350 kV Photoelectron Gun with Inverted-Insulator Geometry

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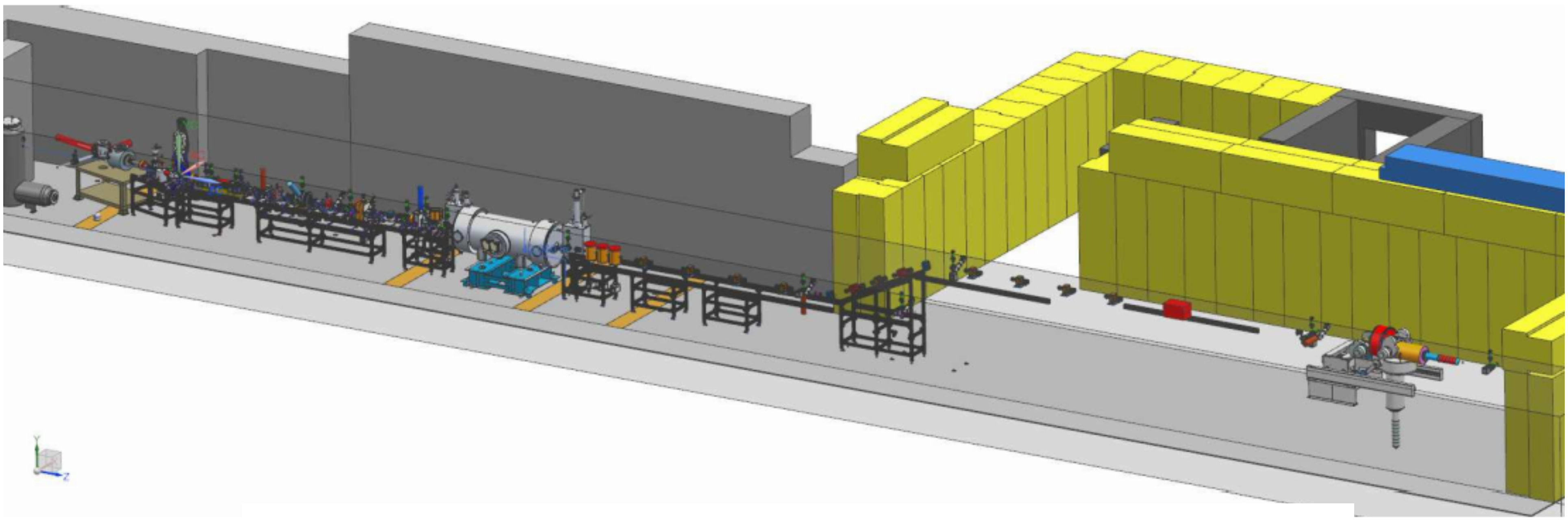
Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

COOL'15 Workshop, Jefferson Lab, September 28 – October 2, 2015

A New Photogun for New Initiatives

- Compact 10 MeV accelerator to commission new hardware destined for CEBAF
  - Polarized target for Hall B - HDIce
  - New SRF capture section for injector
  - Test bed to improve beam quality for demanding parity-violation experiments
- Load-locked gun for JLab's FEL/ERL for DarkLight and other experiments
  - DC high voltage gun, but with CsK_2Sb photocathode
- Electron Ion Collider (MEIC, eRHIC, LHeC)
  - High average current polarized beams and very high current un-polarized beams for cooling proton beams
  - Magnetized beam

