

**ELBE.**

# Recent progress on advanced photocathodes for SC RF guns

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Photocathode Physics for Photoinjectors, Nov. 10-12, 2021

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HELMHOLTZ  
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# Outline

1. Introduction
2. Metal photocathodes in SRF Guns
  - SC cathode: Pb layer on Nb
  - SC cathode: Nb cathode with plasmonic enhancement
  - NC cathode: Cu, Mg
3. Semiconductor photocathodes in SRF guns
  - $\text{Cs}_2\text{Te}$
  - $\text{K}_2\text{CsSb}$  (BNL, KEK, PKU, HZB)
  - GaAs, GaN
4. Summary and outlook

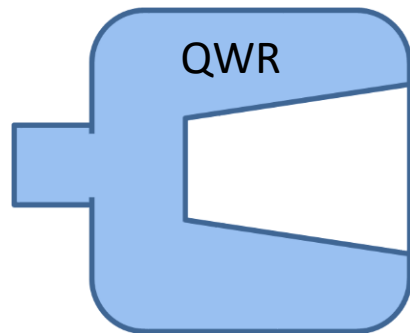
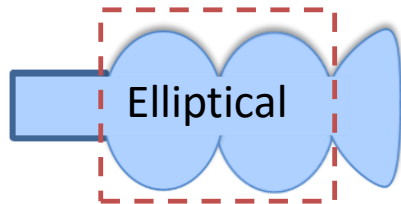
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# 1. Introduction

## Basic SRF gun structures

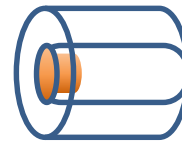
SRF Cavity



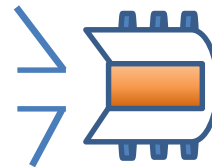
Cathode solution



SC cathode (Nb, Pb, ...)



NC cathode in RF choke



NC cathode with a DC gap

# 1. Introduction

## General requirements for photocathode in photo injectors

- QE, lifetime, thermal emittance, response time
- particle free, smooth surfaces, adhesive feature
- low dark current

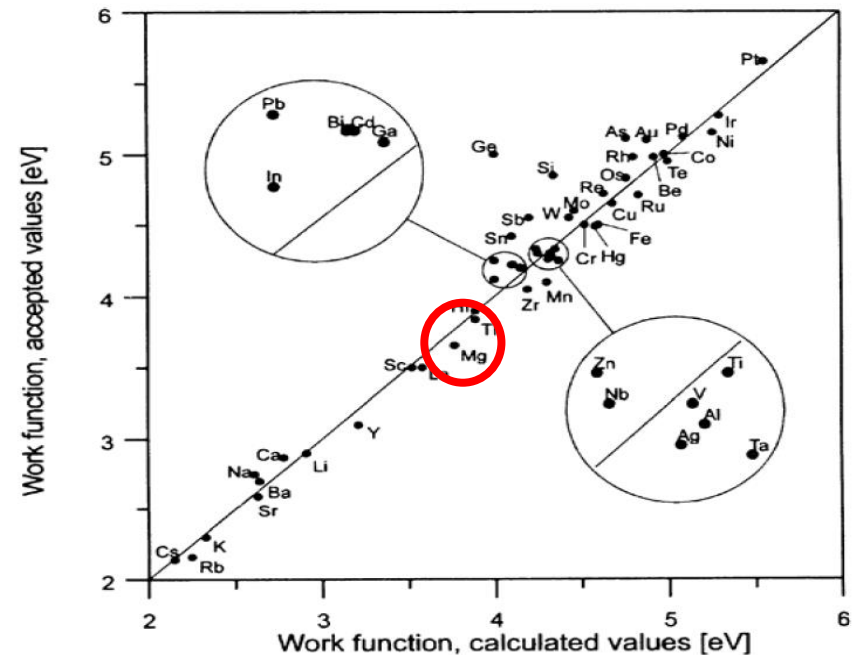
## Specially for SRF guns:

- properties at cryogenic temperature  
thermal conductivity, thermal expansion,...  
(SC) transition temp., critical magnetic field, ...
- Multipacting issue: secondary electron yield
- heat load: laser heating, RF power deposition

## 2. Metal photocathodes in SRF Guns

*Robust and „Clean“ cathode for SRF guns*

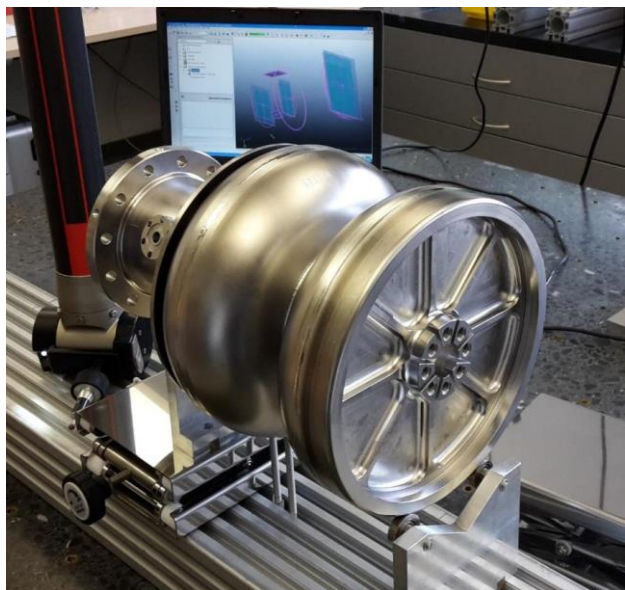
Metal	QE	$\phi$ (eV)
Cu	$10^{-5} - 10^{-4}$	4.6
Mg	$10^{-5} - 10^{-3}$	3.6
Nb	$10^{-6} - ?$	4.3
Pb	$10^{-6} - 10^{-3}$	4.25



