High Voltage DC photoemission guns and a quest for higher operating voltage

Outline:

- Overview of DC photogun designs in operational accelerators at Jefferson Lab
- Practical considerations to reliably apply high voltage
- Successes and failures learned over the two past decades
- Latest developments on 500 kV feedthrough

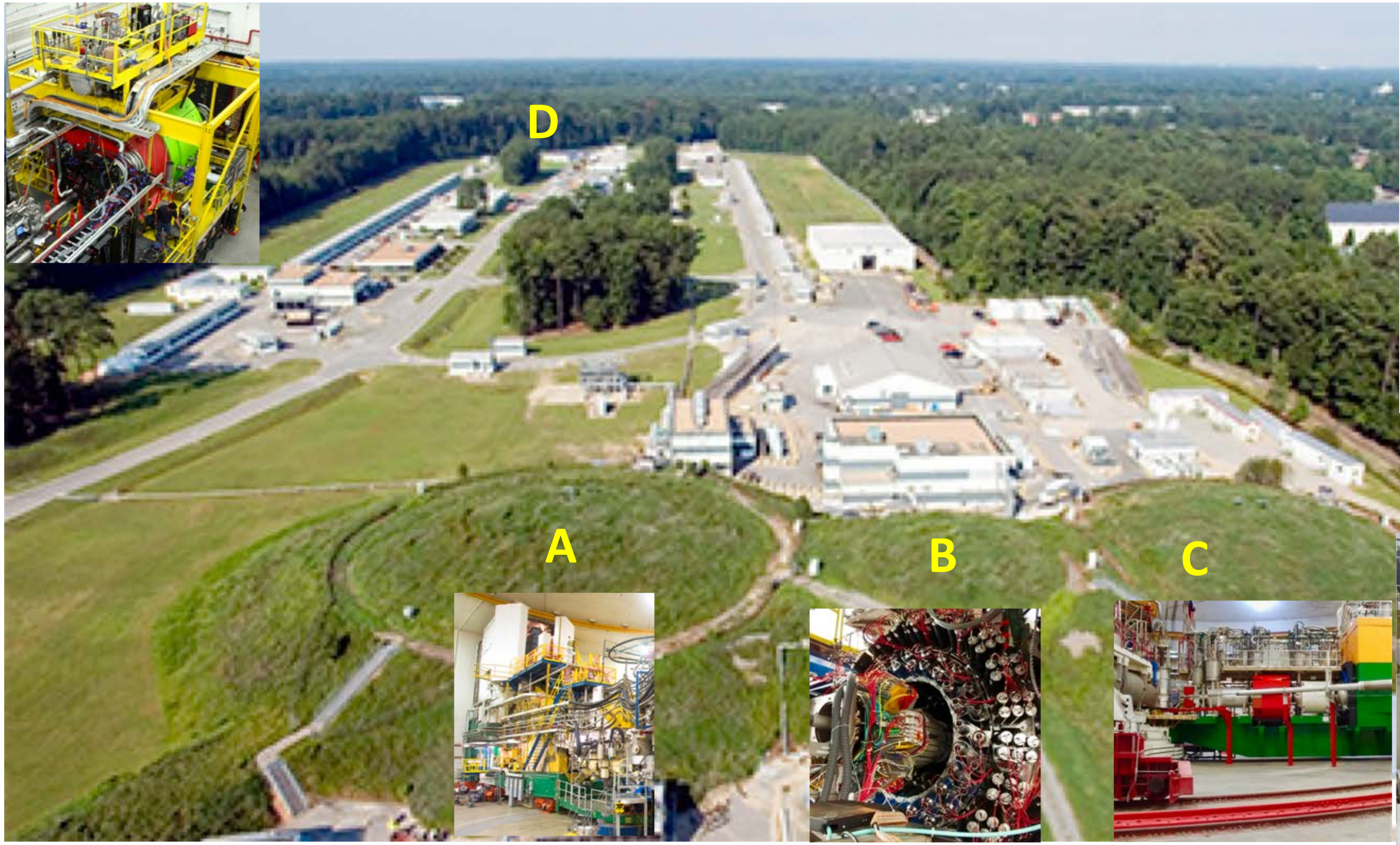
Carlos Hernandez-Garcia

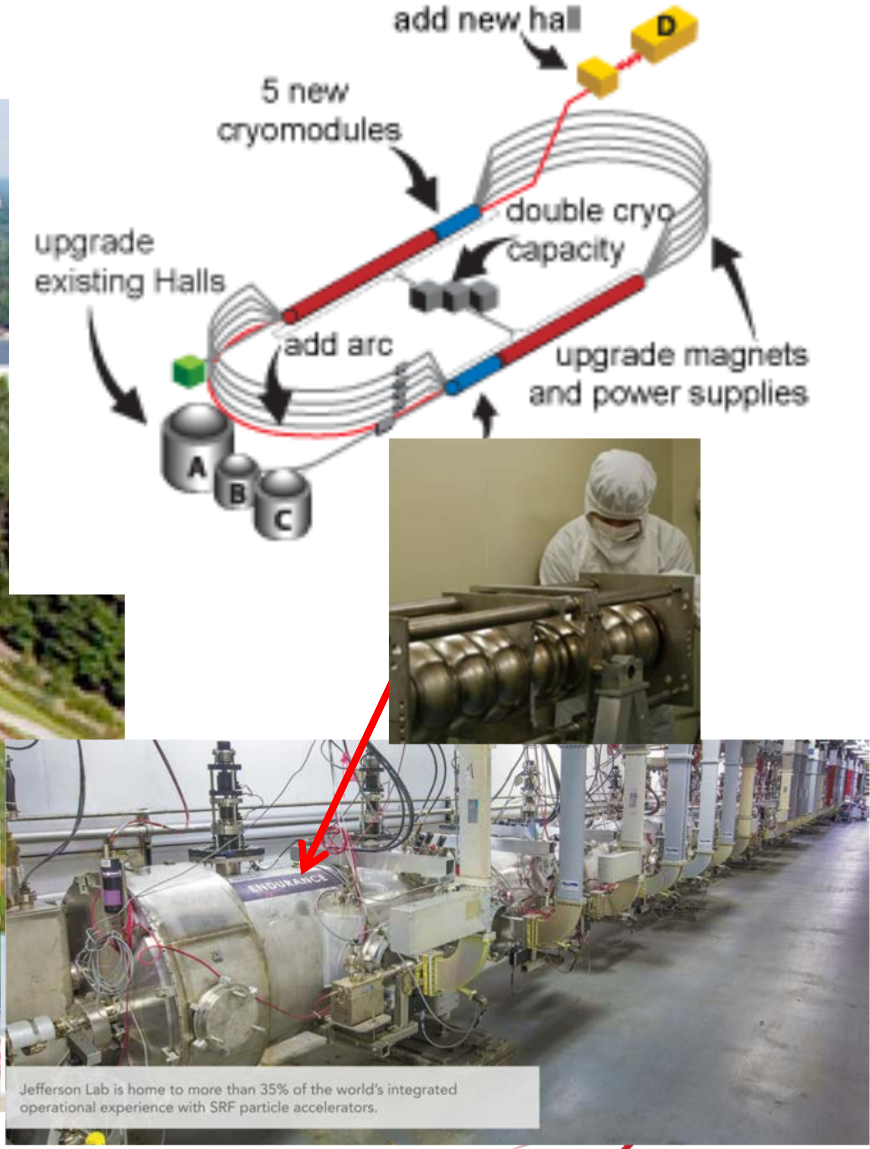
Center for Injectors and Sources

The Jefferson Lab Continuous Electron Beam Accelerator Facility (CEBAF) provides high polarization CW beam to four nuclear physics experimental halls

The electron source is based on a 130 kV DC photogun with strained super lattice GaAs photocathode

The accelerator is based on SRF linacs providing ~ 1 GeV / pass

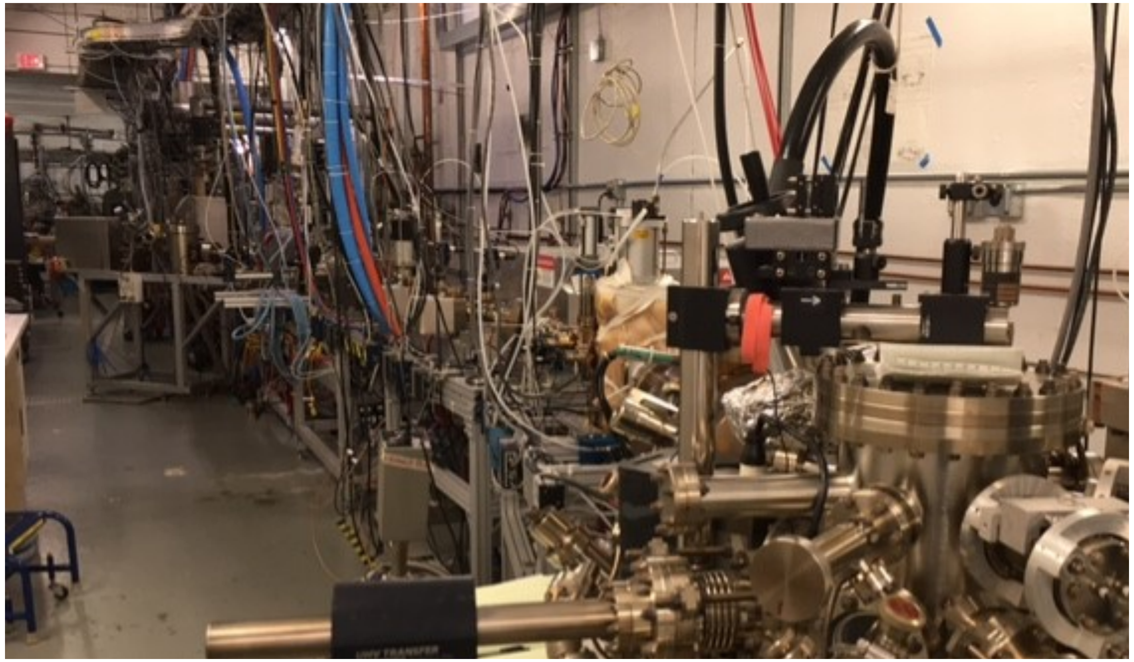




Jefferson Lab is home to more than 35% of the world's integrated operational experience with SRF particle accelerators.

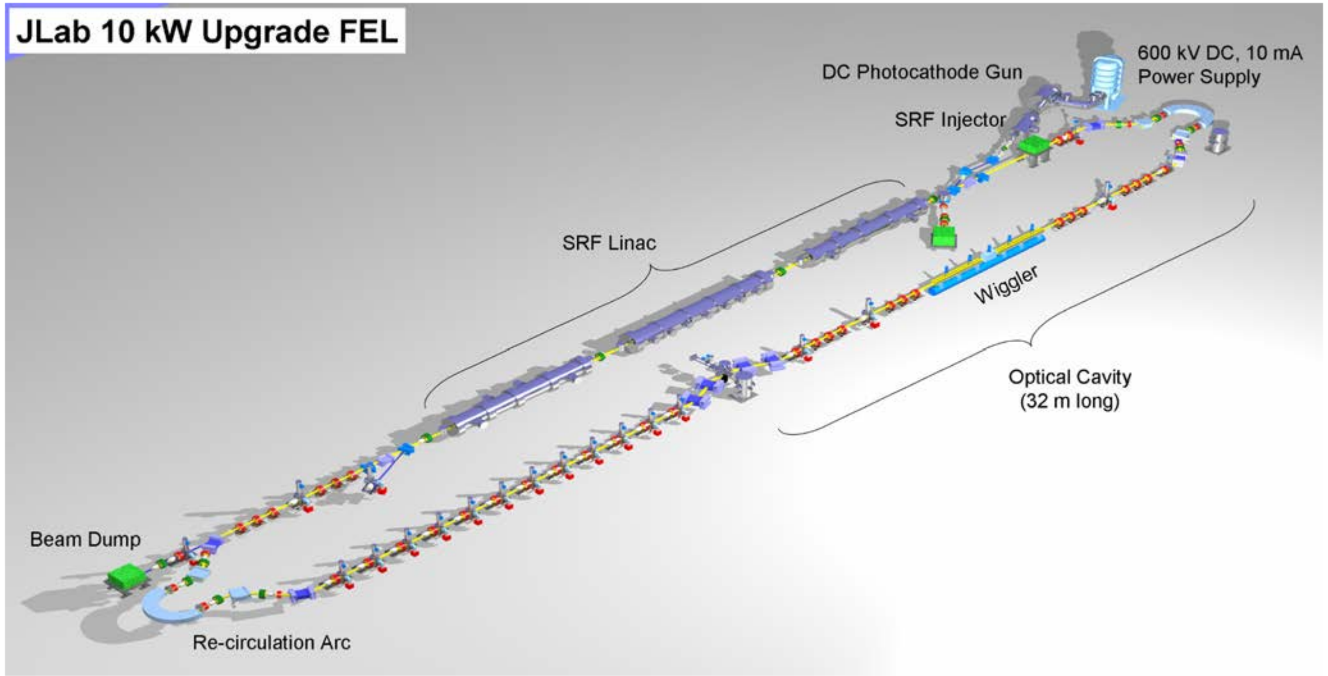
The Jefferson Lab site hosts two additional accelerators

The Upgrade Injector Test Facility UITF is a testbed accelerator based on a 10 MeV SRF booster and 200kV DC photogun with a variety of photocathodes



- Evaluation of polarized hydrogen targets (HDIce)
- Irradiation of wastewater with electron beam

The 10 kW IR-FEL was based on an ERL SRF linac at 150 MeV and 8 mA CW using a 350 kV DC photogun with bulk GaAs (unpolarized beam)



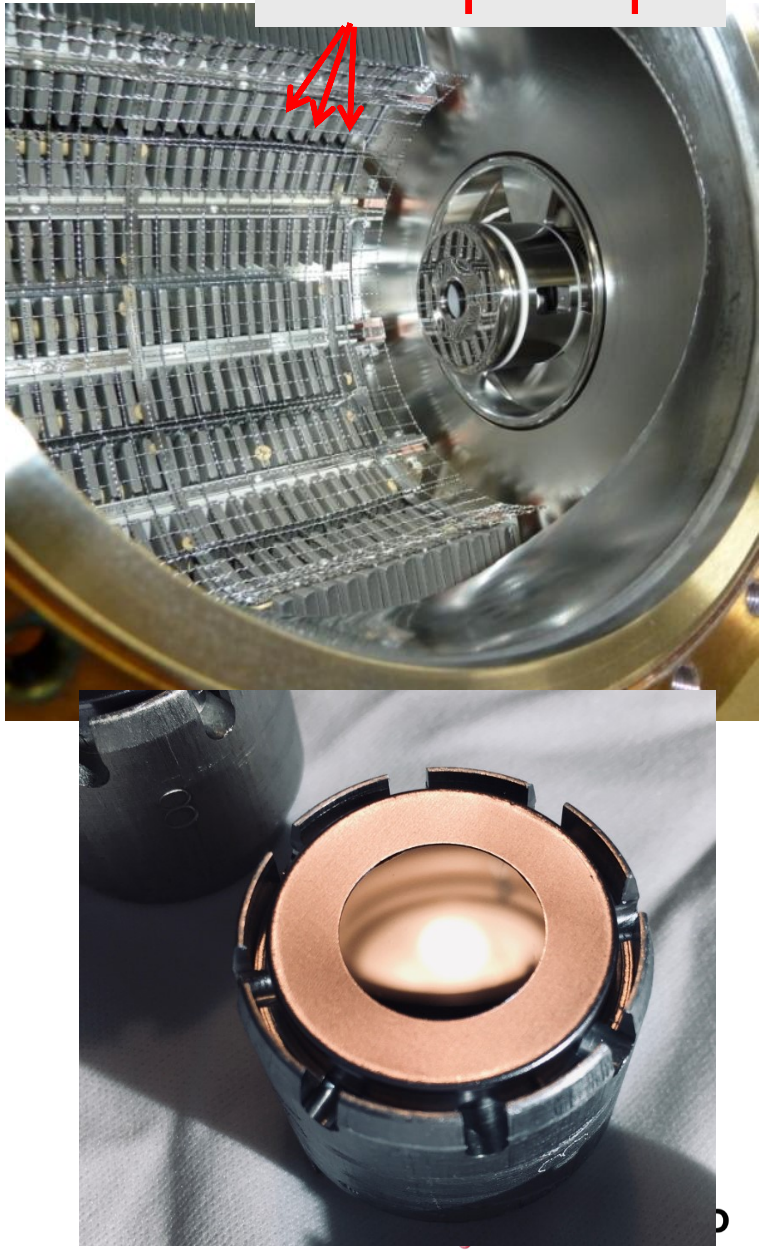
- Demonstrated > 1 MW of recirculated beam power
- Holds the world record at 14 kW CW in the IR

