High voltage DC gun using DBR superlattice GaAs photocathode for EIC polarized electron source

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Electron Ion Collider, BNL

SPIN 2023

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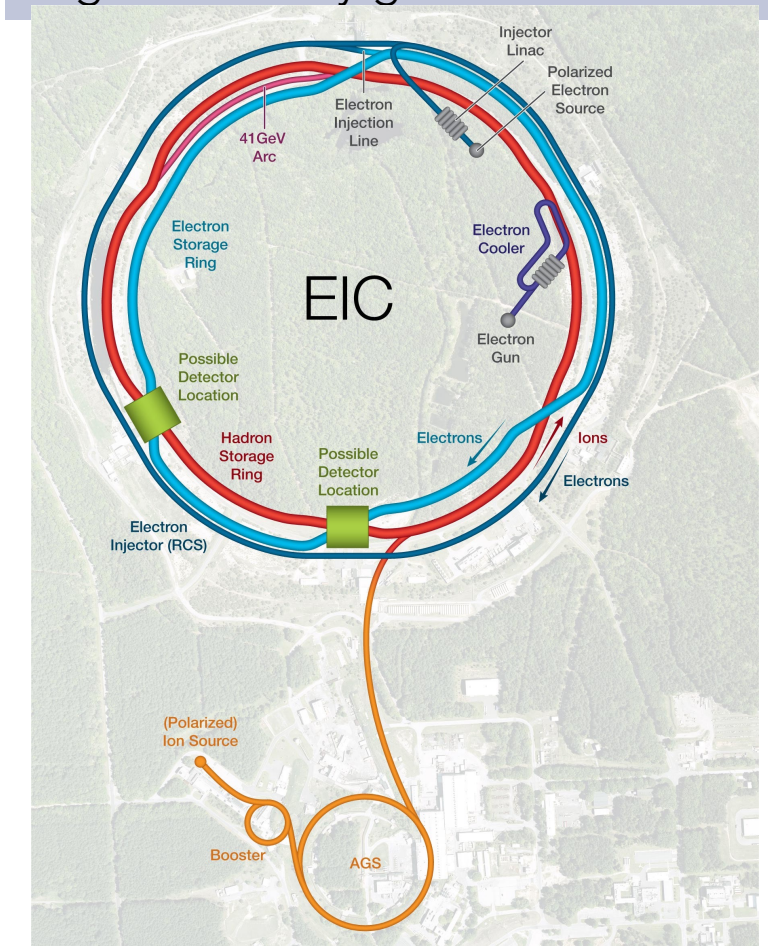
EIC needs high intensity high polarized electron source

E_{cm} = 20 GeV -141 GeV
High luminosity goal: $L = 10^{34} cm^{-2} s^{-1}$



Electron Ion Collider (EIC)

- Hadron storage Ring is existing, and electron storage ring and injector are new.
- We need polarized electron bunches with **spin up** & **spin down**, stored simultaneously
- Sokolov-Ternov self-polarization too slow, produces only polarization anti-parallel to the main dipole field.
- Polarized electron bunches are produced and accelerated in the injector chain and injected at collision energy in the electron storage ring
- Sokolov-Ternov works against spin-down polarization, spin diffusion reduces average polarization. All bunches be exchanged frequently (every 6 minutes on average) to achieve **70% average polarization**
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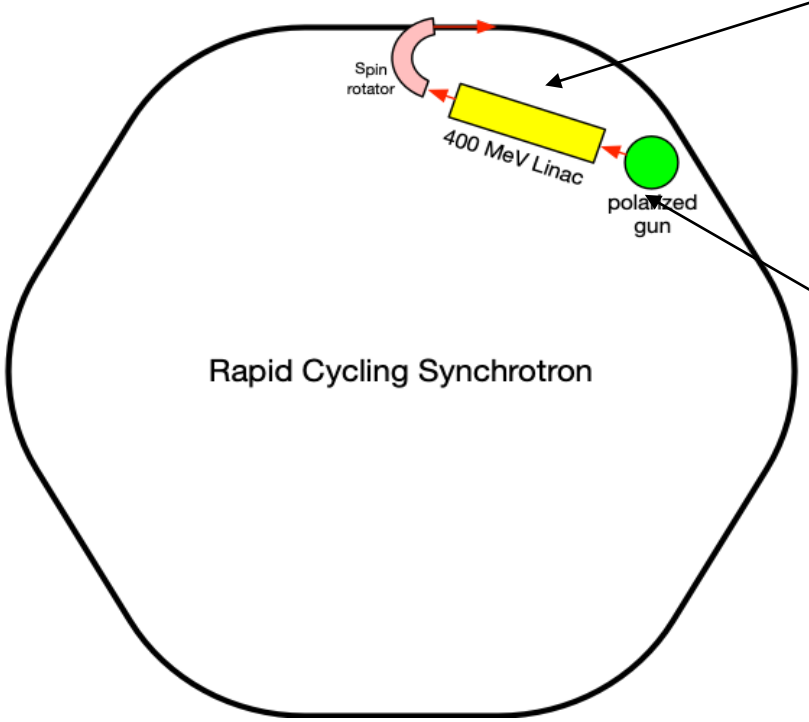
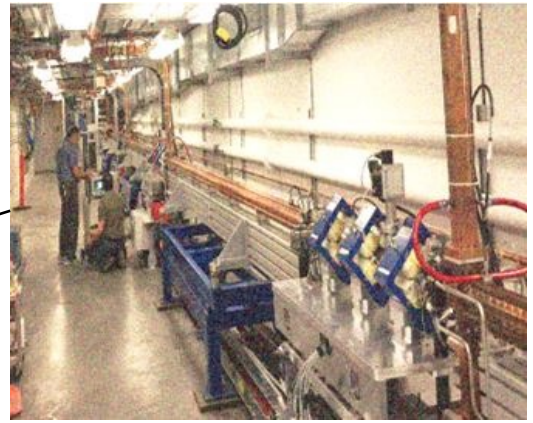
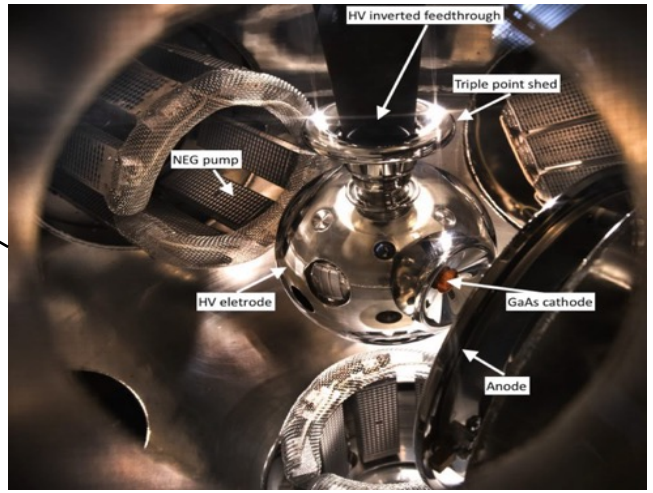
EIC Electron Pre-Injector







- EIC injector: **400 MeV Linac** + **Rapid Cycling Synchrotron (RCS).**
  - 300 kV polarized HVDC gun generates 7nC x 4 polarized electron beam every second and booster energy up to 400 MeV
  - Four bunch merge in the RCS and inject a 28 nC bunch into EIC
  - Rotate the electron spin direction at end of Linac from longitudinal to vertical

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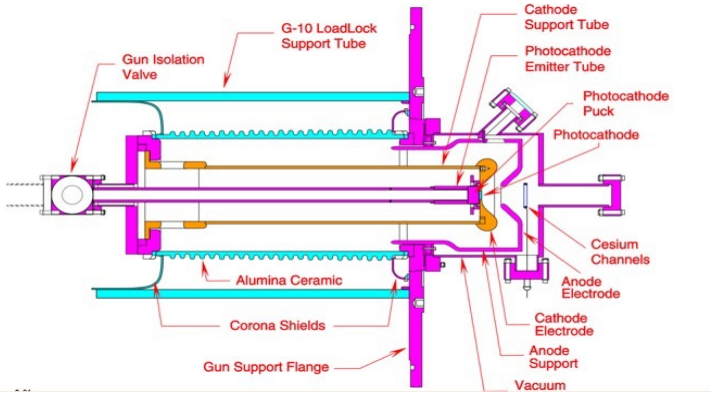
Overview of polarized guns in the world

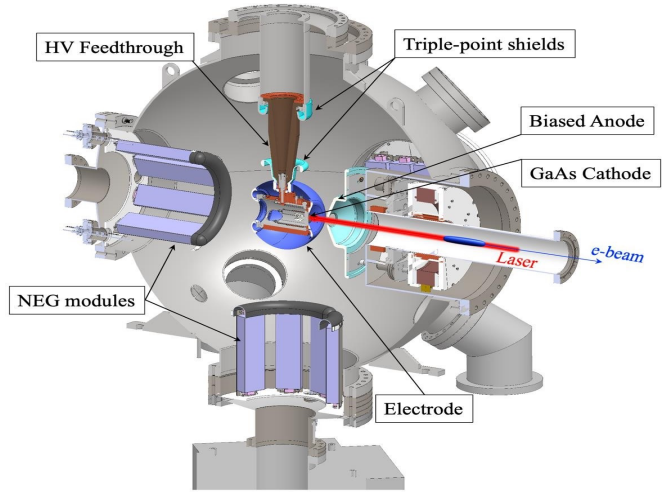
Laboratory	Voltage	Bunch charge	I_pk	I_avg
JLab	100, 200kV	2 or 2.7pC	67~53m A	Up to 4mA
SLC	120kV	8-16 nC	3 A	2uA
MAMI	100kV	0.02 pC		50uA
Bonn- ELSA	50kV	100 nC	100mA	5uA
MIT- BATES	60kV	250 nC	10mA	20 or 120uA
Nagoya	200kV	1.25 nC	2A	NA
NIKHEF	100kV	2us	NA	0.04uA
EIC	**300kV**	**7-16 nC**	**4.8 A**	20 uA, up to 67 uA

