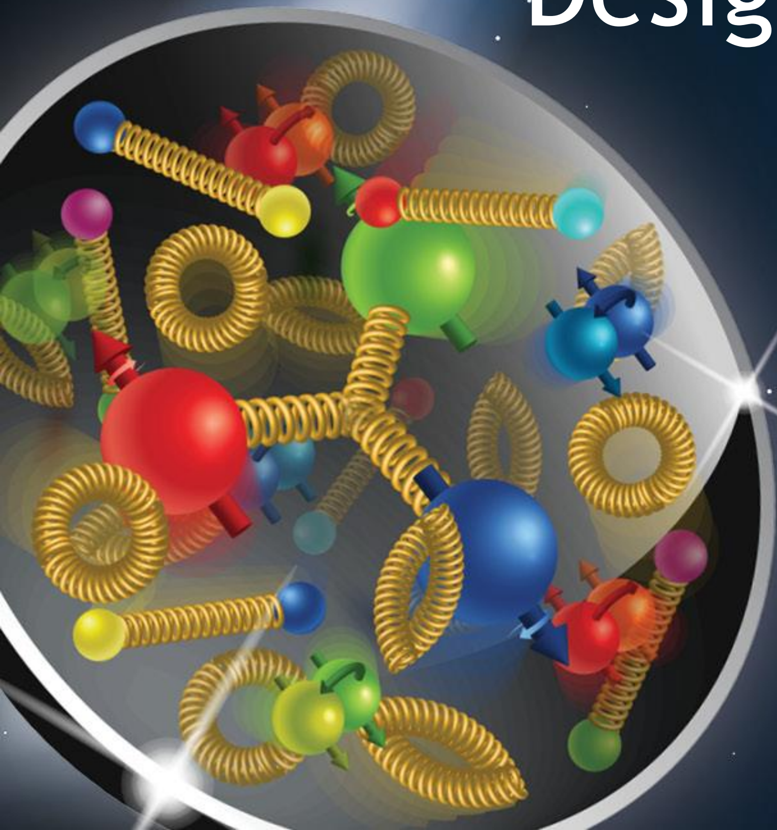
Electron Source Development for the Electron Ion Collider at BNL

Gatling Gun Laser System and Design of New Inverted Gun



Nuclear Physics Accelerator R&D
PI Meeting

John Skaritka BNL

November 13-14, 2018

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Acknowledgements

I. Ben-Zvi, M. Gaowei, R. Lambiase,

V. Litvinenko, W. Liu, R. Napoli,

O. Rahman, E. Wang, F. Willeke

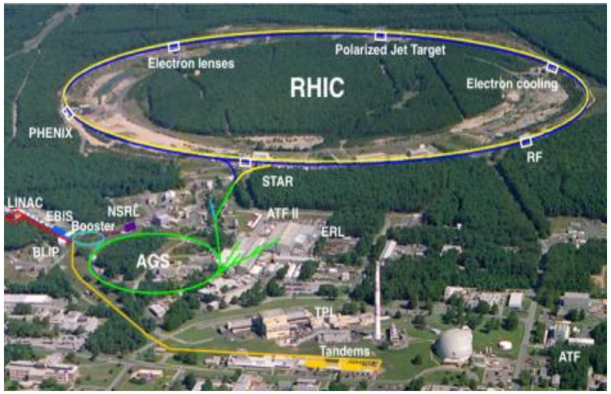
Our Collaborators from the following companies:

Atlas Technologies, UHV Transfer,

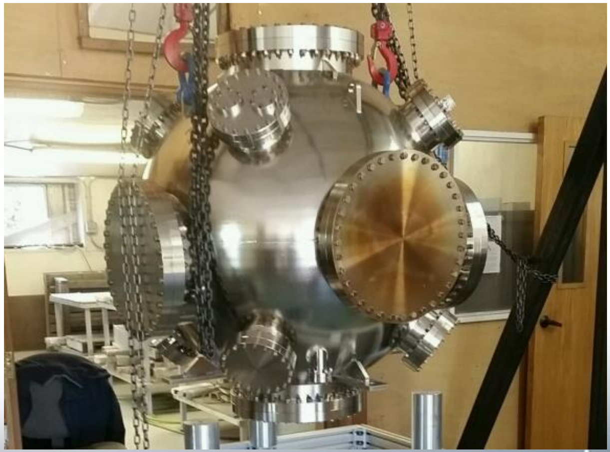
Applied Vacuum , MDC Vacuum,

Pascal Technologies, SAES Getters

Outline: Gatling Gun Laser System and Design of Inverted BNL Gun .



- Funding summary and Introduction
- Jones panel report
- Gatling gun and laser system improvements
- Gatling gun operation and program summary
- Inverted gun design considerations
- Prototype e-gun system design and developmental goals
- Program status and R&D plans for FY18-19
- Summary



Gatling Gun Laser System and Design of New Inverted Gun

Funding Source	PI	R&D Report Priority #	R&D Panel Priority Rating	Total $
FY17 Base	John Skaritka	7, 23	Hi-B, Hi-C	$1,233 K

Introduction: This effort served as a productive bridge between the Gatling gun project and the single large cathode e-RHIC prototype gun project. While the detailed design of the e-RHIC prototype gun was underway and gun system components were being procured all the equipment developed during this period. Examples: Improvements to the drive laser, diagnostic beam line components, end station and XHV vacuum system components would be tested with the Gatling gun in single beam mode and then reused after the source laboratory infrastructure was upgraded to accommodate the high current, high bunch charge at higher voltage operation of the e-RHIC prototype gun.

From Page 32 of the Jones Panel Report

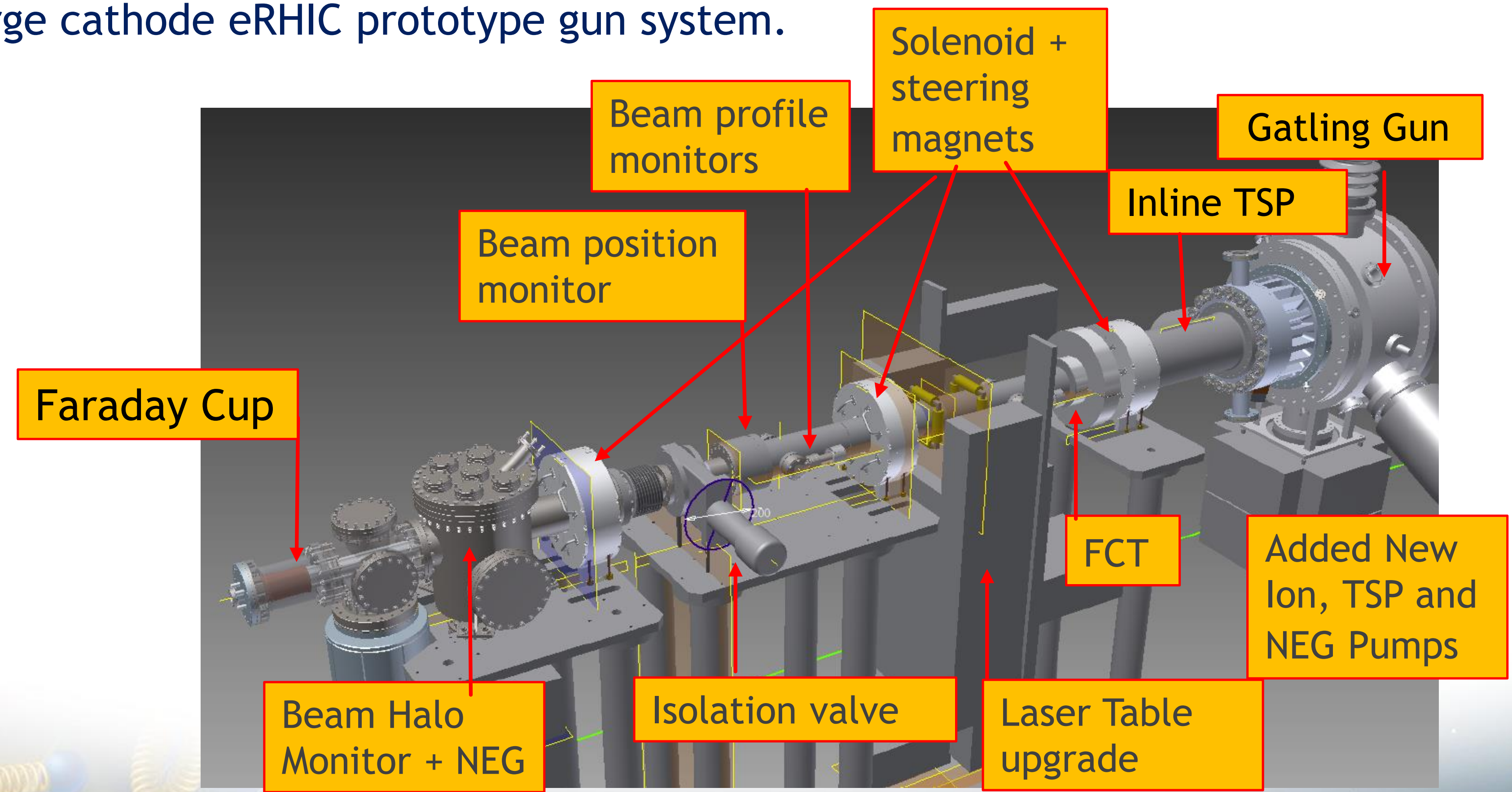
The BNL LR concept team has launched a R&D program to address these issues. The team proposes to:

- Upgrade vacuum system of the existing Gatling gun prototype (previous R&D);
  - Use this gun for bench marking of beam dynamic simulations, and optimization and commissioning of the diagnostic beam line, and
  - Complete the build-up of diagnostic beam line and beam dump.
- Build up a single, new inverted gun with optimized geometry, ultra-high vacuum quality for high gun voltage (350 kV) with a large cathode diameter ~25 mm;
  - Fabricate and assemble the new inverted gun with an optimized geometry, ultra-high vacuum quality for high gun voltage (350 kV) with a large cathode diameter ~25 mm Gatling gun.
- Complete laser parameter optimization.
- Perform systematic measurements on the completed gun (FY18).
- Perform the simulation of beam extraction and transport (underway).
- Work out, optimize and simulate the bunch-stacking scheme.
- With the RF kicker electrical design available, work has already started for alternative stacking schemes.

To date there has been some R&D related to different approaches to polarized sources. BNL has supported the development of the Gatling gun (24 photocathodes in a single vacuum enclosure) concept. However, this approach is not the primary one for the BNL LR concept. The Gatling gun will use a single photocathode to benchmark beam dynamic simulations, and optimize and commission the diagnostic beam line and beam dump.

