LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

High voltage DC gun using Super lattice GaAs photocathode for EIC polarized electron source

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Electron-Ion Collider

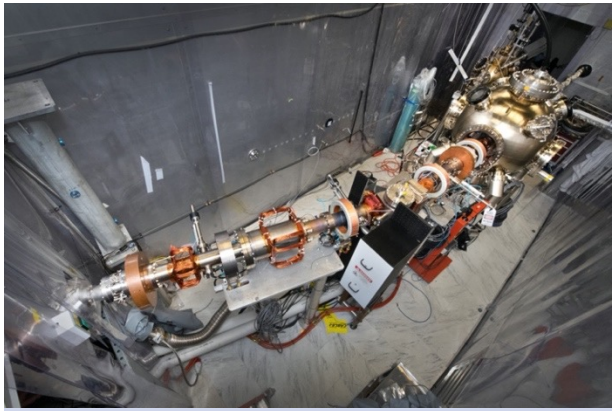
BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

Polarized electron source development at BNL

	EIC	Achieved in stable operation
Bunch charge [nC]	7	7.5 (12)
Peak current [A]	3.8	4.8 (No SCL)
Frequency [Hz]	1 (8 bunches)	1 (9000 bunches)
Voltage [kV]	300	300
Average Current	56 nA	76.5 uA
Polarization [%]	> 85%	Bulk (~35%)/SL (~90%)



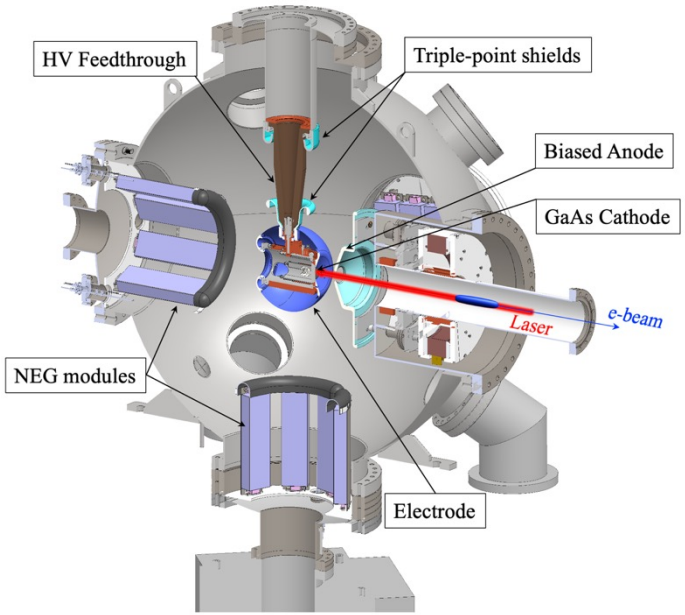
Challenges were:

1. Achieve high voltage with no field emission
2. Have excellent vacuum
3. High charge with high polarization

High voltage is benefit to both nuclear physics and high energy physics program

- Higher charge
- Low emittance
- Long lifetime

HVDC gun design



New features includes:

- Active cathode cooling
- Large cathode
- Semiconductor jacket HV cable
- x,y,z moveable electrically insulated anode.

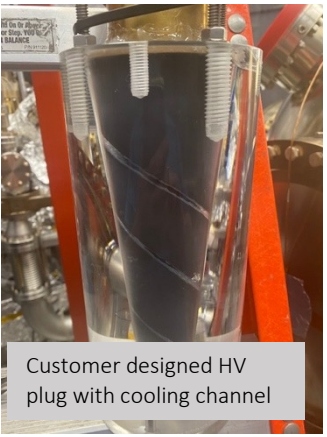
	Inverted gun
Ball diameter	20 cm
Chamber diameter	80 cm
Gap distance	5.7 cm
Voltage	350 kV
Cathode size	1.3 cm
Electrodes angle	22 degs
Cathode gradients	4.0 MV/m
Maximum gradient	9.8 MV/m
Anode diameter	2.2 cm
Peak current	4.8 A
Bunch charge	7 nC
N_emittance	3.6 mm-mrad
Pumping speed	35000 L/s
Anode bias	3000 V

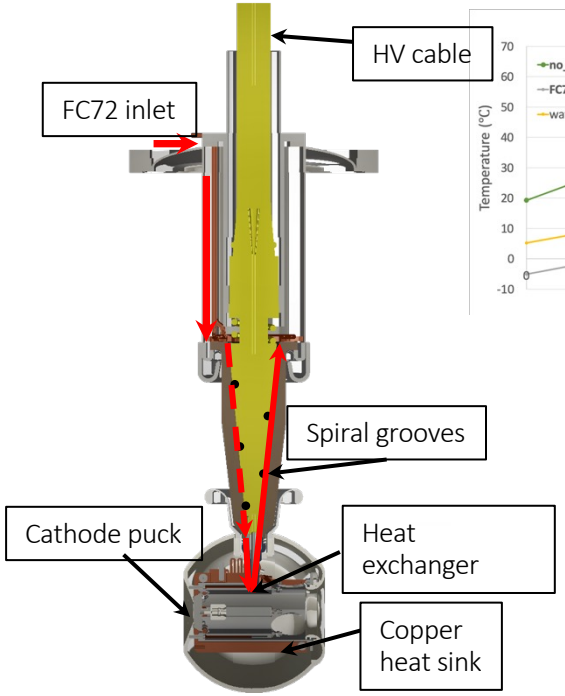
E. Wang et,al Phys. Rev. Accel. Beams **25**, 033401, 2022

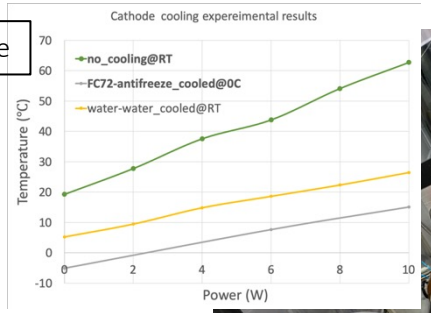
Active cooling of HVDC gun

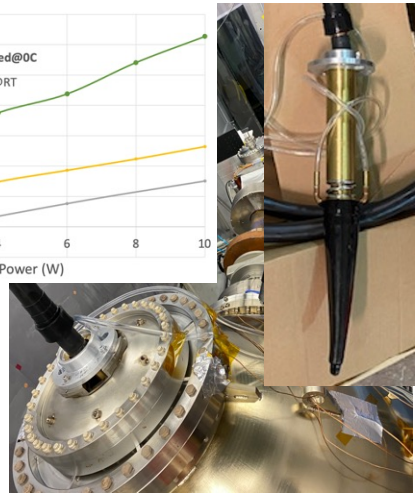
Aiming to absorb the laser power up to 10 W with cathode temperature ~25 ºC

Tested up to 410 kV with flow





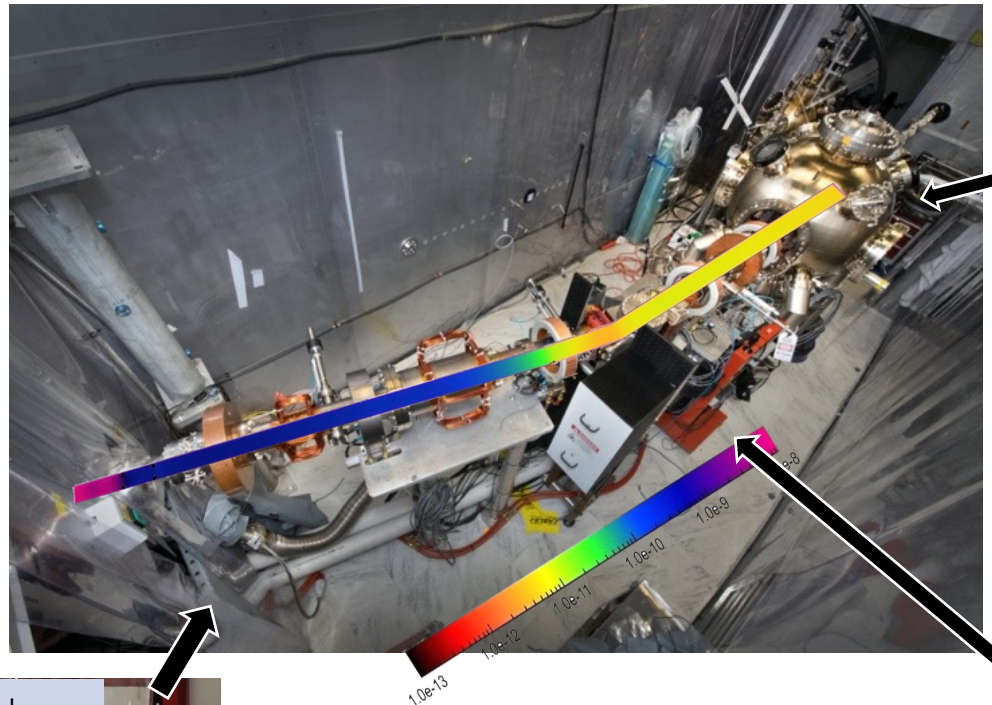




- Tested in the gun with FC 72. Operate @300-350 kV for more than 500 hrs . No failure.
- Maintain every 2-4 months.

