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U.S. DEPARTMENT OF ENERGY

DBR photocathodes for EIC polarized electron source

Omer Rahman

On behalf of the electron source development group

EWPAA 2024, HZDR, Dresden, Germany.

19th September 2024

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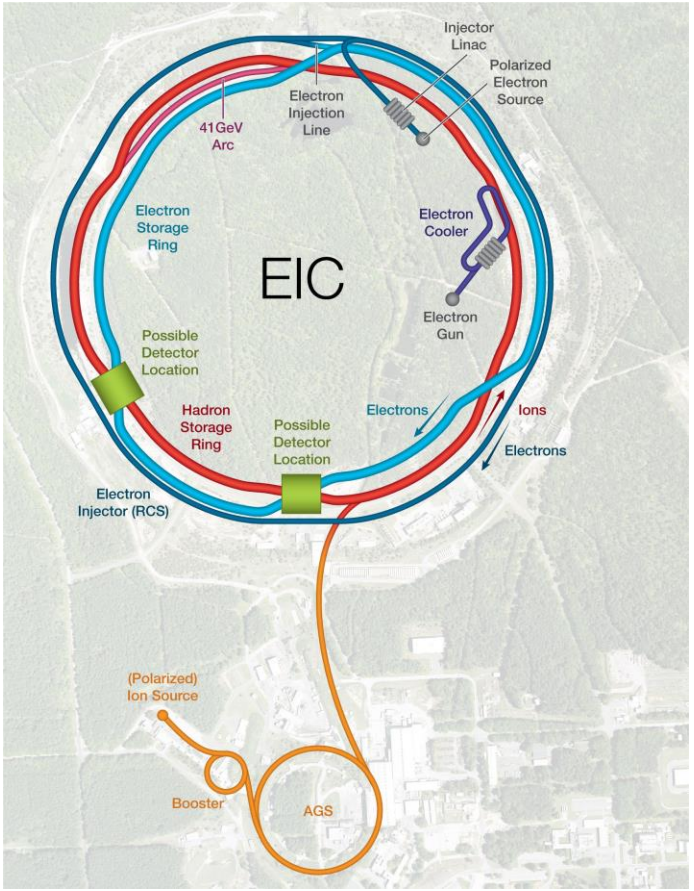
Electron sources for EIC

- Electron ion collider (EIC) requires electron sources for collision (polarized electrons) and hadron cooling (unpolarized electrons).
- High voltage DC gun as the electron sources with suitable photocathodes
- Gun and beam parameters vary based on application in EIC

Parameters	Polarized electron source	Unpolarized electron source
Photocathode	DBR SSL GaAs	Multialkaline
Bunch charge	7 nC	100 pC – 1 nC
Bunch length	1.6 ns	150 ps
Average current	56 nA	98 mA
Gun voltage	300 kV	550 kV



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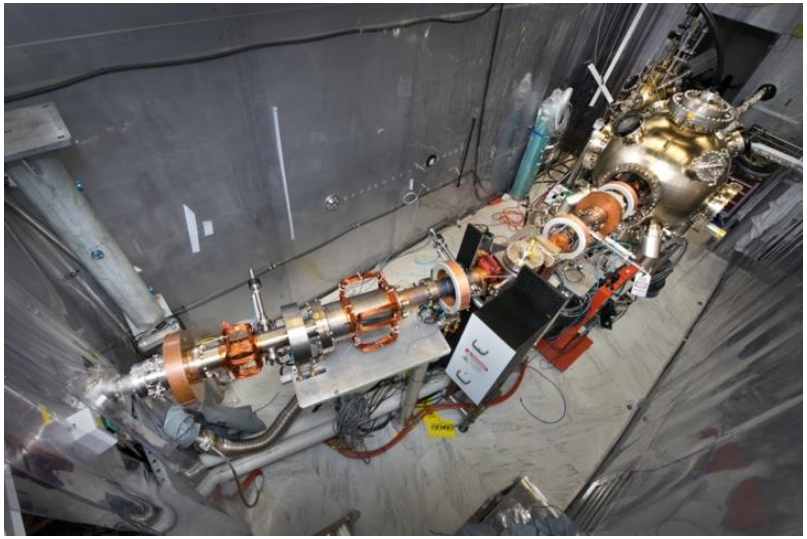
EIC polarized electron source requirement

Parameter	Value	Achieved in stable operation
Bunch charge [nC]	7	7.5 (11.6)
Peak current [A]	4.5	4.8
Frequency [Hz]	1 (8 bunches)	9000
Voltage [kV]	300	350(300)
Average Current	56 nA	67.5 uA
Polarization [%]	> 85%	> 85%



EIC polarized gun at Stonybrook Univ.

Challenges –

1. Achieve high voltage with no field emission
2. Have excellent vacuum
3. **Surface Charge limit** from the photocathode

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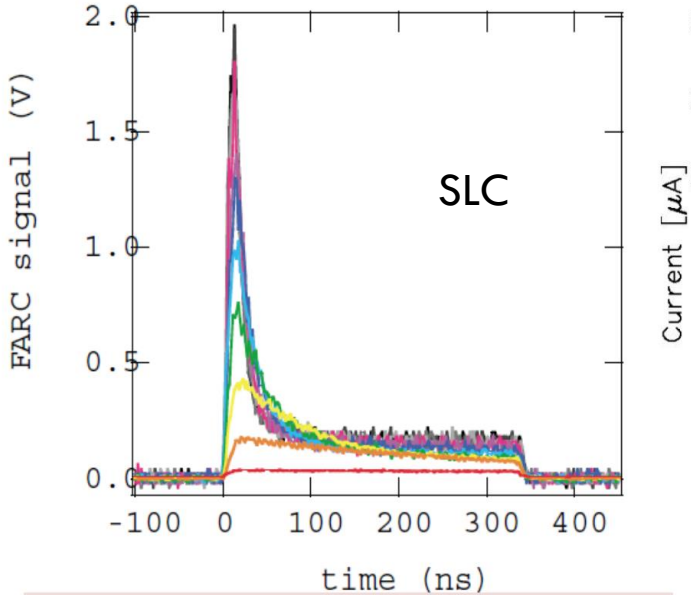
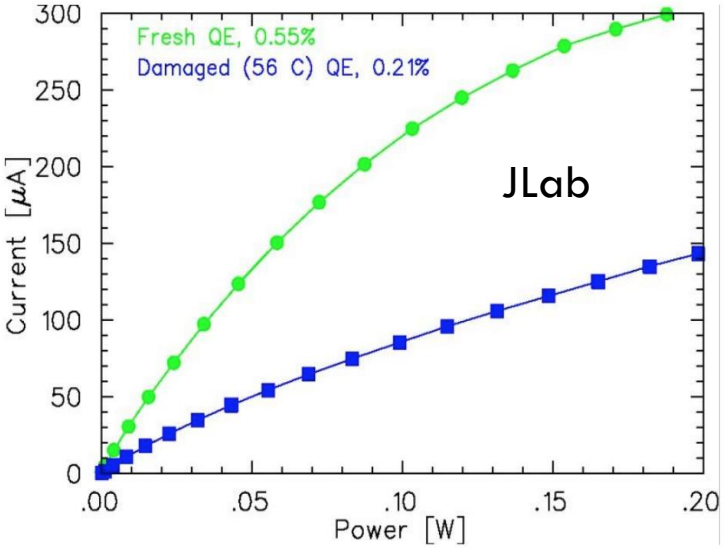
Surface charge limit





- SLC: Difficulty extracting enough charge (nC level 100's ns)
- JLab : Current saturates at low QE with high laser power
- Ways to solve:

1. Heavily doped surface layer of Super lattice
2. Higher gun voltage
3. Larger laser spot

G. Mulhollan, et al., Physics Letters A 282 (2001) 309–318

Graph courtesy:
- Takashi Maruyama (SLAC), PESP 2000
- Matthew Poelker (Jlab)- USPAS 2012

DBR photocathode

High figure of merit spin polarized electron sources grown via MOCVD

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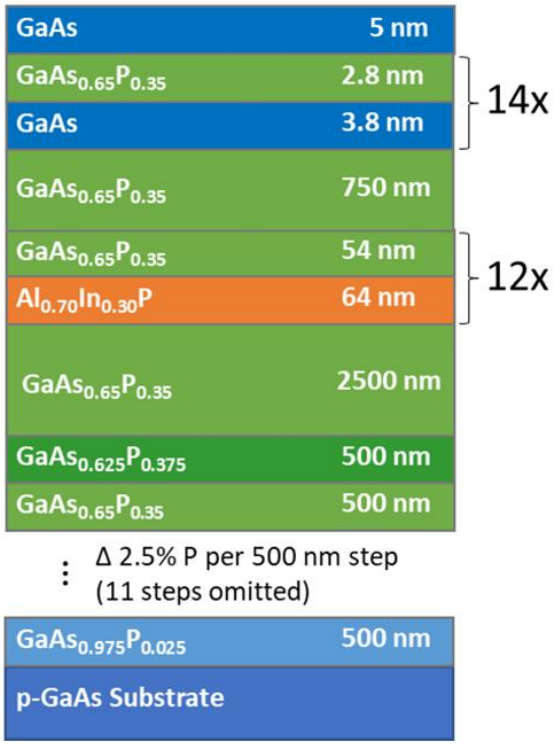