Lide, D. R.. Properties of Solids, in: *CRC Handbook of Chemistry and Physics, Internet Version 2005*. Boca Raton, FL: CRC Press; 2005, P. 124; S. Halas, *Materials Science-Poland*, Vol. 24, No. 4, 2006

## 2. Metal photocathodes in SRF Guns

### SC photocathode: Pb layer on Nb



*Status: in developing,*

- ✓ QE reached  $2.7 \times 10^{-3}$  @ 213 nm
- Waiting for test in gun

1. Pb coating on Nb plug
  2. cleaning after cathode insertion in a clean room
  3. cathode particles (lead) should not heat and quench the cavity
  4. Difficult for exchanging the cathode
- ⇒ only reasonable with lifetime above 100 days

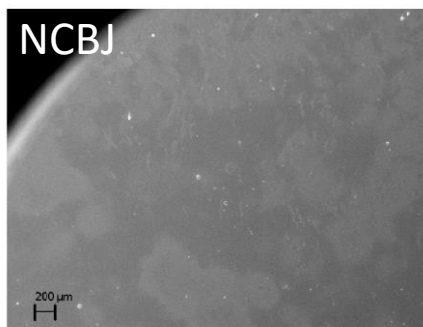


Figure 3: SEM image of a Nb-Pb photocathode with 2 μm Pb film with spherical extrusions.

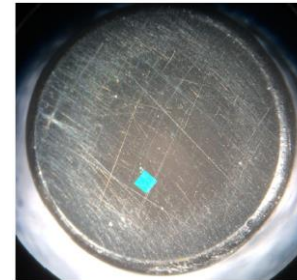
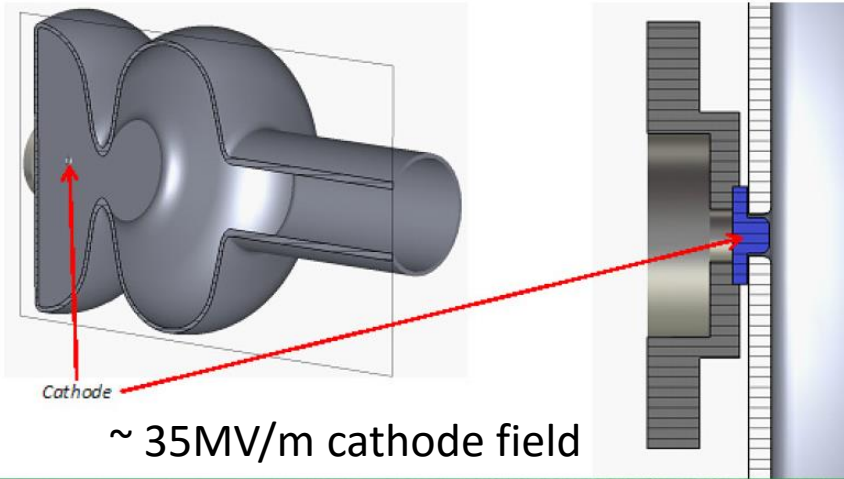
courtesy of E. Vogel, DESY, Germany

## 2. Metal photocathodes in SRF Guns

### SC cathode: Nb cathode with plasmonic enhancement

*Status: in developing*

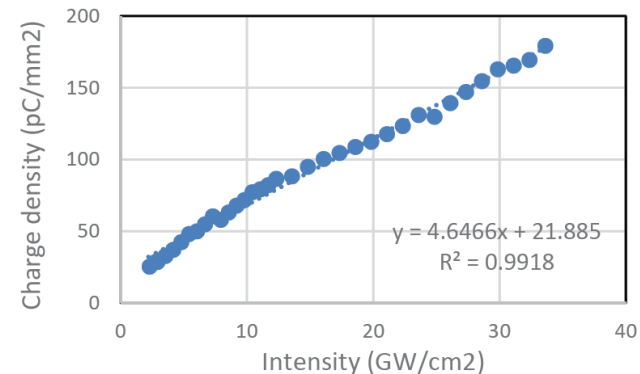
- $QE \sim 1.4e^{-5}$  @ 1030 nm
- Waiting for more results