E-gun Beam Diagnostics

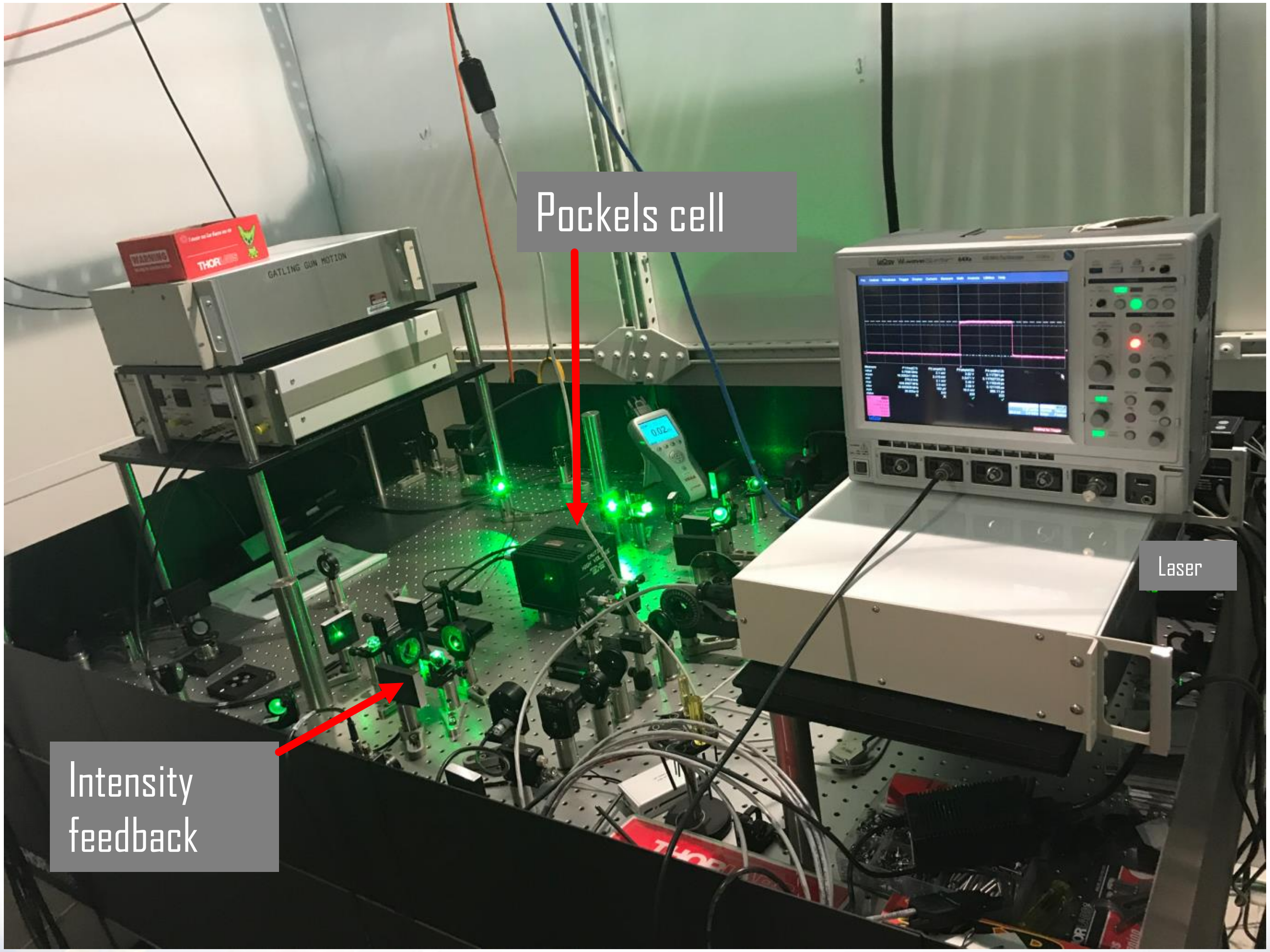
A New Diagnostic Beam Line was assembled and tested. Extreme vacuum conditions were routinely established in the Gun, Beam line, and End Station, All of these components are being reused with the large cathode eRHIC prototype gun system.



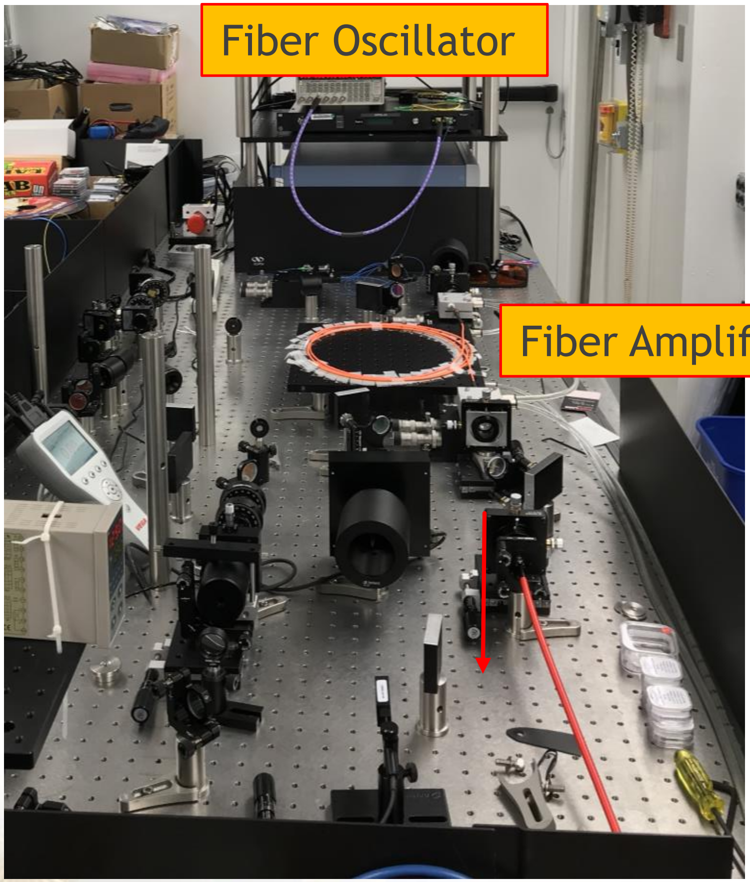
Improvements to Gatling Gun Laser System

- An intensity feedback system to maintain constant beam current while quantum efficiency degrades over the life of the cathode was installed and successfully tested.
- A system for precise remote steering of the beam spot onto the cathode surface was installed and successfully tested.
- A Pockels cell to generate pulse structure for pulsed beam operation and function as a fast shutter being part of a machine protection system was installed.
- These components along with a 780nm laser will be used with the superlattice photocathodes to produce polarized e-beams from the single cathode polarized gun.

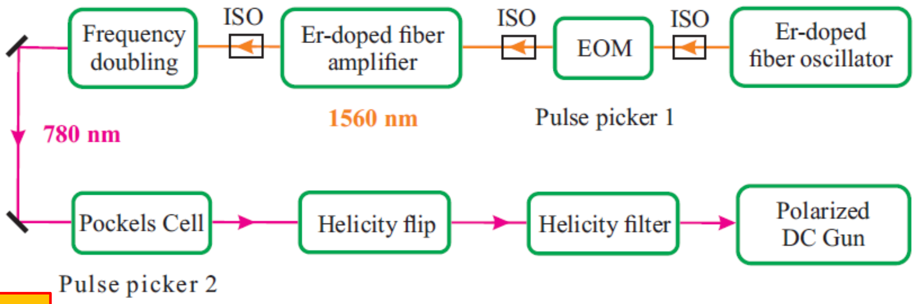
Laser Room at the e-Source Lab



E-Source Laser Development Status

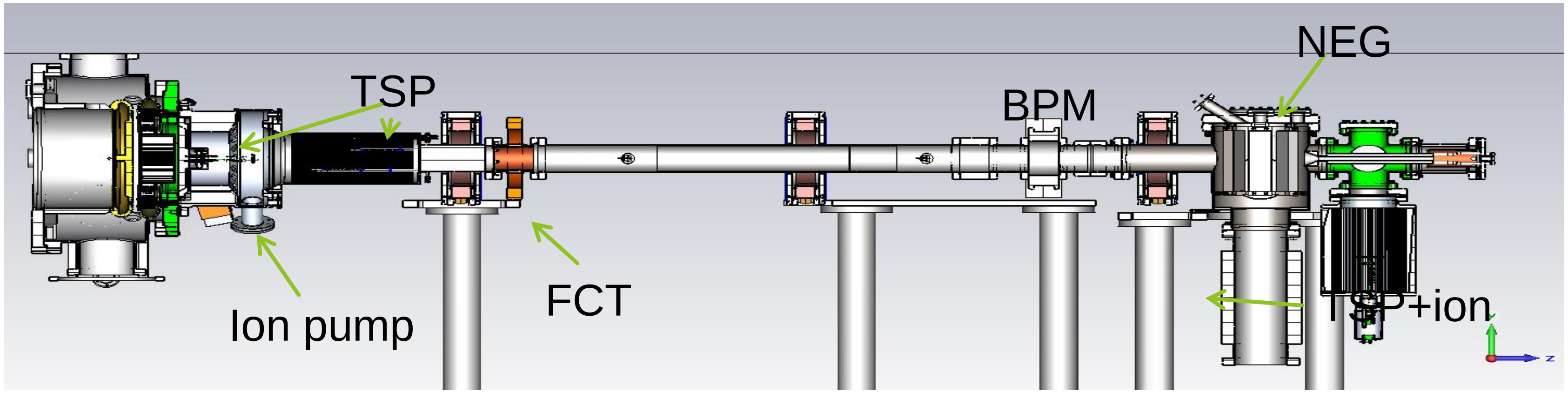


Laser System for ring-ring EIC

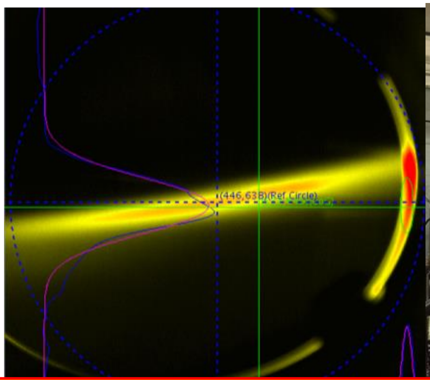


Portions of the laser system for the large cathode prototype gun were purchased assembled and tested up to about 0.5 watts. It is anticipated that the laser will be eventually operate with an output power of up to about 10 watts at 780nm. This is enough power to produce an average photo current of 6 mA.

Gatling Gun e-Beam Test Results



	Results
Gun vacuum [torr]	<1*10^{-11}
High voltage [kV]	100
Diagnostics	FCT, YAG,
Current [uA]	3 to 20 uA stable beam
Beamline vacuum [torr]	<1.0*10^{-11}



Interesting Observation:

With e-Beam on Gun vessel vacuum pressure in dropped to non measurable levels.

Gatling Gun Work in FY16-17

- During this period the Gatling gun and related diagnostic beam line was completed. Beam tests of the Gatling gun producing a beam in DC mode of up to about 100 micro Amps using a green laser on bulk GaAs and up to about 20 micro-amps on running at steady state conditions.

