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U.S. DEPARTMENT OF ENERGY

High Voltage DC Gun for High Intensity Polarized Electron Source

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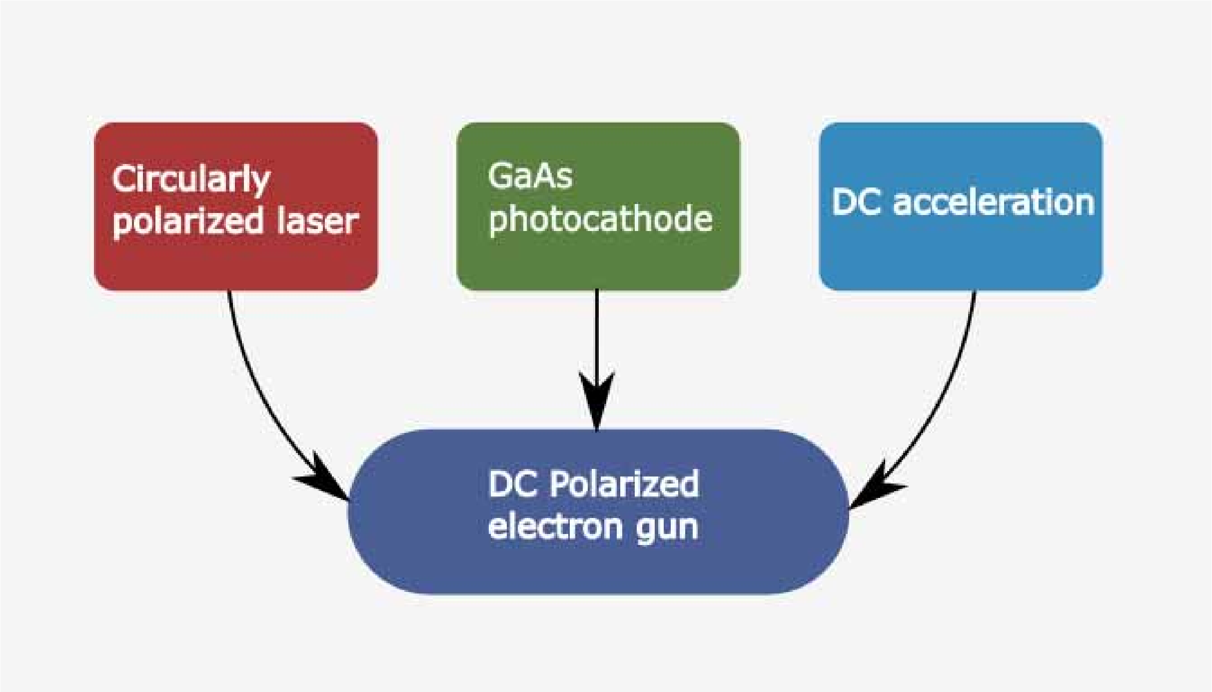
9th August 2022

DC polarized electron sources



- First use in an accelerator in 1970's at SLAC
- Currently being used at CEBAF at JLab, MAMI Mainz. Planned to be used at Electron Ion Collider at BNL
- Used for probes for Nuclear and High Energy physics experiments

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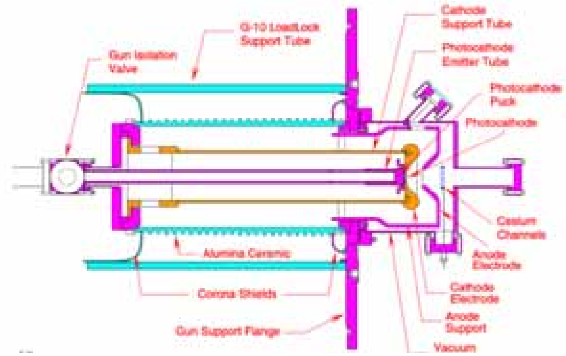
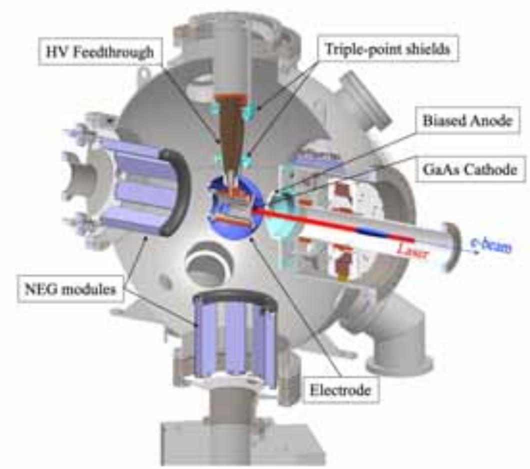
Overview of polarized guns in the world

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 67 uA

In operation
Retired
EIC gun

SLC PES 120 kV gun





BNL EIC inverted 300 KV gun

GaAs for polarized beam

- Needs "activation" with Cs and Oxidant (Oxygen/NF3)
- Circularly polarized light with photon energy of Bandgap (~780 nm)
- Bulk GaAs – about 40% polarization with about 5% QE at 780
- Superlattice GaAs – 100% theoretically, ~95% observed. QE can be 1%-5% (5% shown only for DBR)

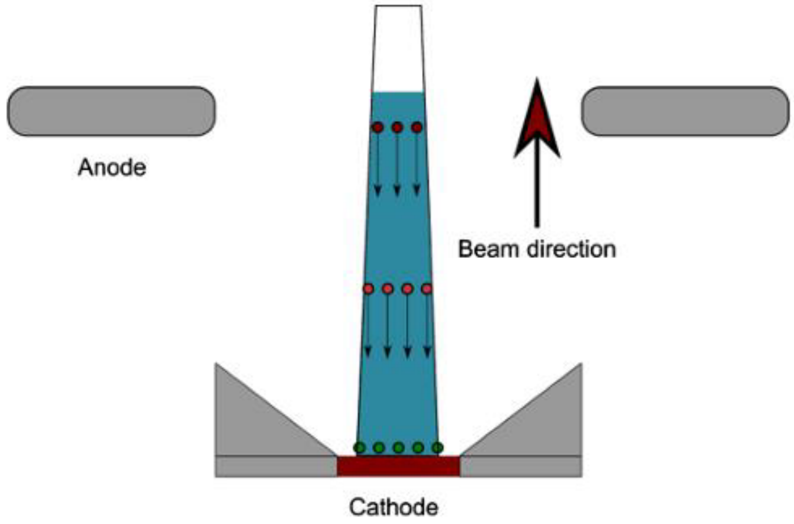
Extremely sensitive to vacuum. Need UHV at the least (better than 10e-11 Torr)

Multiple effects can contribute towards the degradation of "Quantum Efficiency" (electrons emitted per photon).

Many of the challenges in DC guns are related to the lifetime of GaAs in the gun.

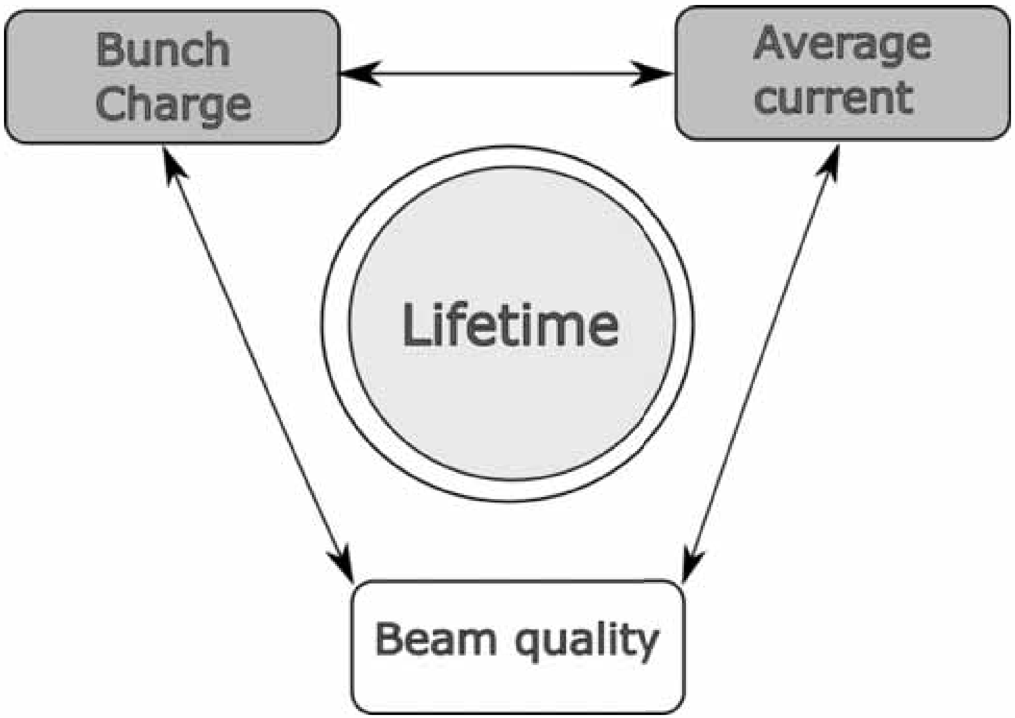
Lifetime limiting Effects

- Poor vacuum (static and dynamic) – Vacuum must be in low UHV (low 11 to 12 scale Torr)
- Unwanted field emission from the gun – spoils vacuum = chemical poisoning
- Ion Back bombardment (IBB) – Only during operation
- Heating of the cathode – Too much laser power without cooling



QE degradation due to IBB depends on:
- Vacuum
- Average current
- Laser spot size