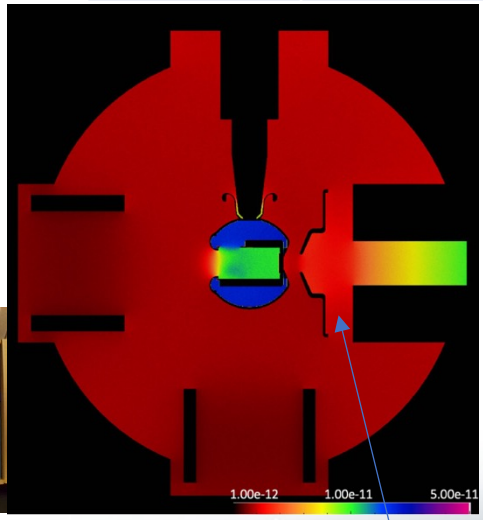
It was designed for high current operation. Not necessary for EIC polarized source. But beneficial towards high current polarized/unpolarized gun.

Beam-line vacuum in experim

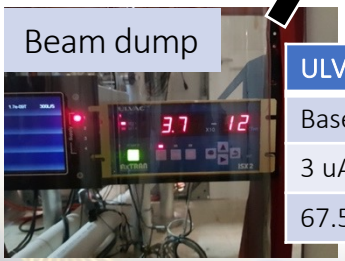


Gun Vacuum
3BG gauge

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

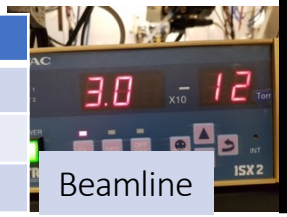


Beam dump



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

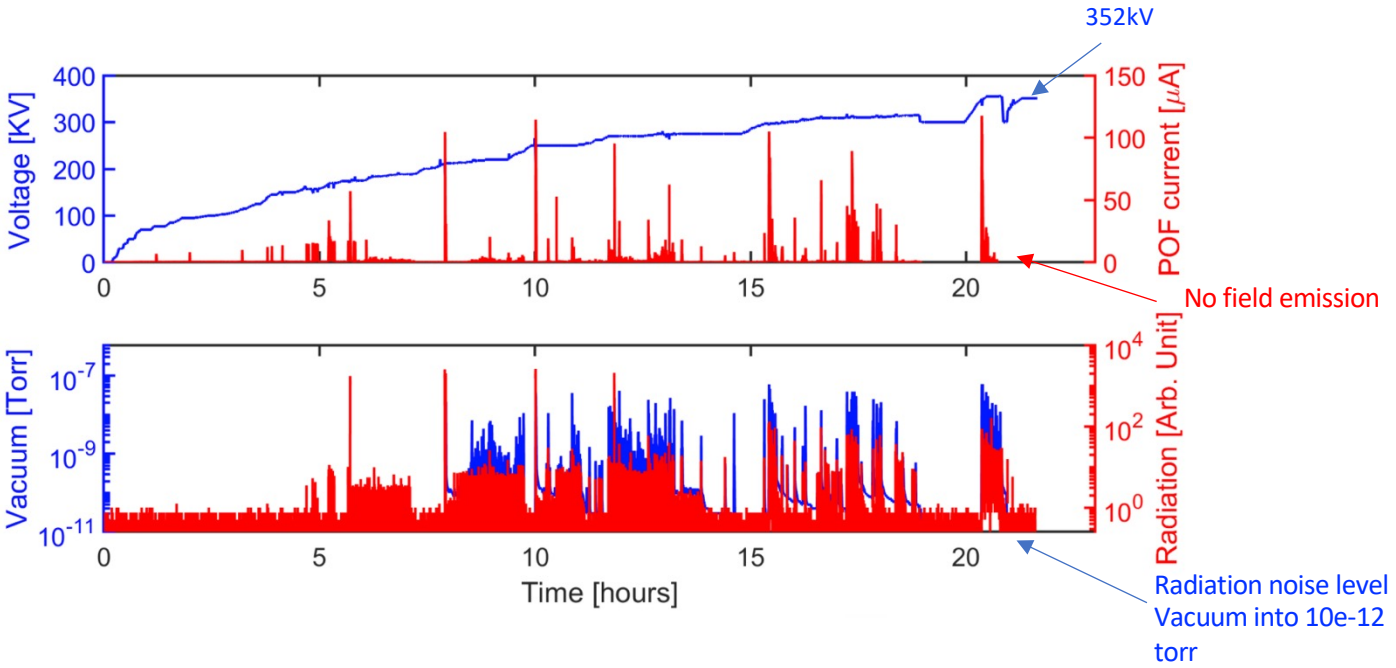
ULVAC gauge	Beam Line
Baseline	3-4 e-12
3 uA	5e-12
67.5 uA	1.5-3 e-11



Beamline

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

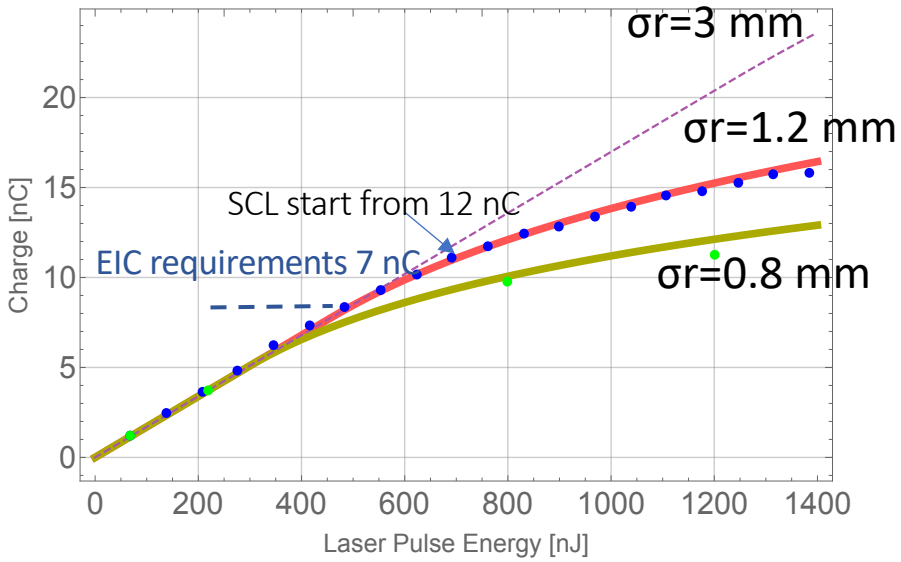
HV conditioning

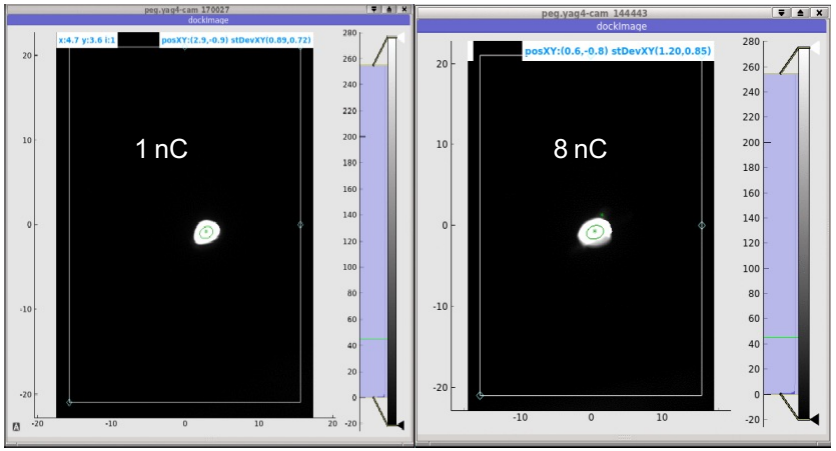


Gun first conditioning performance (vacuum conditioning, total take 23 hrs, Cooling is on):