In operation
Retired
EIC gun

SLC PES 120 kV gun



BNL EIC inverted 300 KV



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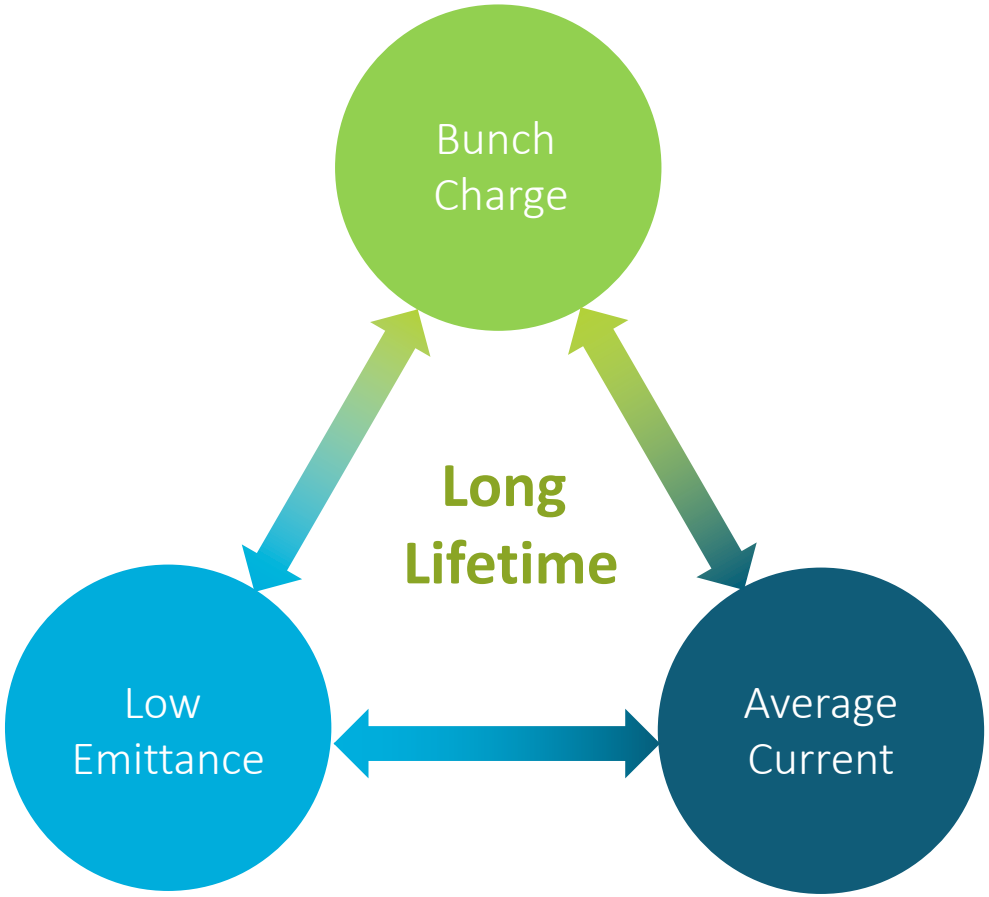
Polarized gun design considerations



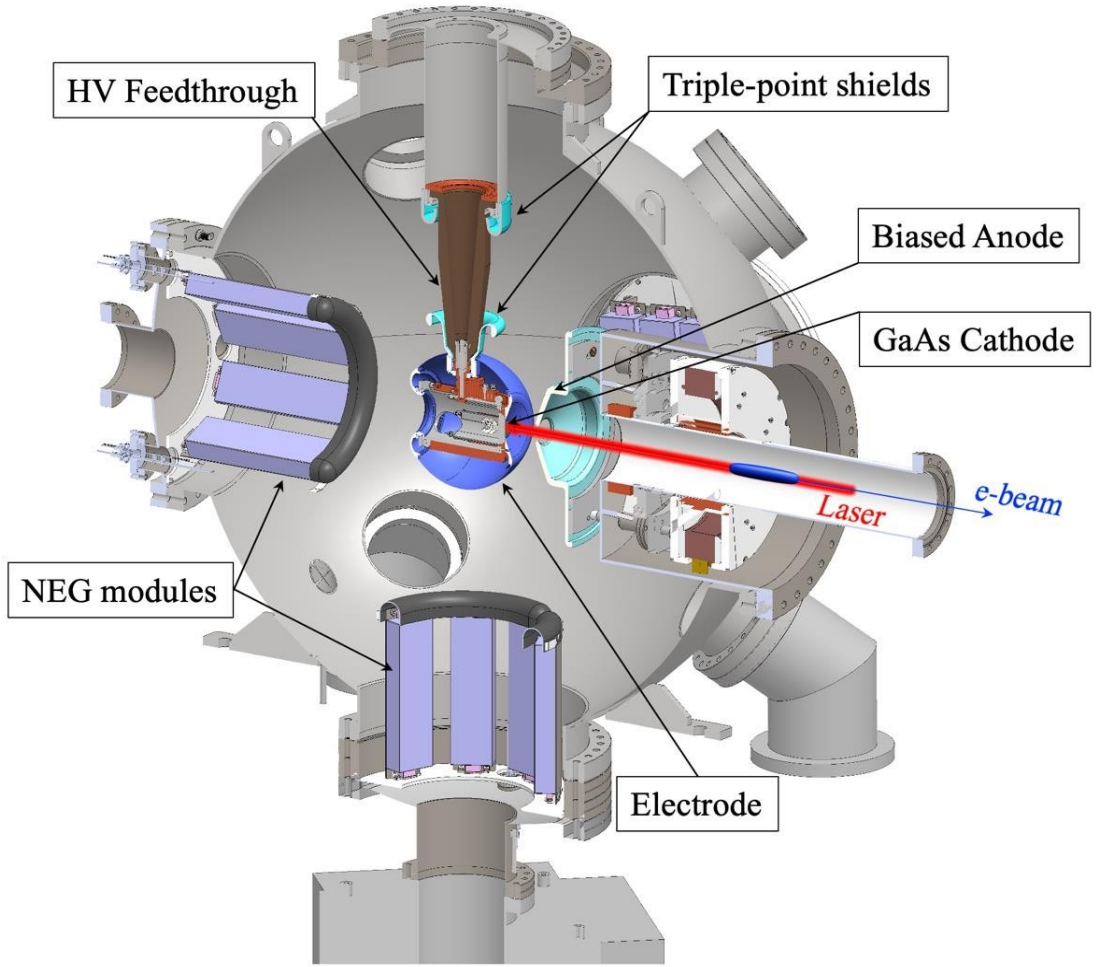
Depends on application. For example –

- **EIC – high bunch charge (7 nC)**
- LHeC – 0.5 nC high bunch charge, 20 mA high average current
- CEBAF – low bunch charge, 100's uA high average current

Good/long lifetime is always wanted !

- Good vacuum
- Field emission free
- Cool the cathode if laser power is high

EIC polarized gun overview



EIC polarized gun needs:

- High charge
- Long lifetime
- High polarization
- High peak current
- Maintenance free

No existing gun can meet all EIC needs.

EIC gun includes new features:

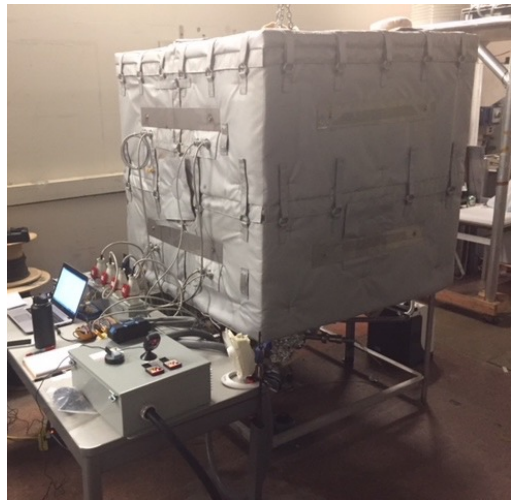
- Active cathode cooling
- Large cathode
- High gradient
- Semiconductor jacket HV cable
- 3D moveable electrically insulated anode.

Achieve extremely good Vacuum

- **Lowering the out-gassing speed**, and **increasing the pumping speed** can get a good vacuum.
  - Choose thin wall
  - 10 hours high-temperature fire
  - A week bake
  - Many non-evaporate getter

