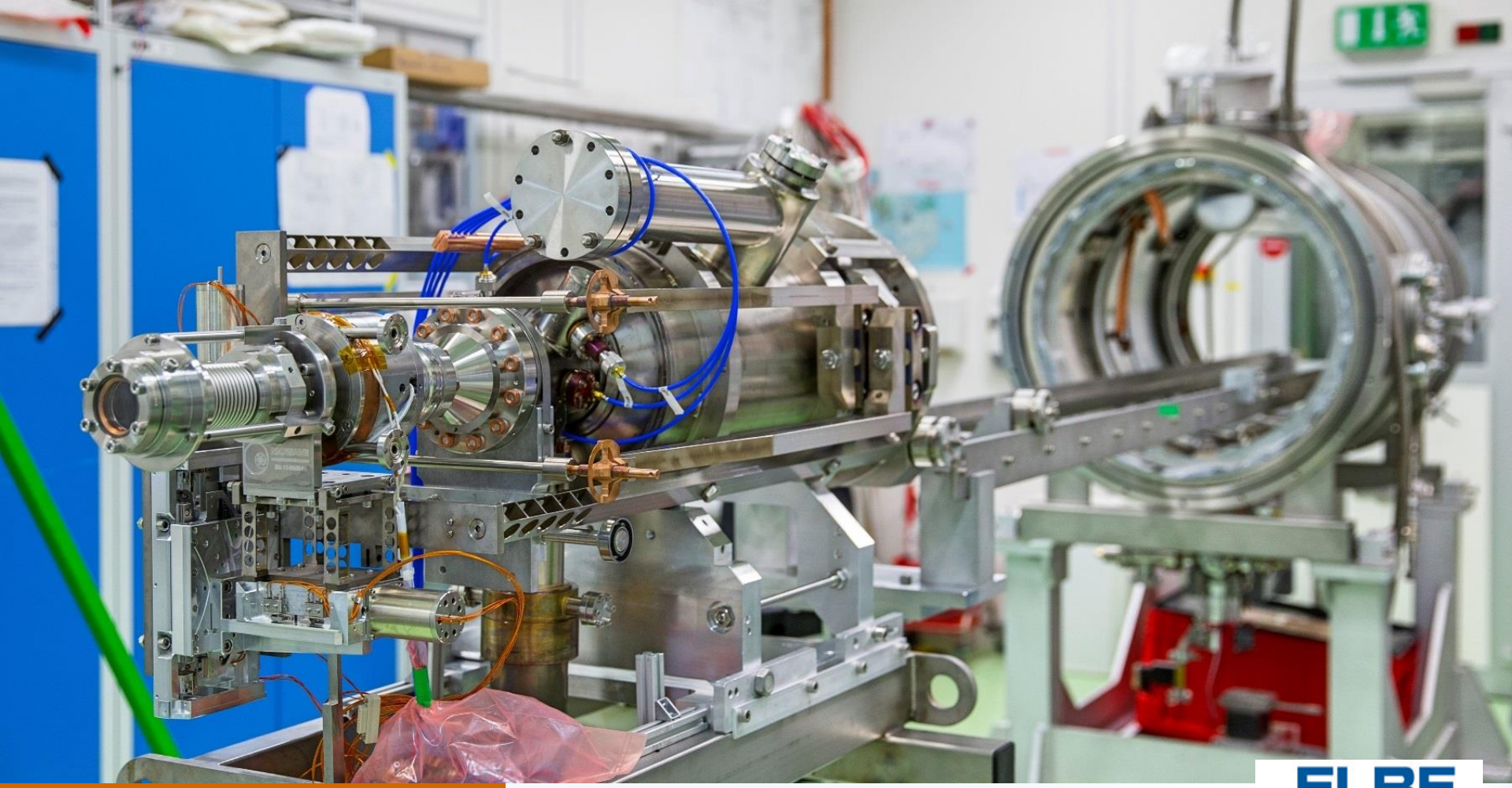


Status of Advanced Photocathodes for SRF Guns

Rong Xiang

Future Light Sources 2023, 27 Aug.–1 Sep. 2023

Outline

1. Introduction

2. Normal conducting photocathodes for SRF guns
   - Metal photocathodes
   - Semiconductor photocathodes

3. Superconducting photocathodes for SRF guns

4. Summary and outlook

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

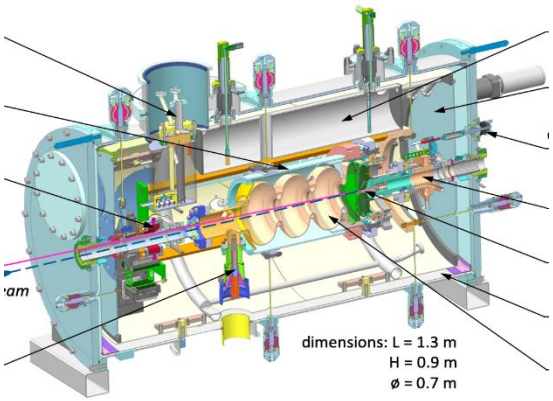
1. Introduction

SRF gun - promising source for high brightness and high current beams required by CW FELs and ERL facilities.

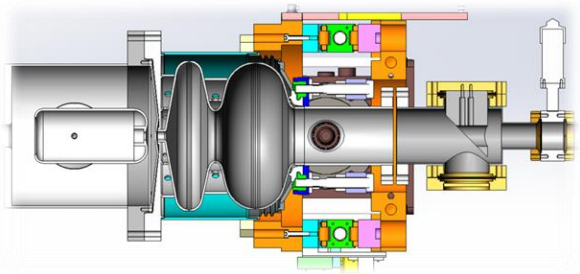
- high gradients on the cathode surface than DC guns – increasing achievable surface current density and reducing thermal emittance contribution;
- high beam energy to mitigate space-charge effects on the way from the gun to the next accelerator cavity;
- outstanding vacuum environment for sensitive cathodes;
- low RF jitter for excellent e- beam and light source stability.