High Voltage DC photoemission gun characteristics makes them an ideal electron beam source in a variety of accelerator applications

- Extreme-high vacuum conditions required for obtaining long-photocathode lifetime from high polarization GaAs photocathodes for nuclear physics

- High CW beam current
  - Hundreds of micro-Amperes polarized beams for nuclear physics
  - Tens of milli-Amperes un-polarized beams for electron coolers, energy recovery linacs and free electron lasers

- High photocathode gradient for injector transmission and for generating bright electron beams in electron microscopy, ultra-fast electron diffraction and free electron lasers

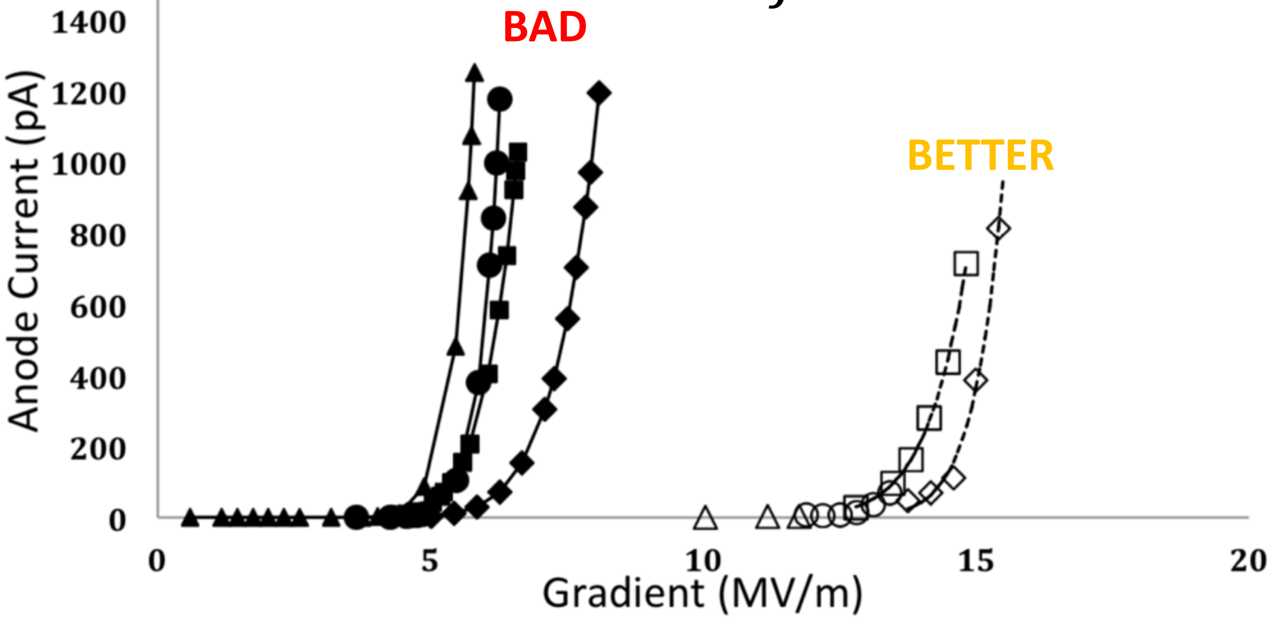


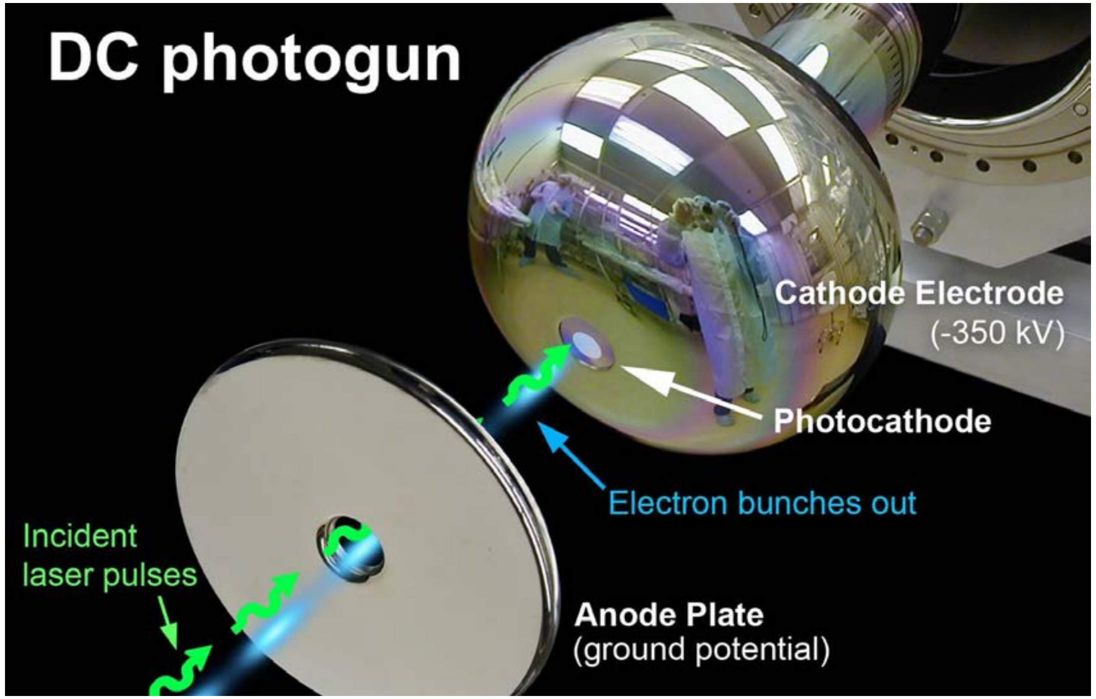
NEG pumps

Compensating for space charge forces within the electron bunch and improving injector transmission imposes challenging requirements

- The photocathode accelerating field must be sufficiently high (often ~ 10 MV/m)
- Electrodes must be free of field emission at the operating voltage to preserve the vacuum conditions necessary for long photocathode lifetime

$$J = AE^2 e^{-B/E}$$





- High voltage must be applied to the electrodes and HV feedthroughs without breakdown

Field emission is a harsh opponent. The electrodes:

- Material choice
  - Minimal amount of inclusions and defects to reduce potential field emitters
  - Increased material hardness helps with field emitter ‘growth’, but once developed field emitters are more difficult to process out, and electrode is more difficult to polish
  - Low Z metals (like titanium) have lower SEY helping to preserve vacuum conditions during high current beam delivery
- Small size to minimize surface area for better vacuum, but shape and size to minimize gradient

$$\boxed{E \propto \frac{q}{r^2}}$$

- Mirror finish polishing to minimize surface roughness and thus potential field emitters
- Vacuum heat treatments to reduce outgassing for vacuum performance
- UHV chemical cleaning and high pressure rinsing to minimize potential field emitters from particulates
- Assembly in best possible clean room conditions to minimize number of foreign particulates
- High voltage conditioning, using Kr gas helps processing field emitters

Similar practices apply to the vacuum chamber and anode electrodes to minimize *voltage induced gas desorption,* typically observed > 200 kV

W. Diamond, “A model of gas desorption and radiation during initial high voltage conditioning in vacuum”, J. Appl. Phys. 126, 193303 (2019)

The high voltage power supply is often based on a Cockcroft-Walton generator inside a vessel filled with compressed sulfur hexa-fluoride (SF_6)

Voltage ranges from 100 to 500 kV DC, and current from 1 to 100 mA

In photoguns using large-bore cylindrical ceramic insulators:

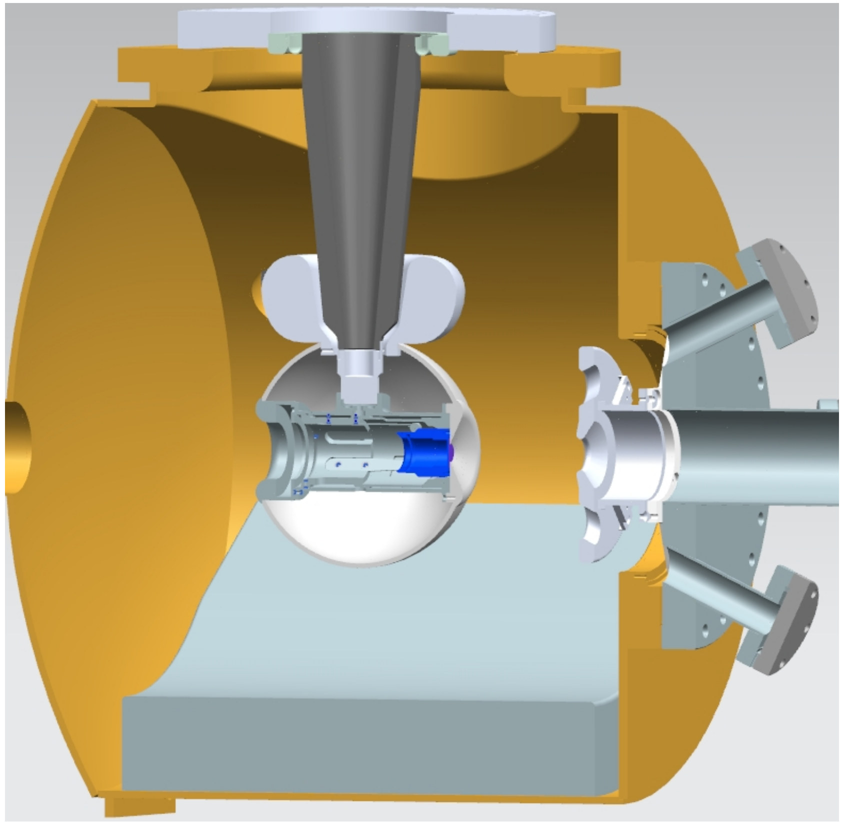
- The cathode is isolated from the vacuum chamber at ground potential with a cylindrical insulator
- The cathode is connected to the power supply via a long electrode stalk coaxial to the insulator and in electrical contact with the biased end of the insulator
- The assembly is enclosed in a vessel pressured with SF_6 to prevent corona discharges. Often the vessel is an appendage of the high voltage power supply

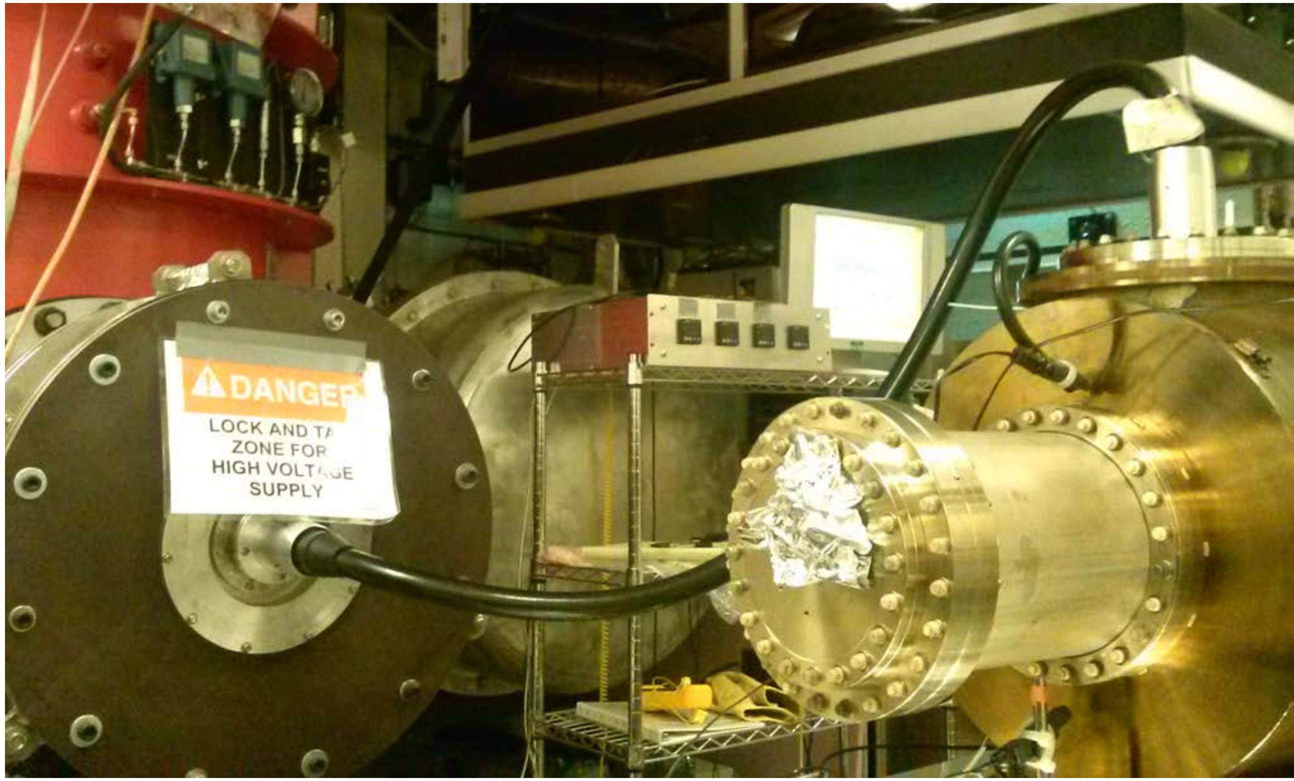
The pictures show the JLab 10 kW IR FEL photogun. It is called a vent-bake gun because it does not have a photocathode loading chamber

In photogun designs based on inverted-geometry ceramic insulators:

- The cathode is isolated from the vacuum chamber at ground potential with a small conical (inverted geometry) insulator

