High Intensity Polarized Electron Source Development for the EIC

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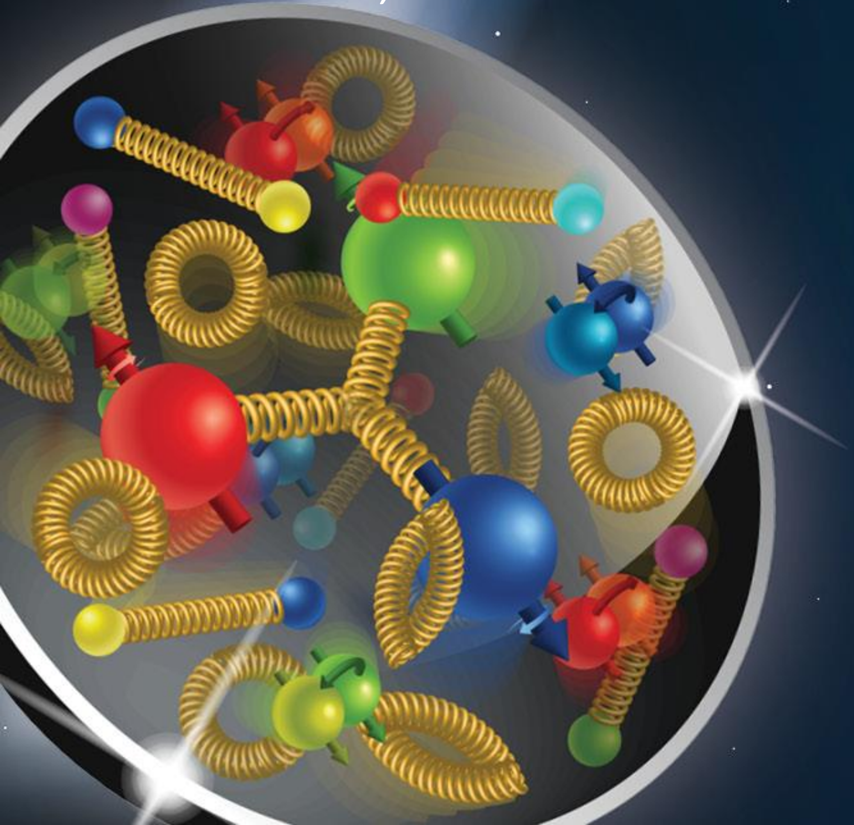
Presented by John Skaritka

at the

19th International Workshop on Polarized Sources, Targets, and Polarimetry (PSTP 2022).

September 26-30, 2022

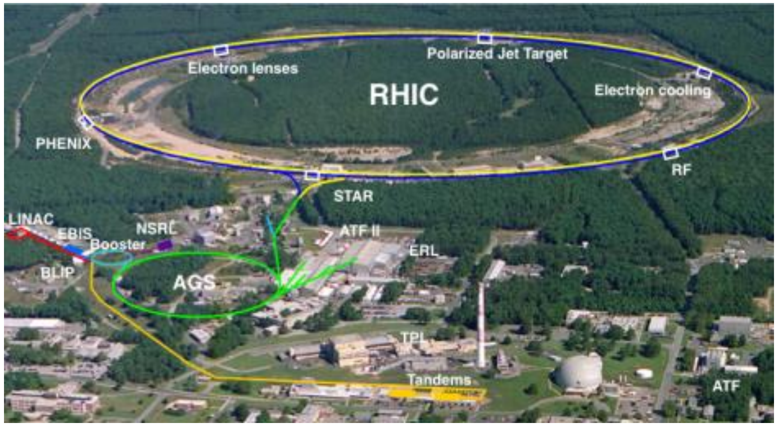


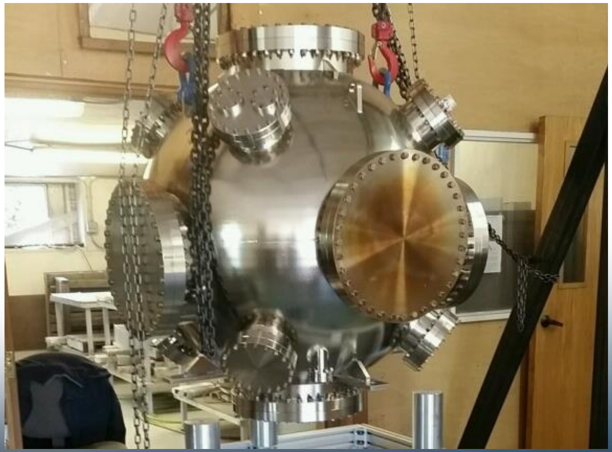
Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

Talk Outline

- **Brief Introduction to the Electron Ion Collider (EIC)**
- Scientific Motivation
- EIC Requirements
- Accelerator Layout
- Accelerator Pre-injector Design and Status
- **Polarized Electron Source for EIC**
- EIC polarized electron source requirements
- e-Source system design
- System component manufacturing and special processing
- e-Source development group facilities
- Gun System assembly
- System conditioning and test results
- Near term planning
- Summary





EIC uses BNL's Relativistic Heavy Ion Collider Facility

- The major part of a future EIC facility already exists
- EIC uses portions of the 2.4 Mile (3.8 kM) RHIC ring magnet system
- Most of RHIC will remain untouched
- RHIC beam parameters will satisfy EIC requirements
- Some changes in the straight sections are required to maintain a constant revolution time independent of energy

Questions to be Answered by the EIC

How is the proton and neutron spin of ½ composed by its constituents?

We don't know how the proton spin is composed. We know that the assumption of quark spin configuration was proven wrong in 1987. Since then, despite many efforts, this remains an unresolved question. The EIC with its two colliding polarized beams will shed light on this mystery.

- **How are the gluons spatially distributed in the nucleons?**

There are hints that the high stability of the proton is due to the fact that the gluons are concentrated near the surface of the nucleon. EIC will enable us to measure this.

- **How does the gluon density saturate?**

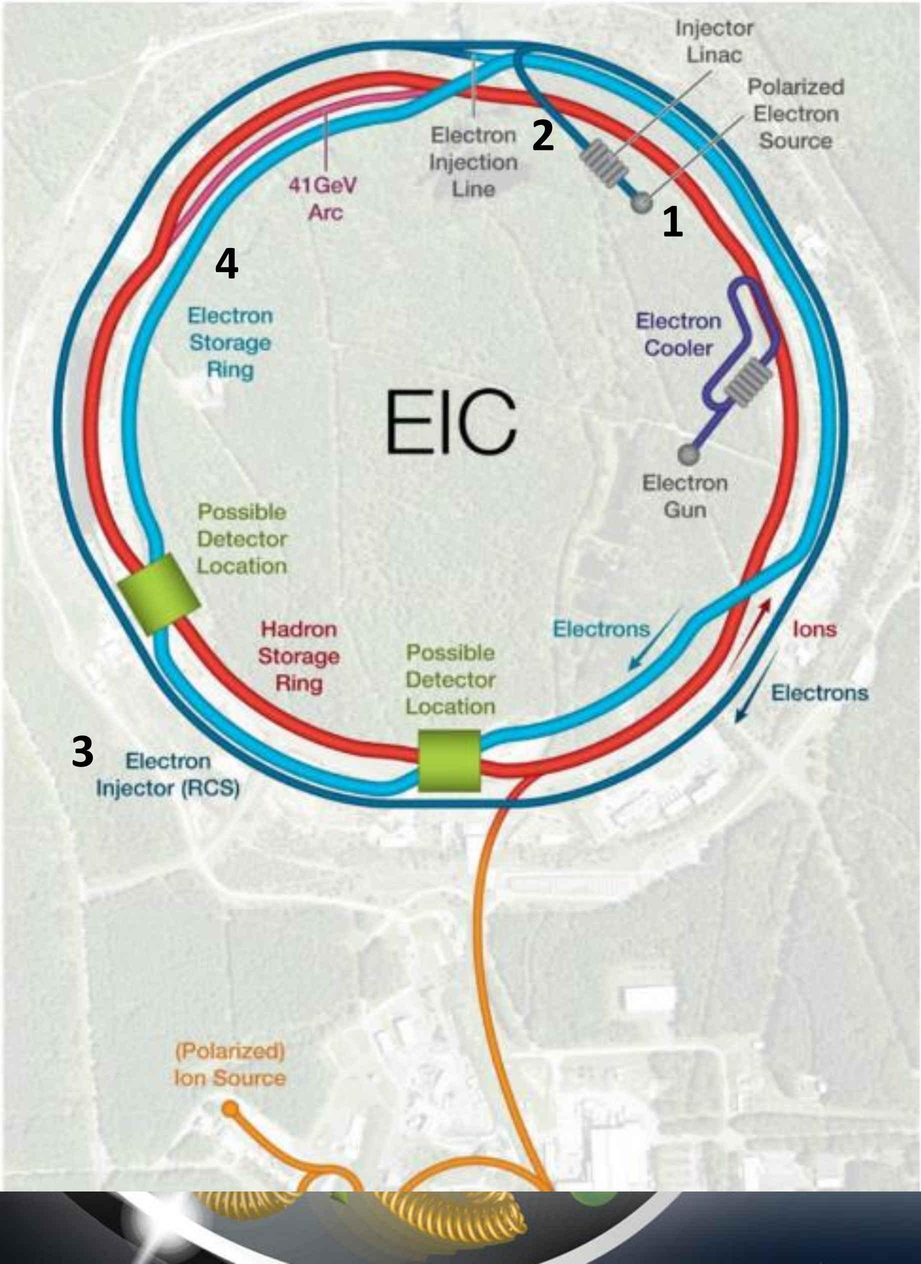
Earlier lepton hadron scattering experiments showed that the density of the gluons increases dramatically if they carry smaller fraction of the nucleon's momentum. First principles tell us this density increase must saturate, but we do not know when and how. Is saturation related to other unexplained phenomena? Electron-Ion collisions at high collision energies will make a significant step forward to understanding.

The EIC will enable novel measurement of nuclear structure and dynamics which will enhance our understanding of the "nucleon's inner landscape".

EIC System Requirements

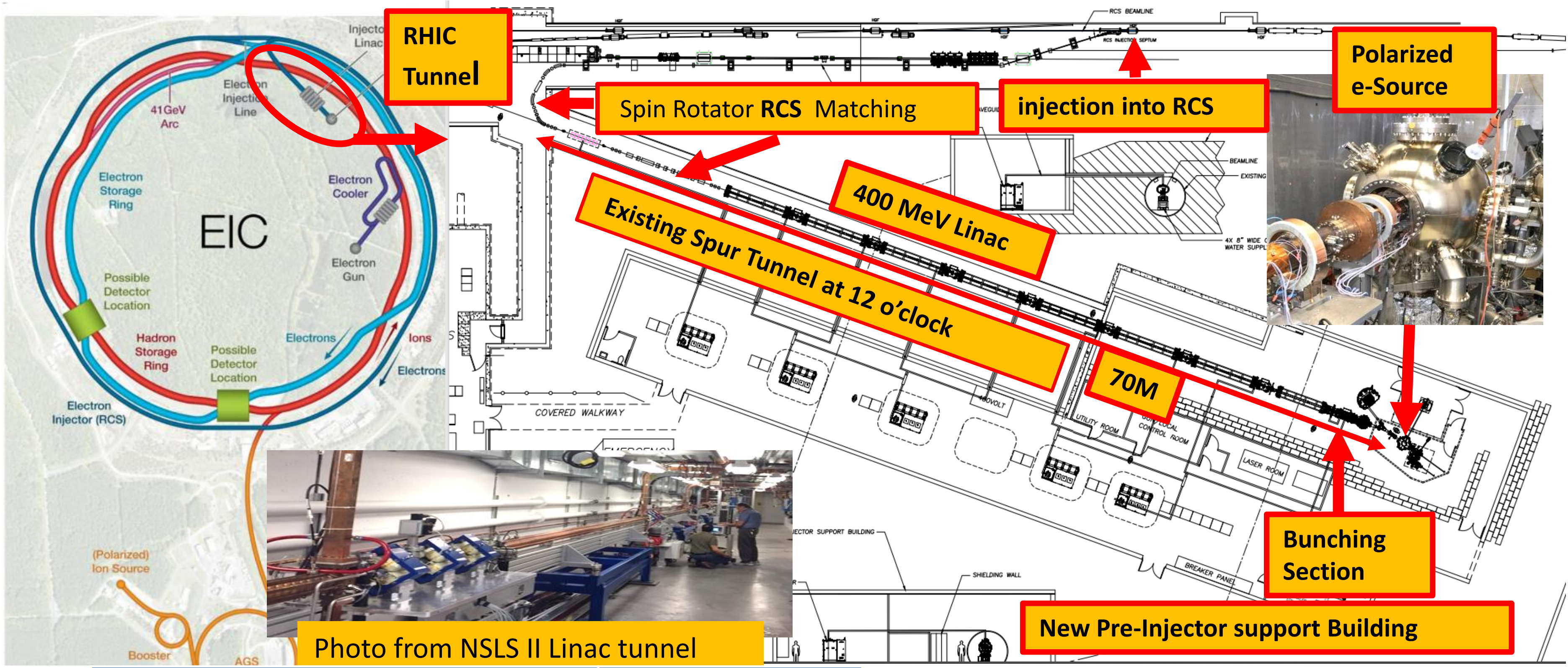
- The EIC facility is designed to meet the performance goals required to deliver the full scientific program recommended by:
- Department of Energy's Nuclear Science Advisory Committee
- National Research Council of the National Academies of Sciences, Engineering, and Medicine.
- Specifically, the design meets the following key performance
  - High Luminosity: $L = 10^{33} - 10^{34} cm^{-2} sec^{-1}$
  - Highly Polarized Beams: 70%
  - Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
  - Large Ion Species Range: protons – Uranium
  - Large Detector Acceptance and Good Background Conditions
  - Accommodate a Second Interaction Region (IR)

EIC Polarized Electron System Description



1. Polarized electron bunches carrying a charge of 7 nC are generated in a state of-the-art polarized electron source.
2. The beam is then accelerated to 400 MeV by the electron LINAC and injected into the Rapid Cycling Synchrotron (RCS) that is also located in the RHIC tunnel.
3. Two batches of four of these 7 nC bunches are injected into adjacent RCS RF buckets, and subsequently merged into two 28 nC electron bunches.
4. Once per second, the two new electron bunches are accelerated to a beam energy of up to 18 GeV, and injected into the Electron Storage Ring (ESR), where they are brought into collisions with the hadron beam.