- Fabricated at Old Dominion university. Tested at BNL.
- Used Metal-Organic Chemical Vapor Deposition (MOCVD) method.
- DBR layer is composed of 12 pairs of $GaAs_{0.65}$ $P_{0.35}$ and $In_{0.30}$ $Al_{0.70}P$ with nominal thicknesses of 54 and 64nm, respectively, and p-type Zn doping of 5e18 cm^{-3}
- No protective As cap
- Tested at mini-mott polarimeter at BNL for ESP and QE
- Surface layer is carbon doped (doping density can be varied based on what is needed)

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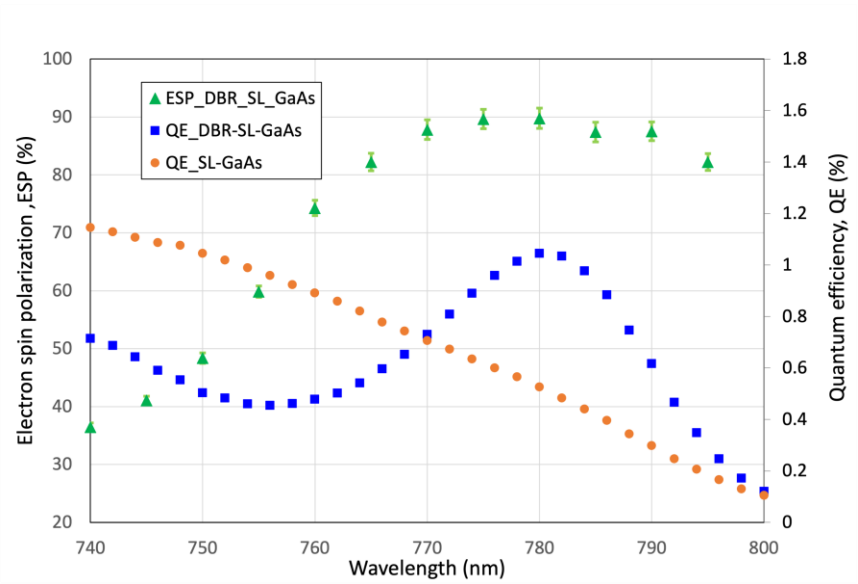
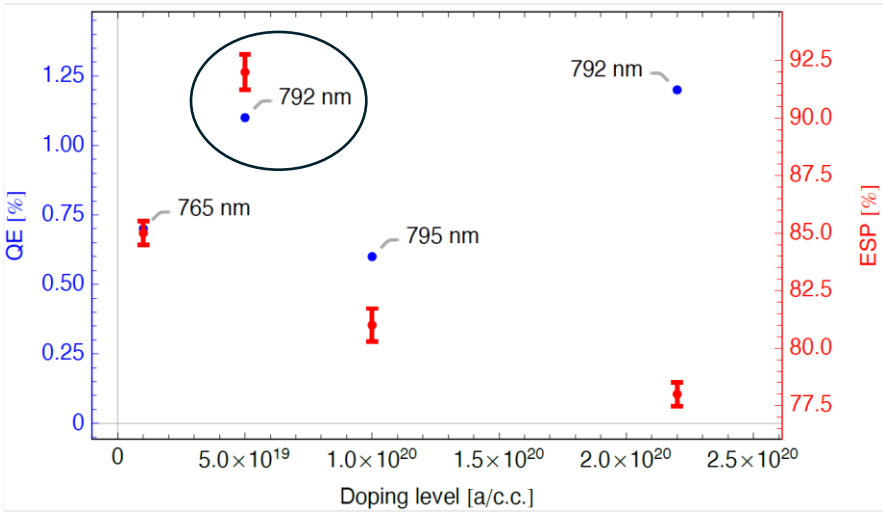
DBR photocathode characterization





- DBR peak QE ~1% at 780 nm with 90% polarization.
- Different surface doping level = different polarization.
- Increasing doping level beyond 5e19 cm $^{-3}$ level decreased polarization
- All samples used for the beam tests had 5e19 cm $^{-3}$ level doping

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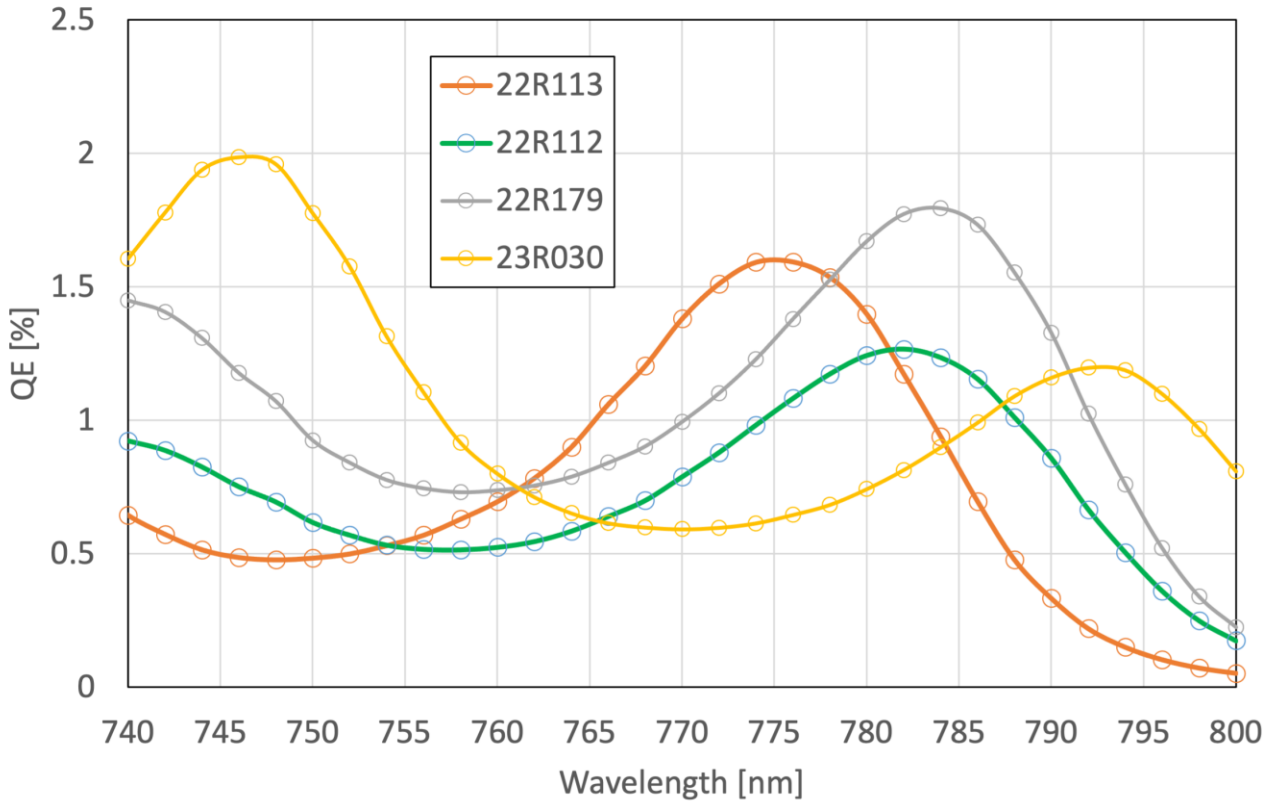
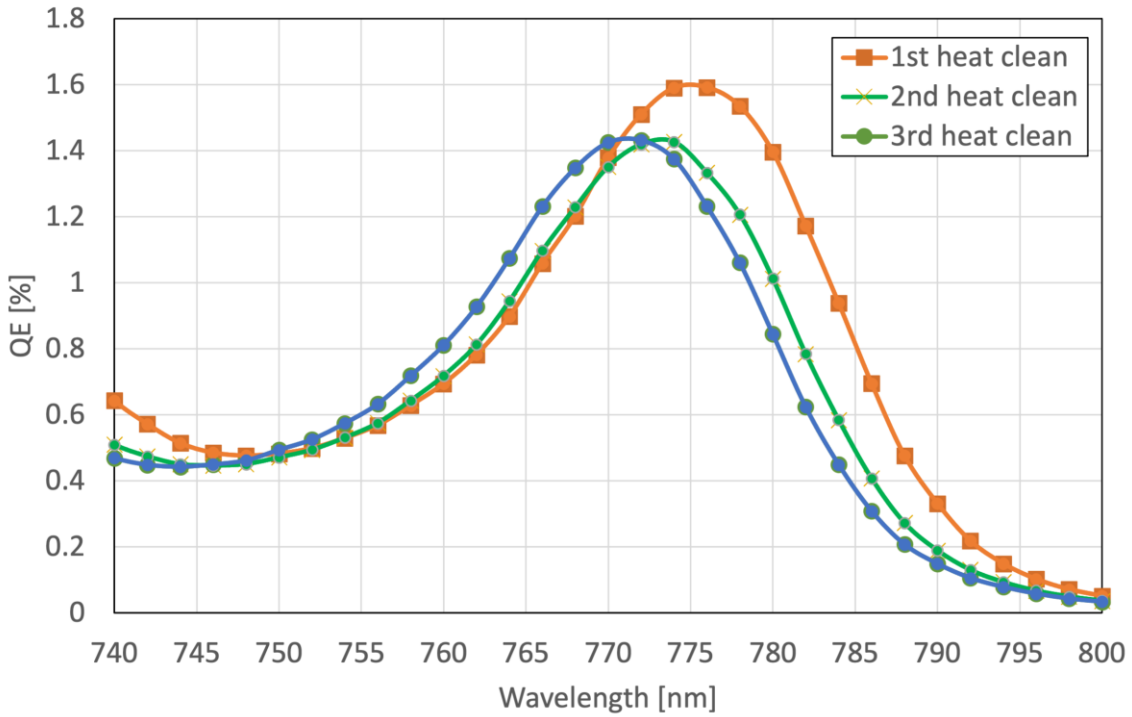
Spectral response variation