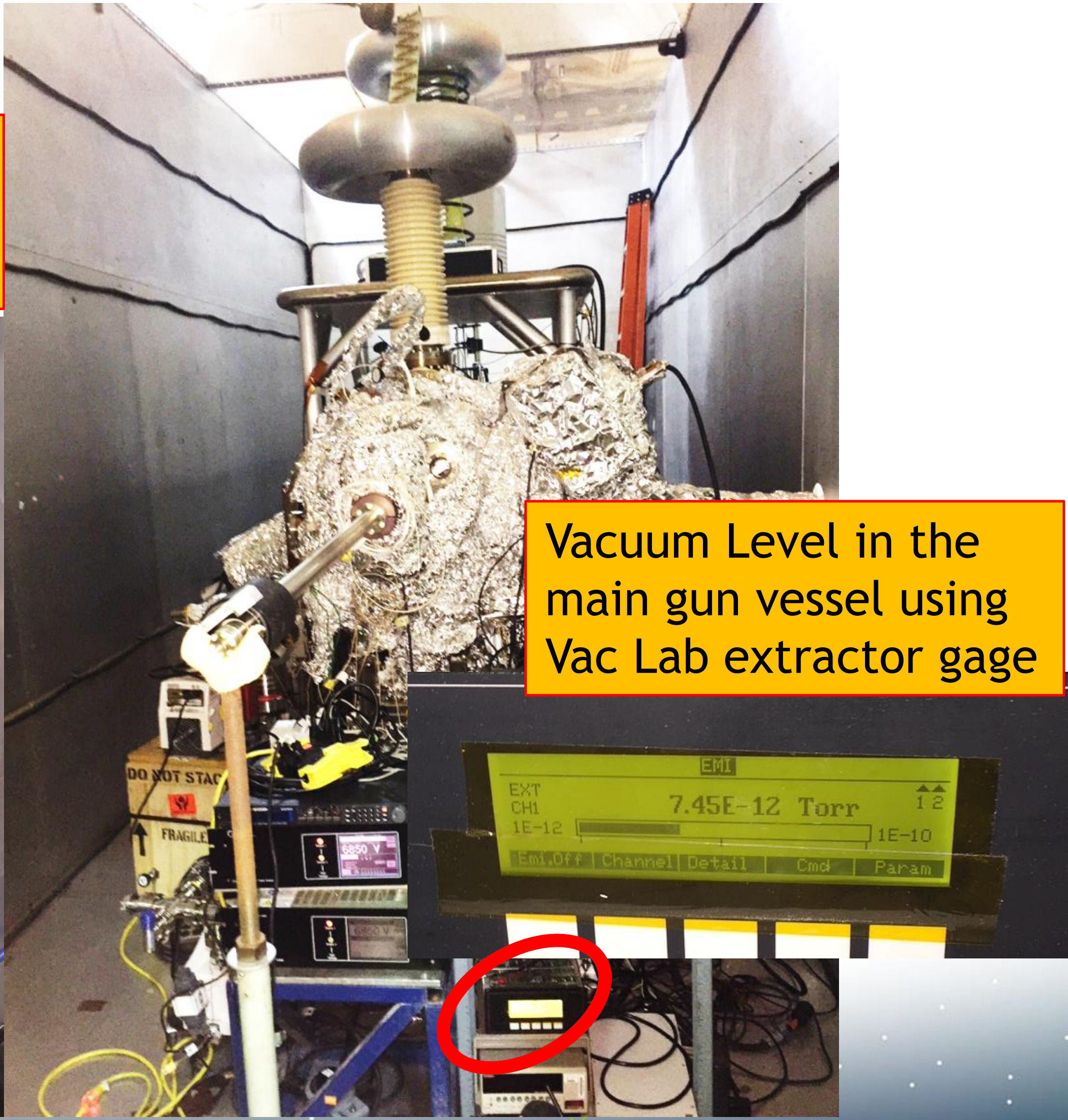
- During the short test period that the Gatling gun operated with an upgraded vacuum system. Cathode life time became significantly longer as compared to earlier runs due to improved vacuum levels in the gun's main chamber.

- We terminated Gatling gun system testing in January 2018. and redirected available resources to the construction of the new inverted gun system components and upgrading the e-Source Laboratory infrastructure.

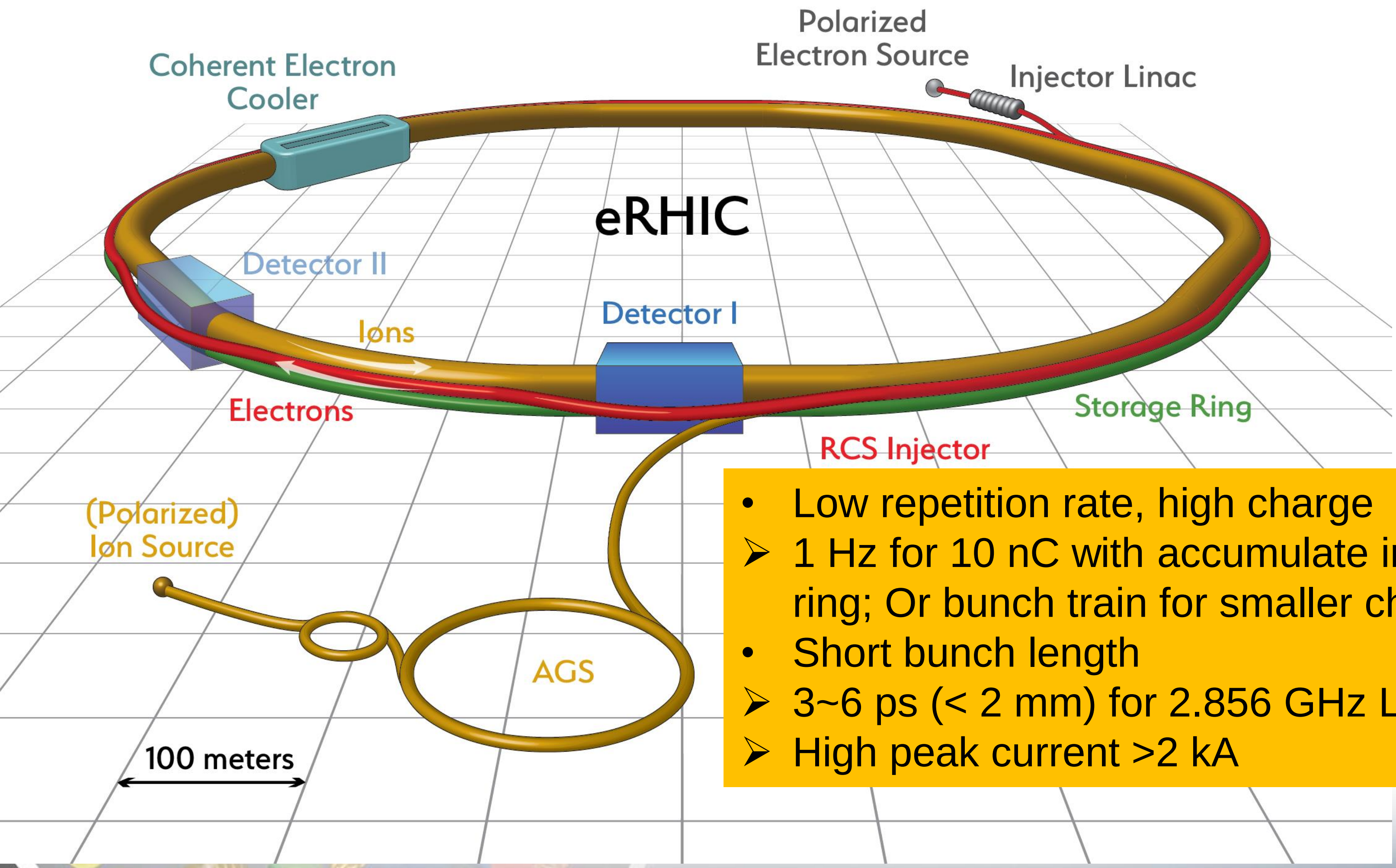
Extreme Vacuum Achieved in Large Complex Gun Chambers

Vacuum Level for a vacuum fired stainless steel end station at opposite end and valved off from beam line

Vacuum Level in the main gun vessel using Vac Lab extractor gage



e-RHIC Baseline Pre-Injector Source Specifications



- Low repetition rate, high charge
  - 1 Hz for 10 nC with accumulate in storage ring; Or bunch train for smaller charge.
- Short bunch length
  - 3~6 ps (< 2 mm) for 2.856 GHz Linac
  - High peak current >2 kA

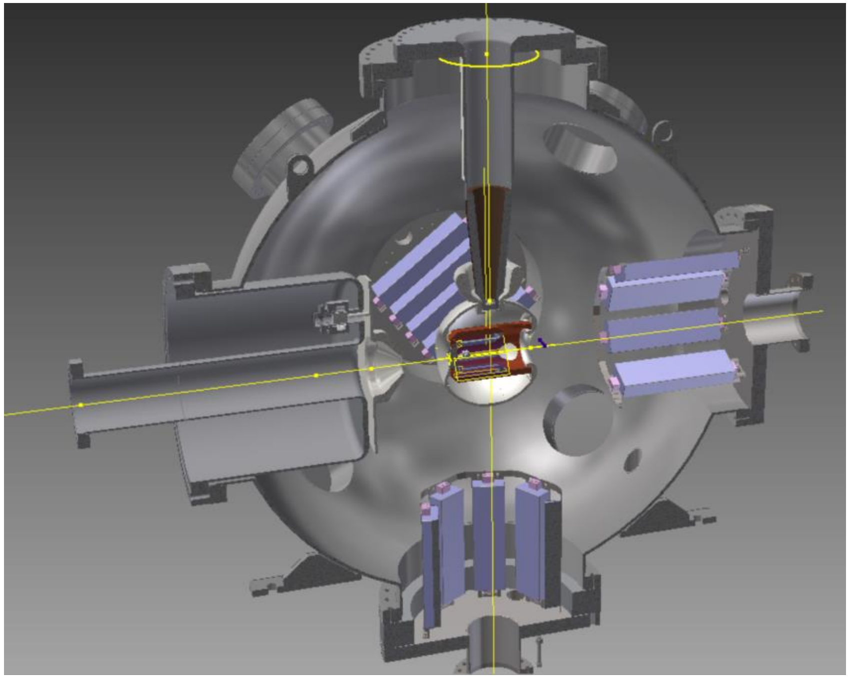
Polarized Gun Prototype Design Considerations

The polarized gun design Goal:

- High average current (>6 mA), high bunch charge (5.3 nC) large cathode inverted gun for L-R eRHIC source.
- High bunch charge for R-R eRHIC source.

Sub-R&D items:

- Achieve and measure XHV
- High power laser
- New high polarization cathode and related simulation
- Eliminate ion back bombardment
- Cathode lifetime experiments and modeling
- Beam halo reduction studies
- Cathode cooling



BNL 1ST inverted gun in fabrication

Design Steps to Optimize DC Gun Geometry

- Determine the constraints of the gun project
  (Time, funding, infrastructure, resources)
- Determine the initial beam parameters
- Select Gun type and high voltage level
- Determine the cathode size and HV electrode(shroud) size.
- Optimize the Pierce shape geometry based on beam performance.
- Optimize Anode shape geometry.
- Optimize Triple point and ground shield design
- Determine the Pump speed requirements
- High voltage check and optimization
- Cathode cooling simulation and design
- Diagnostics and test beamline design.

