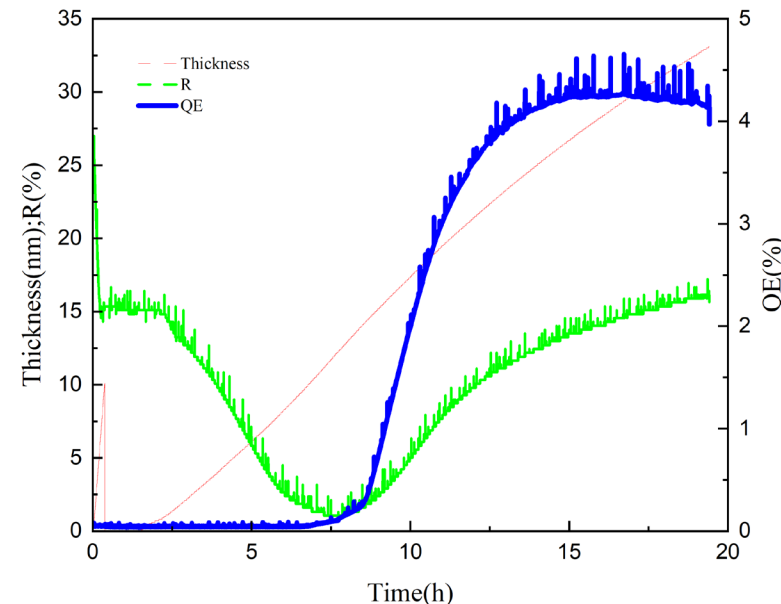


K₂CsSb Photocathode Preparation

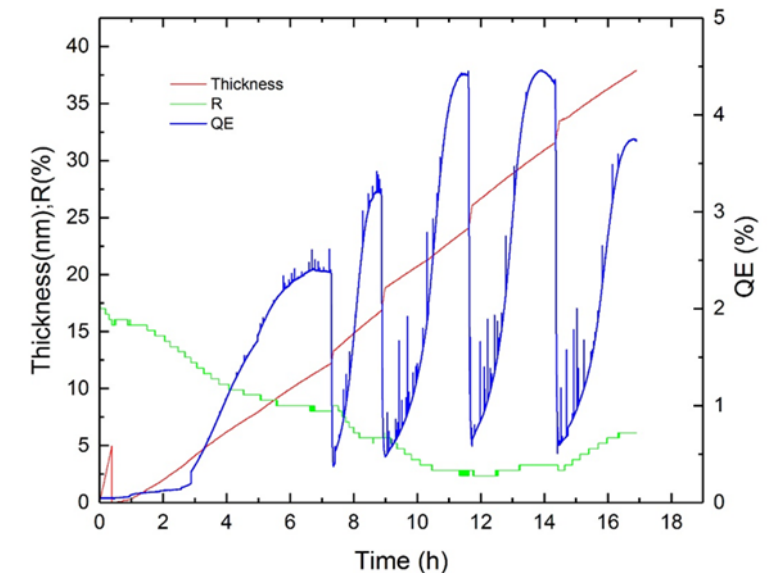
- K₂CsSb photocathode preparation
 - Sequential Sb, K, Cs Deposition
 - Sb, K/Cs Deposition
 - Intermittent Sb, Continuous K/Cs Deposition
 - Upon resolving evaporation-source crosstalk, perform Sb, K, Cs co-evaporation preparation



Sequential Sb, K, Cs Deposition



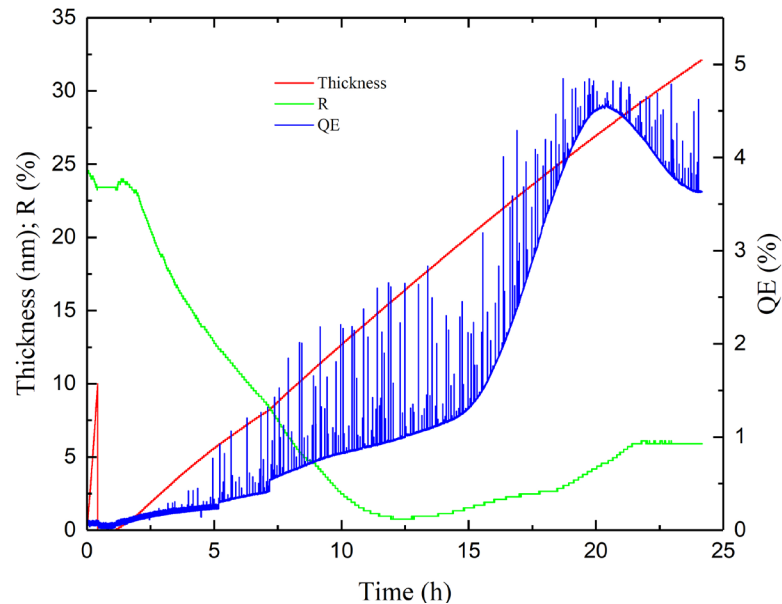
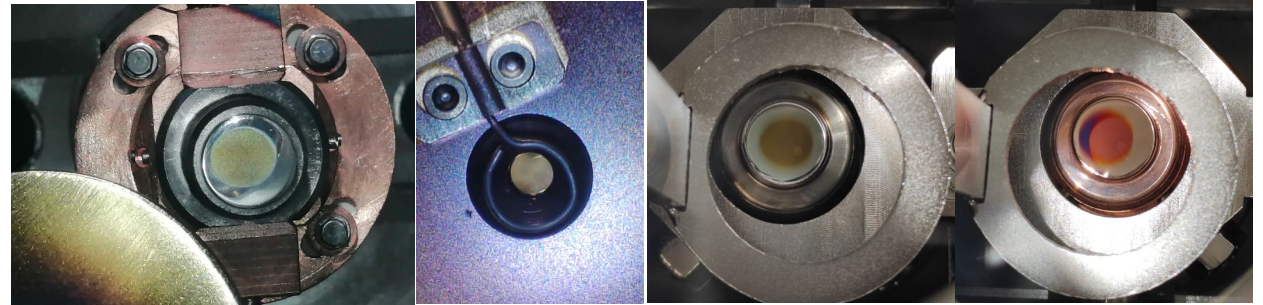
Sb, K/Cs Deposition



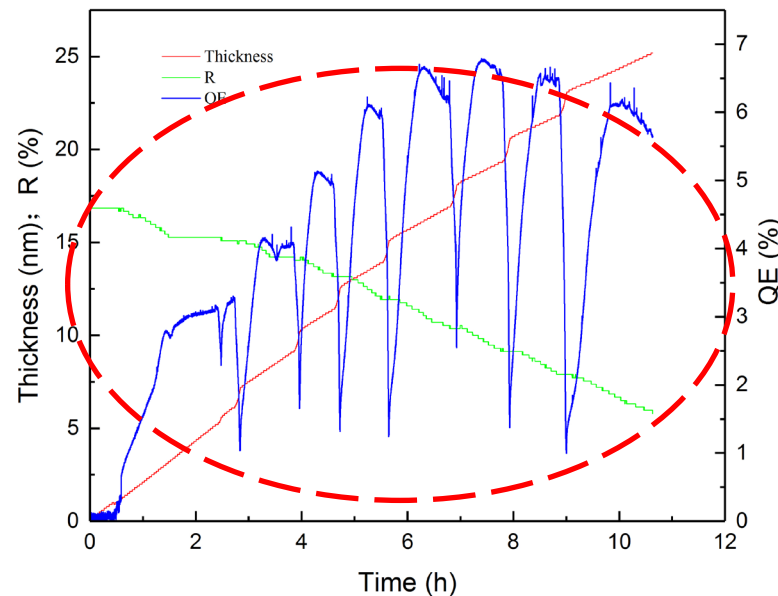
Intermittent Sb, Continuous
K/Cs Deposition