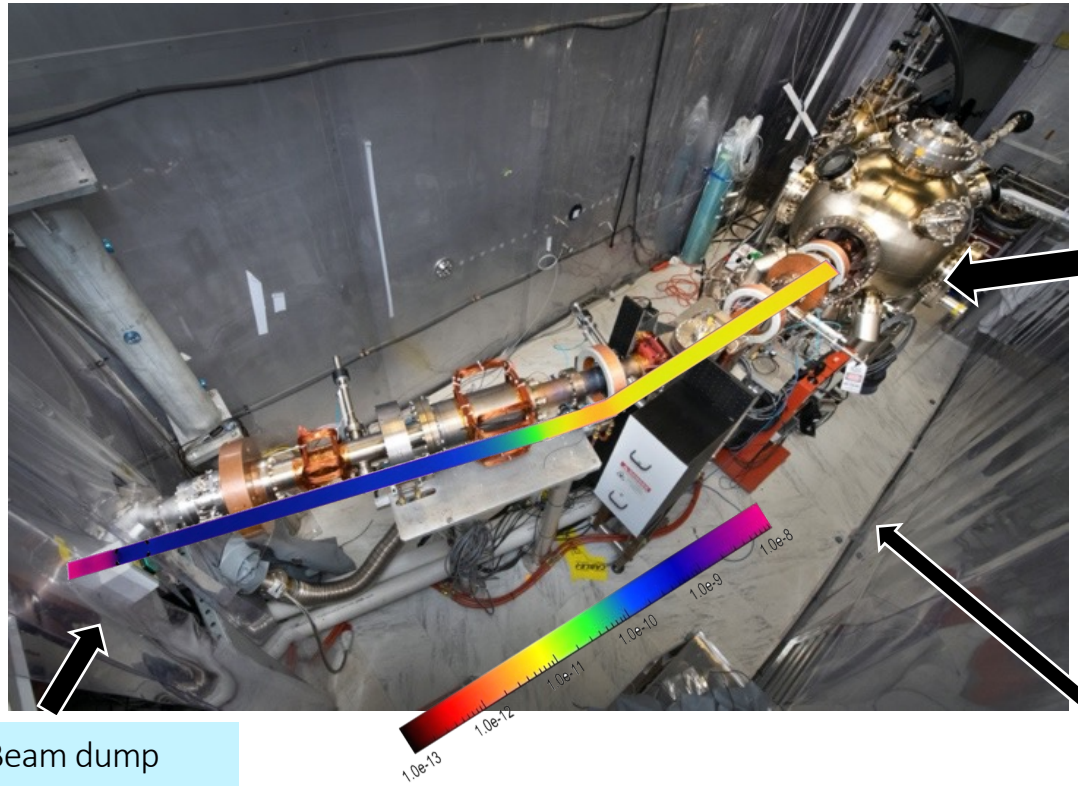
Lowering the out-gassing

increasing the pumping speed



30000 L/s
Non-evaporate getter (gas absorber)

Beam-Line Vacuum in Experiment



Gun Vacuum
3BG gauge

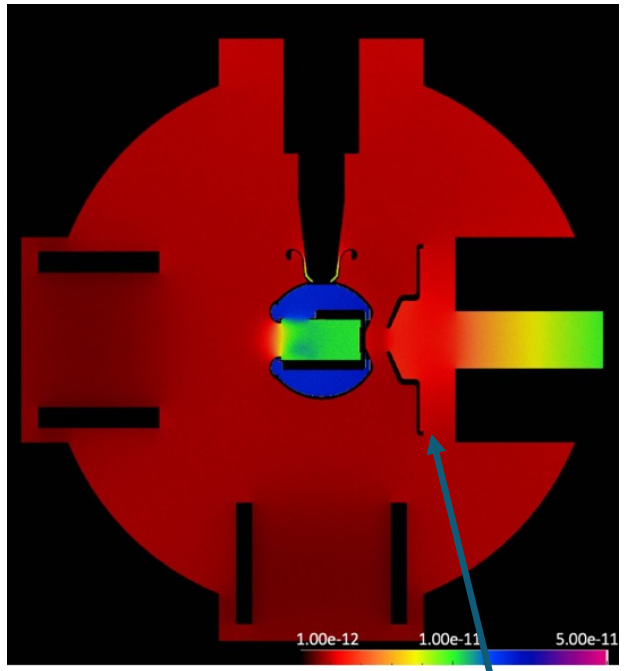
3BG gauge	Gun
Baseline	5-8 e-12
3uA	Low (c.c)
67.5 uA	2e-11,Low (c.c)

Beam dump

ULVAC gauge	Beam dump
Baseline	3-4 e-12
3 uA	3e-10
67.5 uA	1e-9

ULVAC gauge	Beam Line
Baseline	3-4 e-12
3 uA	5e-12
67.5 uA	1.5-3 e-11

Beamline



We added gap in between the anode and the gun chamber to get extra conductivity

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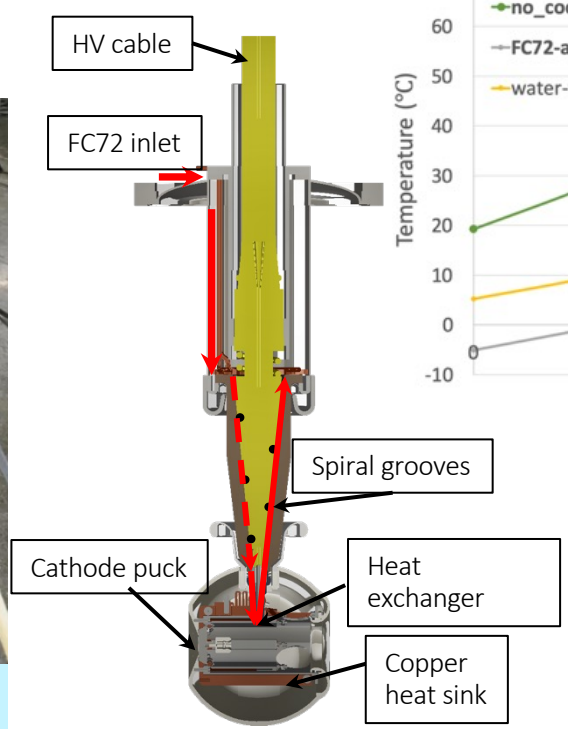
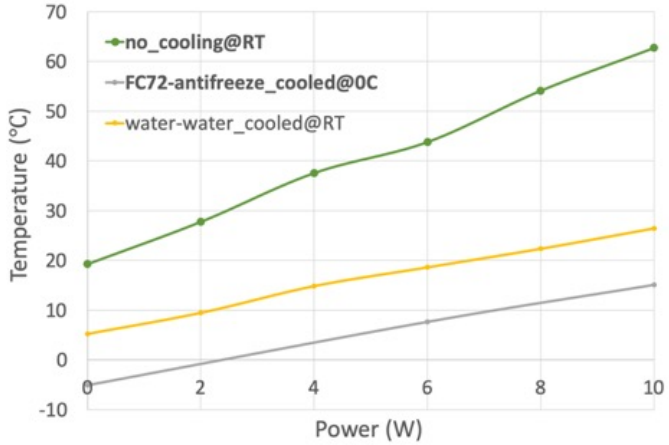
Active Cooling Cathode using HV feedthrough

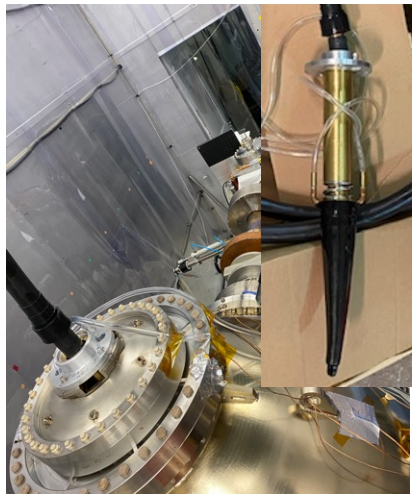
We developed the active cooling HV feedthrough which can absorb the laser power **up to 10 W**.

Tested up to 410 kV with flow

Customer designed HV plug with cooling channel







- Tested in the gun with FC 72. Operate @300-350 kV for more than 500 hrs . No failure.
- Maintain every 6 months.

It was designed for high current operation. Not necessary for EIC polarized source.

Beneficial towards any high current polarized/unpolarized gun.

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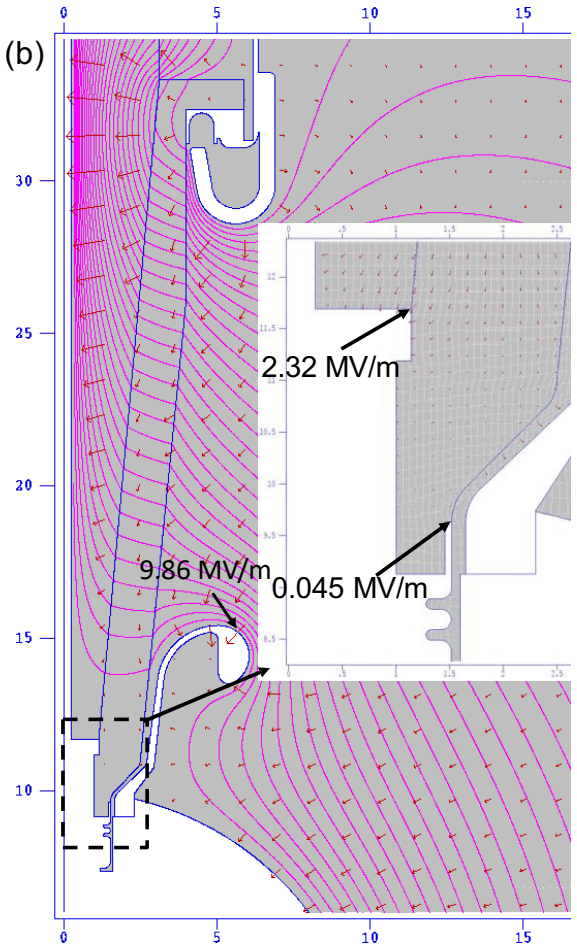
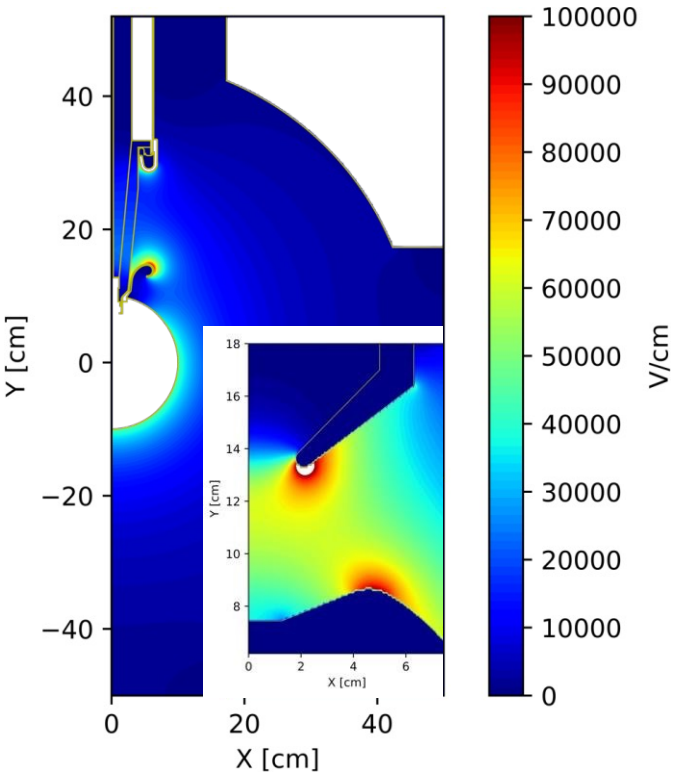
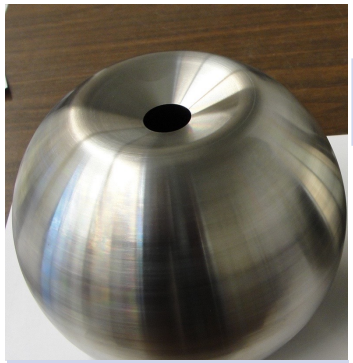
Gun HV design

- Maximum gradient is 9.8 MV/m at 350 kV.
- Triple-point shields (TPS) are applied both on HV and ground side to prevent HV breakdown
- Tweak TPS geometry to minimize wanted beam deflection