Overview of polarized electron DC guns

Laboratory	Photocathode	Polarization	Voltage	Bunch charge	I_pk	Repetition Frequency	I_avg
JLab[1]	GaAs-GaAsP	85%	100, 200kV	2 or 2.7pC	67~53mA	1.5 GHz	1~4mA
SLC[2]	GaAs-GaAsP	86%	120kV	16nC max	5 A	120 Hz	2uA
MAMI[3]	AlGaAs/InAlGaAs	85%	100kV	0.02pC		2.45 GHz	50 uA
Bonn-ELSA[4]	AlGaAs/InGaAs	80%	50kV	100nC	100mA	50 Hz	5 uA
MIT-BATES[5]	GaAsP	50-80%	60kV	250nC	12mA	600 Hz	20 or 200uA
Nagoya[6]	GaAs-GaAsP	92%	200kV	3.2 nC	3.2 A	20 Hz	50 uA
NIKHEF[7]	InGaAsP	80%	100kV	2 nC	2 mA	10 Hz	0.04uA
BNL	GaAs-GaAsP	85%	350kV	10 nC	5 A	1 Hz	10 nA

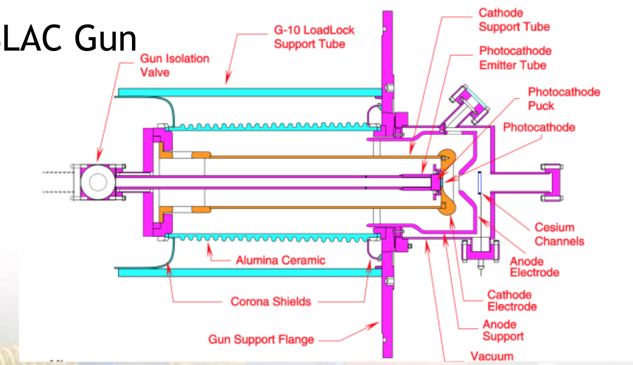
- 16 nC was achieved by SLC DC gun. It is beyond our nominal injector design.
- Can we make it better?
- Minimize beam loss
- Simplify maintenance

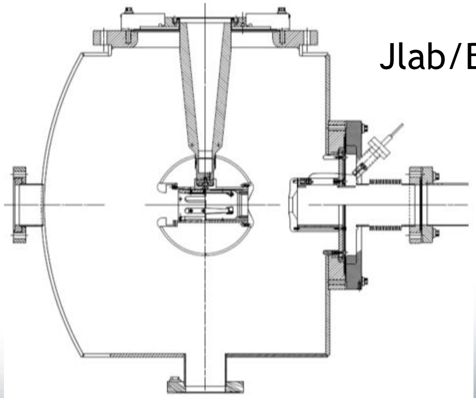
In operation
Shut down
In design

Inverted Gun Design Advantages Over SLAC Gun

	SLC gun	Inverted gun
Voltage	120 kV	>300 kV (improved beam stability)
Cathode size	3 cm^2	5 cm^2
HV feedthrough	Field emission punch issue limits voltage	Inverted design, no FE punching
Size, complexity	Large size; large outgassing area	Simple compact design, will have better vacuum
Cathode exchange	HV and cathode exchange shared same port; difficult to exchange cathode	Separate HV and cathode exchange ports

SLAC Gun





Jlab/BNL Gun

Consideration for Prolonged Cathode lifetime

Larger Laser Size

i. Reduces space-charge emittance growth

ii. Suppresses surface charge limit

Large cathode gun experiments

Cathode lifetime modeling and experiments

Robust photocathode

New high polarization cathode and related simulation

i. Robust activation layers to resist ion back bombardment

ii. Emission from surface state or engineering spin material

Higher Gun Voltage: (Difficult to do above 400kV in a short term)

i. Less ions are created

ii. Reduce space-charge emittance growth

Extremely high vacuum studies

Better vacuum

i. Reduces the ions

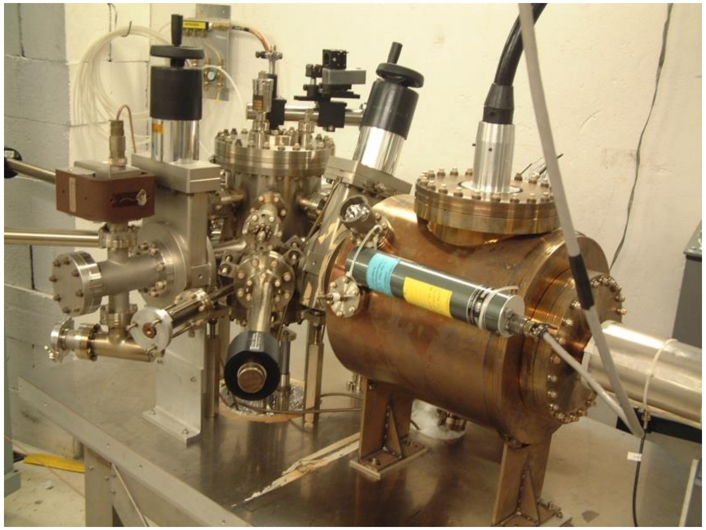
ii. Reduces the molecules desorption

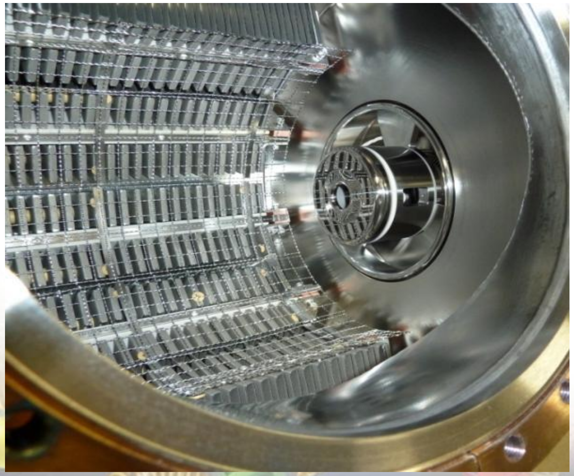
Cathode cooling

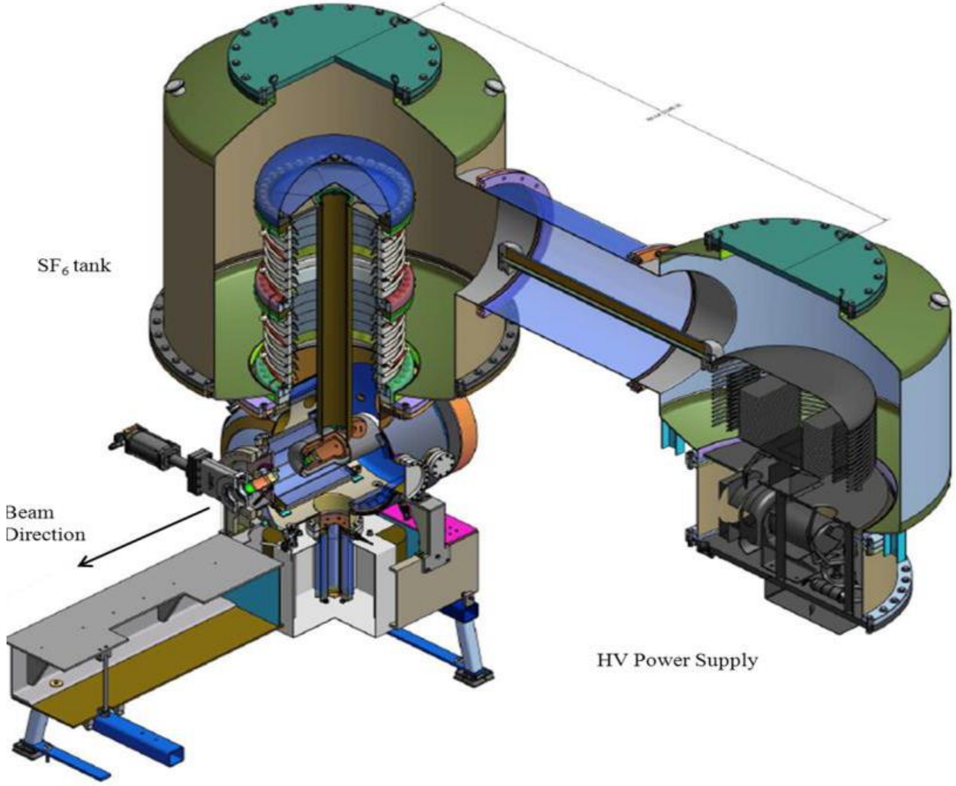
Maintain cathode temperature

i. Lower temperature, longer lifetime

Comparison between Inverted gun and conventional DC gun design

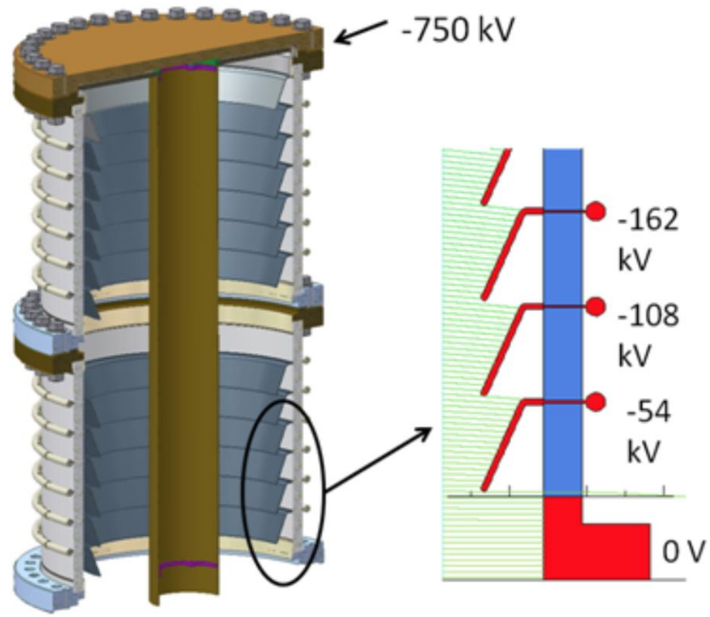






- Inverted gun outgassing area is three folds less than conventional DC gun. Could achieve better vacuum.