Parameters for polarized gun

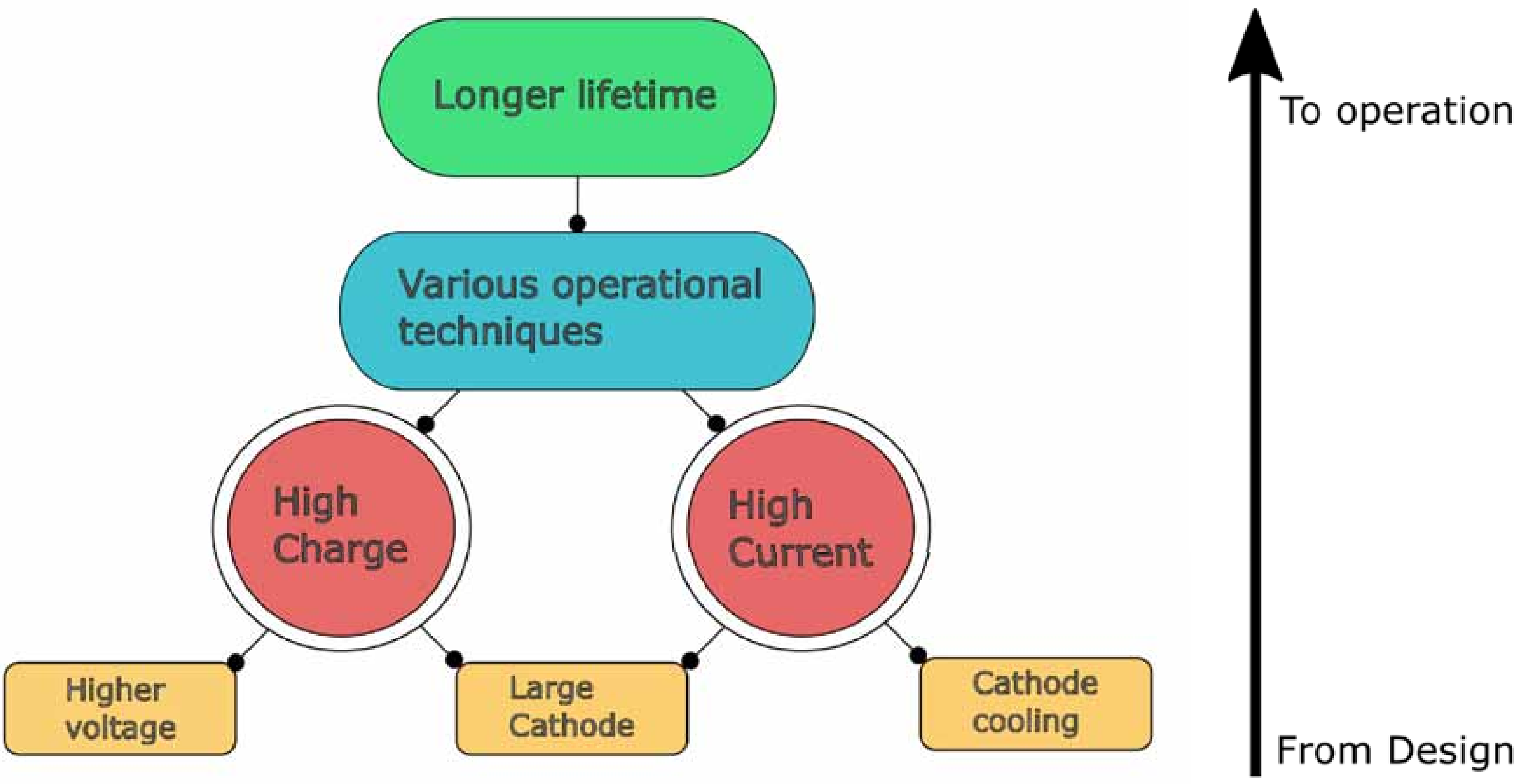


Depends on application. For example –

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

Good/long lifetime is always wanted

Approach towards EIC gun design



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Higher voltage to mitigate Space charge limit

Maximum current density that can be transported across voltage gap:

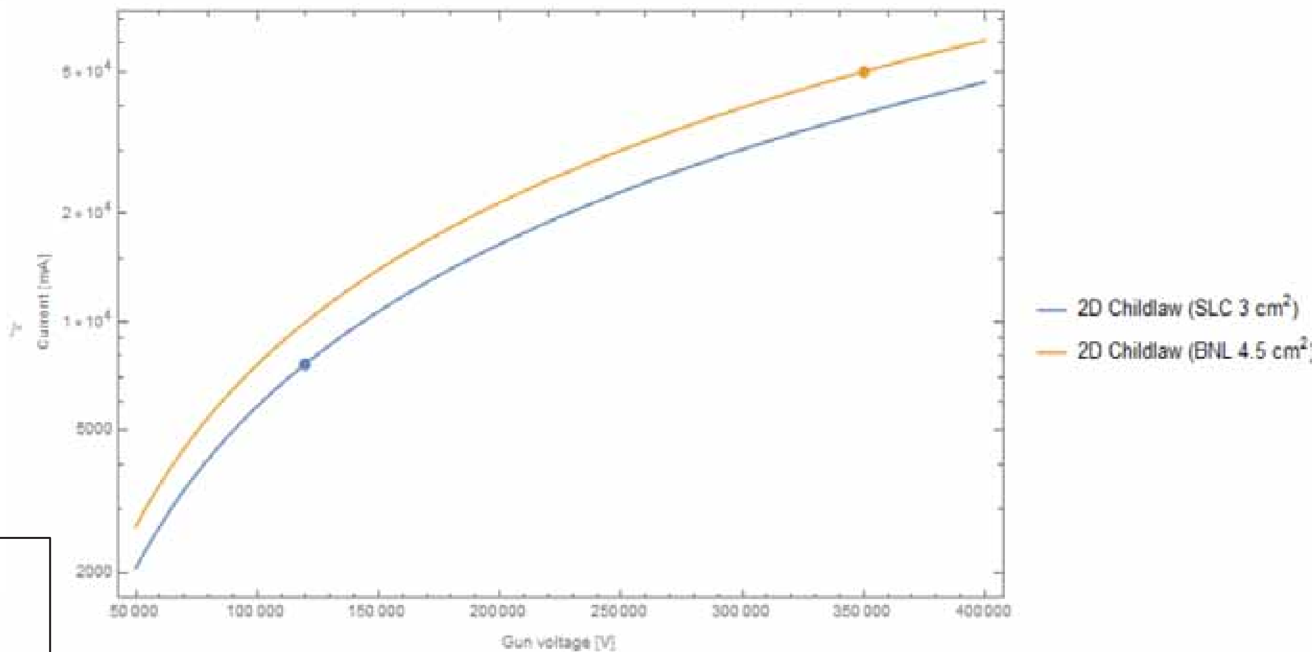
Child's Law 1D (r>>d):

$$j_{1D} = 2.33 \times 10^{-6} V^{3/2} / d^2$$

Child's Law 2D (pencil):

$$j_{2D} = j_{1D}\left(1 + \frac{d}{4r}\right)$$

calculation used 350 KV design



Lau, Y. Y. "Simple theory for the two-dimensional Child-Langmuir law." Physical review letters 87.27 (2001): 278301.

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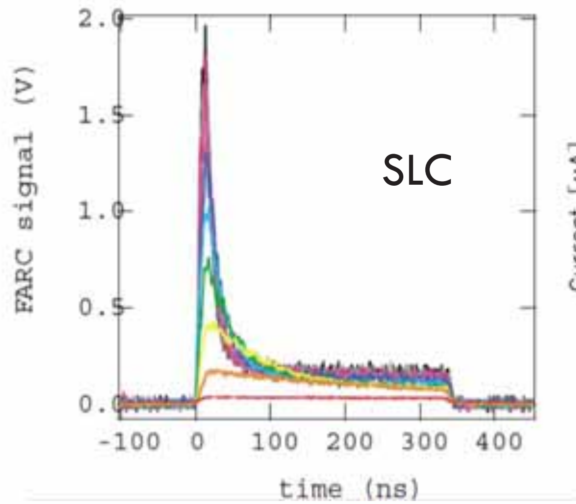
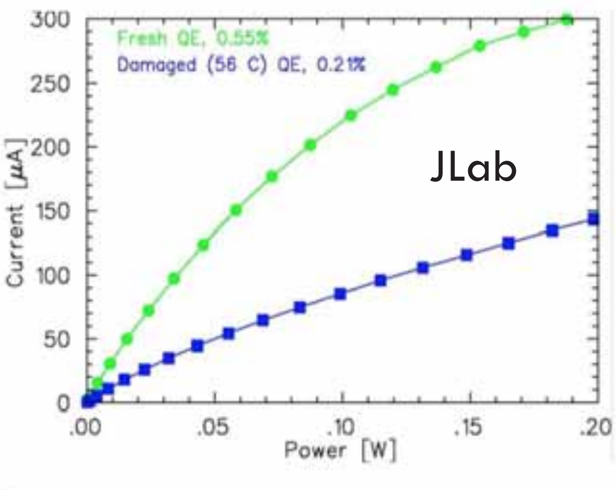
Higher voltage to mitigate surface charge limit





