High Voltage DC Gun for High Intensity Polarized Electron Source

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On behalf of the Electron source development group

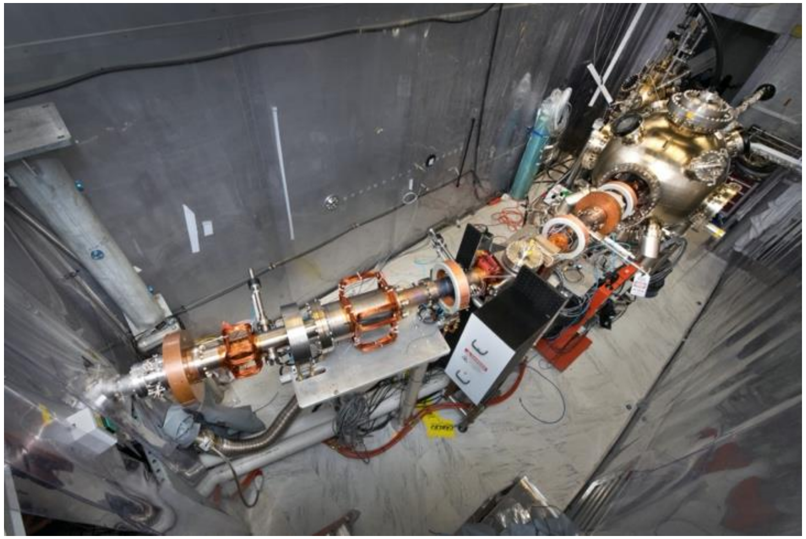
Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

66th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs,
October 3-6th, 2022. Ithaca, NY, USA.

EIC polarized electron source requirement

Parameter	Value	Achieved in stable operation
Bunch charge [nC]	7	7.5 (16)
Peak current [A]	4.8	4.8
Frequency [Hz]	1 (8 bunches)	1 (9000 bunches)
Voltage [kV]	300	350(300)
Average Current	56 nA	67.5 uA
Polarization [%]	> 85%	Bulk (~35%)



EIC polarized gun at Stonybrook Univ.

Challenges –

1. Achieve high voltage with no field emission
2. Have excellent vacuum

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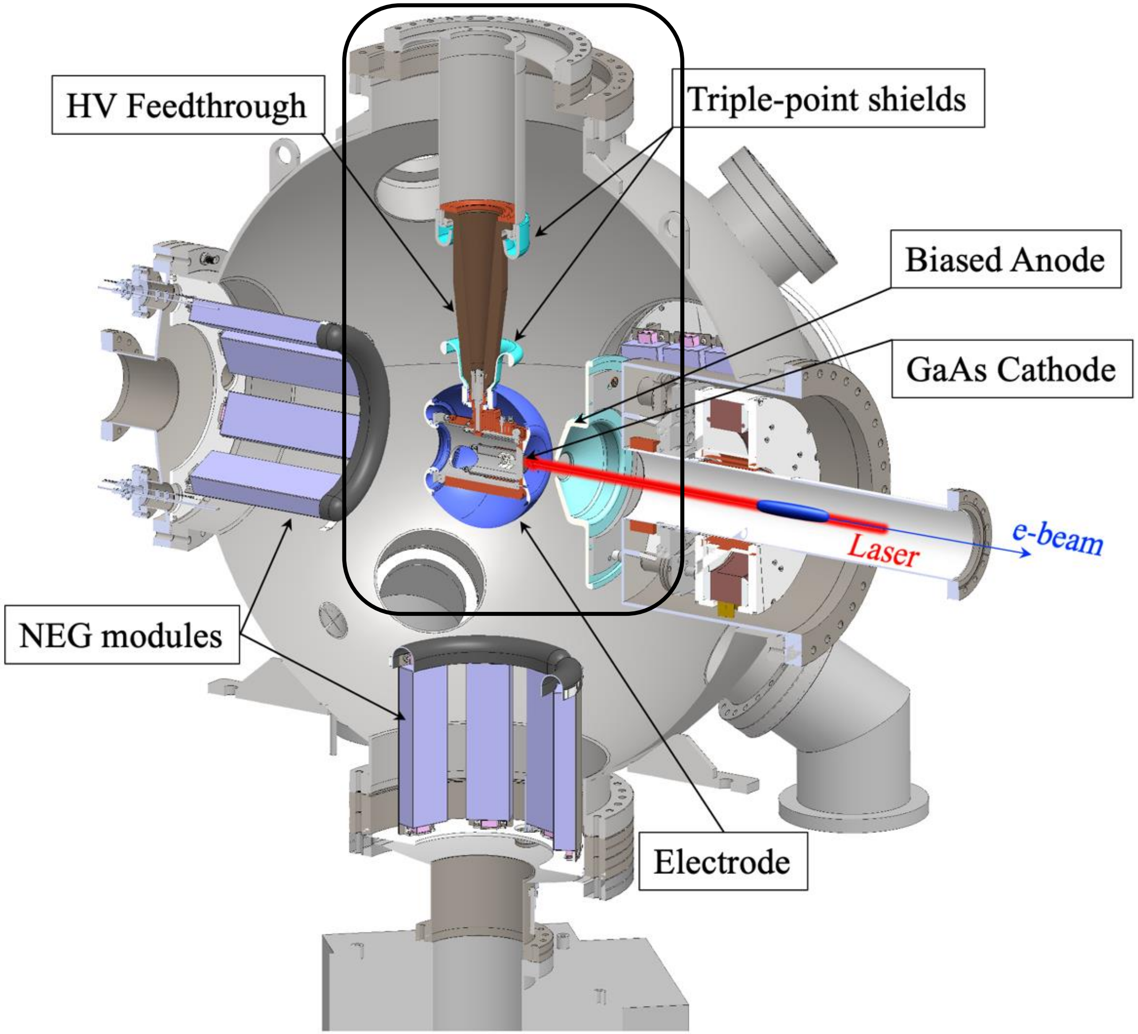
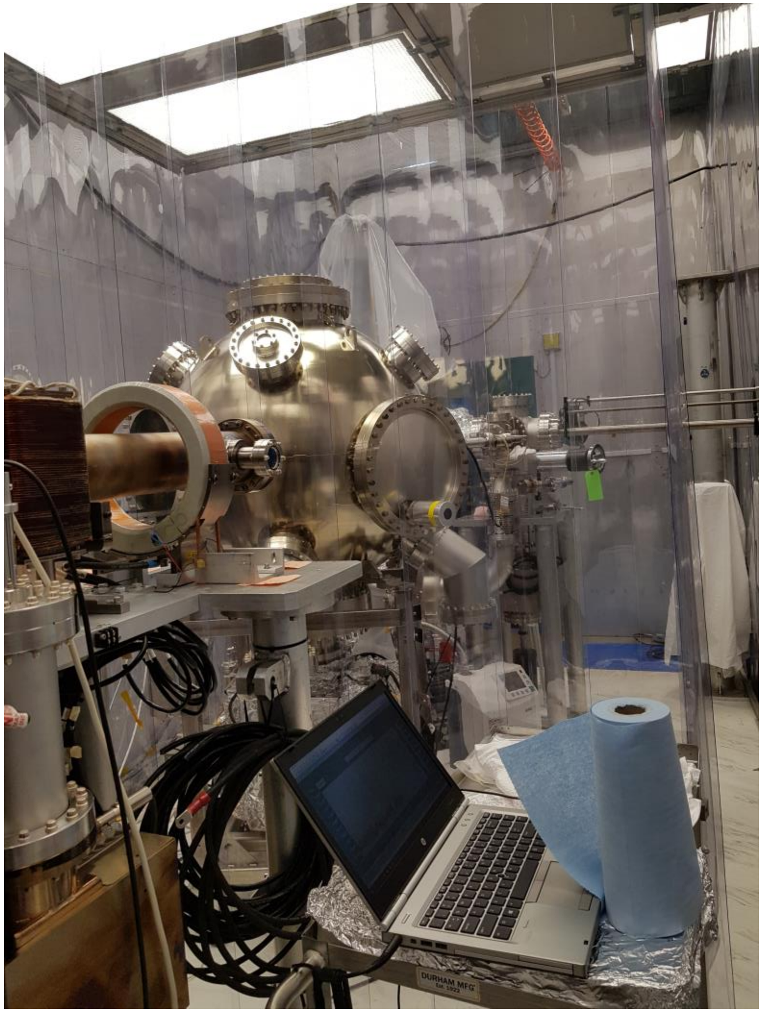
EIC gun overview