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

Bunch charge vs Laser pulse energy



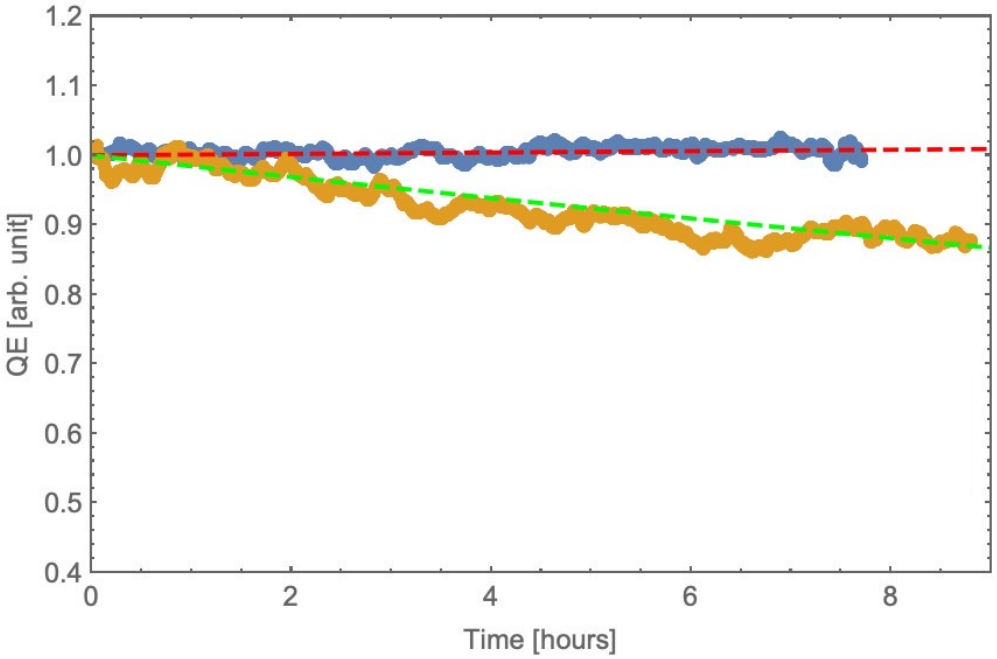


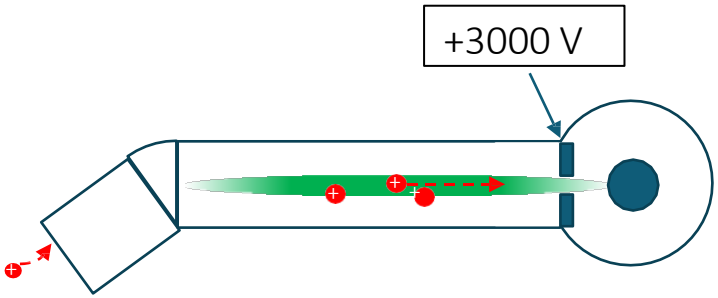
Beam image before the dump

- Space charge limit starts from 12 nC
- EIC requirement is 7 nC
- We can increase active area to increase Space charge limit

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

Cathode lifetime with and without anode bias





- Our 16 deg bending eliminate the ions from FC.
- The ions from gun to 1st bend can be blocked by biased anode.

- Using 7.5 nC bunch charge polarized beam, 5000 pulses/s ~37.5 uA;
- With anode bias, we didn't observe any QE drop for 7 hours.
- Without anode bias 1/e lifetime is 63 hrs. Dominated by the outgassing from FC.
- Charge from 7 hours test= 33 weeks of EIC operation

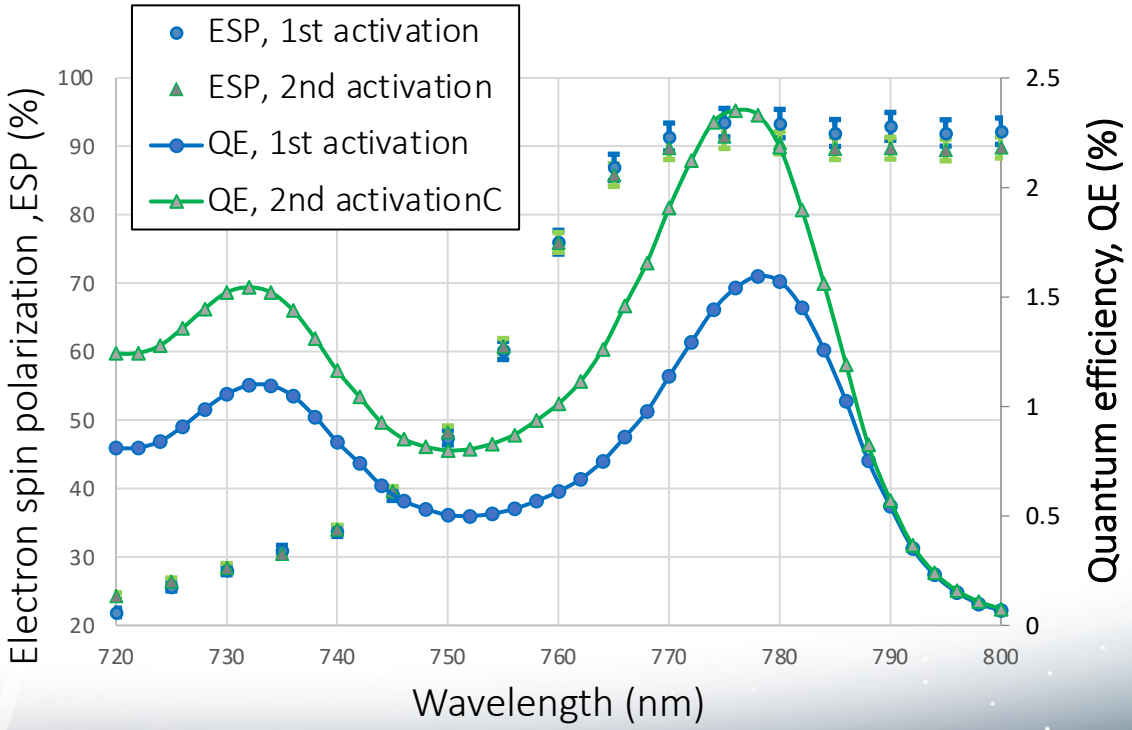
High polarization photocathode

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.

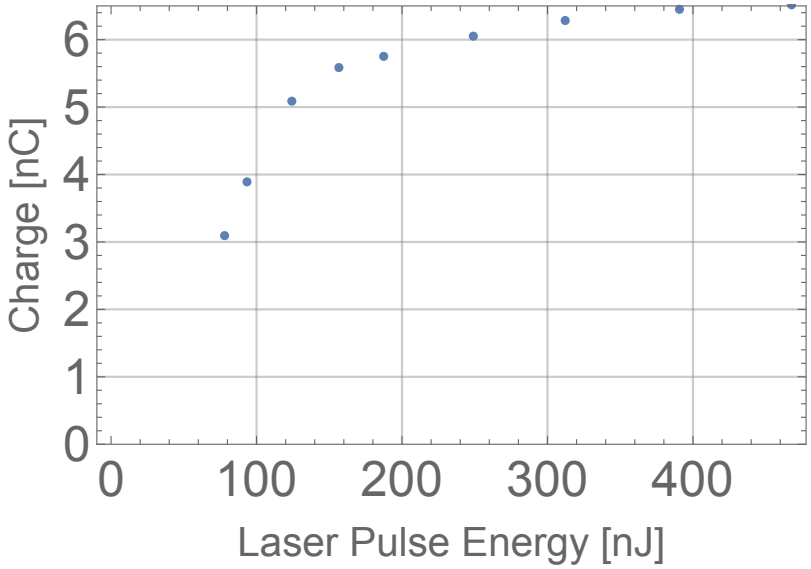
ODU/BNL/JLab: GaAs/GaAsP SL with AlGaAs/GaAsP DBR

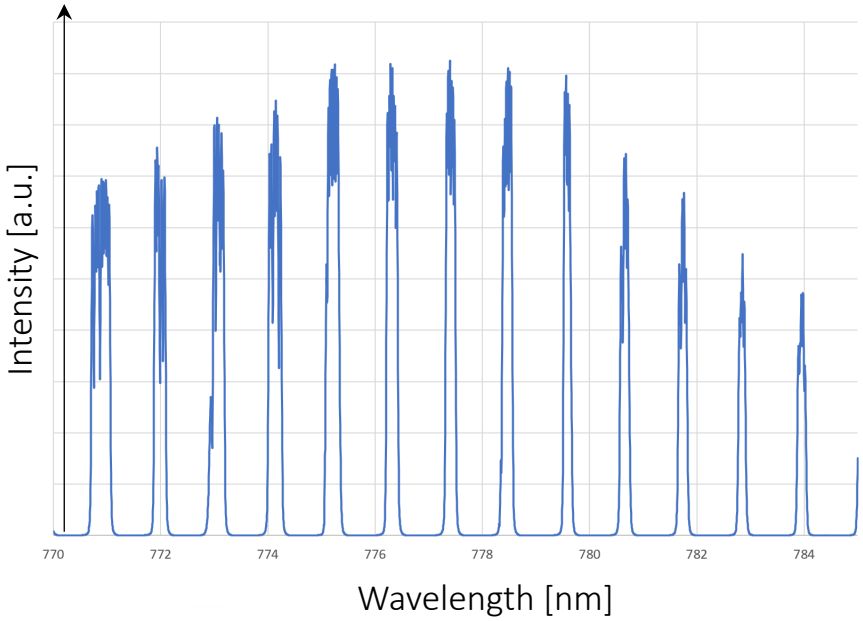
- Best performance: QE=2.35%, ESP=92%

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 $GaAsP_x$ ($x=0$~0.35)	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})		



DBR-SL GaAs performance in the gun





- We developed circular polarized laser with tunable wavelength.
- We tested DBR-SL-GaAs in the gun, generated 6.5 nC bunch charge and showed good lifetime.
- Charge from 9 hours 2 nC with 9000 pulses operation(20 weeks of EIC operation). Decay 10%.
- DBR SL-GaAs cathode tests are still in progress.