Cs₂Te Photocathode Preparation

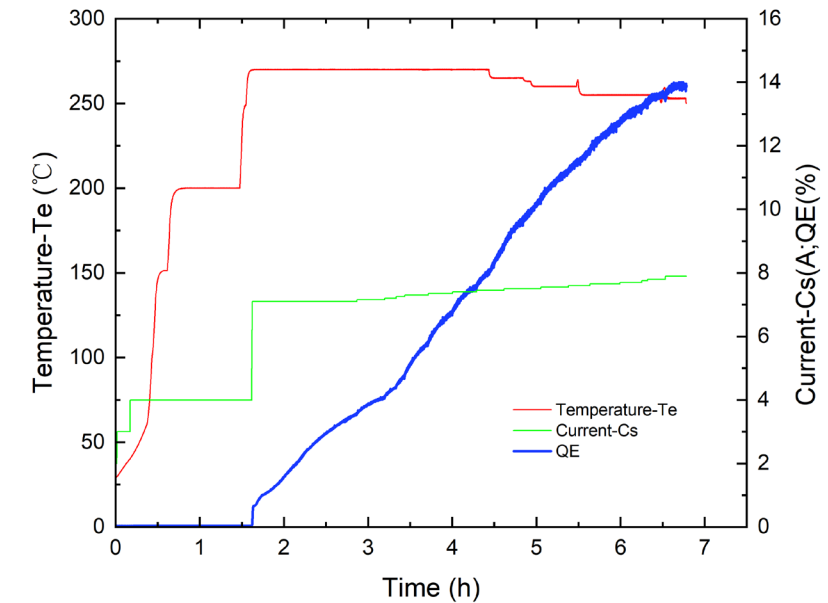
- Cs₂Te Photocathode Preparation
 - Methods: Sequential Te, Cs Deposition; Intermittent Te, Continuous Cs Deposition; Te, Cs Co-evaporation
 - Substrate temperature, source deposition rate and preparation method have no effect on final Cs₂Te QE



Sequential Te, Cs Deposition



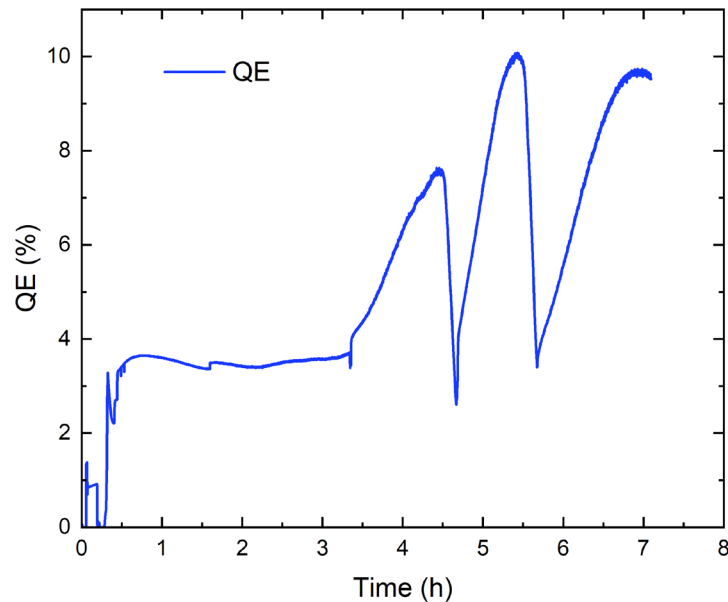
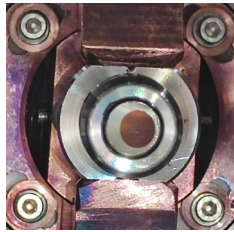
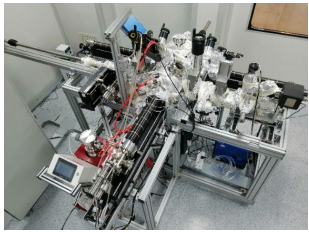
Intermittent Te, Continuous Cs Deposition



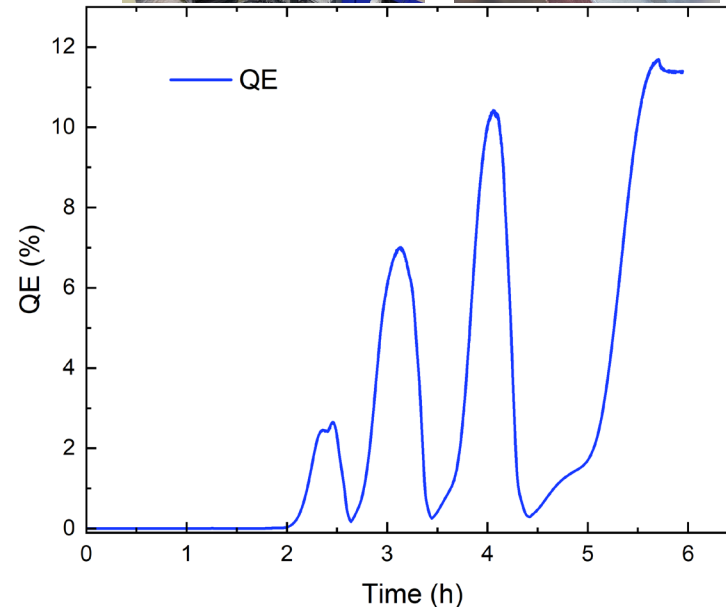
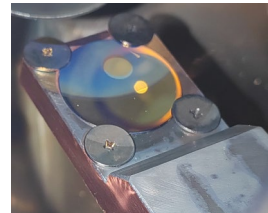
Te, Cs Co-evaporation

Cs₂Te Photocathode Preparation

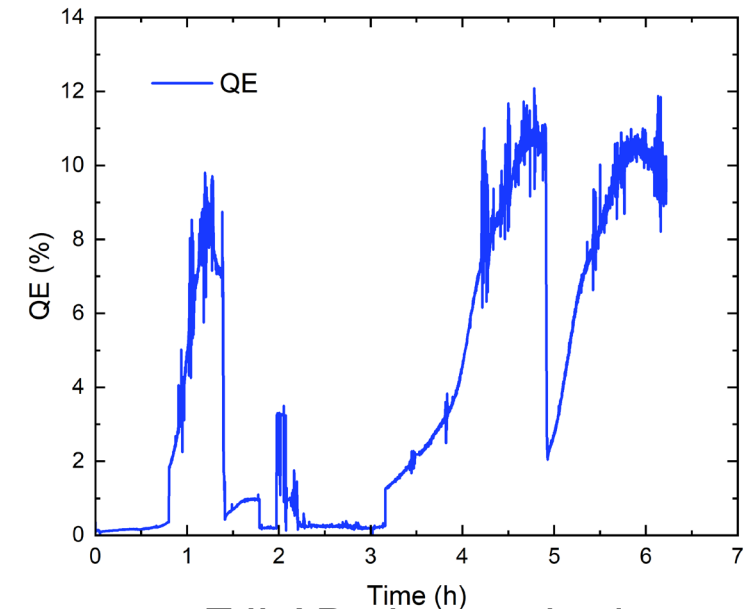
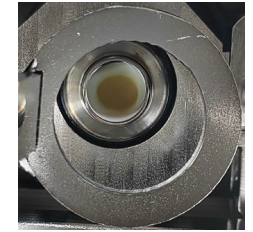
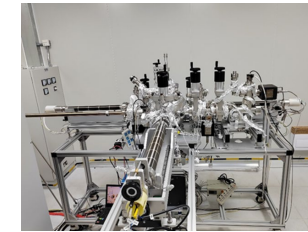
- Cs₂Te photocathode preparation by intermittent Te and continuous Cs deposition on different apparatus



