Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

High-intensity, high-polarization electron gun for the Electron-Ion Collider

Erdong Wang on behalf of the EIC injector team

Electron-Ion Collider, BNL

Linac 2026

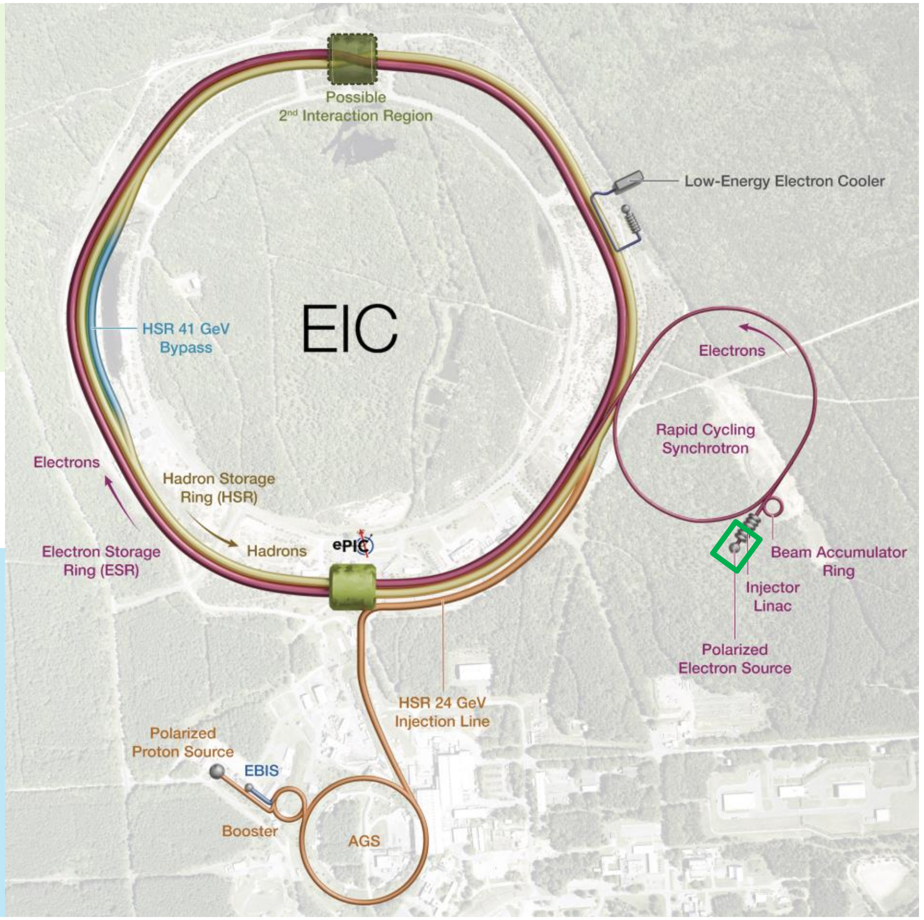
Aug. 18, 2026

@BrookhavenLab

From RHIC to EIC

Brookhaven National Laboratory
Relativistic Heavy Ion Collider (**RHIC**) has been in operation for almost 25 years:
The first machine in the world capable of colliding heavy ions.
The world's only machine capable of colliding high-energy polarized protons.

We are progressing towards constructing a groundbreaking machine for the international nuclear physics community:
the Electron-Ion Collider (**EIC**)
EIC will be the only operating particle collider in the U.S. and likely the only large collider to be built in the world in the next couple of decades.



EIC needs **highly polarized** e-source

- We need polarized electron bunches with **spins up and down**, stored simultaneously.
- Sokolov-Ternov self-polarization is too slow and produces only polarization anti-parallel to the main dipole field.
- Polarized electron bunches are produced and accelerated in the injector chain and are injected into the electron storage ring at collision energy.
- Sokolov-Ternov works against spin-down polarization, and spin diffusion reduces average polarization. All bunches must be exchanged frequently to achieve **70% average polarization.**
- The swap-out injection scheme was chosen for EIC.
- Initial polarization from the electron source dominates the polarization during collisions.

EIC needs high-intensity e-source

- To achieve 10^{33}- 10^{34}cm^{-2}s^{-1} , the total polarized-electron bunch charge required for collisions is 28 nC.
- **Challenge 1:** Can a polarized electron source generate 28 nC?

Gun R&D aimed to achieve a 7 nC bunch charge (as high as possible) and merge four bunches in the booster ring. However, merging four polarized bunches in the booster ring is difficult because of insufficient damping and may cause instability at low energy when RF merging is used.

- **Challenge 2:** Can a linac accelerate a 28 nC bunch charge?

One option is to use an AWA of 1.3 GHz. However, a 10 MV/cavity requires 75 cavities to achieve a linac energy of 750 MeV, which is too expensive.

- **Low-risk solution (current baseline):** Use an accumulator ring for bunch merging and a booster ring for increasing the energy. This reduces the electron source charge requirement to 1 nC.

Our gun R&D was focused on meeting **Challenge 1**: achieving a high charge and high polarization.

Spin considerations

solenoid field

Thomas-BMT equation:

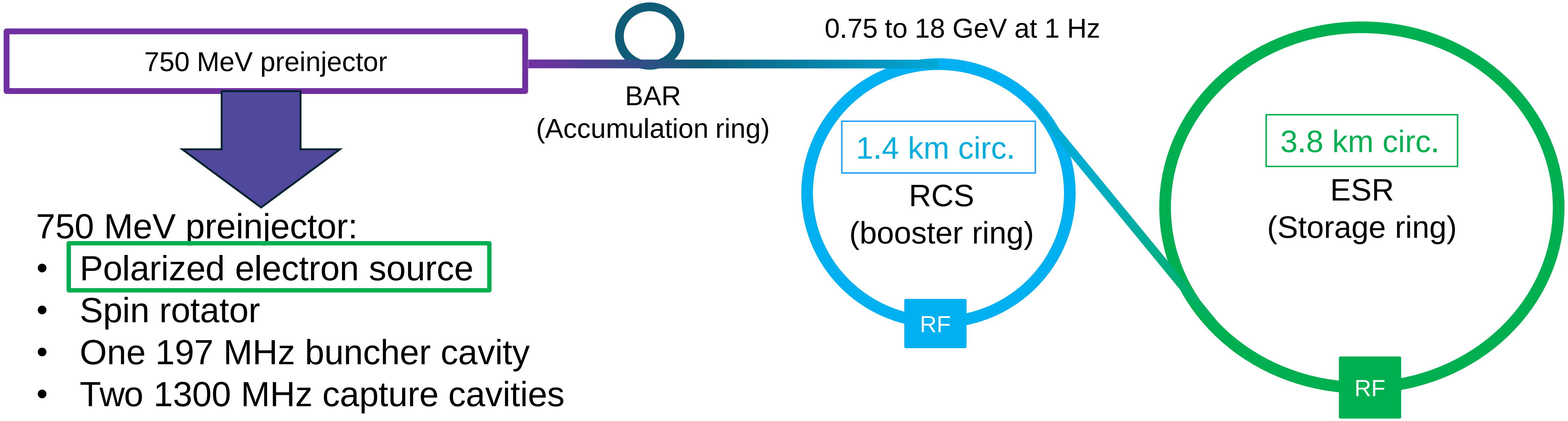
$$\frac{d\vec{P}}{dt} = \vec{\Omega_0} \times \vec{P}$$

$$\vec{\Omega_0} = -\frac{Ze}{m\gamma}[(1+G\gamma)\vec{B_\perp} + \boxed{(1+G)\vec{B}_\parallel} + (G\gamma + \frac{\gamma}{1+\gamma})\frac{\vec{E}\times\vec{v}}{c^2}]$$

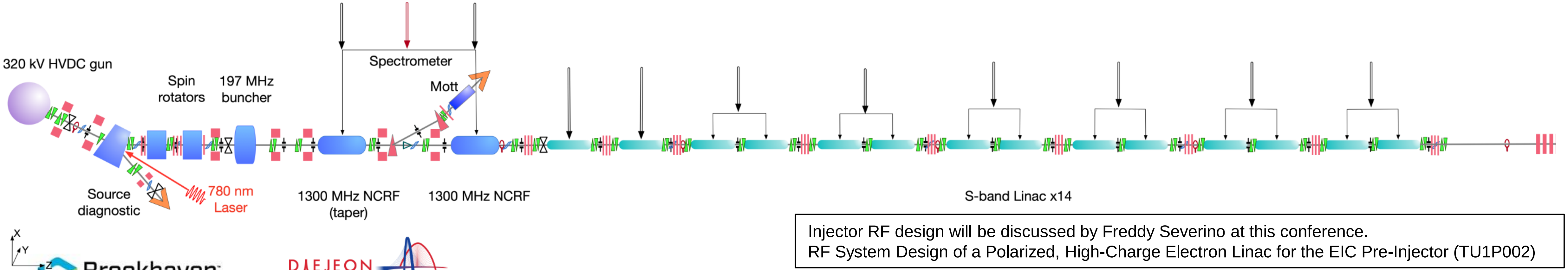
To keep P unchanged $\int_S \frac{B_\parallel}{\gamma} ds = 0$

- A low-energy spin rotator, such as a Wien filter, is preferred to allow flexibility in the beam energy range. After the Wien filter (beam energy 300-320 keV), the spin direction is vertical.
- The solenoid field has to be tuned for transverse matching with space charge.
- **Challenge:** A typical long solenoidal channel used in an S-band linac has a varying longitudinal field, and the entrance and exit gamma values differ within the accelerating structure. Achieving the above condition is not practical during commissioning.
- The aperture of the S-band linac ranges from 1.3 cm to 1 cm in radius. Typically, the **pre-injector taper cavity and the first linac require a solenoidal field** to maintain a small beam size.
- Our approach is to **increase the beam energy to above 10 MeV using an L-band linac before injecting it into the S-band linac**.