E. Wang IPAC 23 TUPA131

Summary

- High voltage polarized gun is helping to get higher charge and good beam quality polarized electron beam, also benefit to the lifetime.
- We have established the HVDC gun which can operate at 300 kV with 7.5 nC polarized electron beam stably.
- Gun includes new features such as: active cooling of cathode, large cathode size.
- Lifetime surpasses EIC requirements by a large margin, for orders of magnitude higher average current
- We tested DBR-SL-GaAs in the gun, generated 6.5 nC bunch charge and showed acceptable lifetime.

Thanks for your attention!

Questions?

Acknowledge
BNL: O. Rahman, C. Degen, P. Inacker, W. Liu, R. Napoli, M. Paniccia, J. Skaritka, J. Biswas

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

Old Dominion University: S. Marsillac and A. Masters

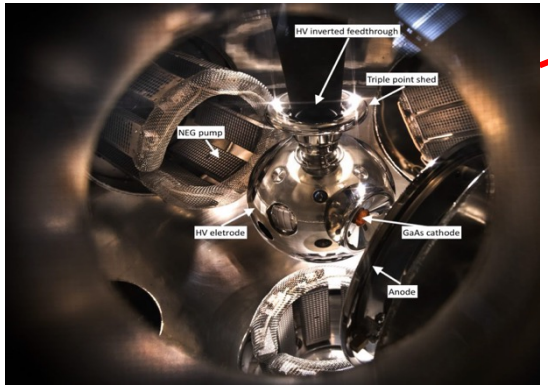
Cornell University: K. Smolenski

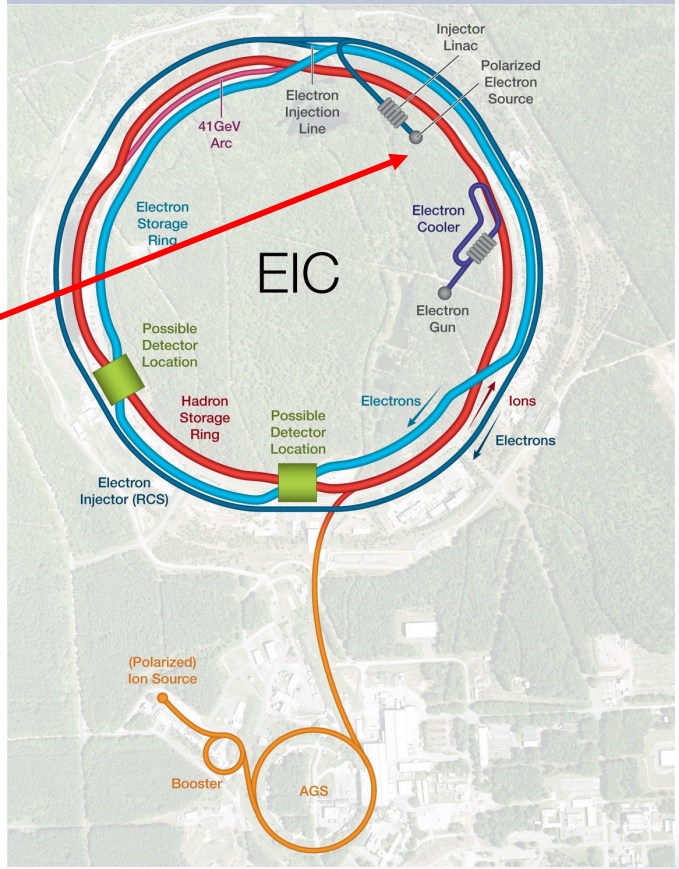
Electron Ion Collider Accelerators

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

Design based on existing RHIC, RHIC is well maintained, operating at its peak performance.

- Hadron storage ring 40-275 GeV (existing)
- Electron storage ring (2.5–18 GeV, new)
- Electron rapid cycling synchrotron (new)
  - High charge polarized pre-injector

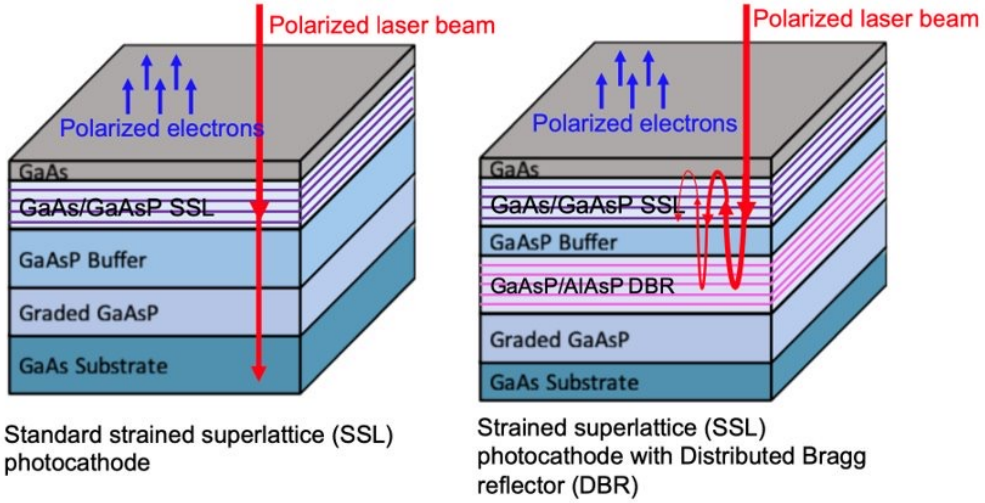




- 300 kV polarized HVDC gun generates 7nC x 8 polarized electron beam every second.
- 400 MeV pre-injector

1. W. Liu, etc., Appl. Phys. Lett. **109**, 252104 (2016)

DBR photocathodes



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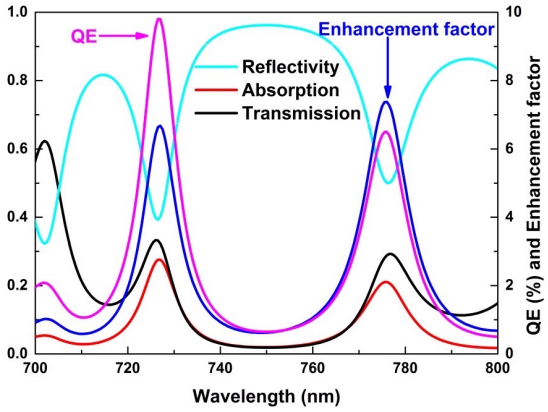
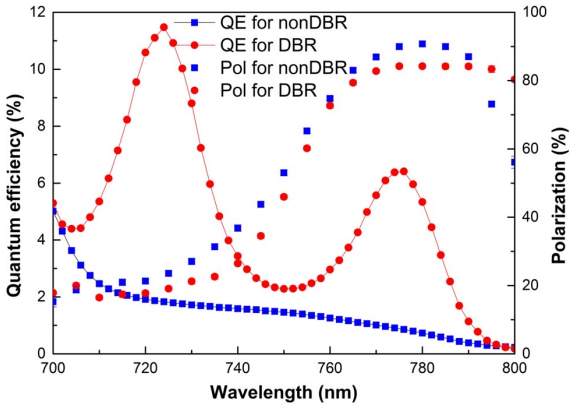
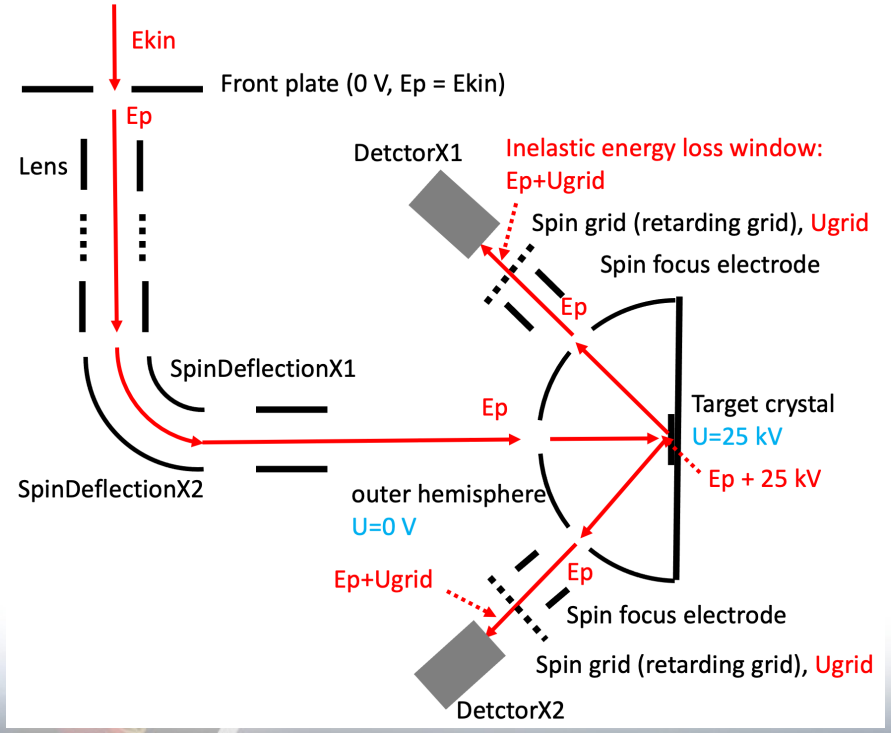