- Different samples using the same recipe and the same MOCVD machine had different spectral response
- Peak QE wavelength can vary as much as 20 nm from sample to sample
- Need a wavelength tunable laser to mitigate this issue.

Peak QE changes from activation to activation



- Wavelength of peak QE varies from activation to activation on the same sample, same spot
- Variation could be as high as 5 nm
- Can be explained using a simple model where QE depends on electron affinity
- If Electron affinity varies from activation to activation, so does wavelength for peak QE
- Operational solution = wavelength tunable laser

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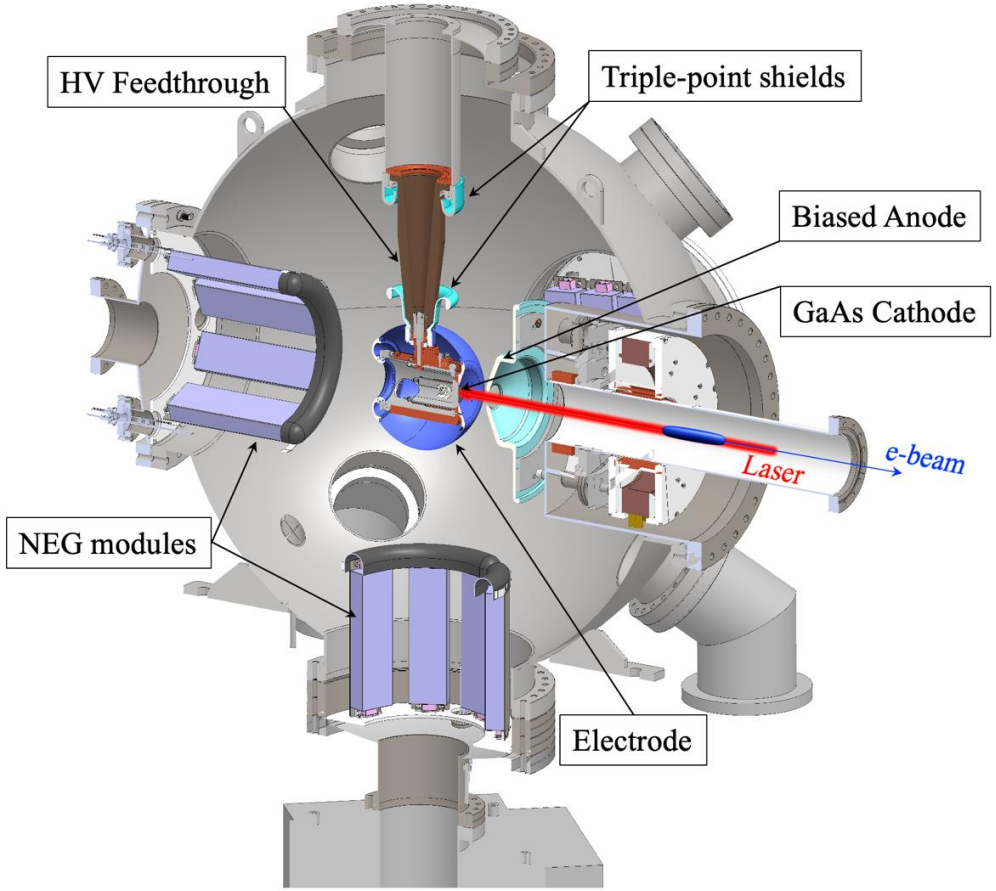
EIC polarized gun overview



Gun design include:

- High voltage feedthrough
- Triple-point shields
- Beam quality, envelope
- Electrode, anode outer shape

Main tools:

- Possion: 2D study
- Opera3D: triple point shield's kick.
- GPT 3D beam tracking, ion back tracking
- Python: field emission tracking, Ion back tracking

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 033401 (2022)

Editors' Suggestion

High voltage dc gun for high intensity polarized electron source

Erdong Wang, Omer Rahman, John Skaritka, Wei Liu, Jyoti Biswas, Christopher Degen, Patrick Inacker, Robert Lambiase, and Matthew Paniccia

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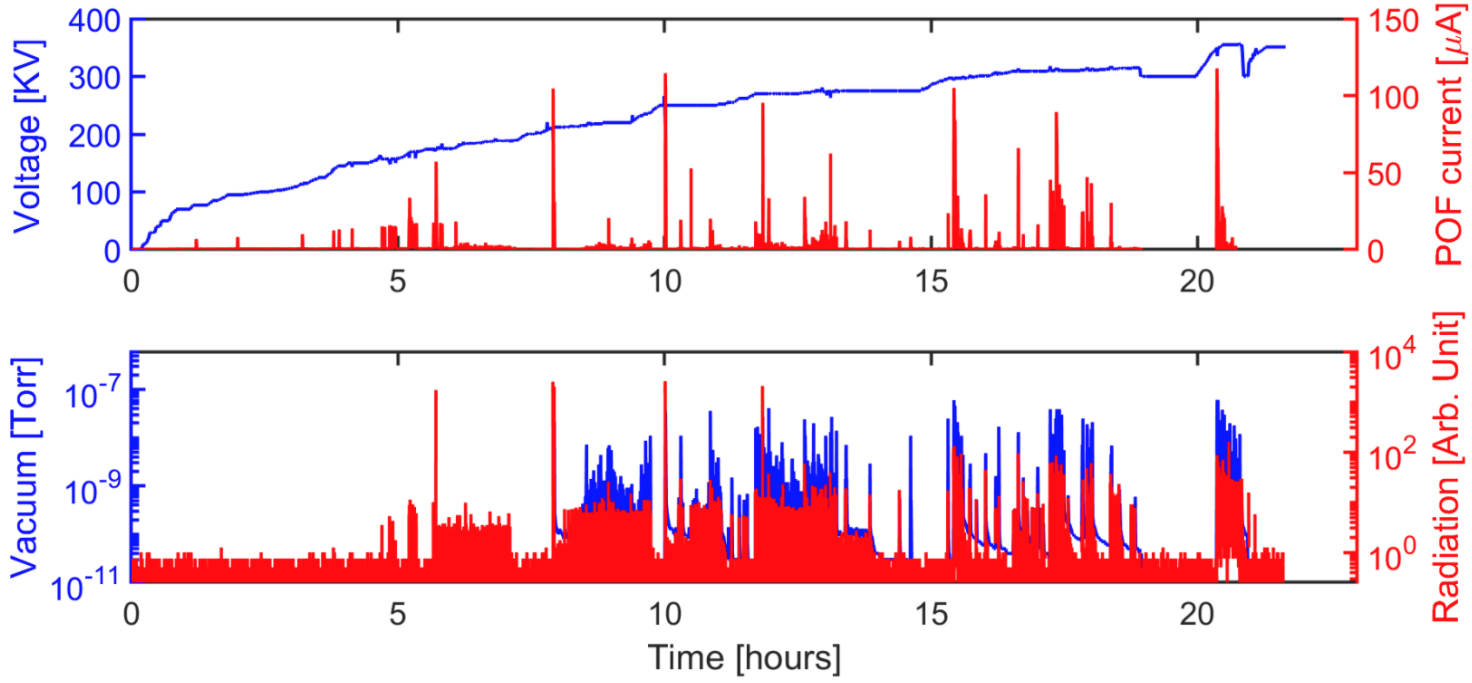
HV conditioning