350kV inverted gun + chopper + buncher + “traditional” JLab ¼ cryomodule

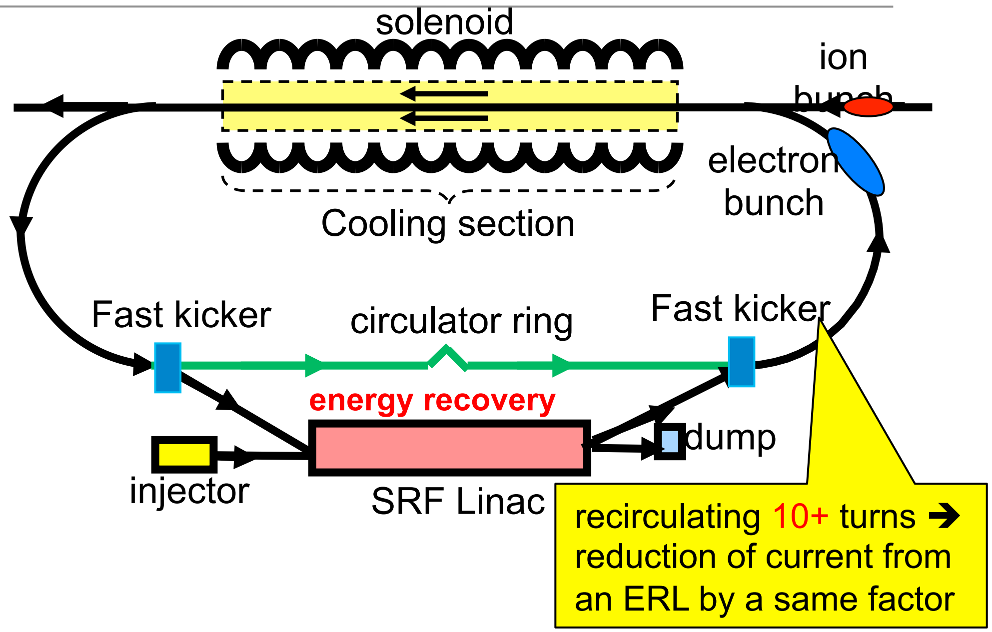


10 MeV beam to commission HDIce

ERL Circulator Cooler Concept

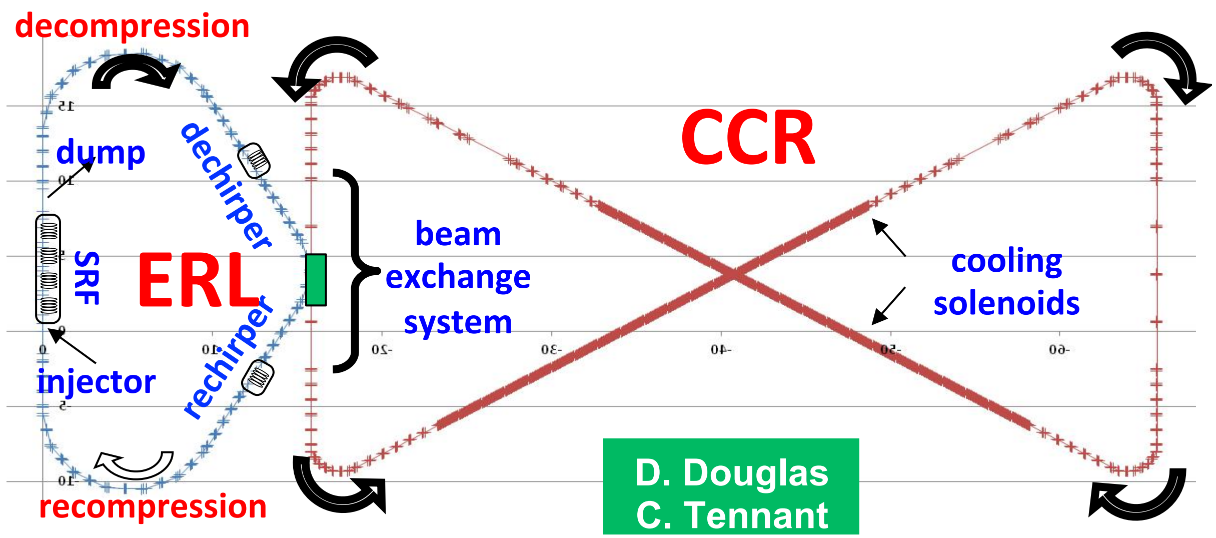
Design Choices

- Energy Recovery Linac (ERL)
- Compact circulator ring to meet design challenges
- Large RF power, up to 81 MW
- Very high electron beam current: 1.5 A