- 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

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

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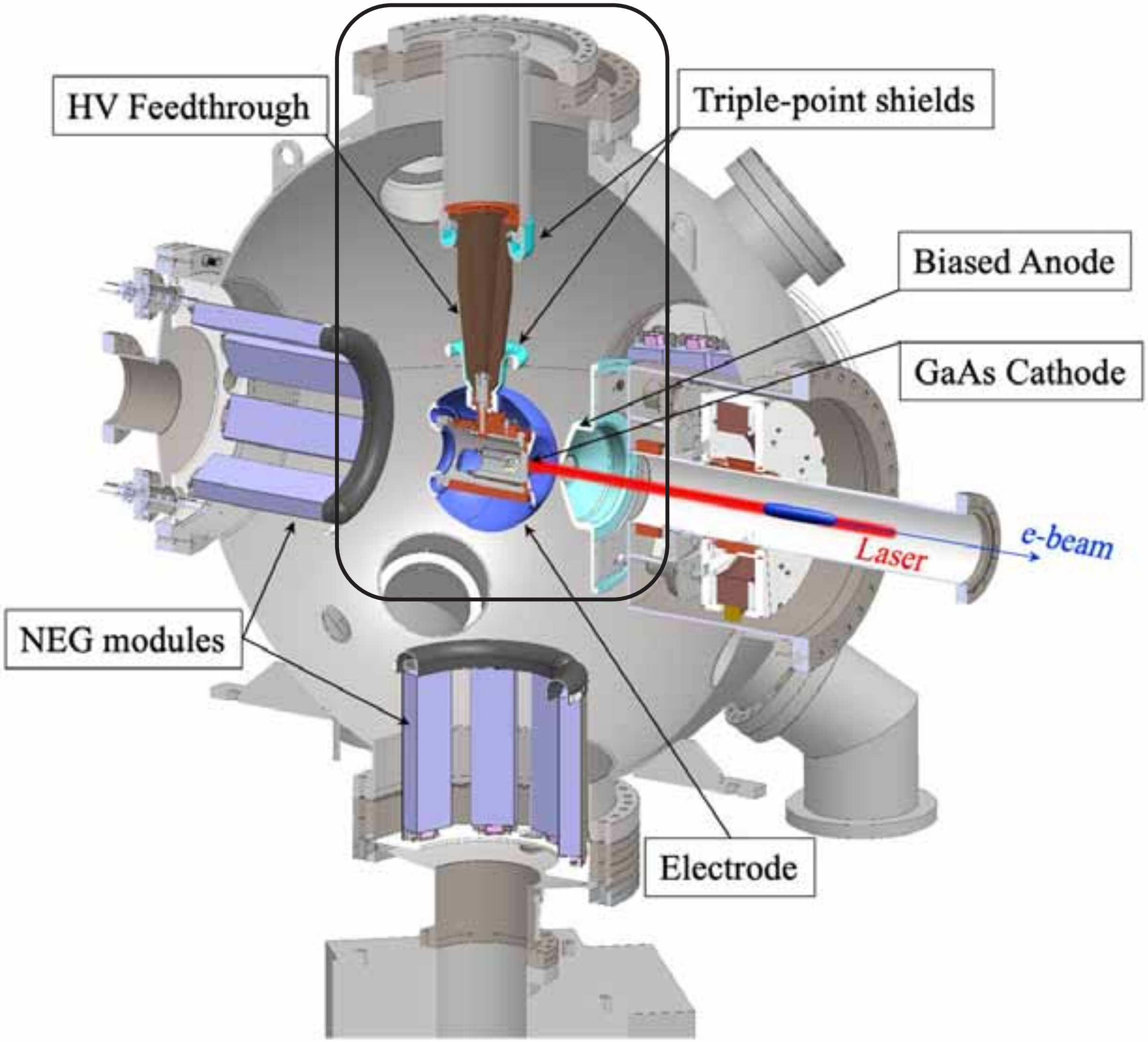
Graph courtesy:
- Takashi Maruyama (SLAC), PESP 2000
- Matthew Poelker (Jlab)- USPAS 2012

EIC gun overview

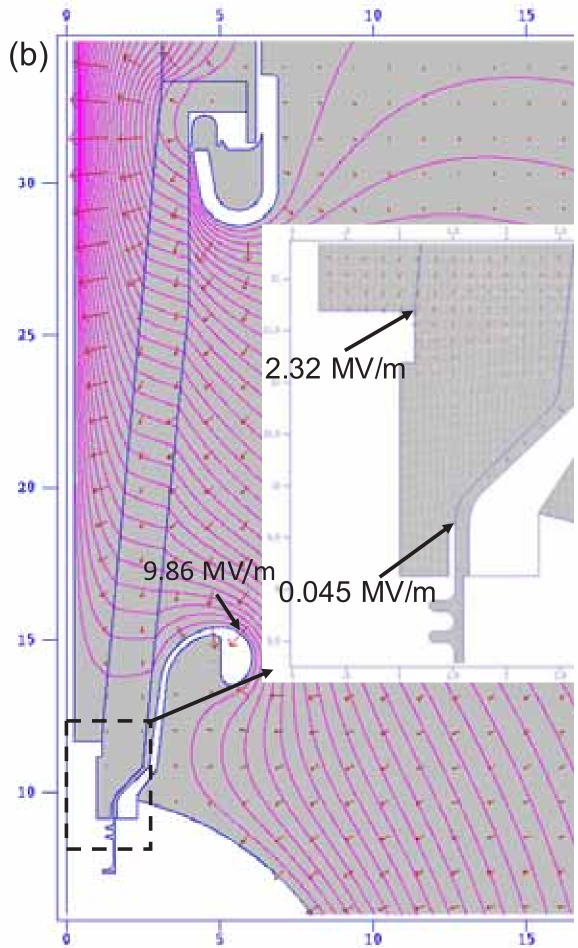


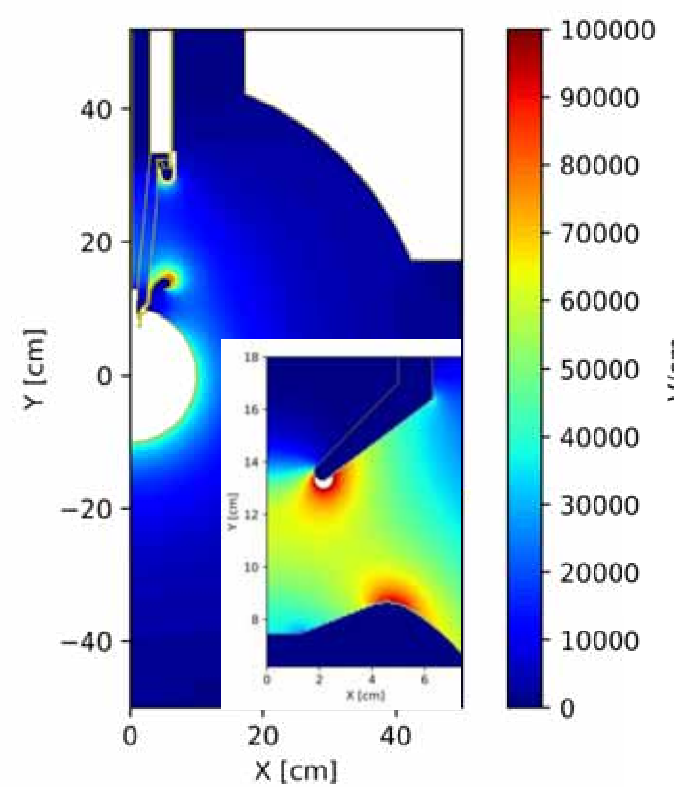
Gun design include:
- high voltage feedthrough
- triple-point shields
- Beam quality, envelop, halo
- Electrode, anode outer shape

Main tools:
- Possion: 2D study
- Opera3D: triple point sheds kick.
- GPT 3D beam tracking, ion back tracking
- Python: field emission tracking, Ion back tracking

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





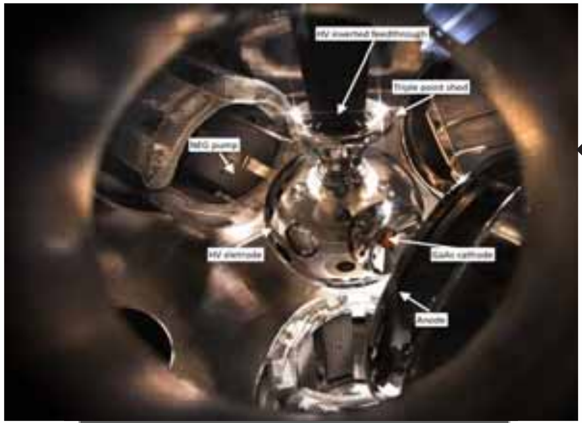
HV electrode treatment and installation

Polish at JLab

HPR at BNL SRF

Installation at SBU

Alignment



Final assembly

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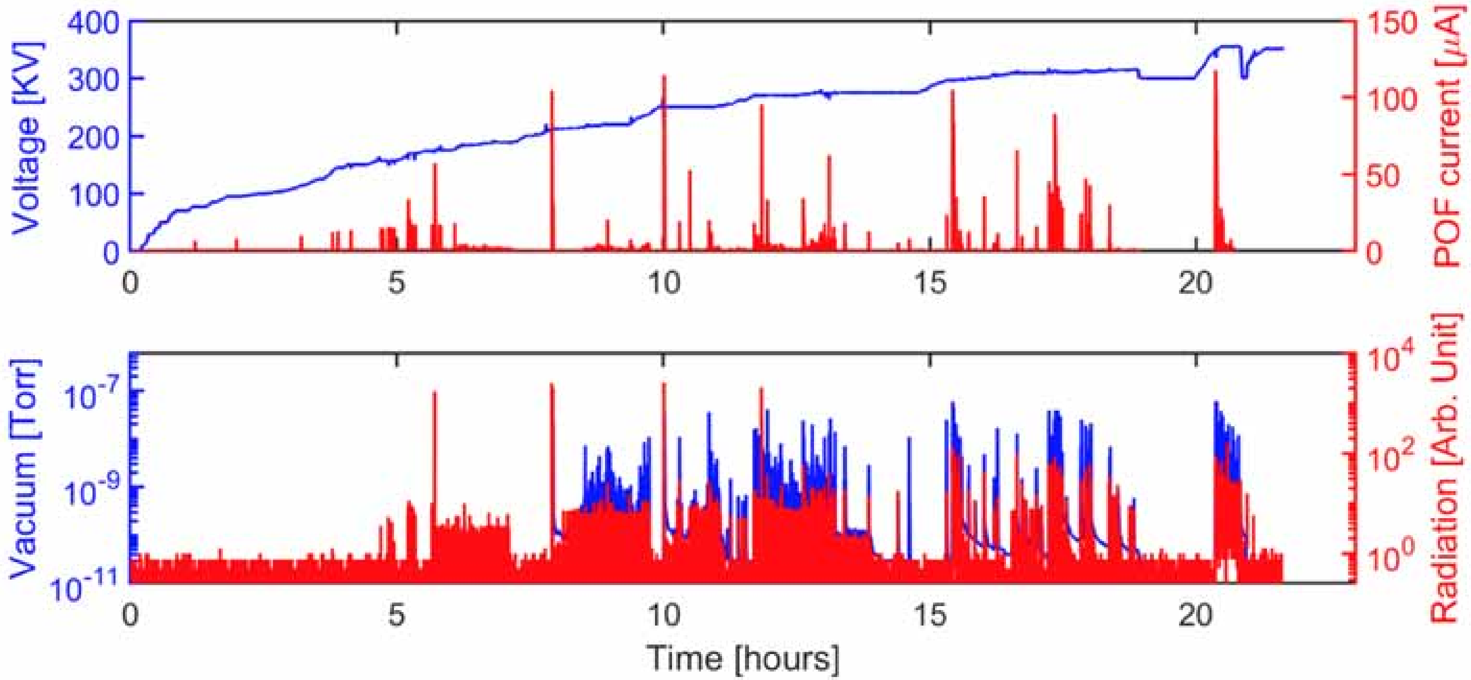
HV conditioning