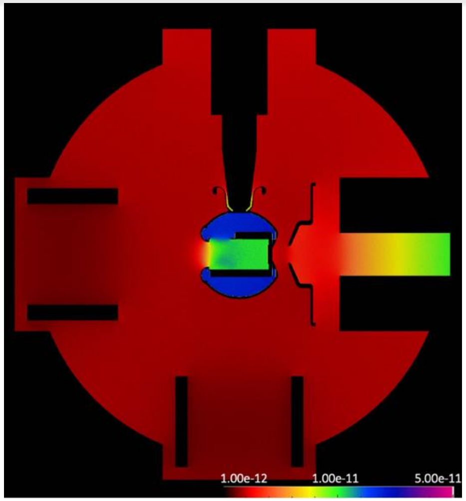
Gun design include:
- High voltage feedthrough
- Triple-point shields
- Beam quality, envelope
- Electrode, anode outer shape

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

Vacuum (static)



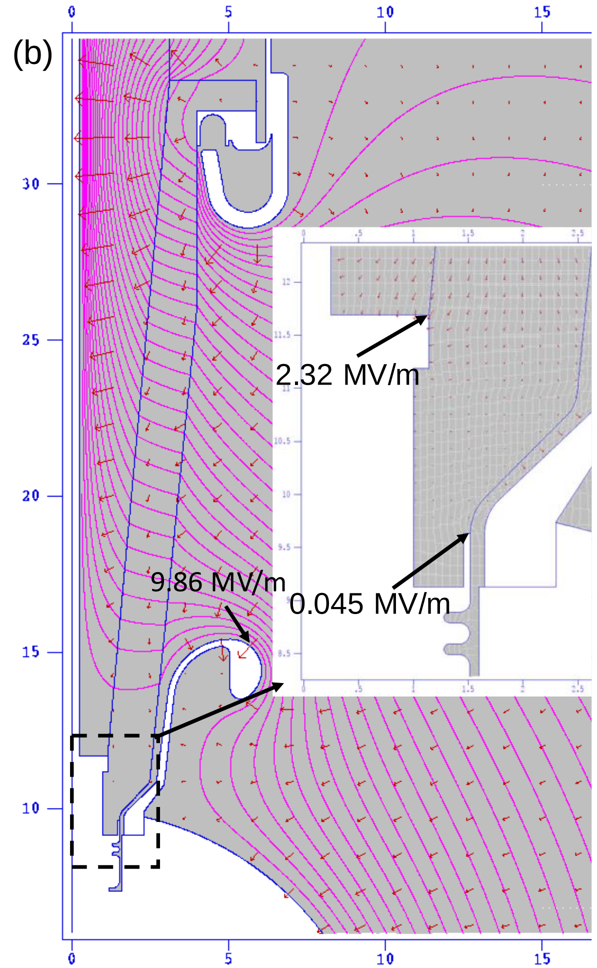
- Gun chamber is large (90 cm in diameter)
- Vacuum fired at 930 C for 4 hours = defuse hydrogen from the bulk of the stainless steel
- (If possible) measure outgassing rate
- (If possible) Reduce flange thickness
- 8000 L/s NEG pumps
- Final static vacuum – 5-9 e-12 torr



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

HV design I

Parameter	Value
Ball diameter	20 cm
Chamber diameter	90 cm
Gap distance	5.6 cm
Voltage	350 kV
Cathode size (radius)	1.26 cm
Electrodes angle	22 degs
Cathode gradient	4.0 MV/m
Maximum gradient	<10 MV/m
Anode aperture (radius)	1.6 cm
Peak current	4.8 A
Bunch charge	7 nC
Pumping speed	35000 L/s
Anode bias	3000 V



- 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 beam deflection in the DC gap

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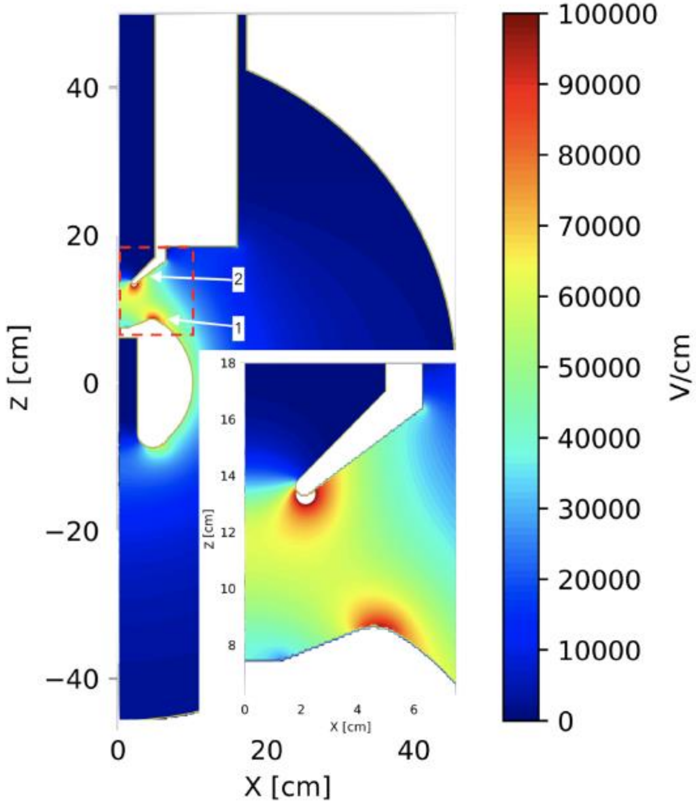
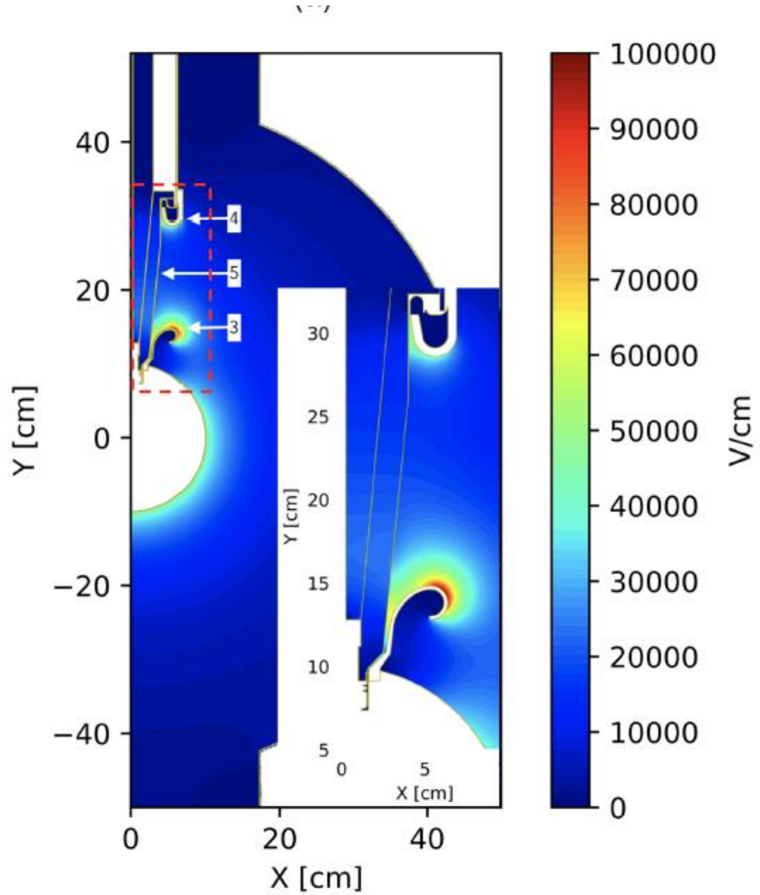
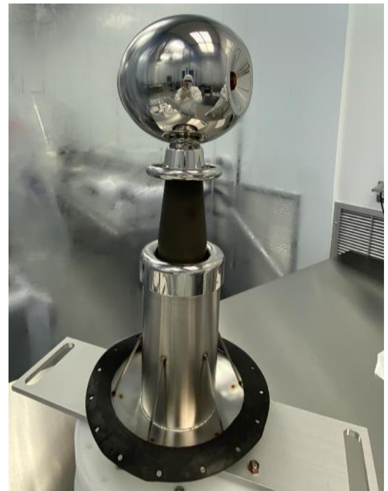
HV design II