1. Introduction

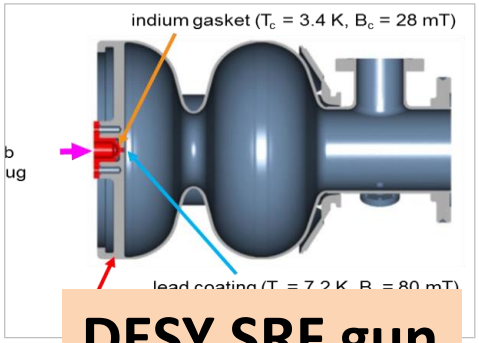
SRF guns for CW high brightness beam



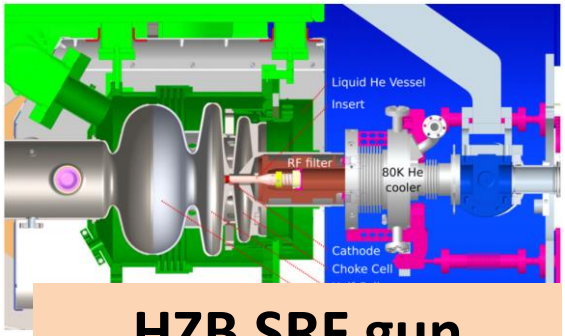
HZDR SRF gun-II in user operation



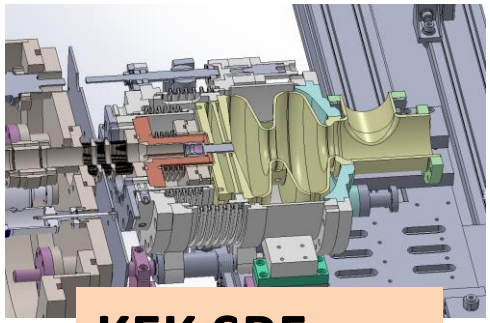
PKU DC-SRF gun



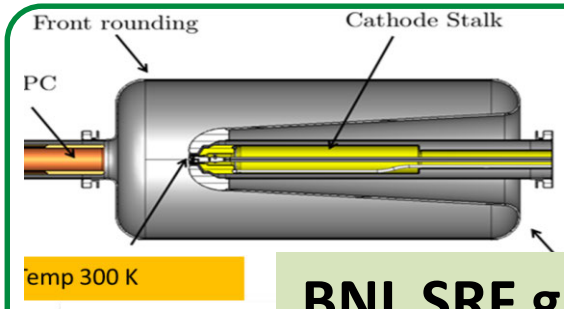
DESY SRF gun



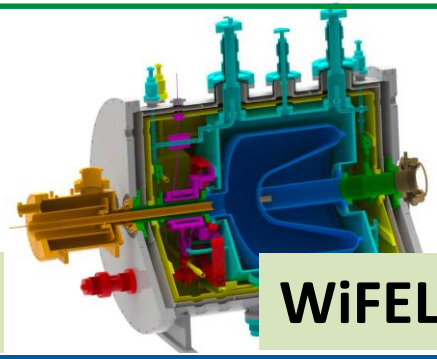
HZB SRF gun



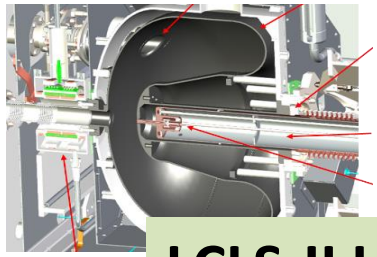
KEK SRF gun



BNL SRF gun



WiFEL gun



LCLS-II HE gun

1. Introduction

Requirements for photocathodes in SRF gun

General requirements for photocathode in injectors

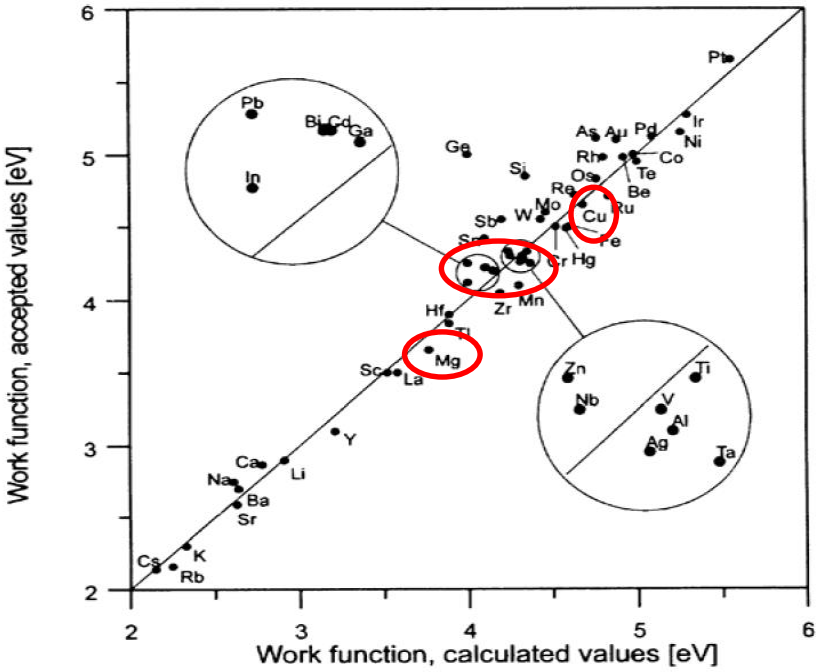
- high QE, low thermal emittance, fast response time
- robust , long lifetime
- low dark current

Specially for SRF guns:

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

2. Normal conducting photocathodes for SRF guns

2.1 Metal photocathodes in SRF Guns



Metal	QE	ϕ (eV)	Tc (K)
Cu	10^{-5} - 10^{-4}	4.6	
Mg	10^{-5} - 10^{-3}	3.6	
Nb	10^{-6} – 10^{-4}	4.3	9.3
Pb	10^{-6} - 10^{-3}	4.2	7.2