SARI photocathode preparation apparatus



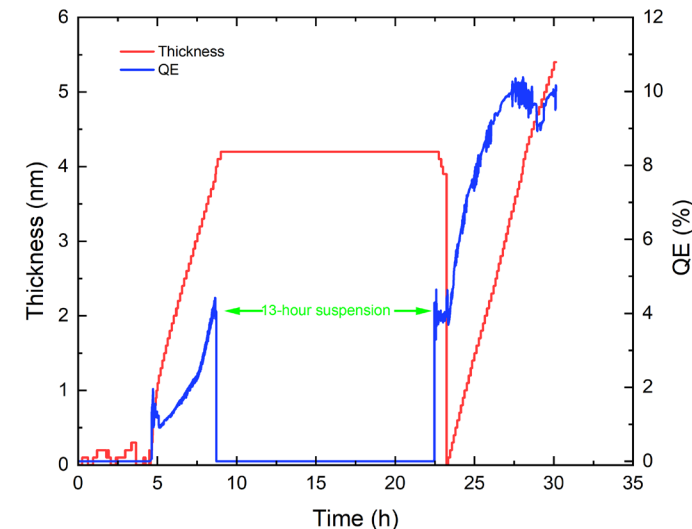
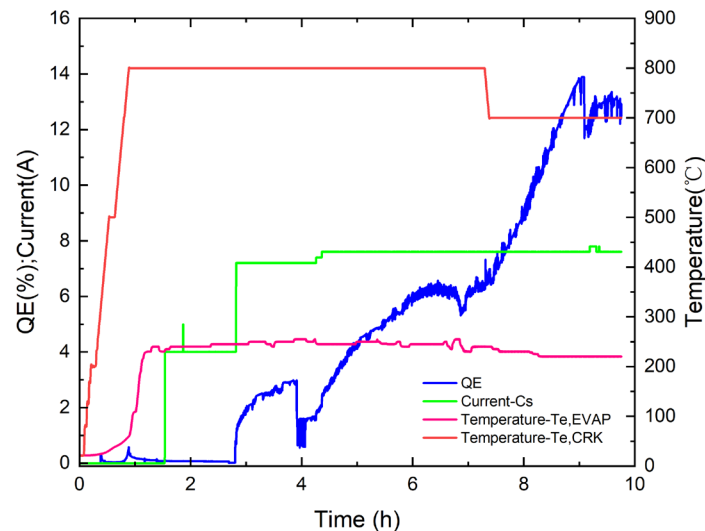
SARI in-situ photocathode research apparatus



ZJLAB photocathode preparation apparatus

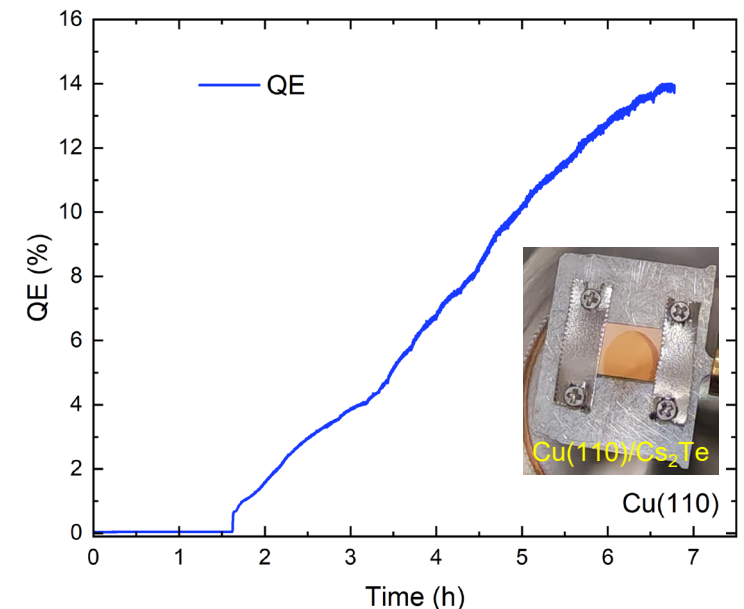
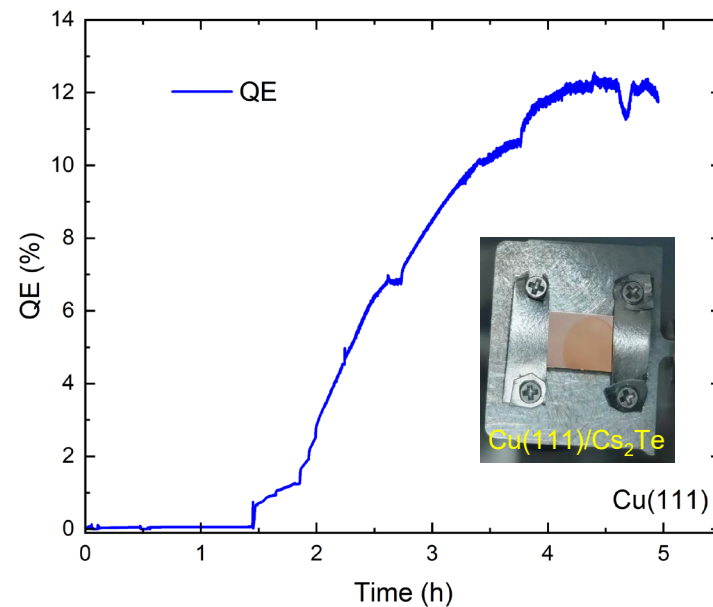
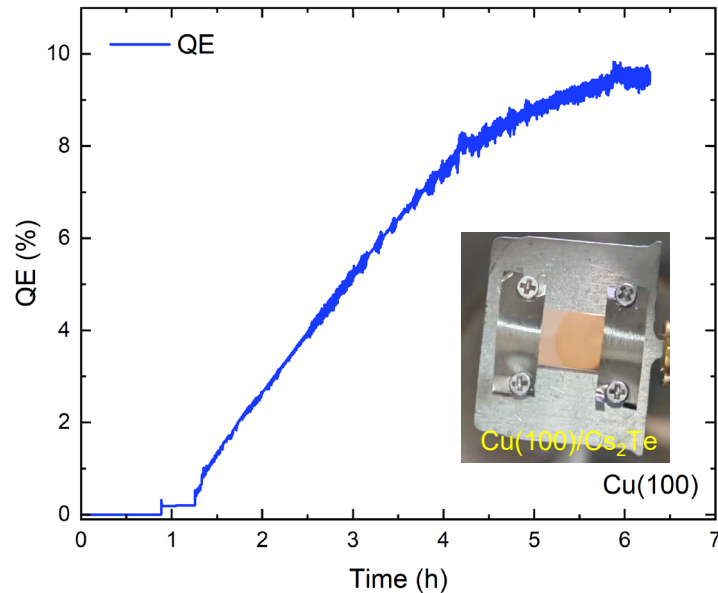
Cs_2Te photocathode co-evaporation