EIC injector concept

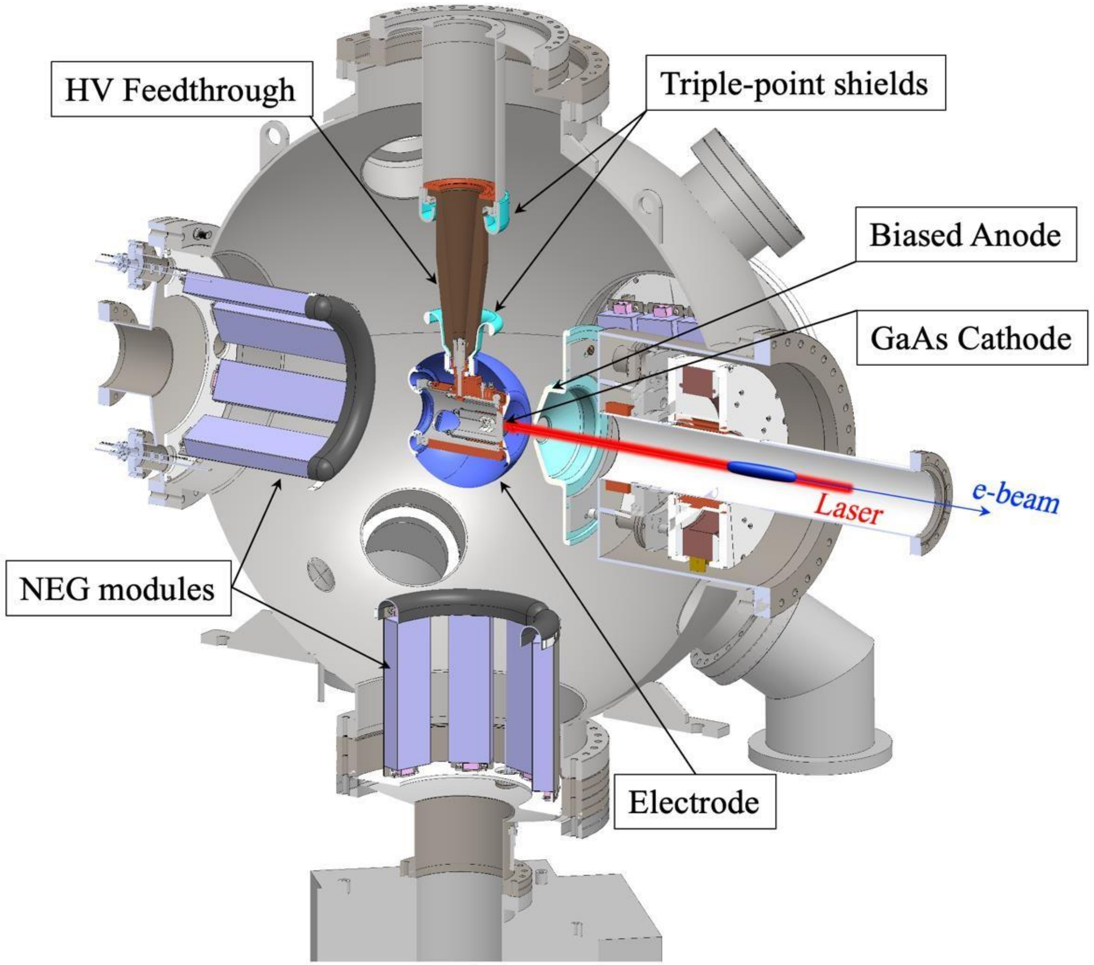


750 MeV preinjector:
- Polarized electron source
- Spin rotator
- One 197 MHz buncher cavity
- Two 1300 MHz capture cavities
- Fourteen 3-meter S-band structures with gradients from 18.2 MV/m to 21.2 MV/m



Injector RF design will be discussed by Freddy Severino at this conference.
RF System Design of a Polarized, High-Charge Electron Linac for the EIC Pre-Injector (TU1P002)

EIC polarized gun overview



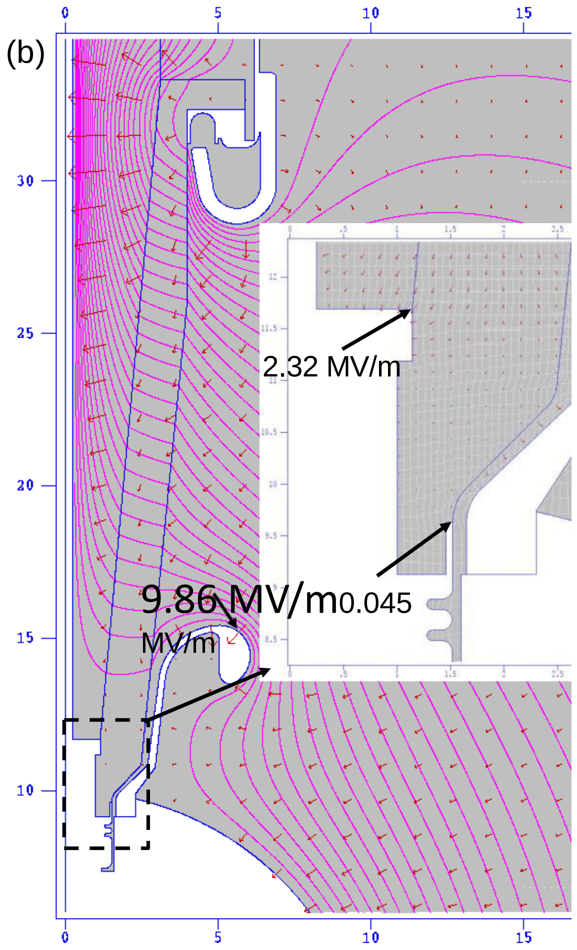
The EIC polarized gun needs:
- High charge
- Long lifetime
- High polarization
- High peak current
- Maintenance-free

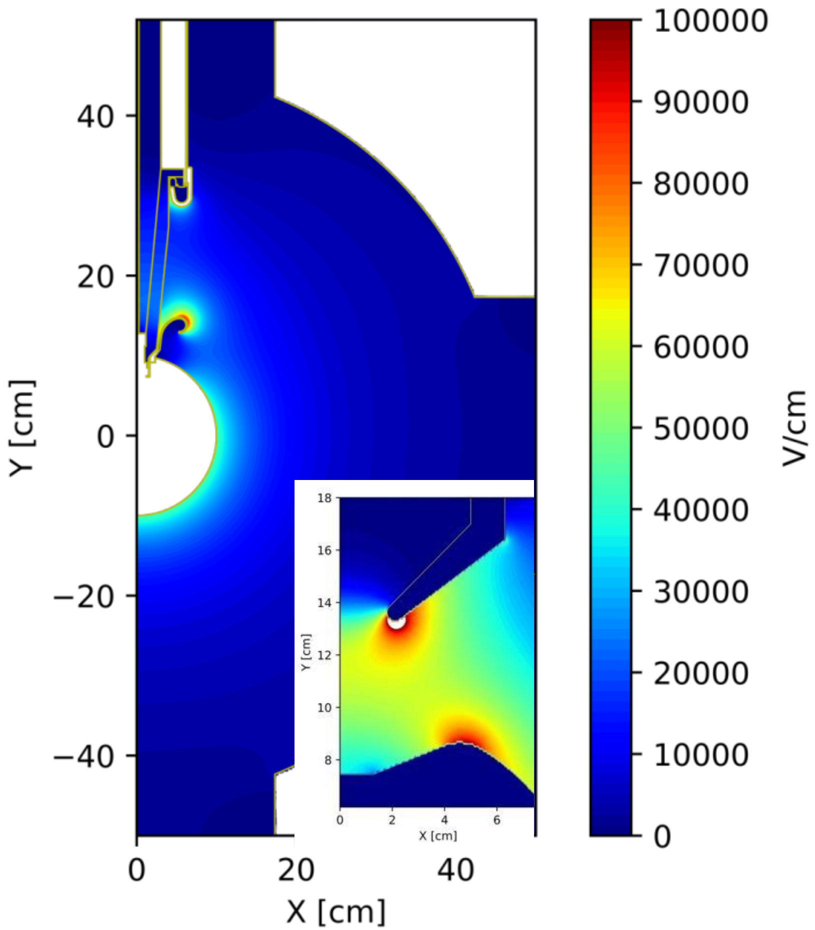
No existing gun can meet all EIC R&D goals.

The EIC gun includes new features:
- Active cathode cooling
- Large cathode
- High gradient
- Semiconductor jacket HV cable
- 3D-movable, electrically insulated anode.