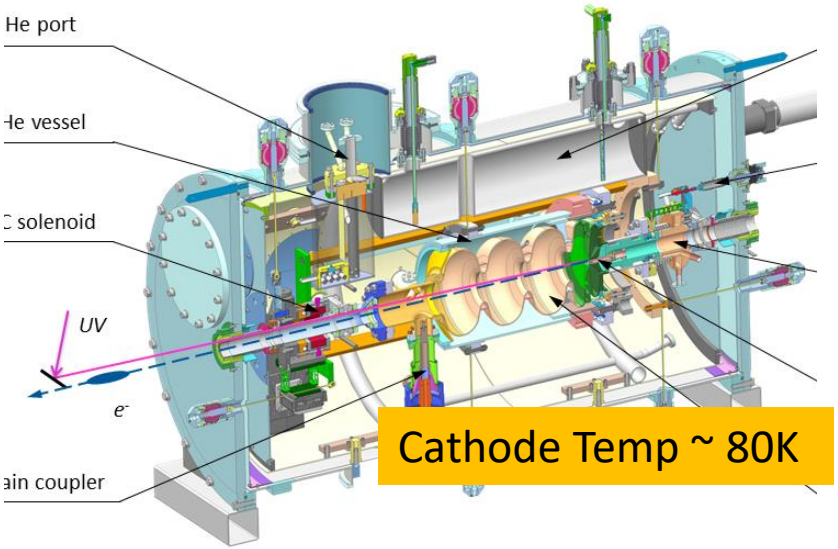
Advantage: robust and „clean“ for SRF guns

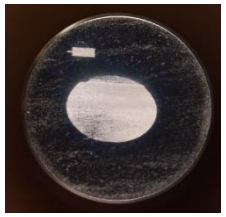
Lide, D. R.. Properties of Solids, *CRC Handbook of Chemistry and Physic, Internet Version 2005*, P. 124;
S. Halas, Materials Science-Poland, Vol. 24, No. 4, 2006
D.H. Dowell et al., NIMA 622, Pages 685-697 (2010)

2. Normal conducting photocathodes for SRF guns

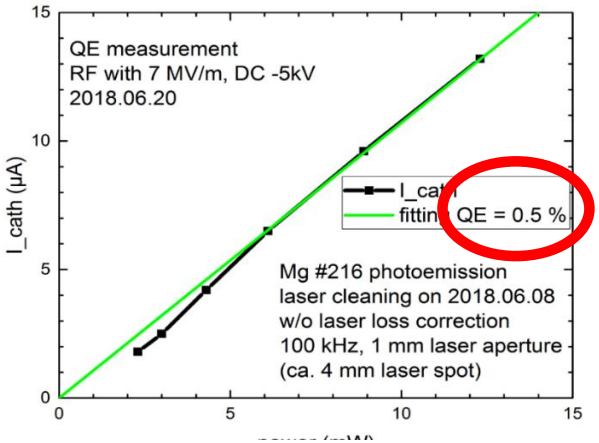
2.1 Metal photocathodes in SRF Guns

Mg, Cu in HZDR SRF gun





Mg plug after laser cleaning



J.Teichert et al. PRAB 24, 033401 (2021)

Cu cathode: gun commissioning

- easy to use
- little dark current
- QE_{258nm}~10^{-5} -10^{-4}

Mg cathode: stable operation

- high QE at UV laser, long life time
- no multipacting problem
- low dark current 30nA @14 MV/m
- repeatable

Highlight:

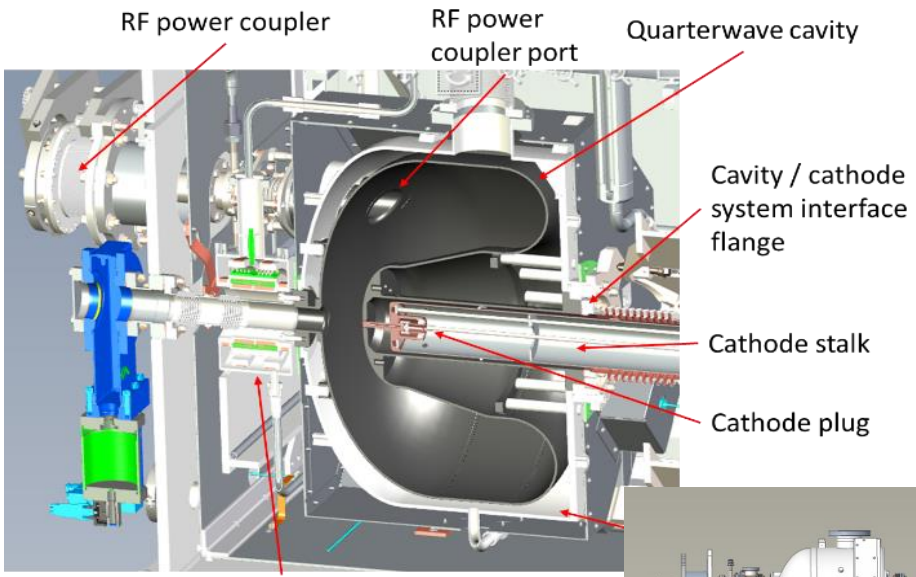
2019 - 2020 stable operation for users

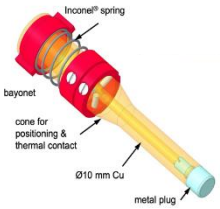
200-250 pC, 100 kHz, 1760 hrs, ~ 57 C

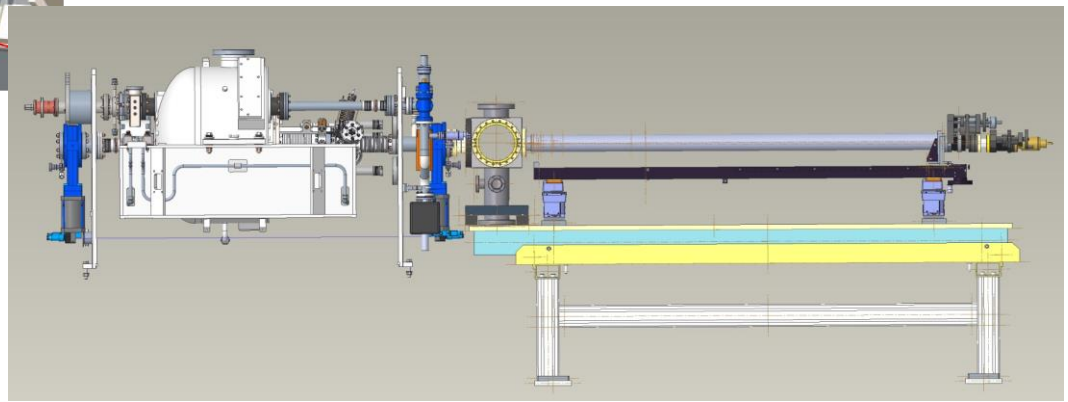
2. Normal conducting photocathodes for SRF guns