single crystal Nb pucks  
with Nano-Patten



RadiaBeam/Jlab SRF gun

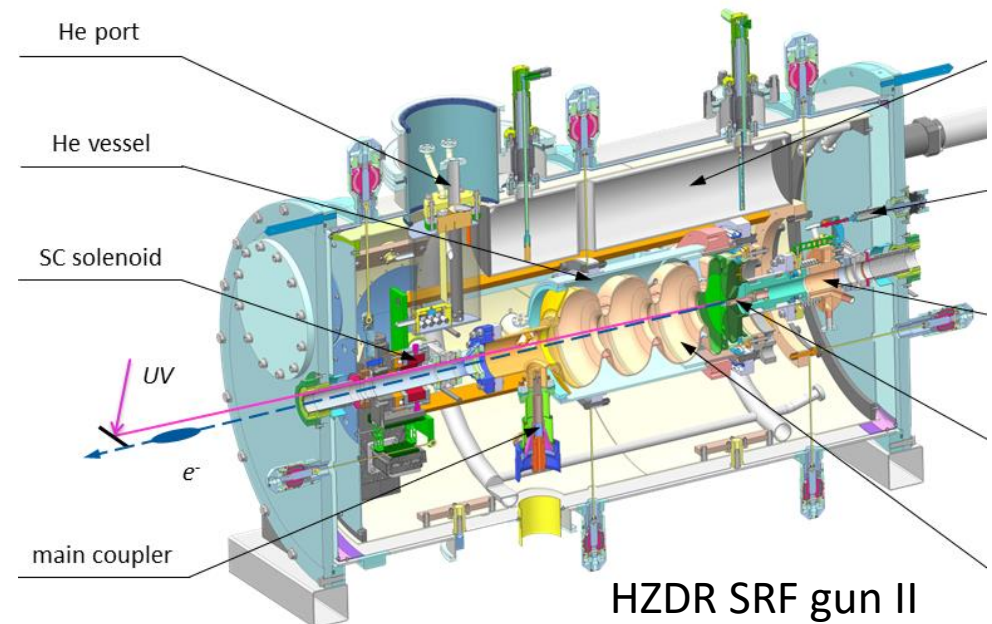


4-photon emission process @1030nm, RT

## 2. Metal photocathodes in SRF Guns

### NC photocathode: Mg, Cu

Parameter	Operation Value
Beam energy	4.5 MeV
Gradient $E_{\text{acc}}$	8 MV/m
Bunch charge	0 - 250 pC
Beam rep. rate	25-250 kHz
Pulse width (rms)	2.3 ps rms in Gauss
Transv. emittance	2-15 mm.mrad
Cathode field	14 MV/m
Dark current	60 nA



### Highlight:

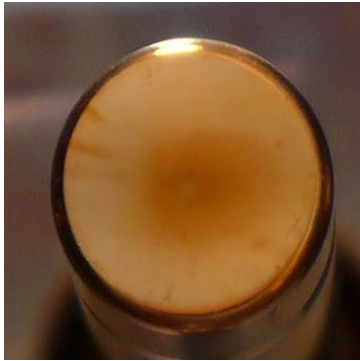
2014 successful commissioning with Cu

2019 - 2020 stable operation with Mg ~ 1760 h beam time, ~ 57 C charge



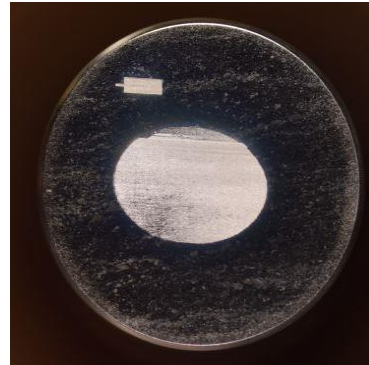
# 2. Metal photocathodes in SRF Guns

## NC photocathode: Mg, Cu



Cu plug (used)

$QE_{258nm} \sim 10^{-5} - 10^{-4}$

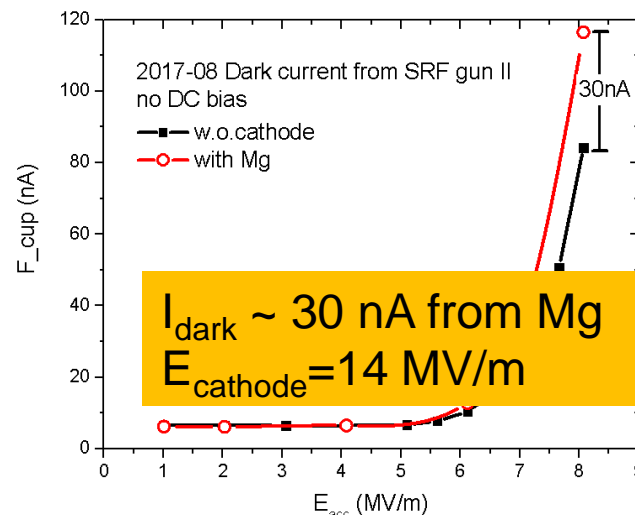
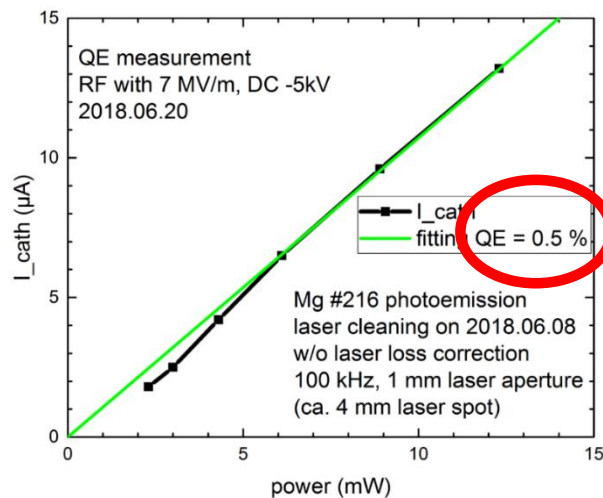


Mg plug after laser cleaning

$QE_{258nm} \sim 0.2\% - 0.5\%$

### Mg cathode status: stable operation

- high QE at UV laser, long life time
- no multipacting problem
- low dark current
- repeatable (can be cleaned several times)