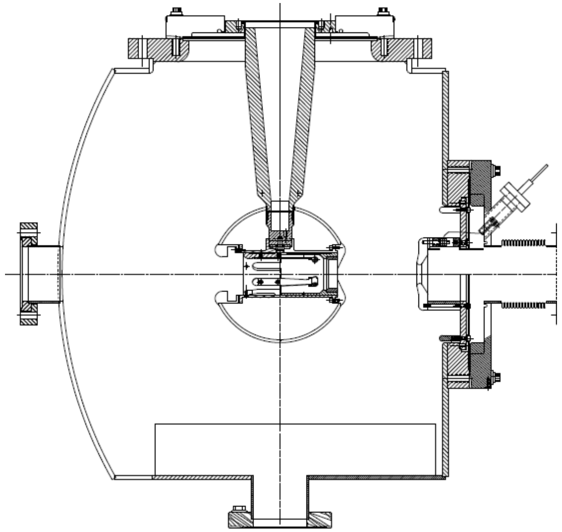
- The cathode is connected to the high voltage power supply via a feedthrough using a cable

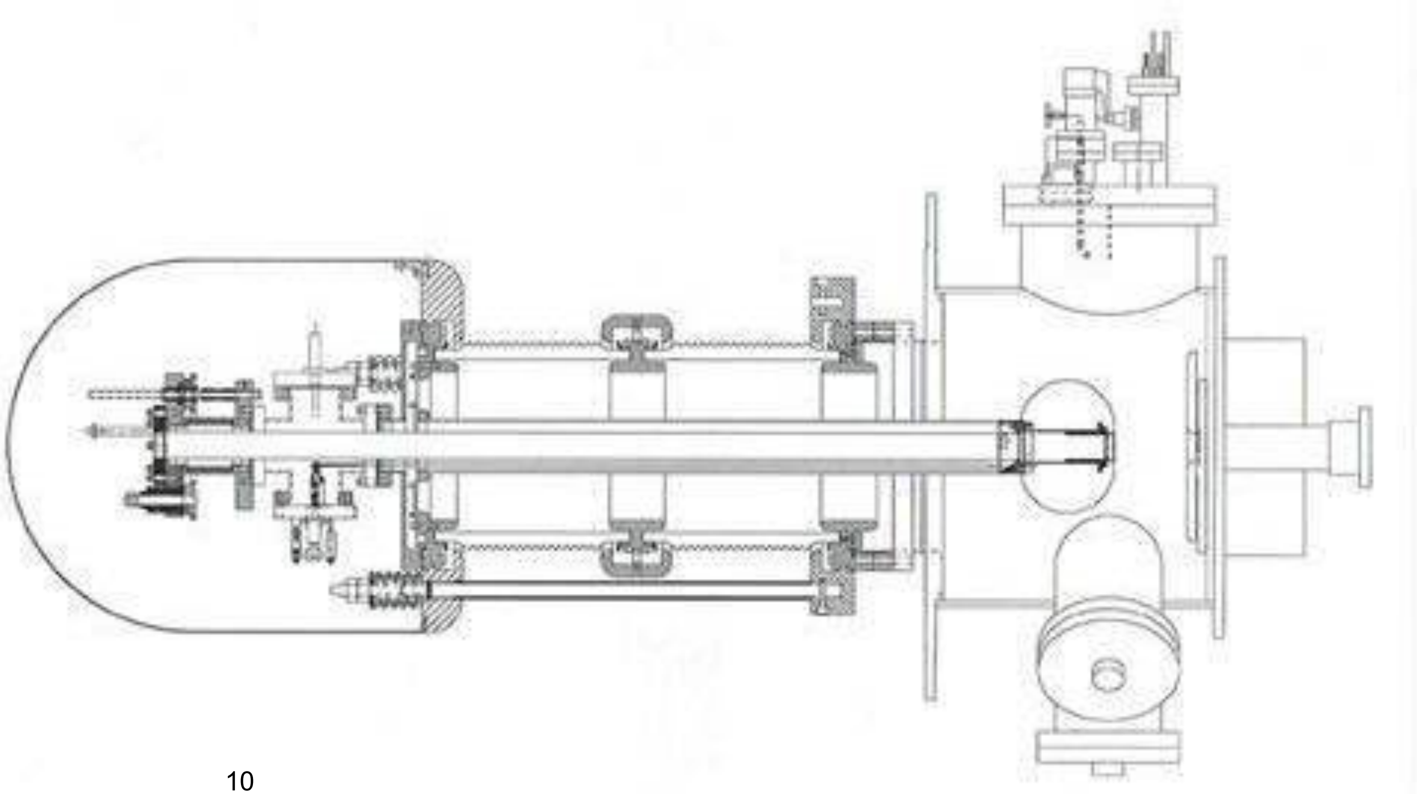




The inverted-geometry insulator photogun design has a number of advantages over the large-bore photogun design

- helps achieving exceptional vacuum because there is less surface area to contribute a gas load
- serves to minimize field emission because there is less metal biased at high voltage, and
- a bulky SF6 tank is not required at the photogun, because a high voltage cable is used to apply high voltage

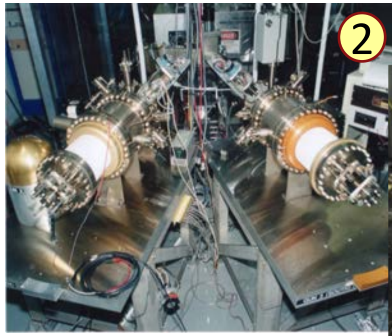


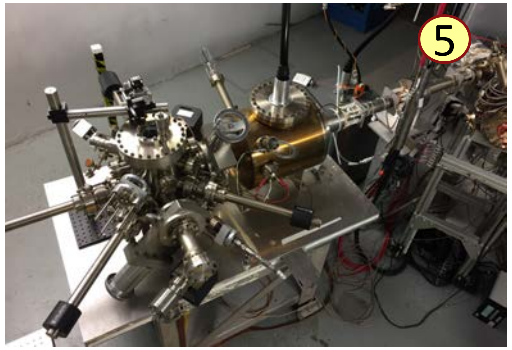


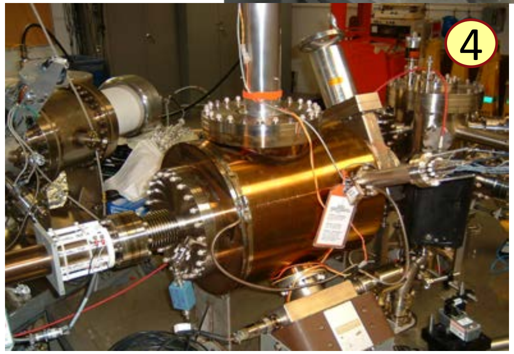
JLab DC photoguns evolution

CEBAF 100-130 kV

- 1990 Thermionic gun
- 1994 First vent-bake vertical photogun [1]
- 1998 Two vent-bake horizontal guns [2]
- 1999 One vent-bake + first load-lock large bore [3]
- 2007 First load-lock with inverted insulator + one vent-bake horizontal both large bore [4]
- 2011 Upgrade load-lock [5]

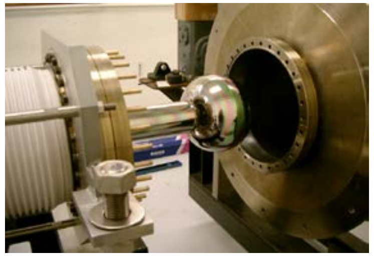






FEL 320-350 kV

- 1998 FEL IR Demo
- 2001 FEL IR Upgrade 5 mA CW from GaAs
- 2005 FEL IR Upgrade 10 mA CW for 14 kV world power record
- 2012- present Semi-load lock

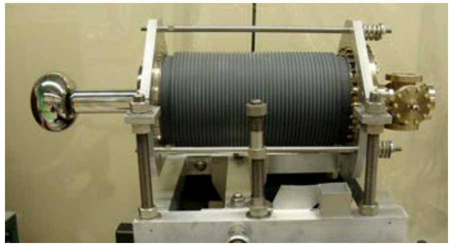


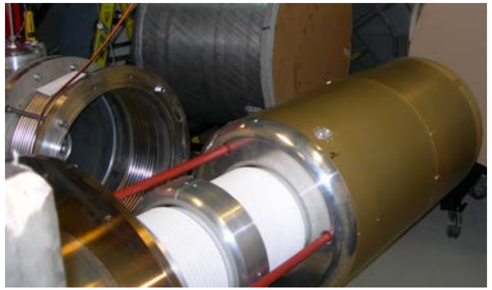
ITF->UITF

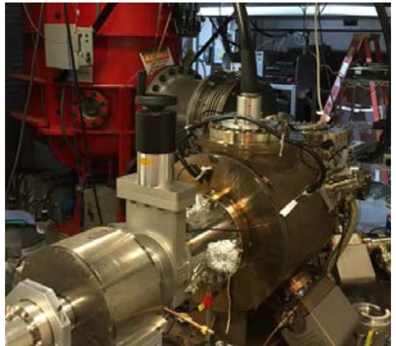
- 1994-1997 Vent-bake FEL gun test
- 1997-1999 CEBAF hor. Gun test
- 2000-2009 Load-lock gun tests large bore insulator, then inverted insulator
- 2011 Inverted gun with Nb at 225kV
- 2012 – present inverted guns with shielding electrodes

GTS 200-450 kV

- 2005 Vent-bake first to make 1 nC from GaAs
- 2016 Inverted insulator test
- 2017 Inverted insulator+multi-alkali 28 mA & magnetized beam
- 2019 Thermionic gun magnetized beam
- 2022 Inverted insulator high gradient cathode





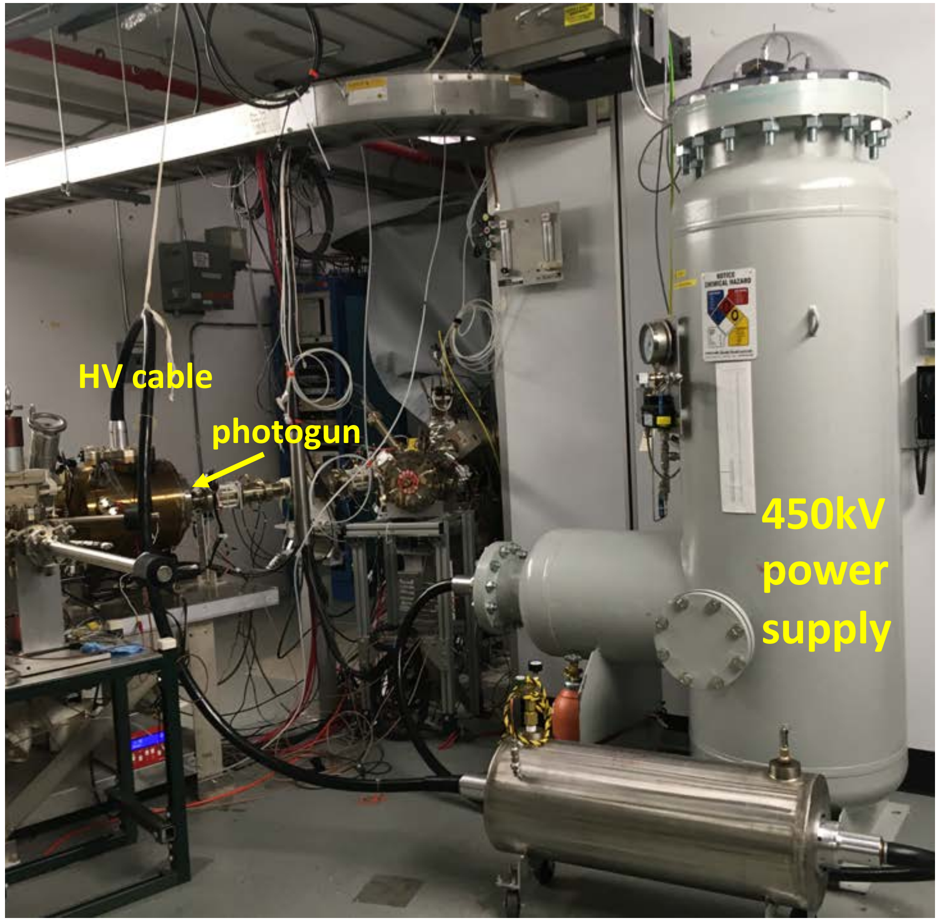


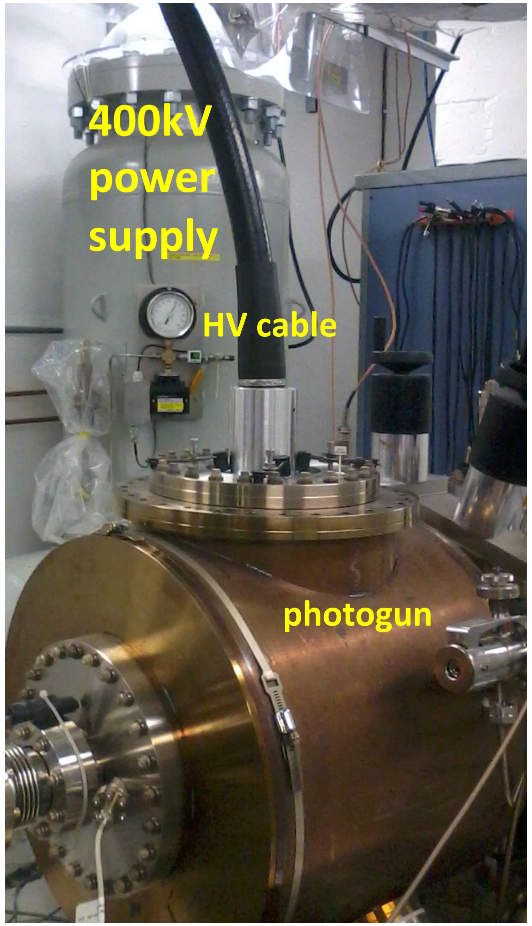
JLab currently operates 3 inverted insulator photoguns that use commercial HV cables

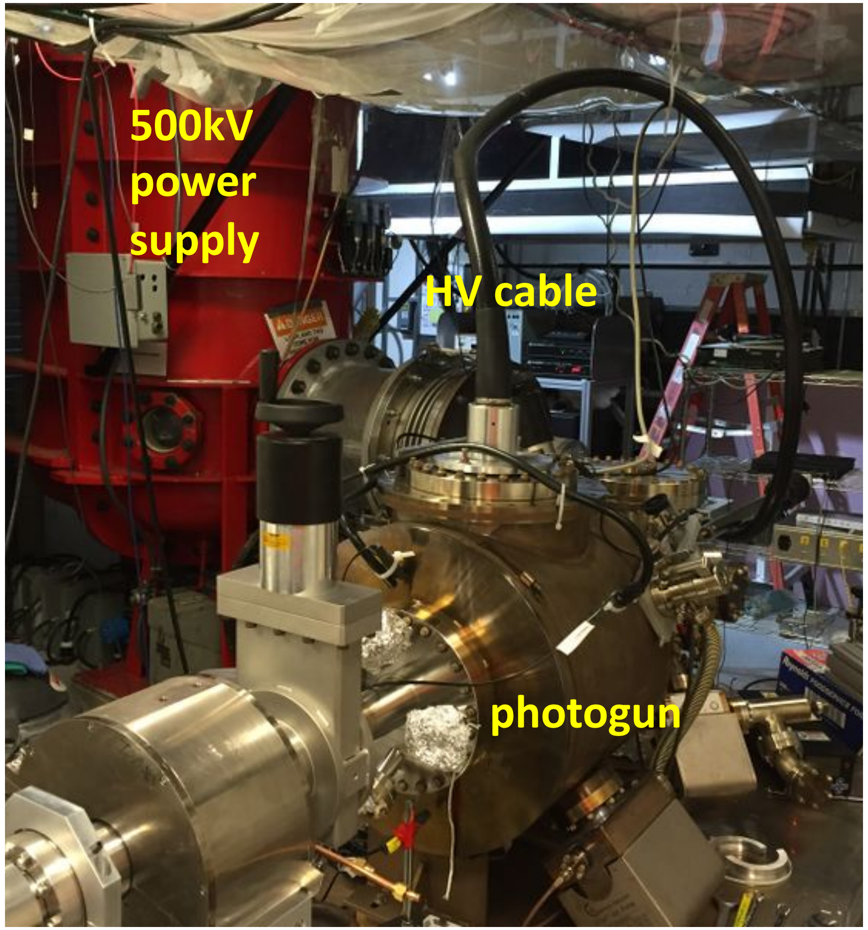
CEBAF 130 kV

UITF 200 kV

GTS 350 kV







The ceramic insulators were developed in collaboration with SCT (France) in two sizes that fit commercial cable terminations