HV electrode treatment and installation

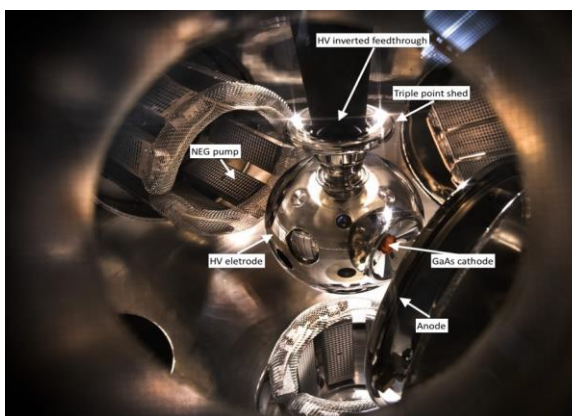
Polish at JLab



HPR at BNL SRF

Installation at SBU

Alignment



Final assembly

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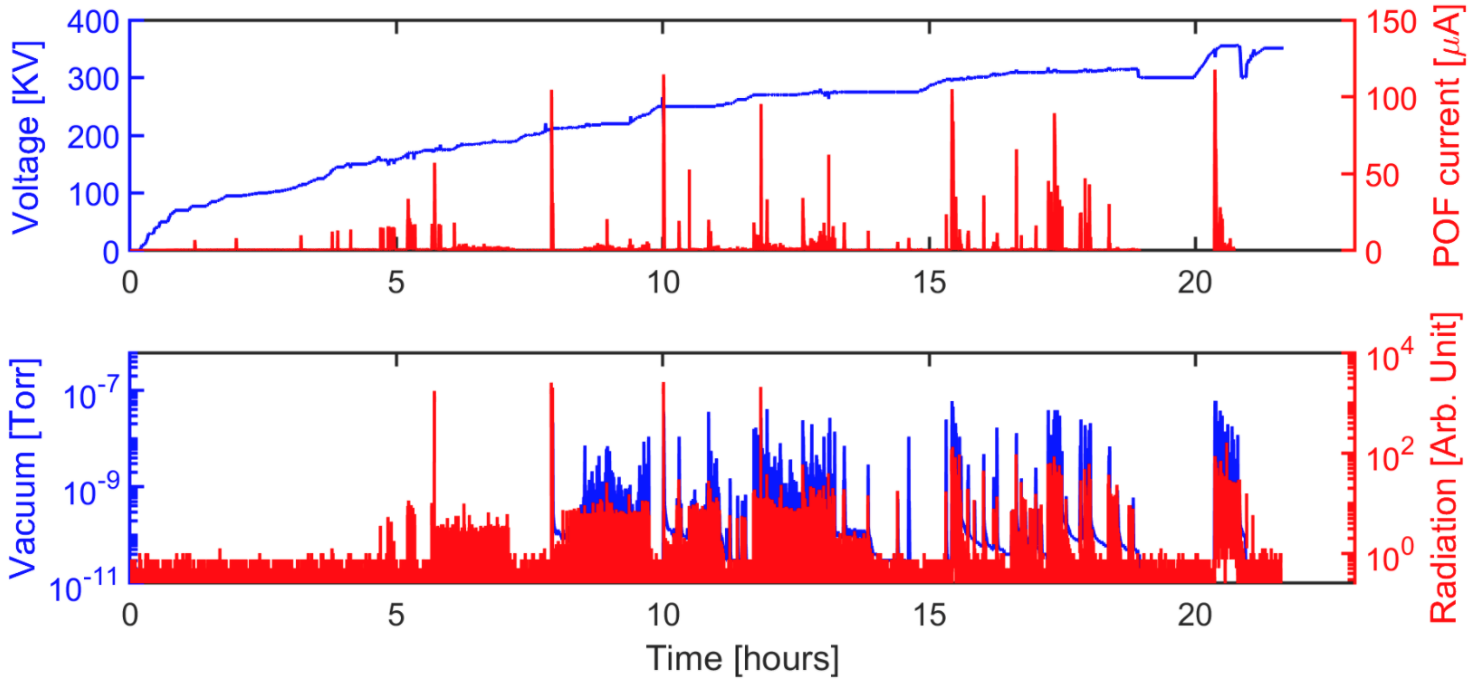
HV conditioning



Gun first conditioned at 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

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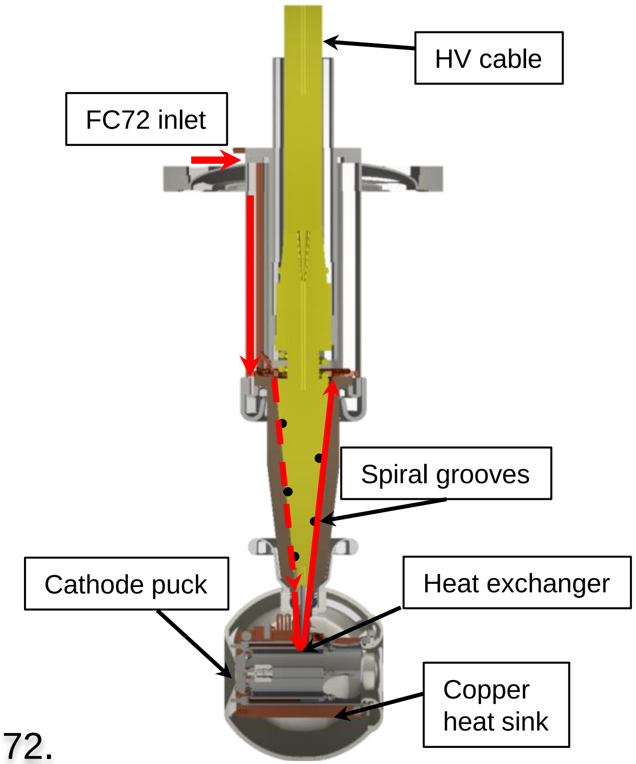
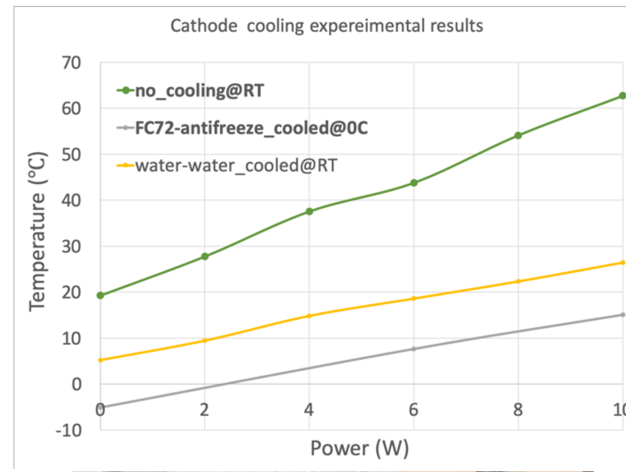
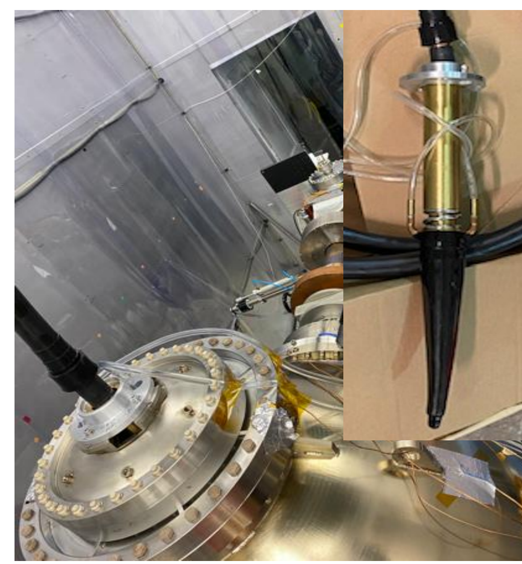
Active cooling in EIC gun

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. Operated @300-350 kV for more than 500 hours reliably