HV Electrode Polish and Clean



Original electrode

crushed corncob

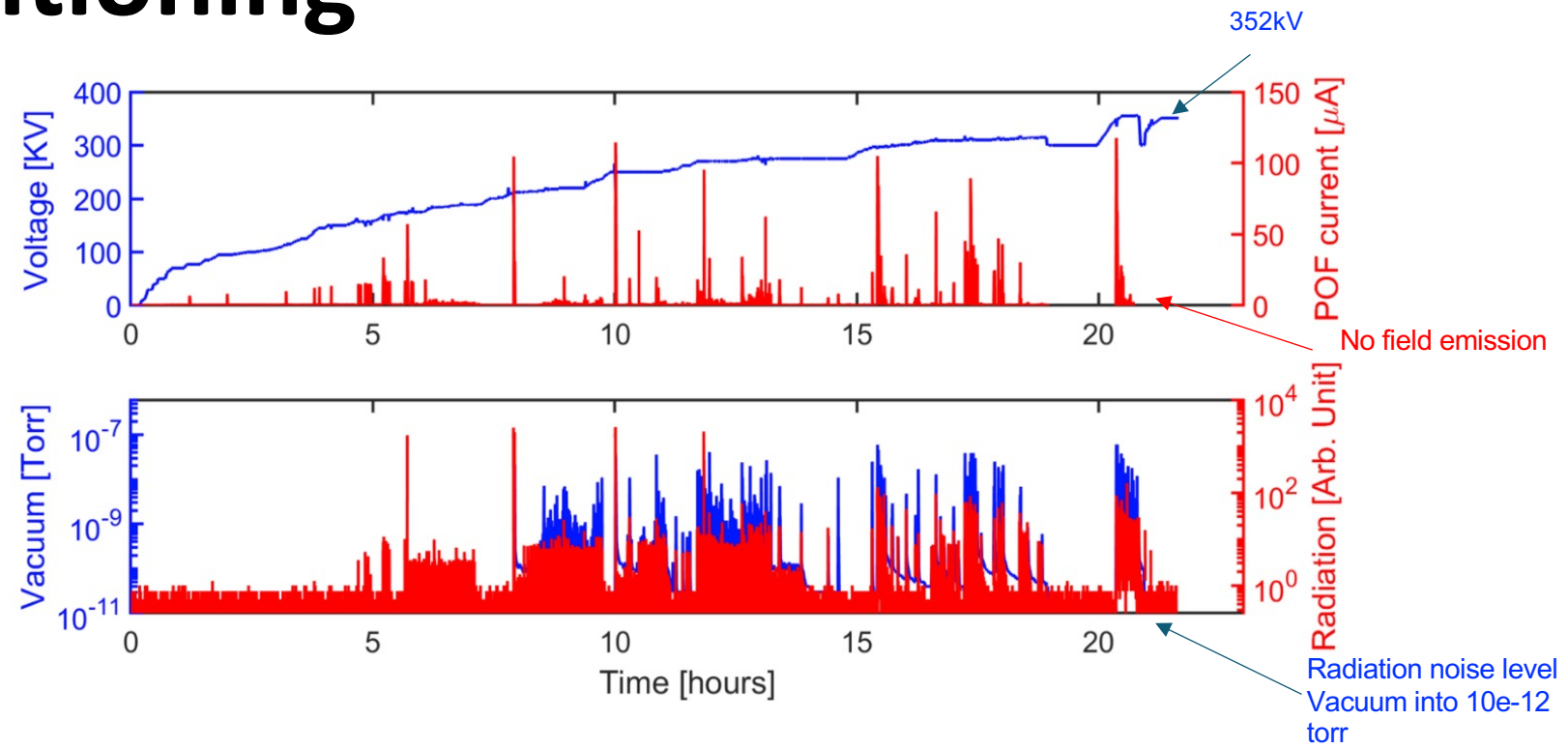
Mirror Polish

High pressure rinsing

Particulate free

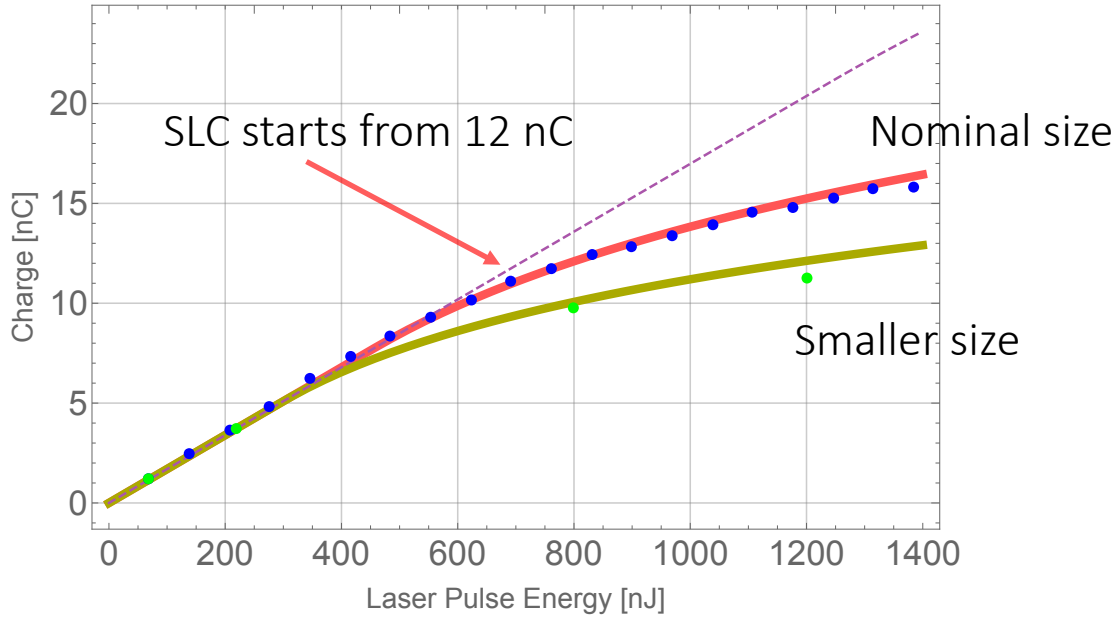
- Rough surfaces or particulates will easily generate unwanted electrons in the high voltage (field emission)
- **Mirror surface polishing** and **particles free cleaning** are the key of gun fabrication towards high voltage and high gradient.

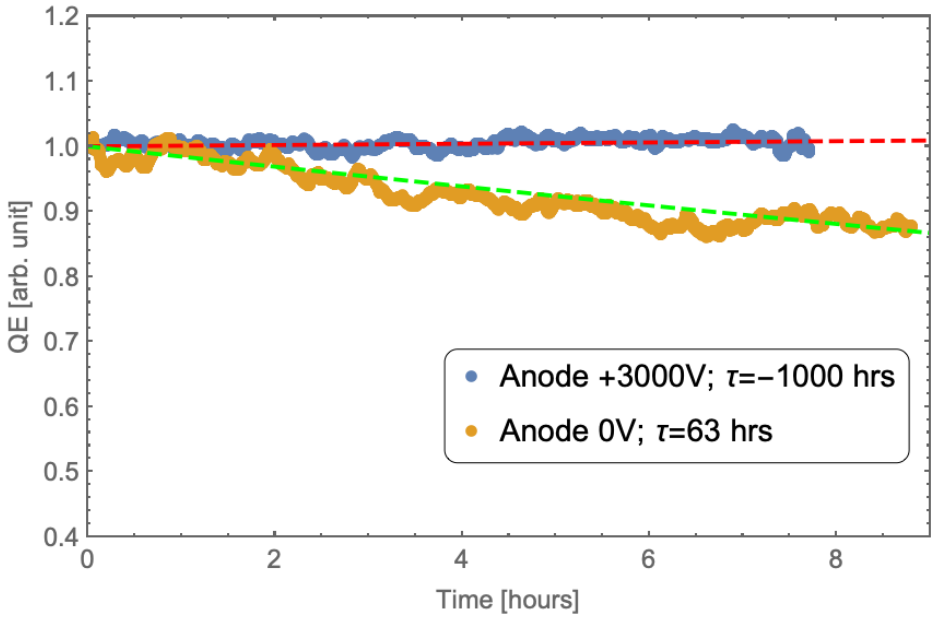
HV Conditioning



- Gun conditioned in Dec 2020 (vacuum conditioning, total takes 23 hrs, Cooling is on):
  - Achieved gun design value 352 kV without field emission (without activated GaAs)
  - Achieved gun design value 325 kV without field emission (with activated GaAs)
- In 2023, we improved the puck clean procedure. The new puck with new SL-GaAs(ODU) sample can achieve 350 kV without any conditioning. We don't need extra conditioning to use new samples/puck.

Bunch Charge and Cathode Lifetime





- Bulk GaAs with 785 nm polarized laser; Gun operates at 300 kV. Run up to 67.5 uA.
- 7.5 nC bunch charge polarized beam, 5000 pulses/s ~37.5 uA;
  - **With anode bias, we didn't observe QE drop.**
  - **Without anode bias** 1/e lifetime is 63 hrs. Dominated by the outgassing from FC.

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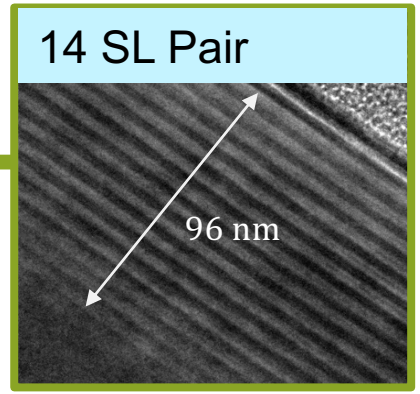
High Polarization Photocathode

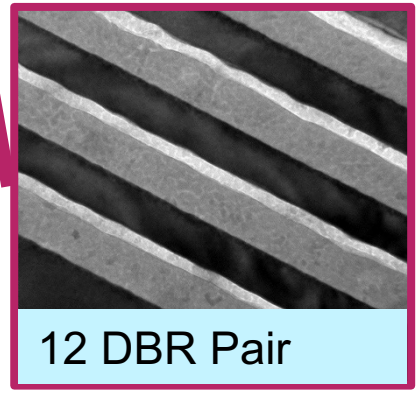
Distributed Bragg reflector (DBR) layer was added to the GaAs photocathode, resulting in a Fabry-Perot resonance in between the surface-vacuum interface and DBR layer that significantly enhances the QE. We are the first successfully used DBR cathode in the HVDC gun.