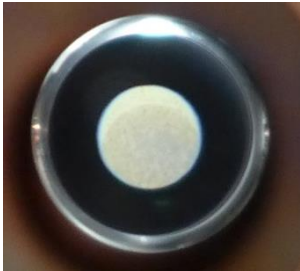


# 3. Semiconductor photocathodes in SRF guns

## Cs<sub>2</sub>Te for HZDR SRF guns

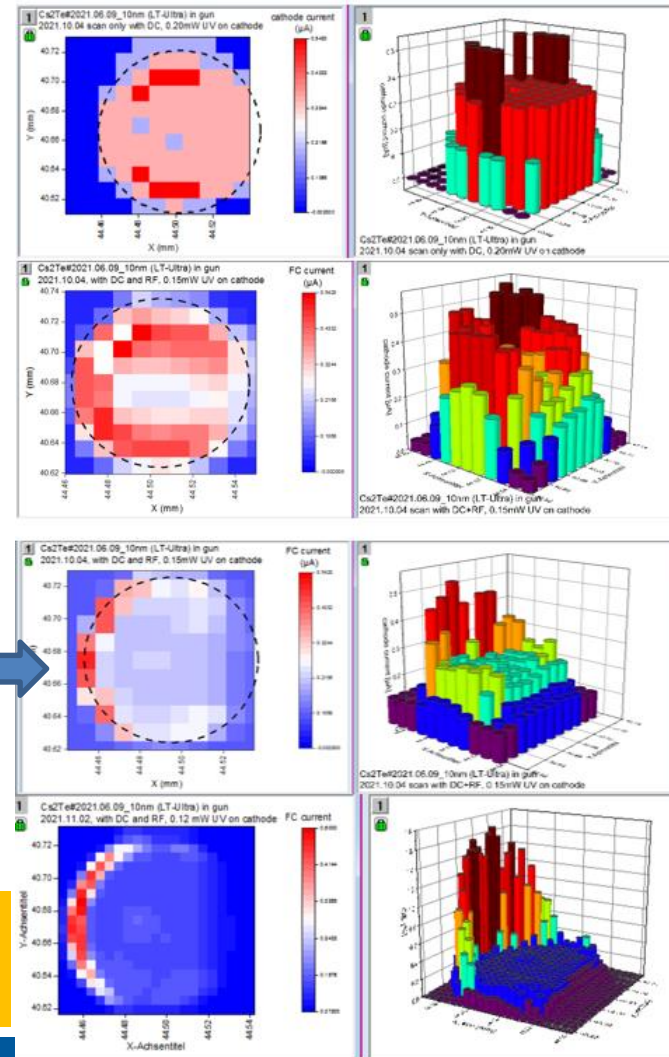
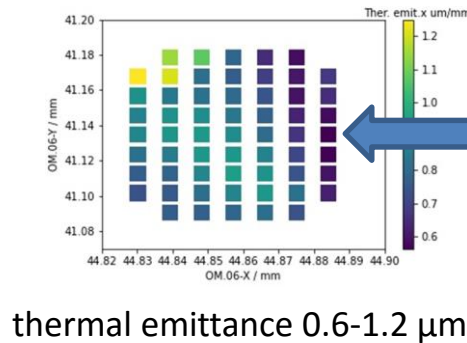
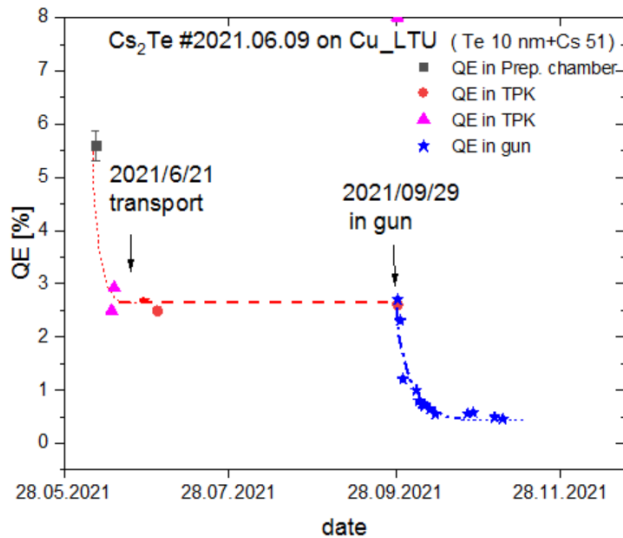
Status: stable operation

2-3 months life time with typical QE ~1%



Cs<sub>2</sub>Te on Mo plug  
bad thermal contact!

Cs<sub>2</sub>Te on Cu plug  
Used since 2020



✓ 2020-2021 extracted **77.7 C** for **2735 h** user beam  
But QE dropping down during transport and gun operation