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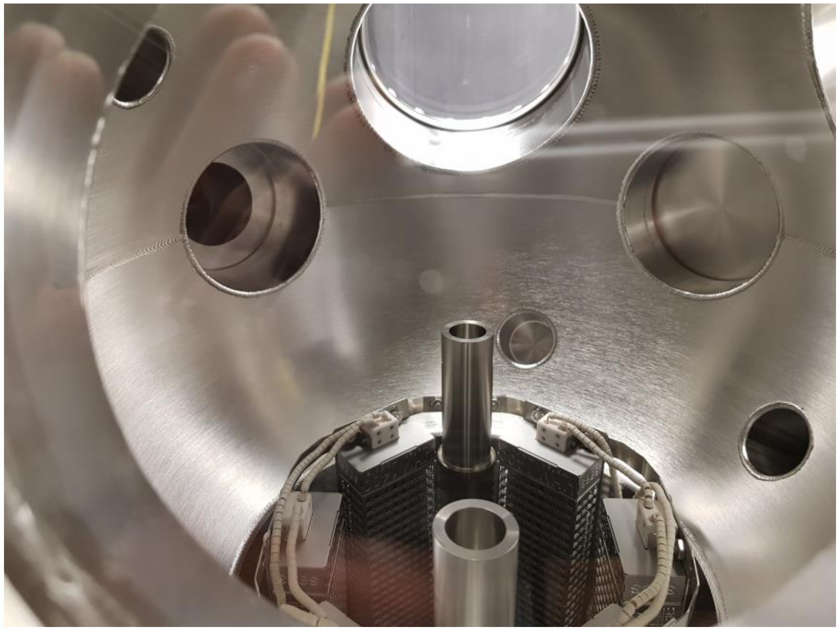
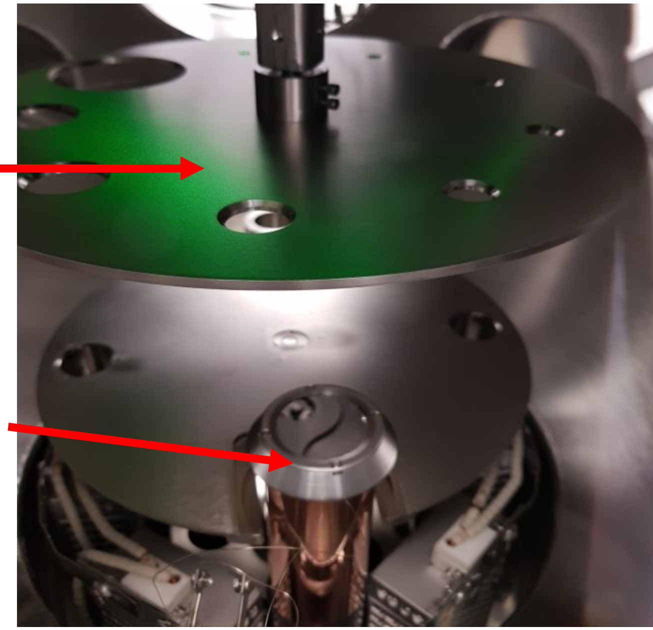
Cathode preparation system with rotatable mask



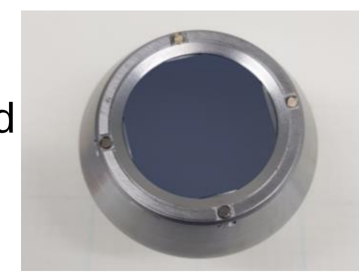
Inside of the Cathode preparation chamber showing the NEG array and the heating and activation stations

Rotatable “mask”

Cathode in Heat Cleaning Station



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



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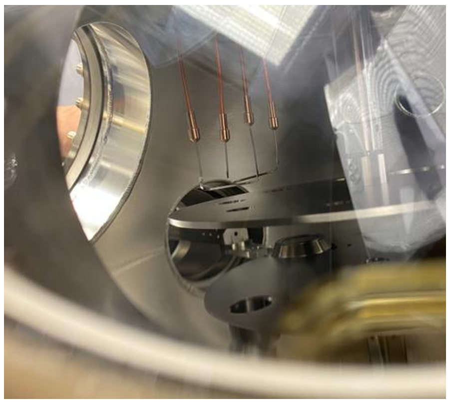
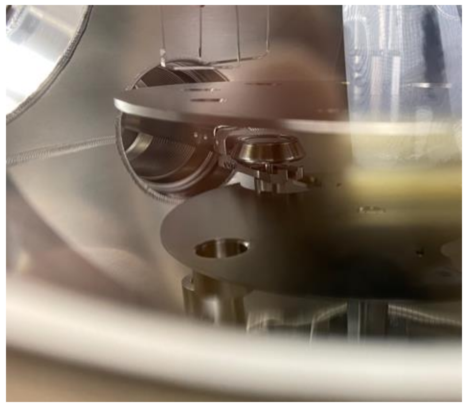
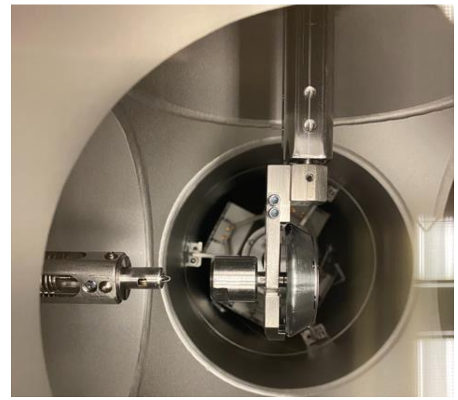
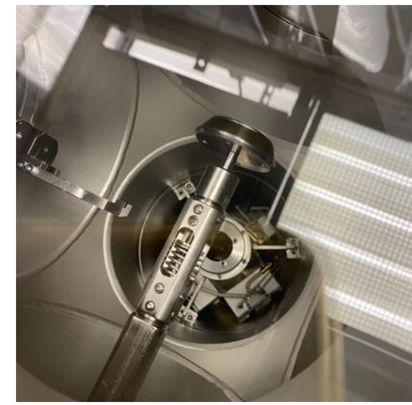
Cathode insertion



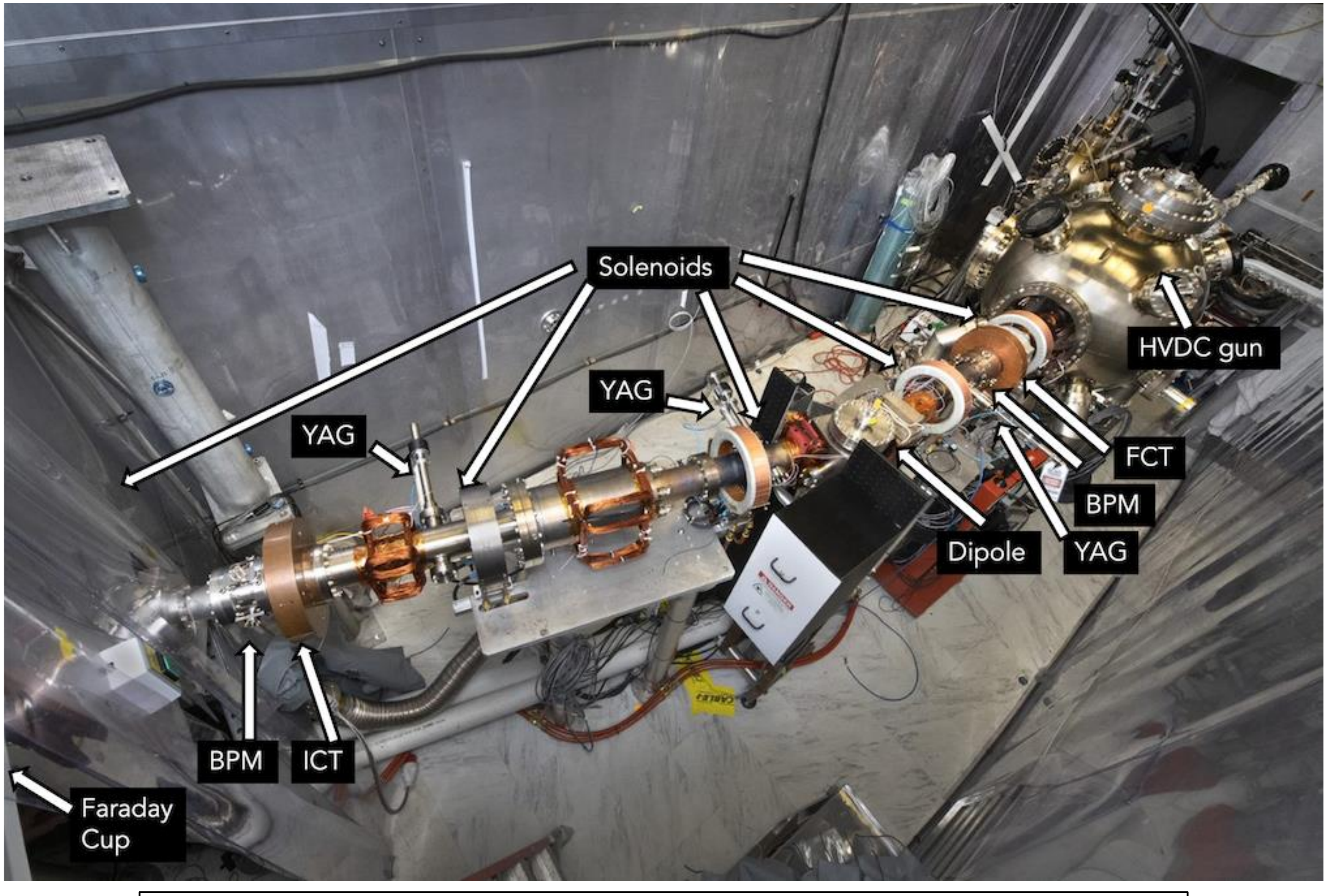






- With several times practice, now can insert a cathode in ~20 mins.
- There is a storage chamber in between the prep chamber and the gun (to minimize unwanted Cs migration)
- Minimal degradation in QE