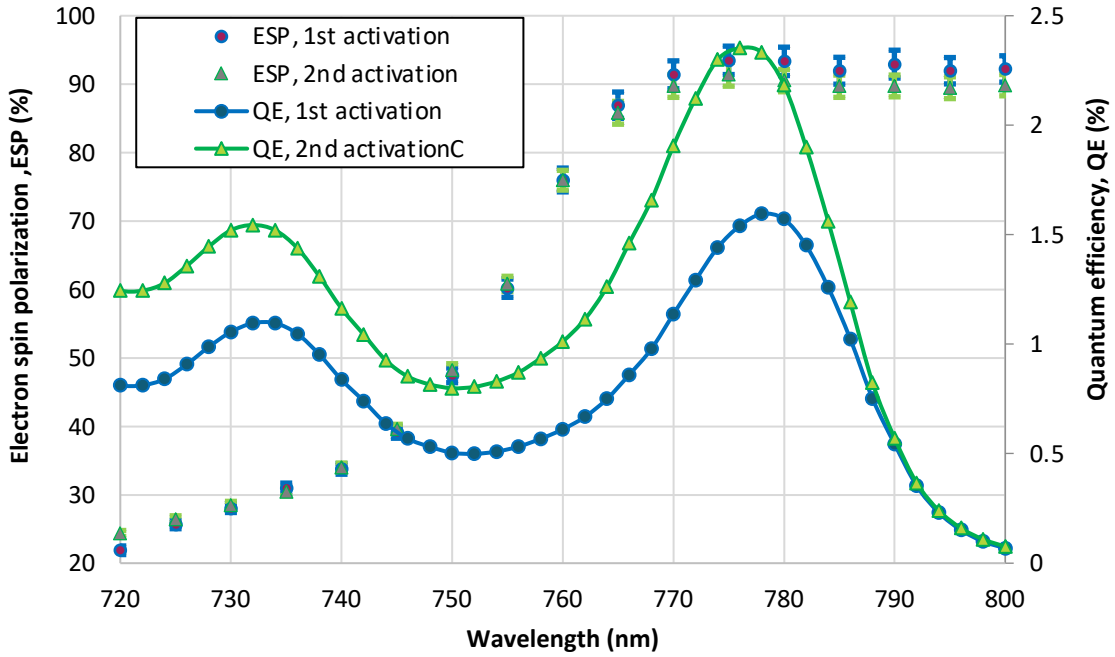
ODU/Jlab/BNL: **GaAs/GaAsP SL with AlAsP/GaAsP DBR**

- Cathode performance: **QE=2.35%, ESP=92%**

GaAs	5 nm	$p=5\times10^{19}$ cm^{-3}
GaAs/GaAsP SL	(3.8/2.8 nm) ×14	$p=5\cdot10^{17}$ cm^{-3}
$GaAsP_{0.35}$	750 nm	$p=5\times10^{18}$ cm^{-3}
$GaAsP_{0.35}$/ $AlAsP_{0.4}$ DBR	(54/64 nm) ×12	$p=5\times10^{18}$ cm^{-3}
$GaAsP_{0.35}$	2000 nm	$p=5\times10^{18}$ cm^{-3}
Graded $GaAsP_x$ ($x=0\sim0.35$)	5000 nm	$p=5\times10^{18}$ cm^{-3}
GaAs buffer	200 nm	$p=2\times10^{18}$ cm^{-3}
p-GaAs substrate ($p>10^{18}$ cm^{-3})		







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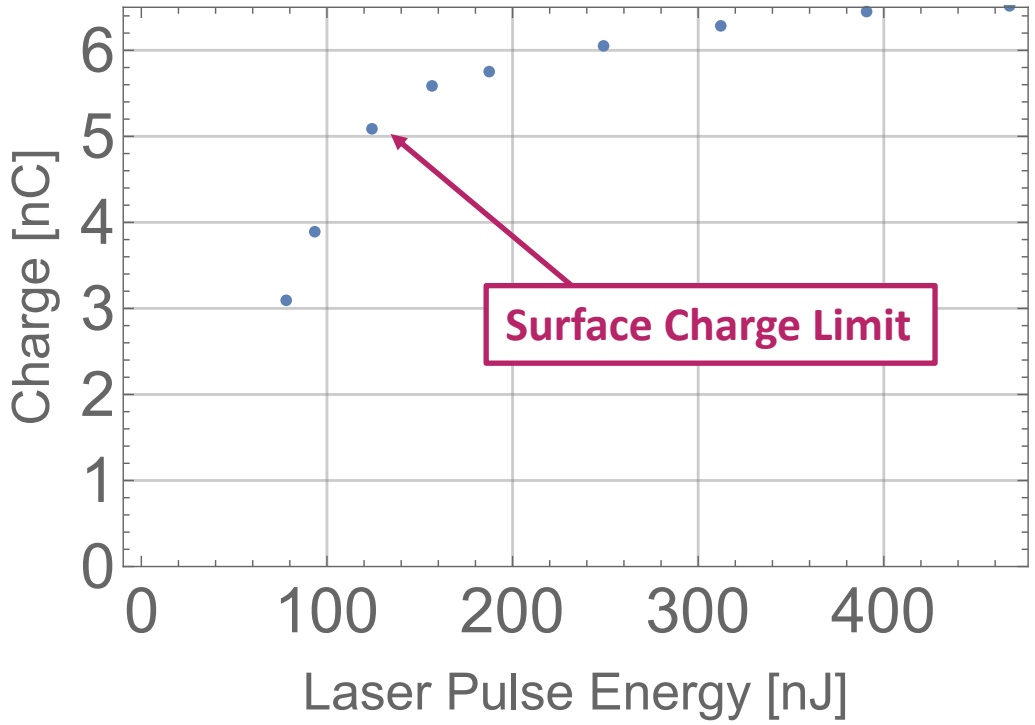
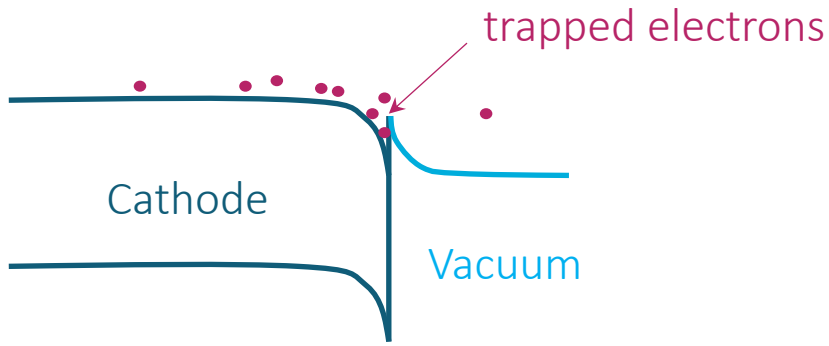
Observed Surface Charge Limit(SCL)

- Surface Charge Limit(SCL) was the main issue towards high bunch charge polarized beam.
- At Feb 2023, we extracted 6 nC maximum bunch charge, **limited by SCL** :





Surface charge limit can be suppressing by:

- Increasing surface doping
- Laser size
- Gun voltage

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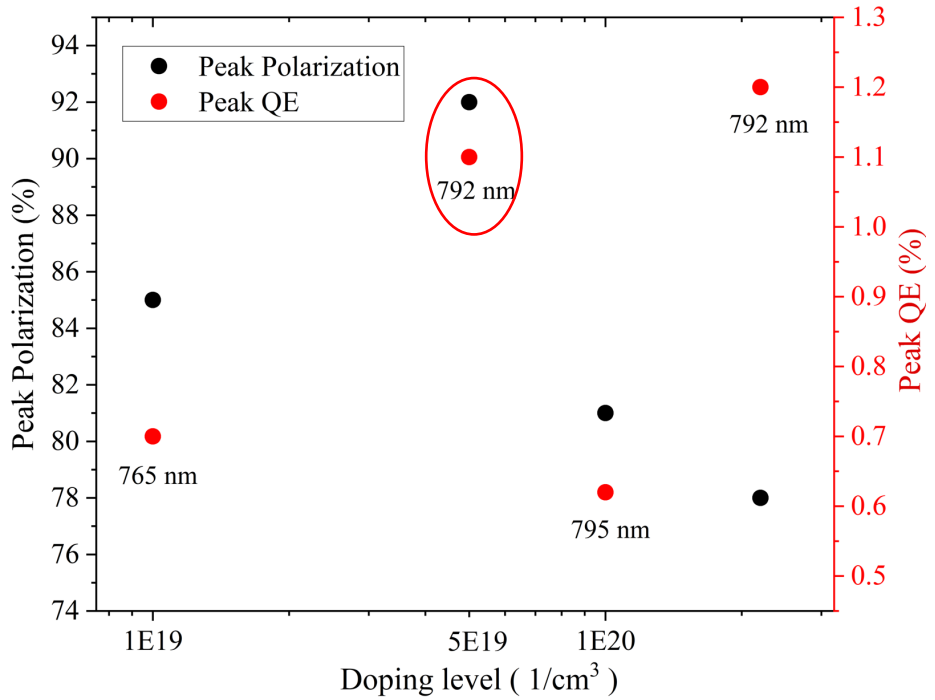
Suppression of Surface Charge Limit

- Various surface doping levels of the cathodes.
- Secondary Ion Mass Spectrometry (SIMS) was used to test doping level changes at different temperatures. We found that **450°C is the optimal temperature**.
- Used a new sample with minimal surface defects and a surface doping level of **5e19 atom/c.c** was obtained from ODU. The resonance QE of 1.2% and spin peak of 92% were measured at 790 nm at BNL.
- The cathode puck underwent a high-pressure rinsing clean.