The cable terminations are standard for X-Ray commercial sources, with two size denominations

R28 in the CEBAF & UITF guns

Ceramic Insulator | Cable Termination | Epoxy Receptacle

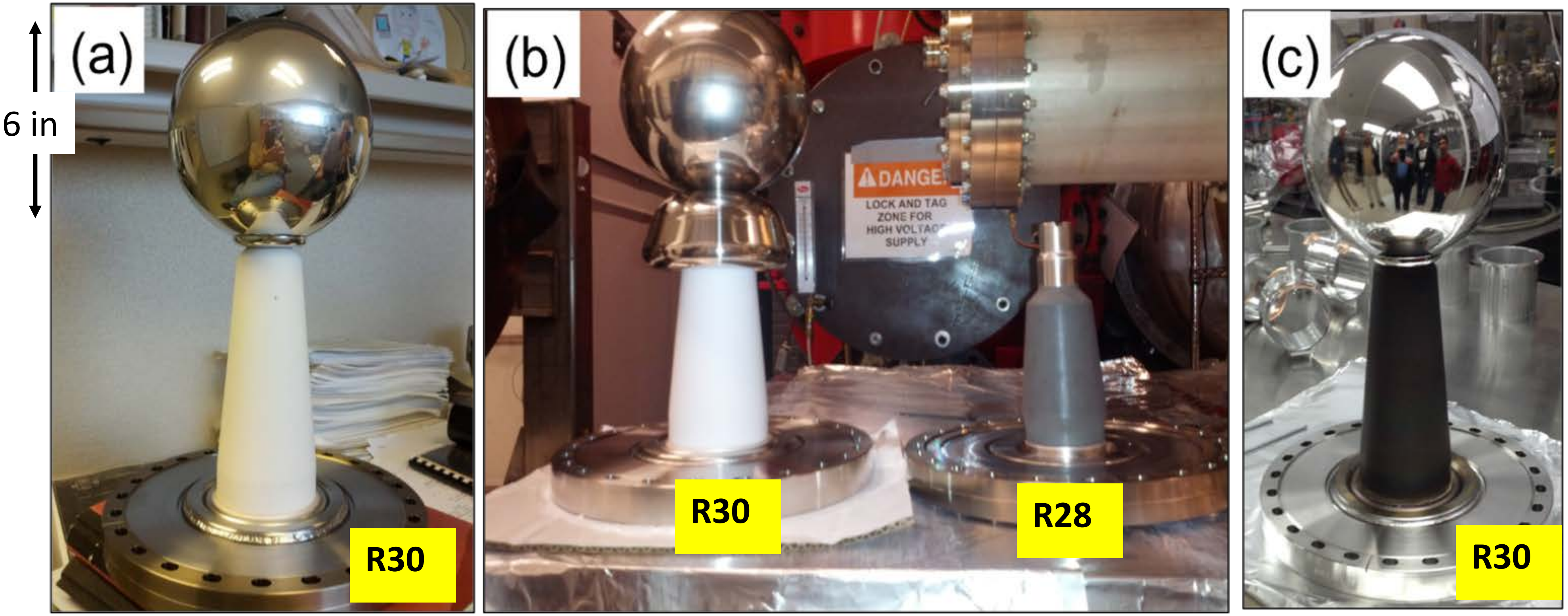
R30 in the GTS gun

Ceramic Insulator | Cable Termination | Epoxy Receptacle

Building a 350 kV photogun based on inverted-geometry ceramic insulator design

- Prototype magnetized *nC bunch charge* source ***was funded by the Jefferson Lab LDRD program***. This three-year project concluded in October 2018 demonstrating magnetized beam up to 28 mA CW

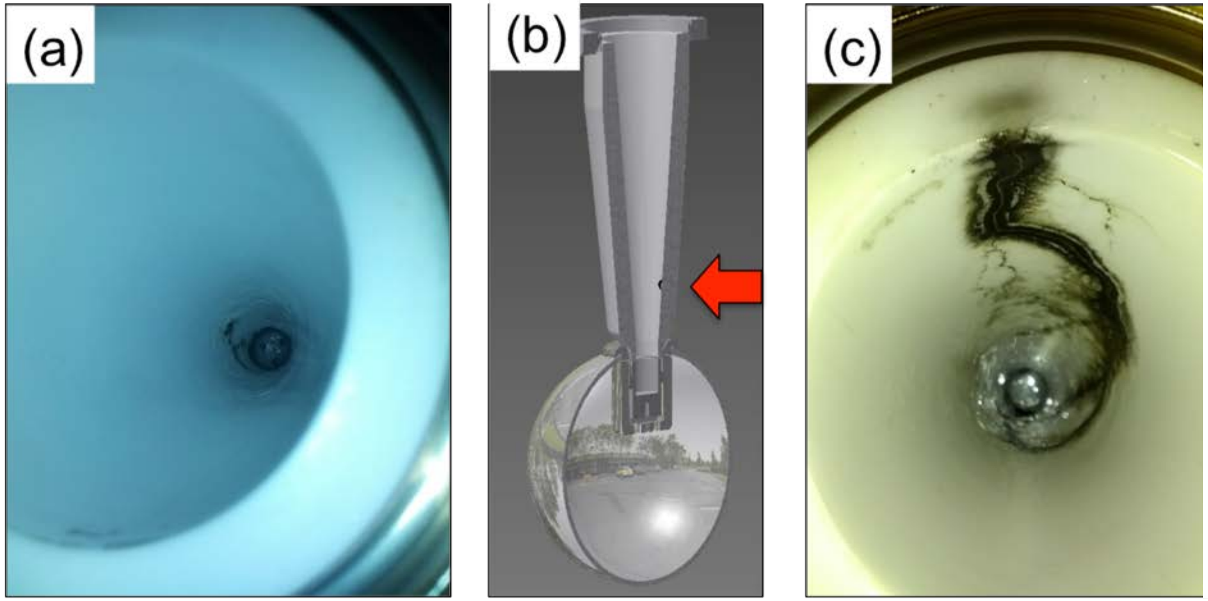
Start with “dummy” electrode (no photocathode) and test different insulators and cathode screening electrodes



C. Hernandez-Garcia, M. Poelker, and J. Hansknecht, “*High Voltage Studies of Inverted-geometry Ceramic Insulators for a 350kV dc Polarized Electron Gun*,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 23, No. 1; February 2016

The reality of HV breakdown

The first test with **R30** pure alumina ceramic suffered breakdown at **~315kV** with subsequent puncture a**t 330kV.**

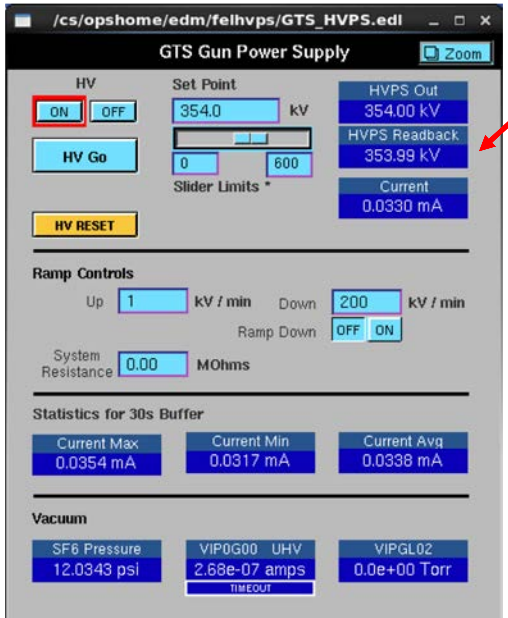


A second test with a **new R30** pure alumina suffered breakdown at **~315 kV.**

Field emission managed via krypton-processing*, i.e., voltage was applied with ~10^{-5} Torr krypton added to gun chamber

* M. BastaniNejad, A. A. Elmustafa, E. Forman, J. Clark, S. Covert, J. Grames, J. Hansknecht, C. Hernandez-Garcia, M. Poelker and R. Suleiman, "*Improving the performance of stainless-steel DC high voltage photoelectron gun cathode electrodes via gas conditioning with helium or krypton*," Nucl. Instr. and Meth. in Phys. Res. A, Vol. 762, pp. 135–141, 2014

Adding a HV triple point junction shield was key for reaching 350 kV w/o breakdown using the pure alumina R30 insulator