Test beam line at SBU



Beamline designed using 3D code General Particle tracer

Vacuum (dynamic)

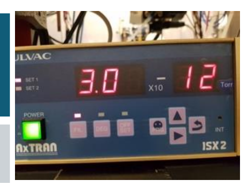
Beam dump

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

Gun Vacuum 3BG gauge

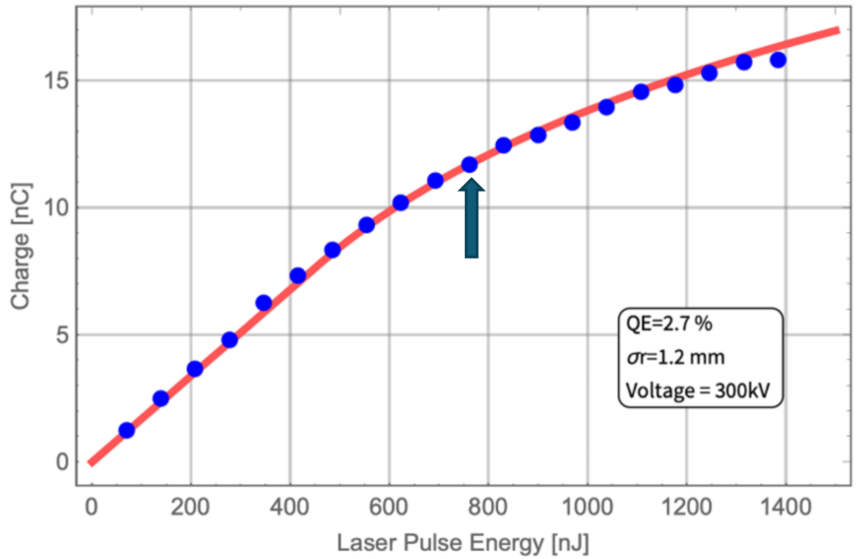
3BG gauge	Gun
Baseline	5-8 e-12
3uA	Low (c.c)
67.5 uA	2e-11,Low (c.c)

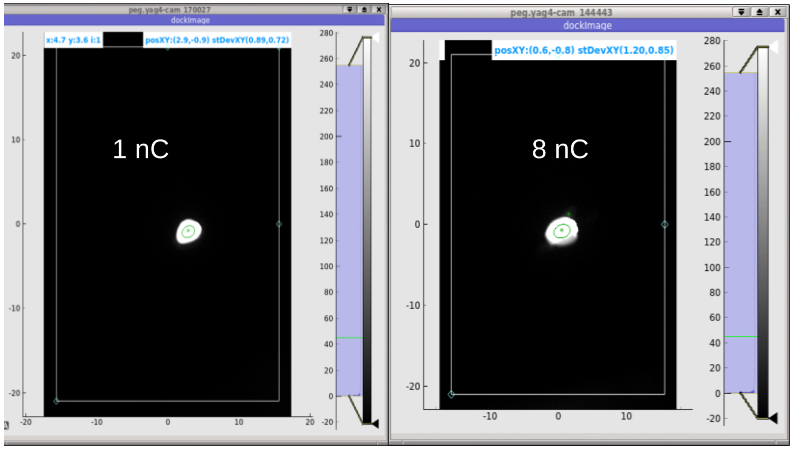
ULVAC gauge	Beam Line
Baseline	3-4 e-12
3 uA	5e-12
67.5 uA	1.5-3 e-11



Beamline

Bunch charge vs Laser pulse energy





Beam image before the dump

- SCL 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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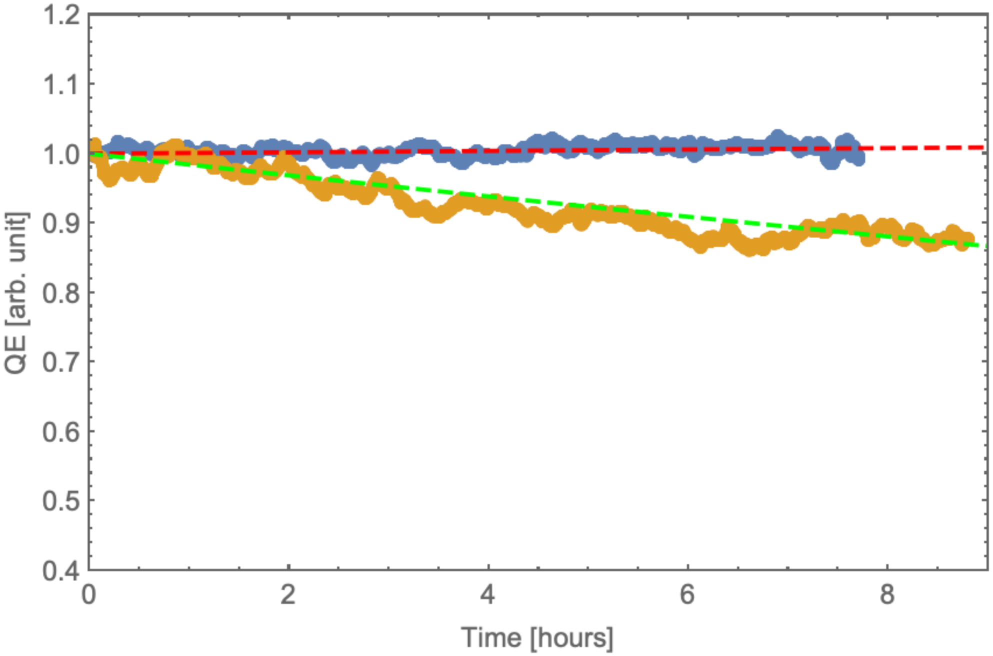
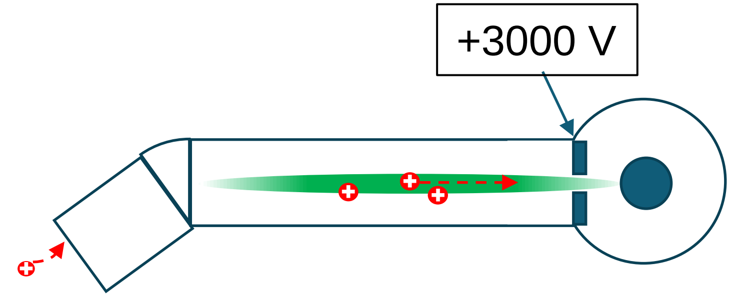
Cathode lifetime with and without anode bias