Gun first conditioned in Dec. 2020 (vacuum conditioning, total take 23 hrs, Cooling is on):

- Achieved gun design value 352 kV without field emission
- "Dark lifetime" is many months
- We did not have to use inert gas to condition
- Generally operated at 300 kV

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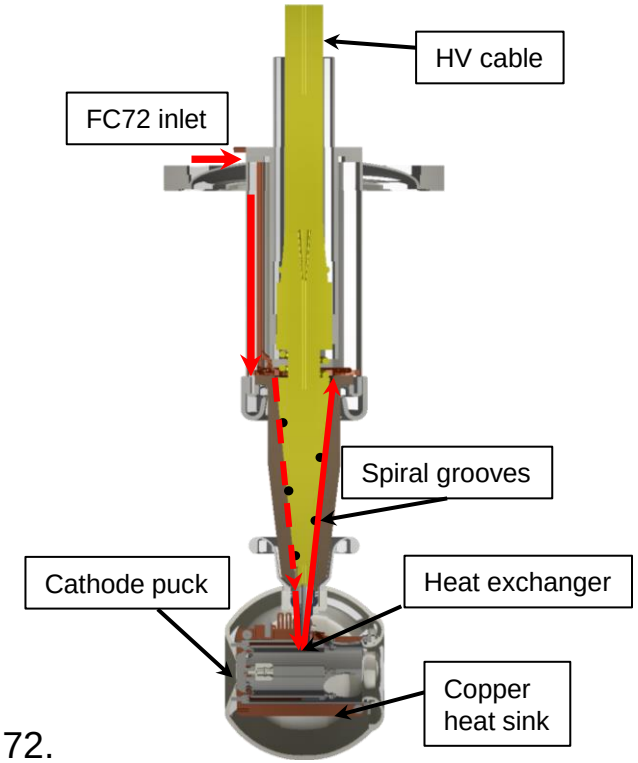
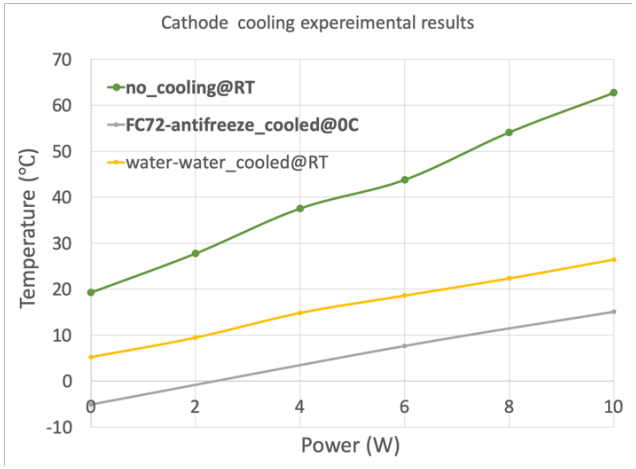
Active cooling in EIC gun

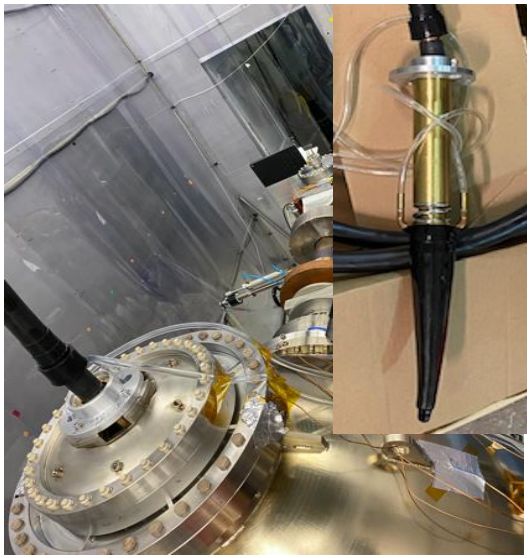
Aiming to absorb the laser power up to 10 W. We collaborated with Dielectric Sciences developed the active cooling HV feedthrough.

Custom designed HV plug with cooling channel





Tested in the gun with FC 72. Operated @300-350 kV for more than 500 hours reliably



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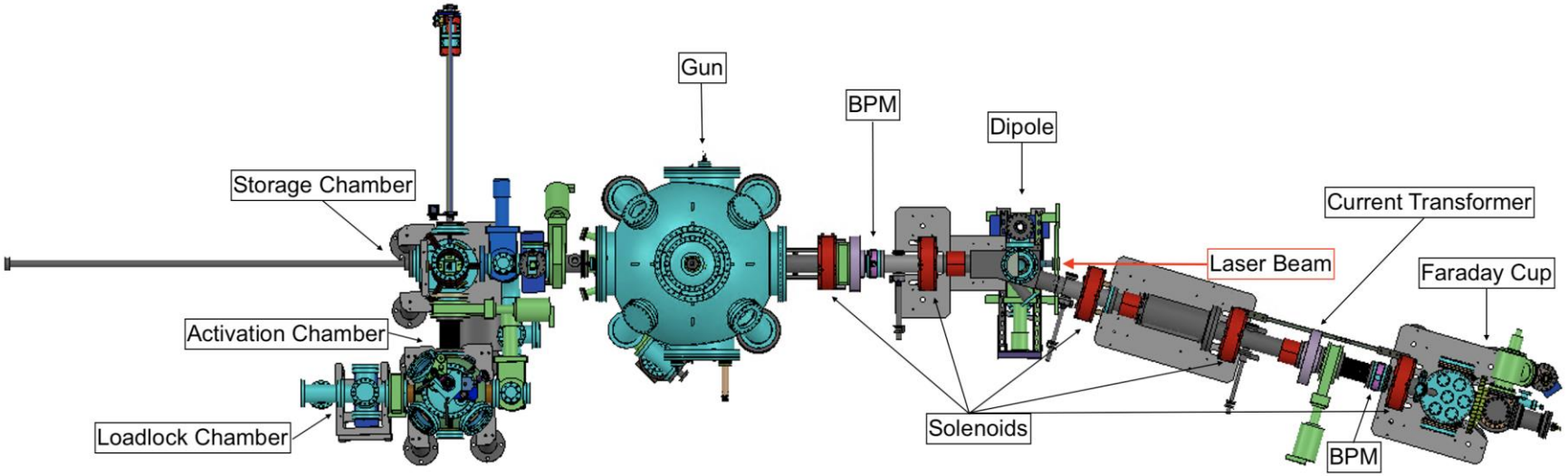
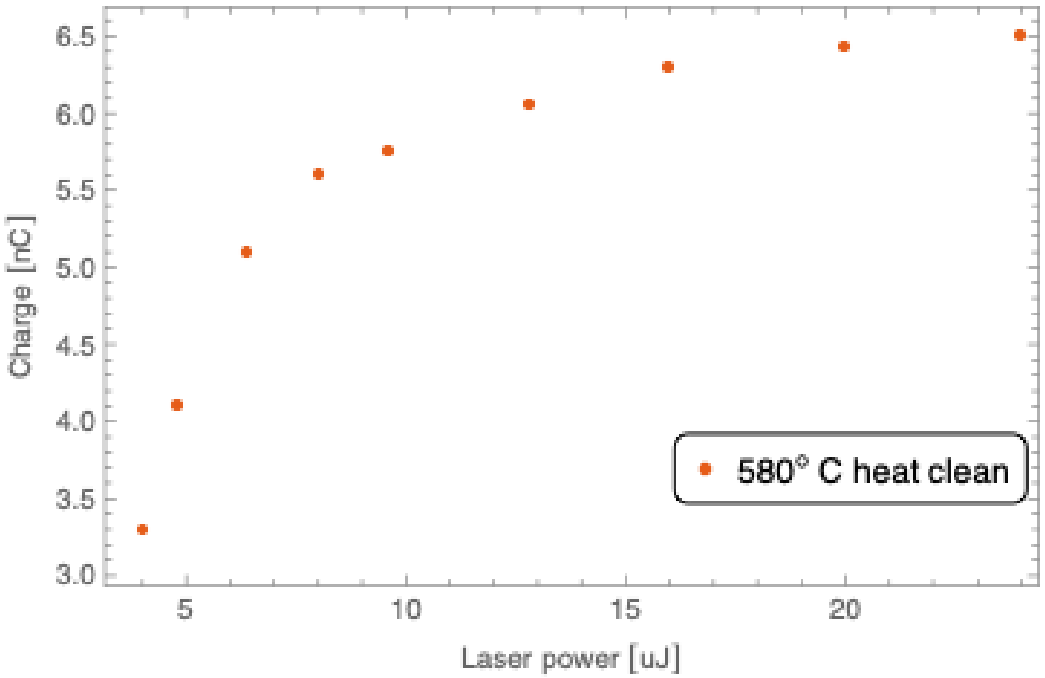
Test beam line