### 3. Semiconductor photocathodes in SRF guns

#### Green photocathodes: bi-alkali antimonide photocathodes

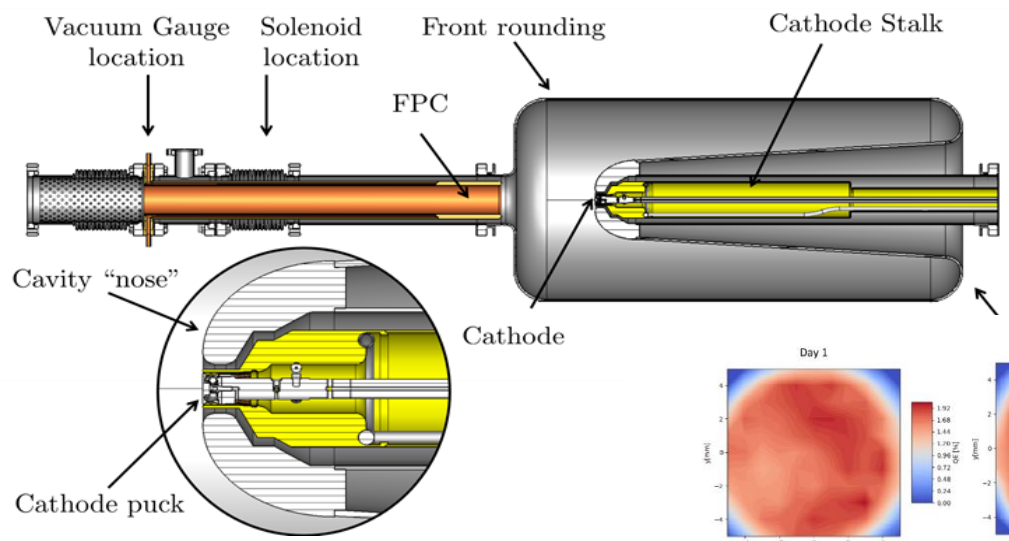
Cathode	Typical wavelength (nm)	QE @ room Temp.	$E_G + E_A$ (eV)	Expected thermal emittance ( $\mu\text{m}/\text{mm}$ )
$\text{Cs}_2\text{Te}$	264	0.1	3.5	0.9
$\text{Cs}_3\text{Sb}$	432	0.15	1.6+0.45	0.7
$\text{K}_3\text{Sb}$	400	0.07	1.1+1.6	0.5
$\text{Na}_3\text{Sb}$	330	0.02	1.1+2.44	0.4
$\text{Na}_2\text{KSb}$	330	0.1	1+1	1.1
$\text{K}_2\text{CsSb}$	543	0.1	1+1.1	0.4

D.H. Dowell et al., NIMA 622, Pages 685-697 (2010)

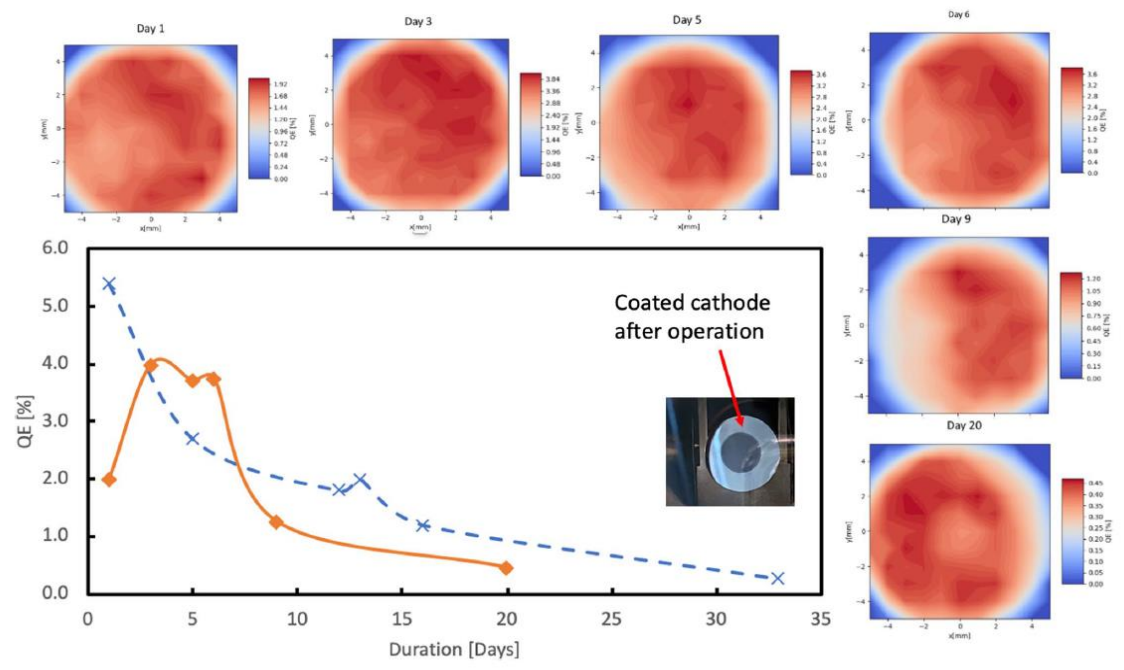
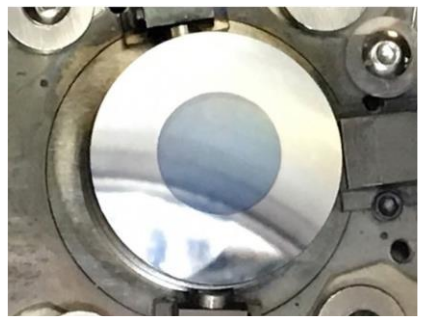
- ✓ Good choice for easier drive laser, high QE and low thermal emittance
- More sensitive than  $\text{Cs}_2\text{Te}$