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

➢Achieved gun design value 352 kV without field emission

We did not have to use inert gas to condition

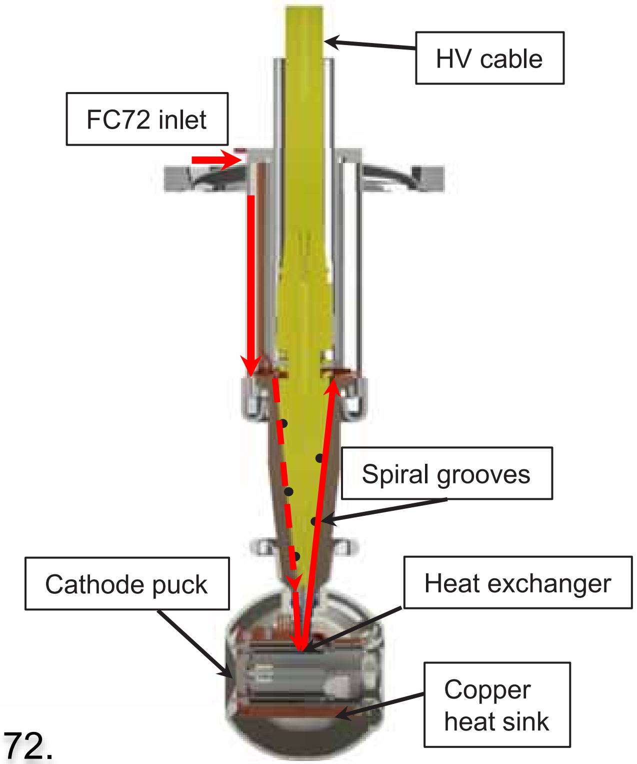
Operational techniques to increase lifetime

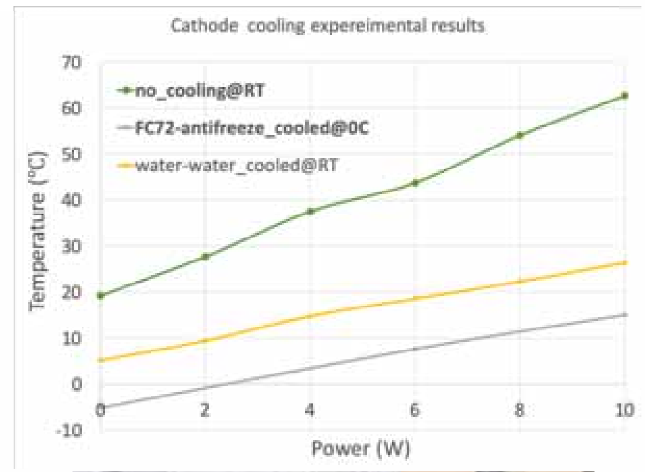
- Active cooling of cathode for high laser power - Integrated
- Masking of active area - Demonstrated
- Offset laser operation - Demonstrated
- Biased anode to block ions from downstream - Demonstrated
- No/minimal beam loss / Good dynamic vacuum - Demonstrated
- Offset anode scheme – Proposed based on simulation

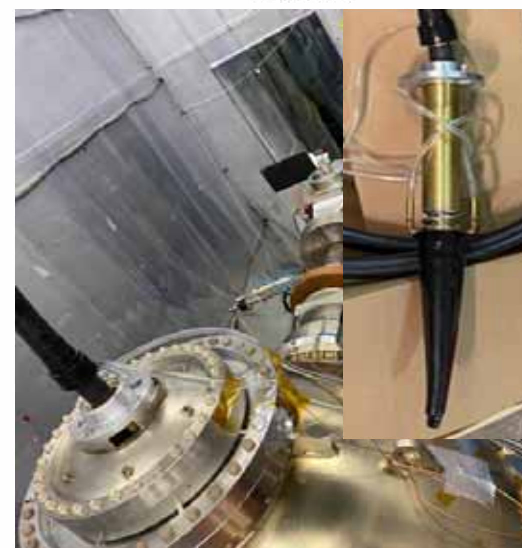
Active cooling in EIC gun

Aiming to absorb the laser power up to 10 W. We are collaborating with Dielectric Sci. developed the active cooling HV feedthrough.

Custom designed HV plug with cooling channel







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

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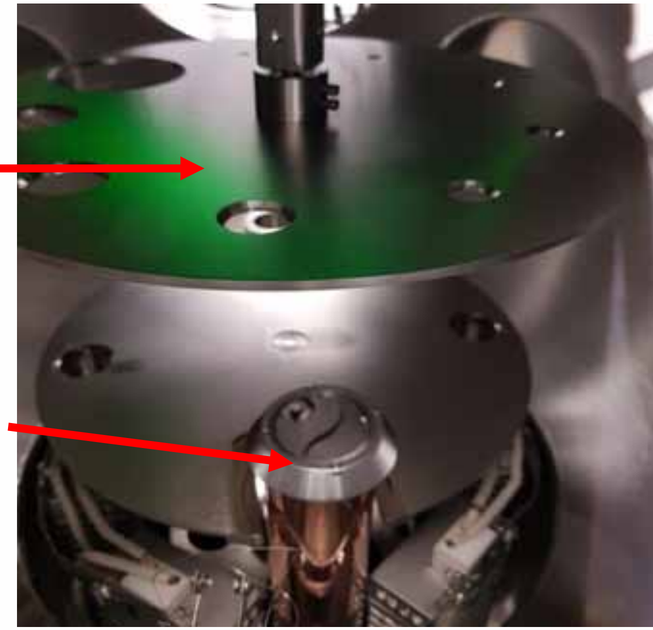
Cathode Preparation system with rotatable mask

Inside of the Cathode preparation chamber showing the NEG array and the heating and activation stations

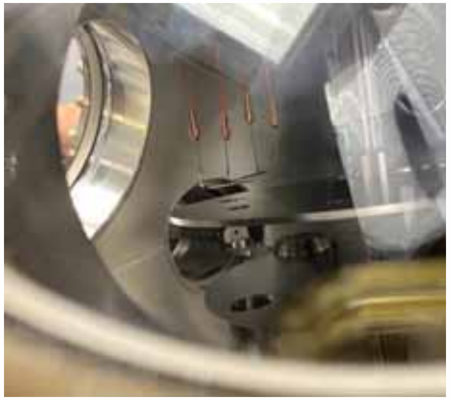
Rotatable "mask"

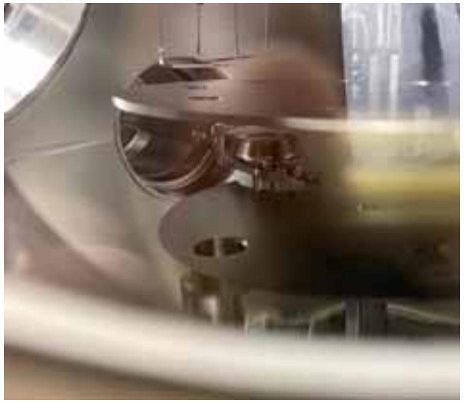
Cathode in Heat Cleaning Station

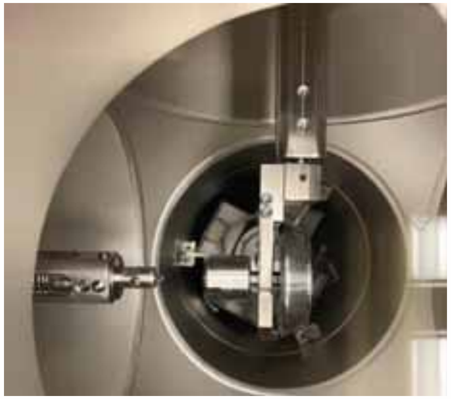


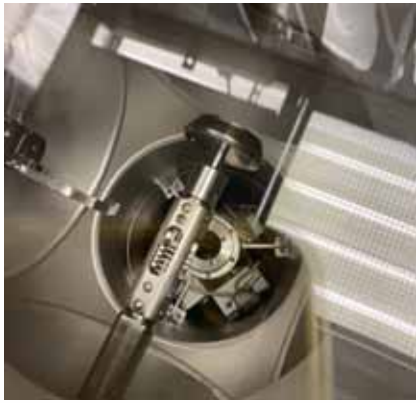
Large Area Cathode holder. 26 mm in diameter contained by a Tungsten cap, the base is moly.