- About 5 meters long, with a 16-degree bend
- ICT and Faraday cup to measure bunch charge
- Anode is biased to +3 kV during lifetime test
- Gun and beamline vacuum ~1 e-11 Torr during lifetime tests with 30-60uA level current.
- No polarimeter or emittance measurement on the beam line

Observed surface charge limit (SCL)

- Acid cleaned cathode to load lock
- Heat cleaned cathode to 580 degree C for an hour
- Activated with ~1% QE at 780 nm and inserted to the gun



- Clear surface charge limiting effect observed
- Laser spot size 8mm diameter
- **Charge starts to saturate at 5.5 nC**
- Increasing voltage to 320 kV did not help.
- Increasing spot size to 12 mm did not help
- Possible diffusion of the dopant due to high heat clean temperature (SIMS measurement confirmed)
- Retry with low temperature heat cleaning @ 450 C

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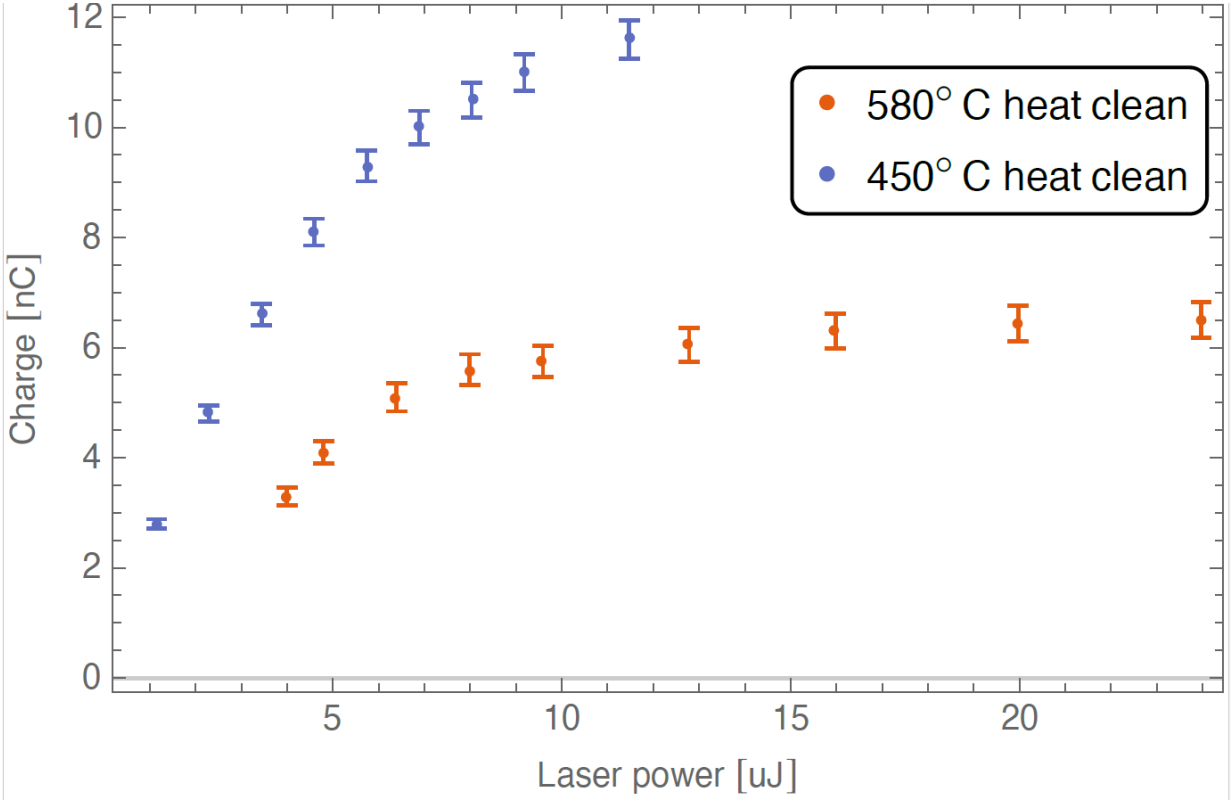
Suppressing SCL



- **<u>Lower temperature heat cleaning works!</u>**
- Maximum extracted charge of 11.6 nC, with linear range up to 9 nC
- Current density of 14.5 A/cm^2 (high intensity).

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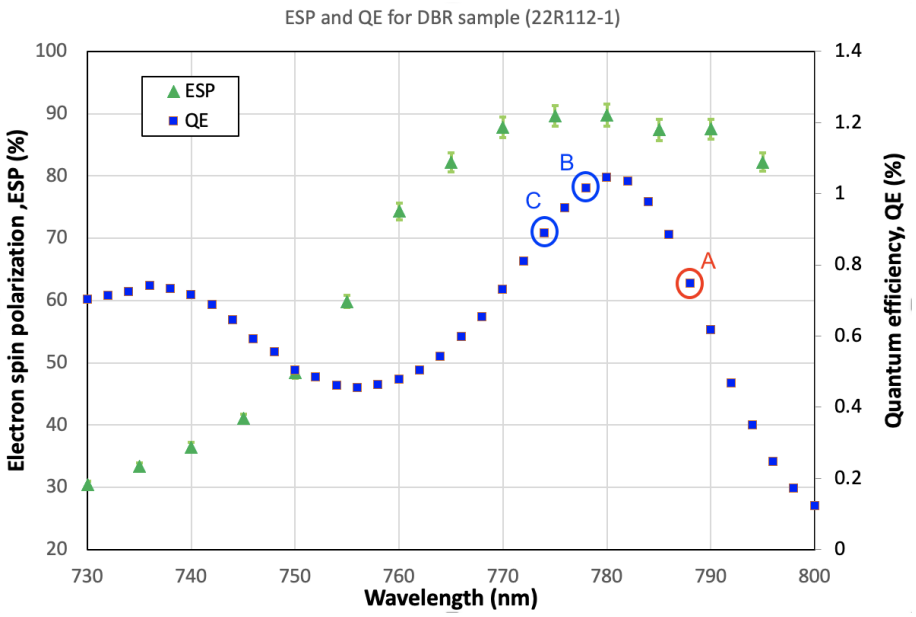
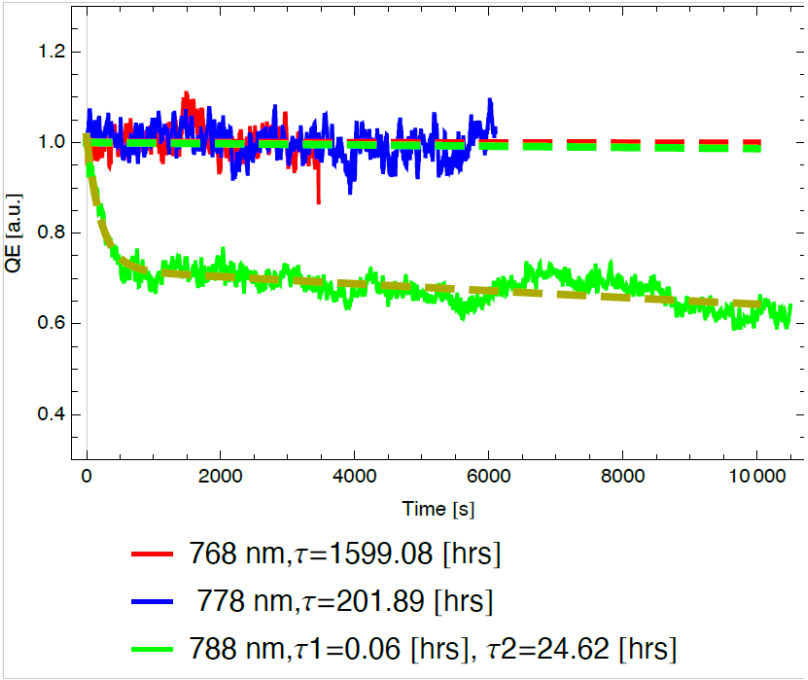
Extracted charge vs laser spot size

Laser size [mm]	Area increase [%]	Charge limit [nC]	Charge increase [%]
8	-	8.8	-
10	56	9.8	11
12	125	11.1	26

- Same location on the cathode, increased laser spot size to extract higher bunch charge
- Extracted charge did not scale linearly with the increase in laser area, as predicted from the previous 1D models
- Hypothesis: **Transverse plane recombination on the cathode surface possibly plays a role in trapped charge recombination**

Lifetime tests





- Average current of about 30 uA.
- 1.6 ns bunch length, 7.5 nC bunch charge, 8 mm laser spot
- Biased anode to +3k
- **Lifetime has wavelength dependency**
- Lifetime on the “right” side of the QE peak is substantially lower.
- **From this gun, EIC cathode lifetime requirements are met with enough headroom**