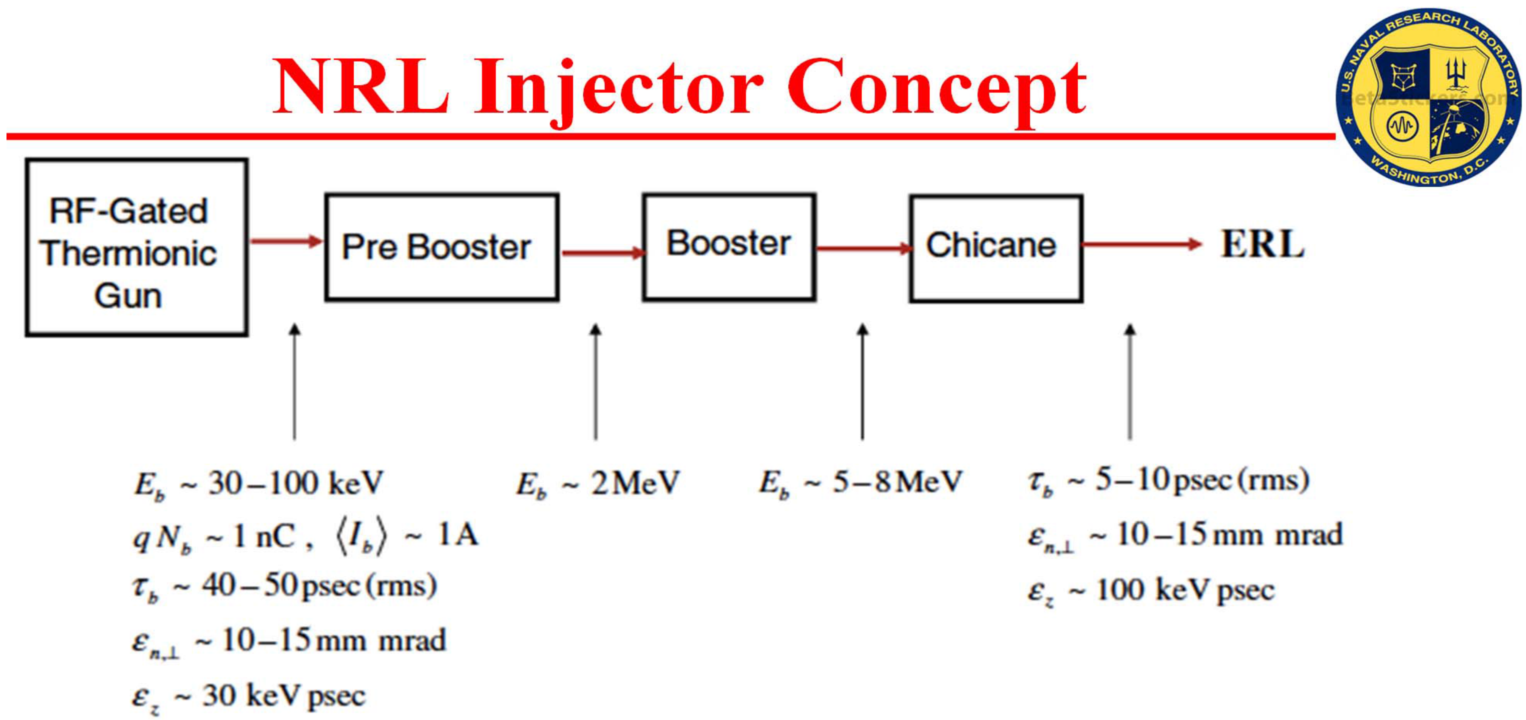
Required technologies

- High current ERL (55 MeV, 15 to150 mA)
- Magnetized beam
- High bunch charge (2 nC)
- Ultra fast kicker