Cathode insertion



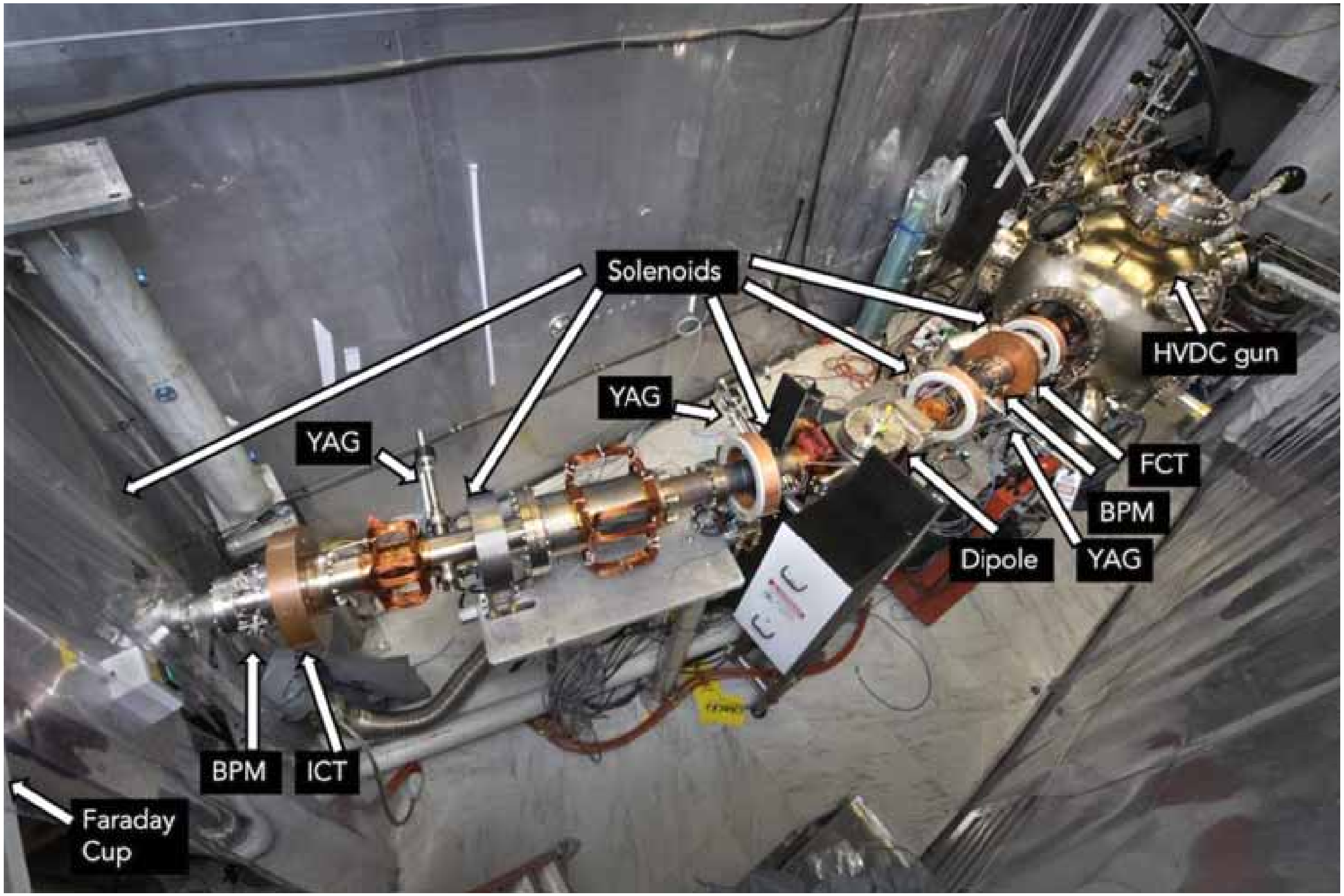






With several times practices, now can insert a cathode in ~20 mins.

Test beam line at SBU



Beamline designed using 3D code General Particle tracer

Beam-line vacuum in experiment

Gun Vacuum 3BG gauge

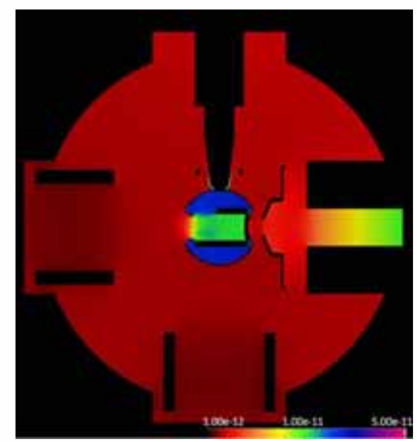
3BG gauge	Gun
Baseline	5-8 e-12
3uA	Low (c.c)
67 uA	2e-11,Low (c.c)

Beam dump

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

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

Beamline



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

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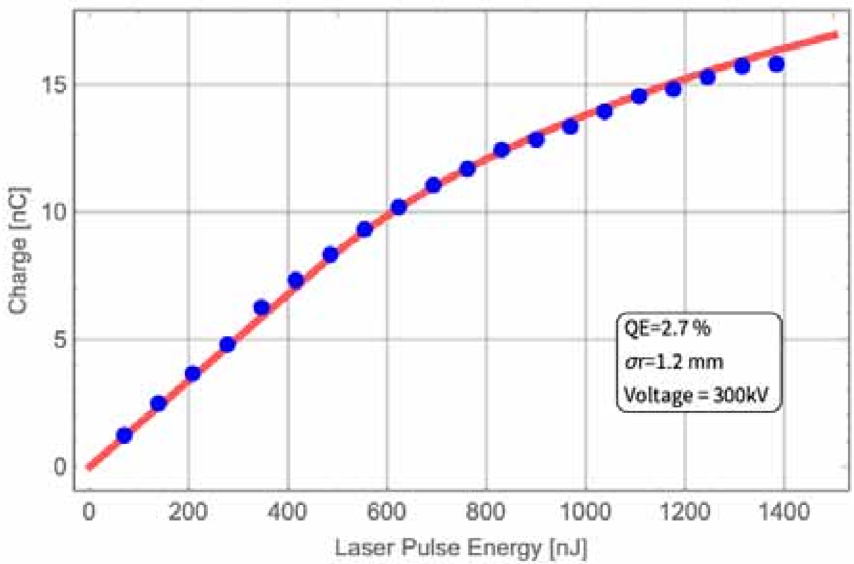
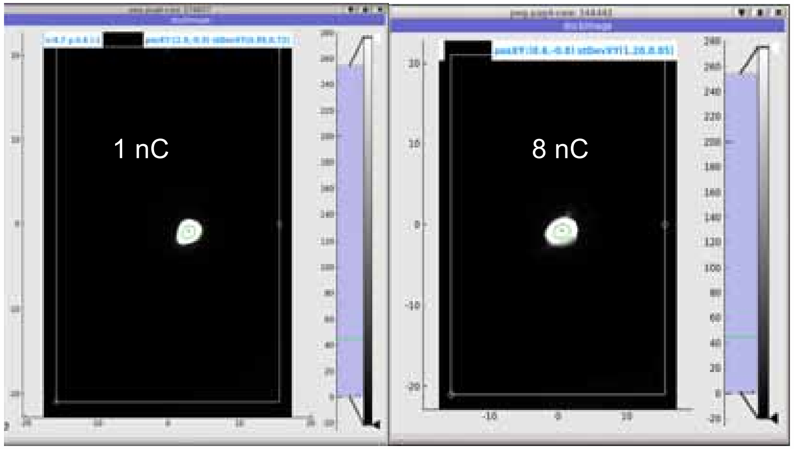
Measured space charge limit



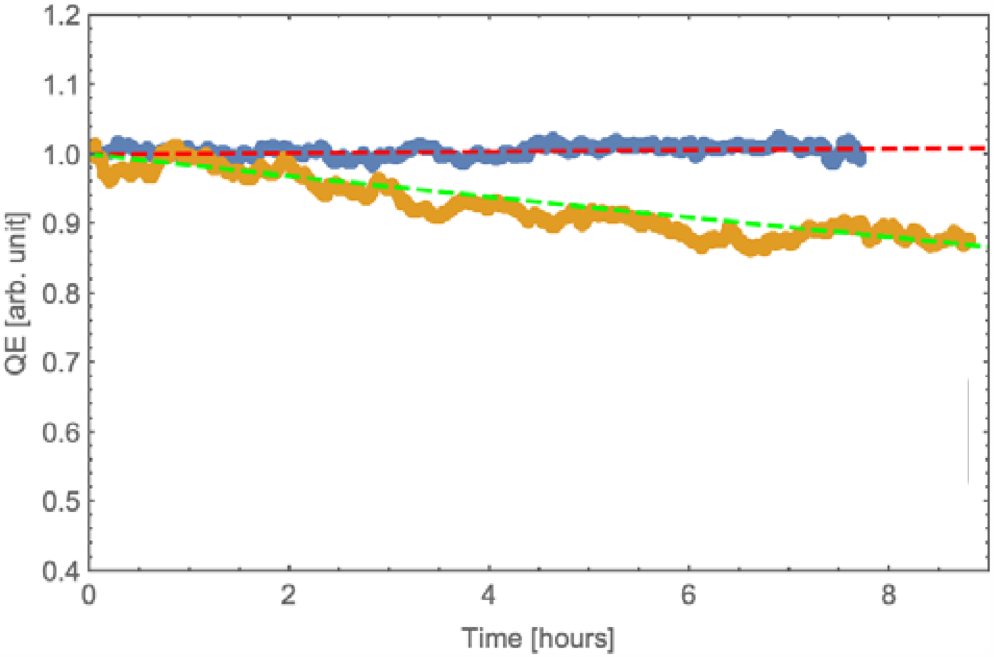


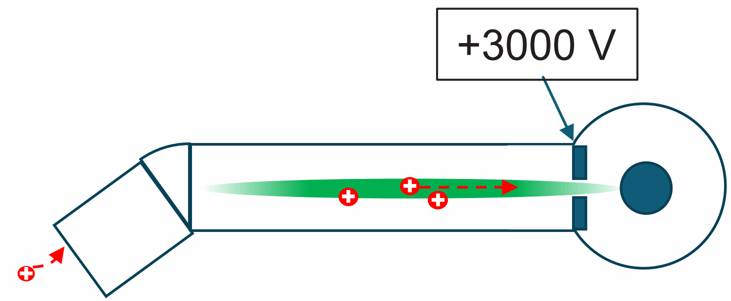
Beam image before the dump

- SCL start from 12 nC
- EIC requirement is 7 nC
- We can increase active area to increase SCL