/cs/opshome/edm/felhvps/GTS_HVPS.edl

GTS Gun Power Supply

HV: ● ON ○ OFF

Set Point: 354.0 kV

Slider Limits *: 0 – 600

HVPS Out: 354.00 kV

HVPS Readback: 353.99 kV

Current: 0.0330 mA

Ramp Controls

Up: 1 kV / min

Down: 200 kV / min

Ramp Down: OFF ON

System Resistance: 0.00 MOhms

Statistics for 30s Buffer

Current Max: 0.0354 mA

Current Min: 0.0317 mA

Current Avg: 0.0338 mA

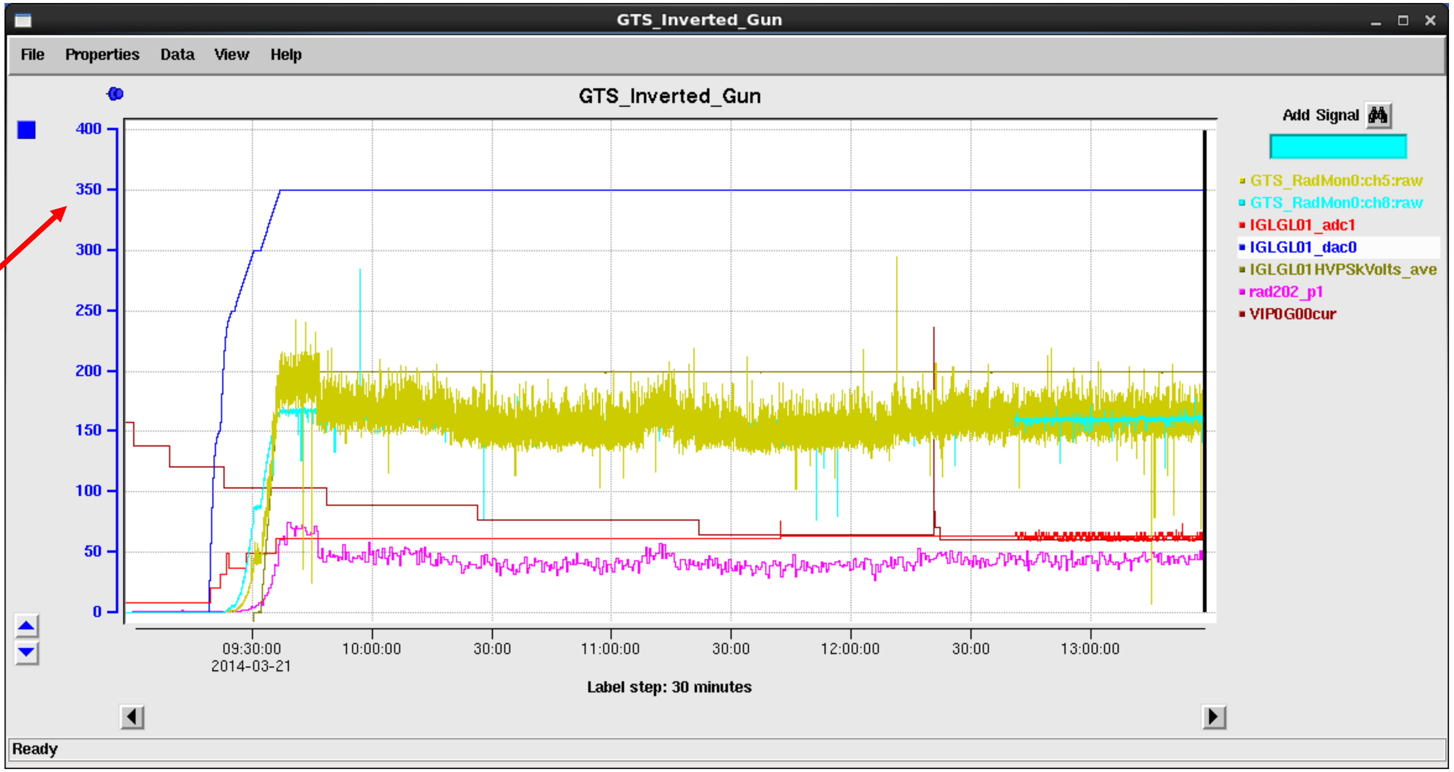
Vacuum

SF6 Pressure: 12.0343 psi

VIP0G00 UHV: 2.68e-07 amps

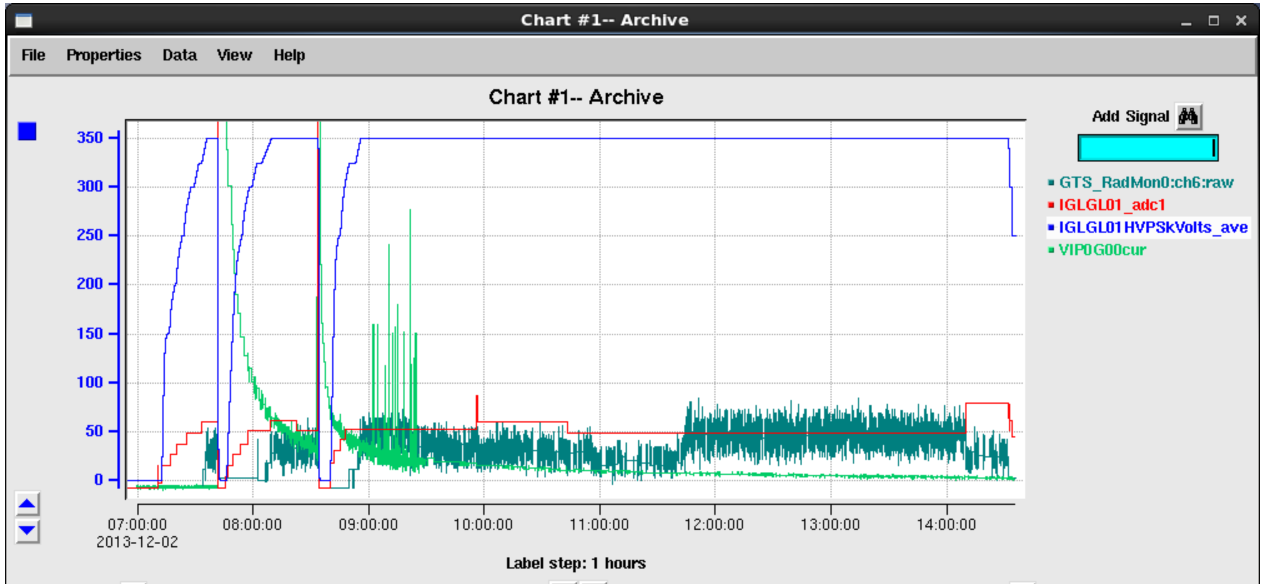
TIMEOUT

VIPGL02: 0.0e+00 Torr



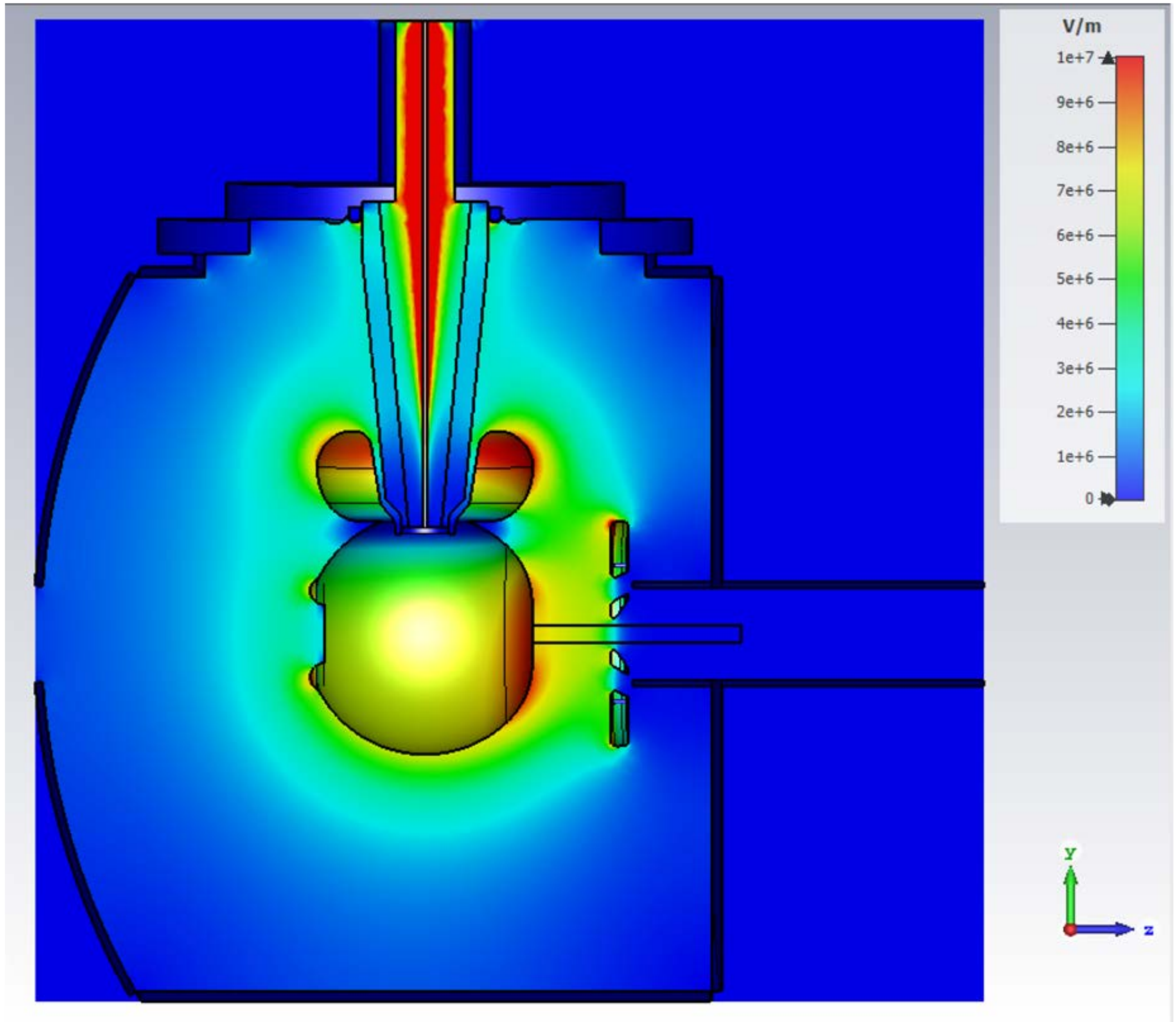
Interestingly enough, the smaller R28 insulator w/o shield reached 360 kV

Insulator type	Length (cm)	Transversal resistivity (Ohm-cm)	Dielectric constant $\varepsilon_1/\varepsilon_0$	Maximum voltage (kV)	Performance
R30 sample 1	20	5.0×10^{15}	9.1	329	Breakdown and puncture near high voltage end
R30 sample 2	20	5.0×10^{15}	9.1	300	Breakdown
R30 with additional screening electrode	20	5.0×10^{15}	9.1	375	370 kV with krypton 4-hr soak, 350 kV in vacuum 4-hr soak. Significant field emission in both cases
R30 ZrO-coated	20	5.0×10^{15}	9.1	340	Breakdown and puncture near ground end
R28 doped	13	7.4×10^{11}	8.4	360	360 kV with krypton 1-hr soak, 350kV in vacuum 5-hr soak, 2 times Minimal field emission in both cases



C. Hernandez-Garcia, M. Poelker, and J. Hansknecht, "*High Voltage Studies of Inverted-geometry Ceramic Insulators for a 350kV dc Polarized Electron Gun*," IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 23, No. 1; February 2016

The gun electrostatic design principles are based on the following requirements:

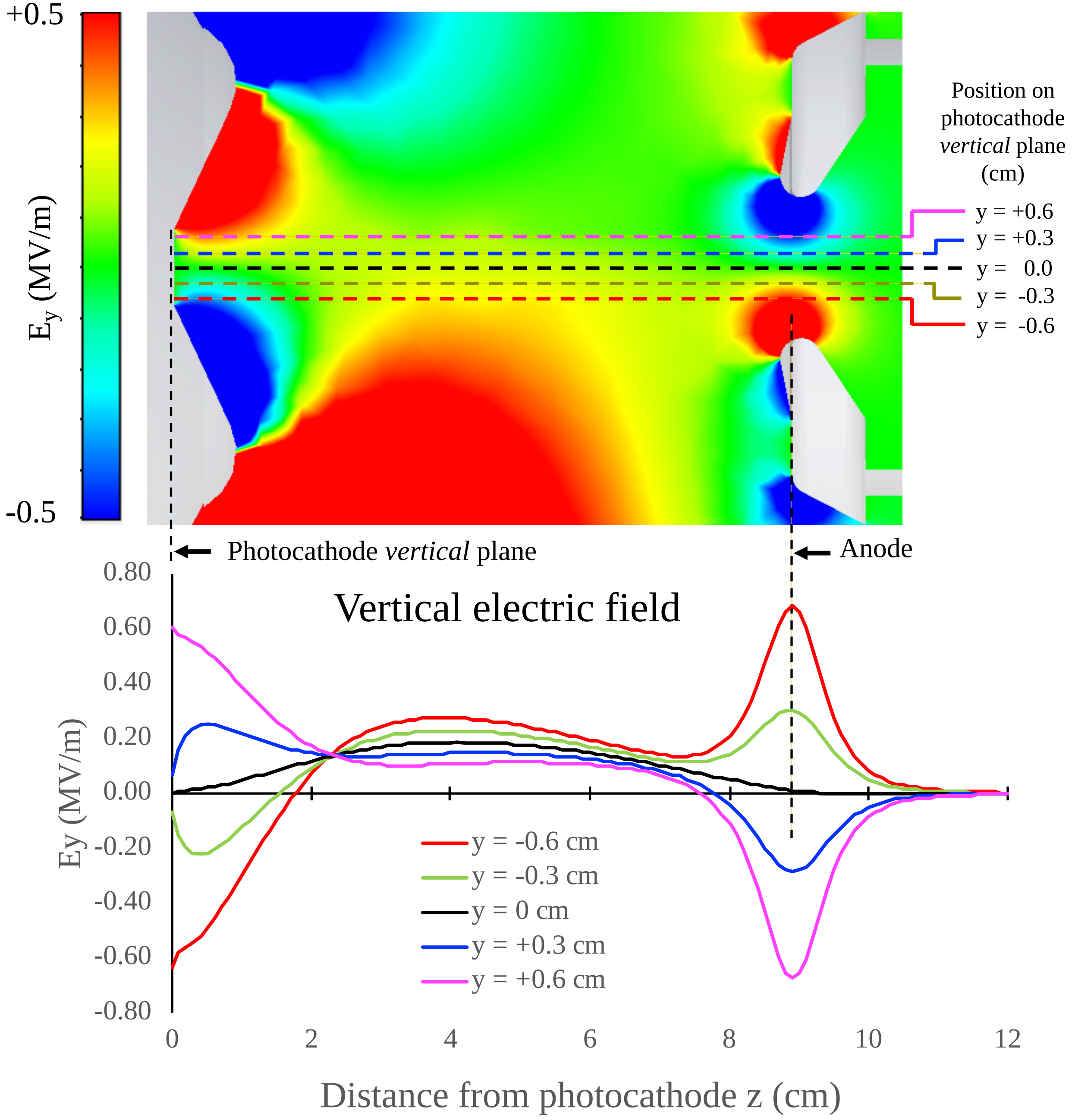


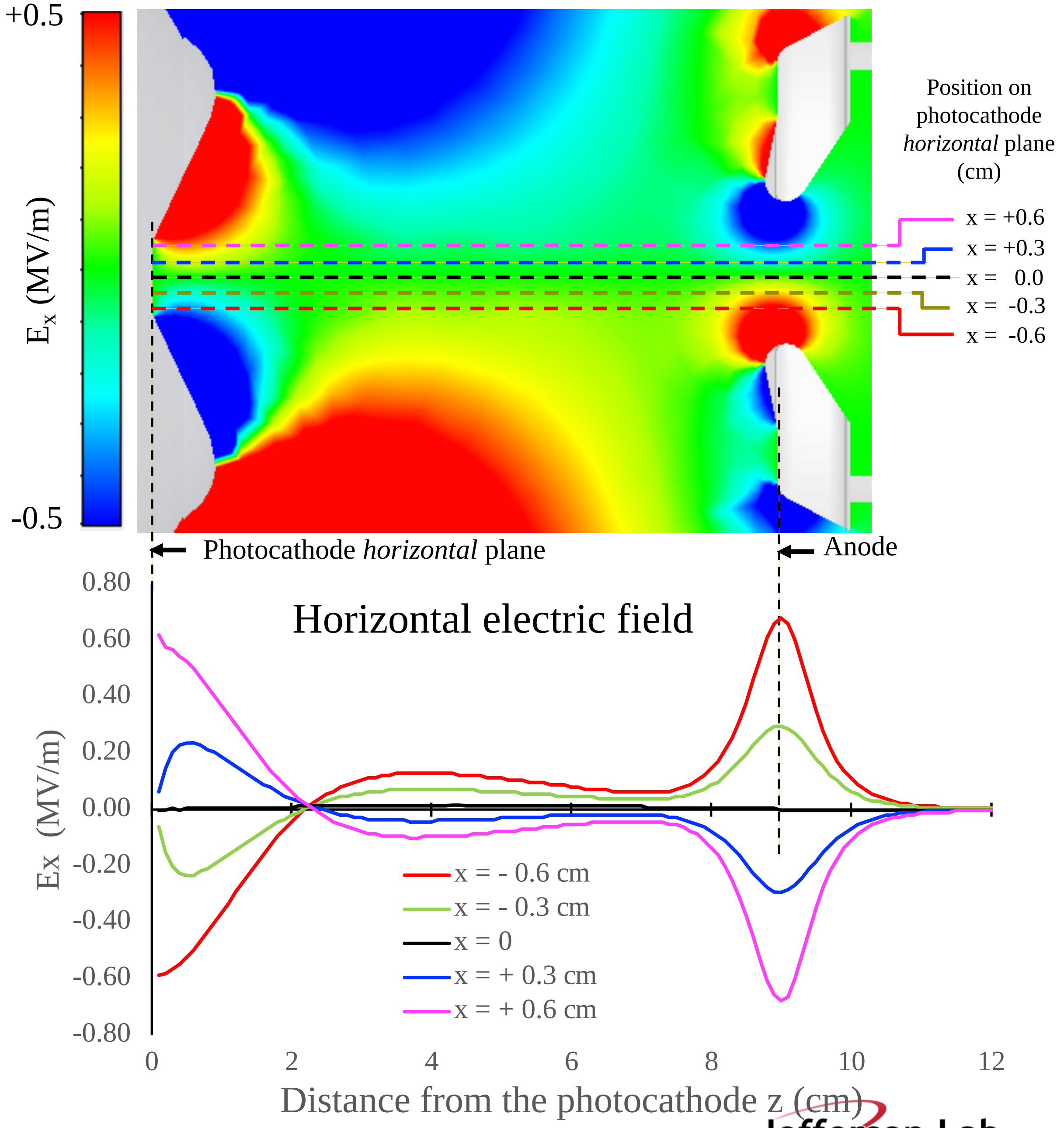
Electron gun electrostatic fields at 350 kV

- No field emission, to provide long photocathode lifetime.
  - Electrode shape and size designed for 10 MV/m max at 350kV
  - Polished electrodes
  - High voltage conditioning
- No breakdown in the high voltage insulator (i.e., arcing)
  - Design triple junction shield
- Radially symmetric electric field in the anode-cathode gap to minimize beam deflection.
  - Intrinsic gun design makes this difficult to achieve

Simulations by Sajini Wijethunga, JLab, now at Fermilab

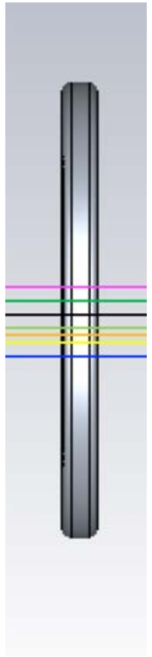
Vertical electric field asymmetry in the anode-cathode gap induces beam deflection