- Problem:
 - Strip-shaped Te and Cs evaporators on one shared support exhibit severe thermal crosstalk, inhibiting Cs-Te co-evaporation
- Solution:
 - Te is placed in an independent cracker source to enable Te,Cs co-evaporation; Te evaporation temperature and Cs heater power must be tuned appropriately
- Following a period of interruption (about 13 hours), the unfinished photocathode was subsequently prepared



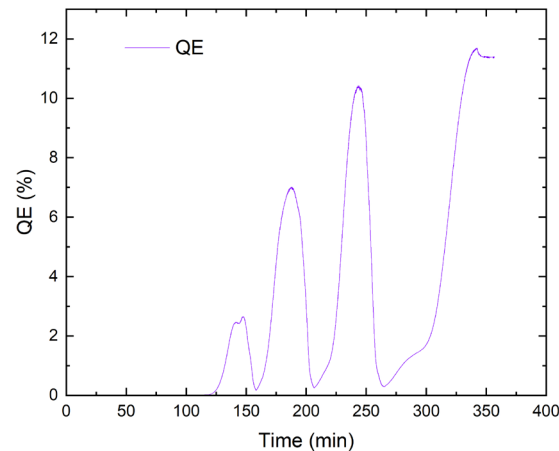
Cs₂Te photocathode preparation on single-crystal Cu substrates

- Single-crystal Cu substrates: Te (cracker) + Cs co-evaporation → Cs₂Te photocathode, QE ~10% @257 nm.
- Cs₂Te photocathodes grown on Cu(100)/(111)/(110)
 - Ex-situ RHEED: substrate single-crystal, Cs₂Te not single-crystal
 - STM: not flat surface (roughness <2 nm); single-crystal Cu exhibits step-terrace structure

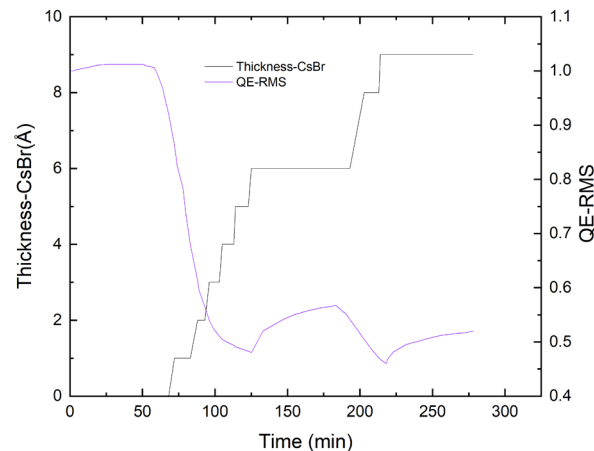


CsBr-coated Photocathode

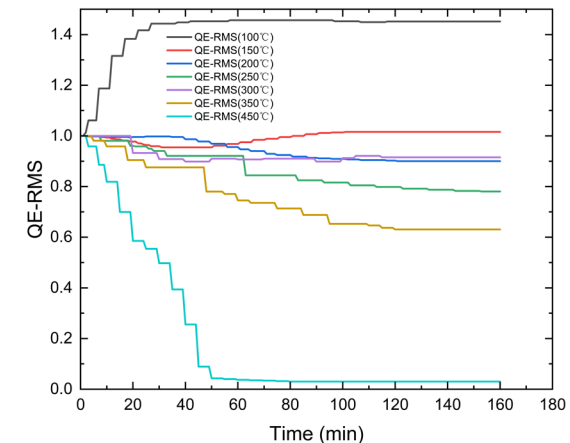
- Cs_2Te @SARI in-situ photocathode research apparatus
 - Cs_2Te photocathode deposition
 - Deposition of CsBr protective layer on Cs_2Te photocathode
 - The temperature-dependent QE of Cs_2Te +CsBr photocathode



Cs_2Te preparation



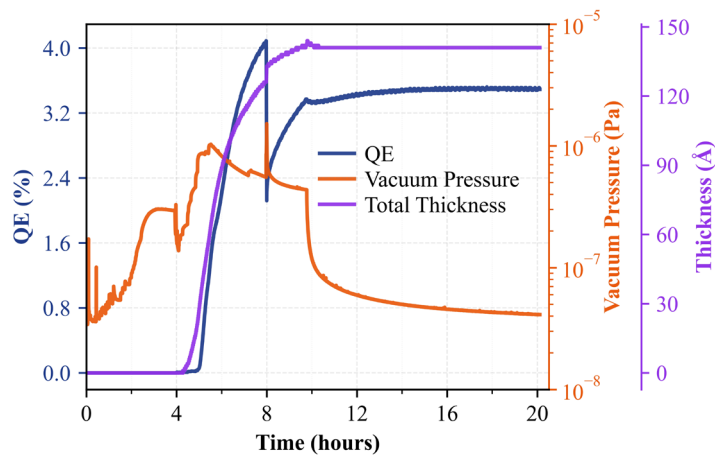
CsBr Protective Layer Deposition



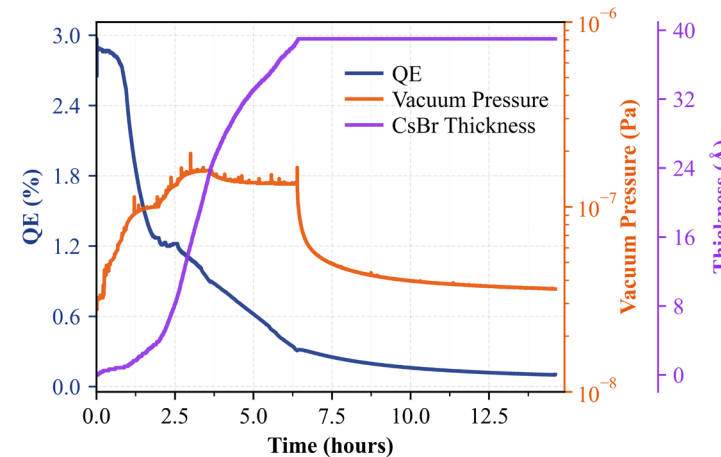
QE of Cs_2Te + CsBr Photocathode at Different Temperatures

CsBr-coated Photocathode

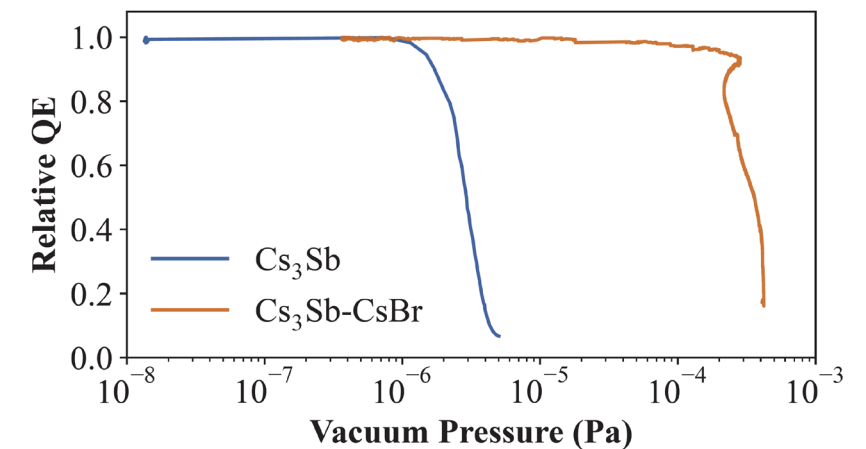
- Cs_3Sb @SARI in-situ photocathode research apparatus
 - Cs_3Sb prepared by sequential deposition Sb and Cs
 - Deposition of CsBr protective layer on Cs_3Sb
 - QE as a function of pressure for uncoated and CsBr coated Cs_3Sb photocathode