- 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

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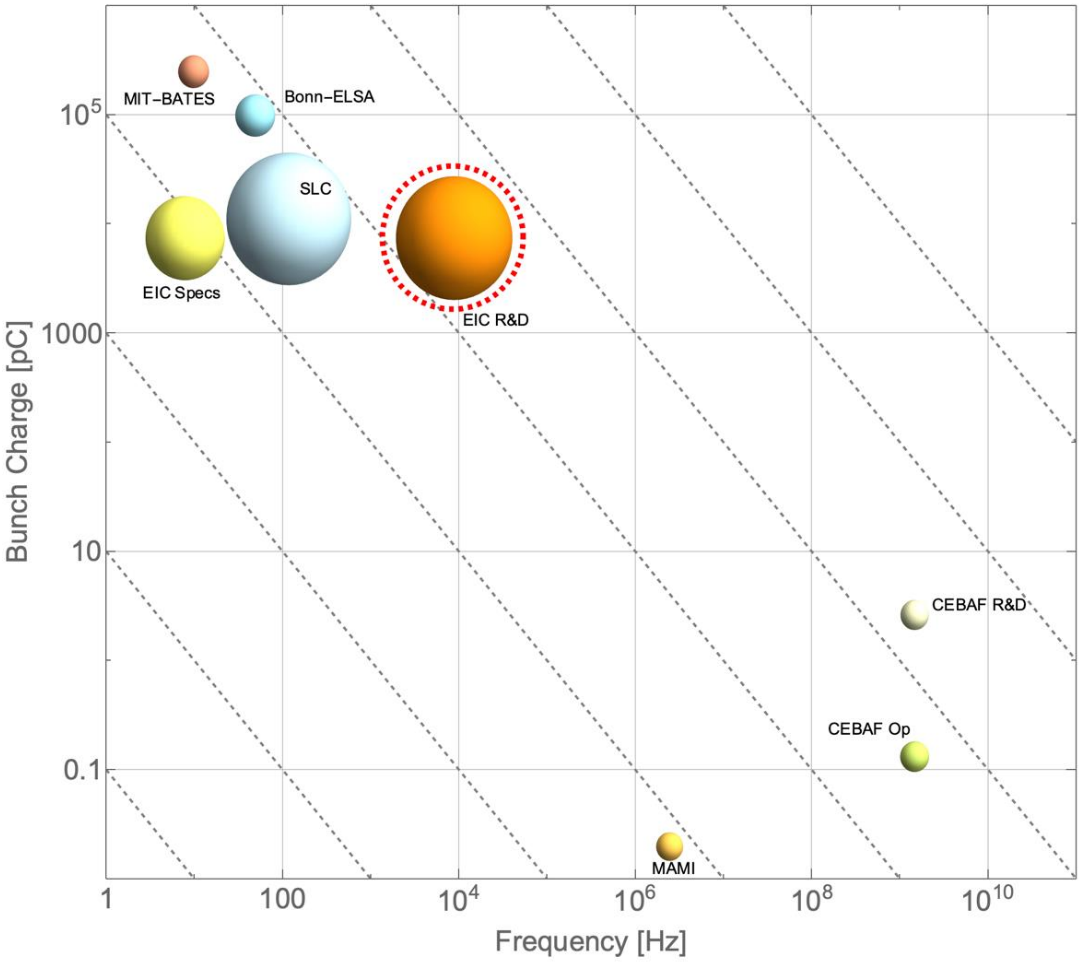
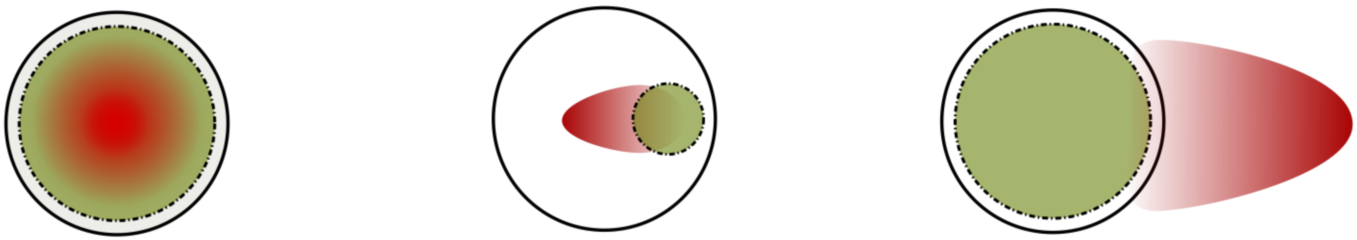
Comparison with other operational and retired polarized gun

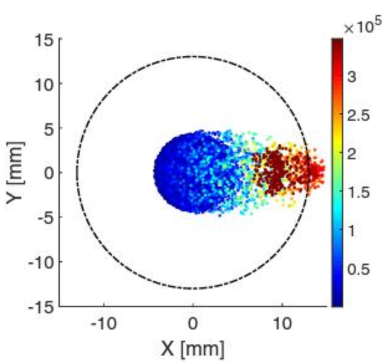


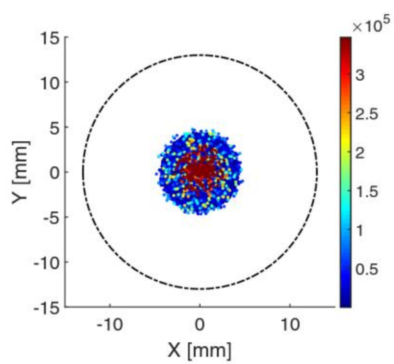
- The slope line shows the average current contour level.
- The ball diameter is representative of the peak current of the gun.
- The red dash line at EIC R&D shows the maximum achieved peak current of 8 A

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 increase 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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[2]*Stony Brook University, Stony Brook, New York 11794, USA*

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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 with no field emission
- 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
- Immediate future plans include – vacuum improvement in the beam stop and beam line, beam test with Superlattice GaAs.

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

Brookhaven National Laboratory, Upton, New York 11973, USA

Acknowledgment

- **BNL**: Erdong Wang, John Skaritka, Wei Liu, Robert Lambiase, Matthew Paniccia, Chris Degen, Jyoti Biswas (I/O), Patrick Inacker, Zach Conway, Scott Seberg, Kevin Smith, Charles Hetzel, Rob Michnoff
- **Jlab**: Matthew Poelker, Carlos Hernandez-Garcia, the late Donald “Bubba” Bullard
- **Cornell University**: Karl William Smolenski

Thank you for your attention!

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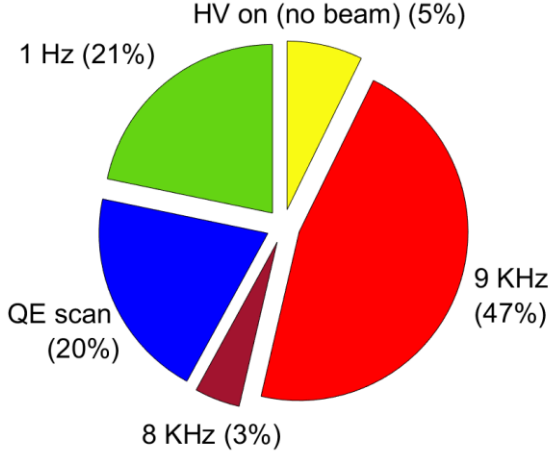
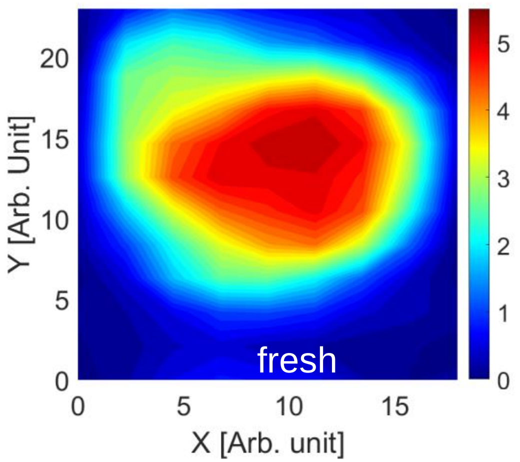
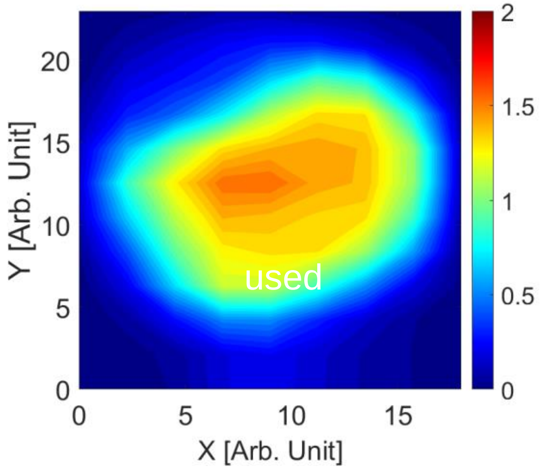
9000 pulse lifetime