2.1 Metal photocathodes in SRF Guns

Cu photocathode for LCLS-II HE SRF gun







Status: in developing

- cryogenic (55-80 K) or warm (300 K)
- first photocathode for gun test

J. W. Lewellen, WEPA03, NAPAC 2022; R. Xiang,et al, SRF2023

2. Normal conducting photocathodes for SRF guns

2.2 Semiconductor photocathodes in SRF Guns

Cathode	Typical wavelength (nm)	QE @ room Temp.	E_G+E_A (eV)	Expected thermal emittance (μm/mm)
Cs_2Te	266	0.1	3.5	0.9
Cs_3Sb	432	0.15	1.6+0.45	0.7
K_3Sb	400	0.07	1.1+1.6	0.5
Na_3Sb	330	0.02	1.1+2.44	0.4
Na_2KSb	330	0.1	1+1	1.1
K_2CsSb	532	0.1	1+1.1	0.4
GaAs(Cs,O)	532	0.1	1.4 ± 0.1	0.44
GaN(Cs)	250-360	0.2-0.3	3.4 -?	-

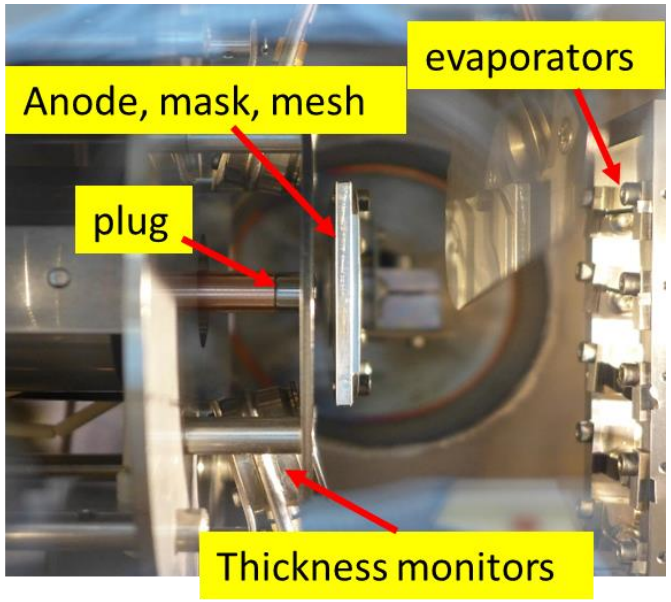
D.H. Dowell et al., NIMA 622, Pages 685-697 (2010)
Xiaohui Wang et al., J. Mater. Chem. C, 2021, 9, 13013

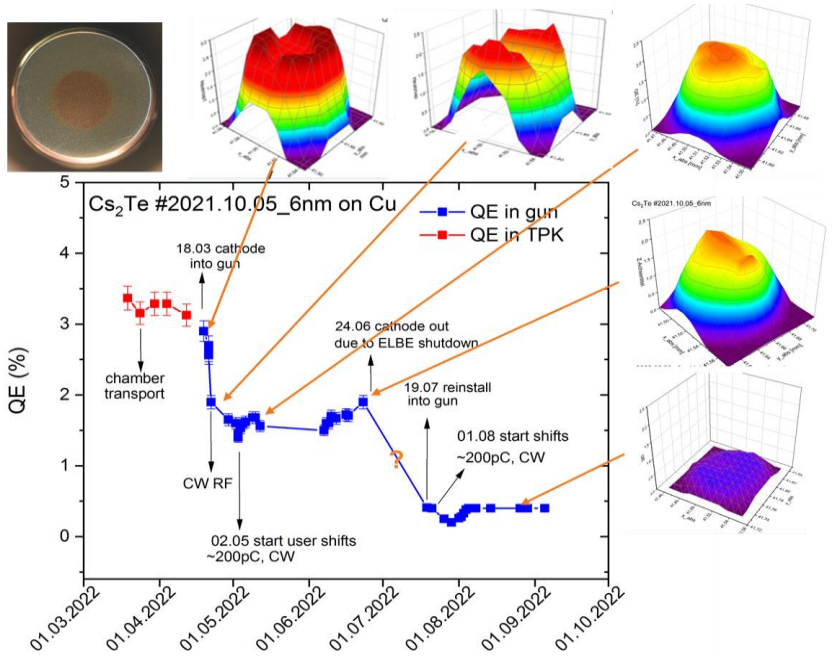
2. Normal conducting photocathodes for SRF guns

2.2 Semiconductor photocathodes in SRF Guns

Cs_2Te for HZDR SRF gun

Status: stable operation





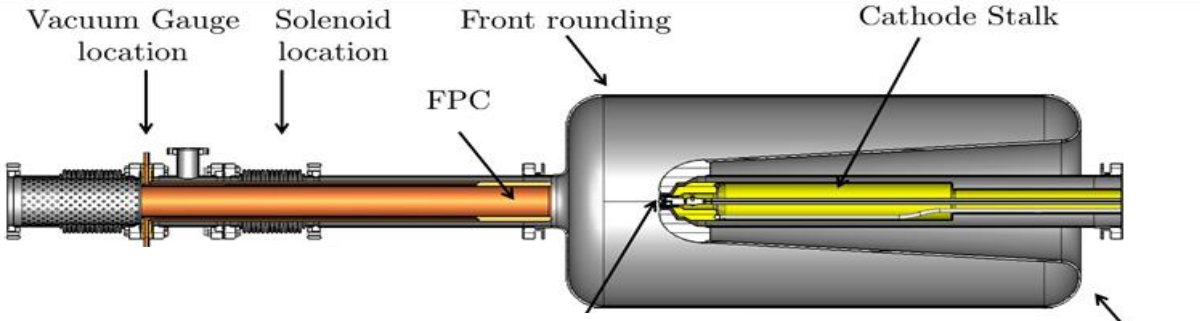
- ✓ Since 2020 for user operation
- ✓ Providing ~200 pC, 2.3 ps, 50-100 kHz
- ✓ 2-3 months life time with QE 0.5%-1%
- ? Possible QE drops due to transport, multipacting, CW RF and beam operation