Proposed by S. Derbenev

AES gridded thermionic cathode in RF gun



Alan Todd, AES, presented at ERL 11 Workshop, Tsukuba, Japan

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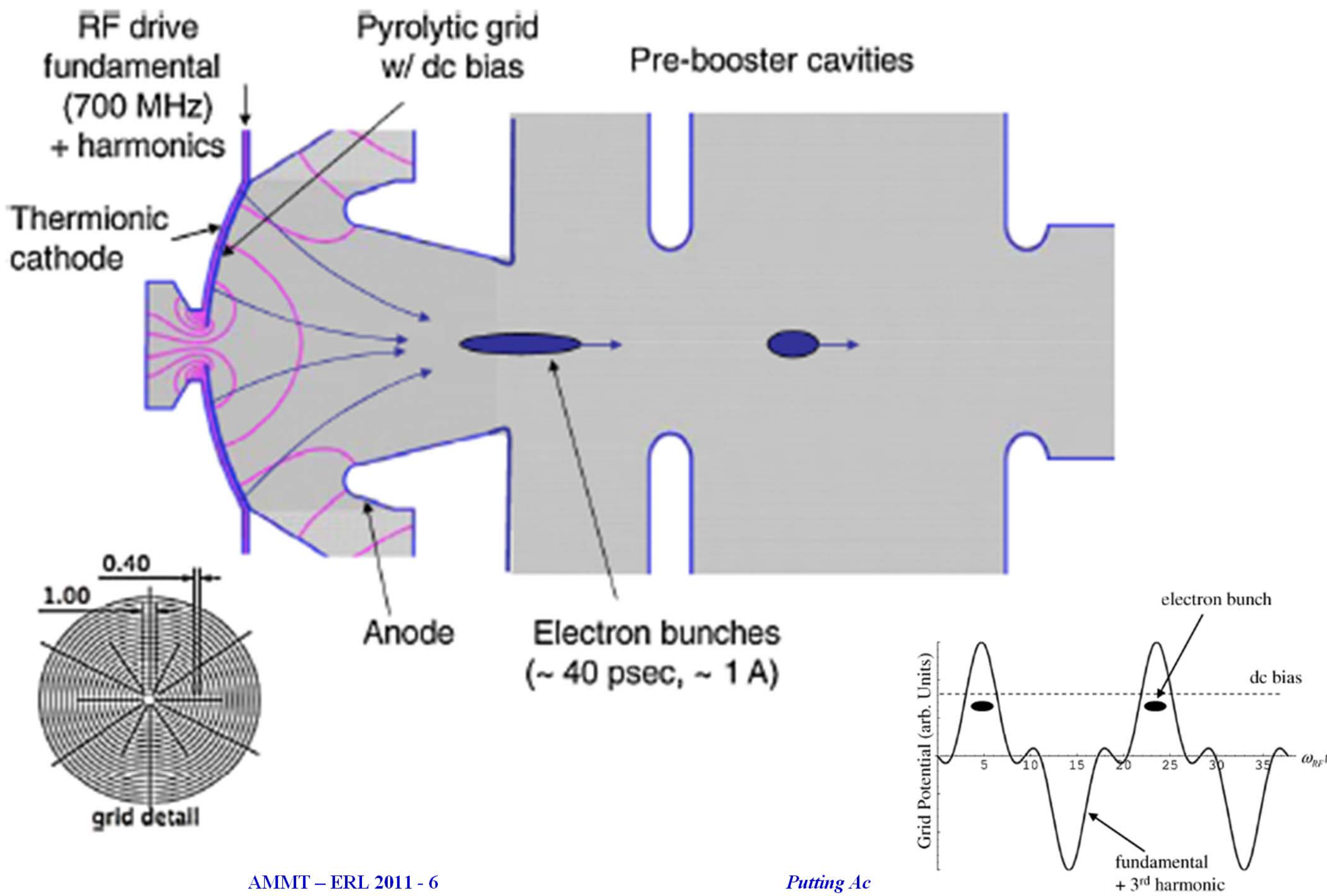