# 3. Semiconductor photocathodes in SRF guns

## K<sub>2</sub>CsSb on Ta plug for BNL 113MHz SRF gun



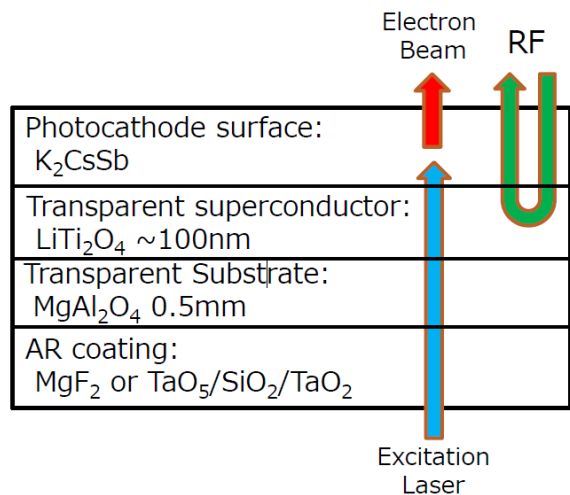
**Status: stable operation**  
 1-2 months lifetime of high QE



Wang, E., Litvinenko, V.N., Pinayev, I. *et al. Sci Rep* **11**, 4477 (2021).

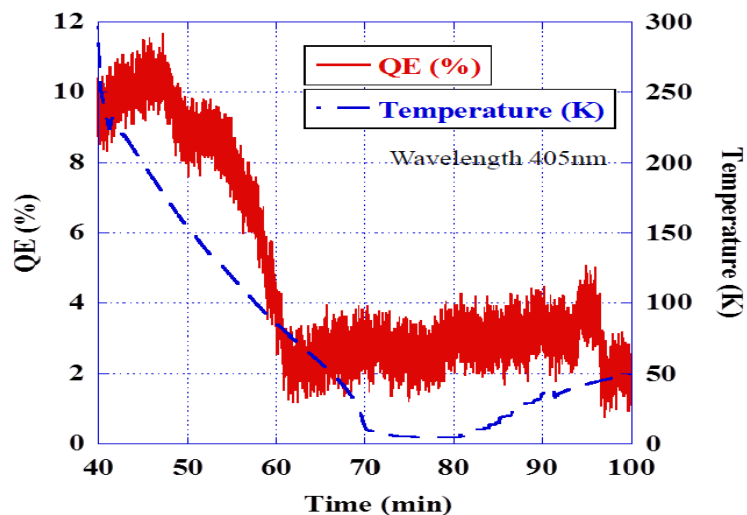
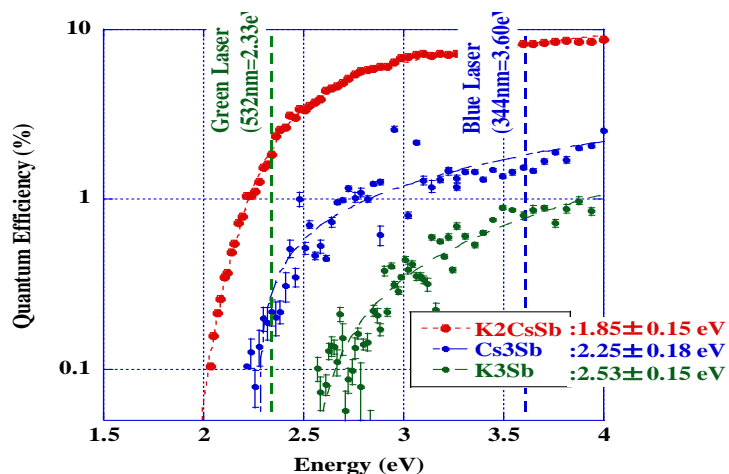
# 3. Semiconductor photocathodes in SRF guns

## KEK: $K_2CsSb$ on transparent superconductor



*Status: in developing*

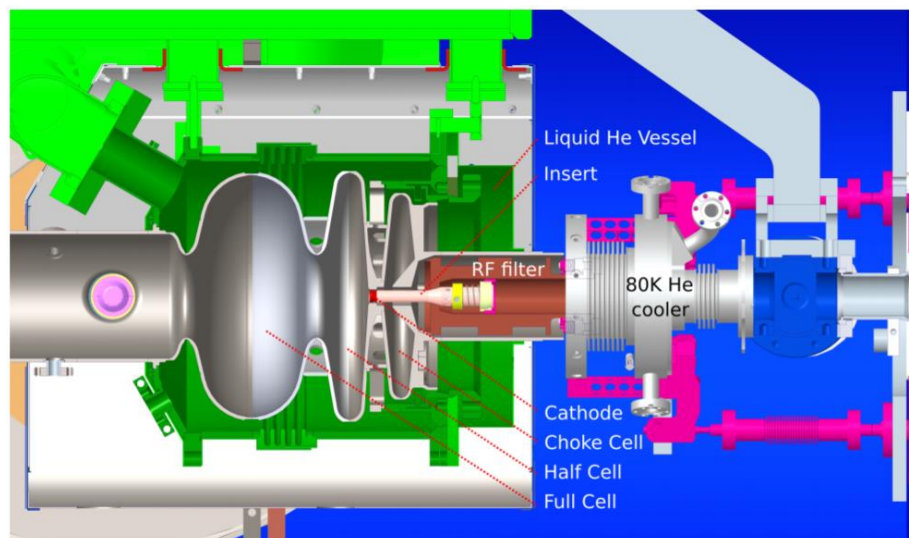
- Cathode rod is also cooled by 2K LHe.
- $K_2CsSb$  photoemitter on SC substrate
- Laser from backside
- QE was decreased during cooling