Cs_3Sb preparation



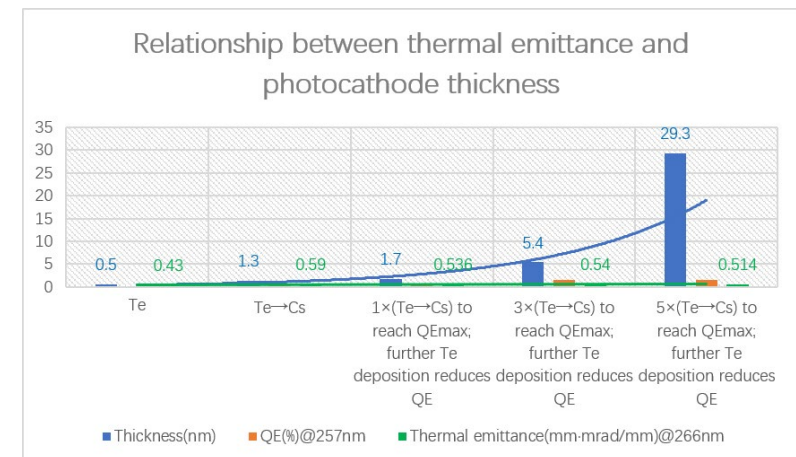
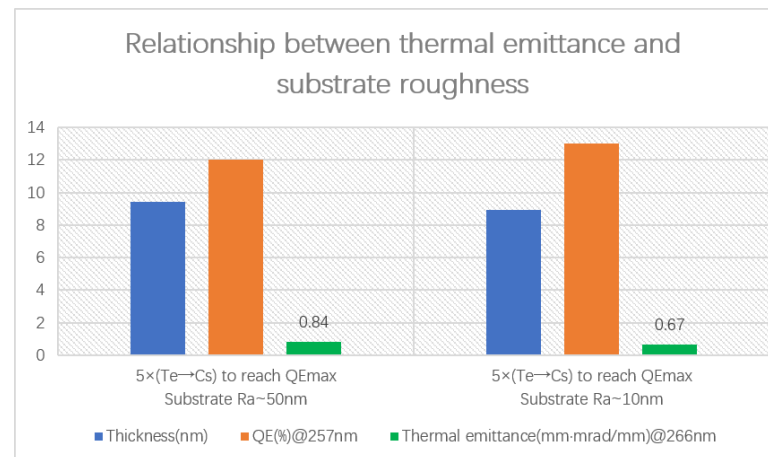
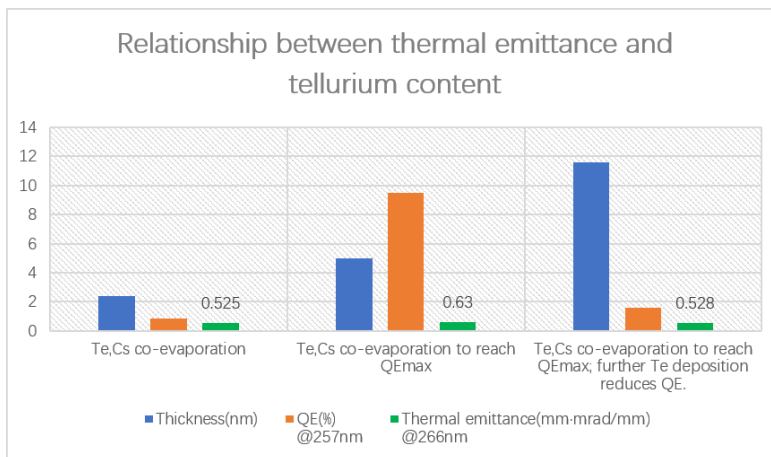
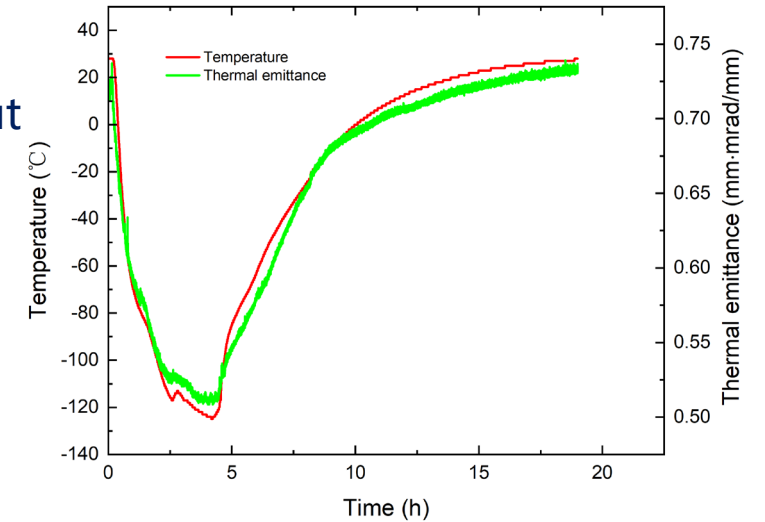
CsBr Protective Layer Deposition



QE vs pressure for uncoated and CsBr₁₅ coated Cs_3Sb photocathodes.

Low-Thermal-Emittance Cs_2Te Photocathode Development

- Low-temperature operation greatly lowers Cs_2Te photocathode thermal emittance at the cost of QE.
- Operating near the photoemission threshold: lowers thermal emittance but also reduces QE
 - Excess Te (Te-rich phase): higher Cs_2Te work function, lower thermal emittance
- Substrate roughness significantly affects thermal emittance: smoother substrates produce lower thermal emittance
- No direct correlation between thermal emittance and film thickness



Cs₂Te Photocathode Operation @ SHINE gun

- Cs₂Te photocathode operation @SHINE photocathode VHF electron gun
 - Support commissioning of SHINE electron gun, injector, Linac and undulator



1 Dec 2023

- Mo plug(Ra~50mm): 36.5nm(Not over-inserted)
- QE=7.5%@255nm(Preparation chamber)
- QE=10%@257.5nm(Electron gun)
- Objective:
- SHINE VHF Gun Commissioning



14 Jan 2024

- Mo plug(no polishing): 36.5mm(Not over-inserted)
- QE=10%@255nm(Preparation chamber)
- QE=12.5%@257.5nm(Electron gun)
- Objective:
- Cs₂Te Photocathode Dark Lifetime (SHINE VHF Gun)
- Dark current: up to 5 μ A



25 Sep 2024

- SS plug(Ra~10nm): 37mm(0.5mm over-inserted)
- QE=11%@255nm(Preparation chamber)
- QE=7.5%@257.5nm(Electron gun)
- Objective:
- SHINE Injector Commissioning
- Gun dark current: abrupt rise 20 nA $\rightarrow$ 400 nA (during commissioning)