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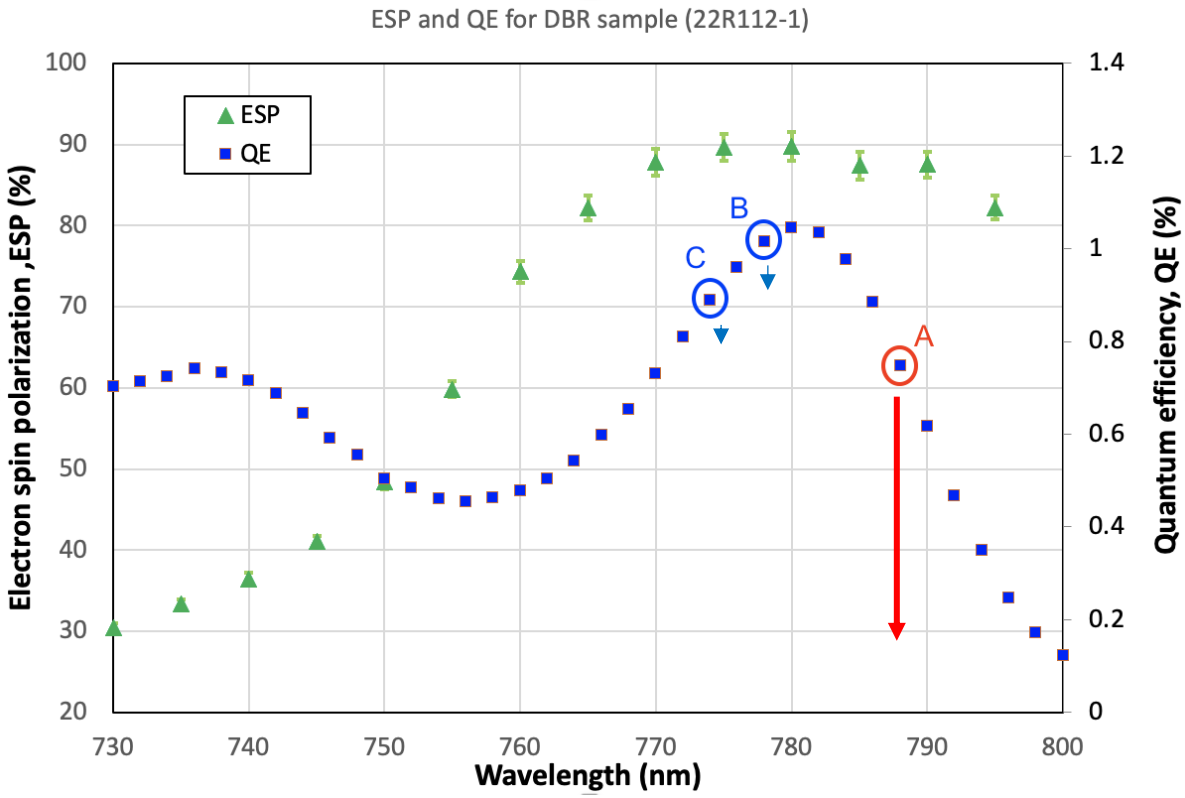
Lifetime observation from DBR SL cathode

- For working point A. The QE **drops 40% in 2 hours** with 30 uA average current.
- For working point B. The QE drops **~ 3% in 1 hours** with 30 uA average current.
- For working point C. The QE is **no decay in 1 hours** with 30 uA average current.
- **The lifetime is wavelength dependent.**



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Future work

- Treat Surface charge limit as a 3D problem
- Instead of uniform doping on the surface, use gradient doping on the surface of the cathode
- Doping concentration is constant under the laser spot, then increases radially outward.
- Test these cathodes in a HV test stand to validate the model

Summary

- DBR photocathodes have been fabricated at ODU in collaboration with BNL and Jlab
- Photocathodes were tested in a HVDC gun at 300 kV at BNL
- A maximum of 11.6 nC bunch charge (1.6 ns bunch length) was extracted, with a linear range up to 9 nC
- Lower temperature (450 degrees C) was found to be crucial towards overcoming Surface charge limit
- Extracted charge did not scale linearly with increasing laser spot size, indicating SCL needs further study
- Lifetime in the gun shows clear dependence on operating wavelength

Wang, E., Rahman, O., Biswas, J., Skaritka, J., Inacker, P., Liu, W., Napoli, R. and Paniccia, M., 2024. High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode. *Applied Physics Letters*, *124*(25).

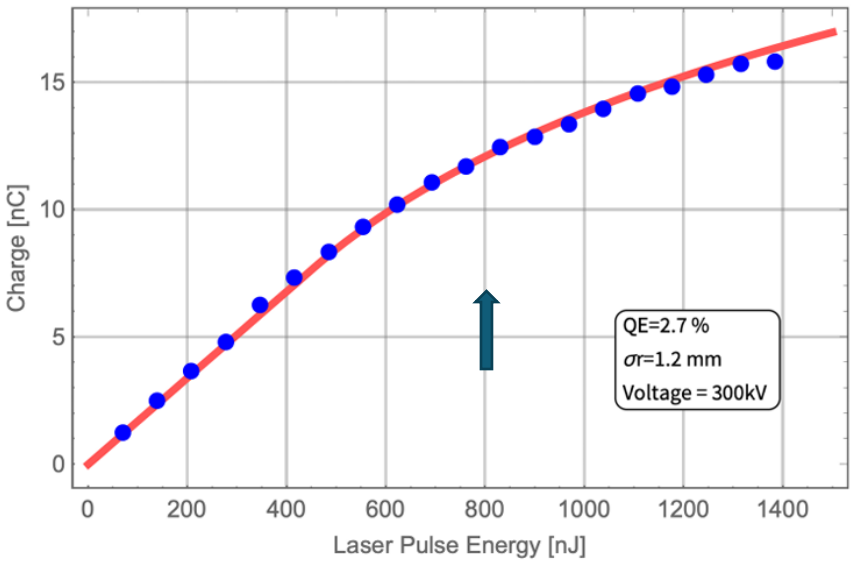
Acknowledgment

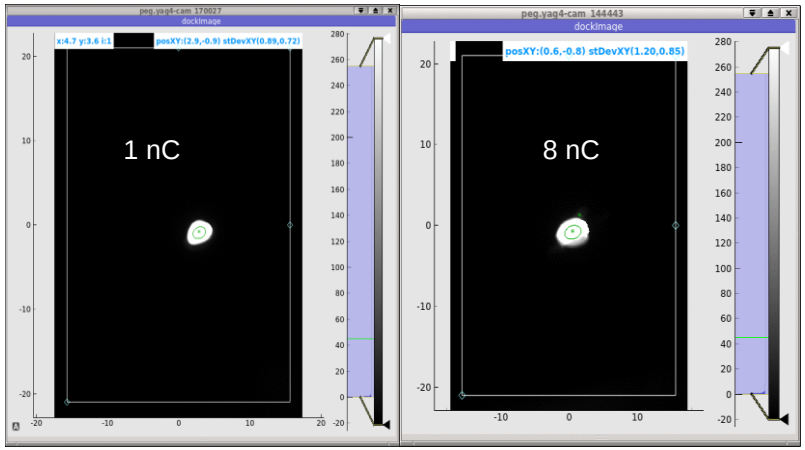
- **BNL**: Erdong Wang, John Skaritka, Robert Lambiase, Matthew Paniccia, Chris Degen, Jyoti Biswas, Patrick Inacker, Scott Seberg, Kevin Smith, Charles Hetzel, Rob Michnoff, Ron Napoli
- **JLab**: Matthew Poelker, Carlos Hernandez-Garcia, the late Donald “Bubba” Bullard
- **ODU** – Sylvain Marsillac and Adam Masters
- **Chong Qing University**: Wei Liu

Thank you for your attention!