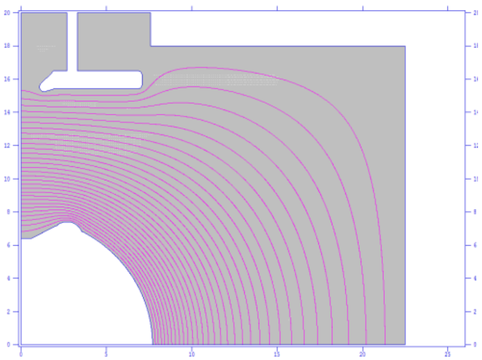
Comparison of High Voltage Feedthroughs

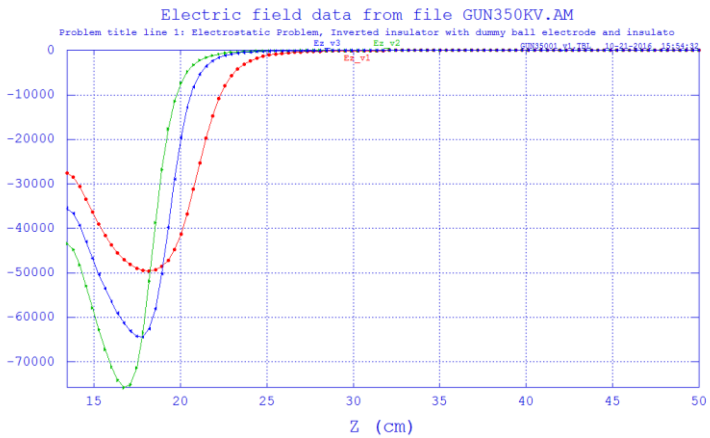


Insulator Type	Length (cm)	Transversal resistivity* (Ohm-cm)	Dielectric constant* $\varepsilon/\varepsilon_0$	Maximum voltage (kV)	Performance
R30 with additional screening electrode	20	5.0×10^{15}	9.1	375	370 kV sustained in multi-hour test, significant field emission
R30 ZrO-coated on vacuum side	20	5.0×10^{15}	9.1	340	Breakdown and puncture near ground end
R28 doped	13	7.4×10^{11}	8.4	365	360 kV sustained in multi-hour test, minimal field emission

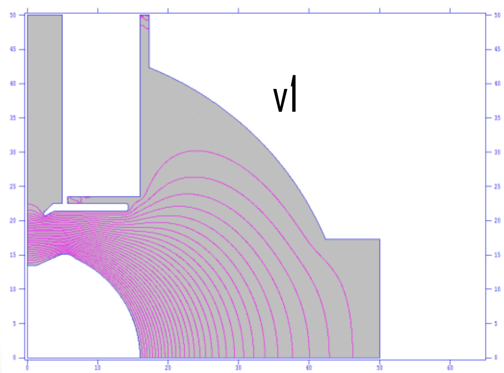
- Both design could shielding field emission punching to ceramic.
- Inverted shape has small area and volume, give lower outgassing
- More off the shelf parts of Inverted shape and cost efficiency.

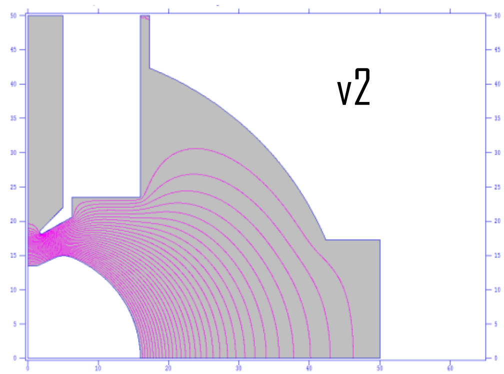
High Voltage Electrode Optimization

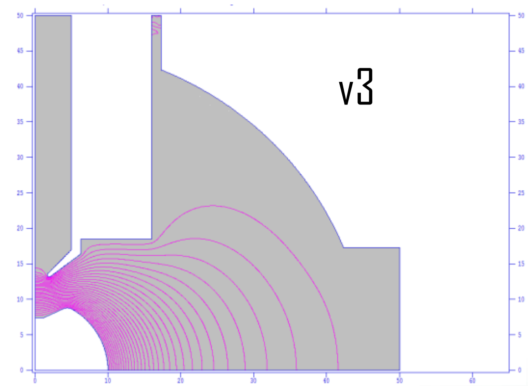




Another limitation is the JLab barrel polishing machine with capability to fit electrodes no more than 20 cm diameter.





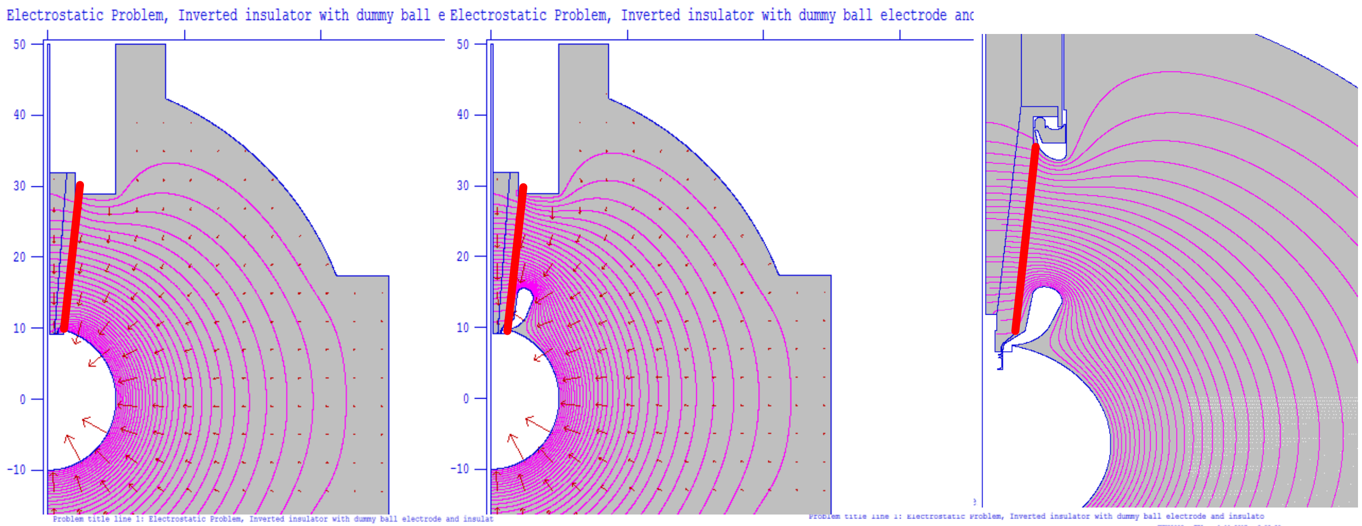


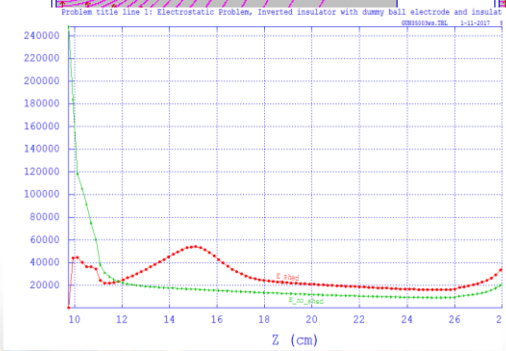
Ball size 32cm,
Gradient: 2.7 MV/m
Gap : 7.3cm

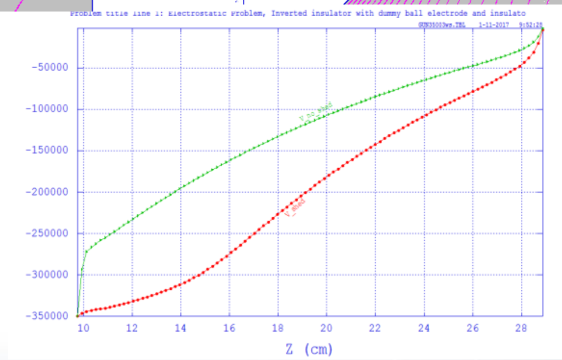
Ball size 32cm,
Gradient: 4.3MV/m
Gap : 4.7cm

Ball size 20cm,
Gradient: 3.5MV/m
Gap : 5.7cm

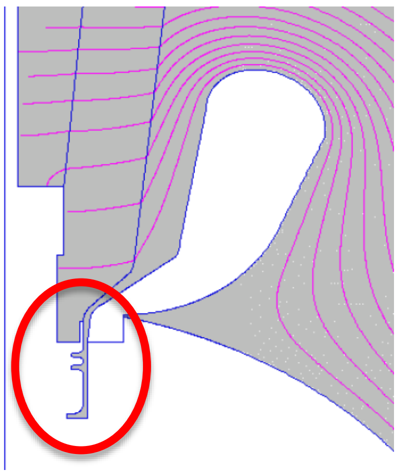
Design of Triple Point Shields on Either End of the Ceramic Feedthrough