2. Normal conducting photocathodes for SRF guns

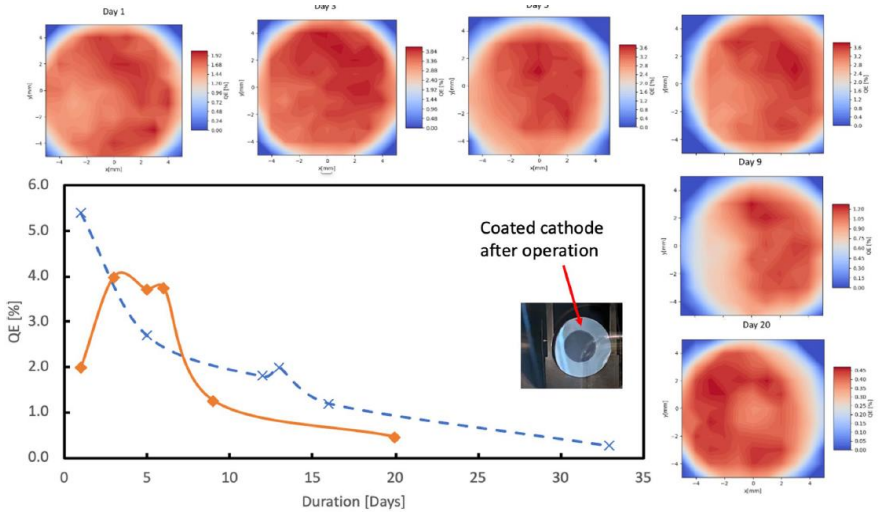
2.2 Semiconductor photocathodes in SRF Guns

K_2CsSb for BNL 113MHz SRF gun

Brookhaven National Laboratory



Cathode Temp 300 K



Status: routine operation

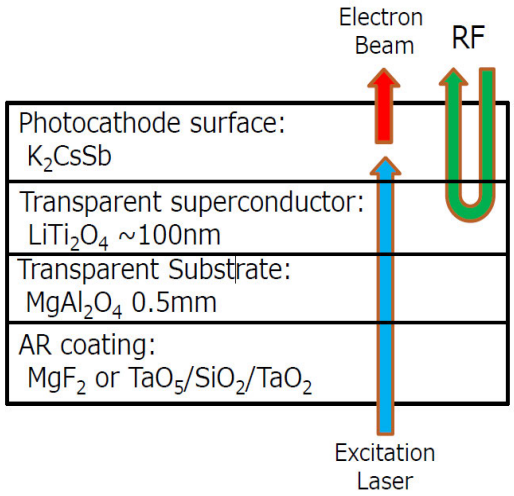
- ✓ 1-2 months lifetime of QE 1- 4 %
- ✓ 1-2 nC/bunch, 375ps, 78 kHz
- ✓ Dedicated procedure against multipacting
- ? Ion bombardment or Cs depletion

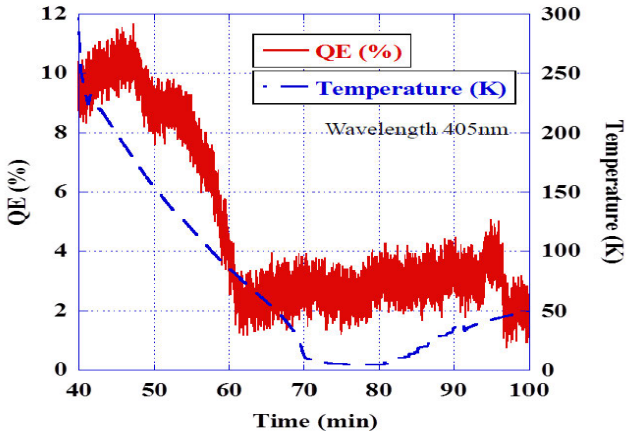
Wang, E., Litvinenko, V.N., Pinayev, I. *et al. Sci Rep* **11,** 4477 (2021).

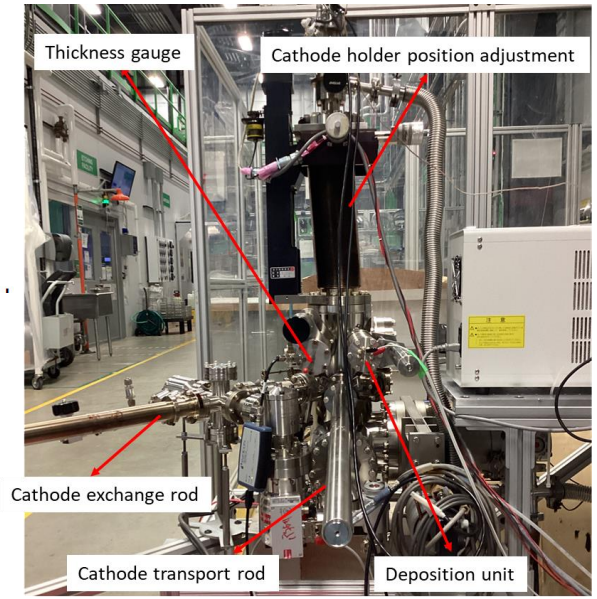
2. Normal conducting photocathodes for SRF guns

2.2 Semiconductor photocathodes in SRF Guns

K_2CsSb on transparent superconductor for KEK SRF gun







courtesy of T. Konomi, Ziye Yin

Status: in developing

- Cathode rod will be operated at 2 K.
- K_2CsSb photoemitter on SC substrate
- Laser from backside
- QE was decreased during cooling in 1st test