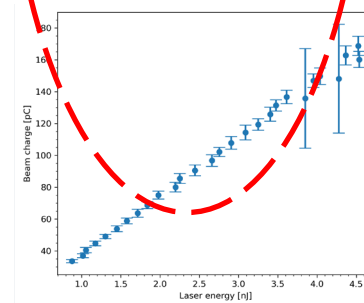
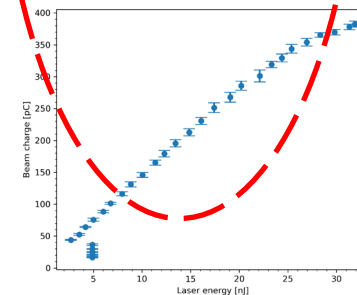
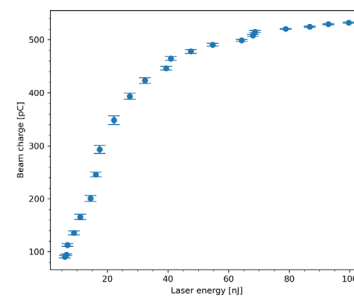
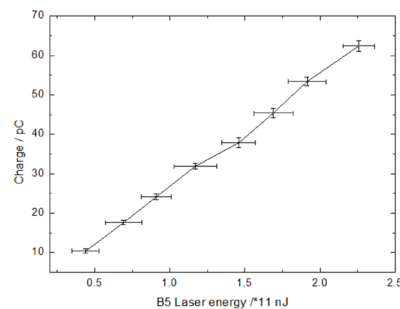
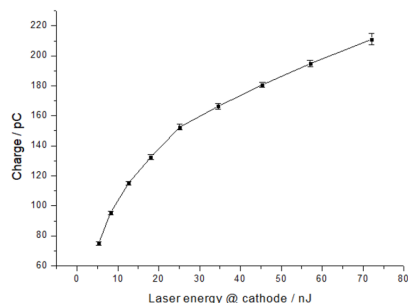
25 Nov 2024

- Mo plug(Ra~15nm): 37mm(0.5mm over-inserted)
- QE=18%@255nm(Preparation chamber)
- QE=7.5%@257.5nm(Electron gun)
- Objective:
- SHINE Injector Commissioning
- Gun dark current: < 2 nA



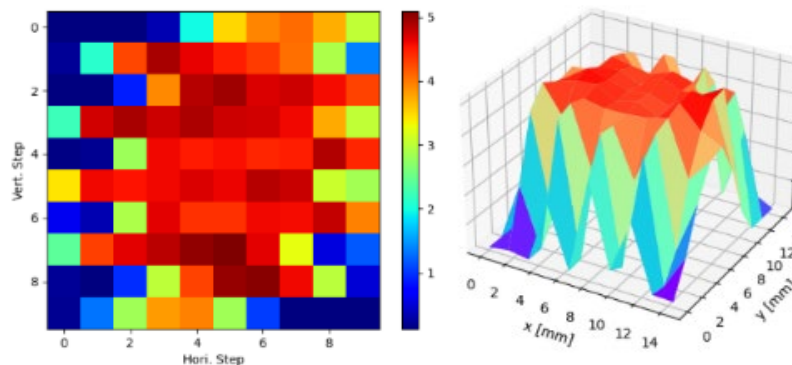
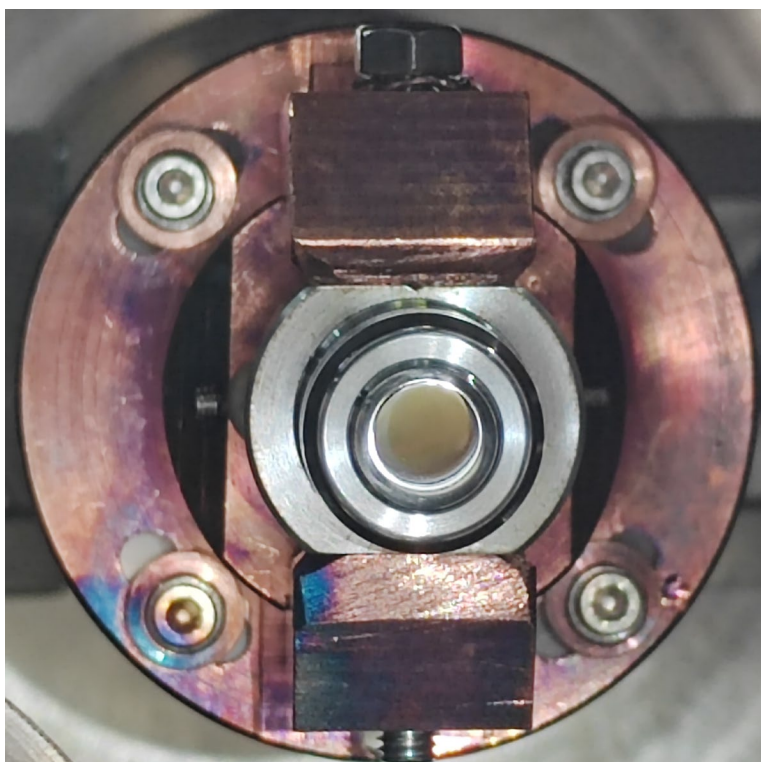
25 Jun 2025

- Mo plug(Ra~15nm): 37mm(0.5mm over-inserted)
- QE=5%@255nm(Preparation chamber)
- QE=18%@257.5nm(Electron gun)
- Objective:
- Linac and undulator commissioning
- dark current: < 2 nA (25 Jun 2025) $\rightarrow$ < 3 nA (26 Jun 2026)

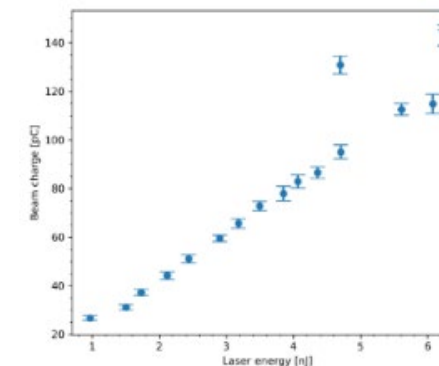


Cs₂Te Photocathode Operation @SHINE gun

- Cs₂Te operation @SHINE VHF electron gun (Prepared on 4 Nov 2024)
 - Injector Commissioning and Acceptance, 22-23 Dec 2024



QE map



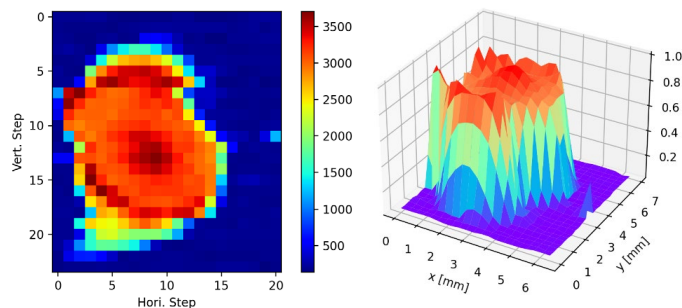
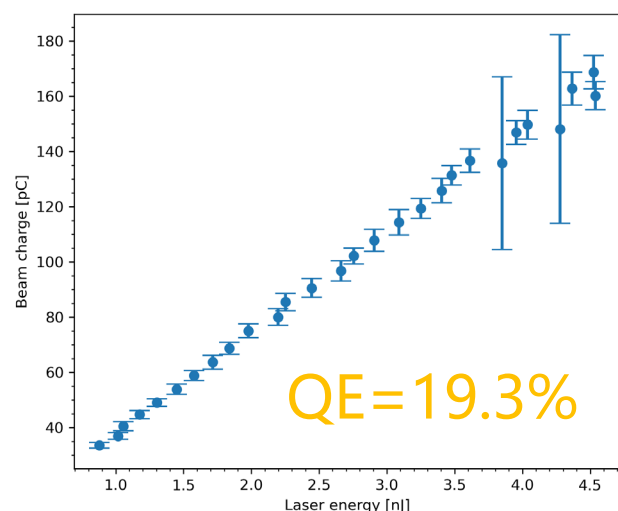
Photoemission Curve: QE>10%