Backup slides

Space Charge limit of the gun





Beam image before the dump

- Space Charge Limit start from 12 nC
- EIC requirement is 7 nC
- We can increase active area to increase SCL (we used a 6 mm spot)

- No obvious beam loss
- Beam shape looks good right before the Faraday Cup

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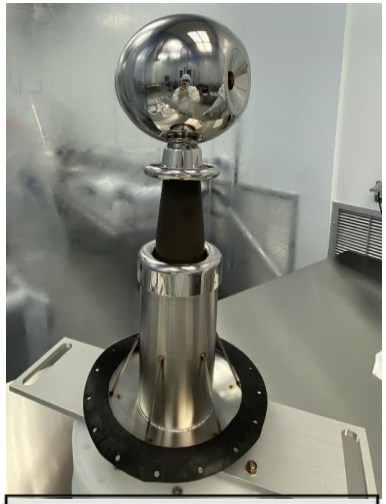
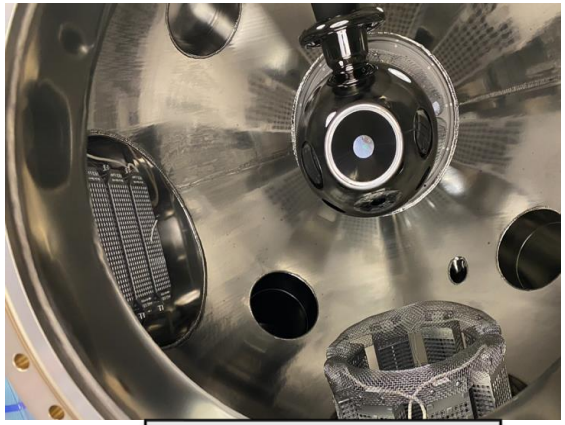
HV electrode treatment and installation

Polish at JLab

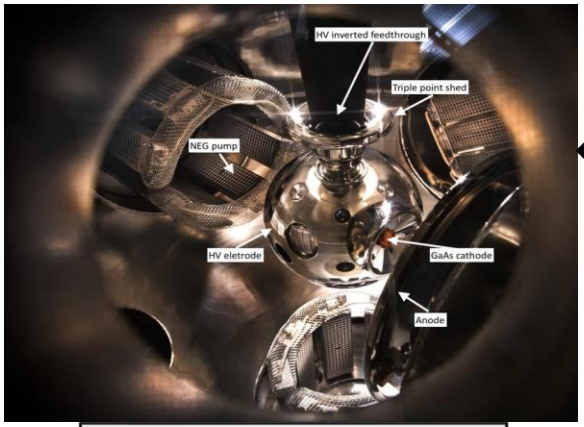


HPR at BNL SRF

Installation at SBU



Alignment



Final assembly

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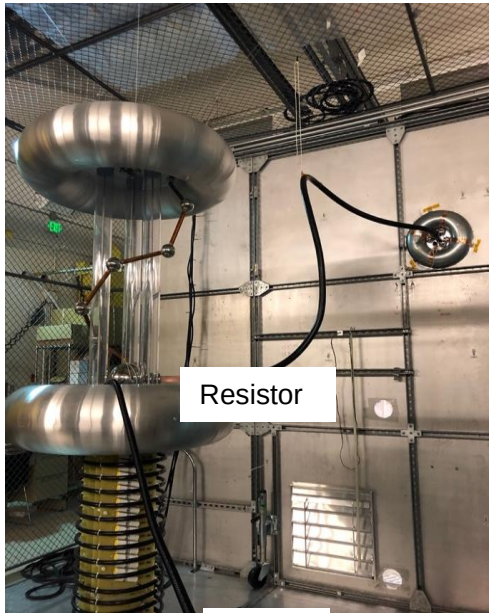
Power supply and HV cable

- 400 kV Power supply is SF6 free set up. (Environment friendly!)
- PS is 5 meter away from the gun within a grounded cage.
- Resistors for gun conditioning and no resistor for beam operation.
- Custom designed Semiconductor jacket to slow down the discharge storage energy(50pF/ft, 46 Joules) into the DC gap if discharge happened



HVPS

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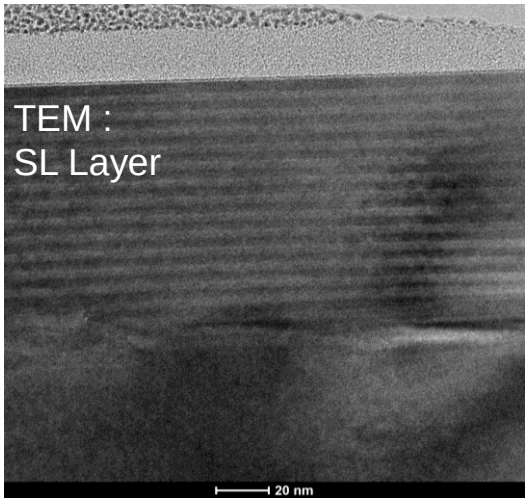
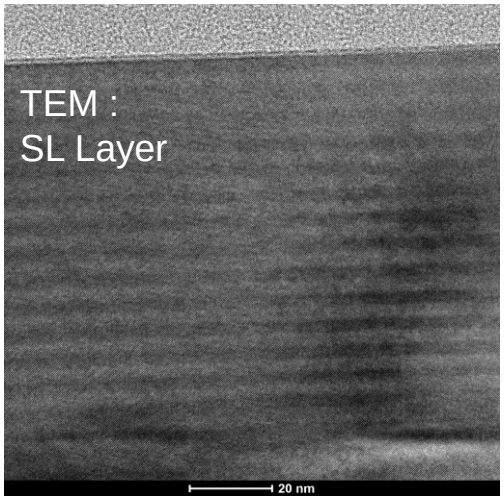
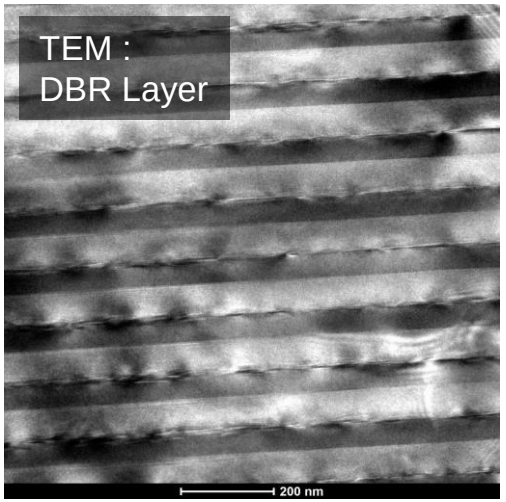
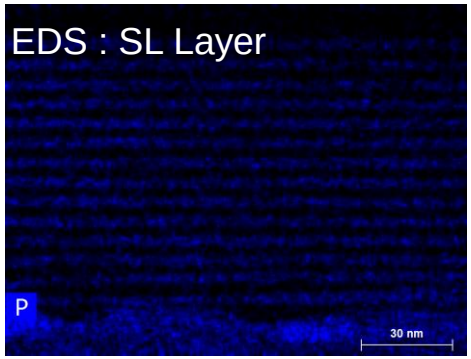
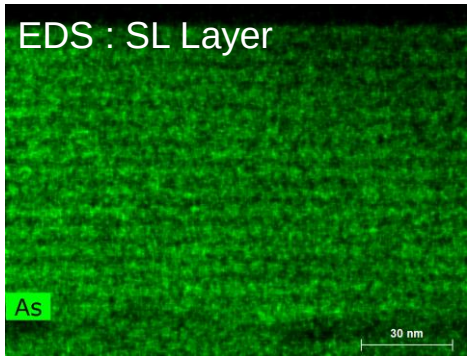
DBR photocathode characterization











- Misfit dislocations are observed, which are common on SL-GaAs and DBR structure
- P content in $GaAs$ vs $GaAs_{1-x}P_x$ well separated
- Peak QE of 2.35% at 776 nm with ESP of 92%