T.Konomi et al., ERL17, MOIACC002

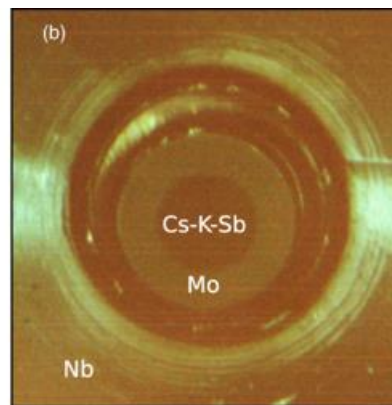
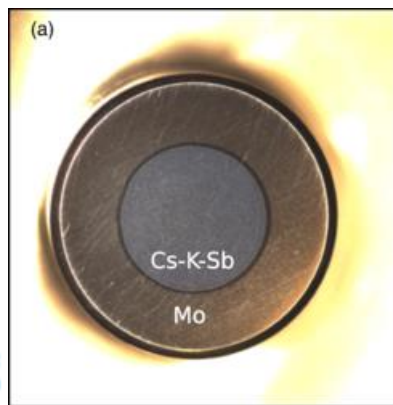
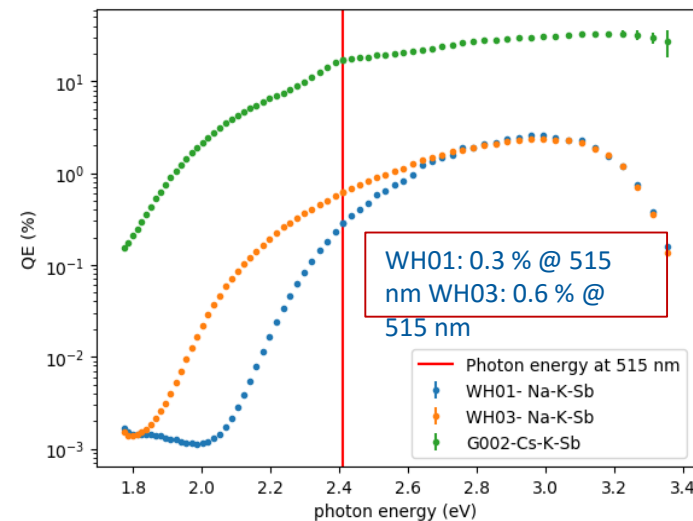
# 3. Semiconductor photocathodes in SRF guns

## HZB: $K_2CsSb$ on Mo plug



*Status: in developing*

- ✓ Successfully prepared in lab
- ✓ transferred into gun
- thermal load study is going on....
- alternative Na-K-Sb is in study
- 



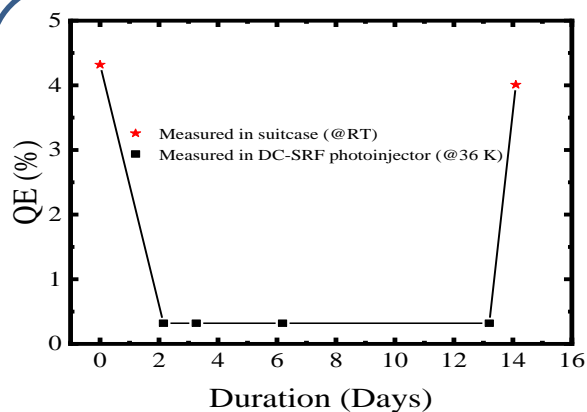
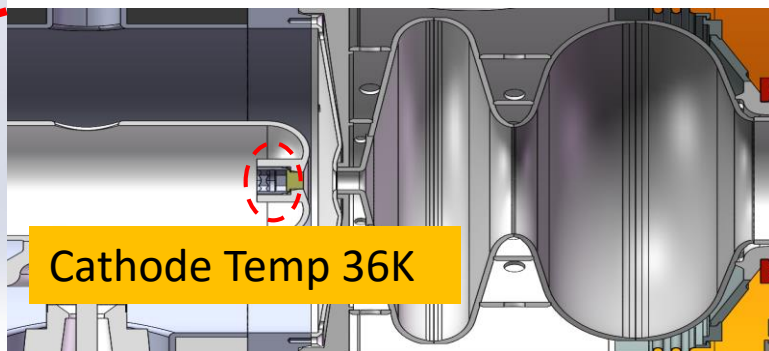
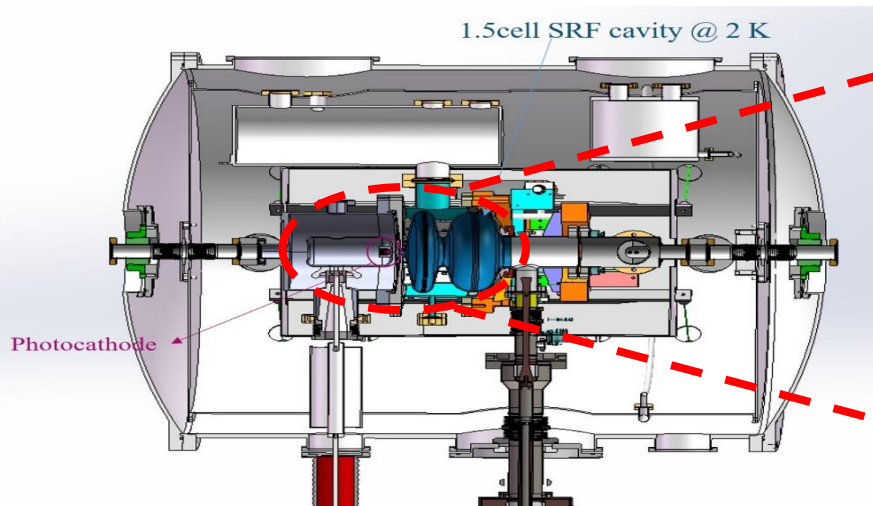
More details in poster of Sonal Mistry