Gun HV design

- The maximum gradient is 9.8 MV/m at 350 kV.
- Triple-point shields are applied on both the HV and ground sides to prevent HV breakdown.
- Cathode gradient: 4.5 MV/m



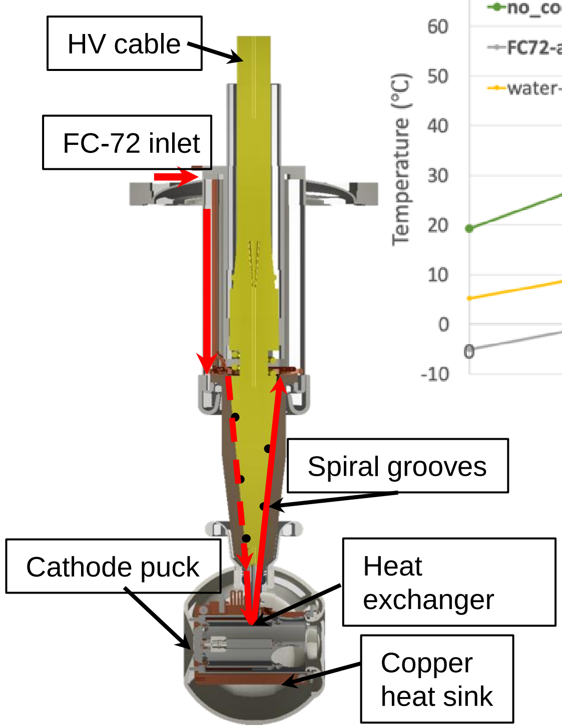


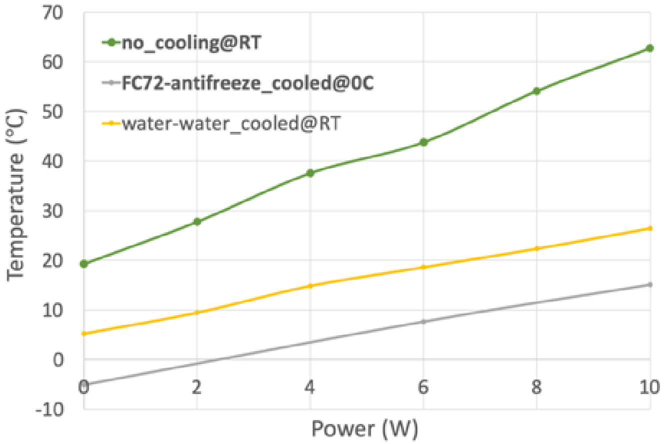
Actively Cooled Cathode Using an HV Feedthrough

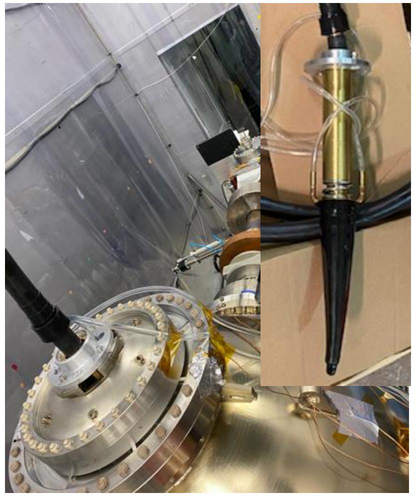
We developed an actively cooled HV feedthrough that can absorb **up to 10 W** of laser power.

Tested up to **410 kV with flow**

Custom-designed HV plug with cooling channel



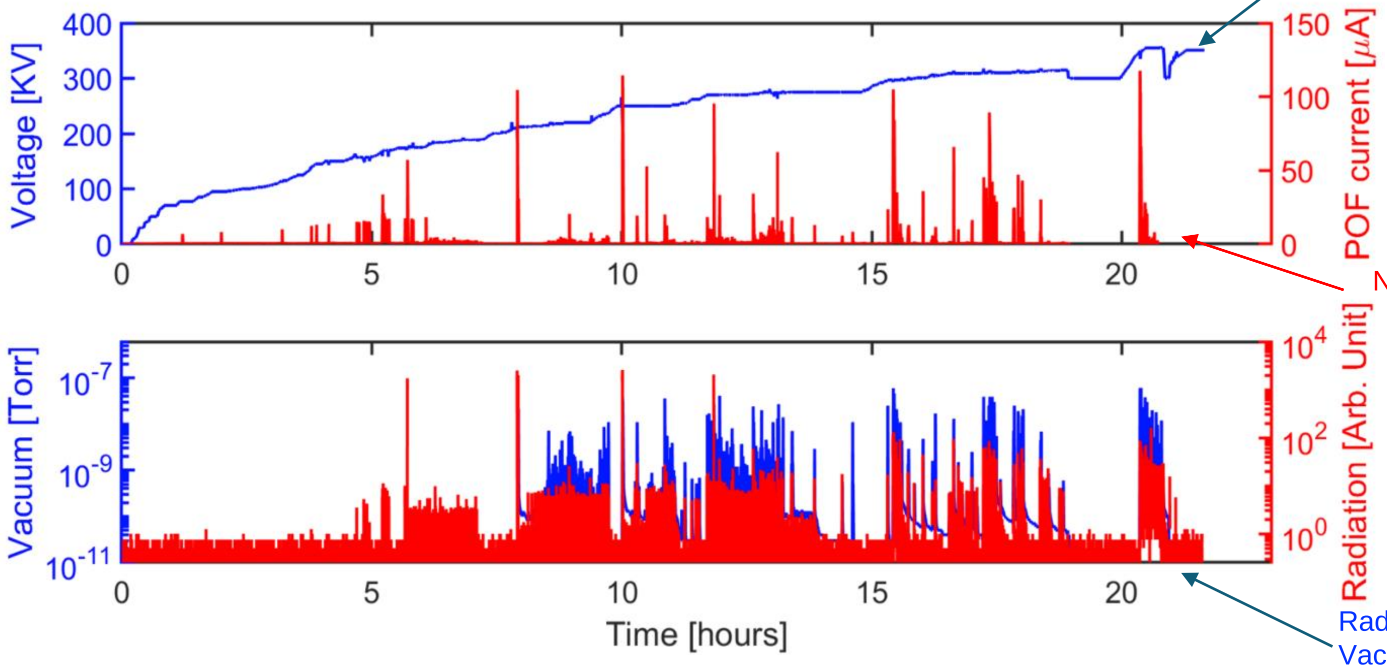




- Tested in the gun with FC-72. Operated at 300–350 kV for more than 500 h. No failures.
- Maintenance every six months.

Designed for high-current operation; unnecessary for the EIC polarized source but **beneficial for any high-current polarized or unpolarized gun.**