Compact Mott detector

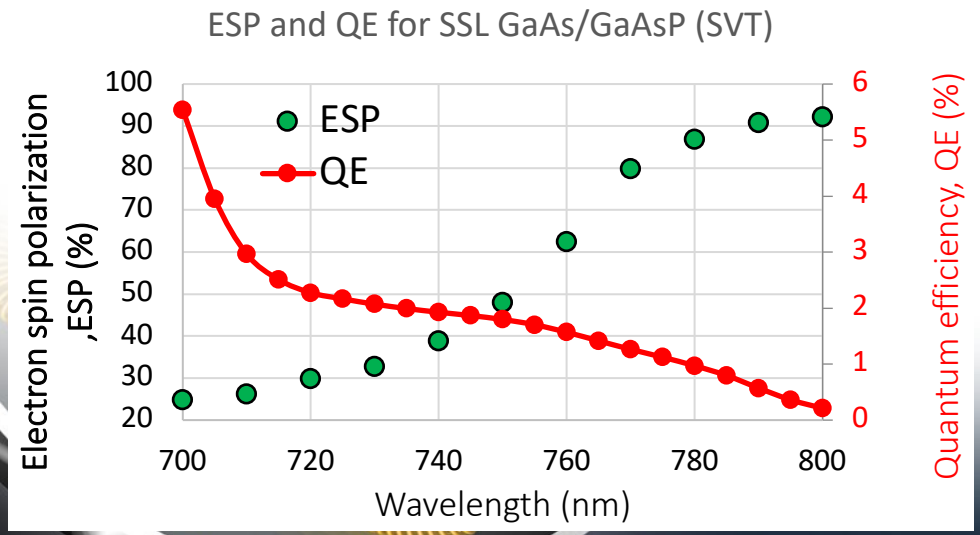
- BNL purchased a retarding field Mott from Specs
- It is used for measure GaAs polarization
- $S_{eff} = 0.26$ for 20-25 kV

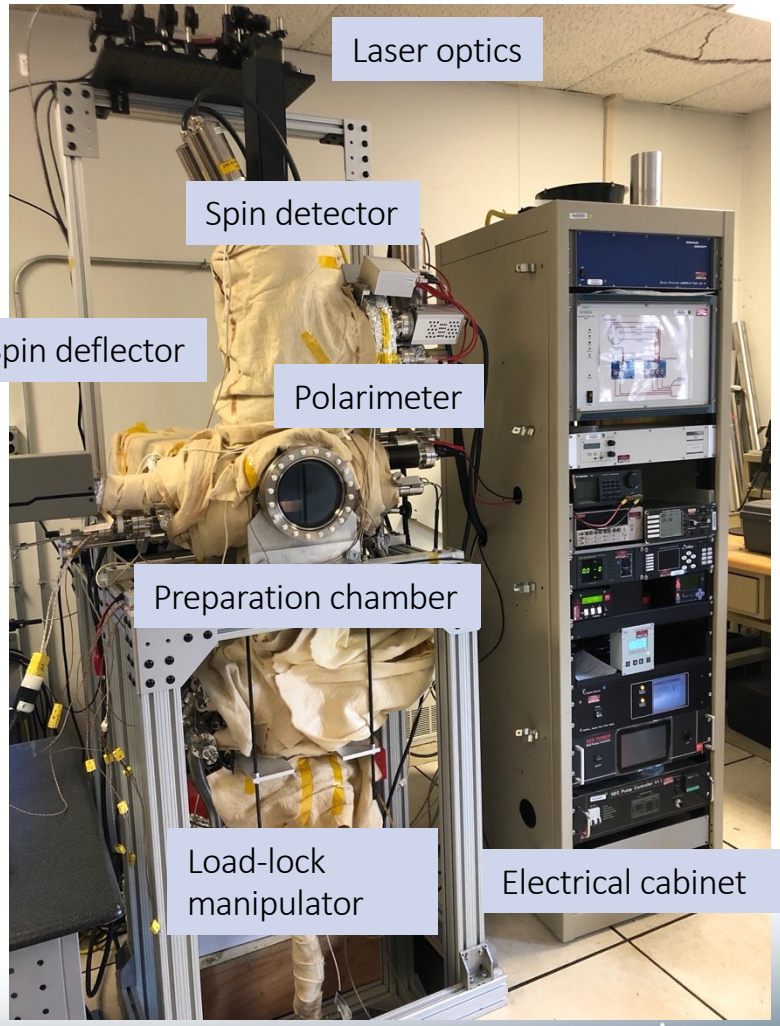


Specs Mott polarimeter system

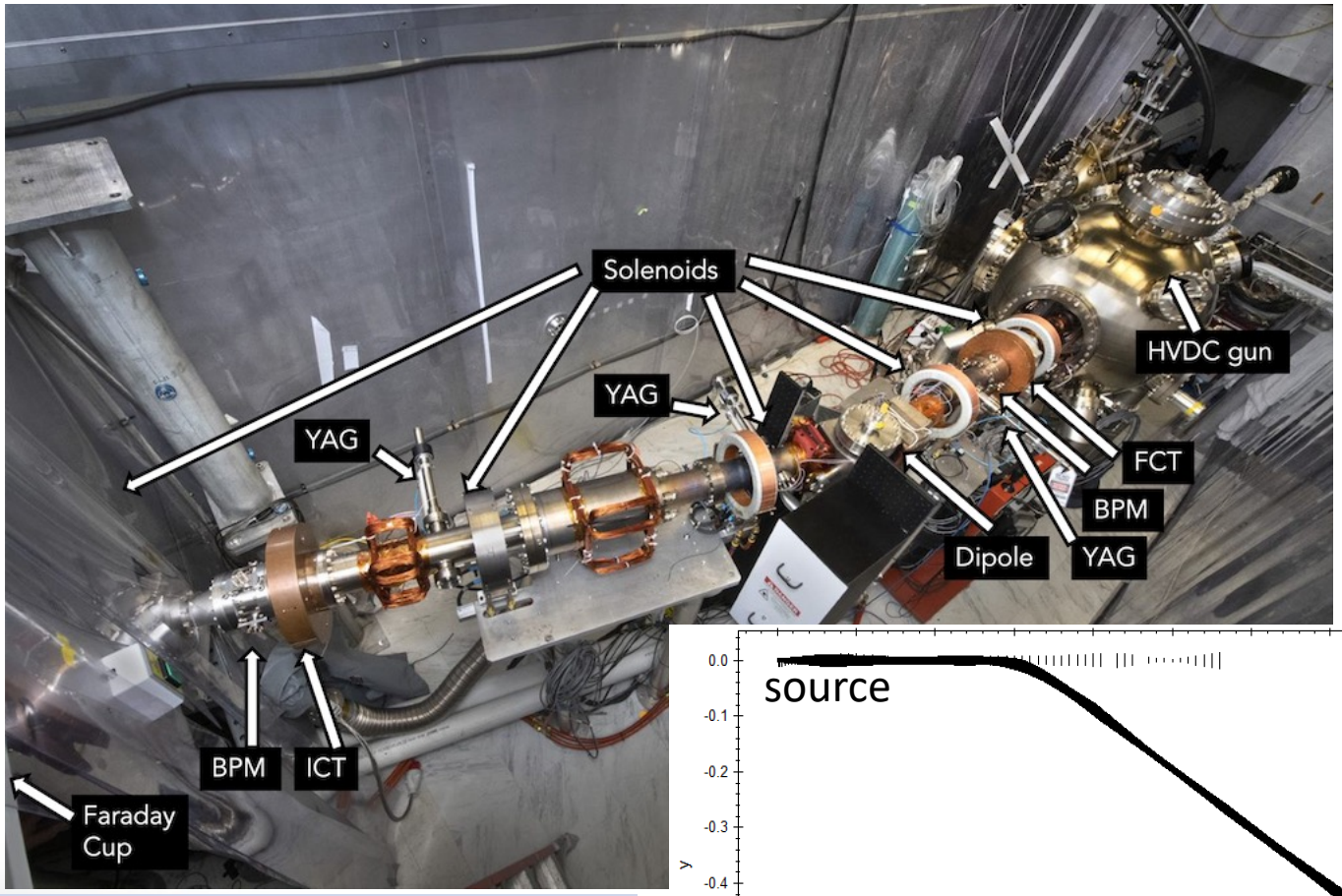
- We established polarization measurement for polarized electron source using mini-Mott.
- Several SL-GaAs samples(SVT ,Sadia, ODU) have been measured.