M. Schmeißer et al., Phys. Rev. Accel. Beams **21**, 113401; J. Kuehn et al., doi:10.18429/JACoW-SRF2019-TUP100

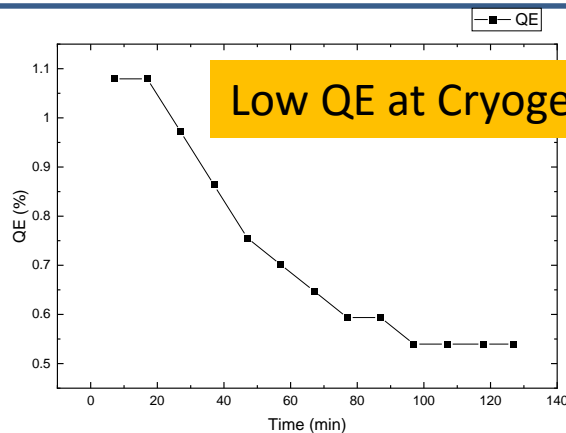
# 3. Semiconductor photocathodes in SRF guns

PKU:  $K_2CsSb$  on Mo plug

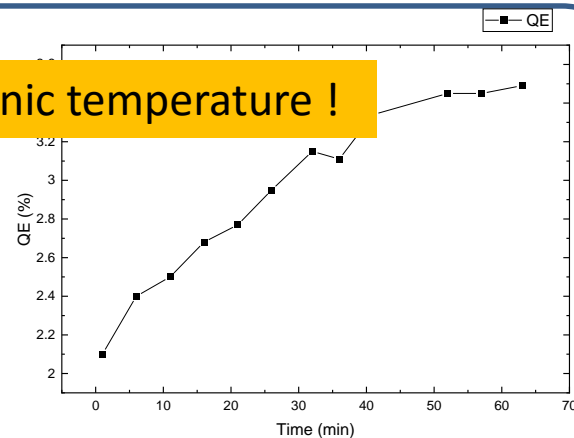
Status: Successful test in gun



QE vs. Temp



Cooling down in gun



Warming up in suitcase

Low QE at Cryogenic temperature !

courtesy of Huamu Xie

more details in Xie's presentation

# 3. Semiconductor photocathodes in SRF guns

## III-V semiconductor GaAs, GaN

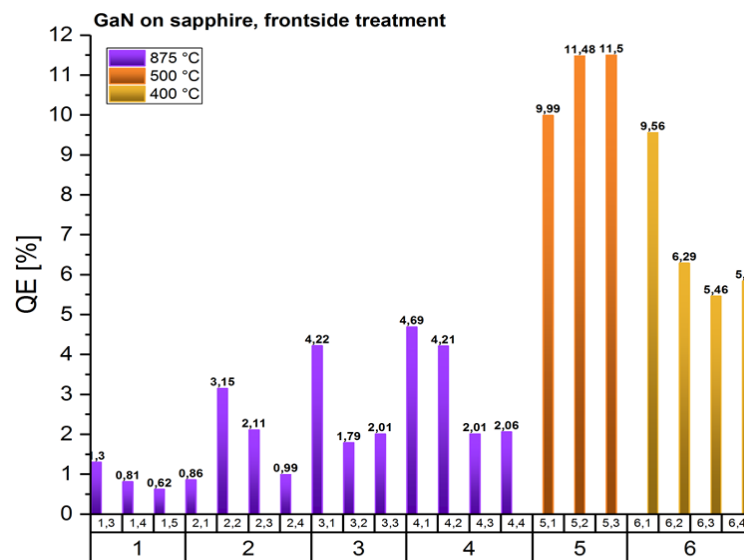
Is the polarized SRF gun possible? !



2010 E. Wang studied GaAs in 1.3GHz SRF gun.  
2021 new plan in BNL 113MHz SRF gun....  
Waiting for more progress....

*GaN status: in developing*

GaN study at HZDR, QE > 10% @310nm



More details in J. Schaber's Poster

E. Wang, BNL-94159-2011-CP

I.Petrushina et al., <https://doi.org/10.18429/JACoW-IPAC2021-WEPA138>

J. Schaber et al., Verhandlungen der Deutschen Physikalischen Gesellschaft; [ISSN 0420-0195](https://doi.org/10.1007/978-3-319-90000-0_195)



## 4. Summary and outlook

- **Proper cathode solution is a key to the successful gun operation**
  - various solutions of cathode integration (cold or warm)
  - NC photocathodes proved in gun
  - Waiting for results of SC photocathodes in gun
- **Both metallic and semiconductor cathodes can be safe for SRF guns**
  - HZDR & BNL for routine operation, PKU & HZB for gun test
- **Technical know-how:**
  - heat load, thermal contact, suppressing multipacting, vacuum during transport and operation, ...
- **Theoretical understanding and full characterization:**
  - QE & intrinsic emittance vs. temperature & operation



# Thank you!

If I miss any information or there is any error in the slides,  
please contact me [r.xiang@hzdr.de](mailto:r.xiang@hzdr.de)