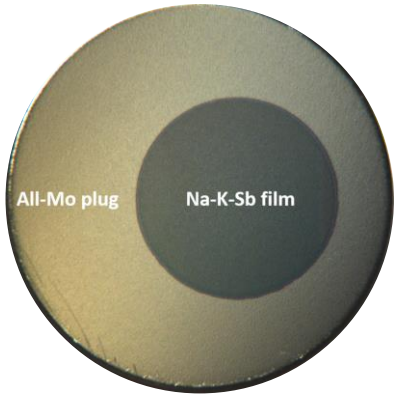
T.Konomi et al., ERL17, MOIACC002

2. Normal conducting photocathodes for SRF guns

2.2 Semiconductor photocathodes in SRF Guns

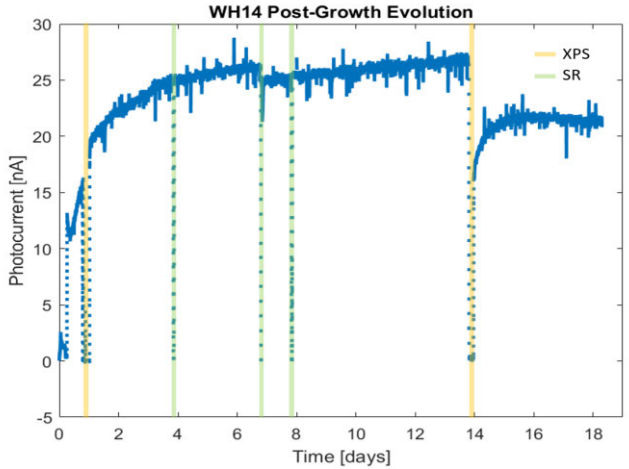
Na-K-Sb for HZB SRF gun SEAlab

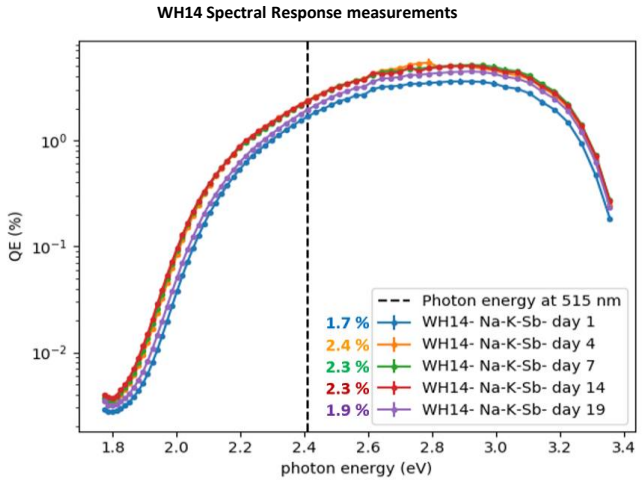
HZB Helmholtz Zentrum Berlin



Status: in developing

- multilayer- and epitaxial-growth
- Promising robustness for Na-K-Sb with QE up to 2.4% at 515 nm wavelength
- Post growth analysis by spectral response (SR) measurements under UHV conditions



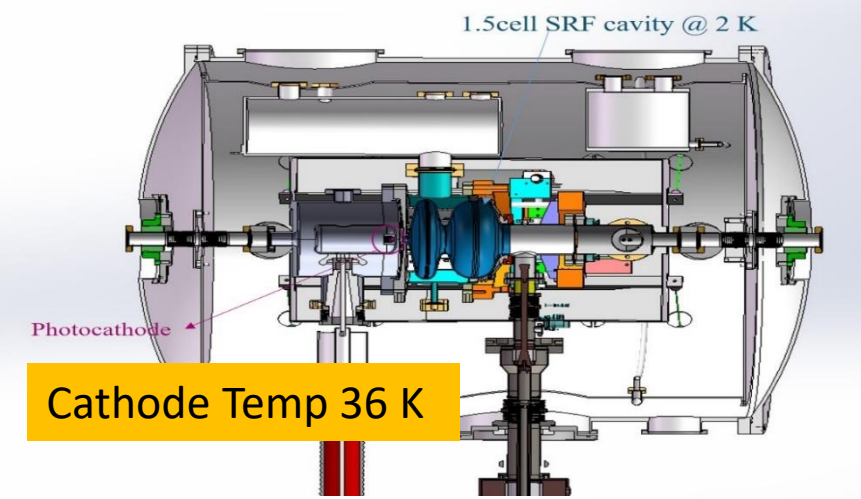


S. Misty, J. Dube, T. Kamps, J. Kuehn, C. Wang, Proceedings of IPAC 2023, THPA141.

2. Normal conducting photocathodes for SRF guns

2.2 Semiconductor photocathodes in SRF Guns

K_2CsSb for PKU DC-SRF gun

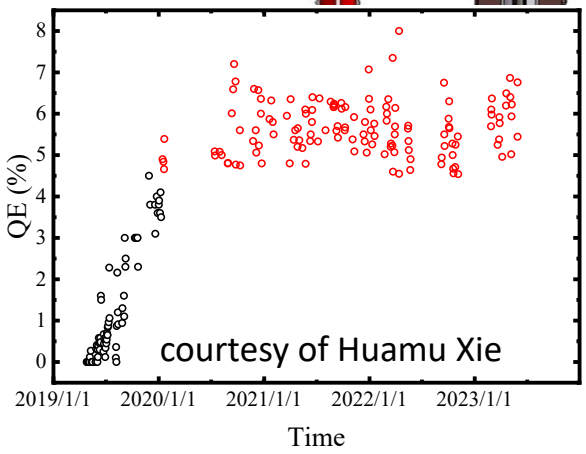


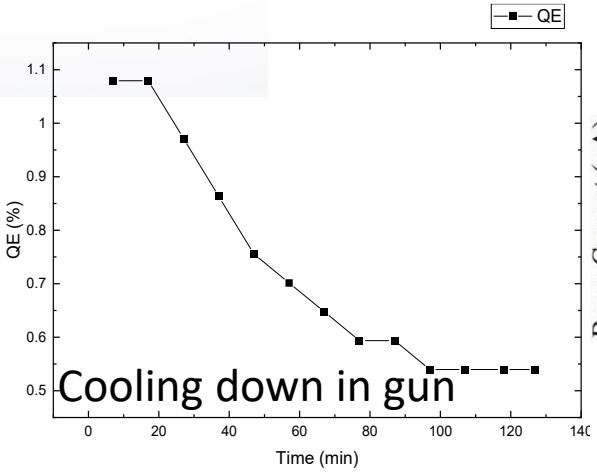
Cathode Temp 36 K

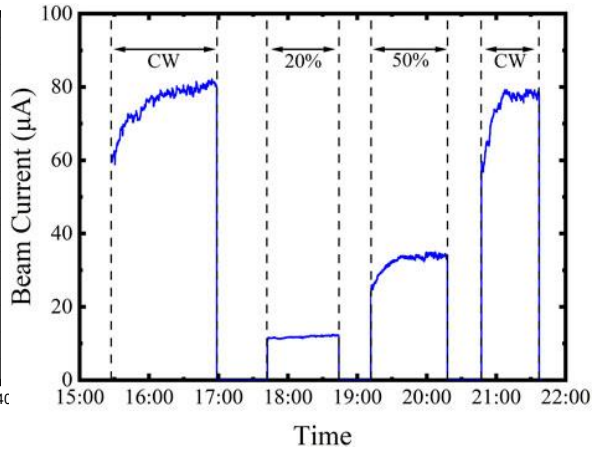
Status: Successful test in gun

- ✓ Successfully prepared in lab
- ✓ tested in gun
- ✓ Low thermal emittance
  0.542-0.559 μm/mm (RT)