- 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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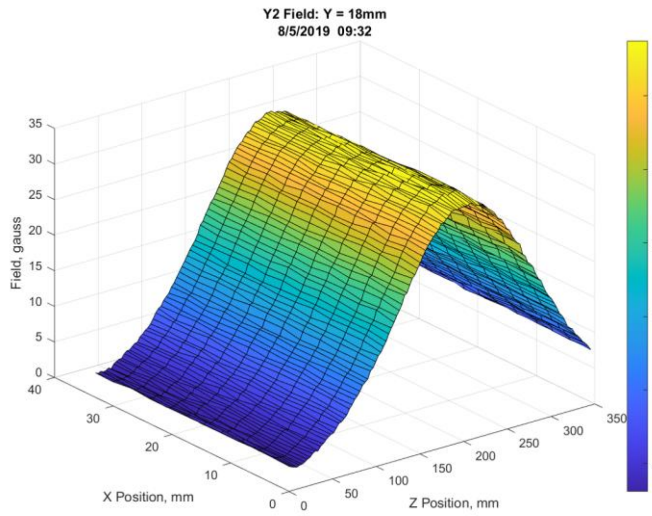
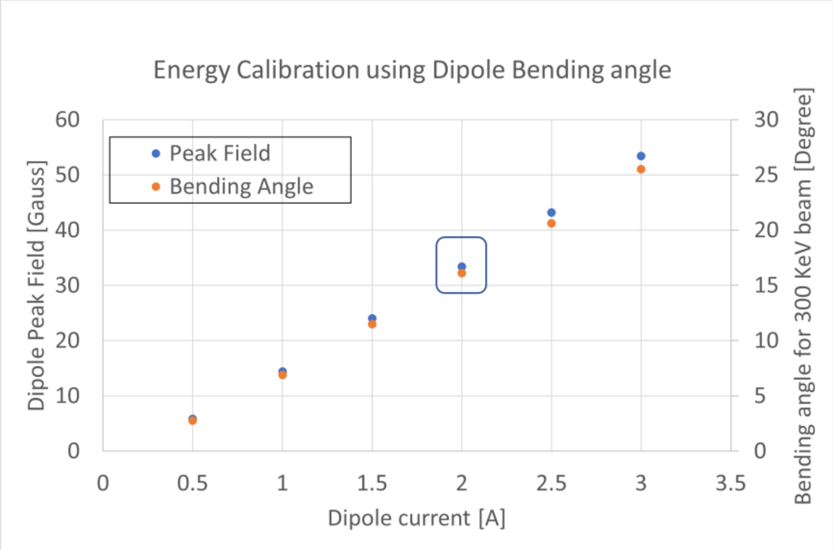
Beam energy calibration using Dipole





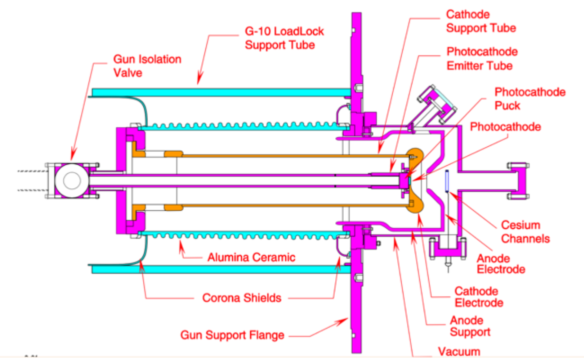
- Dipole field profile along beam path and peak field Vs applied current was measured
- Using the known bending angle (16 degrees) and measured field profile (using the current applied to the magnet during operation), the energy of the electron beam was calibrated.

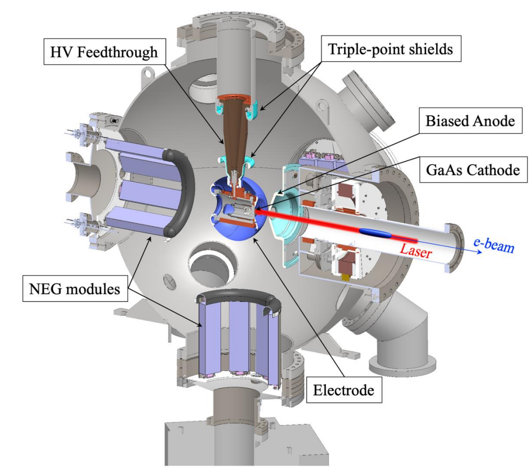
Overview of polarized guns in the world

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
EIC	300kV	7 nC	4.8 A	56 nA

In operation
Retired
EIC gun

SLC PES 120 kV gun





BNL EIC inverted 300 KV gun

Higher voltage to mitigate Space charge limit

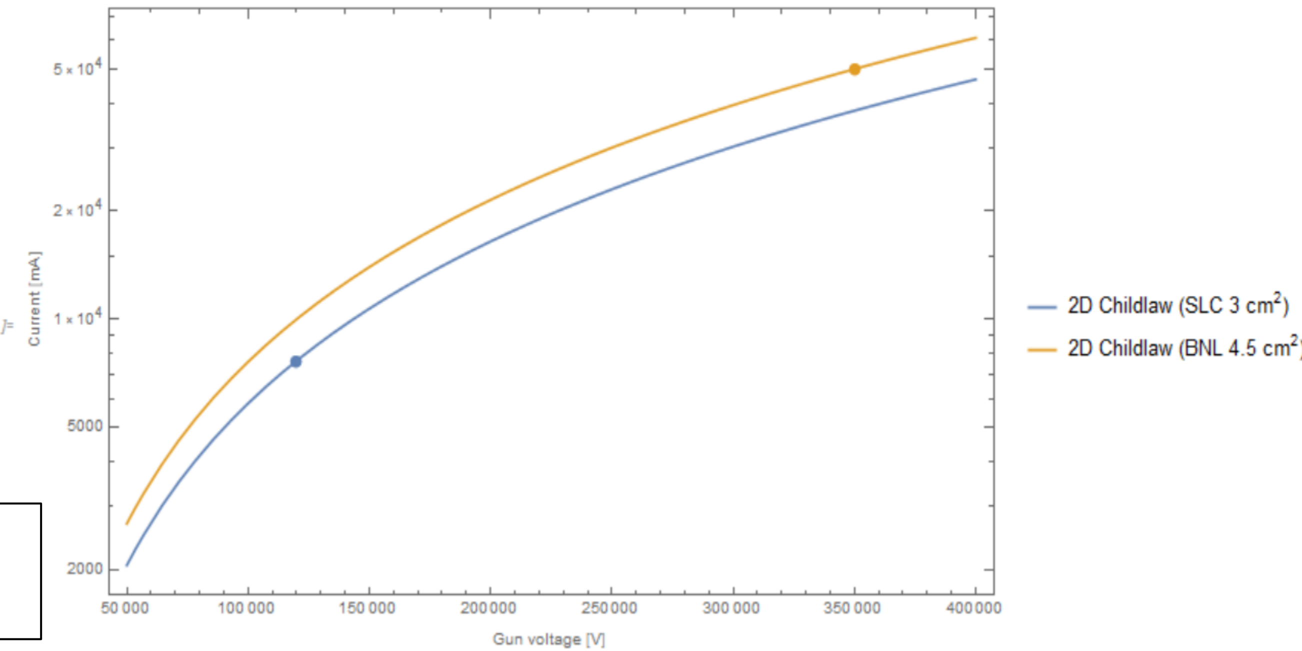
Maximum current density that can be transported across voltage gap:

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

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

Child's Law 2D (pencil):

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



Simulation used 350 KV design voltage

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

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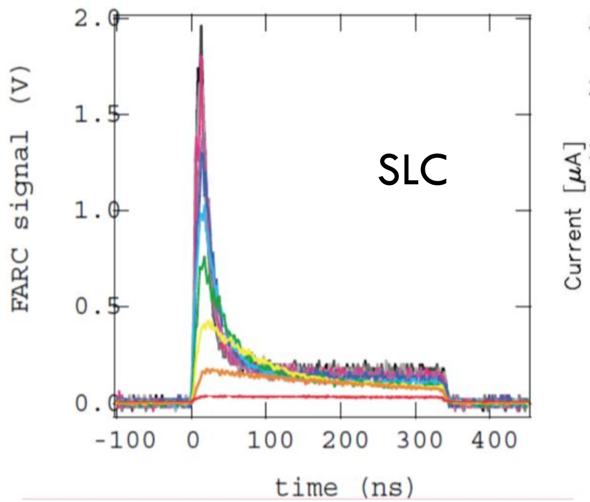
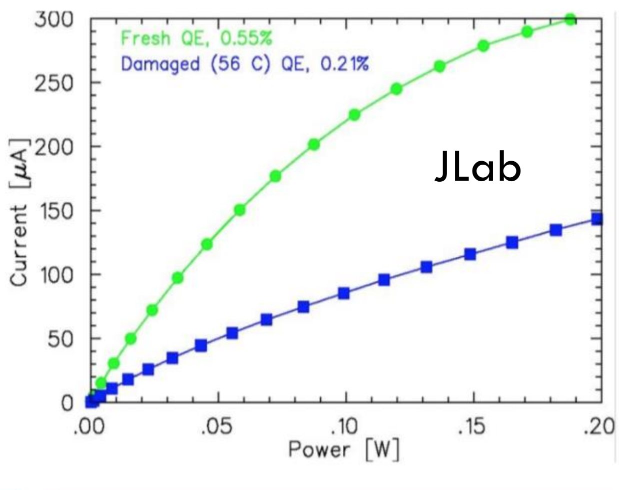
Higher voltage to mitigate surface charge limit