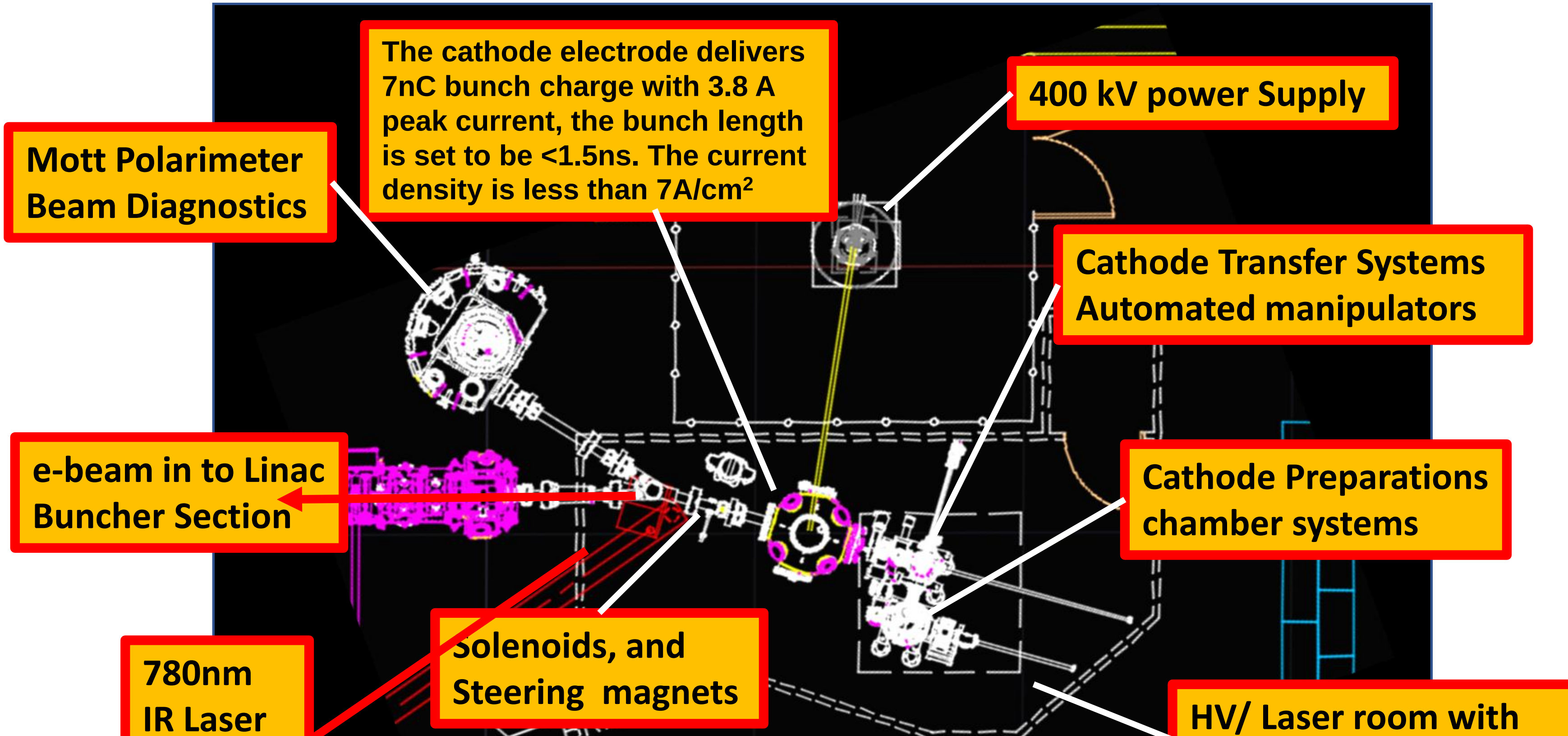
Parameters &Status of EIC Pre-Injector 400 MeV LINAC System



LINAC Performance Parameters	Value
Minimum energy at exit of LINAC	400 MeV
Minimum Energy Margin	> 25 %
Repetition rate f_{rep}	100 Hz
Energy spread ΔE/E	< 0.2% rms
Bunch Length	40 ps
Pulse to pulse time jitter	< 10 ps rms
Retained e-Beam polarization	>85%

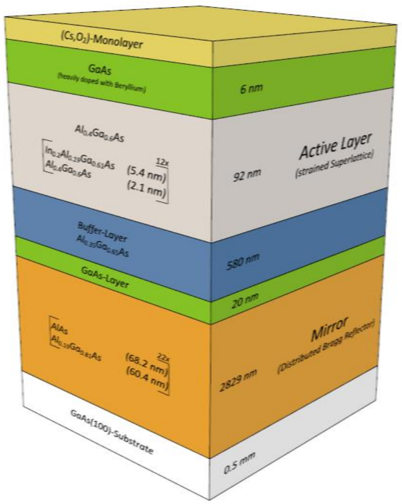
- **Physics Modeling Studies Completed**
  - Draft Specification, Statement of Work and Acquisition Plan Prepared.
- **Reviews Completed September 2022**
  - BNL/RFI found two possible Vendors
  - Market Research Vendor visits underway
  - Procurement Package to be ready for DOE Review by January 2023

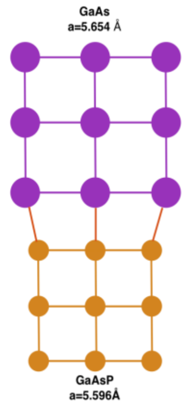
EIC Polarized e-Source System Description and Requirements

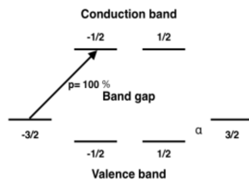


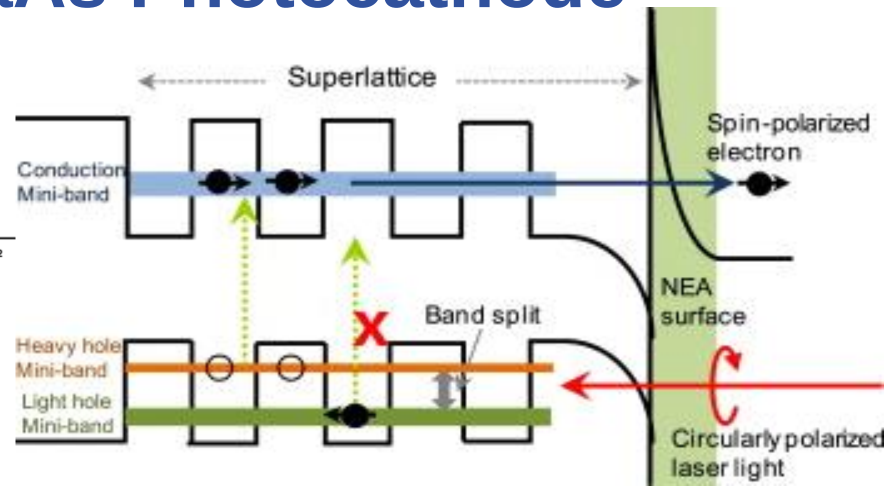
Gap Voltage	280 kV to 330 kV
Peak current	3.8 A
Frequency	1 Hz with 8 bunches
Average current	56 nA
Bunch charge	7 nC
Charge lifetime	34 mC

Super-lattice GaAs Photocathode

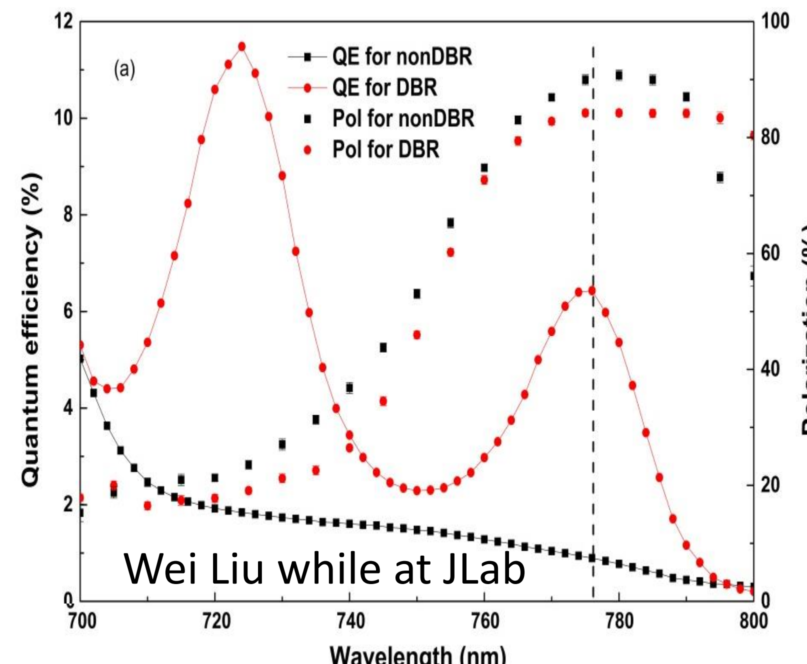




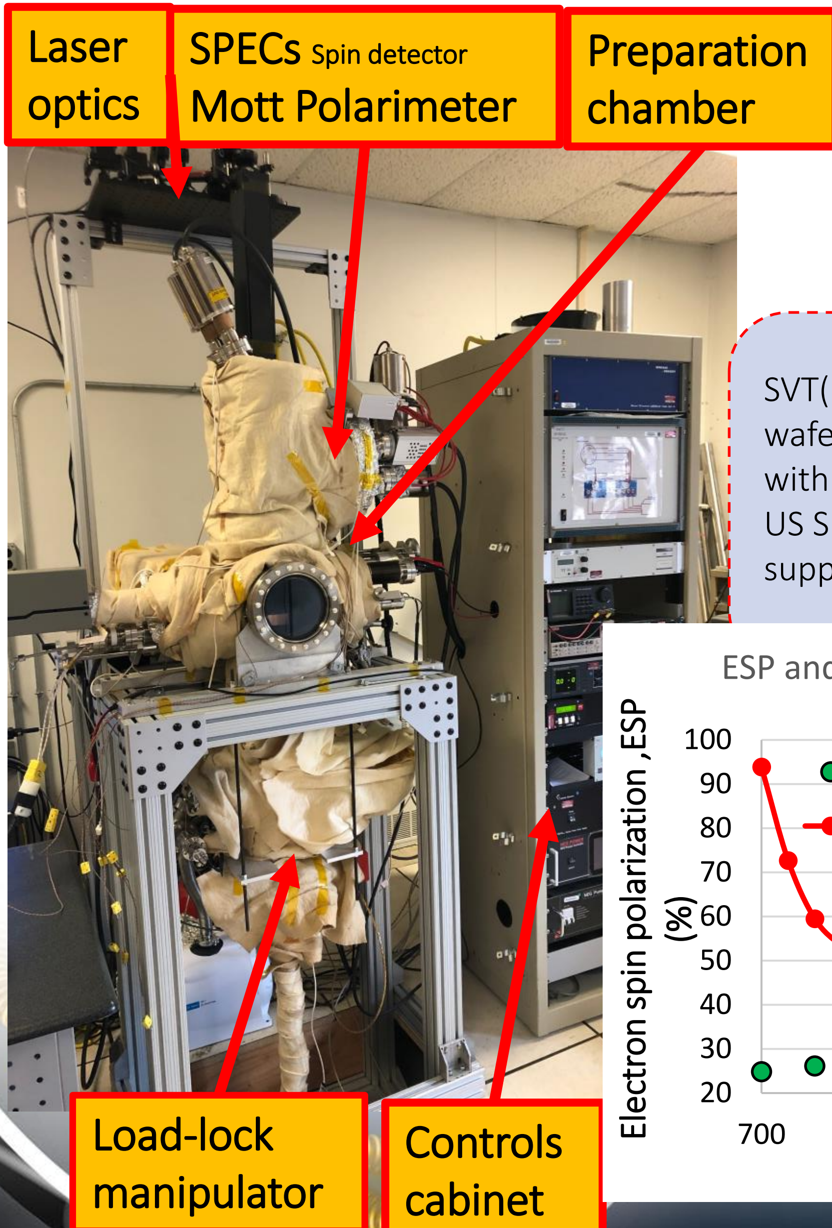




- Superlattice GaAs - 80-90% Polarization and QE of about 1%.
- Distributed Bragg Reflector DBR super lattice GaAs- QE is greater than 5%.
- Achieved >86% polarization.
- Vacuums of 10^{-12} Torr range are needed to achieve these results.

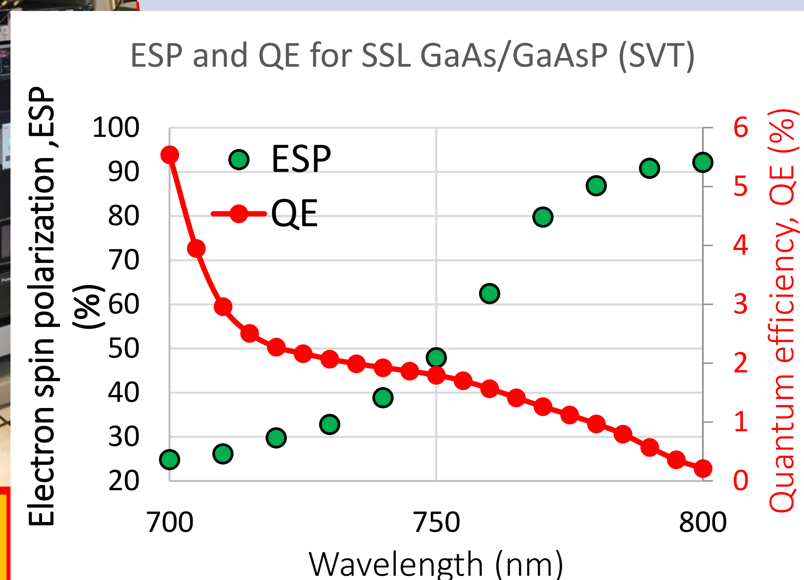


Polarimeter Facility at CAD-BNL to Evaluate Photo-Cathode Performance QE and ESP

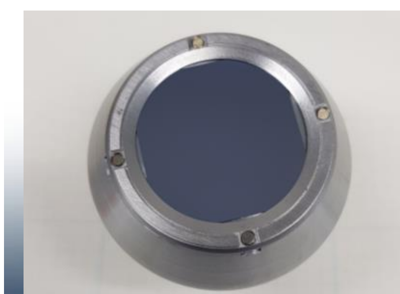


- We established polarization measurement for polarized electron source using mini-Mott.
- Several SL-GaAs samples(SVT ,Sandia, ODU) have been measured.