? reduced QE at low temparture





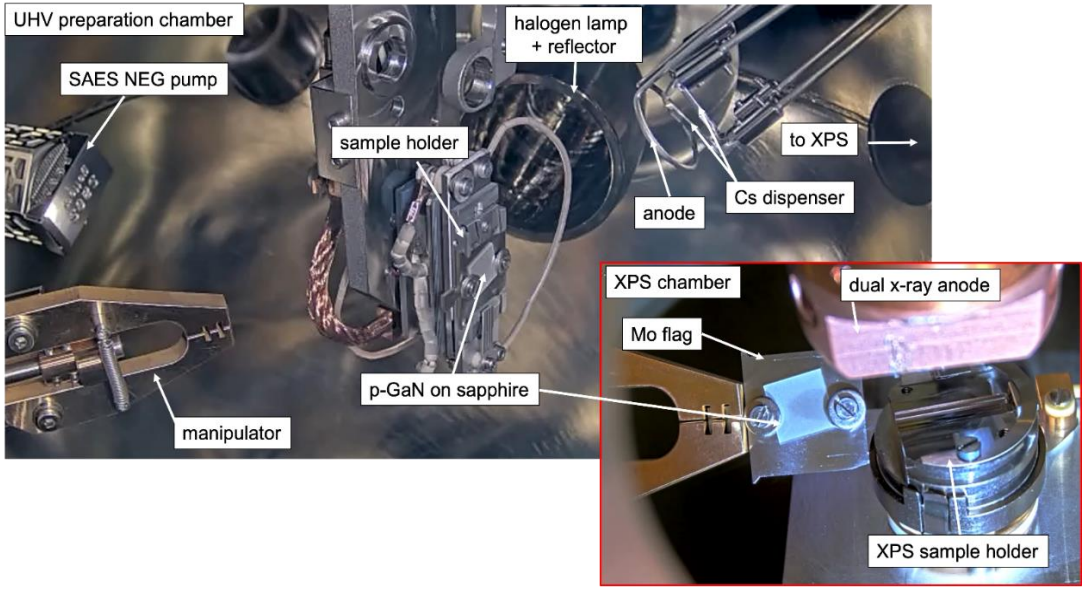


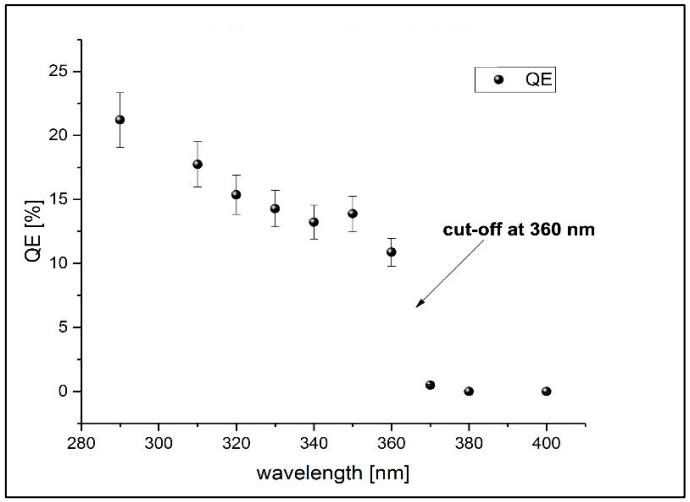
D.Ouyang et al., NIM A Vol. 1026, 2022; Y. Zhao, Front. Phys., Vol. 11, 2023

2. Normal conducting photocathodes for SRF guns

2.2 Semiconductor photocathodes in SRF Guns

GaN(Cs) as potential new cathode





courtesy of J. Schaber

Status: in study

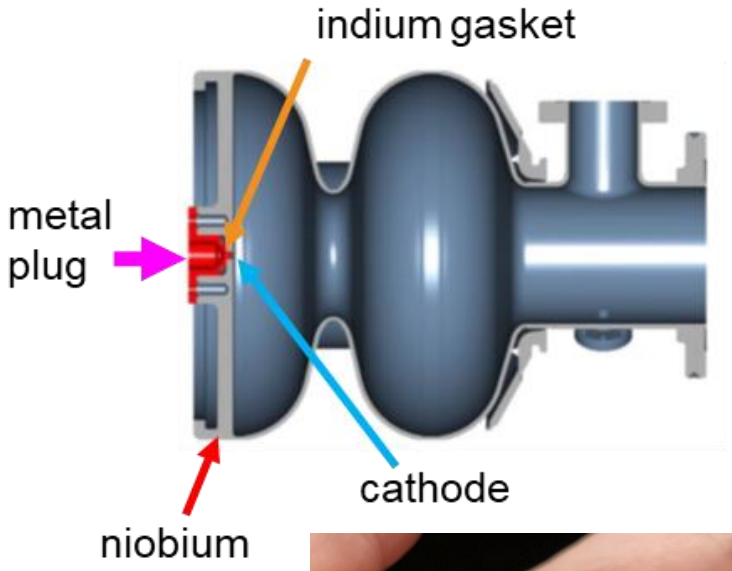
- Commercial high doping p-GaN on sapphire / Si / SiC
- activation only with cesium
- QE~ 11.5 % @ 310nm and lifetime~ 5000 h in storage