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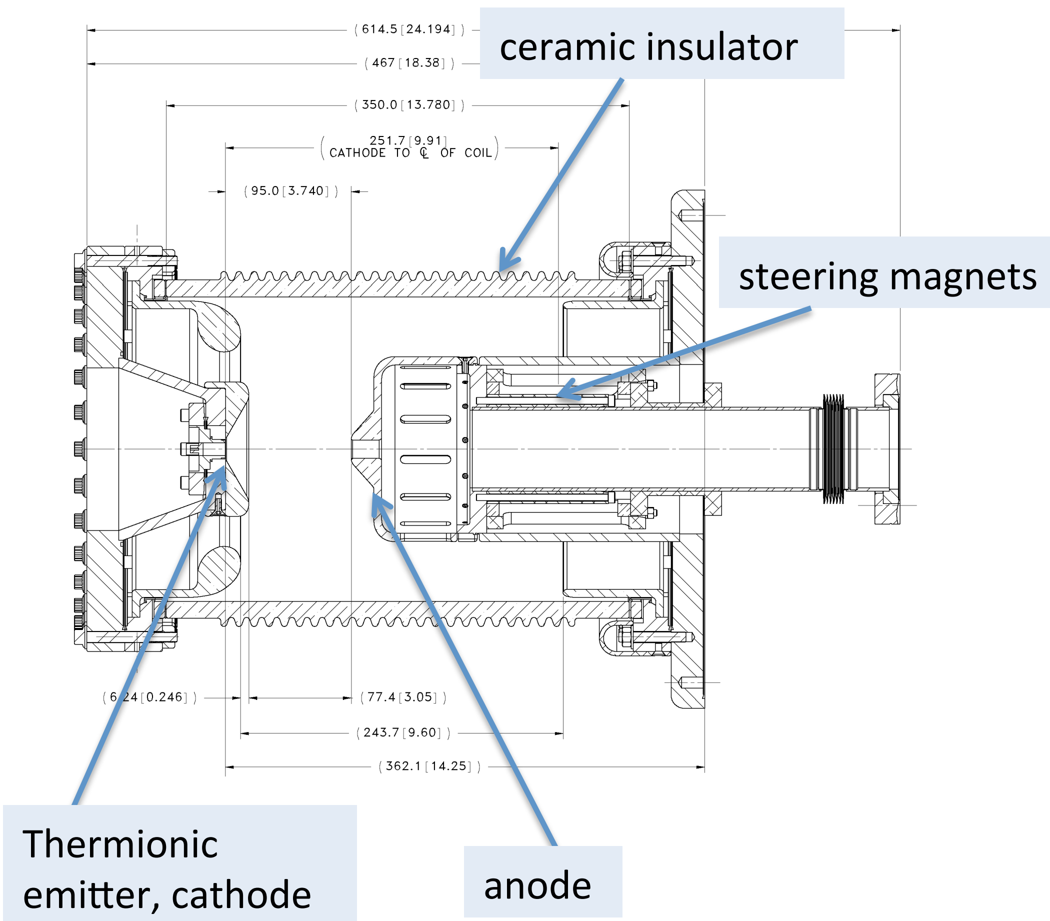
TRIUMF ARIEL rf modulated thermionic gun