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

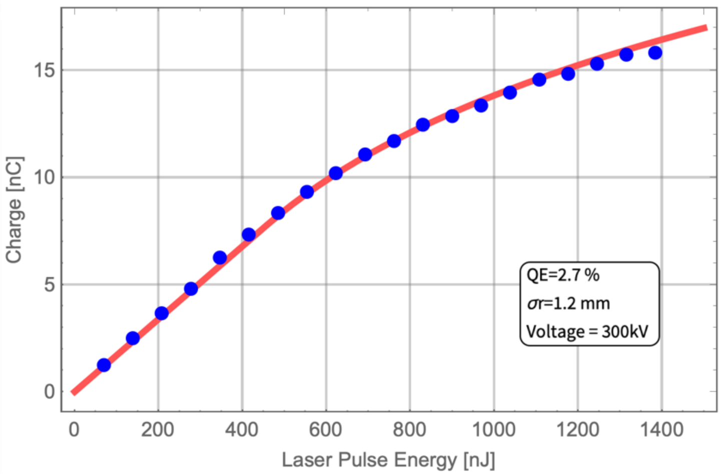
1. Heavily doped surface layer of Super lattice
2. Higher gun voltage

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

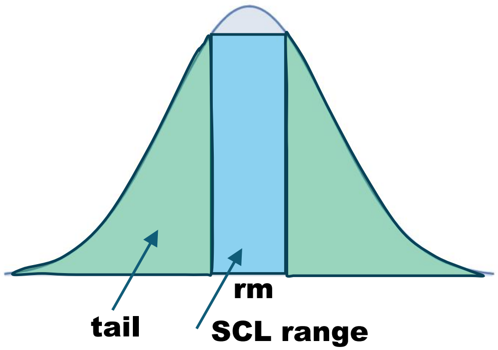
Graph courtesy:

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

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:

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

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

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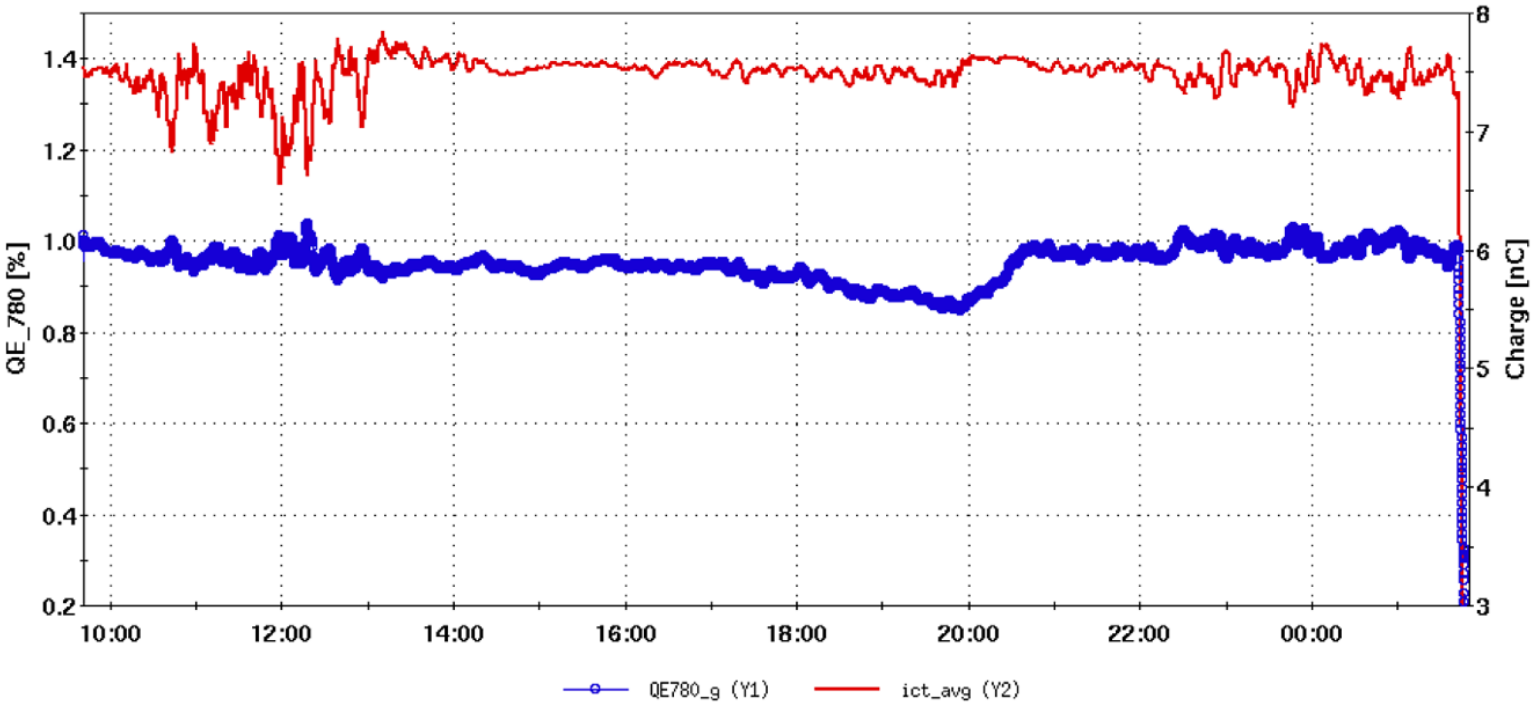
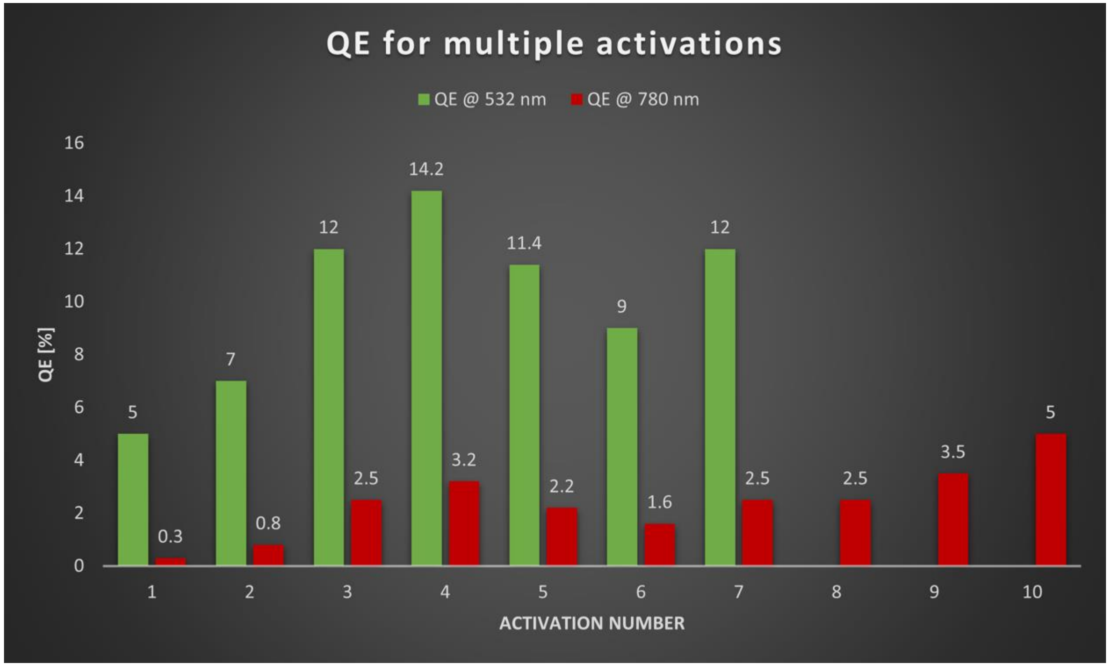
Low current lifetime measurement



- 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%

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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