SVT(USA) was the best vendor. Expert moved to Acken Inc(China). 6 wafers on order but (delayed due to Shanghai lock down and problems with deposition chamber.
US SL-GaAs suppliers growing (ODU, Sandia, et,al). We expect the US supply train will be restored by the EIC start operation.

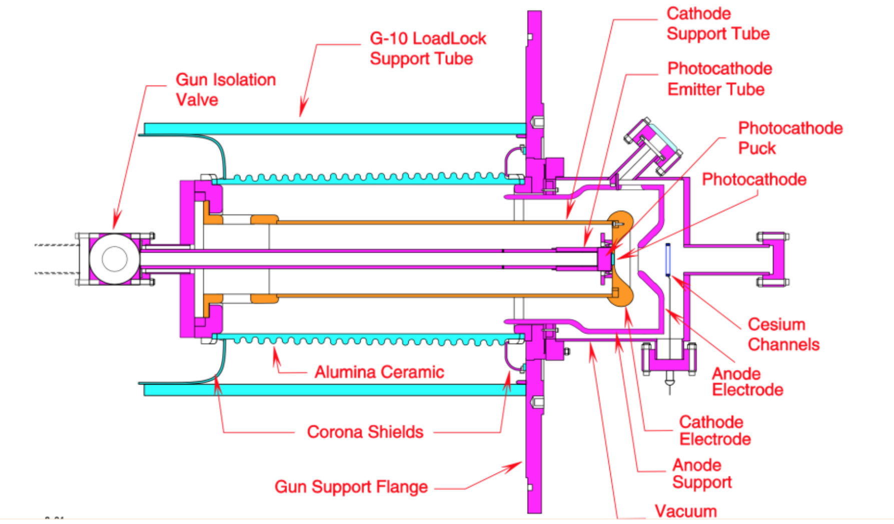


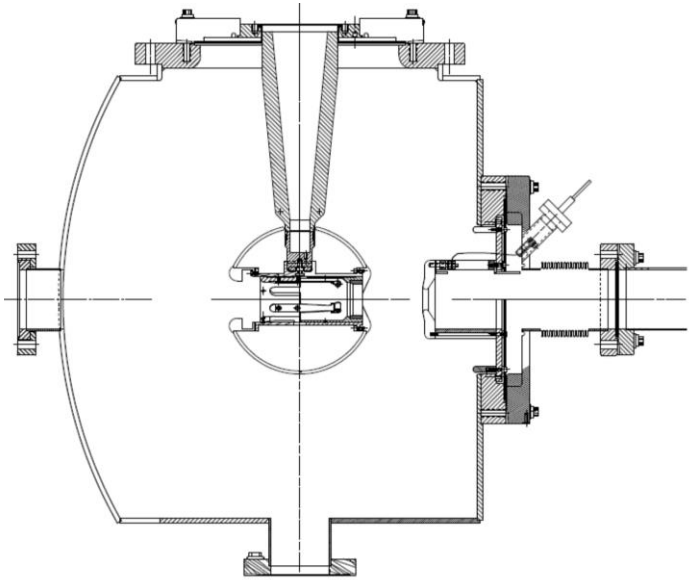
Large Area Cathode holder. 26 mm in diameter contained by a Tungsten cap.



e-Gun design choices for the EIC Pre-Injector

SLC PES 120 kV gun	JLab 350 kV inverted gun



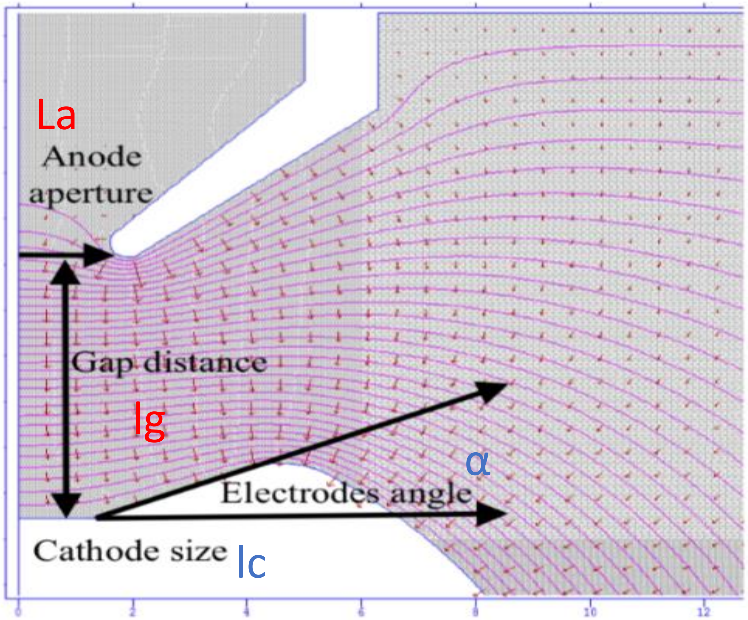


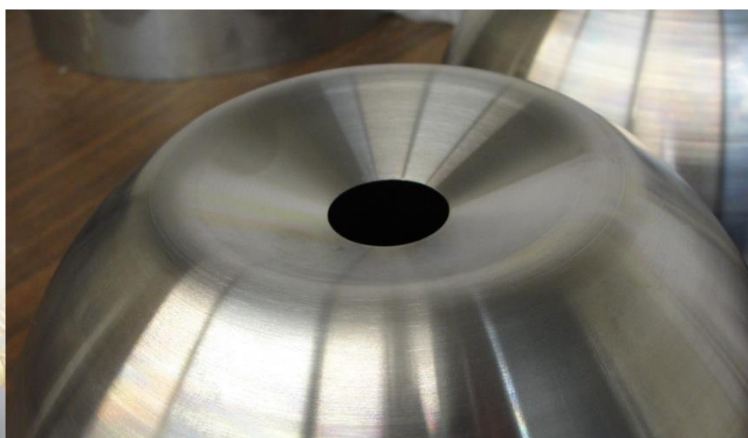
- First load-locked gun used at an accelerator
- High bunch charge, low avg. current, very long operating lifetime 。
- Four days to re-activate photocathode, because load lock at HV...

- Inverted shape has less out gassing surface and eliminated field emission to ceramic
- High average current, long operating lifetime.
- Easy to replace GaAs cathode.
- 10^{-12} torr scale vacuum
- Selected The JLab inverted gun to build upon

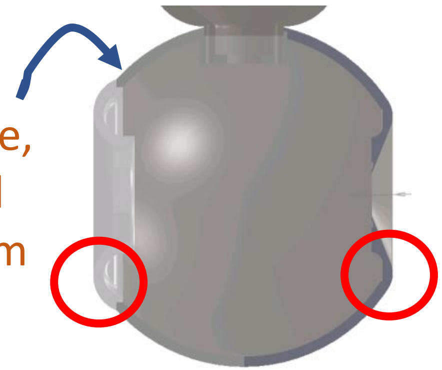
Electron-Ion Collider

BNL Large Cathode Prototype Gun Design





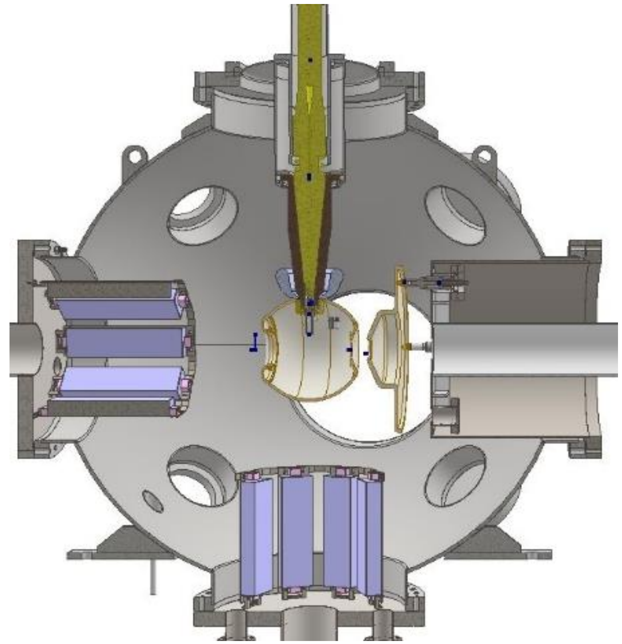
Assemble,
recessed
2.2 MV/m



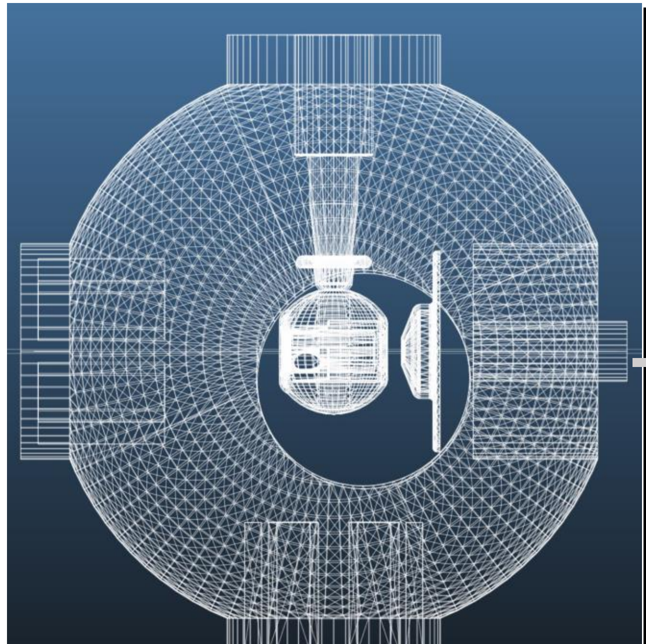
Very well
polished
8MV/m

	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)	20 degs
Cathode gradients	3.8 MV/m
Maximum gradient	<10 MV/m
Anode radius(la)	1.7 cm

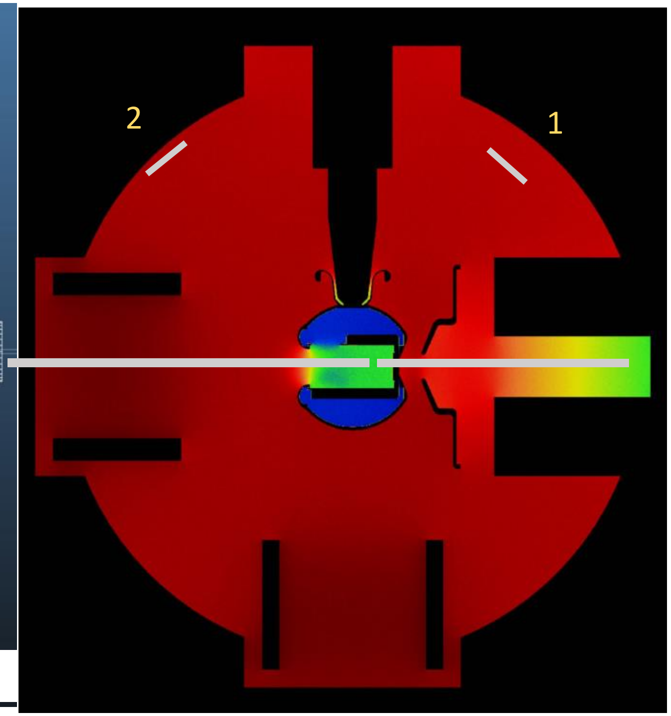
Vacuum Simulation e-Gun Vessel – using molflow+:

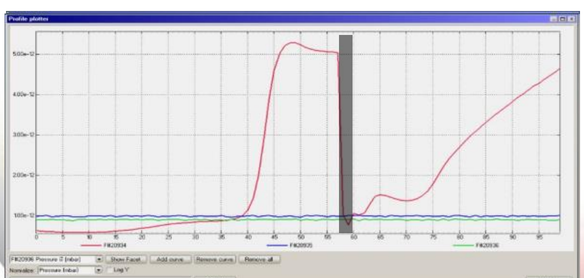


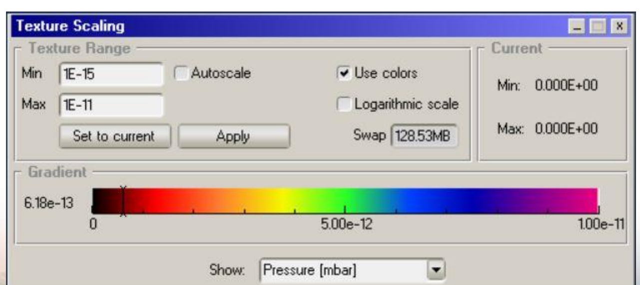
3D CAD design of BNL 350 KV DC Gun



Molflow+ vacuum space model

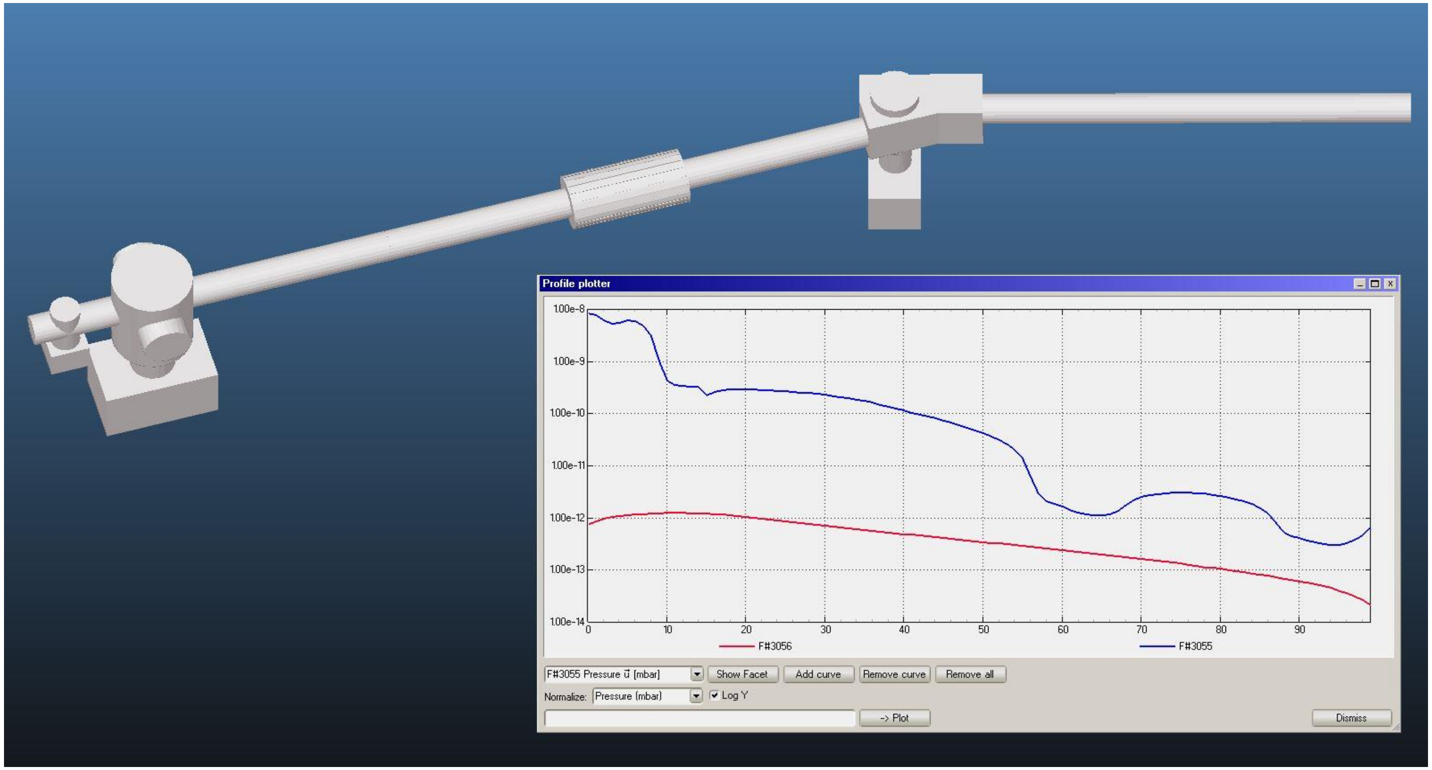






Position	Pressure (Torr)
Cathode	8.6×10^{-13}
Gauge - 1	7.7×10^{-13}
Gauge - 2	6.9×10^{-13}

Vacuum Isolation Study of the Beam Line



A Molflow+ simulation of the diagnostic beam line illustrates the feasibility to maintain a relatively large pressure differential up to 4 decades between the faraday cup in the beam dump and the entrance to the gun vessel that in addition to the biased Anode will maintain extreme vacuum conditions at the cathode surface during accelerated life e-beam testing.

Final HVDC e-Gun Design

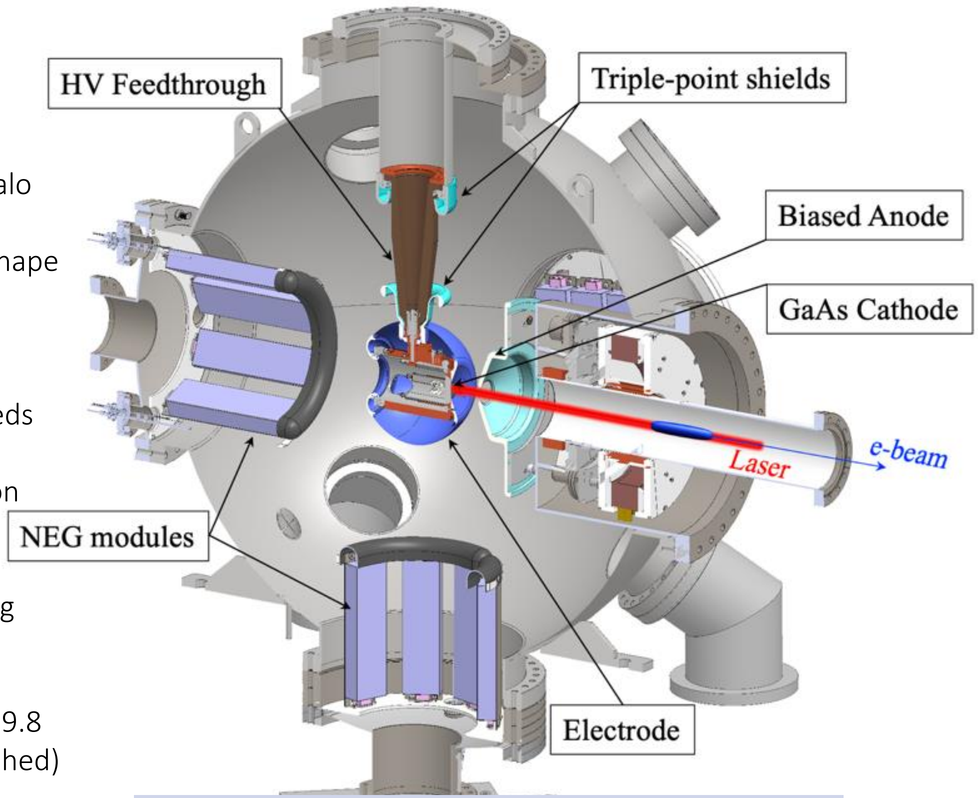
Gun design include:

- high voltage feedthrough
- triple-point sheds
- Beam quality, envelop, halo
- NEG pump positioning.
- 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

Maximum gradient @350 kV: 9.8 MV/m(gap nose, triple point shed)

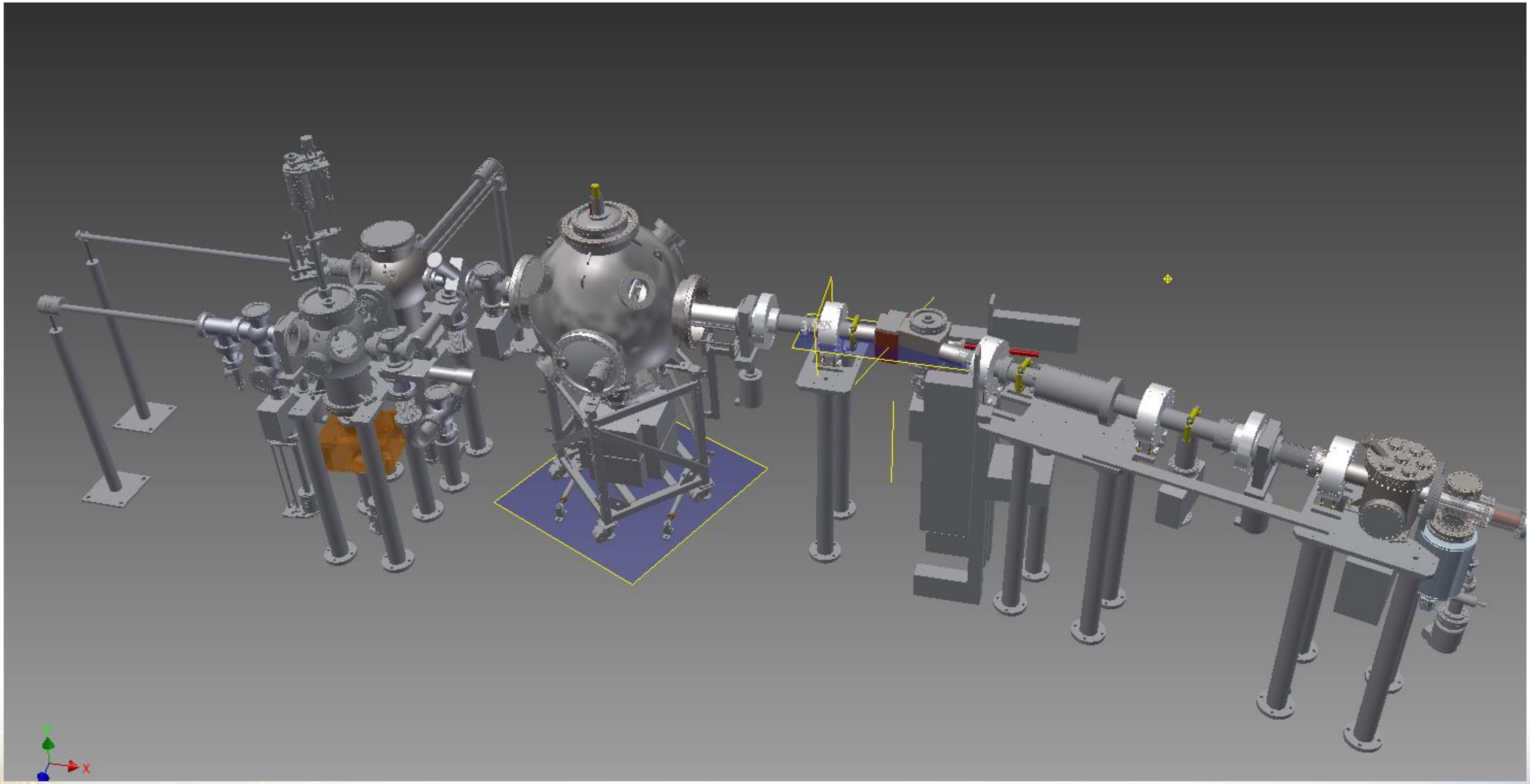


New features includes:

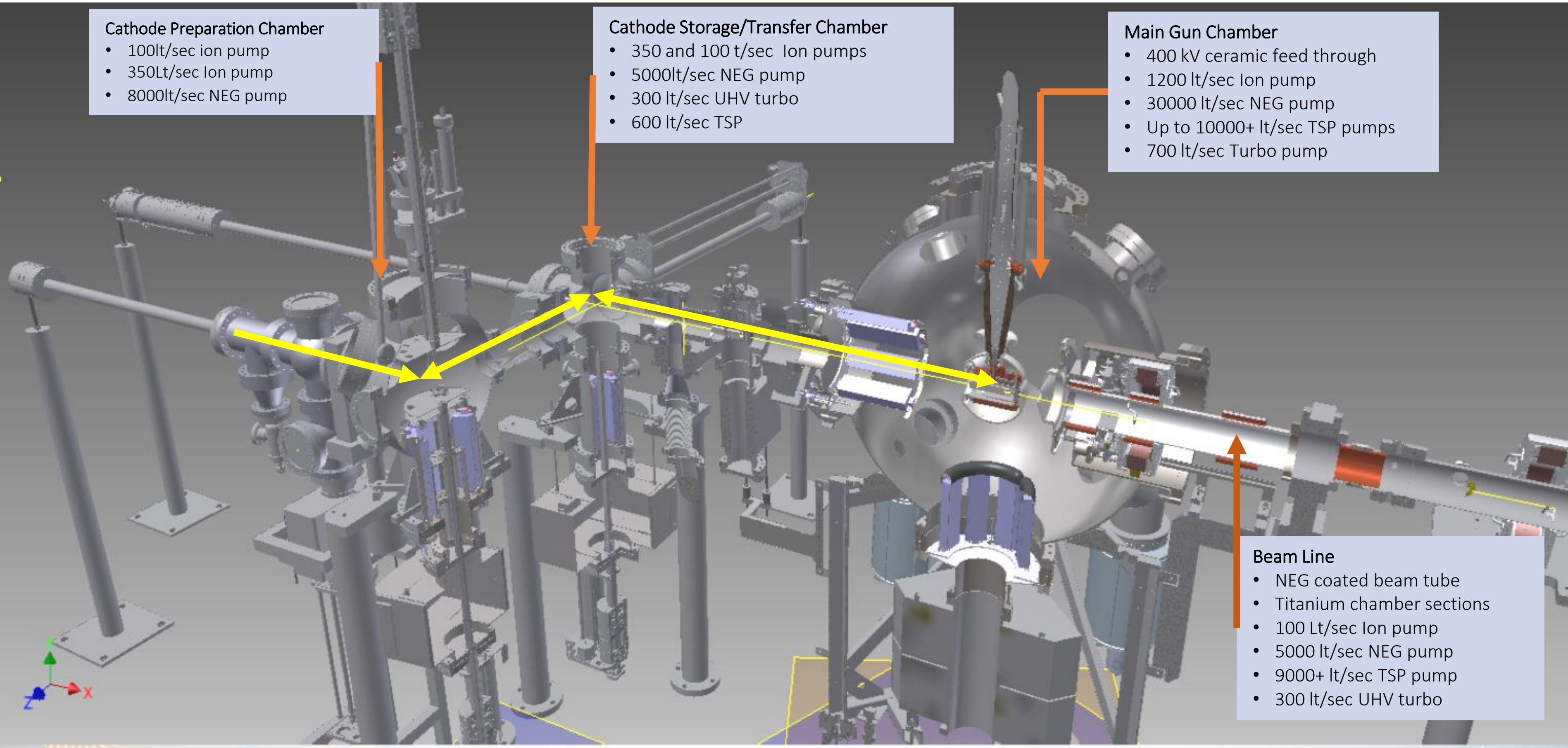
- Active cathode cooling
- Large cathode
- Semiconductor jacket HV cable
- x,y,z moveable electrically insulated anode.