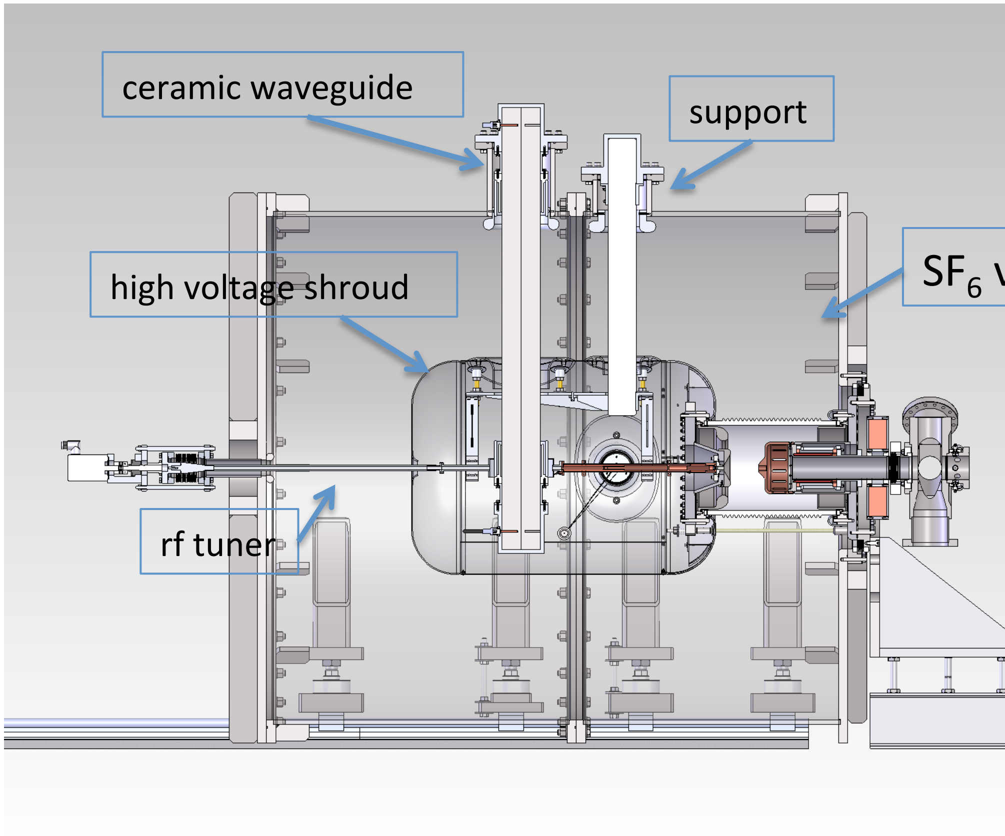


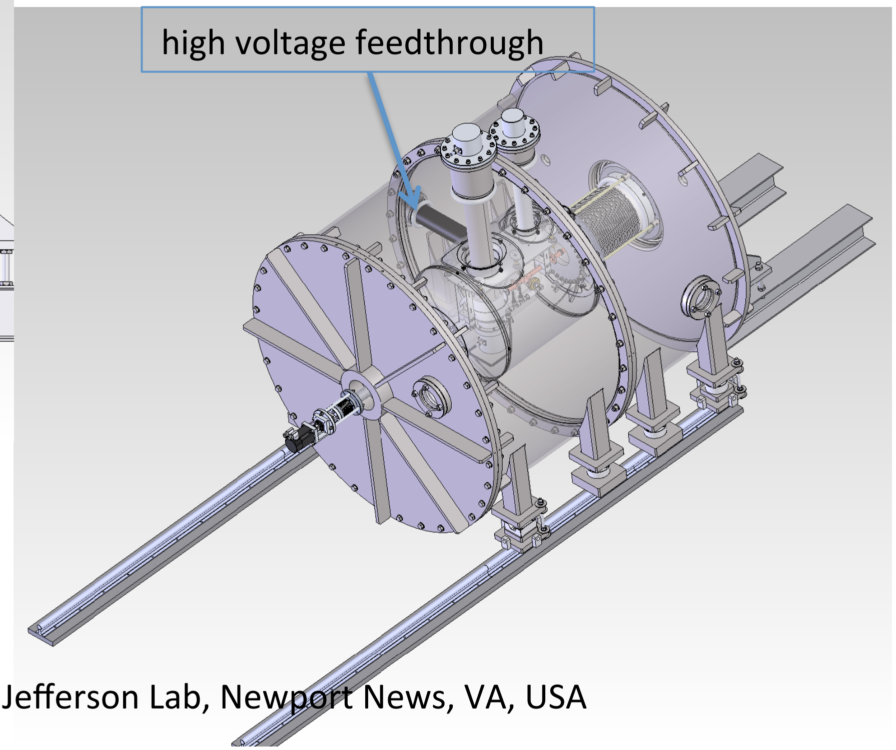
- rf modulation frequency **650** MHz,
- pulse length +/- **16º** (137 ps).
- average current **10** mA
- charge / bunch **15.4** pC
- kinetic energy **300** keV
- normalized transverse emittance ~**5** µm
- duty factor for macro pulsing **0.1-100**% (3 W-3 kW)