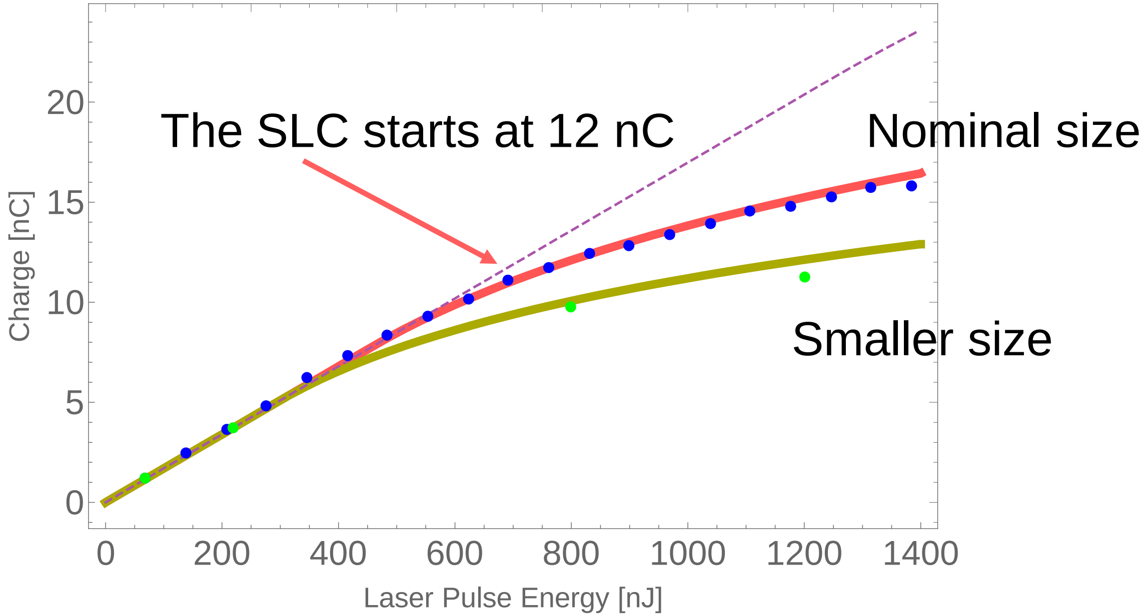
HV Conditioning

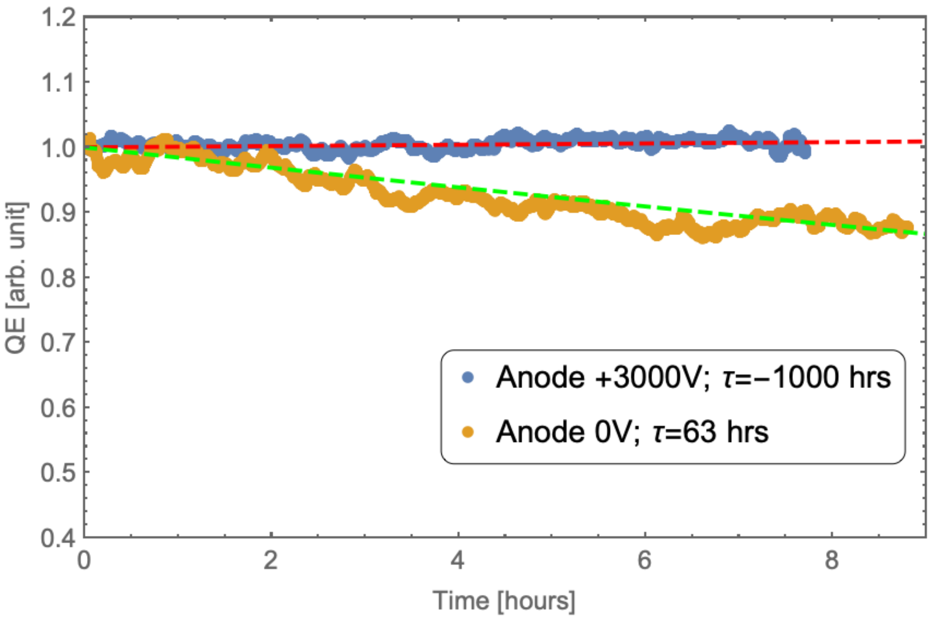


- The gun was conditioned in Dec. 2020 (vacuum conditioning took a total of 23 h with cooling on), achieving its design value of 352 kV without a cathode.
- In 2023, we improved the puck-cleaning procedure. The new puck with a new SL-GaAs (ODU) sample can achieve 350 kV without any conditioning. We do not need extra conditioning when using new samples/pucks.

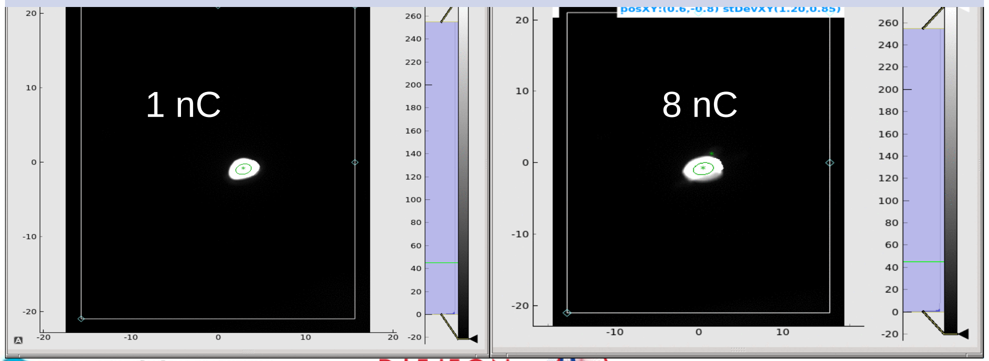
Erdong Wang et al. Phys. Rev. Accel. Beams 25, 033401 (2022)

Bunch Charge and Cathode Lifetime





Beam image before the dump



- The baseline vacuum is 3–5 × 10^{-12} Torr
- Bulk GaAs with a 785 nm polarized laser; the gun operates at 300 kV and was operated up to 67.5 µA.
- A polarized beam with a 7.5 nC bunch charge at 5,000 pulses/s (~37.5 µA).
  - **With anode bias, we did not observe a QE drop.**
  - **No anode bias:** 1/e lifetime = 63 h (FC outgassing).

Benjamin Belfore et al. High figure of merit spin-polarized electron sources grown via MOCVD. *Appl. Phys. Lett.* 27 November 2023; 123 (22): 222102.

High Polarization Photocathode

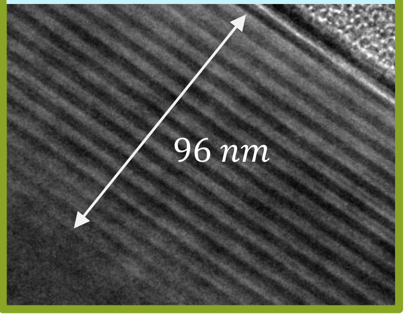
Distributed Bragg reflector (DBR) layer was added to the GaAs photocathode, resulting in a Fabry-Perot resonance between the surface-vacuum interface and the DBR layer that significantly enhances the QE. We were the first to successfully use a DBR cathode in an HVDC gun.

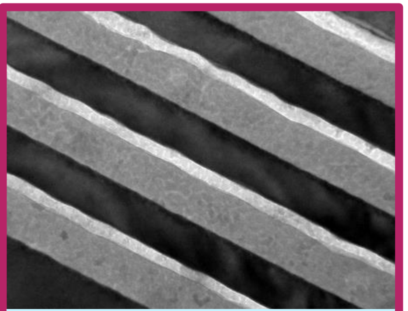
ODU/JLab/BNL: **GaAs/GaAsP SL with AlAsP/GaAsP DBR**

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

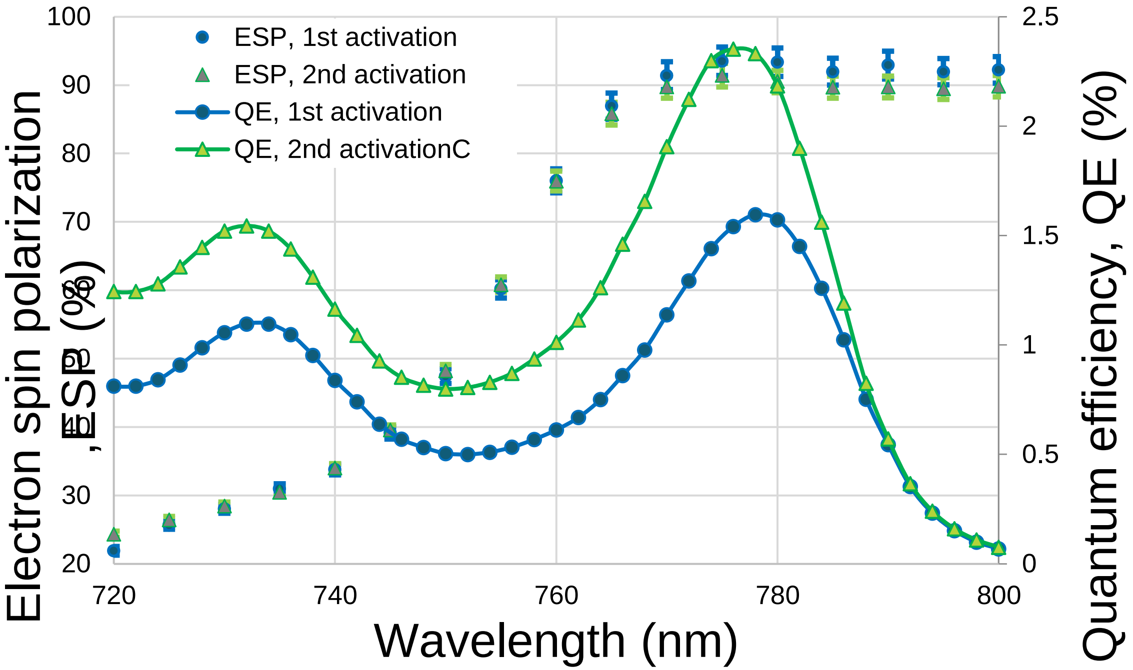
GaAs	5 nm	p=5×10^{19} cm^{-3}
GaAs/GaAsP SL	(3.8/2.8 nm) ×14	p=$5\cdot10^{17}$ cm^{-3}
$GaAsP_{0.35}$	750 nm	p=5×10^{18} cm^{-3}
$GaAsP_{0.35}$/ $AlAsP_{0.4}$ DBR	(54/64 nm) ×12	p=5×10^{18} cm^{-3}
$GaAsP_{0.35}$	2000 nm	p=5×10^{18} cm^{-3}
Graded $GaAsP_x$ ($x = 0\sim0.35$)	5000 nm	p=5×10^{18} cm^{-3}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