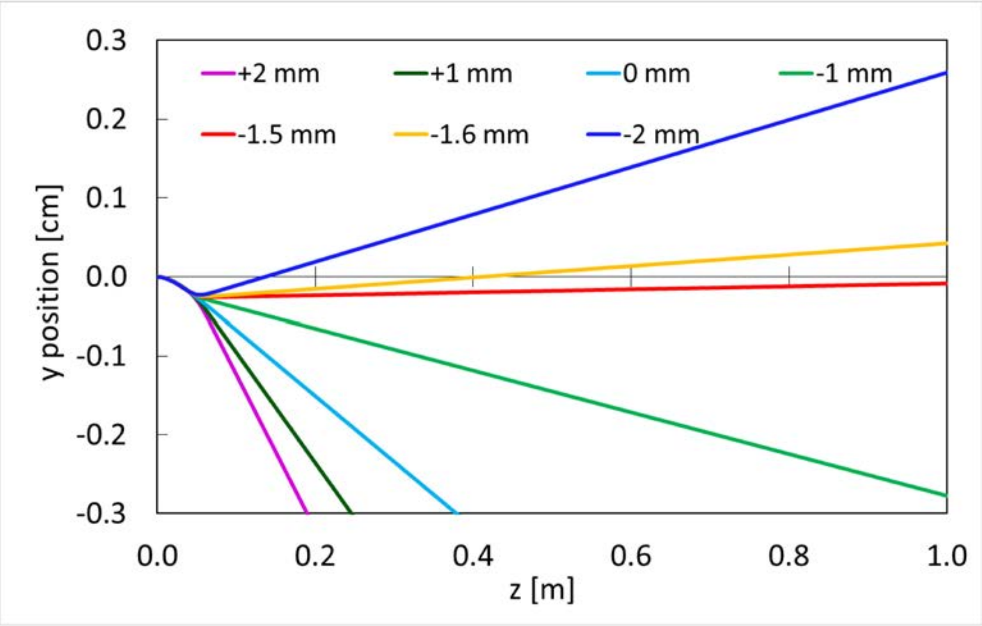


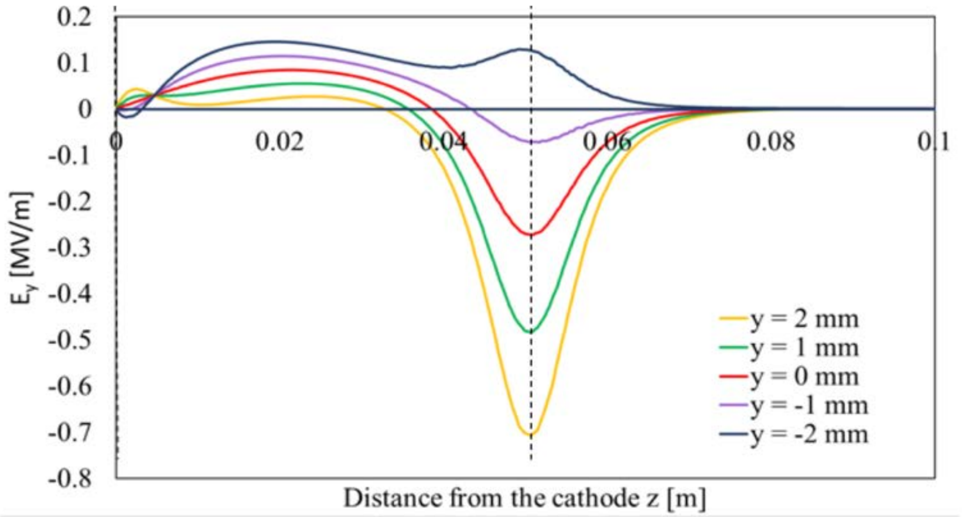
Jefferson Lab

Shifting the anode vertically or tilting the anode compensates the beam deflection

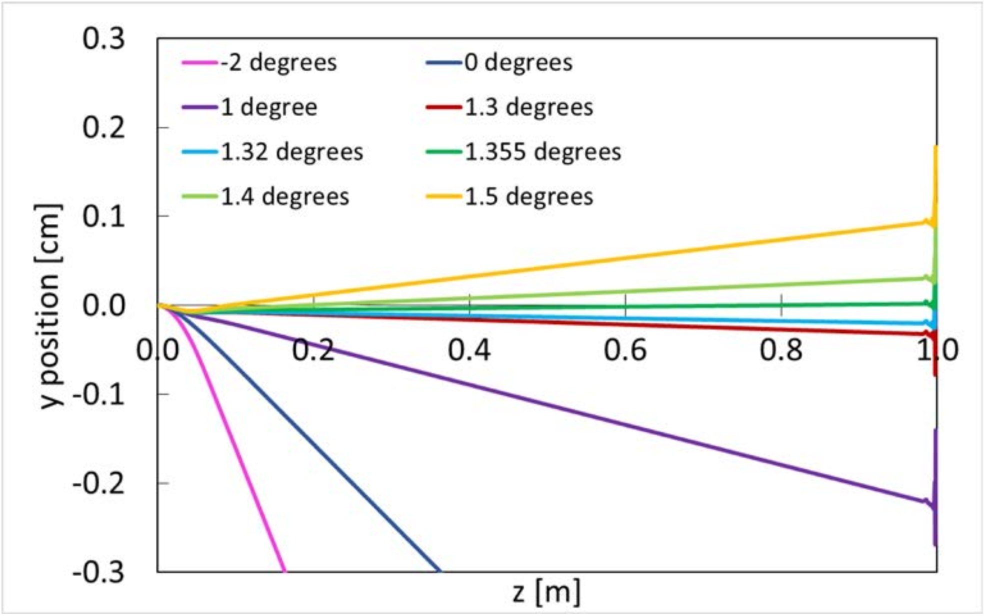


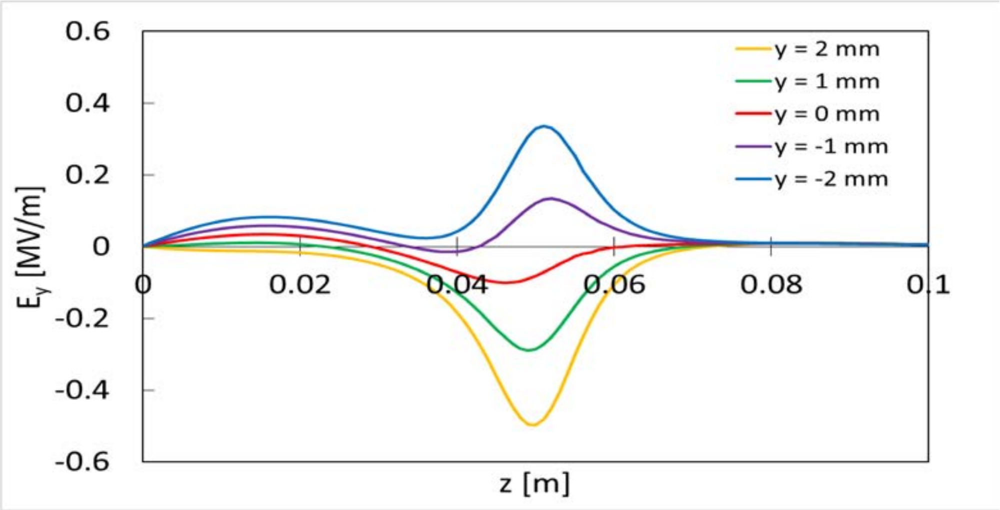
Beam deflection vs anode vertical shift





Beam deflection vs anode tilt





Simulations by Sajini Wijethunga, JLab, now at Fermilab

Triple junction shield design principles: where vacuum metal and insulator meet

To reduce risk of breakdown along the insulator:

- Minimize gradient along the insulator
- Minimize gradient at triple junction
- Make the potential along the insulator as linear as possible

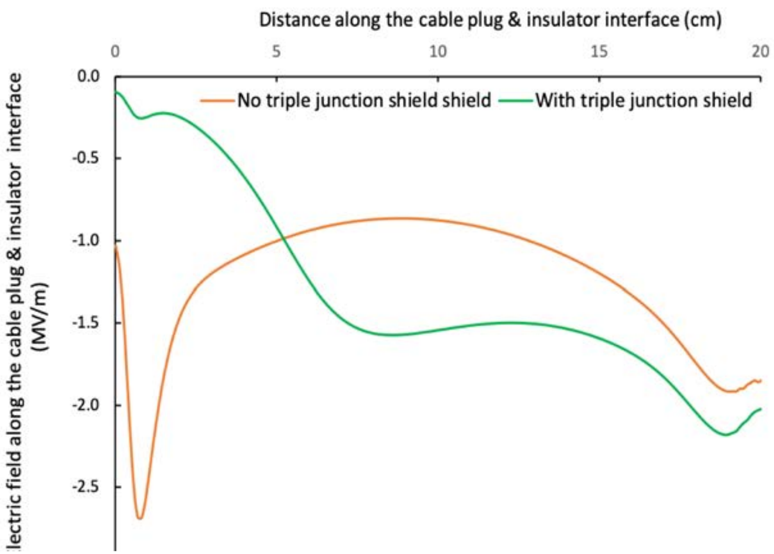
To reduce risk of field emission:

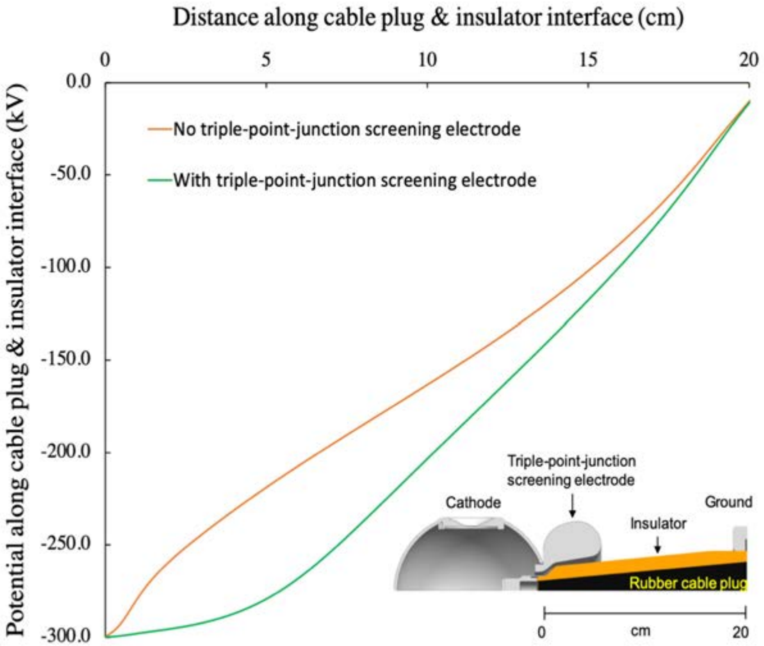
- Adjust height and cusp radius to maintain 10 MV/m max at 350kV

To minimize distortions to gradient in anode-cathode gap:

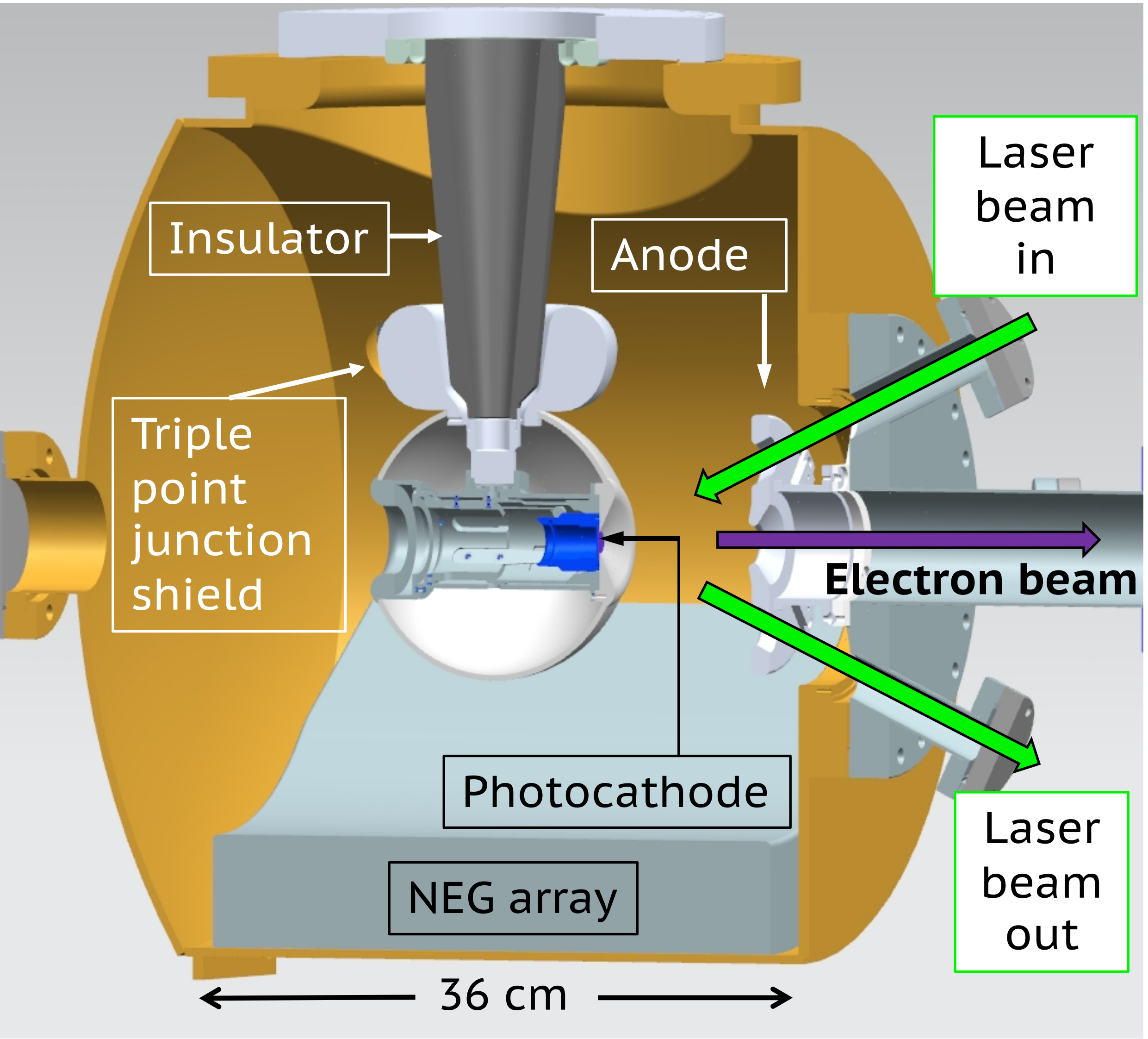
- Keep outermost radius smaller than ball electrode radius

CST simulations: Gabriel Palacios-Serrano, JLab





The engineering design evolves from the electrostatic optimization



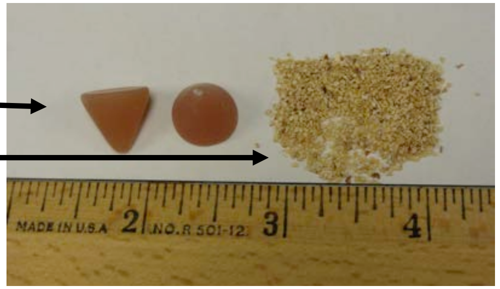
- The vacuum chamber was vacuum fired to 400^{o} C for ~ 100 h to minimize outgassing
- The electrodes were vacuum fired at to 900^{o} C for ~ 24 h to minimize outgassing
- The anode and mounting flange allow for laser to illuminate the photocathode at 25^{o}
- The ceramic insulator is doped to drain charge for minimizing arcing
- The ball cathode and triple junction shield are barrel polished in corncob to < 100 nm rms surface roughness for minimizing field emission*

The electrodes are then mirror polished using centrifugal barrel tumbling

- Diamond paste polishing is a labor intensive process that takes about 3 weeks
- Implementing centrifugal barrel polishing has reduced polishing time from weeks to hours
- Profilometry measurements shows surface rms roughness is comparable between the two polishing methods