	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	20 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

The EIC Prototype Electron Source and Experimental Beam line at Stony Brook University



Sectioned view of HVDC e-Source Vacuum System and Cathode Transport path through Gun System



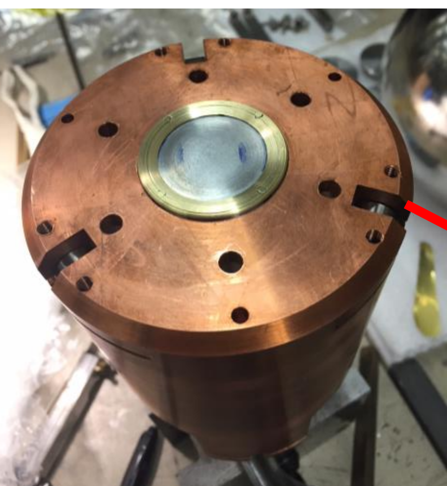
Polarized e-Gun Component Manufacturing

Inverted Gun Cathode Shroud

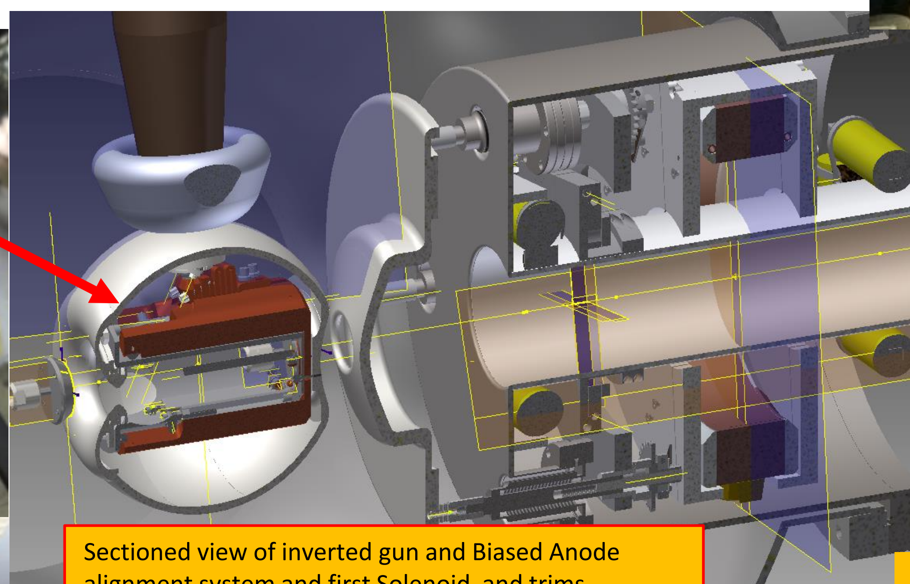
Titanium Anode)

Cathode Storage Chamber, (Titanium,)

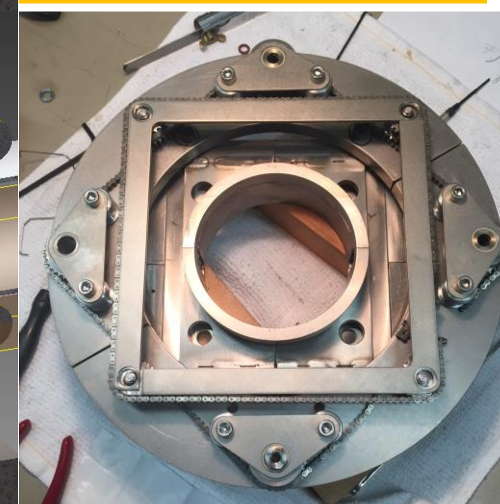
Cathode Activation Chamber



Cathode Puck in Copper heat sink



Sectioned view of inverted gun and Biased Anode alignment system and first Solenoid and trims



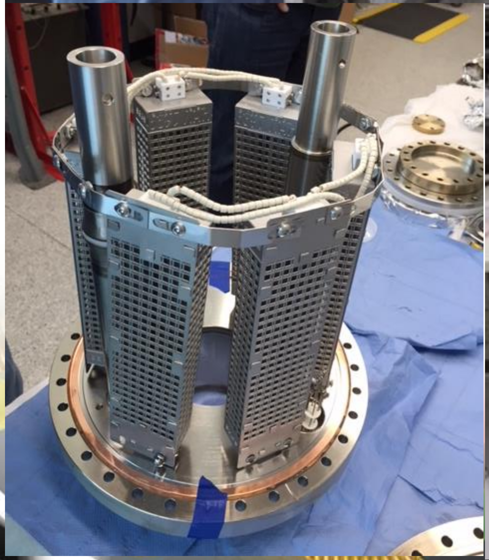
Anode alignment system,

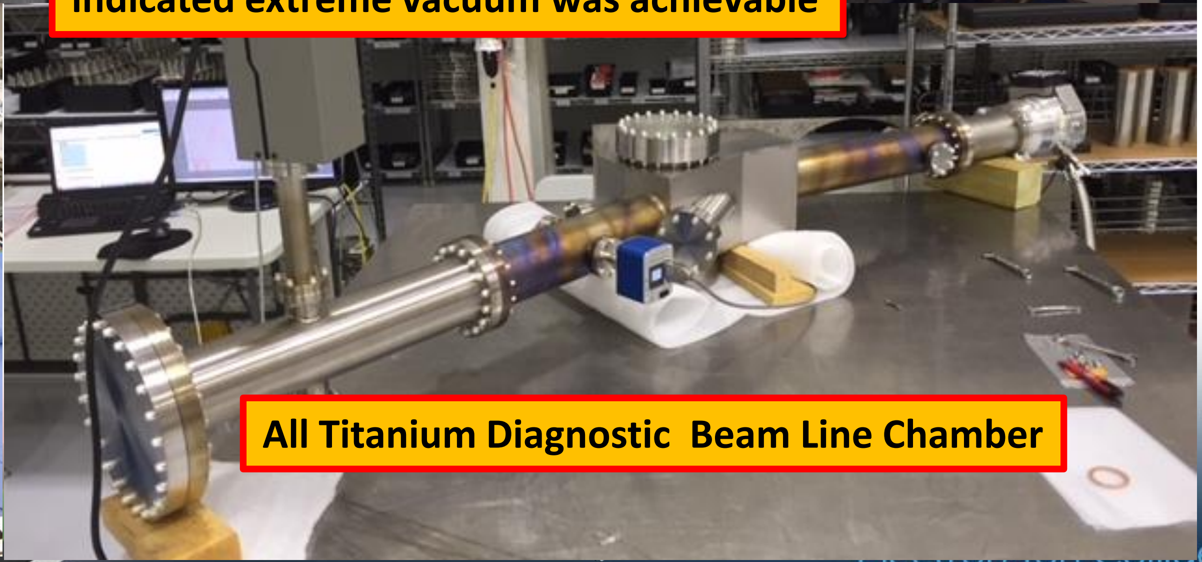
EIC e-Gun Vacuum System Stainless Steel Components High Vacuum Fire Processing

- All stainless-steel components were vacuum fired at 920-950 C for a period of > 2 hours at temperature and then Argon gas quenched to reduce the Hydrogen content at and near the surfaces of all in vacuum components.

System Component Assembly and Vendor testing

Vessel out gassing rate measurement Performed by BNL at Atlas Technologies indicated extreme vacuum was achievable





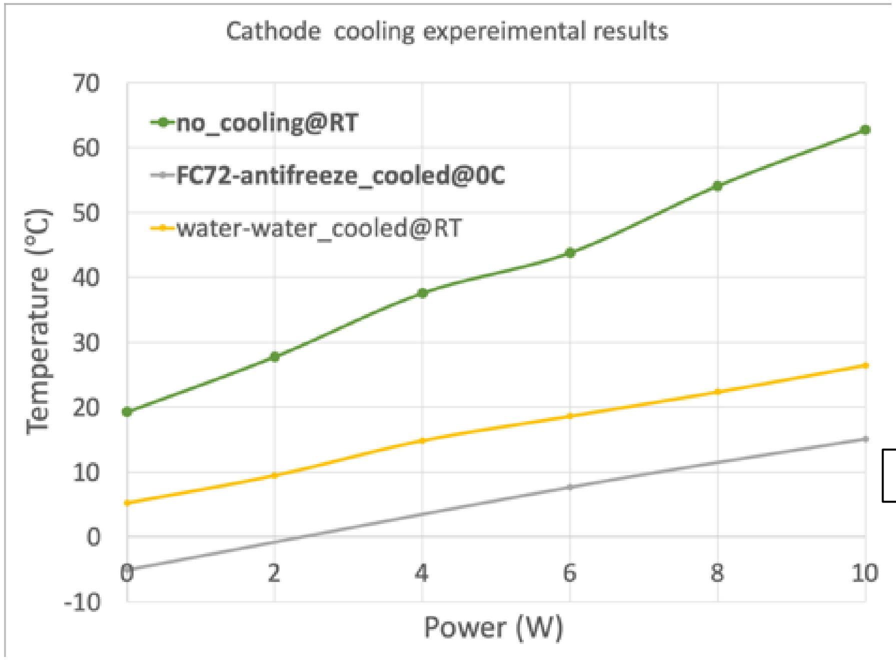
All Titanium Diagnostic Beam Line Chamber

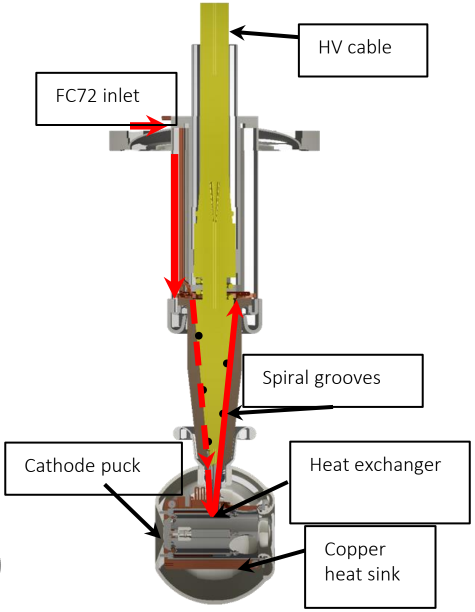
Active Cooling of HVDC e-Guns

Aiming to absorb laser power up to 10 W. We collaborated with Dielectric Sciences Inc. to develop the actively cooling HV feedthrough.

This is one of the critically important enabling technologies that has made our gun possible and will be the subject of the next talk by Robert Lambiase

Tested up to 410 kV with flow



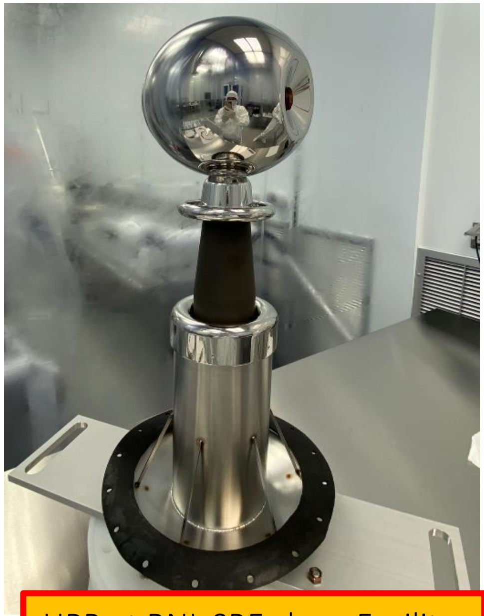


The EIC gun prototype was originally designed **for high current operation and demonstrates that a fluid cooled cathode** was possible and could be used for high current polarized/unpolarized guns.

The Ceramic Feedthrough was successfully reproduced in the United States by the MPF Company,, tested to 425 kVolts
Contact Dwane Mallery 1- 864-876-9853