- 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 QE drop.
- 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

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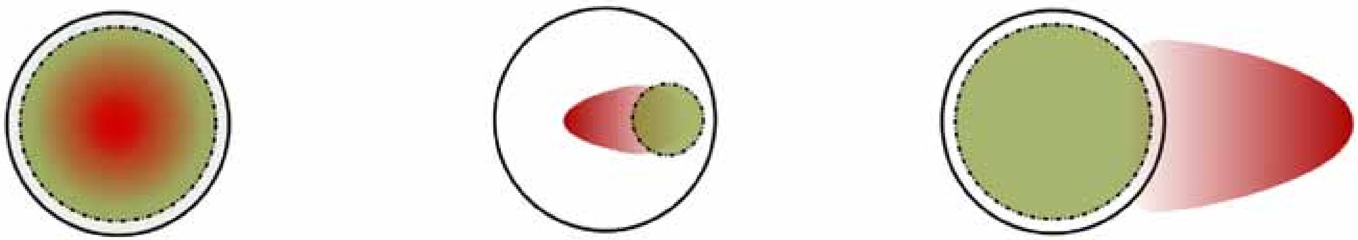
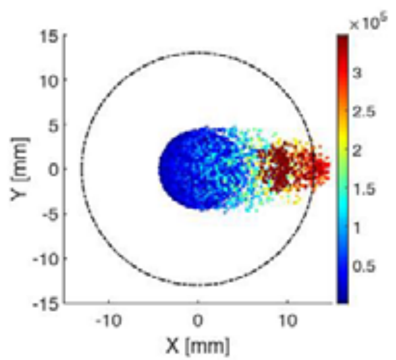
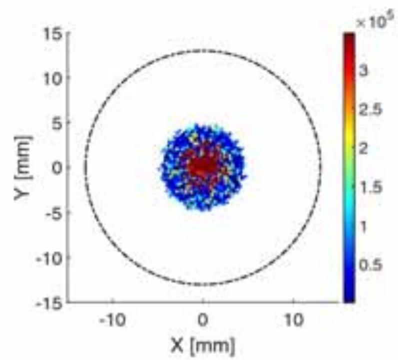
Offset anode scheme



Laser on center | Laser off center | Anode off center





- Offset the anode instead of the laser
- Use transverse kick in the DC gap
- Laser spot size can be increased = higher lifetime
- Lifetime will be increased depending on the available cathode spot

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 083401 (2019)

Increasing charge lifetime in dc polarized electron guns by offsetting the anode

Omer Rahman,[1] Erdong Wang,[1,*] Ilan Ben-Zvi,[1,2] Jyoti Biswas,[2] and John Skaritka[1]
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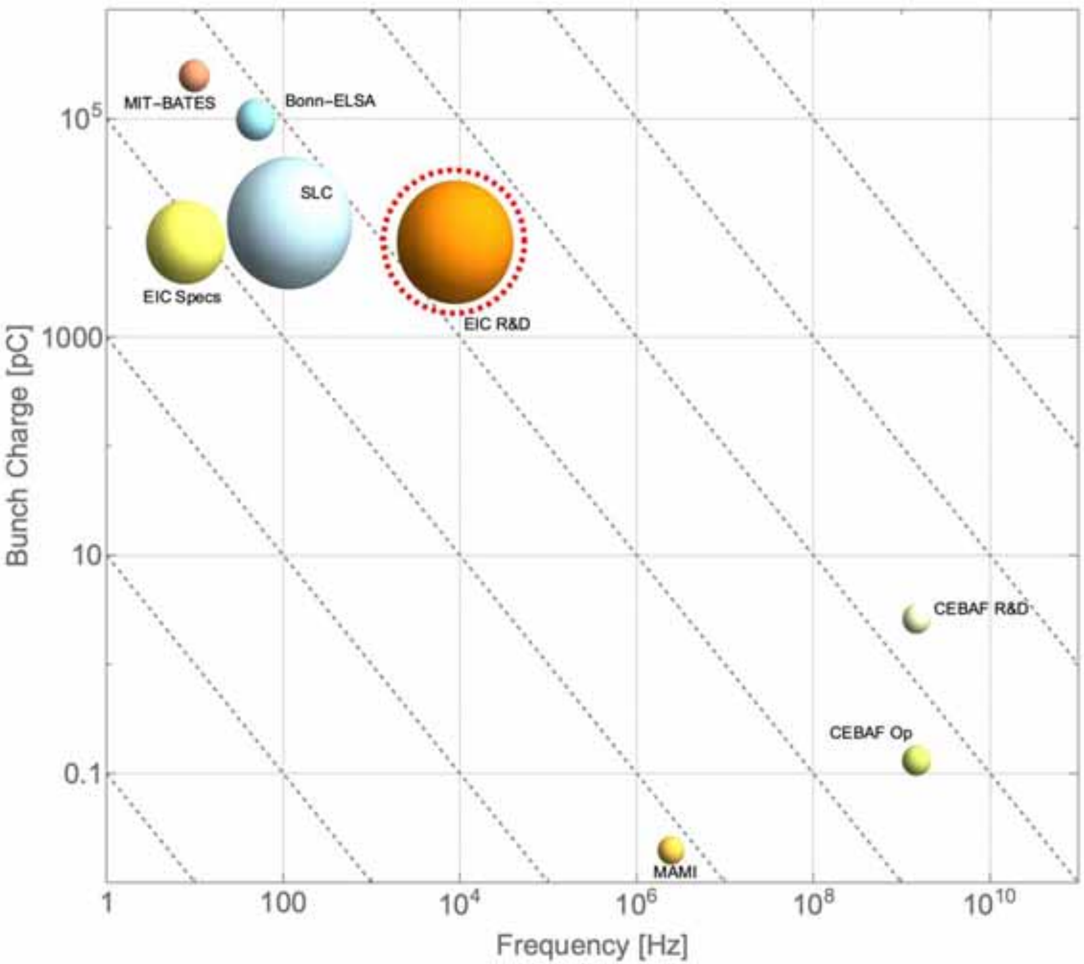
Comparison with other operational and retired polarized gun



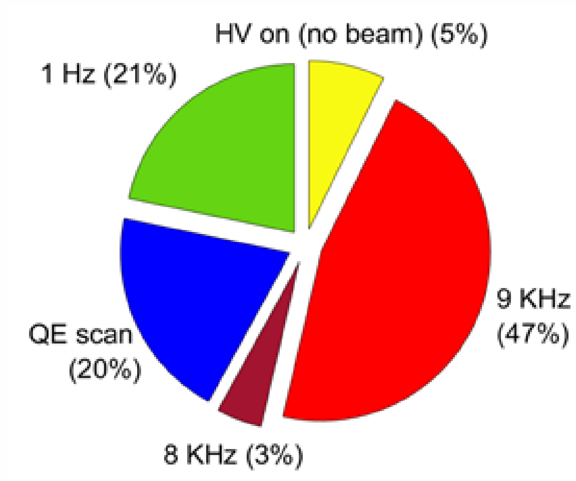
- The slope line shows the average current contour level.
- The ball diameter is representative of the peak current of the gun.
- The red dash line at EIC R&D shows the maximum achieved peak current of 8 A

Summary

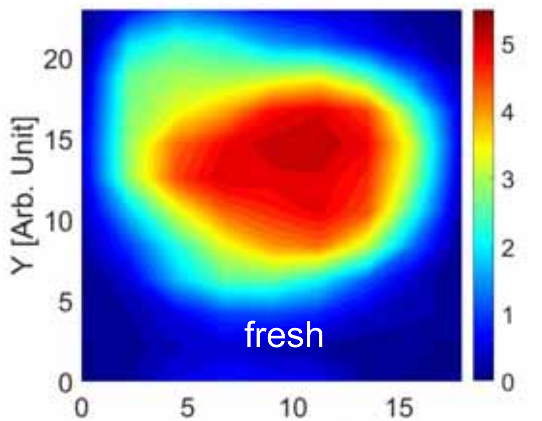
- A 300 KV polarized electron gun was designed, constructed, and commissioned for EIC
- Gun includes new features such as: active cooling of cathode, large cathode size.
- Excellent HV performance – conditioned up to 350 KV and routinely operated at 300 KV
- Up to 16 nC of bunch charge was extracted, 7.5 nC is the regular mode of operation
- Lifetime surpasses EIC requirements by a large margin, for orders of magnitude higher average current.

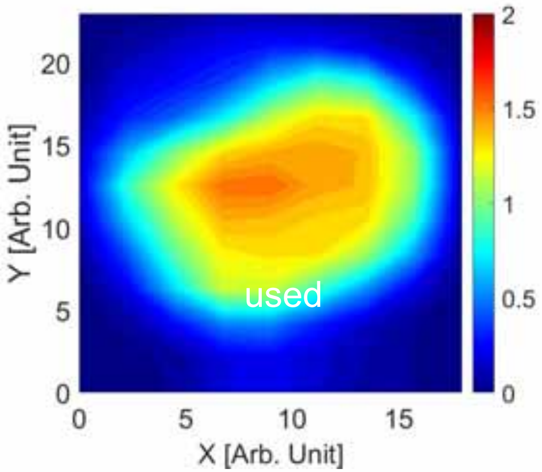
Thank you for your attention!