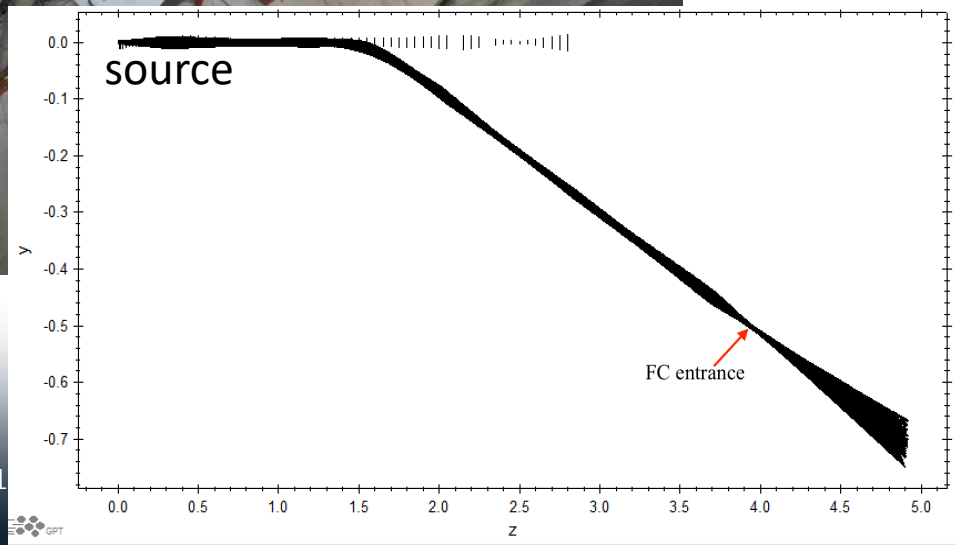
SVT(USA) was the best vendor. Expert moved to Acken Inc(China). 6 wafers order submitted(delayed due to Shanghai lock down, delivery time Aug. 22nd)
US SL-GaAs vendor is growing (ODU, Sadia, et,al). We expect the US supply train will be restored by the EIC start operation.





Test beam line at SBU





Beamline designed using 3D code GPT

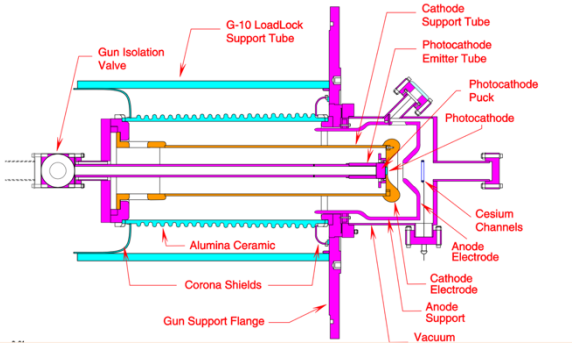
Overview polarized guns in the world

Laboratory	Voltage	Bunch charge	I_pk	I_avg
JLab[1]	100, 200kV	2 or 2.7pC	67~53mA	Up to 4mA
SLC[2]	120kV	8-16 nC	3 A	2uA
MAMI[3]	100kV	0.02 pC		50uA
Bonn-ELSA[4]	50kV	100 nC	100mA	5uA
MIT-BATES[5]	60kV	250 nC	10mA	20 or 120uA
Nagoya[6]	200kV	1.25 nC??	2A??	NA
NIKHEF[7]	100kV	2us	NA	0.04uA
EIC	300kV	7-16 nC	4.8 A*	3 uA, up to 76 uA

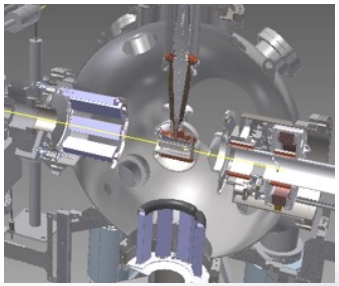
* 1.6 ns laser; 3.5-8 A; No charge limit up to 4.8 A

In operation
Shut down
EIC gun achieved

SLC PES 120 kV gun



- First load-locked gun used at an accelerator
- High bunch charge, low avg. current
- Four days to activate photocathode,



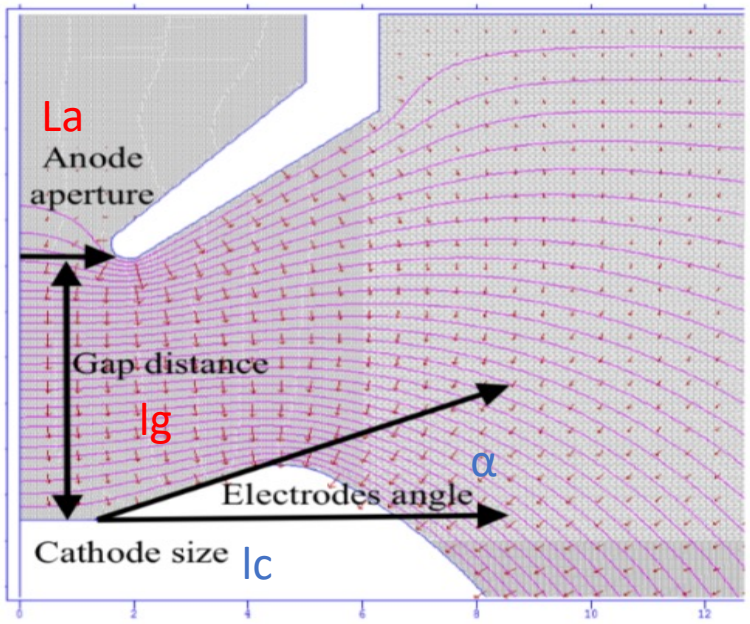
- Inverted gun, first cooled cathode set up
- High voltage
- Lifetime > month

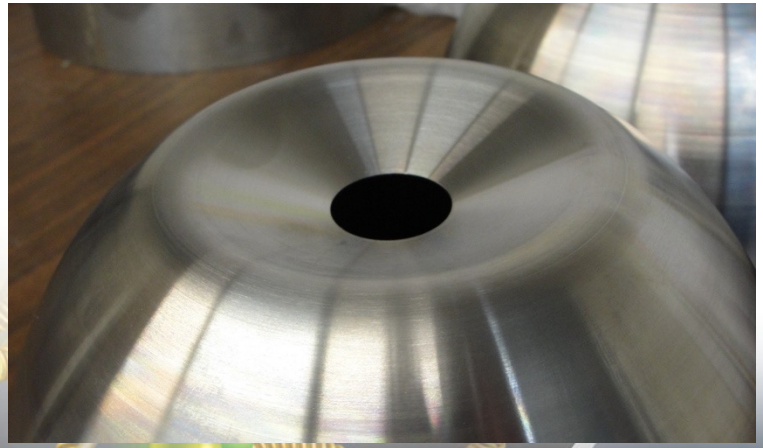
EIC polarized electron source development scope change

	ERL eRHIC (abandoned)	EIC
Bunch charge [nC]	5.3	5.5-7
Bunch length [ps]	1760	20-40
Energy spread dp/p	1e-3	2.5e-3
Frequency [Hz]	1.2 M	1 (8 bunches)
Energy [MeV]	20	400
Average Current	6.3 mA	28-56 nA
Polarization [%]	> 85%	

- By change the scope, our planned beam dump , differential pumping, laser and MPS are not available.
- Limited up to 76 uA average current>> EIC requirements.