14 SL Pairs

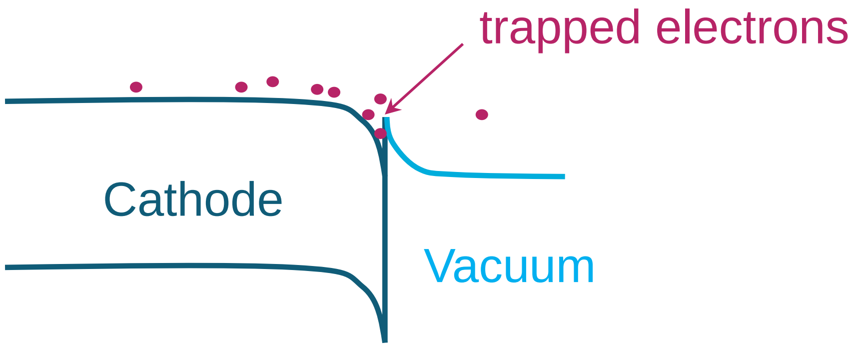


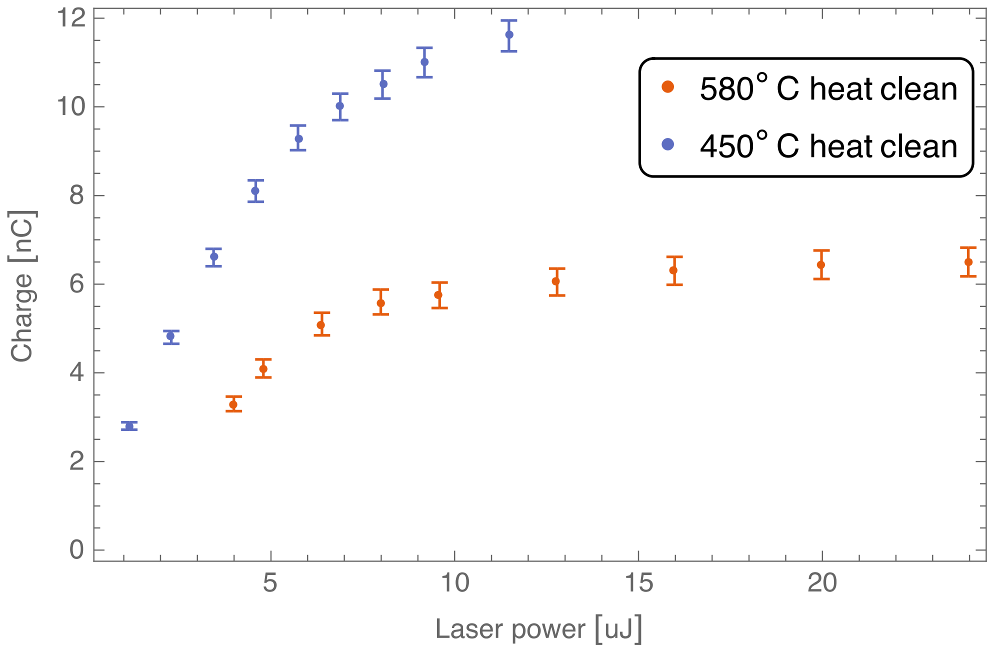


12 DBR Pairs



Generated a high-intensity polarized electron bunch



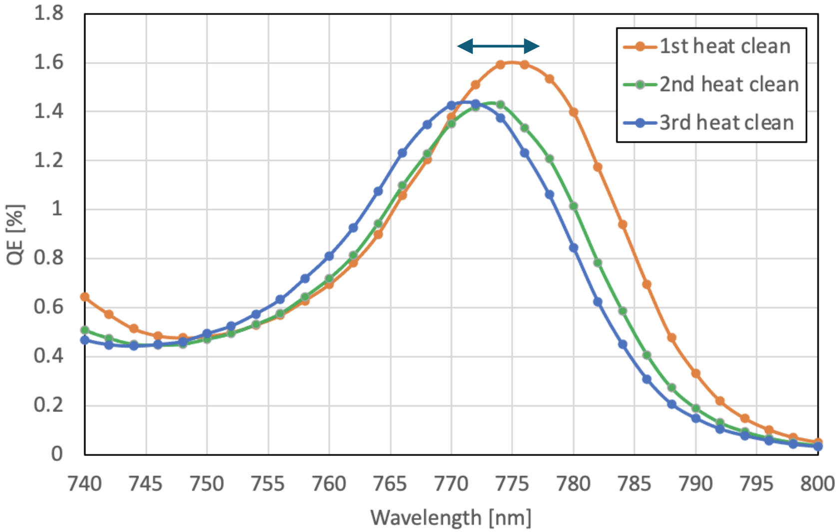


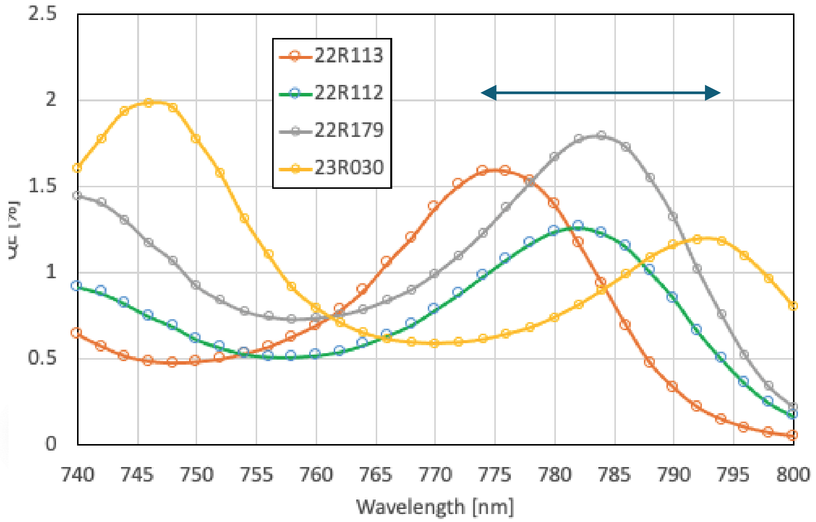
- Feb. 2023: maximum bunch charge of 6 nC, **limited by the surface charge limit (SCL).**
- June 2023: maximum bunch charge of 11.6 nC achieved through:
  - ➢ Optimized cathode surface-doping levels
  - ➢ Revised surface cleaning: acid wet cleaning + 450 °C heat cleaning

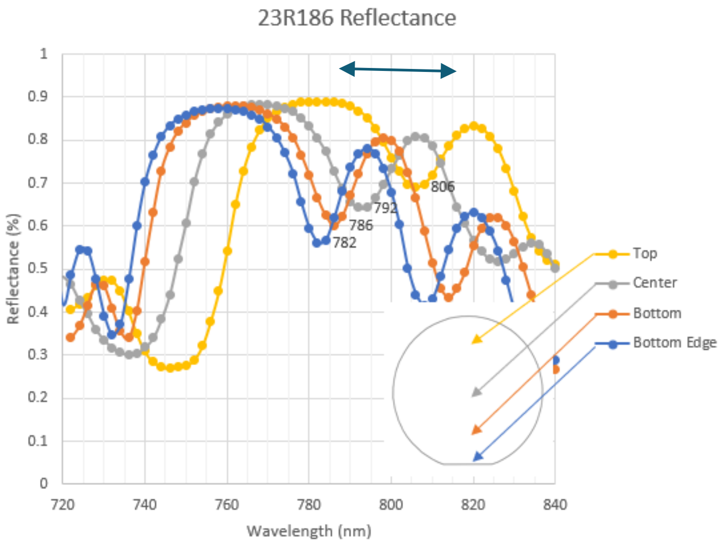
Highly Polarized (85%–90%)

- DBR-SL-GaAs with 785 nm polarized laser;
- Maximum bunch charge 11.6 nC (8 mm)
- Operated up to 30 µA.
- Limited by the surface charge limit
- Doubling the size/power increases the charge by only 20%