→ thermionic source with rf-modulation applied to grid

Friedhelm Ames, TRIUMF , presented at EIC14, March 17-21, Jefferson Lab, Newport News, VA, USA

TRIUMF ARIEL rf-modulated thermionic gun





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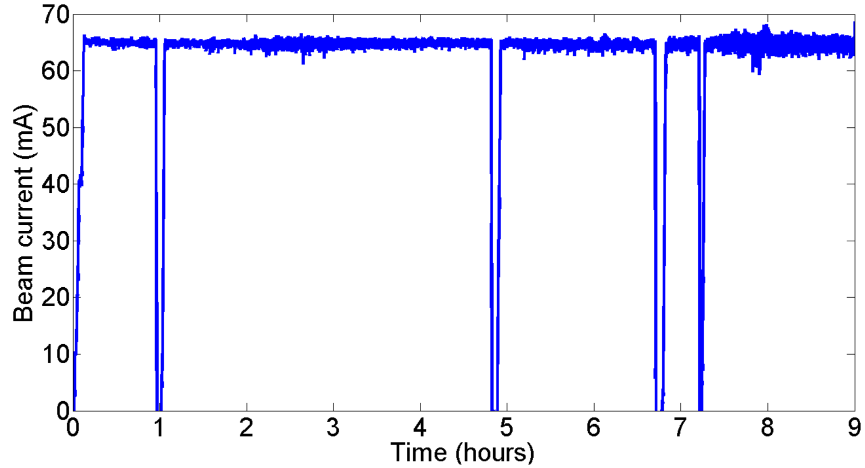
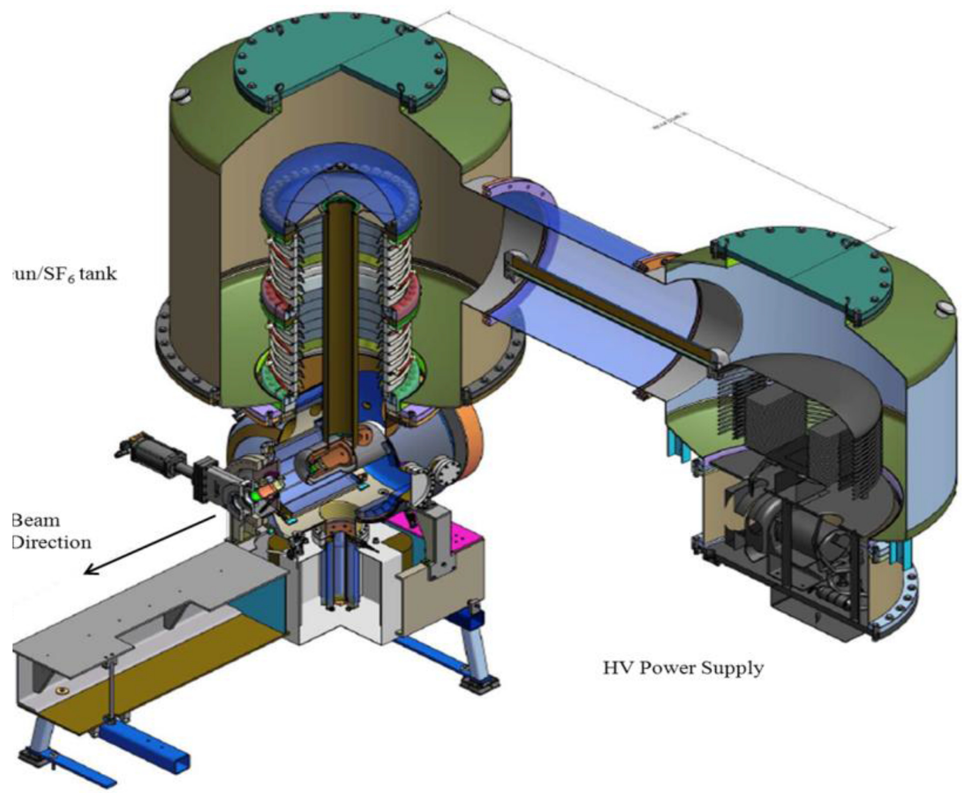
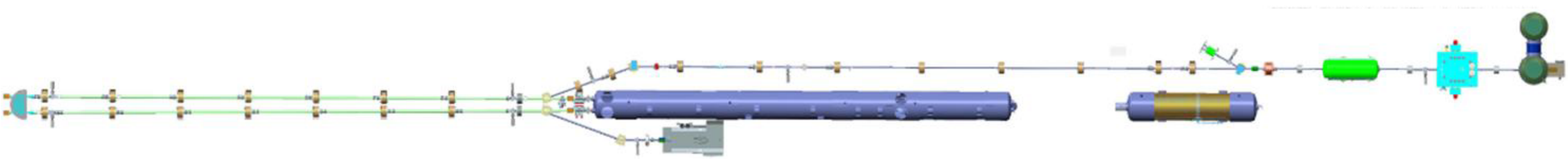
Low-Energy RHIC electron Cooling (LEReC)