From machine shop

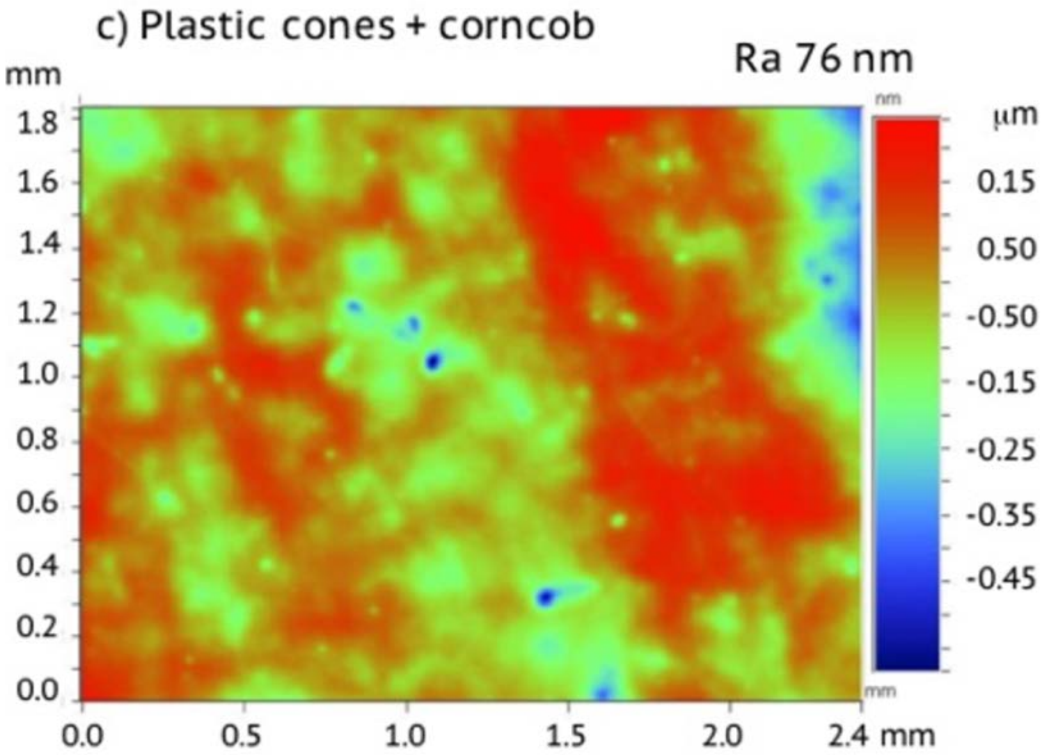
After barrel polishing
60 min. plastic cones
60 min. crushed *corncob*



Barrel polishing machine at JLab SRF

* C. Hernandez-Garcia, D. Bullard, F. Hannon, Y. Wang and M. Poelker, Review of Scientific Instruments **88**, 093303 (2017)

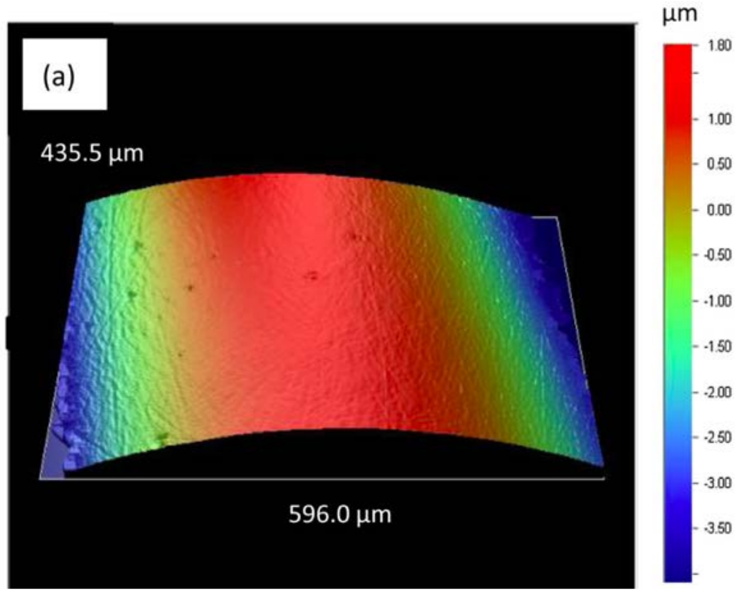
The surface finish of electrodes polished in the tumbler is similar to traditional hand polishing with sand paper and diamond grit



c) Plastic cones + corncob

Ra 76 nm

Diamond paste polishing   Ra 30 nm*

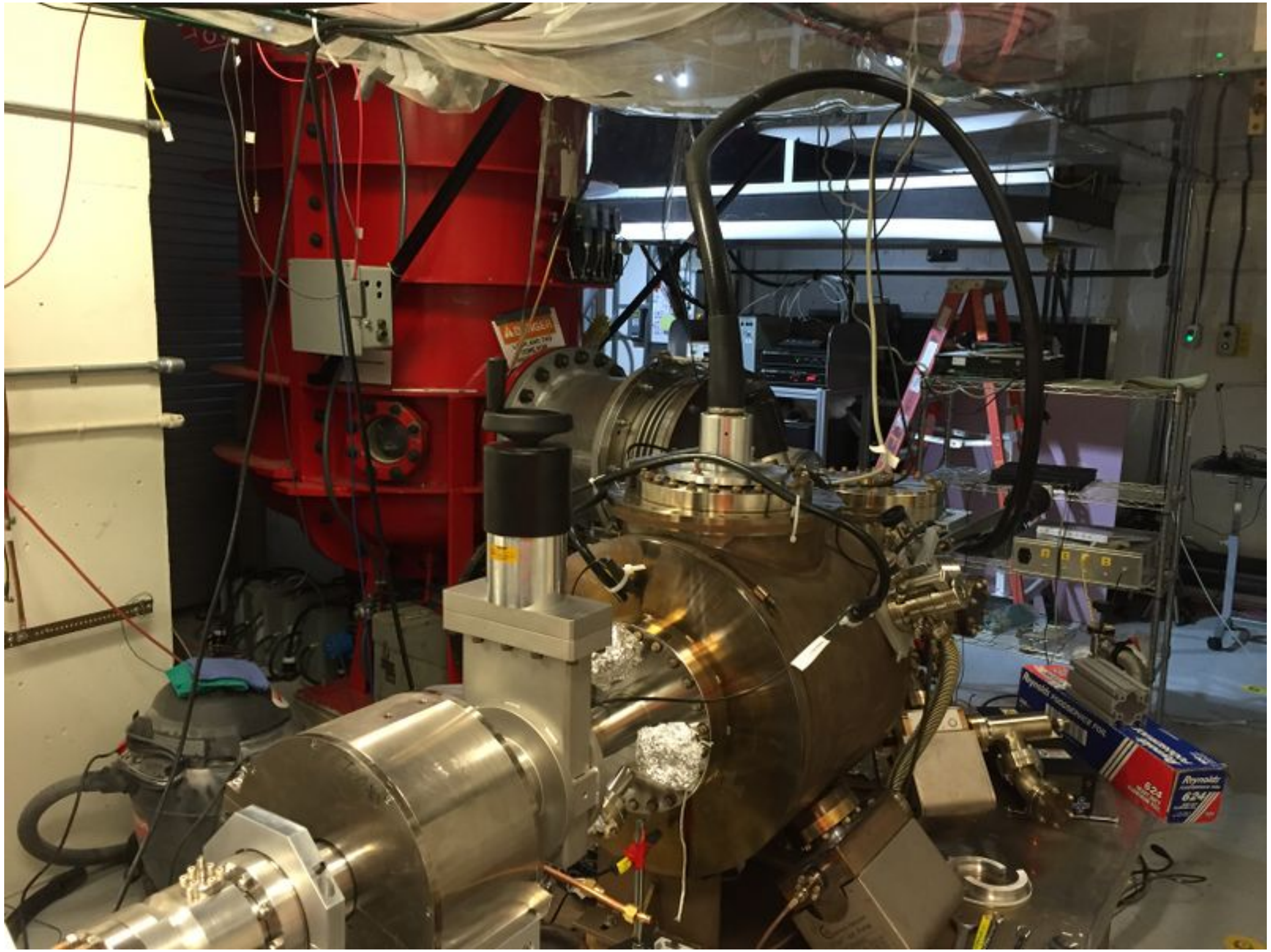


* M. BastaniNejad, A. A. Elmustafa, E. Forman, S. Covert, J. Hansknecht, C. Hernandez-Garcia, M. Poelker, L. Das, M. Kelley, P. Williams, "*Evaluation of electropolished stainless steel electrodes for use in DC high voltage photoelectron guns*," J. Vac. Sci. Technol. A, Vol. 33, No. 4, Jul/Aug 2015

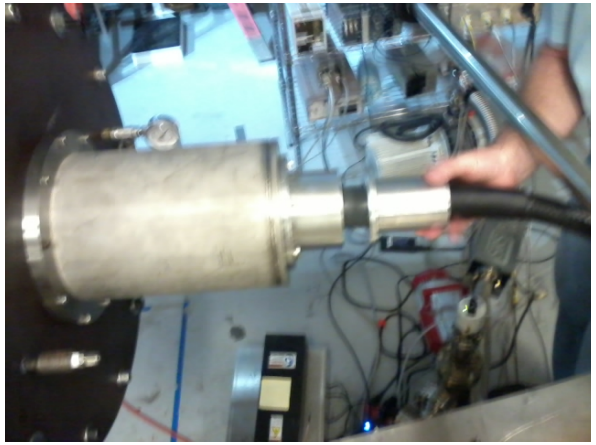
* C. Hernandez-Garcia, D. Bullard, F. Hannon, Y. Wang and M. Poelker, Review of Scientific Instruments **88**, 093303 (2017)

After assembly in a clean room class 1000, the gun was vacuum baked at 250^o C for ~ 50 h

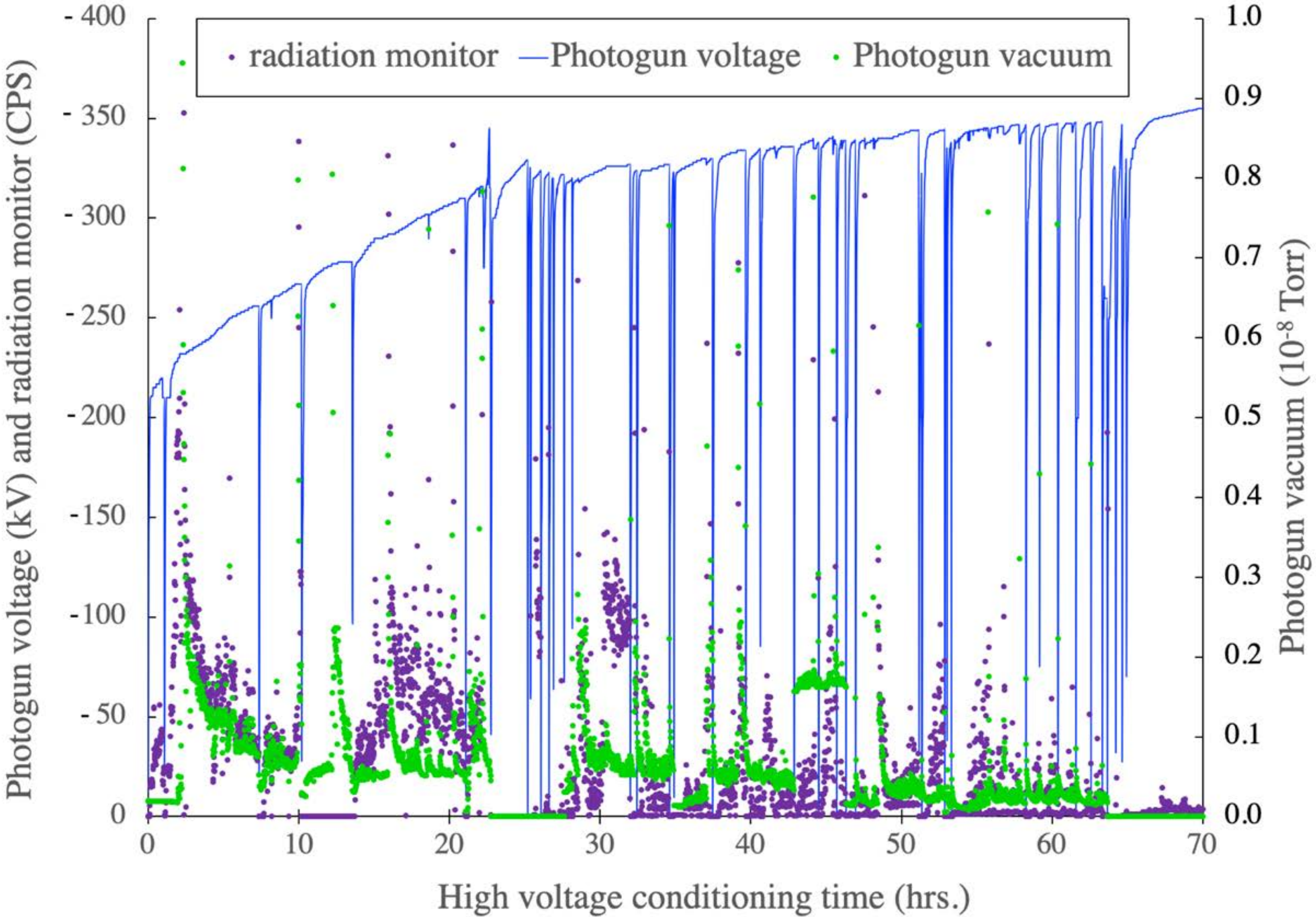
The gun HV feedthrough was connected with a HV cable to the 500kV 5 mA DC power supply



- The gun could also be connected to a 225 kV 30 mA DC power supply for higher current
- Radiation monitors (Geiger tubes) were placed around the gun to monitor field emission during high voltage conditioning