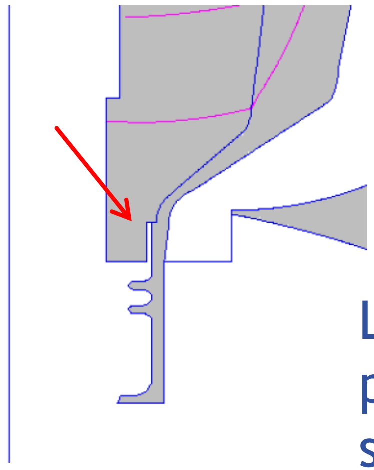


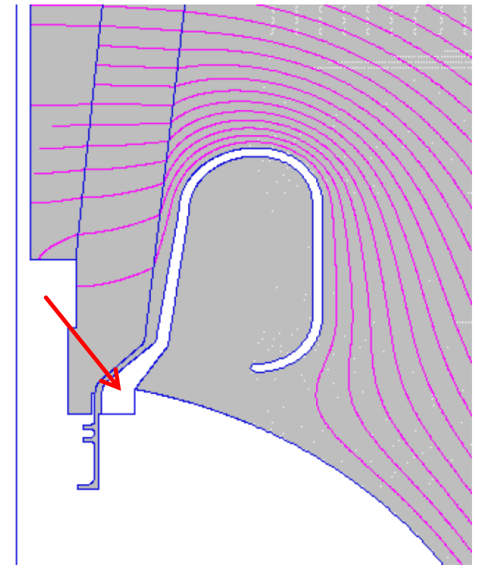




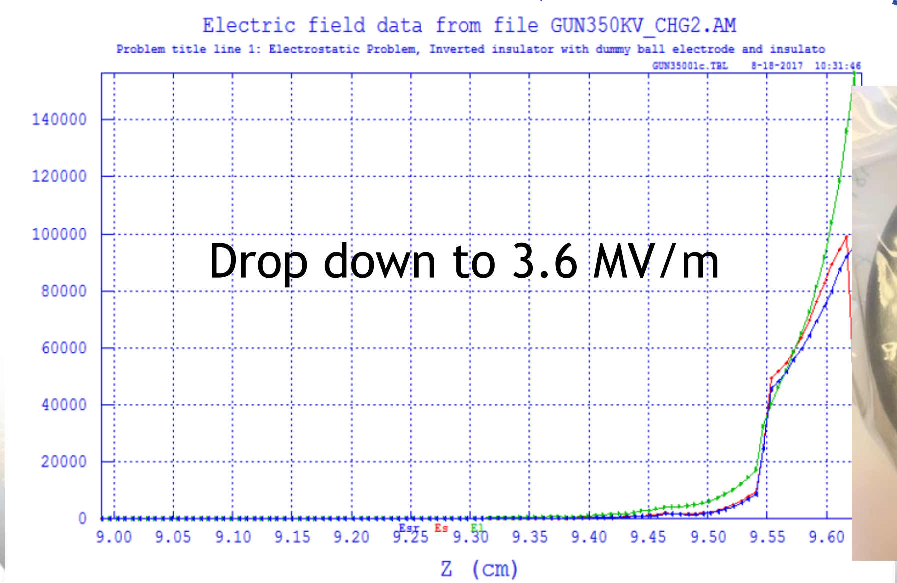
HV (Triple Point) Shield Optimization





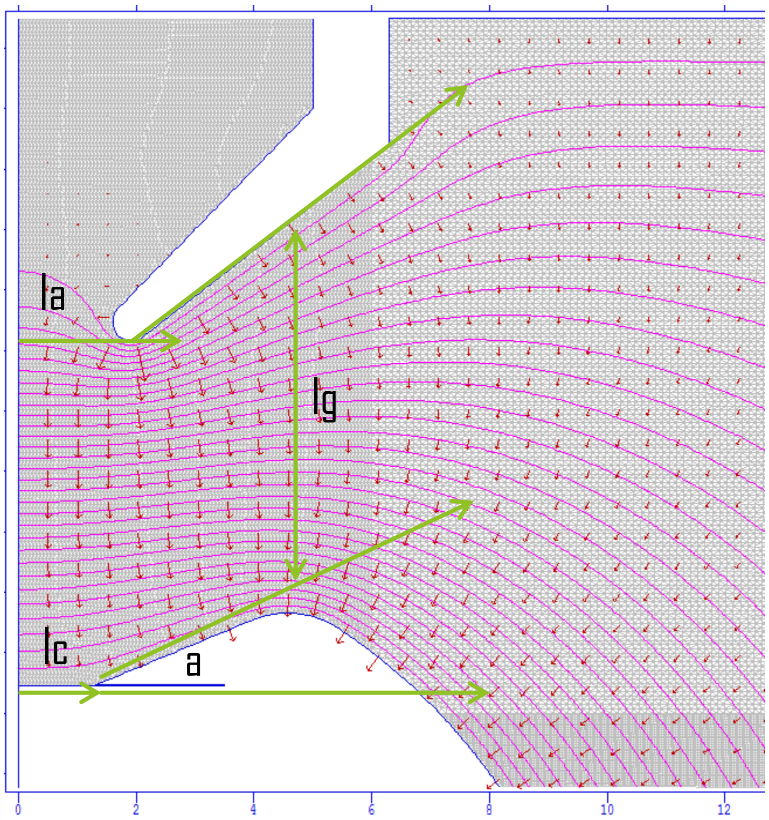


Low outgassing printed stainless steel TP shield



First known use of stainless steel 3D printing for a XHV part. Outgassing study indicate superior performance compared to conventionally construction.

Electrode Geometry Optimization

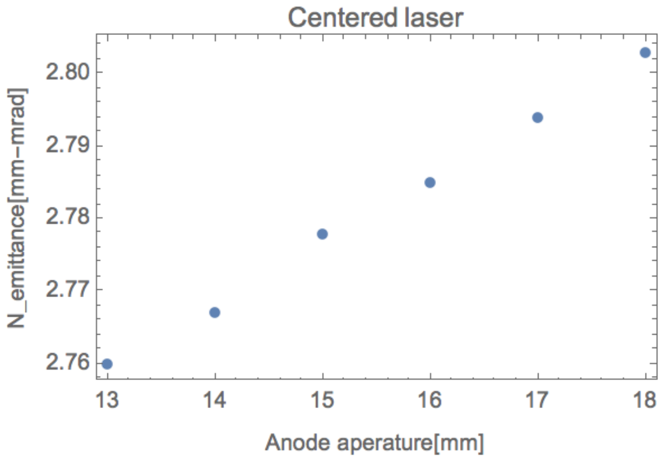


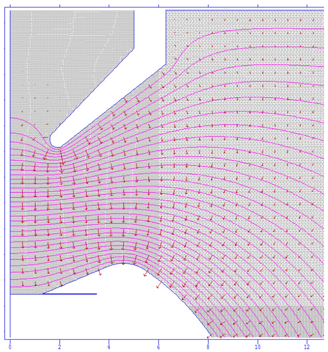
Conceptual design:

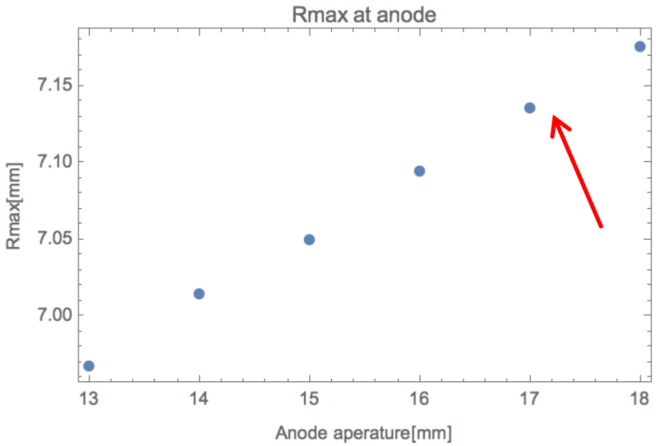
- Anode defocusing f= 4V/ E2-E1=-22 cm
- Space charge defocusing=-9.7cm
- Pierce shape focusing length should be designed close to 7 cm.

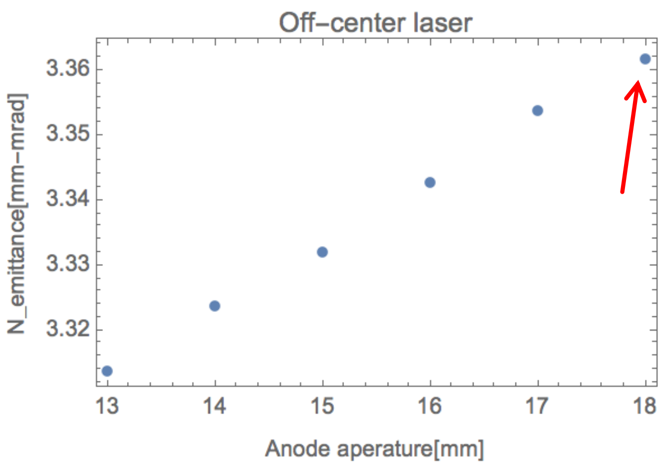
Optimizing parameters: 1. Laser position; 2. Electrons angle; 3. Anode-electrodes distance; 4. Anode aperture

Anode optimization: determine “la”





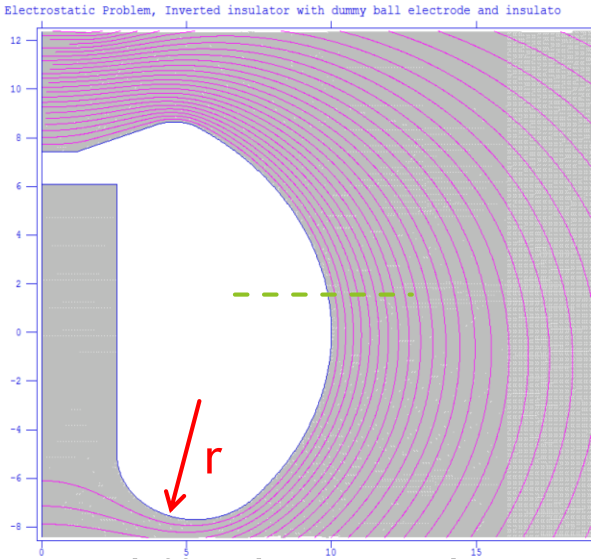


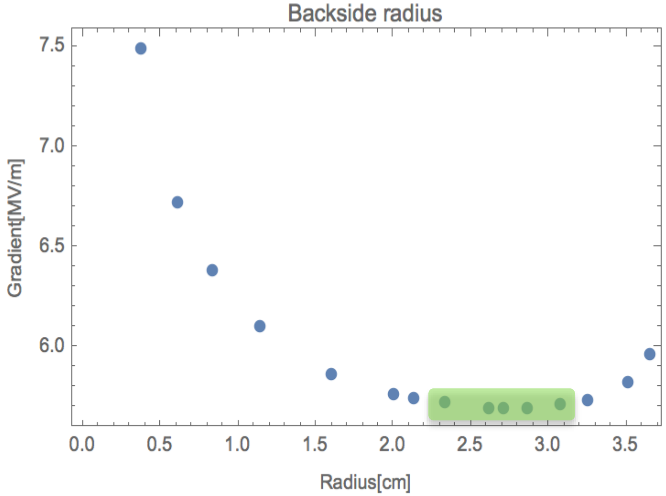


- Anode angle is same as electrode angle.
- Off center 6 mm and r = 3.5~4 mm, anode position is 6 cm.
- Anode is designed movable. Can be optimized in experiment if use alternative voltage.

Increase anode size will enhance defocusing		
Anode hole size	↑	?
Beam quality	↓	bad
Laser spot size	↑	good
Beam loss	↓	good

Shroud Assembly Design and Cathode Injection

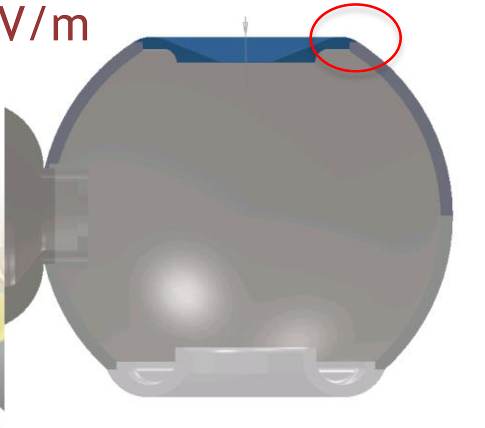




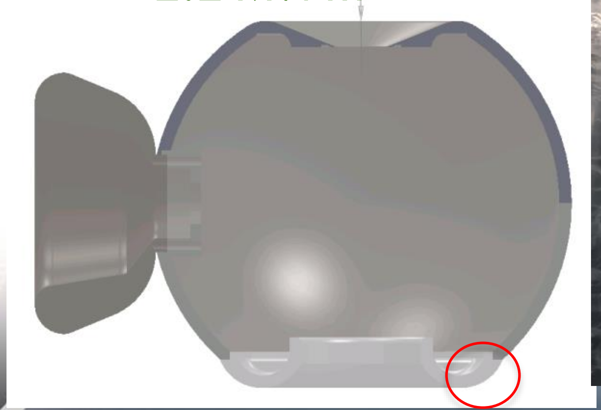
Cathode insertion hole in the back of the Shroud

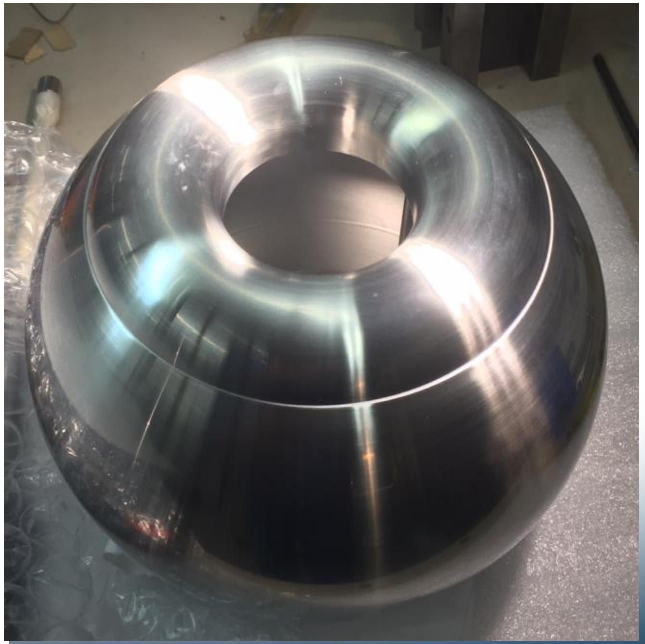
It is difficult to machine a sphere shape, our design separates it into three parts.