Variation in DBR Sample Resonance Frequency





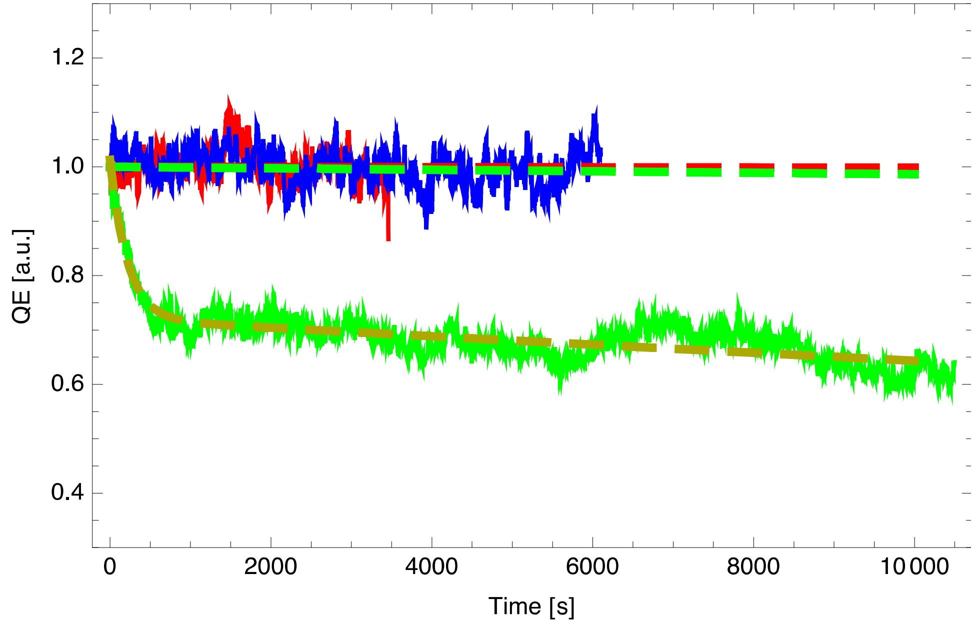


Provided by A. Master

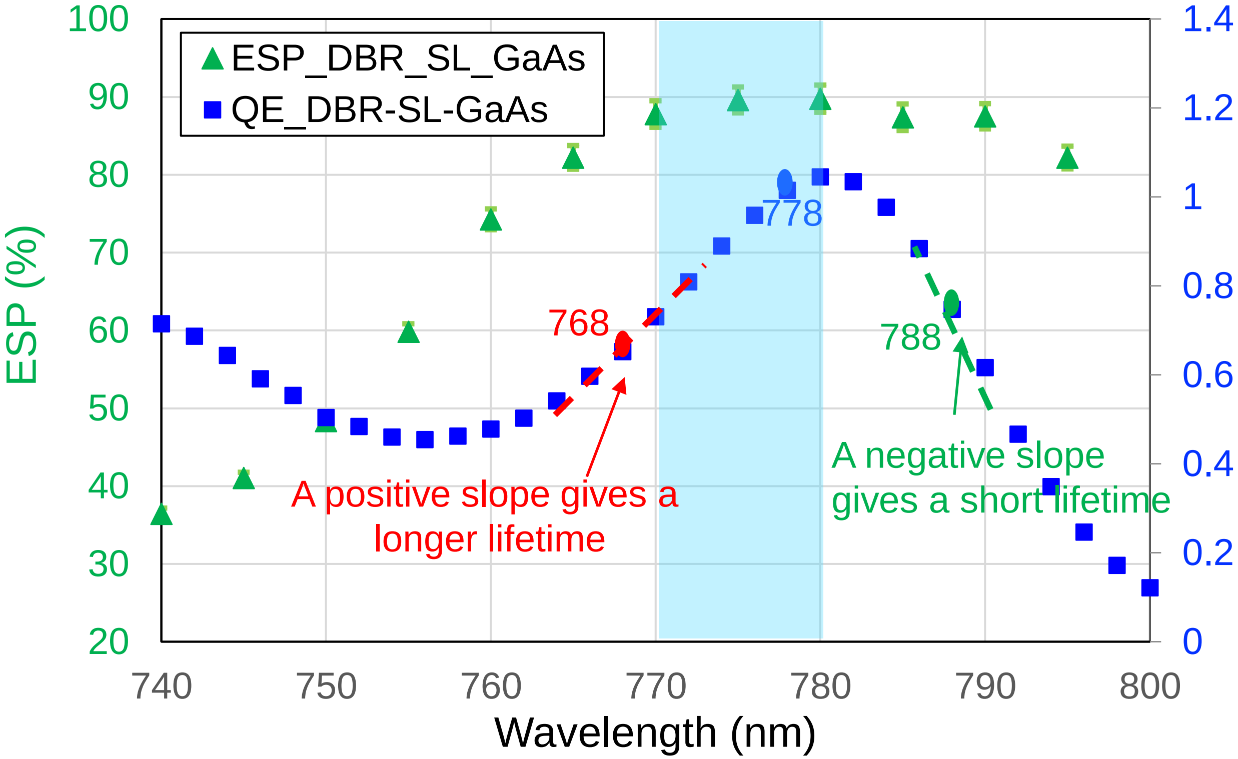
- The DBR resonance frequency varies (~20 nm) due to:
  - Repeated heat cleaning and QE measurements (same sample, location, and temperature)
  - Different samples
  - The same sample at different locations
- Our approach: circularly polarized laser **with tunable wavelength** for DBR-SL-GaAs cathode.

Erdong Wang et al.; High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode. Appl. *Phys. Lett.* 124, 254101 (2024)

Lifetime of a DBR-SL Cathode



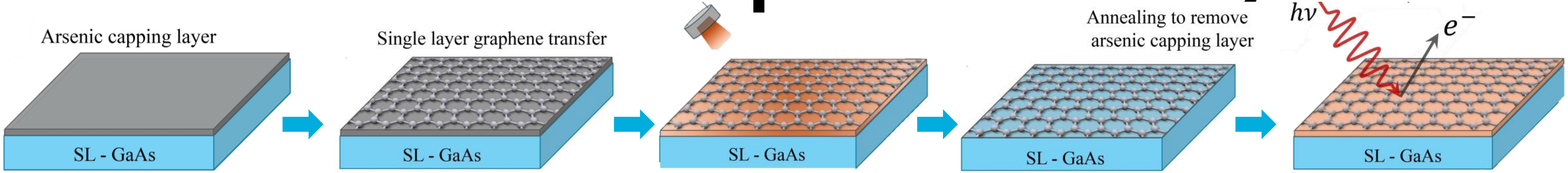
Working zone=Resonance wavelength - ESP drop threshold

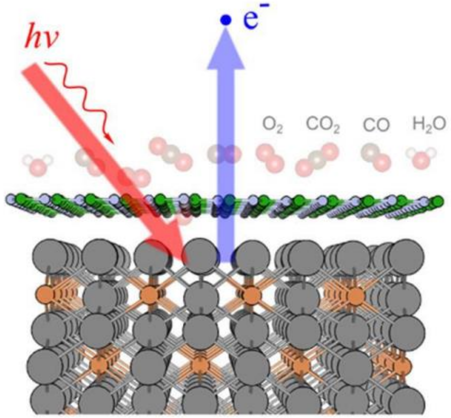


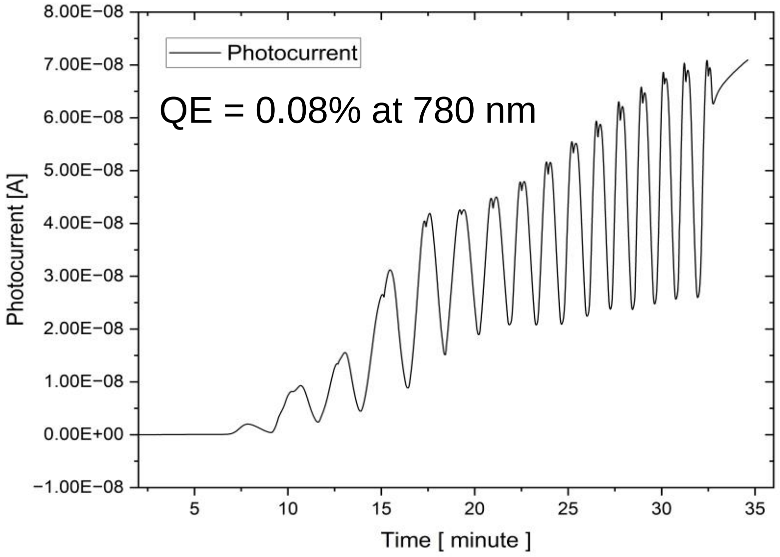
- Lifetime measured at 30 µA average current.
- Lifetime is wavelength-dependent; **working zone: high QE, high ESP, and long lifetime.**
- At 30 µA, 9 h delivers >28 EIC weeks of charge with 10% decay; storage lifetime: one month.

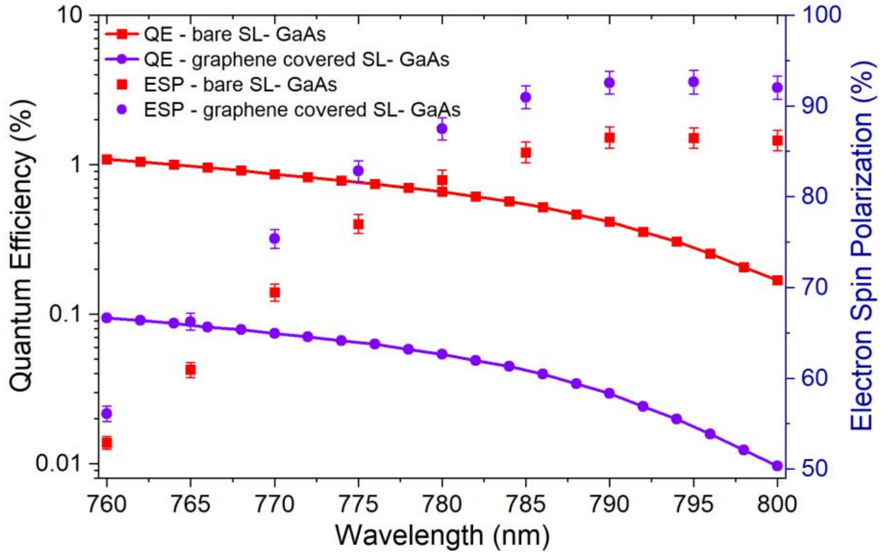
Jyoti Biswas et al. Single-layer graphene protective layer on GaAs photocathodes for spin-polarized electron source. *APL Mater.* 1 June 2025; 13 (6): 061101

R&D: GaAs with 2D protection layer









- Successful growth of SL-GaAs with a CsO activation layer beneath the graphene.
- The graphene protection layer makes the GaAs cathode **less susceptible to heating and gas**.
- Graphene-coated GaAs shows **higher polarization** than regular O-Cs coating.

Summary

- The EIC needs a **highly polarized, high-intensity** electron source.
- A prototype high-voltage DC polarized electron gun was designed and constructed to fulfill all the requirements for the electron beam from the EIC polarized electron source.
- The gun has been successfully conditioned up to 350 kV without any field emission and has consistently operated at 320 kV. An electron beam exceeding 11 nC (beyond the R&D goal), with spin polarization >90%, was generated from a DBR-SL-GaAs photocathode with a good lifetime. This **exceeded the EIC requirements**.
- **Highlighted achievements:**
  - The highest operating voltage in a polarized gun: **320 kV**
  - **Simultaneous operation at 30 μA average current and 7.5 nC bunch charge**
  - First operational DC gun with a **Distributed Bragg Reflector** superlattice GaAs polarized cathode (We found an **optimal laser wavelength range** for high QE/long lifetime/high polarization operation)
  - The highest current density from a polarized cathode: **14.5 A/cm^2**.
  - Graphene-coated Superlattice GaAs cathode shows much higher polarization than conventional activation.

Thanks!
Questions?