? test in SRF gun environment

J. Schaber er al., Scientific Reports 13 (1), 3188, 2023

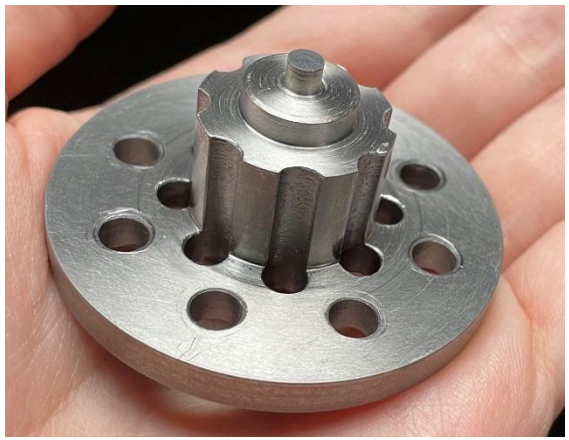
3. Superconducting photocathodes for SRF guns

SC photocathode for DESY SRF gun

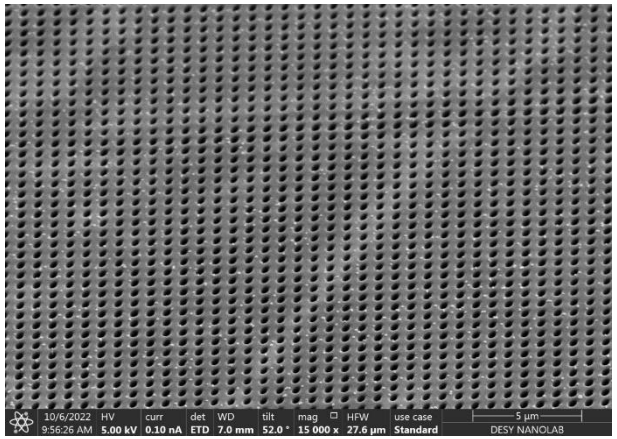


Status: in developing

1. Pb coating on Nb plug (or Cu Plug)
   - QE reached 2.7 x 10^{-3} @ 213 nm
   - air-stable photocathode
   - better adhesion required
2. Surface plasmon enhanced Nb (or Cu)



courtesy of D. Bazyl, E. Vogel

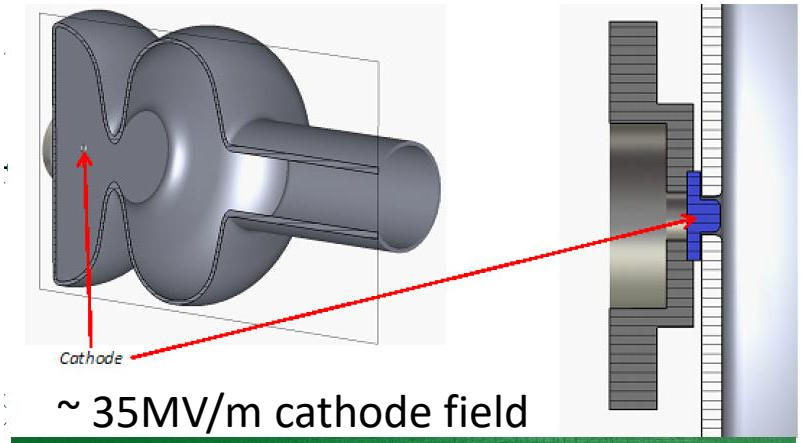


Nanostructured Cu (credit: DESY NanoLab)

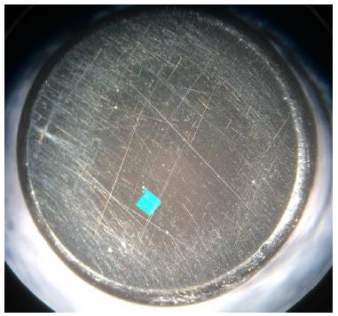
E. Vogel et al., SRF2019,THP080; J. Lorkiewicz et al., Vacuum, Volume 179, Sep. 2020, 109524

3. Superconducting photocathodes for SRF guns

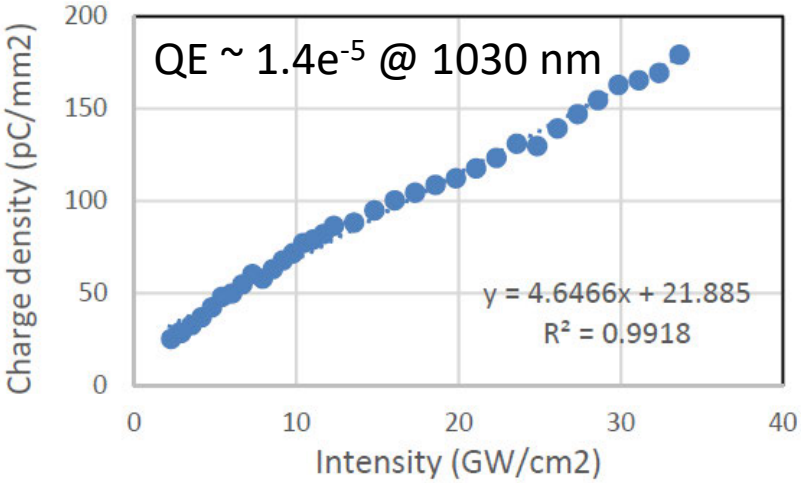
SC photocathode: Plasmonic Nb cathode @ Jlab / RadiaBeam



~ 35MV/m cathode field



nano-patterned area on Nb plug



F.E. Hannon, et al., IPAC2019, TUPTS069, Melbourne, Australia

4. Summary and outlook

- **Proper cathode solution is a key to the successful gun operation**
  HZDR, BNL - routine operation
  HZB, PKU - test beam
  DESY, KEK, SLAC/MSU - active developing
- **Both metal and semiconductor cathodes can be safe in SRF guns**
  various solutions of cathode integration (cold or warm)
- **Important: technical know-how**
  heat load, thermal contact, suppressing multipacting,
  particle free operation, vacuum during transport and operation, …
- **Theoretical understanding and full characterization:**
  QE & intrinsic emittance vs. temperature & RF & beam operation
- **The ideal photocathode for an SRF gun?**
  Beam requirements
  Method to integrate cathode to cavity
  Laser cost
  Development phase: commissioning, user operation

Acknowledgement

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Mengjia Gaowei (BNL)
Jana Schaber (HZDR)
Julius Kühn, Thorsten Kamps (HZB)

Thank you !

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