BNL Large Cathode Prototype Gun Parameters

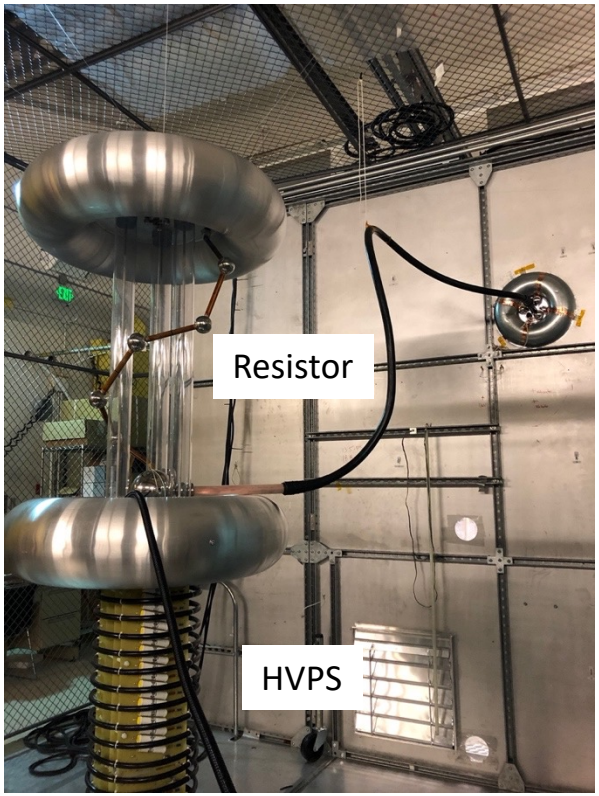


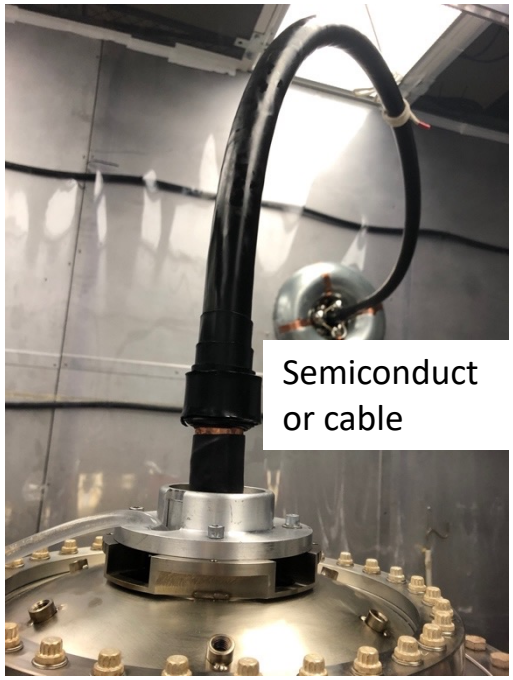


	Inverted gun
Ball diameter	20 cm
Chamber diameter	80 cm
Gap distance (lg)	5.7 cm
Voltage	350 kV
Cathode radius (lc)	1.3 cm
Electrodes angle (**α**)	22 degs
Cathode gradients	3.8 MV/m
Maximum gradient	<10 MV/m
Anode radius(la)	1.7 cm
Pumping speed	20000 L/s
Anode bias	3000 V
Peak Current	4 A
Charge	7 nC
Target emittance	3.4 mm-mrad

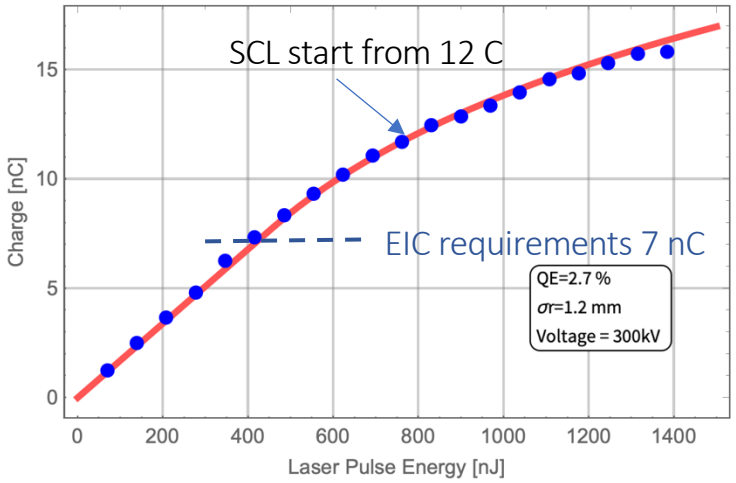
Power supply and HV cable

- 400 kV Power supply is SF6 free set up.
- PS is 5 meter away from the gun within a grounded cage.
- Resistors for gun conditioning and 460 ohm resistor for beam operation.
- Custom designed Semiconductor jacket to reduce the storage energy(50pF/ft, 46 Joules) into the DC gap if discharge happen





Space charge limit

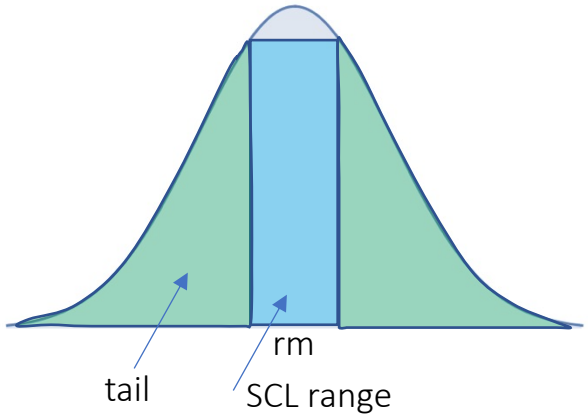


$785 \pm 1.3\ nm$

FWHM 1.64 ns

Longitudinal flattop

Transverse Gaussian



A Gaussian radial distribution on the cathode,

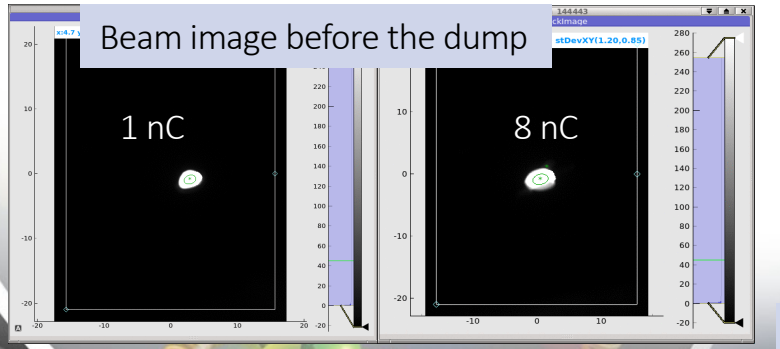
Surface charge density: $\sum(r) = \frac{Q_{bunch}}{2\,\pi\,\sigma_r} e^{-\frac{r^2}{2\sigma_r^2}}$

$$Q_{emitted} = Q_{scl} + Q_{tail} = \pi r_m^2 J_{2d} + QE\frac{e\,E_{laser}}{\hbar\omega} e^{-\frac{rm^2}{2\sigma_r^2}}$$

Pencil shape 2D space charge limit:

$$J_{2d} = 2.33 \times 10^{-6} V^{3/2}/d(1+\frac{d}{4r})$$

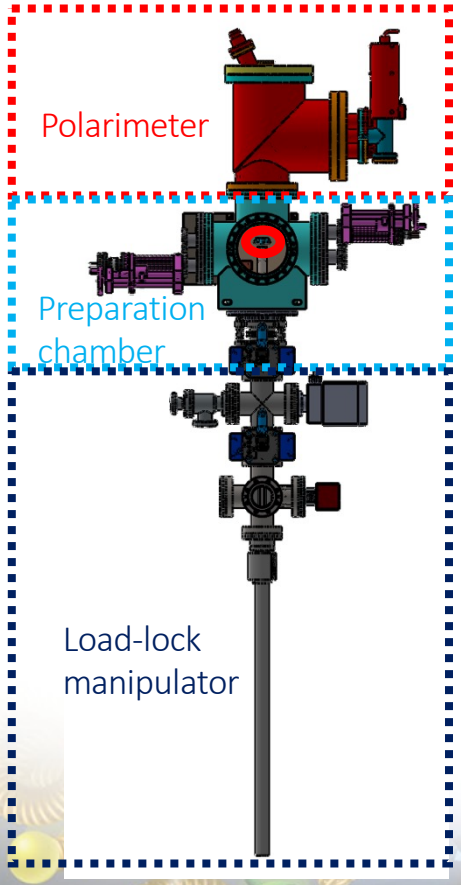
If rm>0, then space charge limit happen

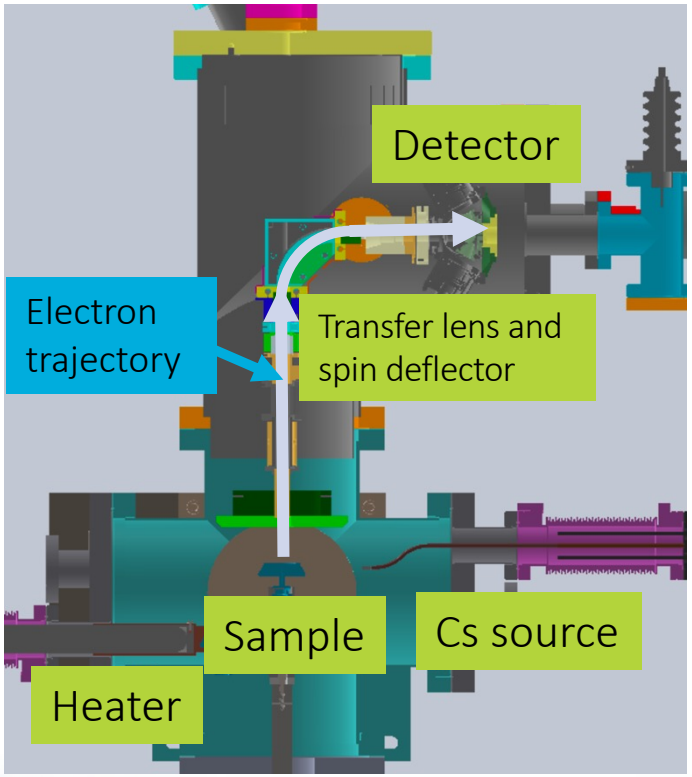


Cathode activation size is 6 mm in diameter, while our cathode size is 2.6 cm. We can get higher charge if have large activation area.