Acknowledgments:

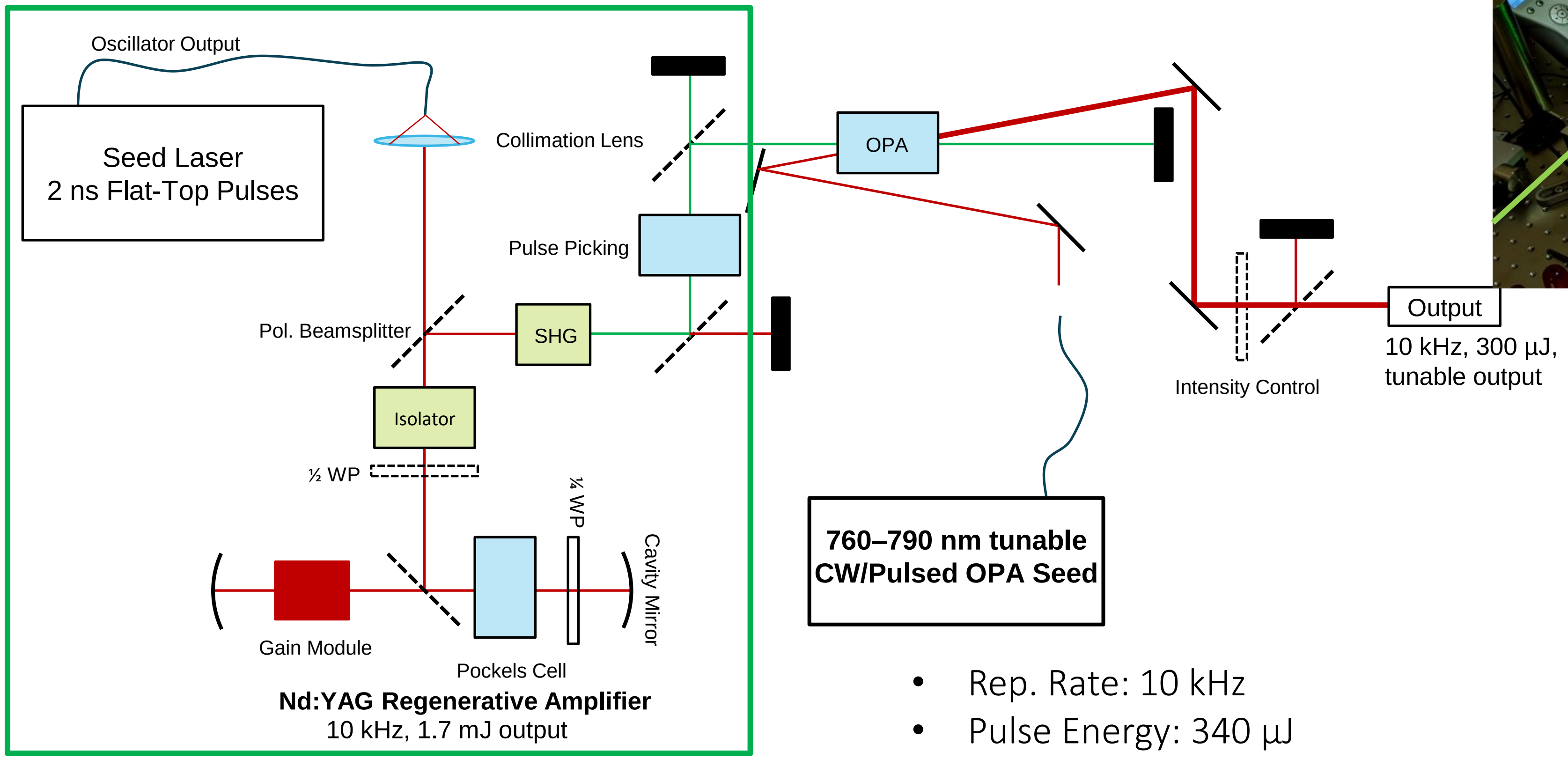
BNL: O. Rahman, P. Inacker, J. Biswas, M. Gaowei, J. Skaritka, C. Degen, B. Lambiase, R. Napoli, M. Paniccia

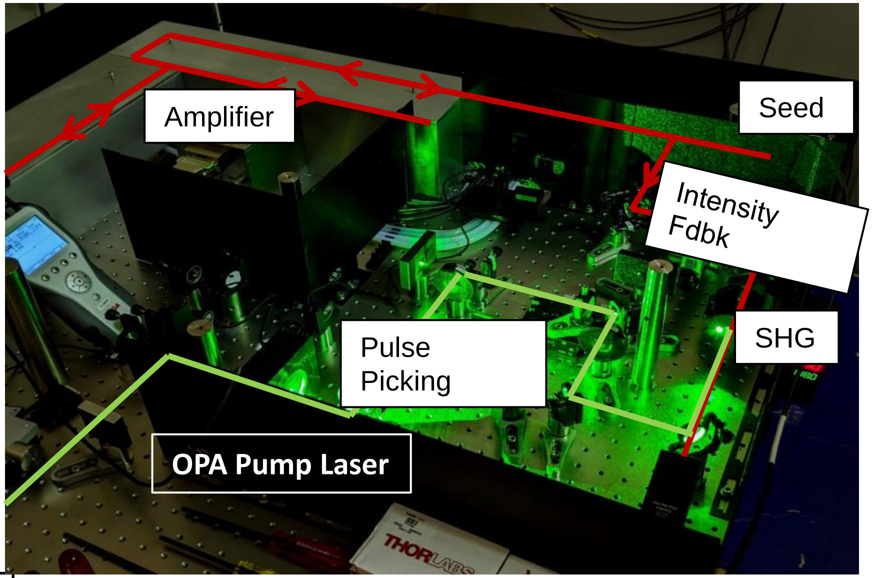
JLab: M. Poelker, C. Hernandez-Garcia (xlight), the late D. Bullard

Old Dominion University: S. Marsillac and A. Masters

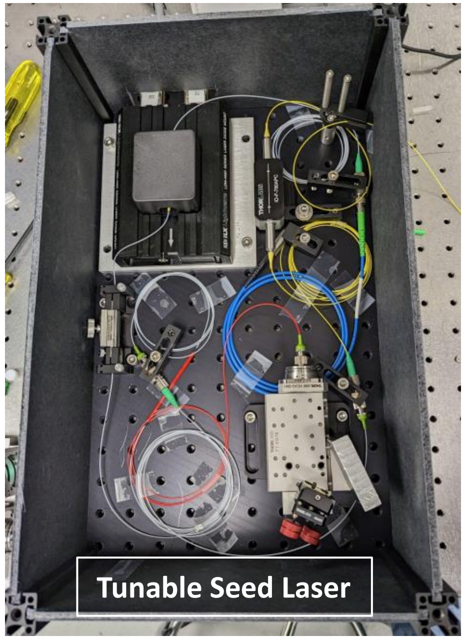
Tunable Solid-State Nd:YAG OPA Laser Overview

OPA Pump Laser





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



HV Electrode Polishing and Cleaning

Original electrode

crushed corncob

Mirror Polishing

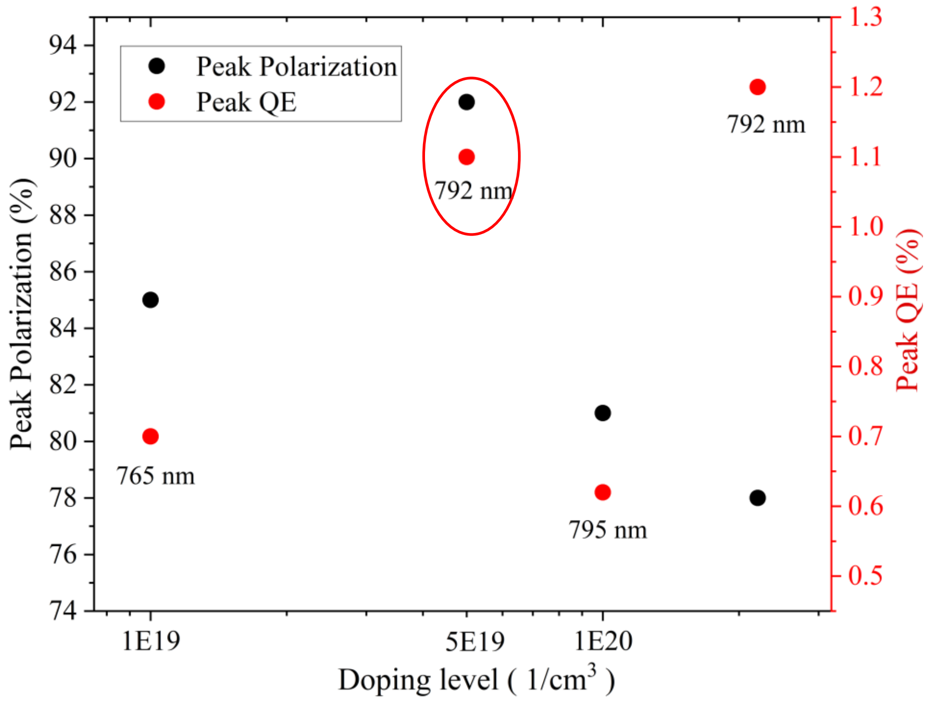
High-Pressure Rinsing

Particle-Free

- Rough surfaces or particulates will easily generate unwanted electrons under high voltage (field emission).
-
- **Mirror-surface polishing and particle-free cleaning are key to gun fabrication for high-voltage, high-gradient operation.**