Welding, good polishing 8MV/m

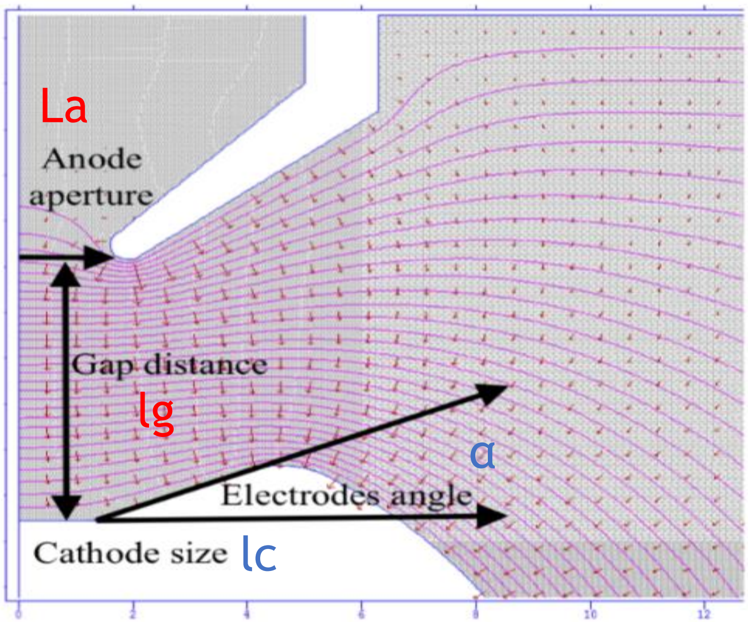


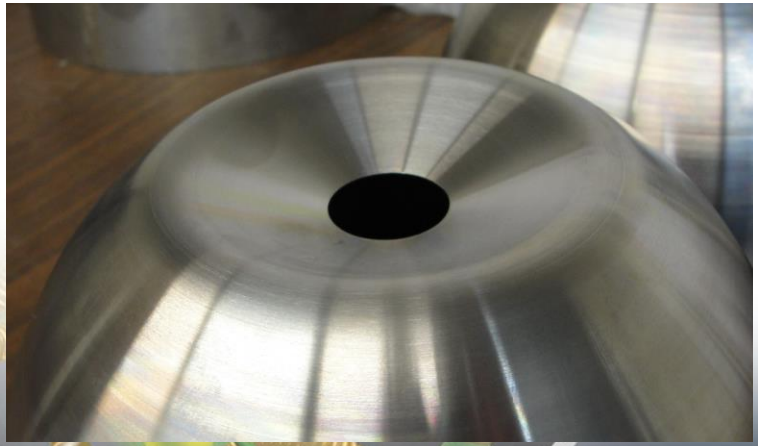
Assemble, recessed 2.2 MV/m





BNL Large Cathode Prototype Gun Design





	Inverted gun
Ball diameter	20 cm
Chamber diameter	80 cm
Gap distance (lg)	5.7 cm
Voltage	350 kV
Cathode size (lc)	1.50 cm
Electrodes angle (α)	22 degs
Cathode gradients	4.0 MV/m
Maximum gradient	10 MV/m
Anode diameter (la)	2.2 cm
Pumping speed	35000 L/s
Space charge limit	Up to 45 A
Anode bias	3000 V

Comparison of Polarized e-

	SLC	Inverted gun (JLab)	Inverted gun (BNL)
Voltage [kV]	120	350	350
Gradient [MV/m]	1.8	3.4	4.2
Cathode size [cm2]	3	1.13	4.98
Pulse length [nS]	2	0.01	1.5
Bunch charge [nC]	16 (9~12)	0.003	10
Average current [uA]	5	4000	NA (to be measured)
Charge lifetime[C]	<1 (20% loss)	80 (0.1% loss)	NA (to be measured)
In-situ Cs evap.	Y	N	N
Bias Anode	N	Y	Y

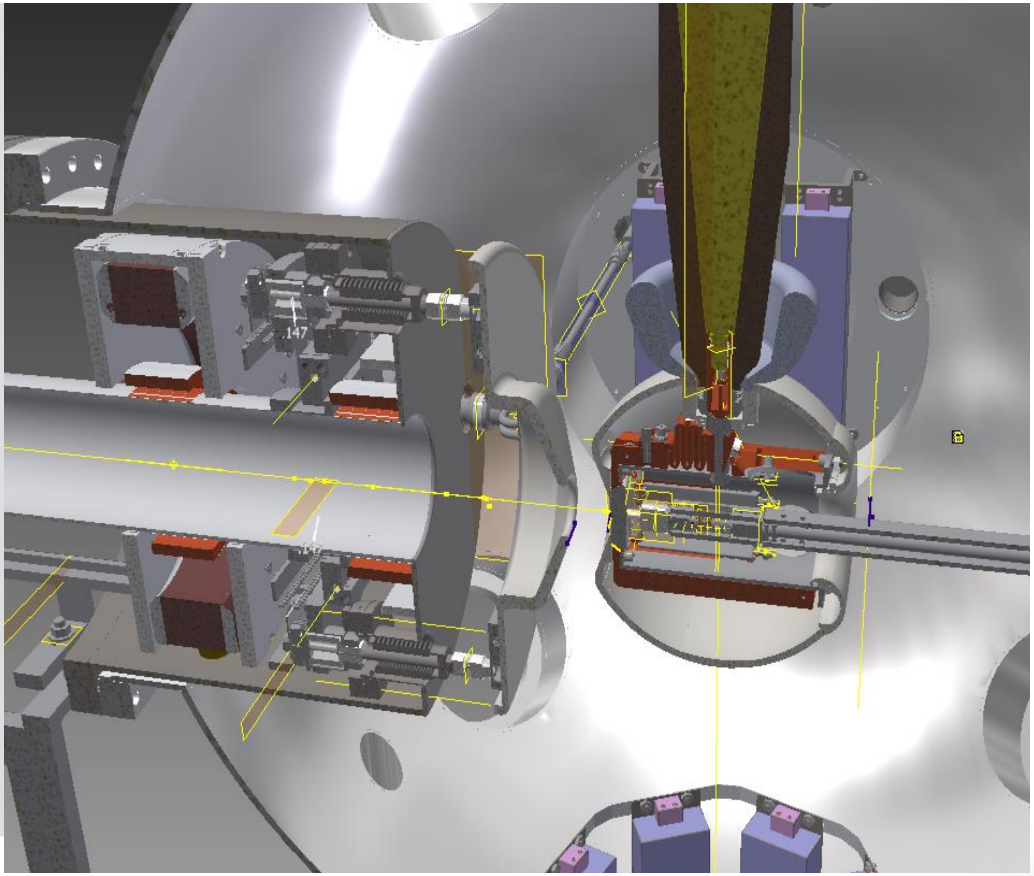
Polarized e-RHIC Prototype Gun Design

The polarized gun R&D

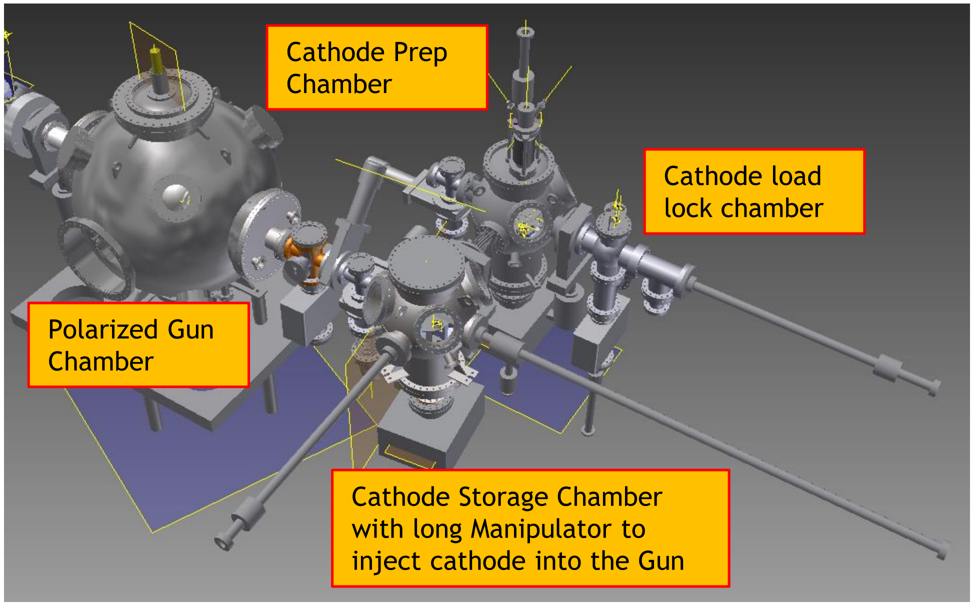
- High average current (6~50 mA), high bunch charge (5.3 nC) large cathode inverted gun for L-R eRHIC source.
- High bunch charge for R-R eRHIC source.