9000 pulse lifetime



- 67.5μA average current operation showed clear QE decay during operation even with the anode biased.
- The beam dump and beam line vacuum read 2e−9Torr and 4e−11Torr. Gun got into -11 torr scale.
- Back stream gas poison the cathode.
- For short beamline, without differential pumping, beamline is not suitable for high current test





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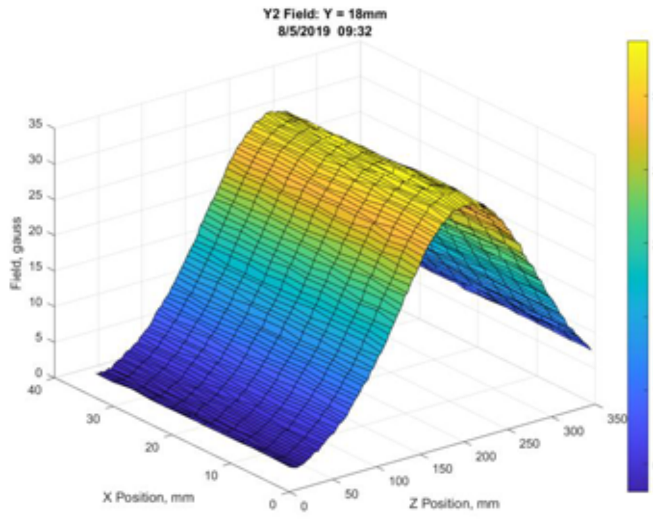
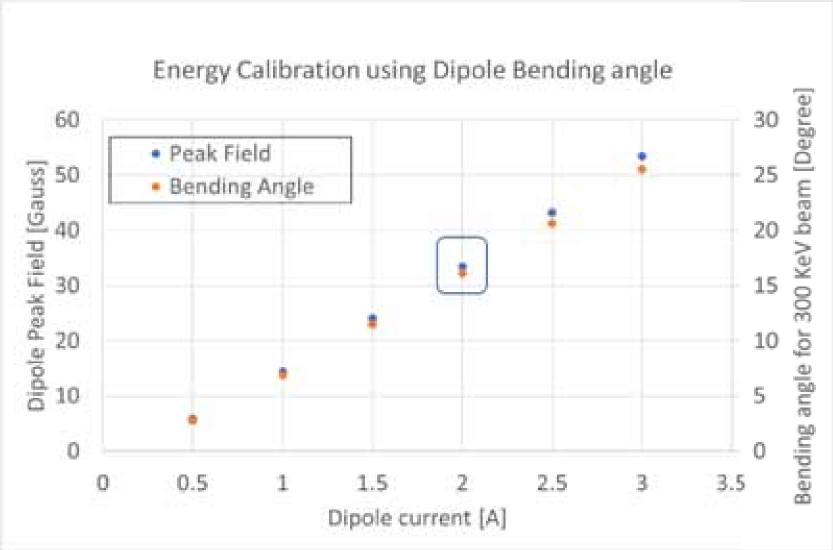
Beam energy calibration using Dipole





- Dipole field profile along beam path and peak field Vs applied current was measured
- Using the known bending angle (16 degrees) and measured field profile (using the current applied to the magnet during operation), the energy of the electron beam was calibrated.

EIC polarized electron source requirement

	EIC	Achieved in stable operation	R&D deliverable
Bunch charge [nC]	7	7.5 (12)	Y
Energy spread dp/p	2e-3	NA	N
Peak current [A]	3.8	4.8 (No SCL)	Y
Frequency [Hz]	1 (8 bunches)	1 (9000 bunches)	Y/N*
Voltage [kV]	300	300	Y
Average Current	56 nA	76.5 uA	Y
Polarization [%]	> 85%	Bulk (~35%)	Y/N**

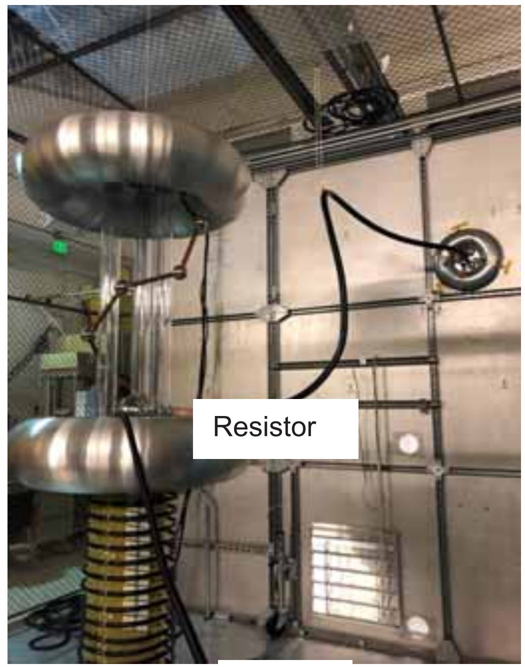
EIC polarized gun at Stonybrook Univ.

*** Our laser rep. rate is 10 kHz**
**** Measure GaAs polarization at retarding field Mott polarimetry. Our gun beam line doesn't have Mott polarimeter.**

EIC lifetime requirement in CDR : 24x7x3600x8= 4.8 e6 bunches /week

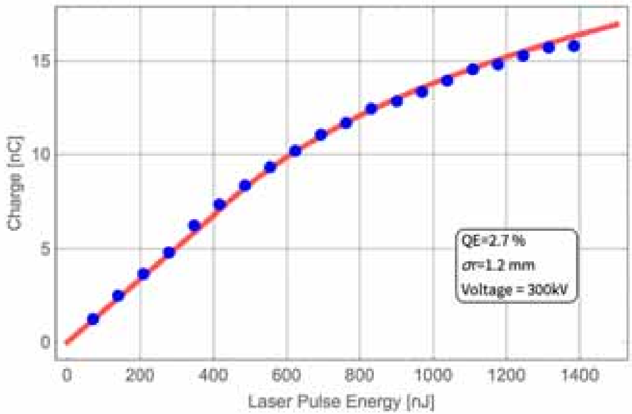
Power supply and HV cable

- 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 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 happen

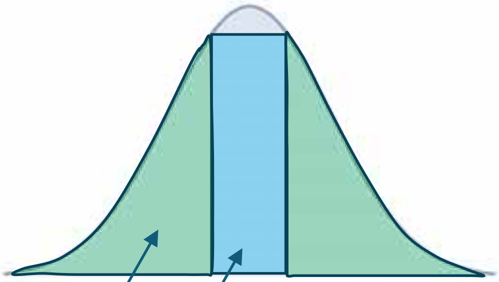


HVPS

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: $\Sigma(r) = \frac{Q_{bunch}}{2\,\pi\,\sigma_r} e^{-\frac{r^2}{2\sigma_r^2}}$

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

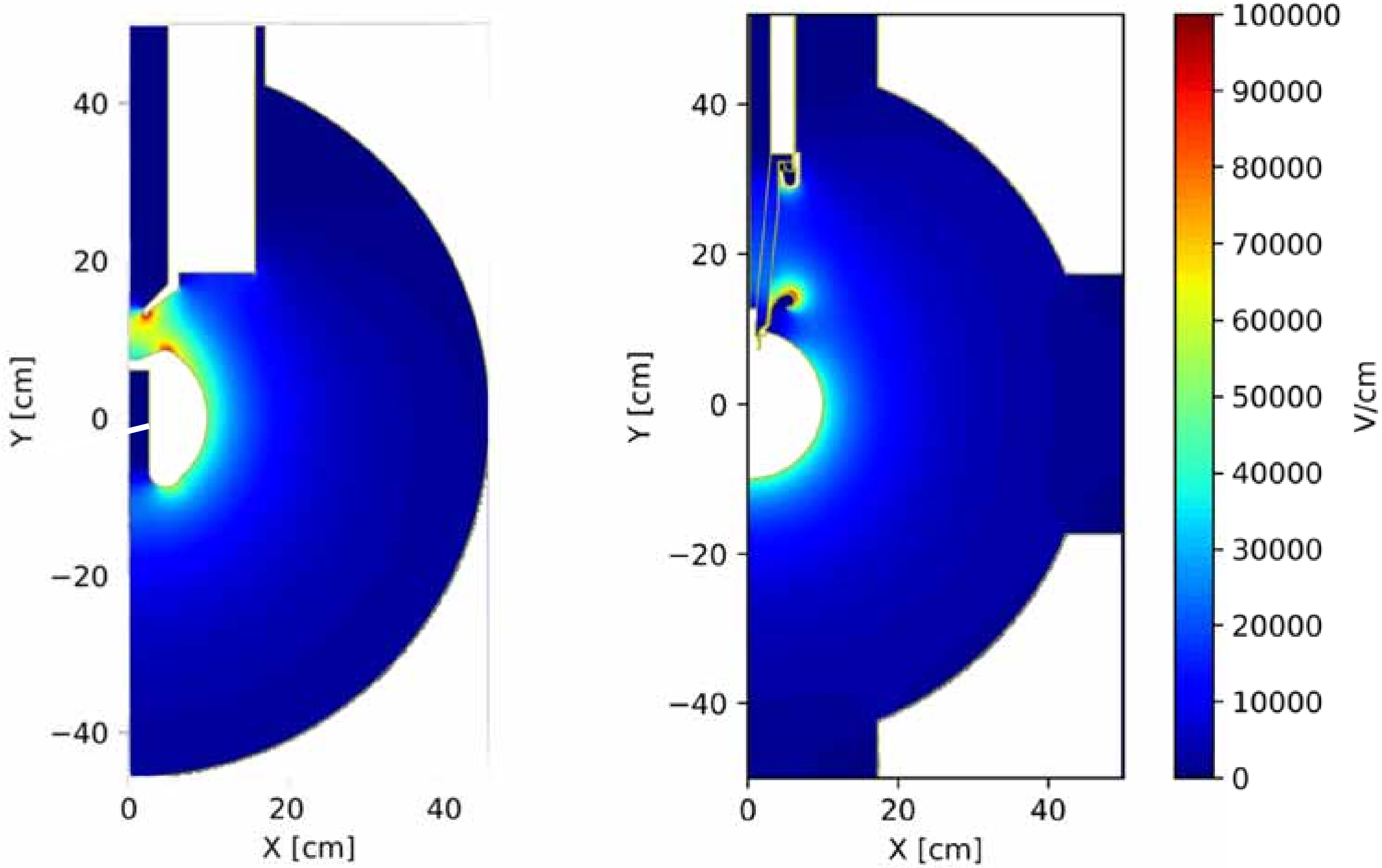
Pencil shape 2D space charge limit:

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

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.