50pC/4ps/12.5A	1	2	3	Average	unit
Proj. Emittance @x	0.40	0.40	0.44	0.413±0.026	mm mrad
Proj. Emittance @y	0.50	0.51	0.52	0.51±0.0096	mm mrad
Slice Emittance @y	0.328	0.268	0.384	0.327±0.094	mm mrad
100pC/10ps/10A					
Proj. Emittance @x	0.62	0.53	0.57	0.573±0.037	mm mrad
Proj. Emittance @y	0.55	0.56	0.55	0.55±0.0047	mm mrad
Slice Emittance @y	0.413	0.522	0.433	0.456±0.047	mm mrad

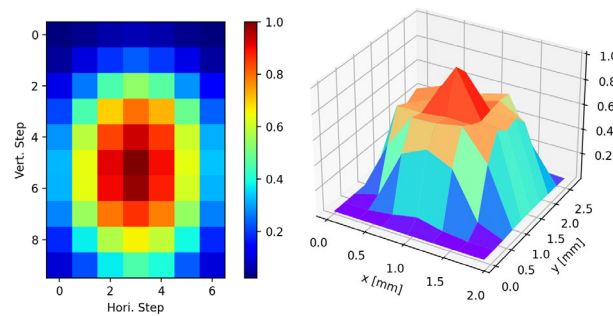
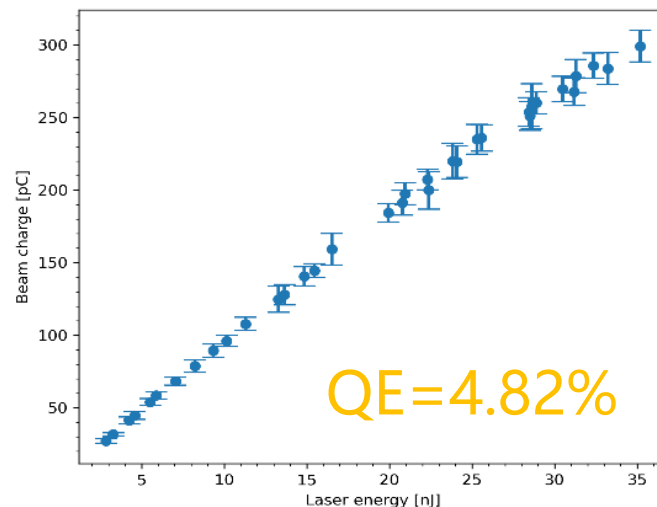
Emittance

Cs₂Te Photocathode Operation @ SHINE gun

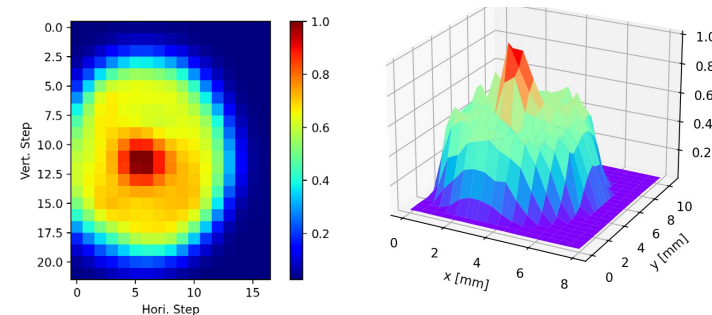
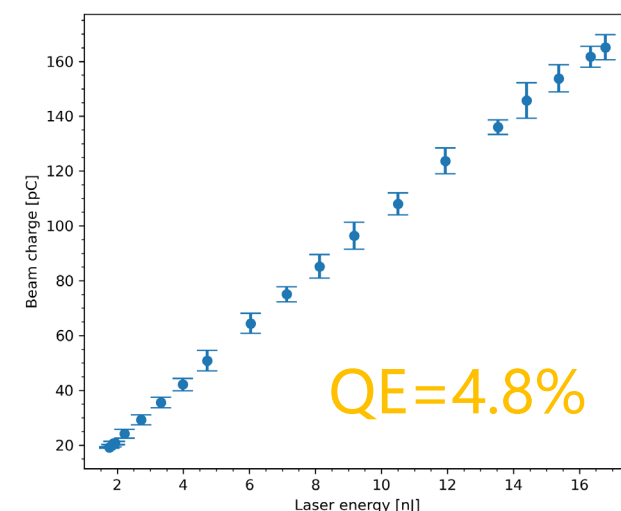
- Cs₂Te operation @SHINE VHF electron gun (Prepared on 11 Apr 2025)
 - Linac and undulator commissioning (L1/BC1 Test and Acceptance, 2-3 Nov 2024)



25 Jun 2025



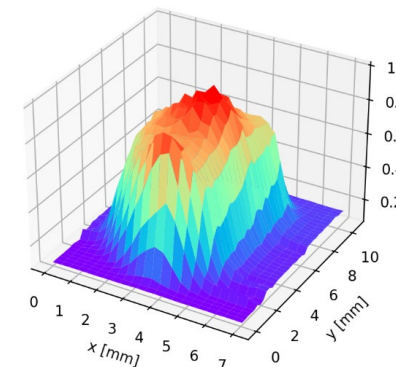
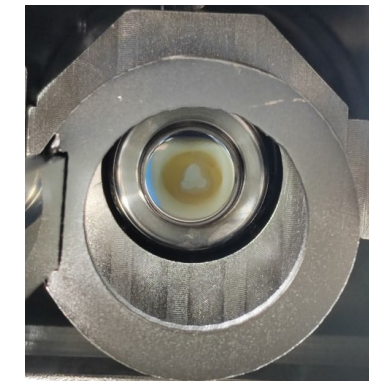
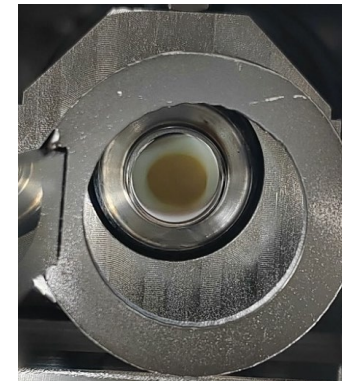
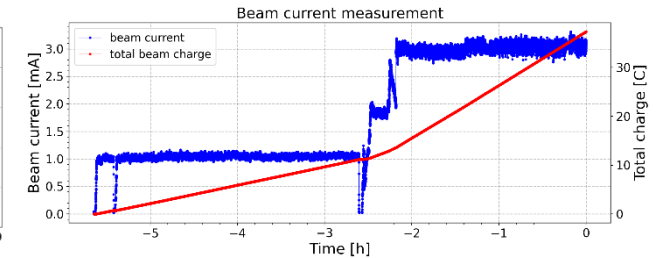
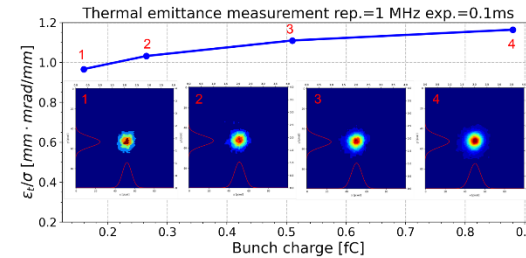
26 Jun 2026