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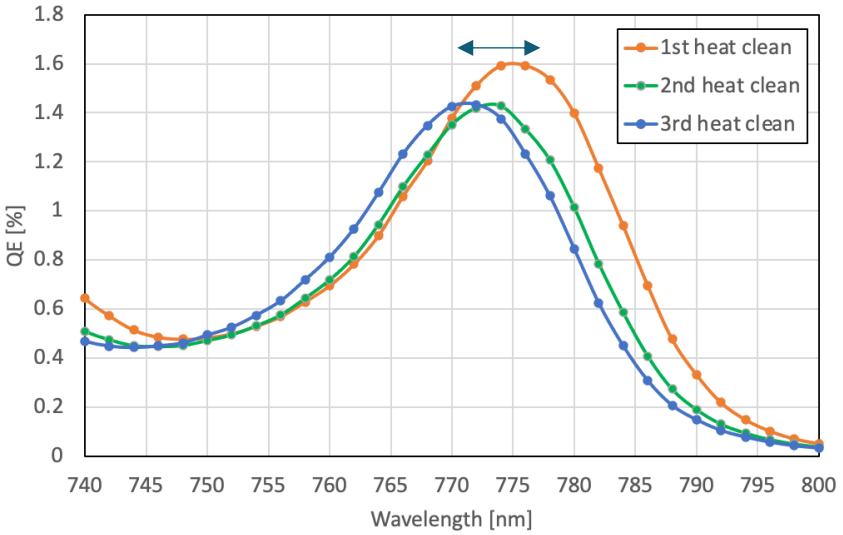
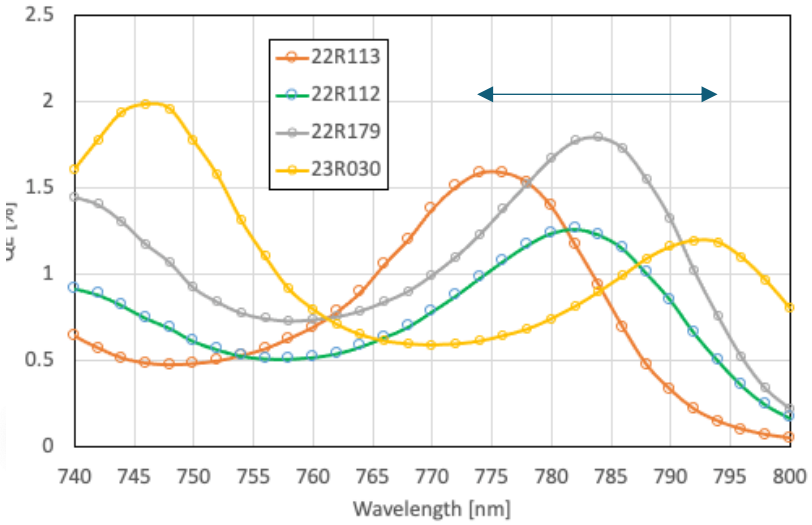
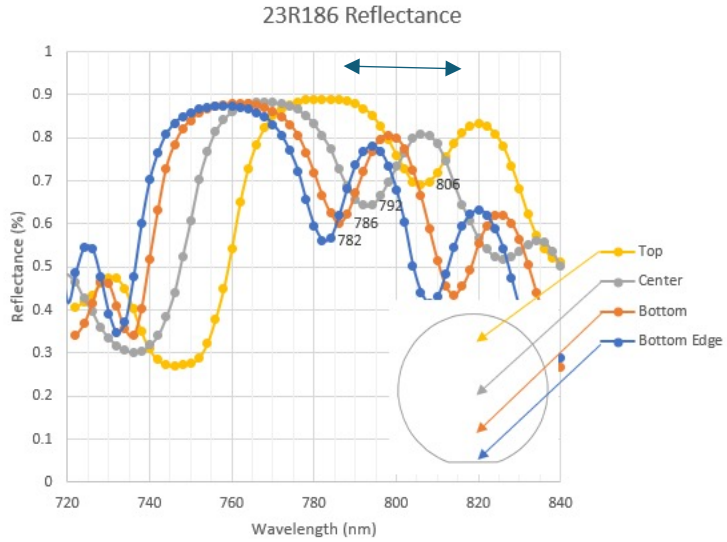
Third figure is provided by A. Master

DBR samples resonance frequency variation







- Vary the DBR resonance frequency(~20 nm):
  - Iterations of heat clean and QE (same sample, same location, same temperature)
  - Different samples
  - Same sample on different location

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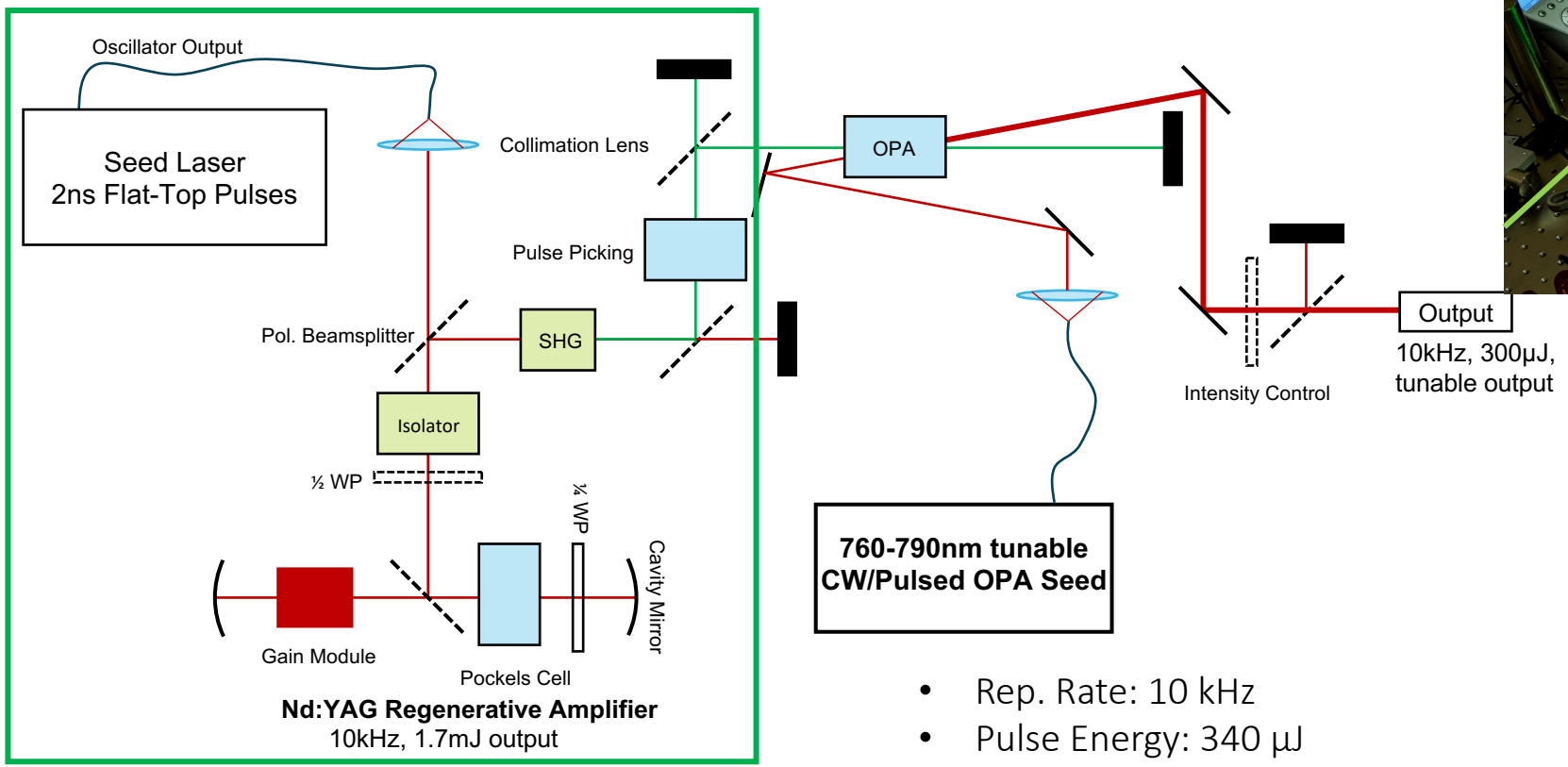
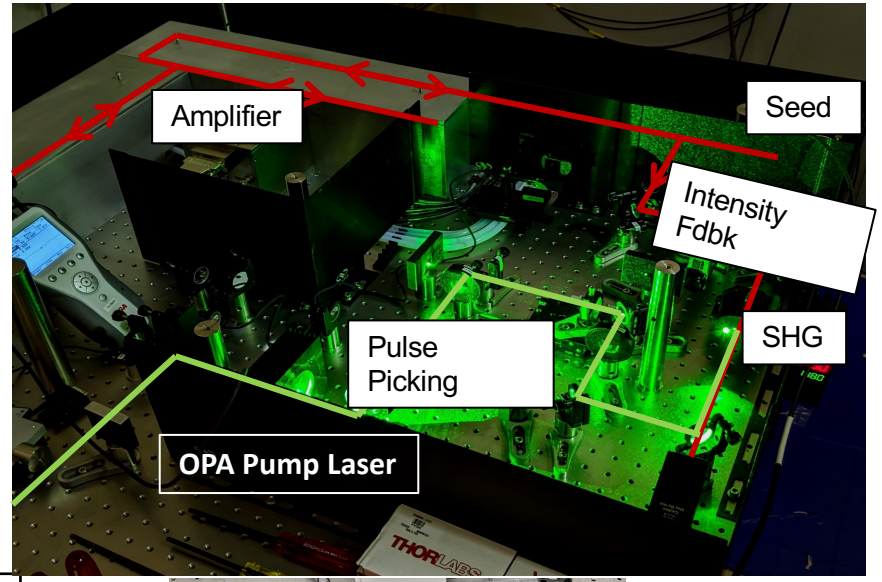
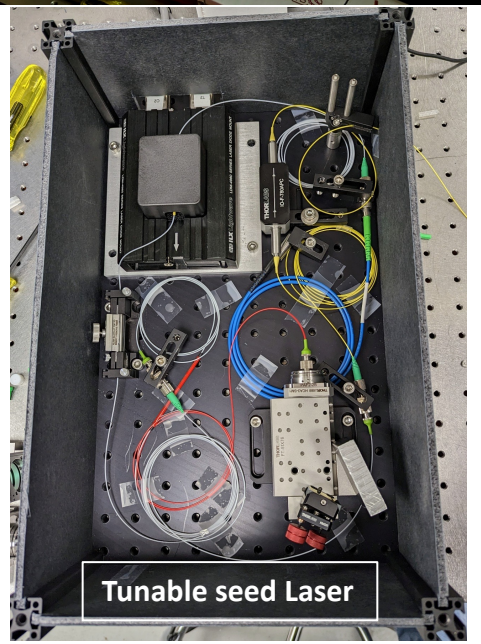
Tunable, Solid State, Nd:YAG OPA Laser Overview