Sub-R&D items:

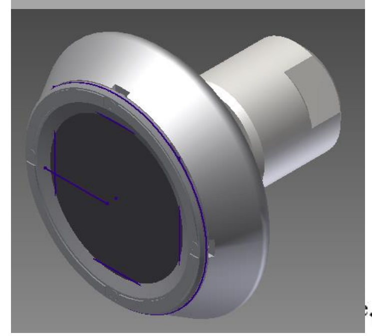
- Achieve and measure XHV
- High power laser
- Eliminate ion back bombardment
- Surface charge limit measurement
- Lifetime as the function of charge
- Beam halo reduction studies
- Cathode cooling

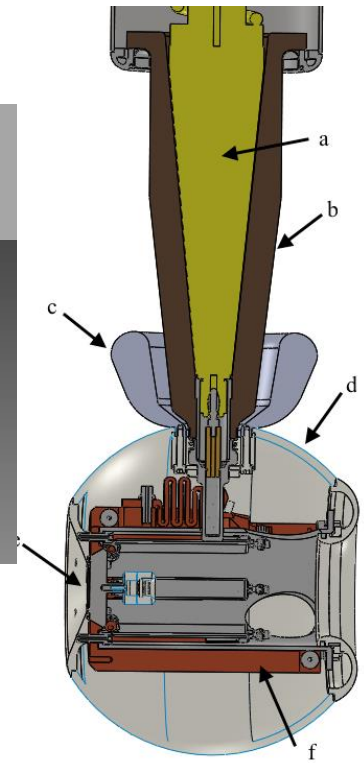


Gun Cathode and Cathode Prep System Design



Large 26mm GaAs Cathode





Cathode preparation system

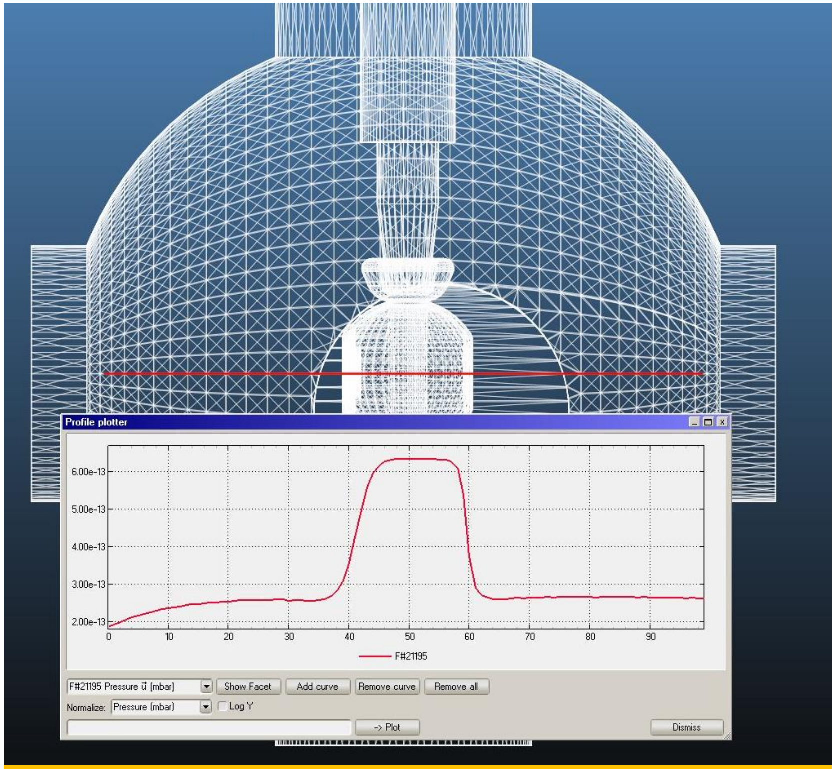
HV DC Gun

Inverted Gun electrode

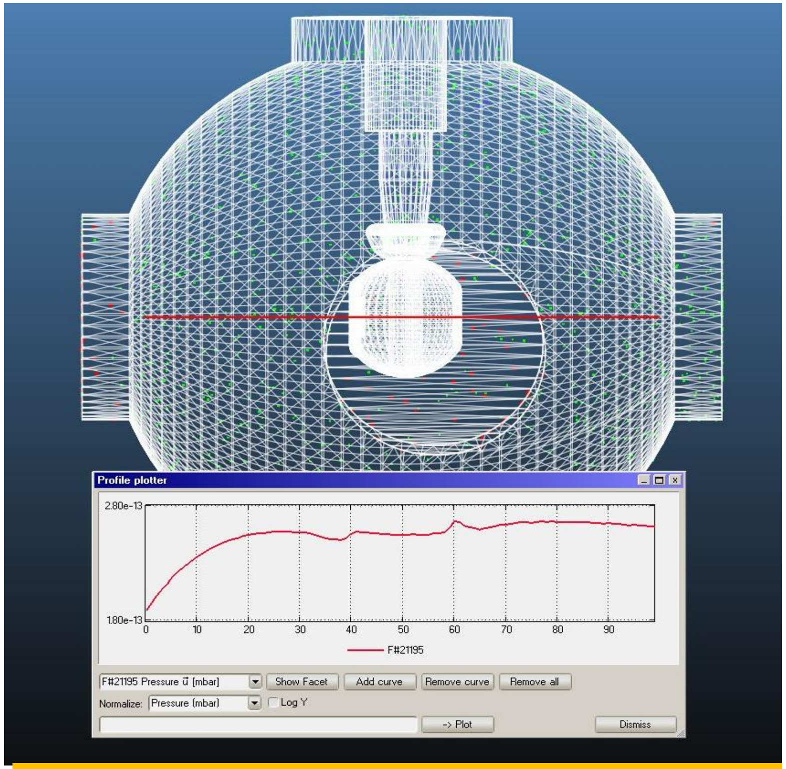
The RR gun will be similar to the R&D gun, except

- More optimized chamber
- Pumps setup
- Optimized Pierce shape (similar to SLC gun)
- Larger cathode

Mol-flow study of NEG coating the inside of the Cathode Shroud at Extreme Vacuum

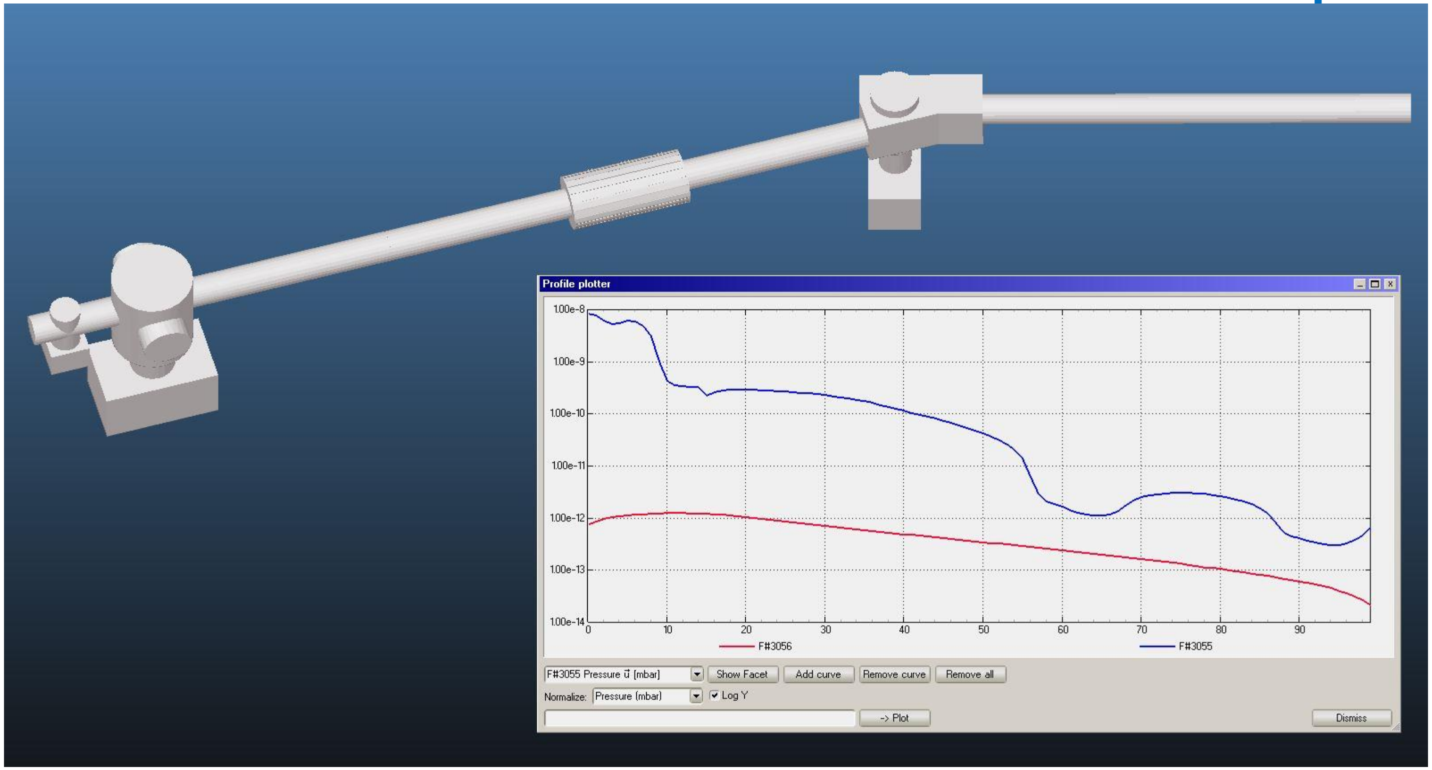


Main vessel simulation #1: (without NEG coating)
stainless steel, outgas/area(mbar*L/s/cm^2) = 1E-13
ceramic, outgas/area(mbar*L/s/cm^2) = 1E-11
NEG coating pumping: 0.2 L/s/cm^2



Main vessel simulation #2: (with NEG coating)
stainless steel, outgas/area(mbar*L/s/cm^2) = 1E-13
ceramic, outgas/area(mbar*L/s/cm^2) = 1E-11
NEG coating pumping: 0.2 L/s/cm^2

Vacuum Isolation of the Beam Stop



A Molflow+ simulation of the diagnostic beam line illustrates the feasibility to maintain a relatively large pressure differential of about 5 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 high current beam operation.

Cost Summary to Date

Lab Base R&D	FY10+FY11	FY12+FY13	FY14+FY15	FY16+FY17	Totals
a) Funds allocated				1,232,811	1,232,811
b) Actual costs to date				1,232,811	1,232,811

Schedule

Activity	Start Date	End Date
Building 912 Infrastructure		September 30, 2020
Gun System Installation	March 28, 2017	May 11, 2018
Beam Test	December 15, 2017	July 23, 2018
High Charge Gun Design	January 1, 2017	September 16, 2018
Second High Charge Test	September 16, 2018	July 6, 2019
High Current High Bunch Charge Studies	October 31, 2018	January 30, 2019

Summary of Gatling Gun Prototype Gun Design

- In 2017 work on the Gatling Gun a multi-cathode e-source and its diagnostic beam line was completed and the detailed design of a single large cathode source design, that is complimentary to polarized sources under development, or operating at laboratories such as MIT, JLab, and Cornell proceeded as planed. The majority of the detailed design work for prototype gun system was completed during this period.
- The work on the Gatling Gun and its diagnostic beam line gave BNL staff extensive experience with extreme vacuum system preparation and operation into the 10^{-12} Torr vacuum range, essential for polarized source operation using GaAs cathodes.
- These extreme vacuum levels were routinely achieved during the last year of the Gatling gun program and vacuum levels dropped to non-measurable levels during periods of e-beam operation. This experience has been incorporated into the design of the new inverted gun prototype that now is being prepared for installation.
- During this period BNL staff became adept at preparing bulk and stained GaAs cathodes with high quantum efficiency exceeding 11 % with bulk GaAs and 1% with strained superlattice GaAs. This experience has been incorporated into the design of the cathode preparation system for the new inverted gun.
- Many vacuum system and e-beam diagnostic component used with the Gatling Gun and its diagnostic beam line will be reused on the new inverted gun prototype and its associated diagnostic beam line.
- This work was completed as of Spring 2018

Thank you for your attention !