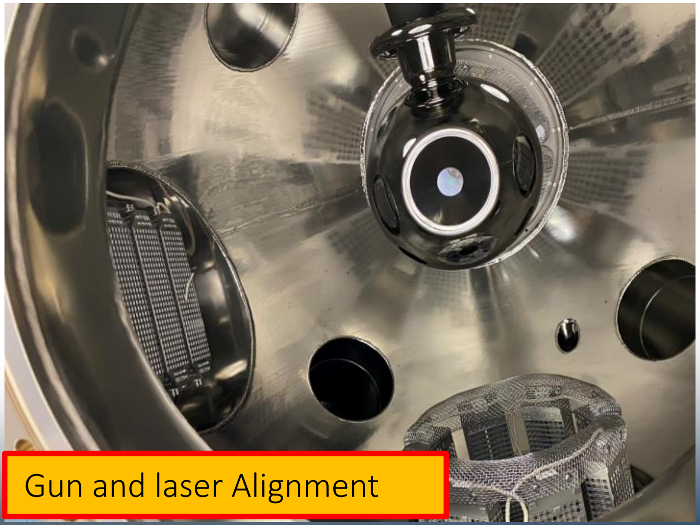
HV electrode treatment and installation

Corn cob polish at Jlab



HPR at BNL SRF clean Facility

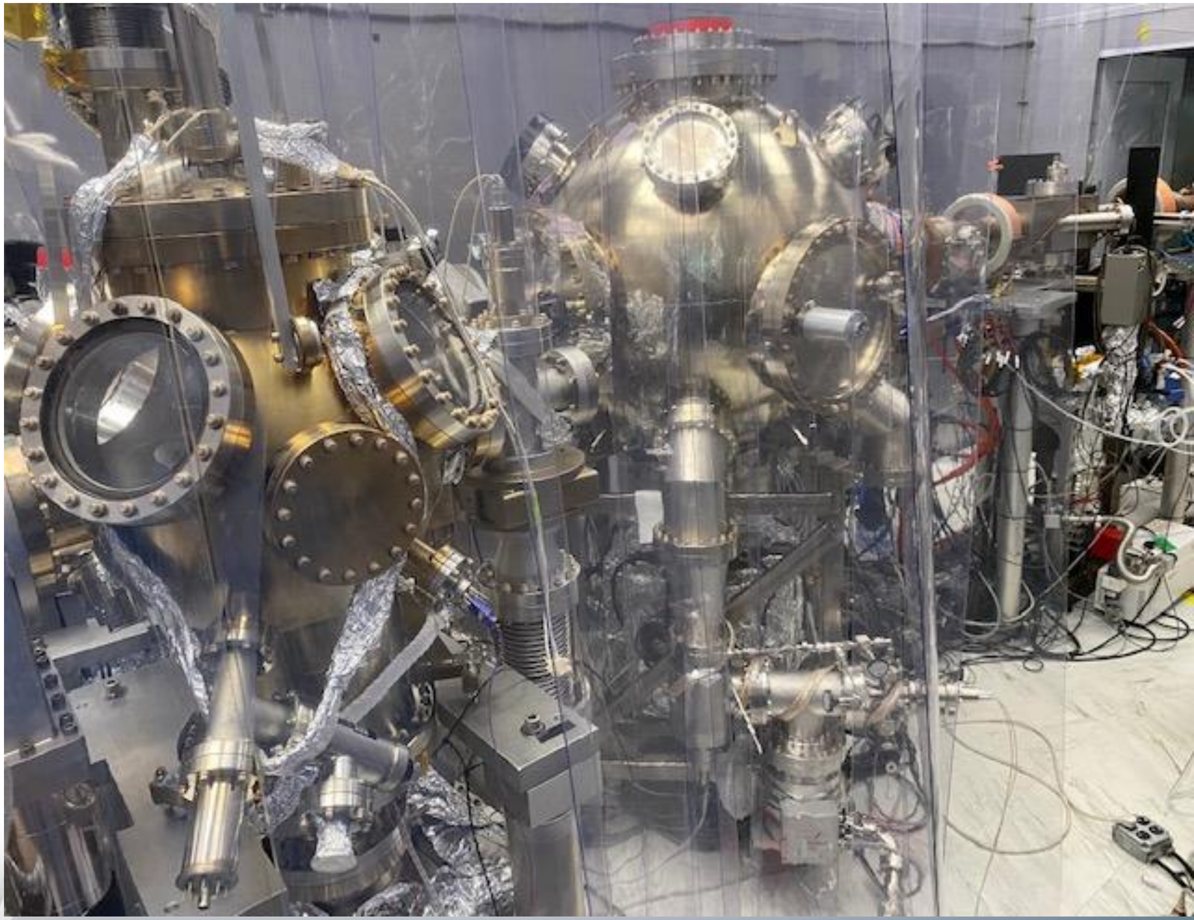
Installation at SBU



Gun and laser Alignment

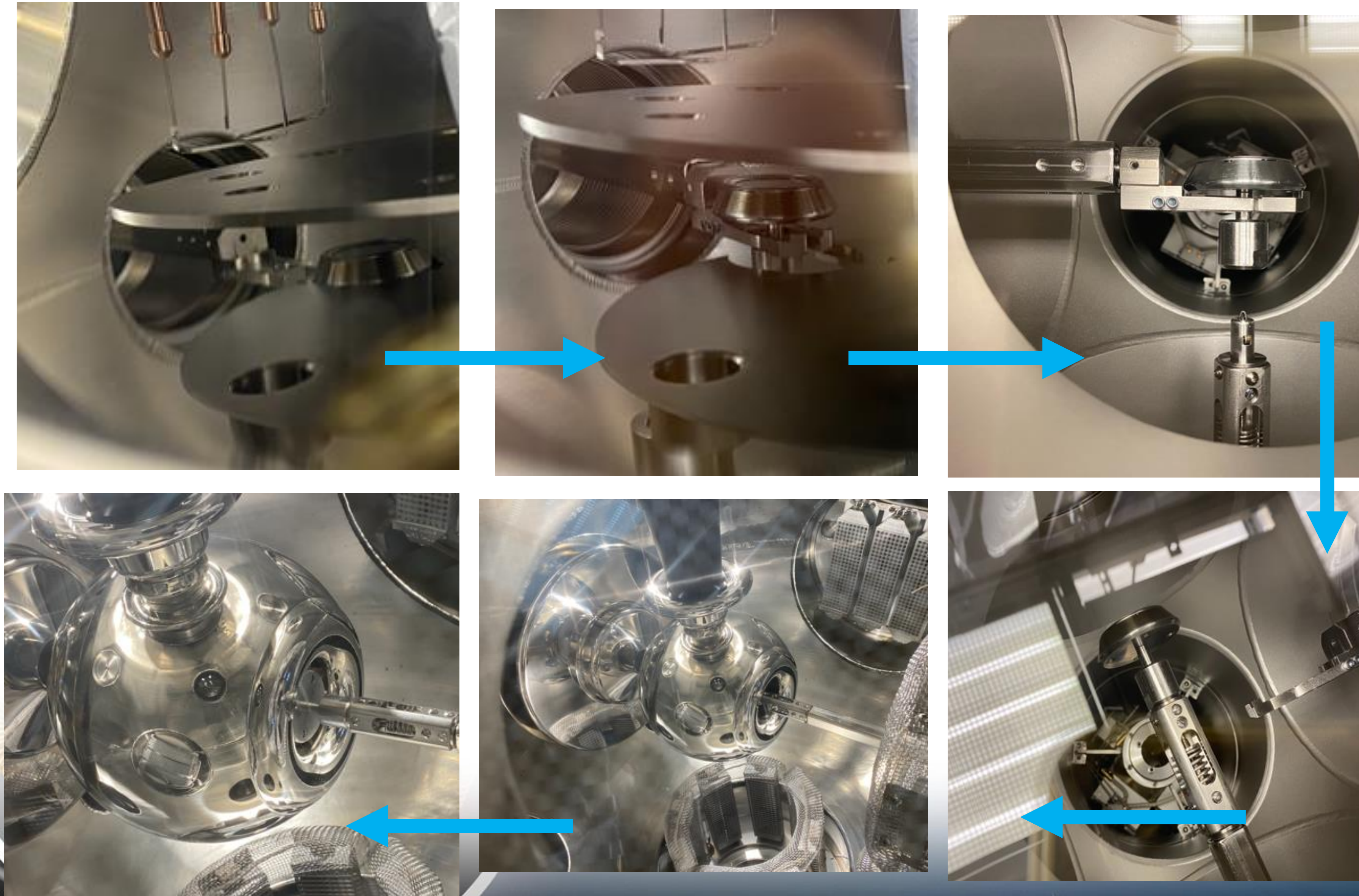
Final assembled gun

Cathode Insertion into Preparation, e-Source and beam line Chambers in gun cleanroom

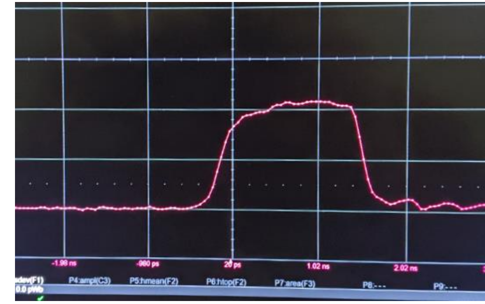


Cathode transfer from Preparation to Gun Chambers

,We can now insert a cathode in about 30 minutes.

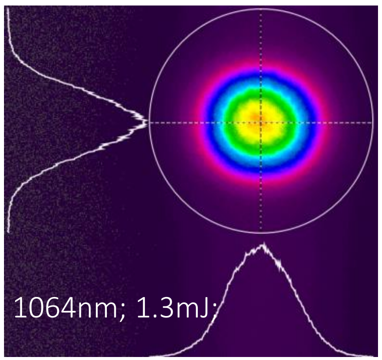


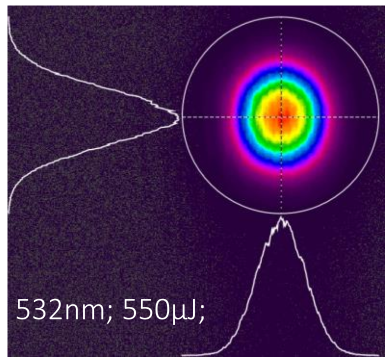
Polarized Laser Overview

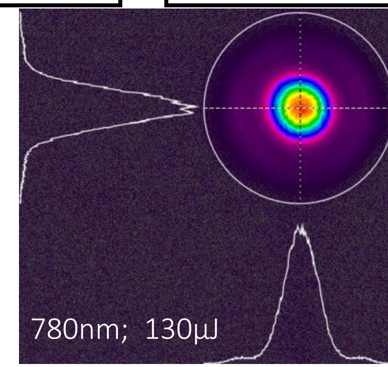


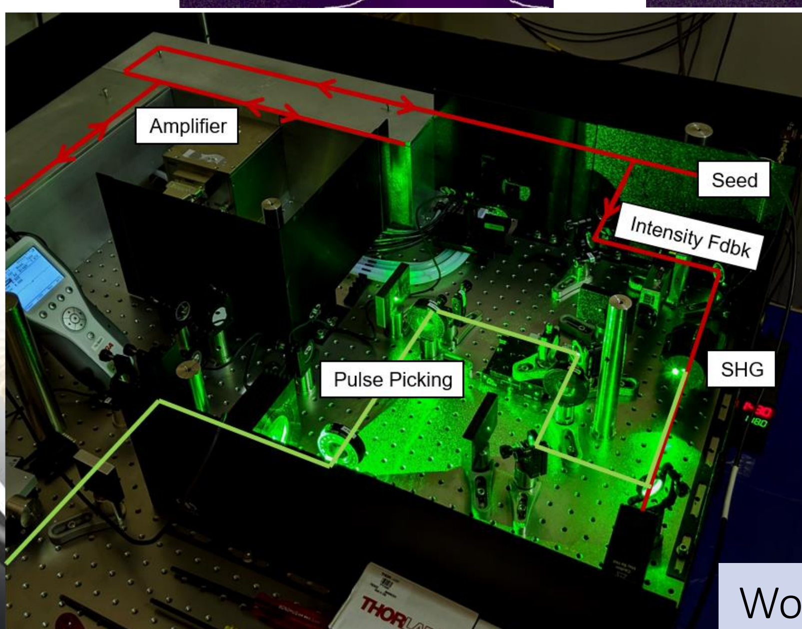
20MHz Seed — Regenerative Amplifier — SHG — Pulse Picker — OPA — Helicity & Intensity Control

780nm Pulsed Seed









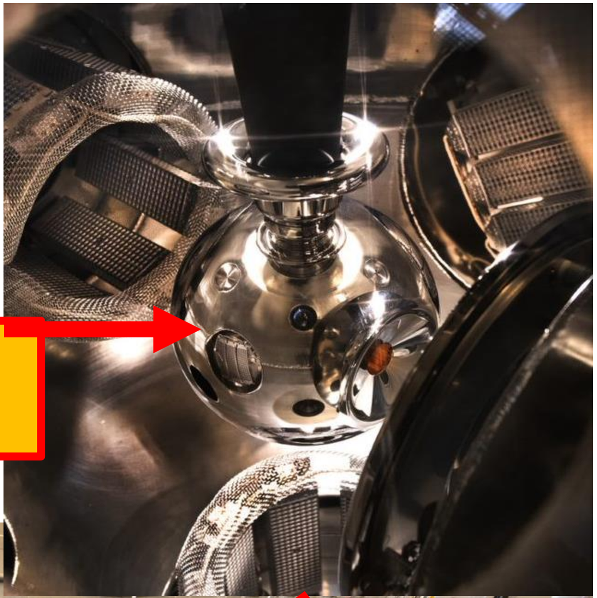
Parameter	Specification	Achieved
Repetition Rate	1-2Hz	1Hz-10kHz
Pulse Energy		
532nm	20µJ	500-800µJ
780nm	60µJ	130µJ
Longitudinal Profile	Flat or Gaussian	Flat
Flatness	5% (@780nm)	Flat
Transverse Profile	Gaussian	Gaussian
Pulse On/Off Contrast	70dB	>70dB
Jitter rms	10ps	5.5ps

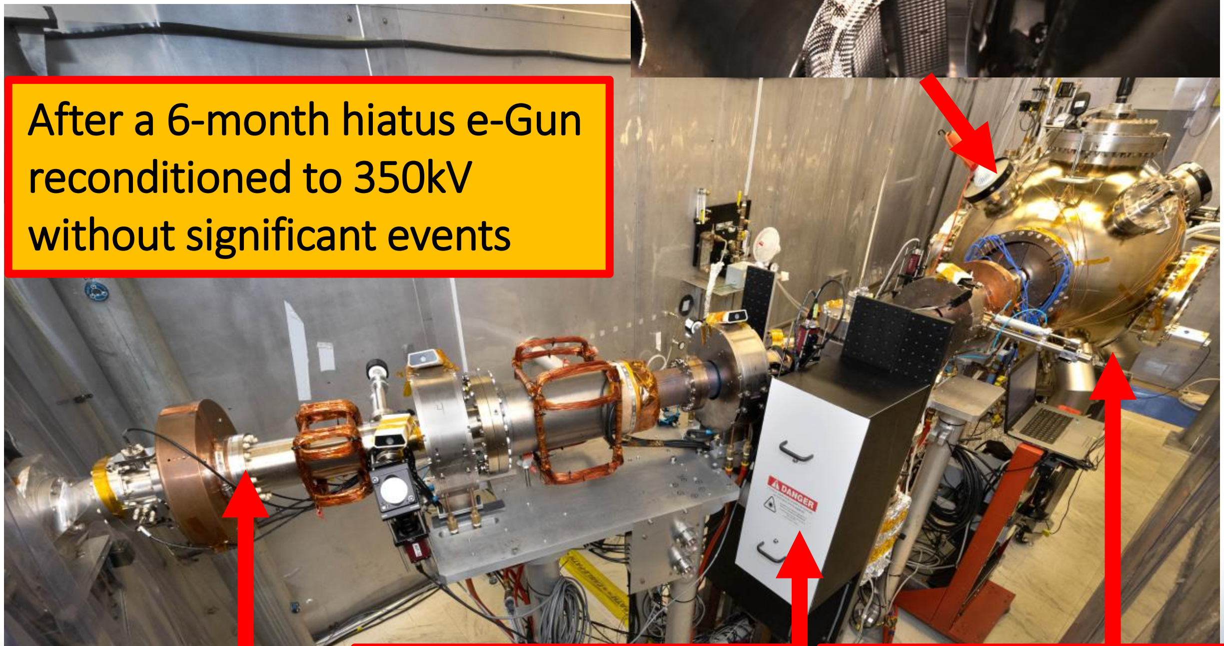
Work continues to reduce noise and to increase rep. rate