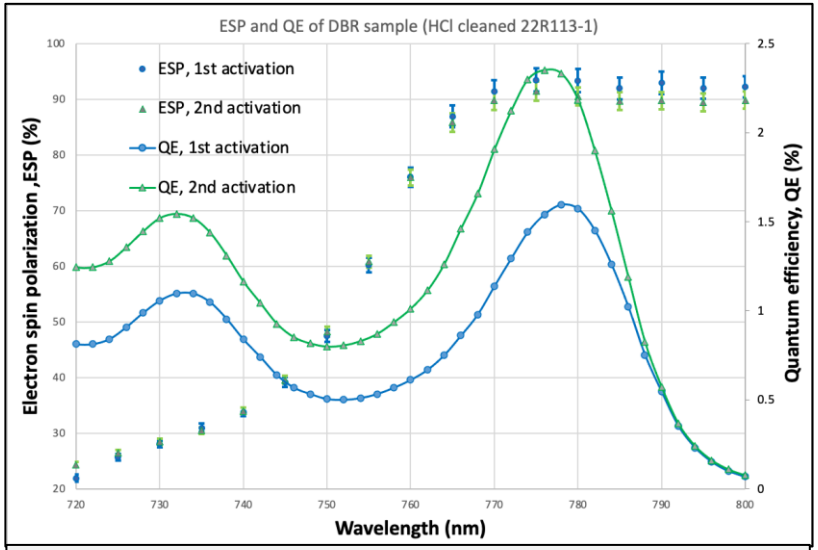


Image Courtesy: Wei Liu

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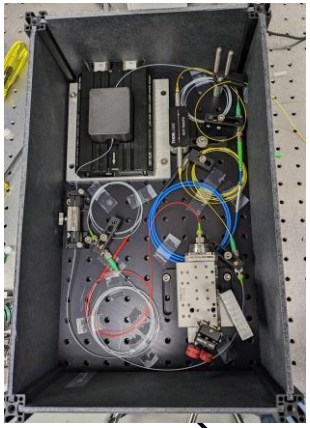
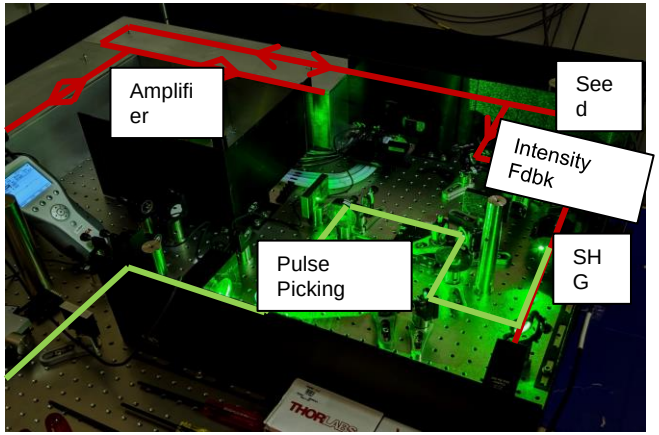
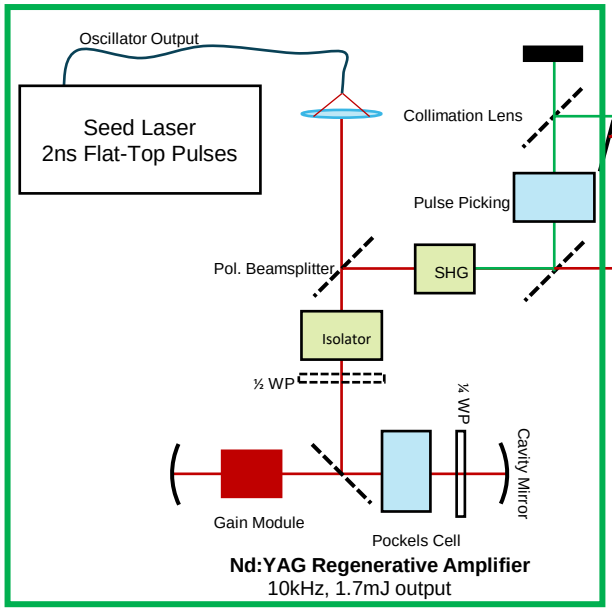
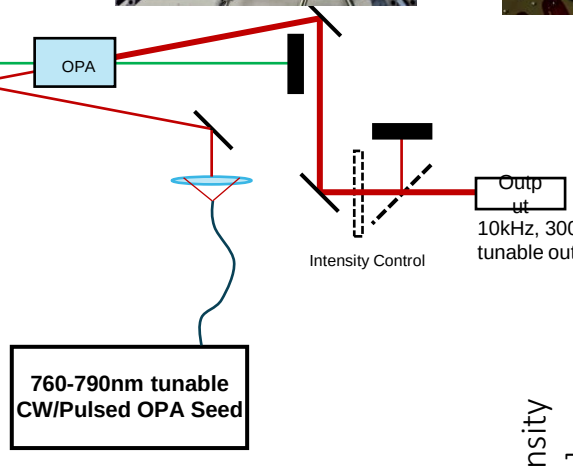
Tunable, Solid State, Nd:YAG OPA Laser Overview





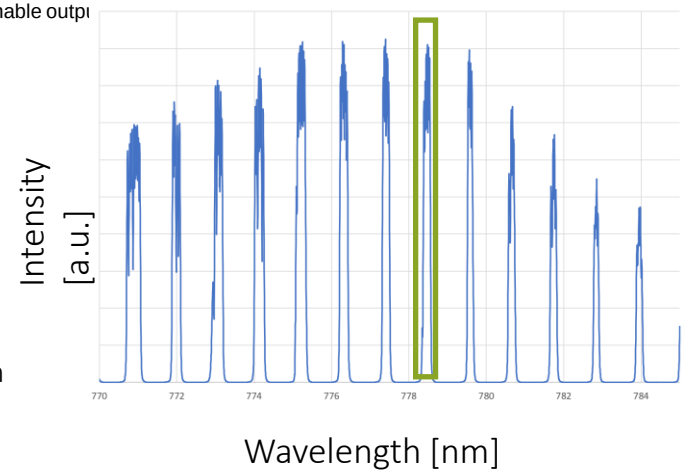
OPA Pump Laser





Outp
ut
10kHz, 300µJ,
tunable outpı

- Rep. Rate: 10 kHz
- Pulse Energy: 340 µJ
- Tunability: 760nm – 790 nm
- Spectral Bandwidth: ~50 pm



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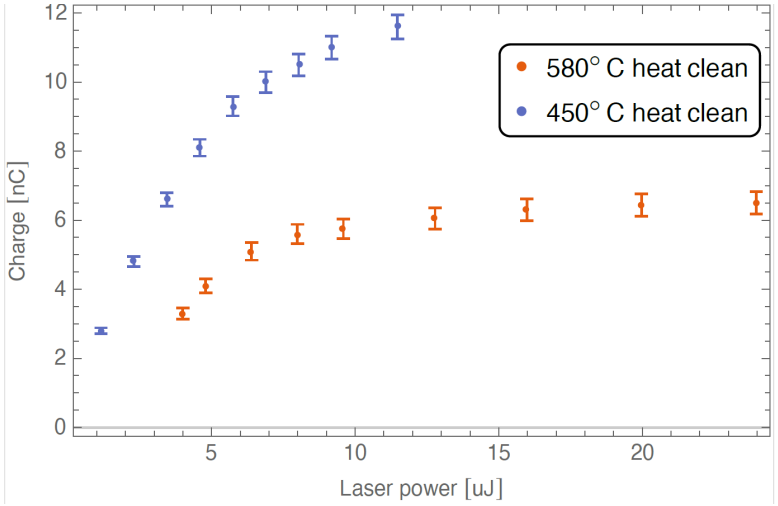
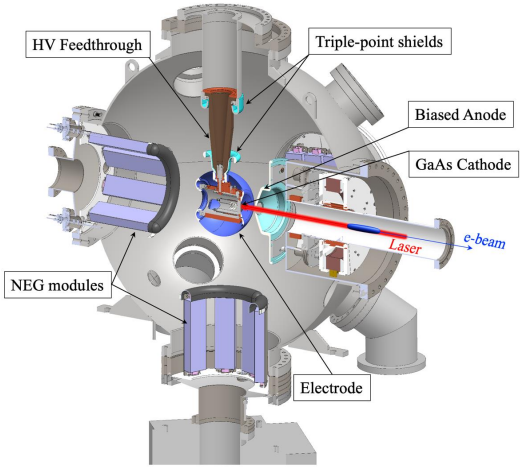
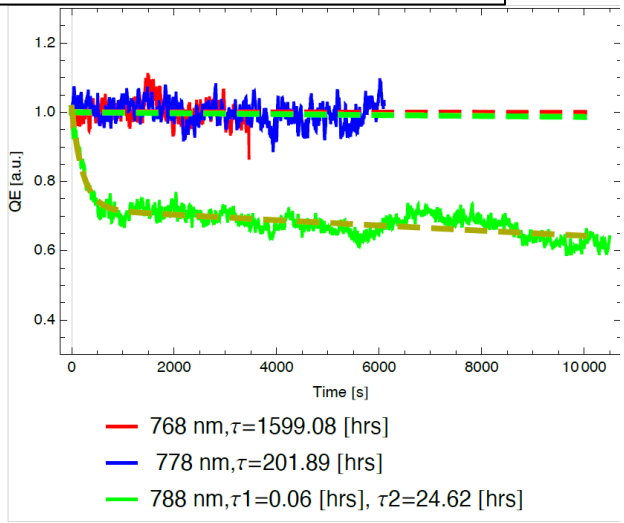
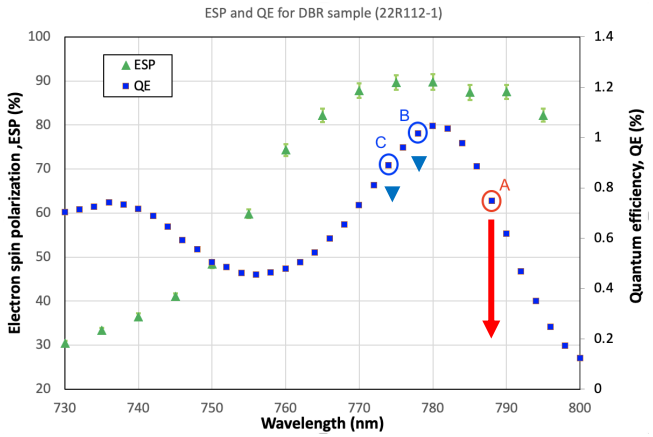
Summary

- DBR SSL GaAs tested in 300 kV DC gun at BNL
- Maximum of 11.6 nC bunch charge, with 9 nC as the beginning of surface charge limit (SCL), was extracted. Exceeds EIC requirement.
- Lower temperature, 450 degrees C, heat cleaning helped with increasing SCL.
- For DBR SSL GaAs, lifetime is wavelength dependent.
- Increasing laser spot size did not linearly increase SCL. Need to consider SCL a 3D problem instead of 1D.









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