OPA Pump Laser







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

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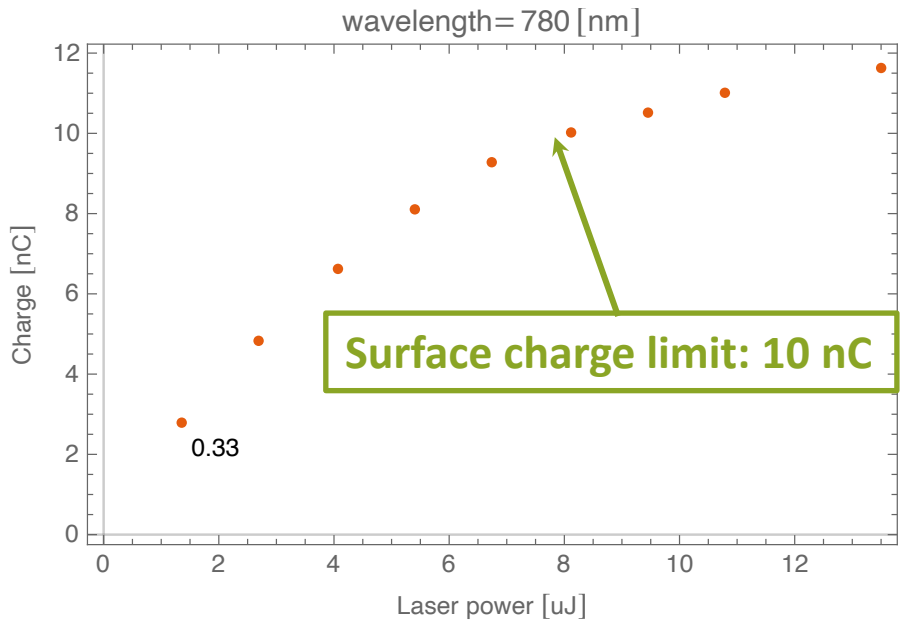
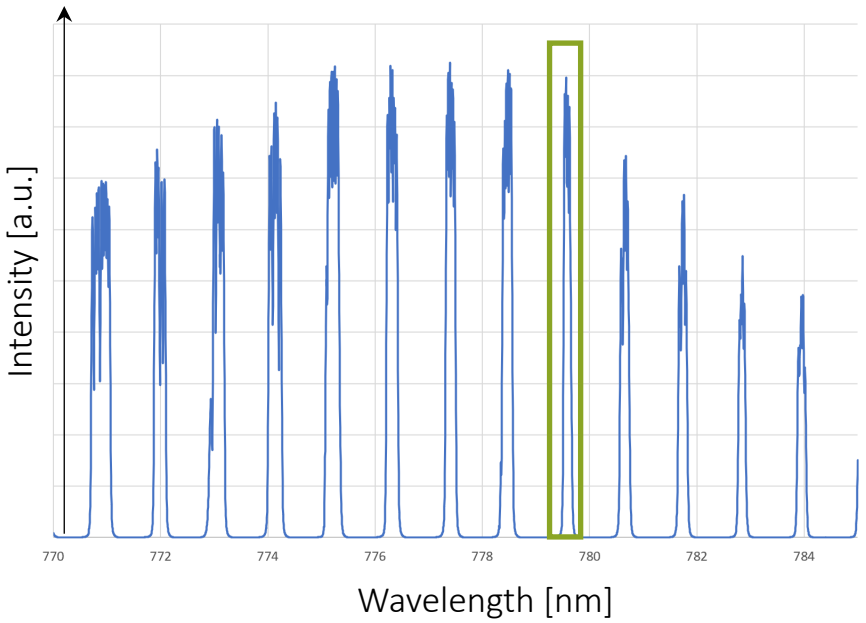
DBR-SL GaAs Performance in the Gun

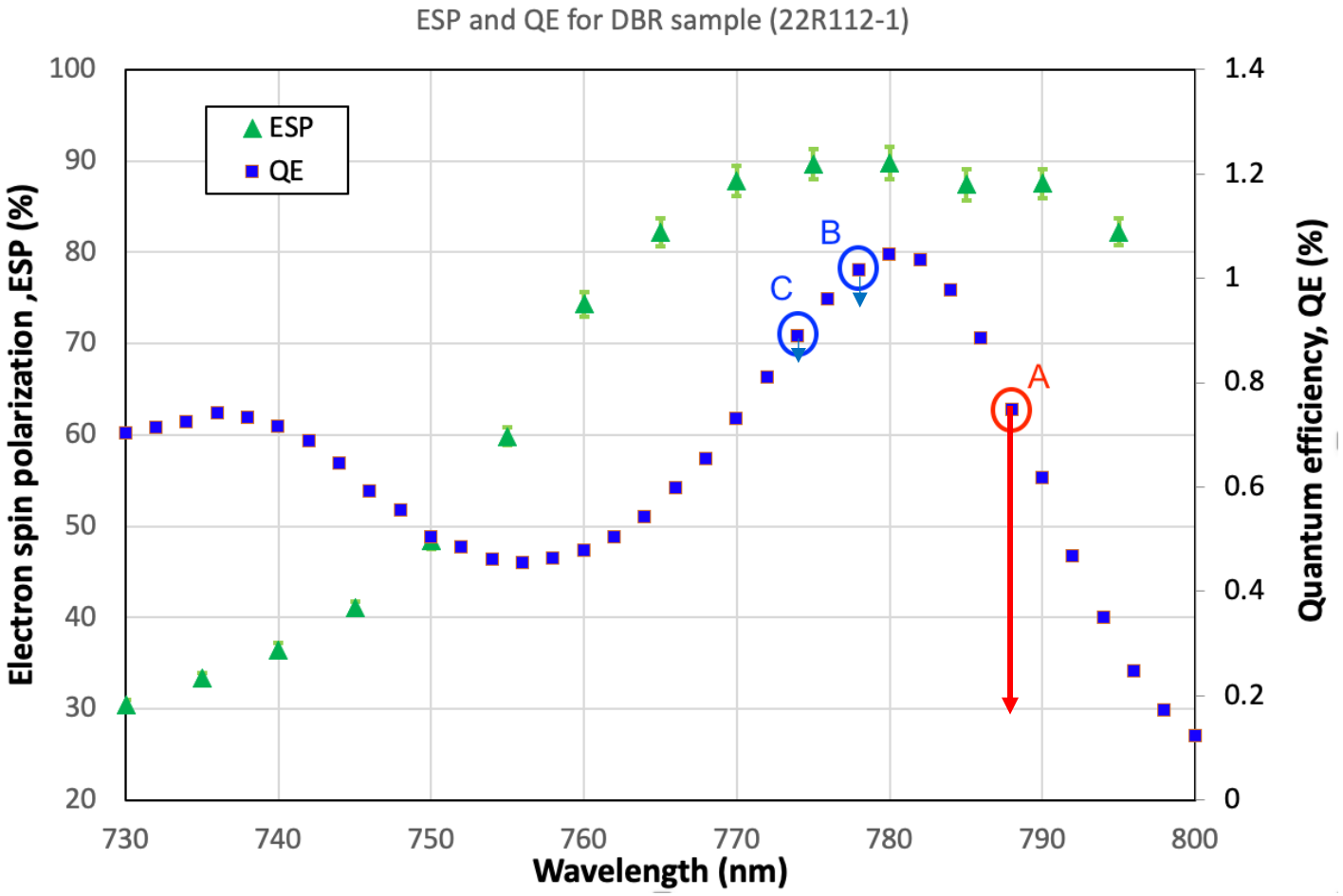




- We developed circular polarized **laser with tunable wavelength** for DBR-SL-GaAs cathode.
- We tested DBR-SL-GaAs **in the gun at 310 kV**, generated 11 nC bunch charge(1.6 ns length, and 8 mm laser spot).
- Charge from 9 hours , 20 uA operation, **Decay 10 %.**

Lifetime observation from DBR SL cathode

- For working point A. The QE **drops 75% in < 2 hours** with 1 uA average current.
- For working point B. The QE drops **~ 3% in 4 hours** with 20 uA average current.
- For working point C. The QE is **no decay in 2 hours** with 20 uA average current.
- **The lifetime is wavelength dependence.**



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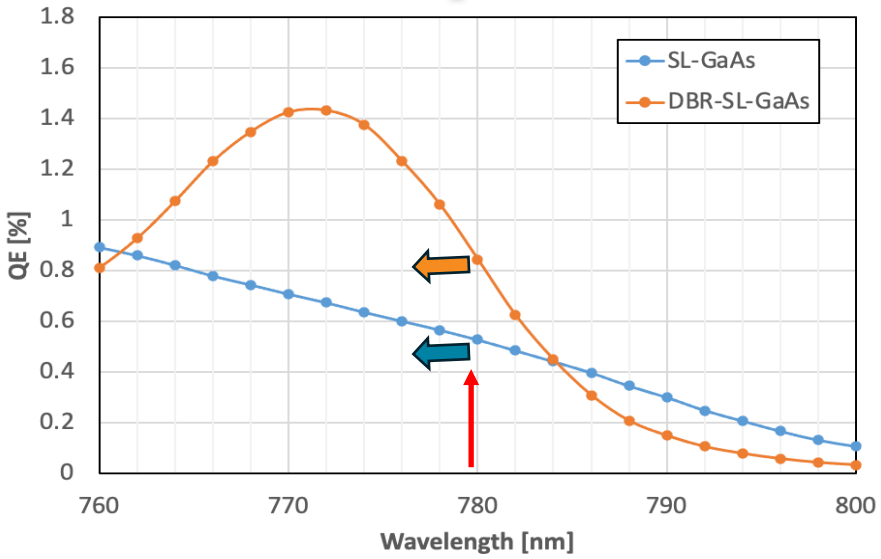
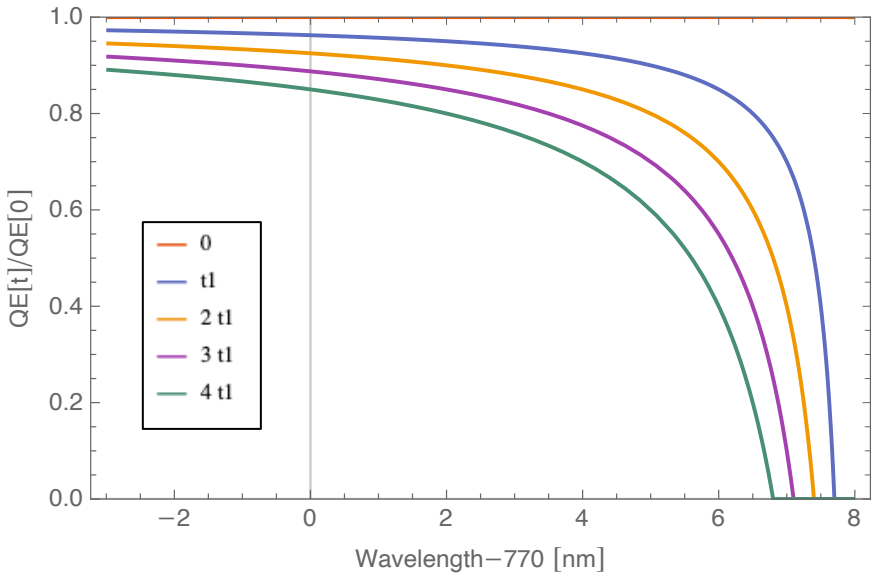
Wavelength dependence lifetime