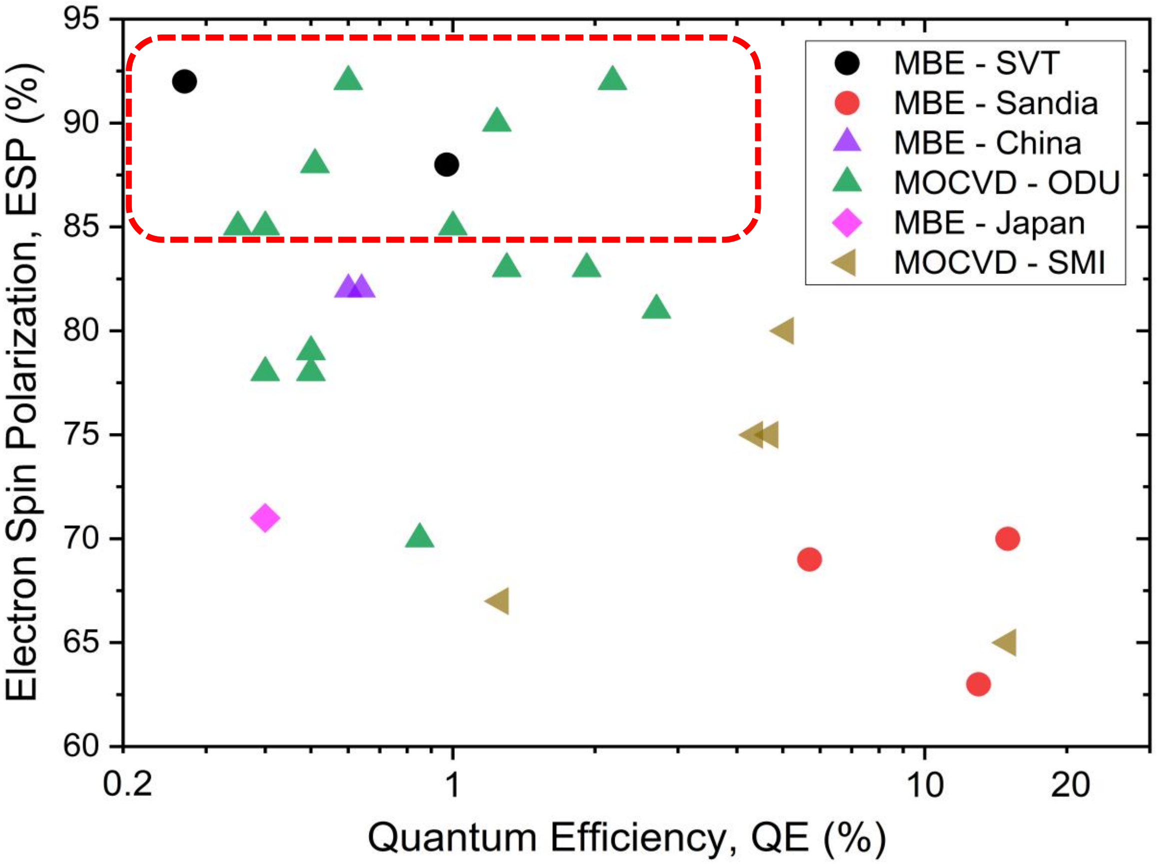
Suppression of Surface Charge Limit

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



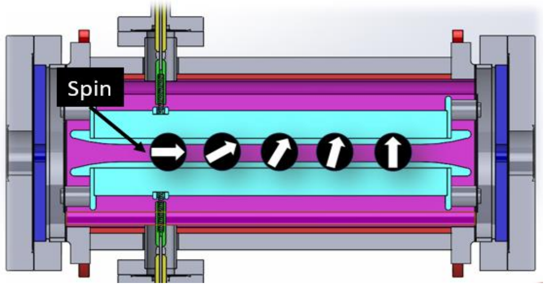
GaAs cathode wafer testing

- DBR-SL-GaAs was tested in an HVDC gun. Lifetime was measured at an average current of 30 µA (3 orders of magnitude higher than needed). The charge generated by this cathode in a single activation is equivalent to more than 28 weeks of continuous EIC operation.
- We have a dedicated micro-Mott polarimeter to measure the quantum efficiency (QE) and electron spin polarization (ESP). Over the past five years, we have tested more than 50 samples; however, only a small number have achieved polarization at or above 85%, which is the EIC requirement.
- There is currently no stable cathode vendor. GaAs is also subject to export controls. We have five usable samples, including one good sample. We ordered six samples from Acken in China, but the order is restricted by export controls.



Low-Energy Spin Rotator: Wien Filter

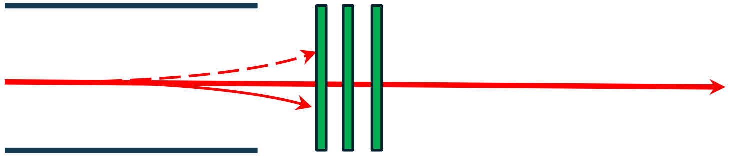
- A Wien filter can address the difficulties of the dipole-solenoid spin rotator: **small energy acceptance and CSR.**
- **Wien filters are in operation at many laboratories, such as** CEBAF, Mainz, Dalinac.
  - Higher energy requires a greater length. (We have the highest-voltage polarized gun.)
  - They typically operate in the <10 pC range with nearly zero space charge, resulting in a small energy spread.
  - High space charge requires placing the focusing element very close. (Our bunch charge is higher than that of other polarized injectors.)



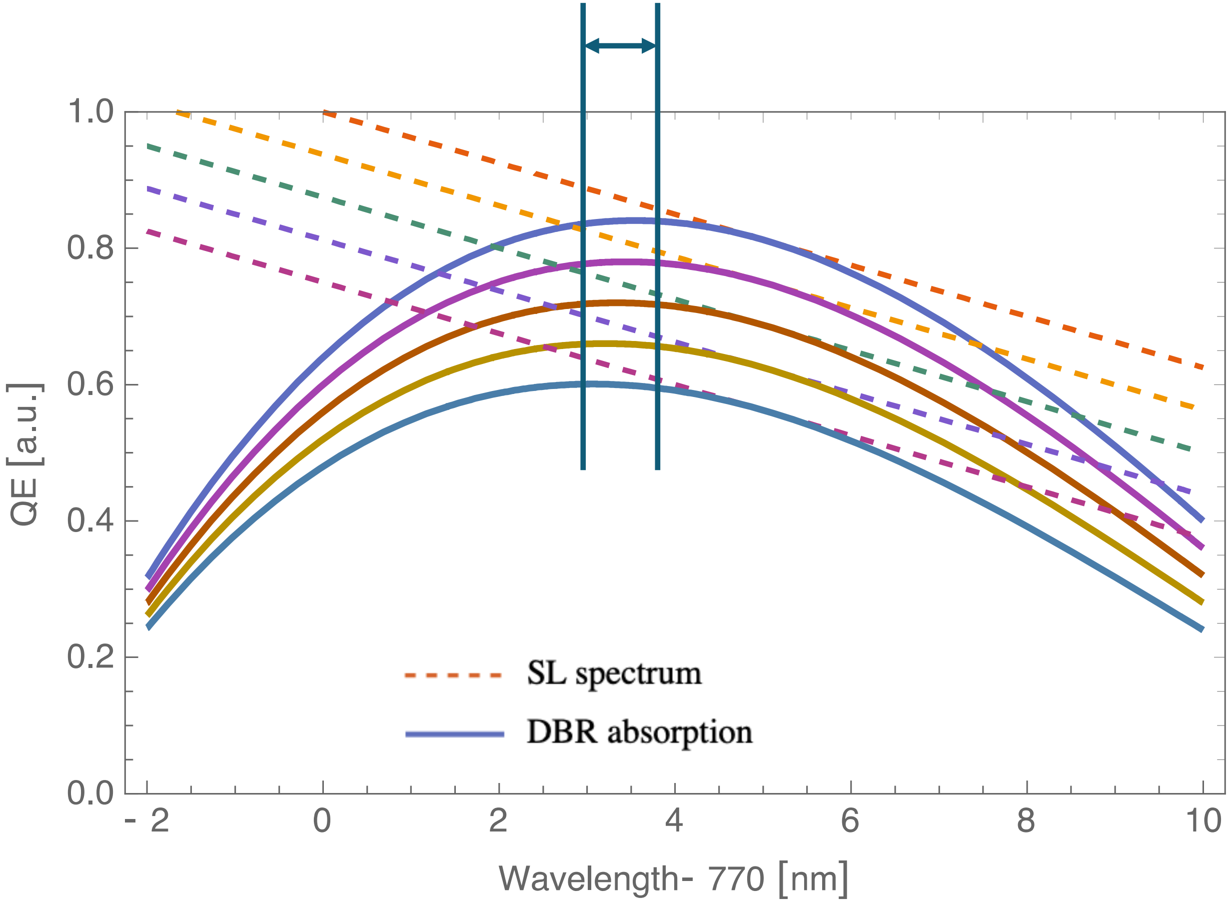
Our approach:
Use two Wien filters, each of which rotates the spin by 45°.
Place a triplet between the Wien filters to focus the beam (~achromatic).

Single Wien filter

Double Wien filters



Peak-Frequency Change Is Also Relevant to Activation



DBR-SL spectrum =
DBR-layer absorption × SL spectrum

When the SL spectrum shifts to the left because of an increased work function, the DBR resonance peak also shifts to the left.

With long-term use of DBR-SL GaAs, will the QE decrease progressively faster if the initial operating point is at the peak?