14 Aug 2026

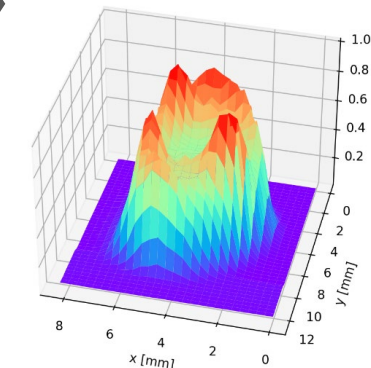
Cs₂Te Photocathode Operation @ ZJLAB/SARI gun

- Cs₂Te photocathode operation @ZJLAB/SARI photocathode VHF electron gun
 - Beam-on tests at 0.5 mA, 1 mA, 3 mA; 7×24 h continuous operation at 0.1 mA;
 - 7×24 h continuous operation at 1 mA;
 - 10-day continuous operation at 0.45 mA;
 - 30-day continuous operation: 0.5 mA (20 d) & 1 mA (10 d)



Before
operation

QE=18%
Dark current<1nA
Thermal emittance:
0.97 mm mrad



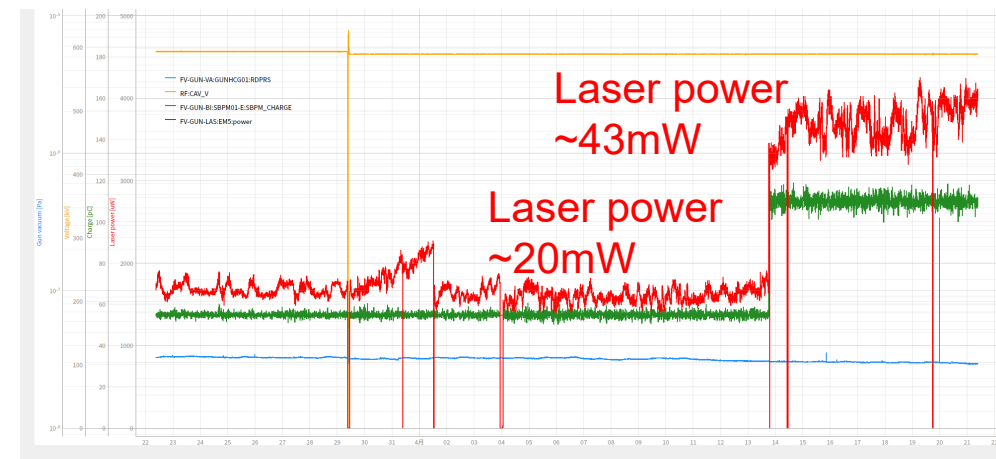
After
operation

QE=8%
Dark current<1nA
Thermal emittance: 20
0.95 mm mrad

Time	Current	QE@257nm
2024.12.27-2025.01.06	0.1mA	16%→5%
2025.03.22-2025.03.29	1mA	18%→8%
2025.12.09-2025.12.18	0.45mA	5.8%→1.34%
2026.03.21-2026.04.21	0.5mA/1mA	13.1%→10.7%

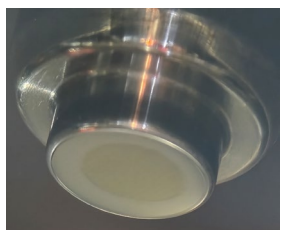
Cs₂Te Photocathode Operation @ ZJLAB/SARI gun

- Cs₂Te photocathode operation @ZJLAB/SARI photocathode VHF electron gun
 - 30-day continuous operation: 0.5 mA (20 d) & 1 mA (10 d)
 - 03.21-04.13: Beam-on at 0.5 mA (55 pC & 9 MHz)
 - 04.13-04.21: Beam-on at 1 mA (110 pC & 9 MHz)
 - Slight QE drop, no dark current increase

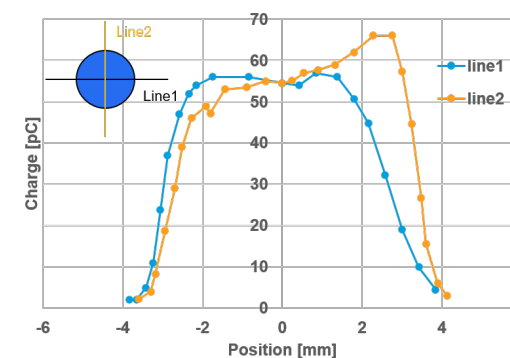


Gun voltage
590kV
Laser power
~43mW
Charge
55-110pC
Vacuum
Pressure:
3E-8Pa

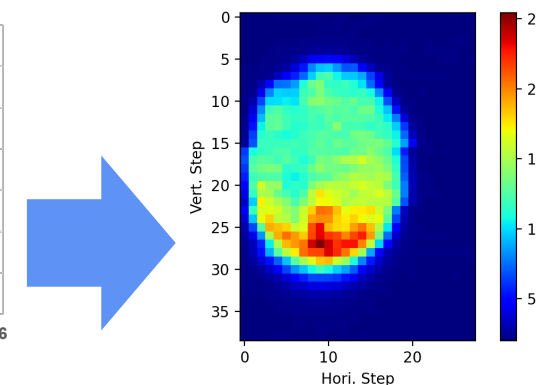
Time	Current	QE@257nm
2024.12.27-2025.01.06	0.1mA	16%→5%
2025.03.22-2025.03.29	1mA	18%→8%
2025.12.09-2025.12.18	0.45mA	5.8%→1.34%
2026.03.21-2026.04.21	0.5mA/1mA	13.1%→10.7%



Cs₂Te photocathode after 1-month beam extraction



20 Mar 2026: Coarse charge scan on two axes using 1.2 mm-diameter laser



21 Apr 2026: QE map

Summary and Future Plans

■ Conclusions

- Designed, assembled, and commissioned photocathode apparatus.
- Developed photocathode preparation processes.
 - High QE photocathodes preparation process.
 - Low emittance Cs_2Te photocathode preparation process.
- Cs_2Te photocathode performance characterization.
- Cs_2Te photocathode operational tests.

■ Plans

- Study on Cs_2Te , K_2CsSb , Na_2KSb photocathodes in CW electron guns (QE, thermal emittance, lifetime, etc.)
- Research Directions
 - $\text{K}_2\text{CsSb}/\text{Cs}_3\text{Sb}$: QE enhancement
 - $\text{K}_2\text{CsSb}/\text{Cs}_3\text{Sb}$ + protective layers: Lifetime extension
 - Na_2KSb : Apparatus modification & preparation process development
 - K-Te/K-Cs-Te: Preparation process development
 - Cs_2Te : Epitaxial growth on single-crystal substrates

Thank You for Your Attention

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