Established polarization measurement

It is for GaAs polarization measurement, not suitable for gun beam.





The system at 966 has 3 parts:

- Load-lock manipulator (BNL)
- Preparation chamber (BNL)
- Polarimeter (*Specs*)

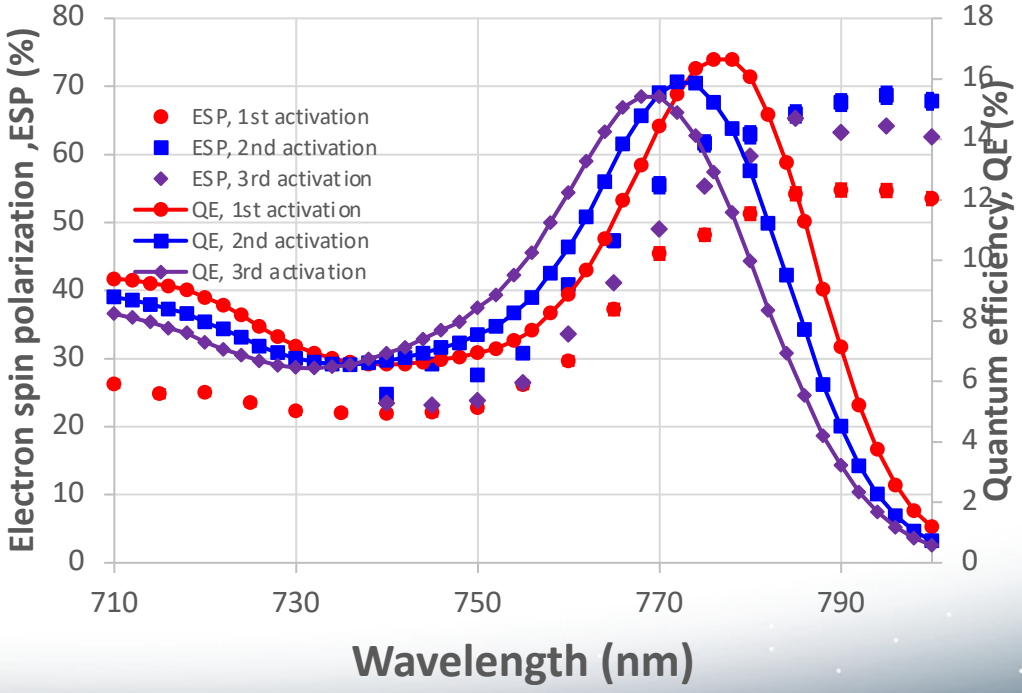
•Feature of the system:

- The load-lock system is matched to the polarized gun load-lock.
- Use the same cathode puck as the gun puck.
- The Mott system is light source II beamline compatible.

MBE photocathode progress

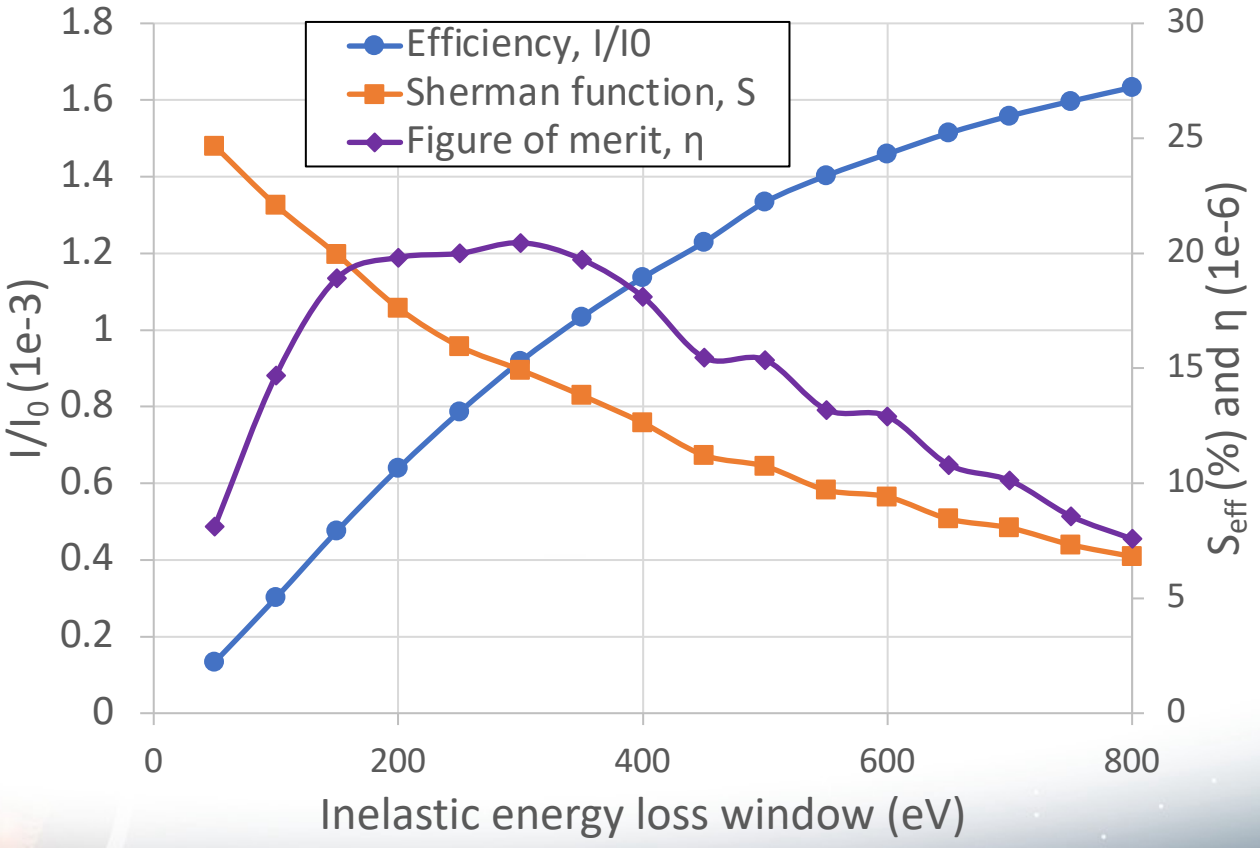
BNL and Sandia: SC GaAs/GaAsP SL with AlGaAs/GaAsP DBR
2 DBR samples
Best performance: QE=16%, ESP=61%

GaAs	5 nm	$p = 5x10^{19}$ cm^{-3}
$GaAs/GaAs_{0.62}P_{0.38}$	(4/4 nm) x30	$p = 5x10^{17}$ cm^{-3}
$GaAs_{0.81}P_{0.19}$ (+2.6%)	309 nm	$p = 5x10^{18}$ cm^{-3}
$AlAs_{0.81}P_{0.19}/GaAs_{0.81}P_{0.19}$	(66.7/56.4 nm) x 10	$p = 5x10^{18}$ cm^{-3}
$GaAs_{0.81}P_{0.19}$	2000 nm	$p = 5x10^{18}$ cm^{-3}
$GaAs->GaAs_{0.81}P_{0.19}$	2750 nm	$p = 5x10^{18}$ cm^{-3}
GaAs buffer	200 nm	$p = 5x10^{18}$ cm^{-3}
GaAs substrate		$p > 1x10^{18}$ cm^{-3}



Polarimeter performance

- The initial energy of electron from photocathode is 200 eV
- The Sherman function is almost linear for ΔE<200 eV
- The theoretical effective Sherman function is 0.27



Measured ESP

- Several GaAs samples have been measured.
- Reasonable ESP for bulk GaAs and SSL GaAs/GaAsP photocathodes are obtained with error < 2% of the value