EIC Polarized e-Source and Diagnostic Beam Line Results

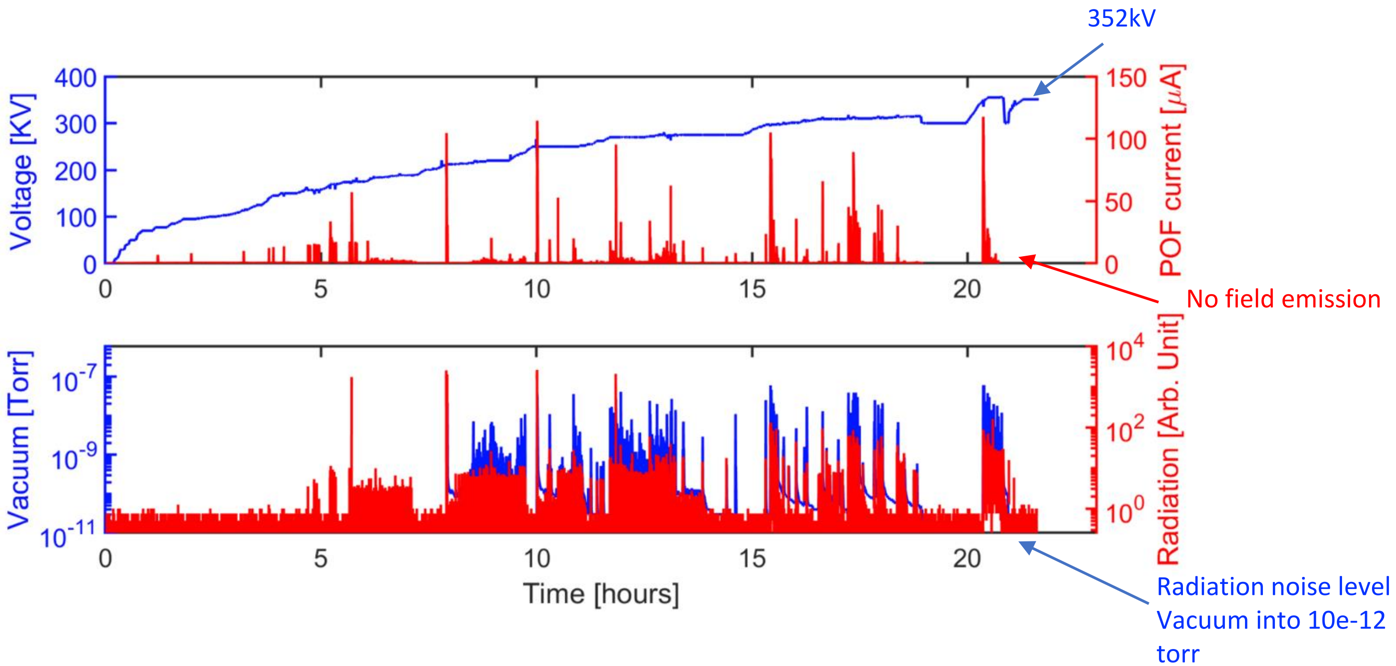
e -Gun performance since December 2020

- 16 nC gun SCL*
- 7-10nC @ 300kV
- Accelerated Life tests >9000bunches/sec.
- Cathode exceeds EIC required charge lifetime by >30 weeks.
- Gun operates at full current in 10^{-12} Torr
- Polarized beam from bulk Cathode material.





High Voltage e-Gun Conditioning

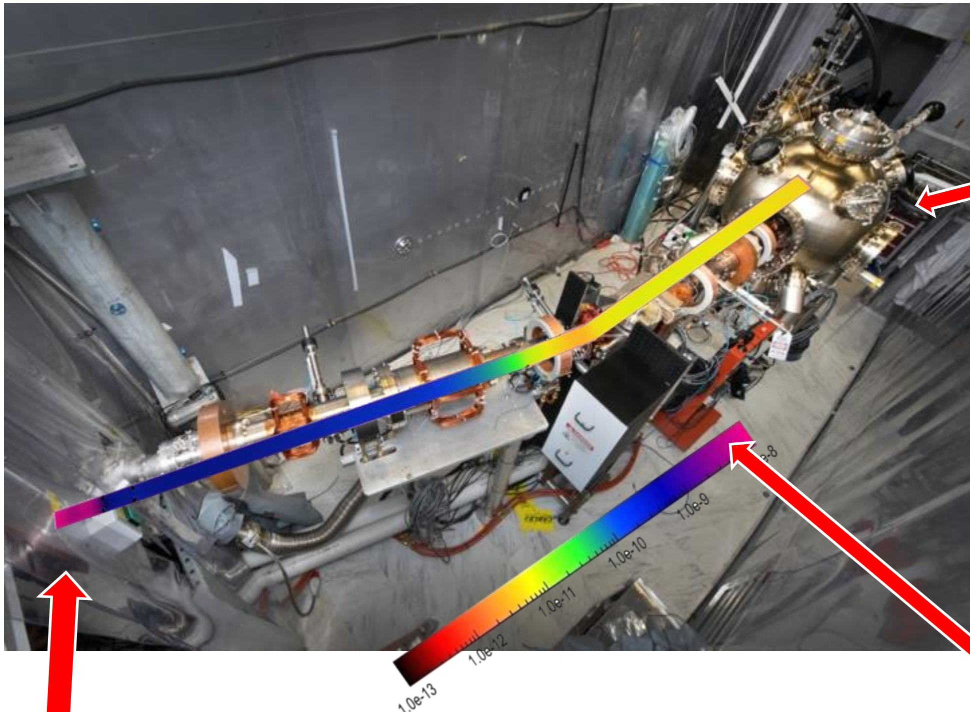


Gun conditioned at Dec. 2020(vacuum conditioning, total take 23 hrs, Cooling is on):

- Achieved gun design value 352 kV without field emission(without activated GaAs)
- Achieved gun design value 325 kV without field emission(with activated GaAs and new puck)

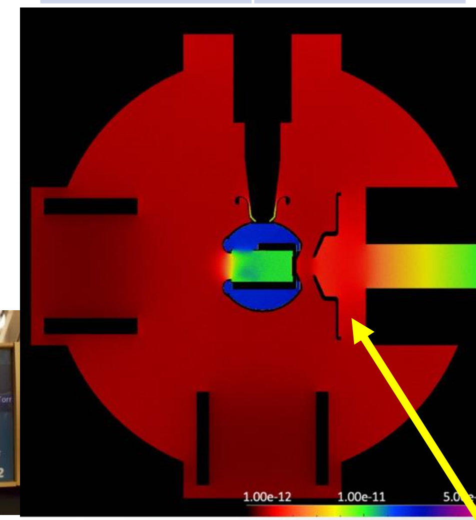
We didn’t use inert gas conditioning

e-Gun and Beam-line Vacuum Measurements



Gun Vacuum
3BG gauge

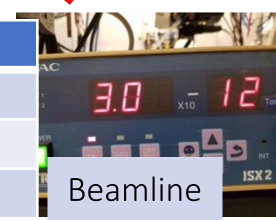
3BG gauge	Gun
Baseline	5-8 e-12
3uA	Low (c.c)
67.5 uA	2e-11,Low (c.c)



Beam dump

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

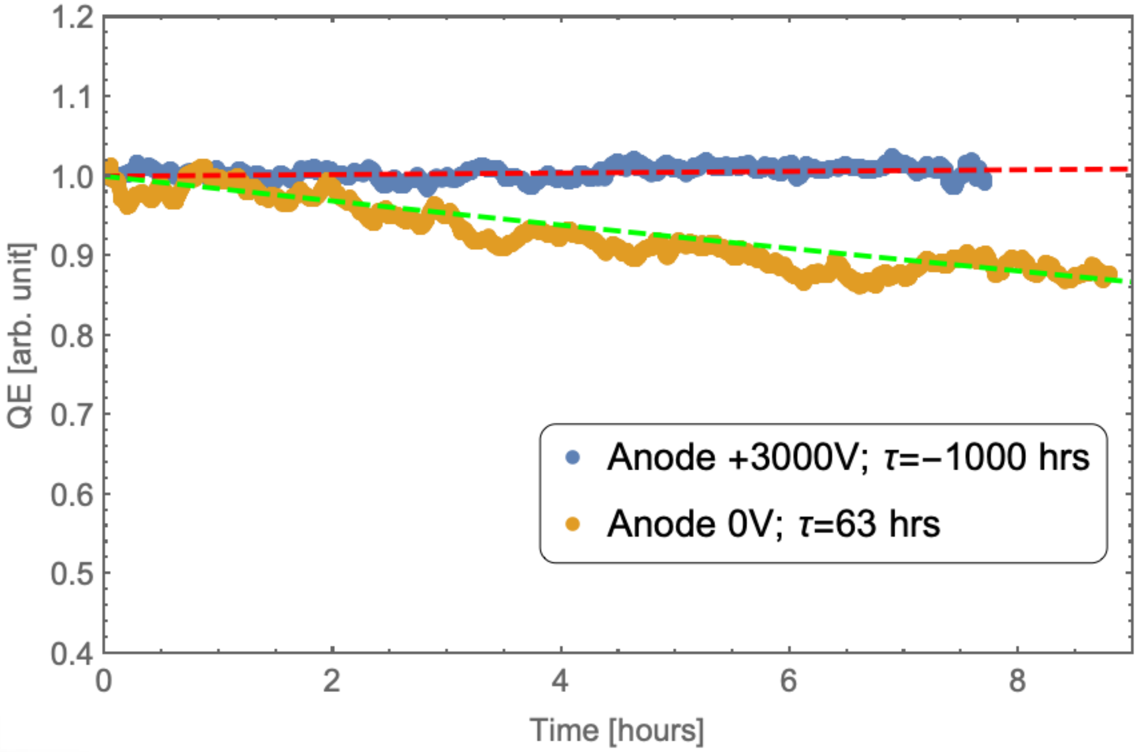
ULVAC gauge	Beam Line
Baseline	3-4 e-12
3 uA	5e-12
67.5 uA	1.5-3 e-11

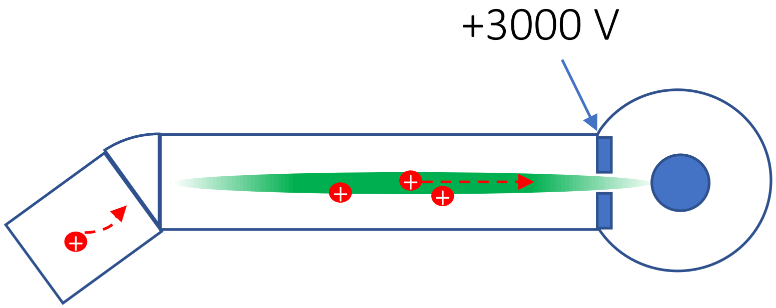


Beamline

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

Cathode Lifetime with and without anode bias

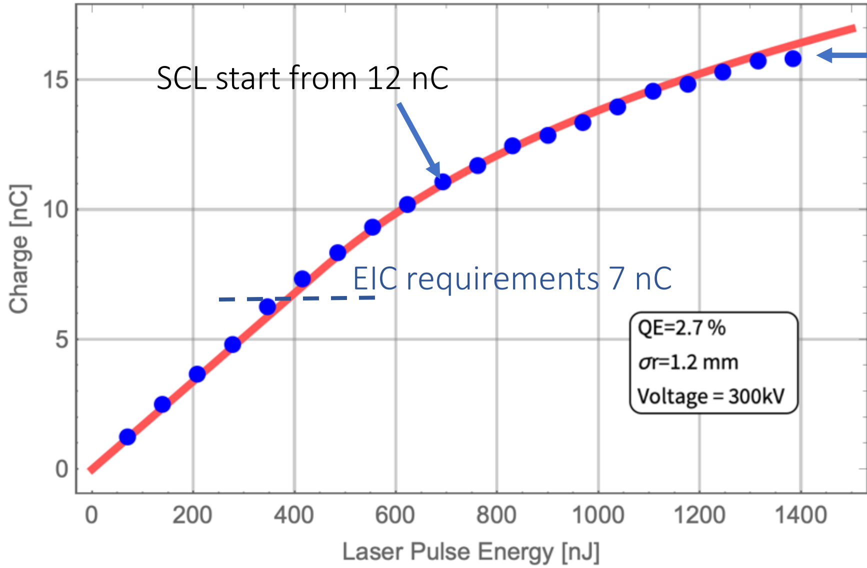




- Our 16 deg. bend reduce the ions from the FC.
- The ions from gun to 1st bend can be blocked by biased anode.

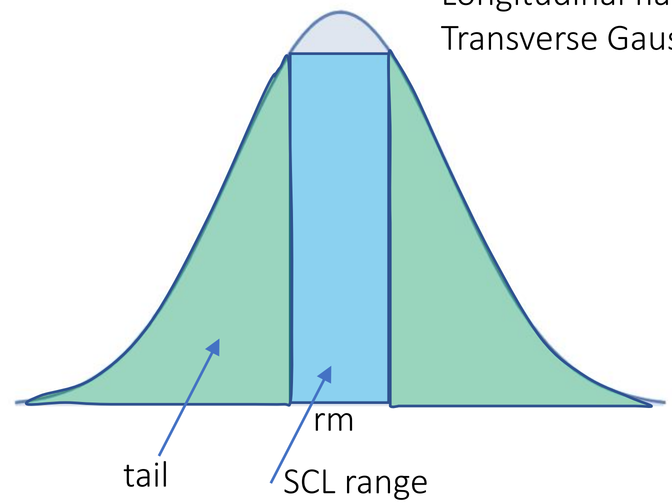
- Using 7.5 nC bunch charge polarized beam, 5000 pulses/s ~37.5 uA;
- With anode bias, we didn't observe QE drop.
- Without anode bias 1/e lifetime is 63 hrs. Dominated by the outgassing from FC.
- Charge from 7 hours test= 35 weeks of EIC operation

e-Gun Space Charge Limit

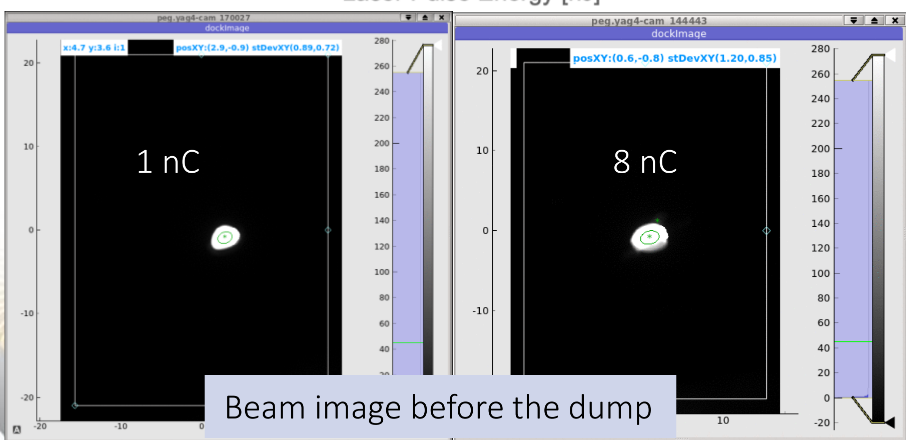


SCL bunch Charge 16nC

$785 \pm 1.3\ nm$
FWHM 1.64 ns
Longitudinal flattop
Transverse Gaussian



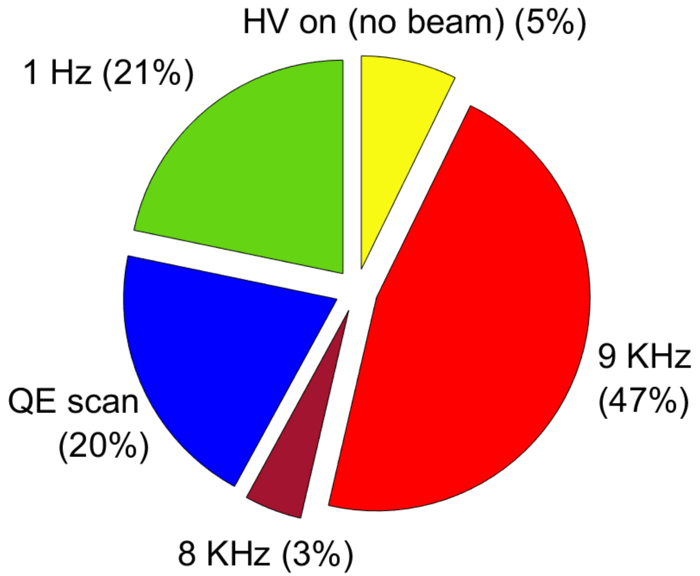
A Gaussian radial distribution on the cathode,