If rm>0, then space charge limit happen

HV design II



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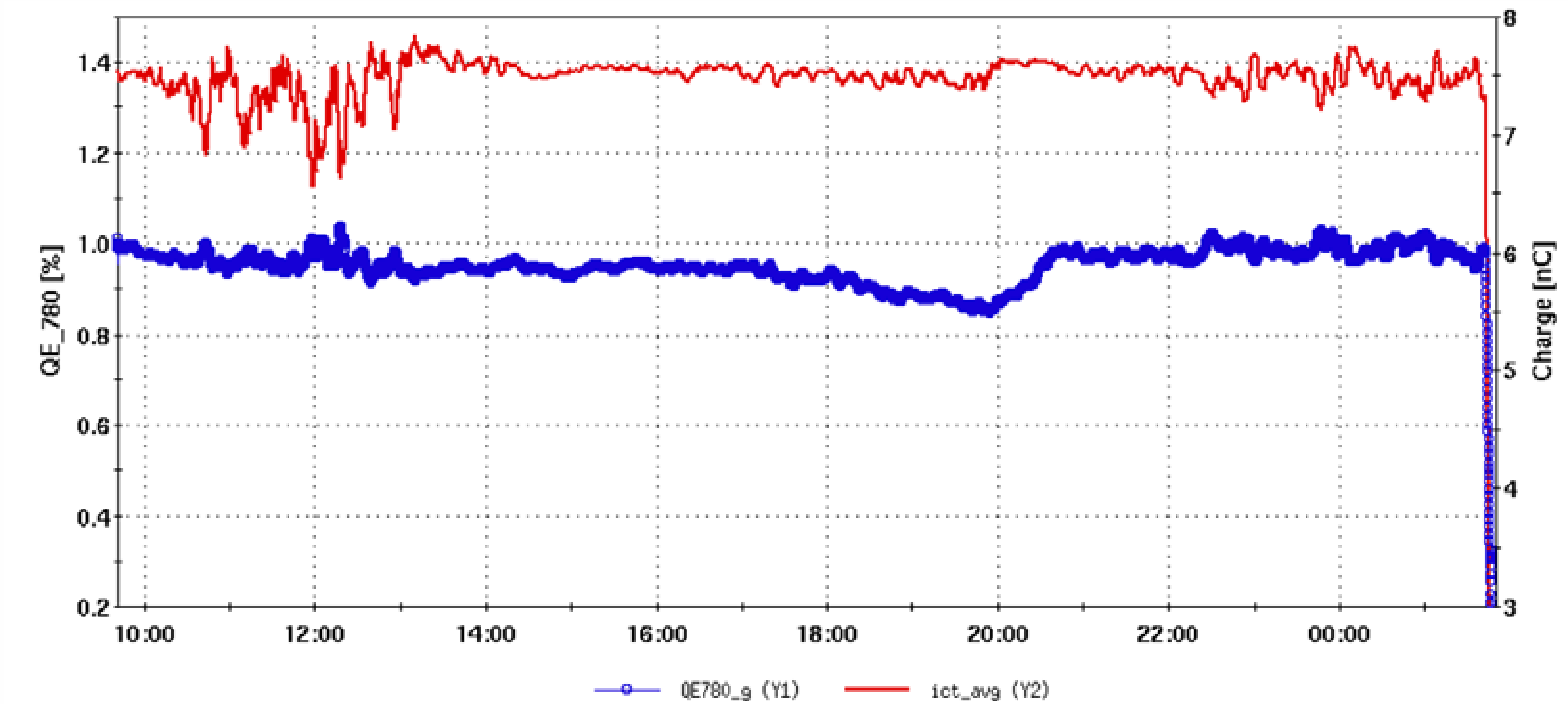
Low current lifetime measurement



- Using 7.5 nC bunch charge polarized beam, 400 pulses/s;~3 uA average current
- We didn't observe any QE drop in 16 hrs.
- QE~1%

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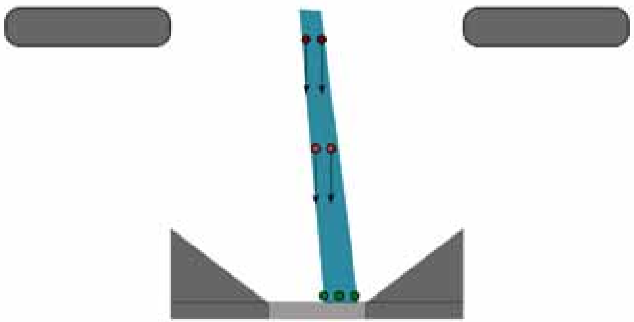
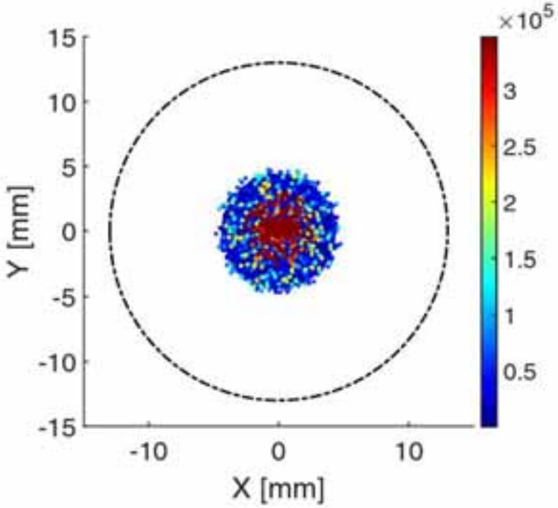
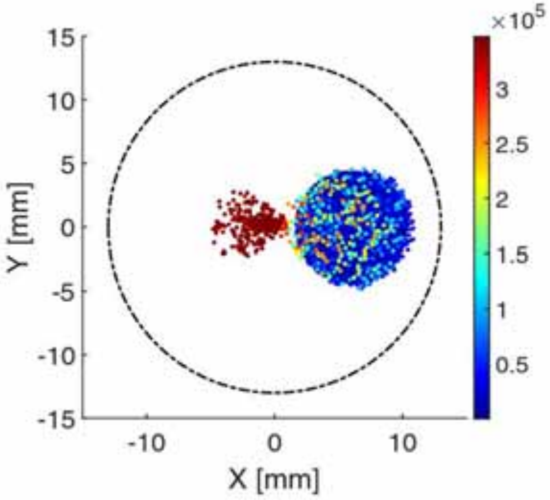
Increasing lifetime of GaAs in DC guns

- Improve Vacuum
- Offset laser
- Masking of photocathode active area
- Larger laser spot and cathode size
- No field emission
- Higher voltages







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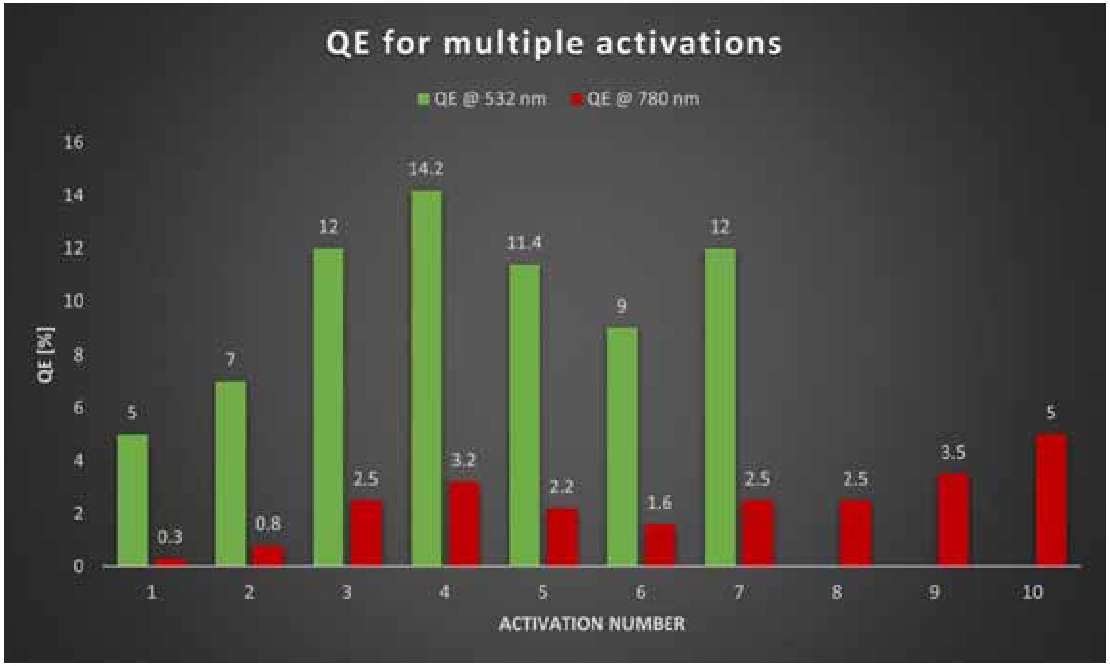
Bulk GaAs activation at 780 nm

- Cathode activation chamber was commissioned.
- Multiple activations @ 780 nm, maximum achieved QE is about 5%
- Immediately after transport, there was negligible QE drop.
- Activation #7, #10 were used for lifetime test.



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