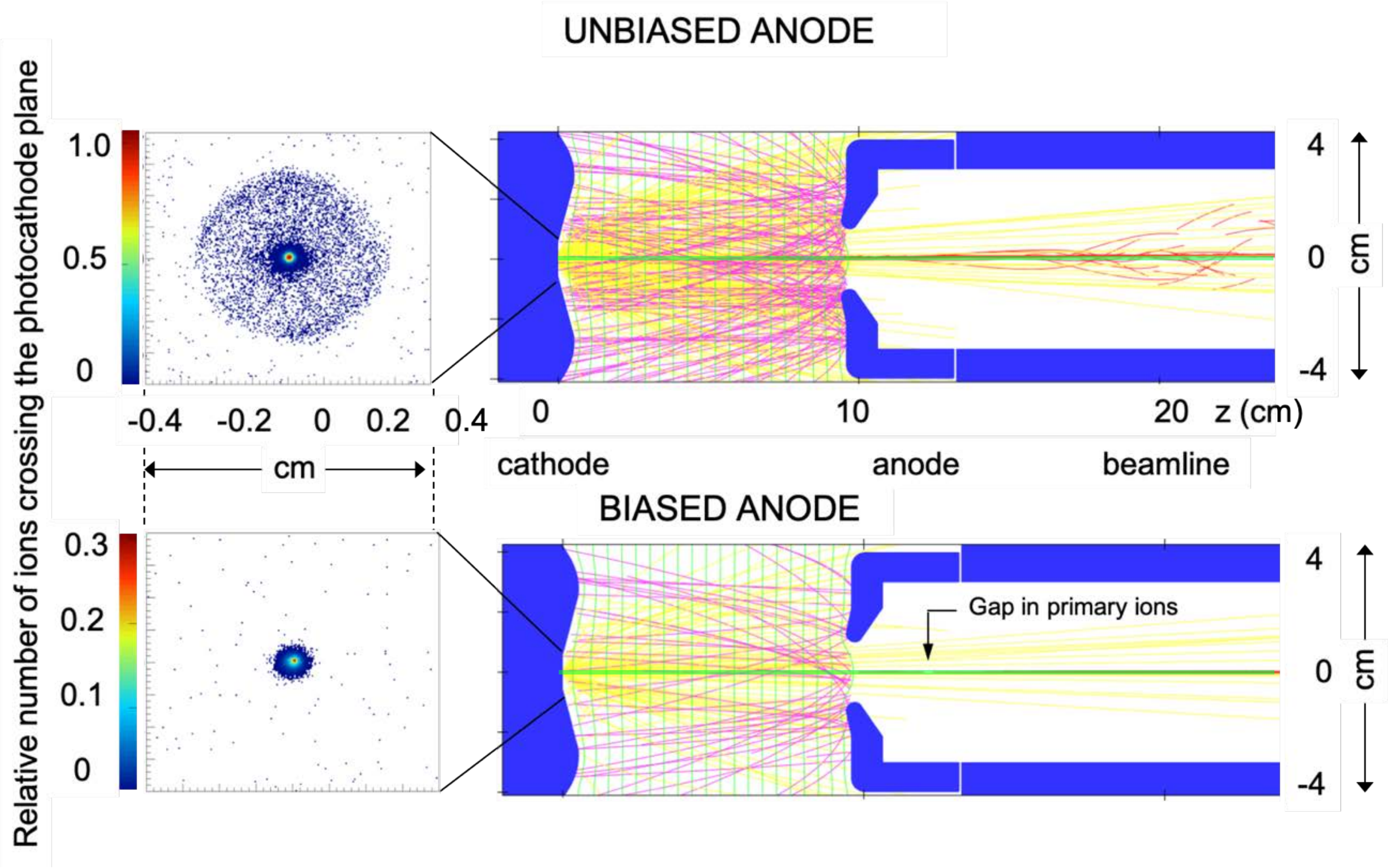
High voltage conditioning with Kr gas serves to eliminate field emission*



- The purpose of high voltage conditioning is to achieve vacuum and radiation levels indistinguishable from background at 350kV DC
- Kr gas is injected at ~10^{-5} Torr into the gun vacuum chamber during high voltage conditioning.
- Kr facilities field emitter ‘burn out’ by ion back bombarding and by increasing stainless steel work function as it is implanted at the gun electrode bias voltage

*M. BastaniNejad, A. A. Elmustafa, E. Forman, J. Clark, S. Covert, J. Grames, J. Hansknecht, C. Hernandez-Garcia, M. Poelker and R. Suleiman, “Improving the performance of stainless-steel DC high voltage photoelectron gun cathode electrodes via gas conditioning with helium or krypton”, Nucl. Instr. and Meth. in Phys. Res. A, Vol. **762**, pp. 135–141, 2014

Biasing the anode has shown improved photocathode lifetime in the CEBAF gun and was key for achieving 5 mA CW at 300 kV in the GTS gun

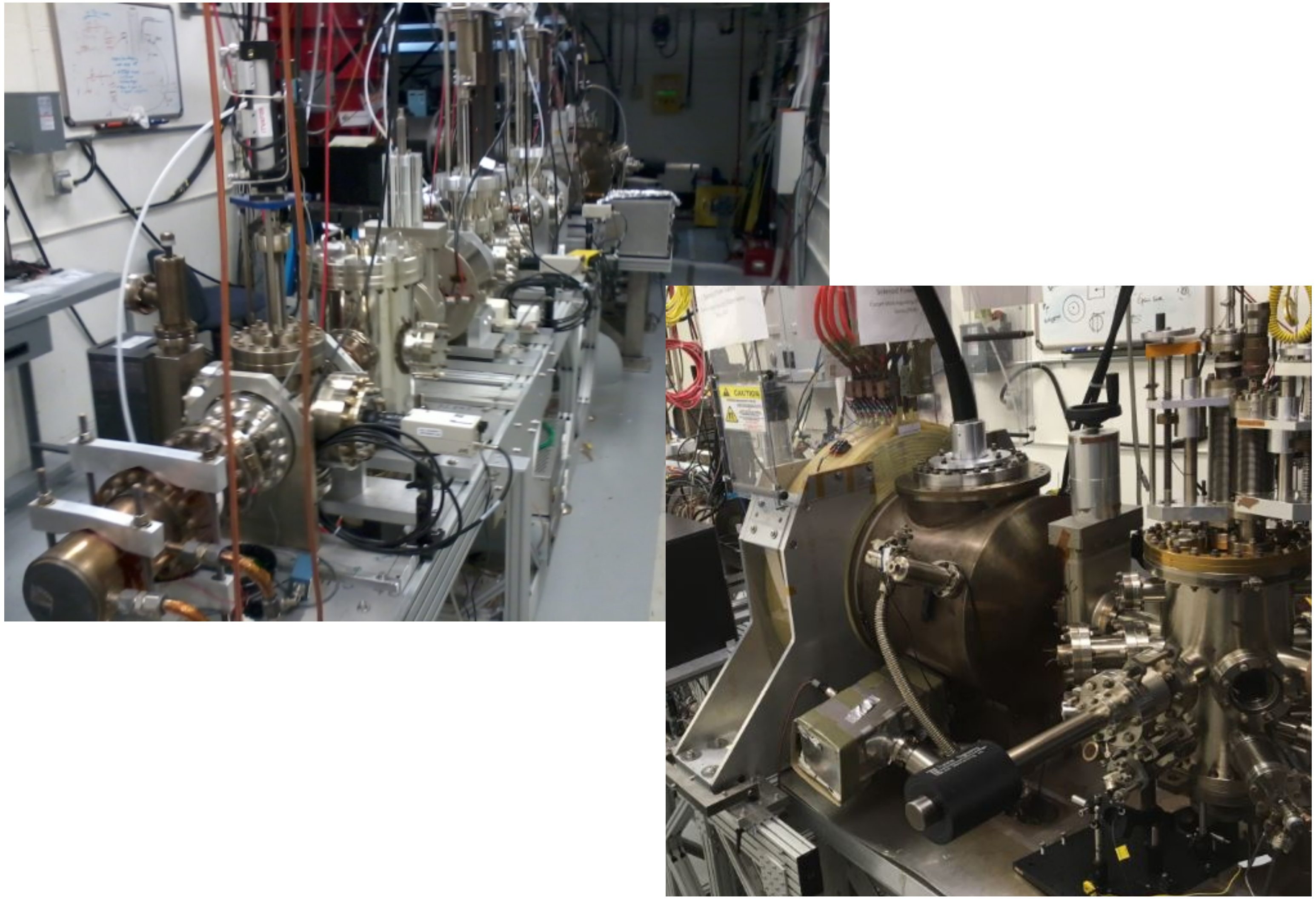


- Ions in the beamline (**red**) are attracted to the potential well formed by the electron beam (**green**)
- These trapped ions are then accelerated towards the negatively biased photocathode where they generate secondary electrons (**yellow**) upon impact which in turn strike the anode and generate secondary ions (**pink**).
- The + biased anode repels ions back to the beam line
- Ions in the anode-cathode gap still strike the photocathode

J. Grames, P. Adderley, J. Brittian, J. Clark, J. Hansknecht, D. Machie, M. Poelker, M. Stutzman, K. Surles-Law, and E. Pozdeyev, A biased anode to suppress ion back- bombardment in a dc high voltage photoelectron gun, in Proceedings of the 12th International Workshop on Polar- ized Ion Sources, Targets and Polarimetry (PSTP 2007), Upton, 2007, AIP Conf. Proc. 980, 110 (2008)

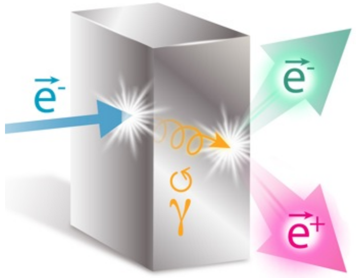
This photogun with R30 inverted insulator demonstrated over 1000 h of 300 keV beam delivery in a test beam line

- Photogun biased at −300 kV DC
- Anode biased at +1 kV VDC
- Cs_2KSb photocathode on GaAs substrate with measured *thermal emittance at 0.45 ± 0.02 mm mrad / mm*
- Drive laser was operated at 374 MHz with 22 ps rms pulse length
- The laser spot size at the photocathode was 0.04 cm rms shifted 0.25 cm off center
- Measured beam dump current 4.5 mA resulting in 12 pC bunch charge
- The 1/e QE charge lifetime for the Cs_2KSb photocathode was ~6600 C
- Gun Vacuum: 5 X 10^{-12} Torr (background) increased to 5 X 10^{-11} Torr at 4.5 mA CW



C. Hernandez-Garcia, et al., "*Compact -300 kV dc inverted insulator photogun with biased anode and alkali-antimonide photocathode*," Phys. Rec. Acc. And Beams, 22, 113401 (2019)

The quest for higher operating voltage inverted geometry insulators continues toward developing a reliable 500 kV inverted insulator – cable solution



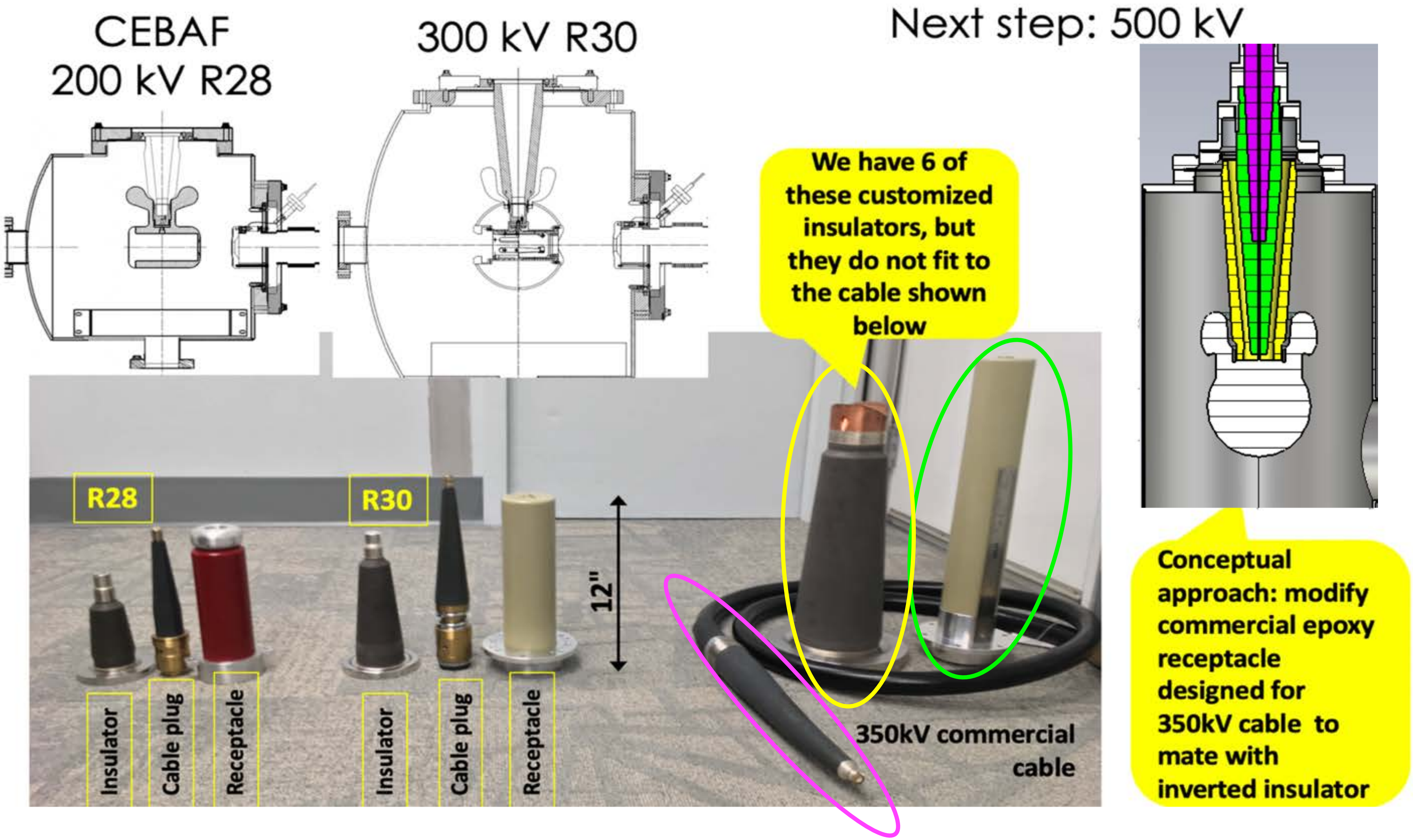
- *Motivation*: A future photogun based a 500 kV feedthrough design could then be used in a 400 kV photogun with margin for high voltage conditioning to generate ***high bunch charge spin-polarized electron or positron beams***.
  - No field emission at 400 kV!
  - ~ 1×10^{-12} Torr while delivering beam!

Physical Review Letters – Editor's Suggestion and Focus Story
Production of Highly Polarized Positrons Using Polarized Electrons at MeV Energies
D. Abbott et al. (PEPPo Collaboration), Phys. Rev. Lett. 116, 214801 – Published 27 May 2016

- There is no inverted insulator feedthrough capable of 500 kV that fits commercial cable connectors

- Commercial cable connectors are rated to ~ 400 kV max in SF_6, and have never been tested > 350 kV connected to inverted insulators in vacuum*

The proposed plan is an evolution from our experience developing and operating high voltage inverted insulator photo-guns connected to power supplies using commercial components



We have 6 of these customized insulators, but they do not fit to the cable shown below

Conceptual approach: modify commercial epoxy receptacle designed for 350kV cable to mate with inverted insulator

Summary

- HV and vacuum considerations are deeply intertwined in the overall design and ultimate performance of DC photoguns (i.e. beam properties, reliability)
- Large-bore ceramic insulator photoguns have demonstrated operations in the range of 350 to 500 kV (KEK, Cornell, BNL, JLab) and production of un-polarized electron beams up to 65 mA CW (Cornell)
- Inverted geometry ceramic insulator photoguns have provided highly polarized electron beam at 130 keV and 0.2 mA CW for nuclear physics experiments at JLab for over a decade, and have demonstrated up to 300 keV and 5 mA CW un-polarized beam
- But achieving 200-300 kV operations w/o field emission in inverted insulators photoguns is still challenging
- The quest for higher operating voltage inverted insulator photoguns required by high bunch charge high polarization applications is an arduous journey, but significant progress has been made over the past two decades at several laboratories such as BNL and JLab.