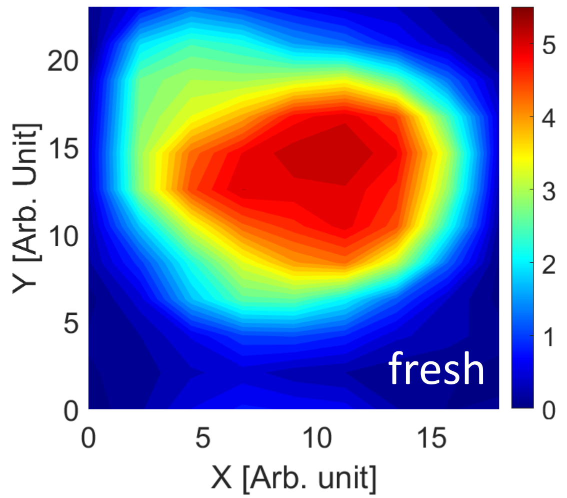


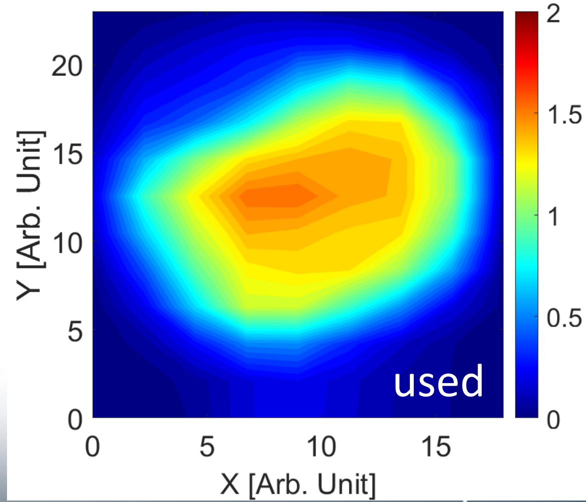
Beam image before the dump

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

9000 Pulse/Sec LifetimeTest QE Maps







- 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.
- Failure mode being back streaming gas is poisoning the cathode but **no classic evidence of ion back bombardment**

EIC e-Source Requirements Achieved and Plans for additional work

	EIC requirement	Achieved in stable operations
Gap Voltage	280 kV	300 kV
Peak current	3.8 A	4.8 A
Frequency	1 Hz with 8 bunches	9000 Hz
Average current	56 nA	76 μA
Bunch charge	7 nC	7.5 nC
Charge lifetime	34 mC	$\gg$ 10C

- The Laser system is being upgraded to improve stability and implement exact EIC pulse train requirements out of the e-Source.
- Strained Superlattice GaAs Cathodes, will first be evaluated in the Polarimeter and then incorporated into the e-Source for Charge Lifetime testing of fully polarized beams. These Cathodes will then be retested in the Polarimeter to confirm polarization levels that occurred in the gun.
- In the EIC gun and beam line extended accelerated Life testing is only limited by outgassing from the beam stop in the end station.
- An orifice and halo viewer will be installed ahead of the end station to improve vacuum isolation by 10 to 100X to advance accelerated charge lifetime studies and to study e-source beam halo.

• Summary of the Polarized gun R&D

- We have designed, built, and tested a HVDC polarized electron gun to meet the EIC polarized electron beam requirements.
- This gun employs various novel concepts, including a cathode cooling system which could be implemented in future high current electron sources.
- The gun was conditioned up to 350 KV without any field emission and was consistently operated at 300 KV.
- High bunch charge, up to 16 nC, produced partially polarized beam generated from bulk GaAs photocathodes using a 785 nm laser.
- Gun performance, including operational lifetime, exceeds all EIC requirements. Lifetime experiments with up to 37.5 uA level average currents, with biased anode, show no observable QE decay.
- The polarization measurement Mott polarimeter has been established.
- SL-GaAs supply chain is in much better shape compared to last year.
- A robust and reliable polarized e-Source will be the critically enabling component for any future Polarized e-Source facility.

Thankyou for your Attention!

Acknowledgments for our Team Colleagues:

Erdong Wang

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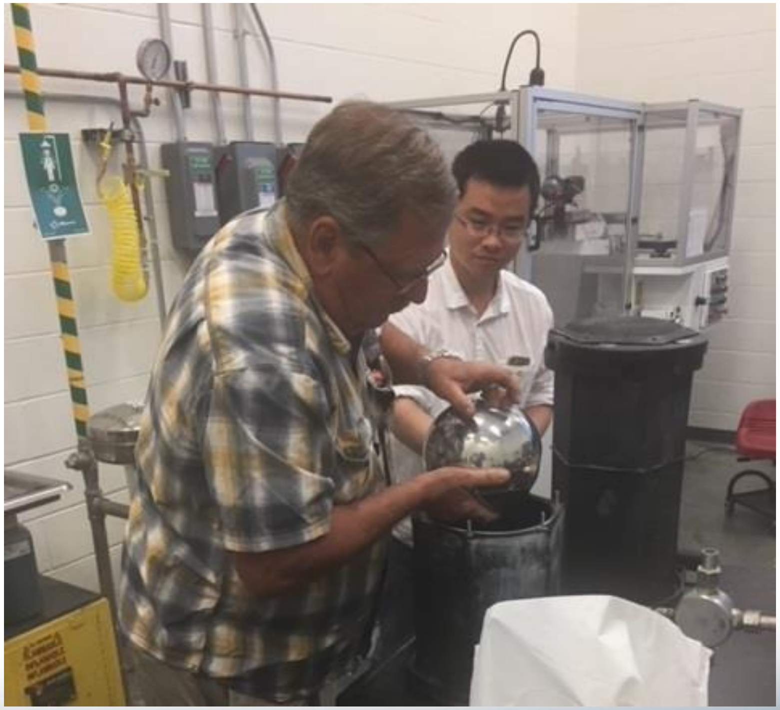
Wei Liu

Ron Napoli

Jeff Selecta SBU Retired

Jeff Thompson SBU

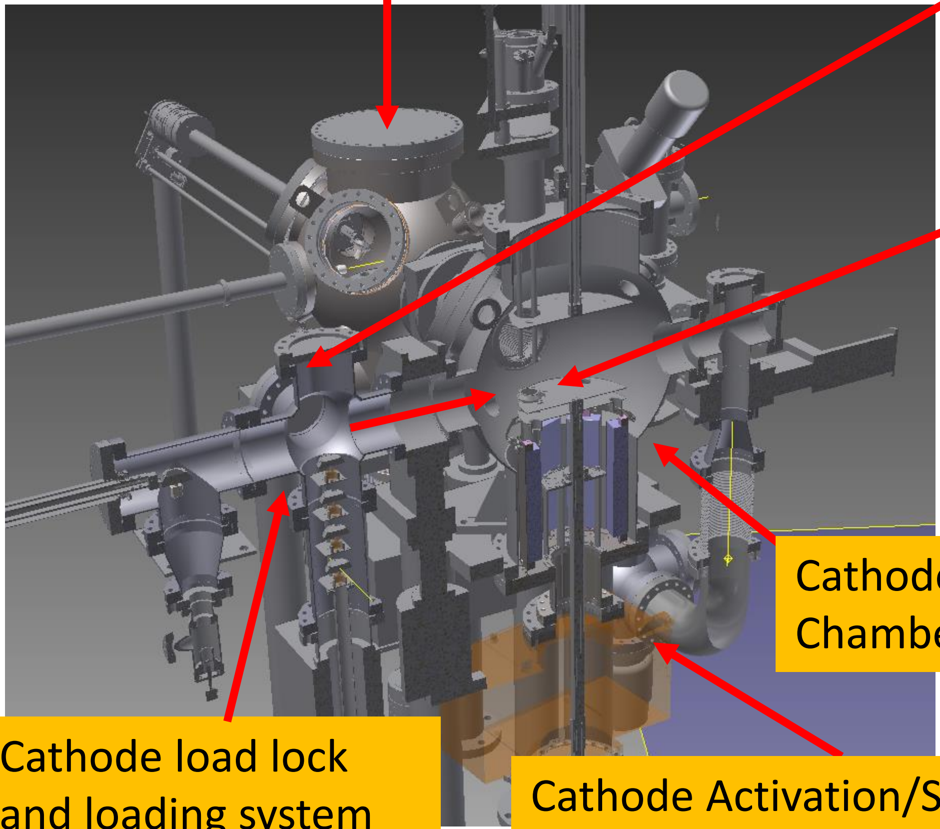
We get many supports from **CAD** instrumentation group, control group, power supply group, SRF group, survey group, **NSLS** II vacuum group, **JLab** injector center and **SBU** machine shop. And our industrial suppliers: Dielectric Sciences, UHV Transfer, MDC, Atlas Technologies. And to **Don "Baba" Bullard our Jlab Colleague** who shared with us how to achieve perfection, passed away this year. Many thanks Baba !!



Back-Up Slides

Bulk/SSL/DBR GaAs Cathode Preparation

Storage Chamber will store up to 4 activated cathodes in a critical vacuum : $<10^{-12}$Torr



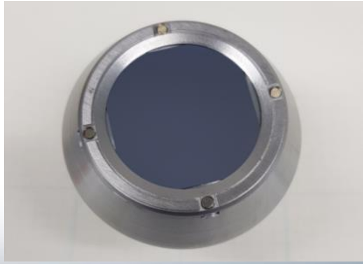
Fresh samples loaded in load-lock
Transferred to activation chamber
Activation and Storage chamber vacuum : 10^{-12} Torr (critical)
Surface heat cleaned at 580 Celcius (Critical)
Monolayer of Cs- Oxygen deposited to achieve NEA (Negative Electron Affinity) – 'Activation'
Bulk GaAs: QE – 12%-15% for 532 nm
Strained Superlattice (SSL) GaAs : QE – 1% at 780 nm
DBR have ESP >90% and QE > 5% at 780 nm

Cathode Activation Chamber

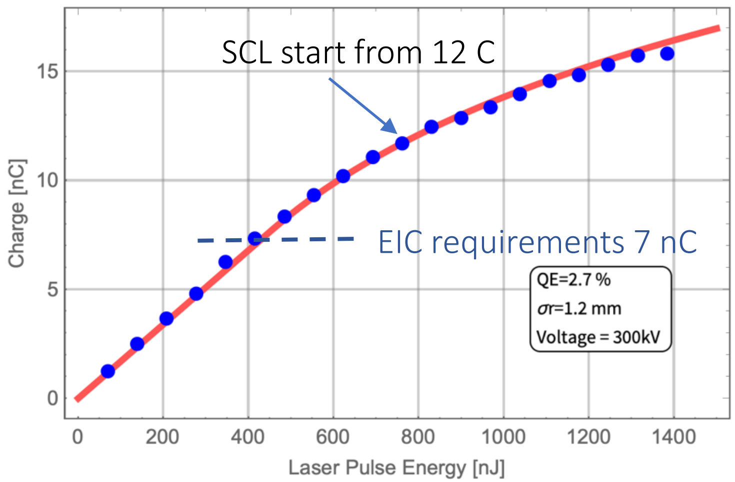
Cathode load lock and loading system

Cathode Activation/Storage chamber vacuum System

Large Area Cathode holder. 26 mm in diameter contained by a Tungsten cap.



e-Gun Space Charge Limit



$785 \pm 1.3\ nm$
FWHM 1.64 ns
Longitudinal flattop
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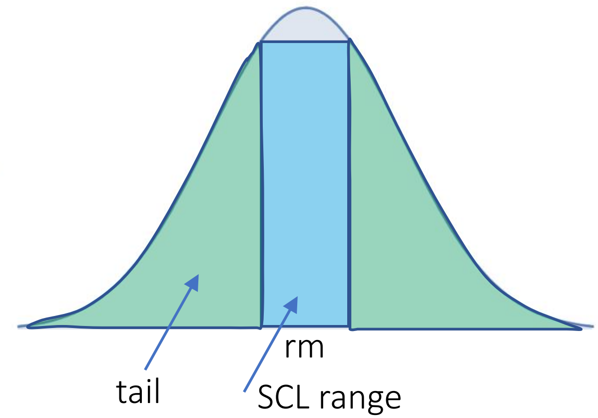

A Gaussian radial distribution on the cathode,

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 bunch charge if we use a large activation area