- DBR sample has much large slope than SL-GaAs at right edge, causing the short lifetime.

$$QE \propto (h\nu - \varphi_{eff})^2$$

- Long time operation is increasing effective work function due to losing activation material or chemical poisoning.
- It is approximately equal to shift the spectrum to the left, but laser photon energy is fixed.
- **The large slope has fast QE drop.**





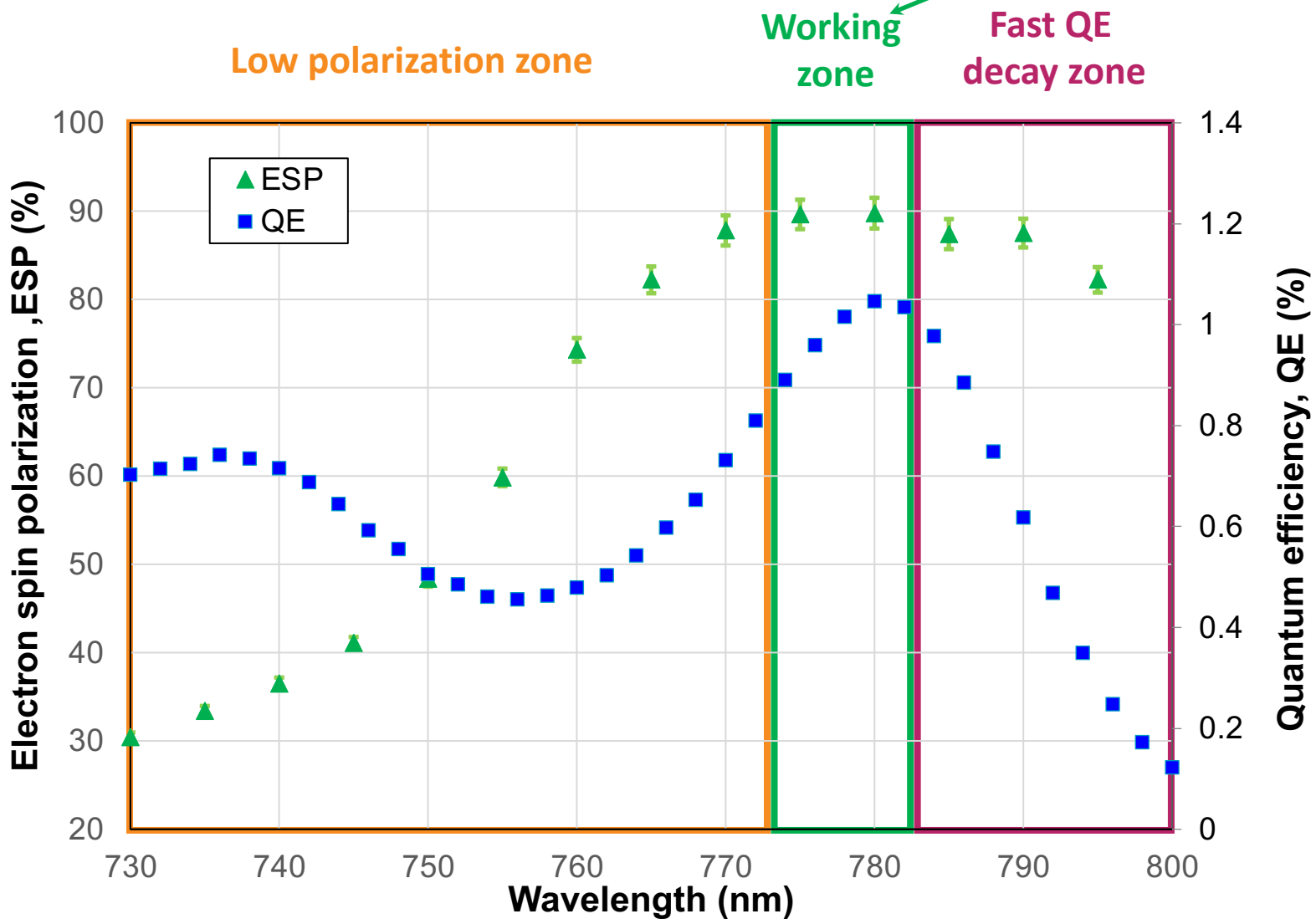
DBR cathode working zone

Working zone=
Resonance wavelength - ESP drop threshold

The working zone is from the left edge of the DBR resonance peak, while with good polarization

A good DBR cathode:

- High polarization
- High QE
- Large working zone



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Summary

- A prototype High Voltage DC polarized electron gun was designed and constructed to fulfill all the requirements for the EIC polarized electron source e-beam.
- This cutting-edge gun incorporates several innovative concepts, notably a cathode cooling system that holds potential in future high current electron sources, large cathode and new HV cable.
- The gun has been successfully conditioned up to 350 KV without any field emission and has maintained consistently operated at 310 KV.
- Exceeding 11 nC,with spin polarization > 90% , electron beam was generated from DBR SL-GaAs photocathode that had good lifetime. Beyond the EIC requirements.
    - We found optimal doping level and heat treatment temperature to suppressing Surface charge limit
    - We observed DBR resonance shift due to various samples, different locations and various activation
    - Lifetime is strongly wavelength dependence. We proposed a working zone for DBR cathode operation.

Thanks!
Questions?

Acknowledgement:

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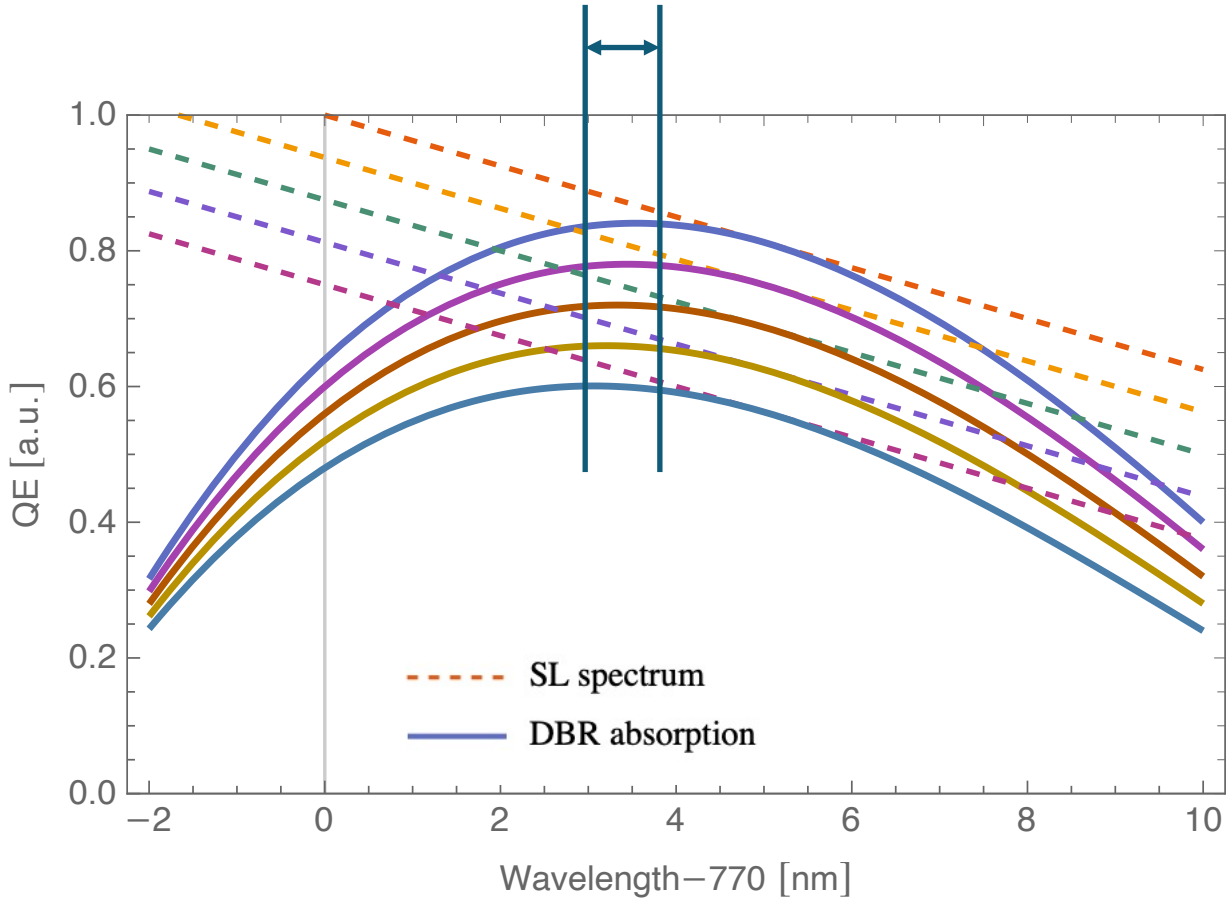
Jlab: M. Poelker, C. Hernandez- Garcia, the late D. Bullard

Old Dominion University: S. Marsillac and A. Masters

Peak frequency change also relevant to activation



DBR SL spectrum=
DBR layer absorption x SL spectrum

When the SL spectrum shift to the left due to increase work function, the DBR resonance peak will shift to left as well.

By using DBR-SL GaAs for long time, the QE will drop faster and faster if the initial working point on the peak?