- Peak current of 75mA (world record)
- NaKSb photocathode
- 2.6 day 1/e lifetime at 65mA
- 8h at 65mA
- With only 5W laser power
- now pushing to 100mA

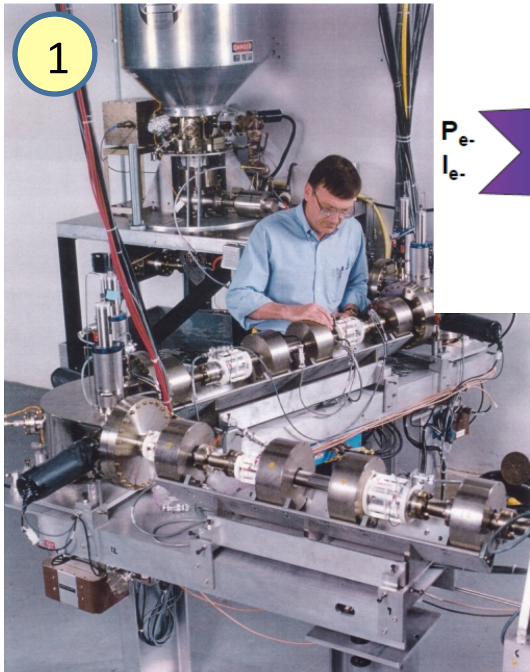
Cornell DC high voltage photogun

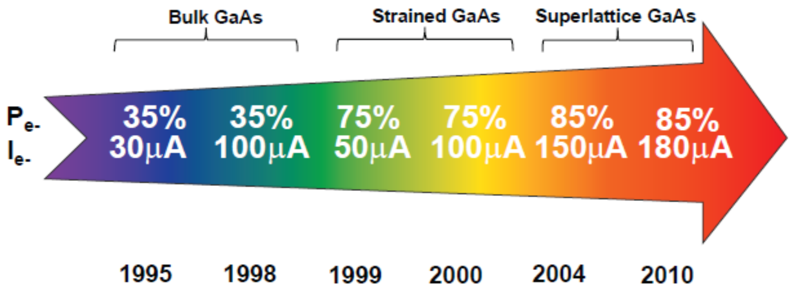




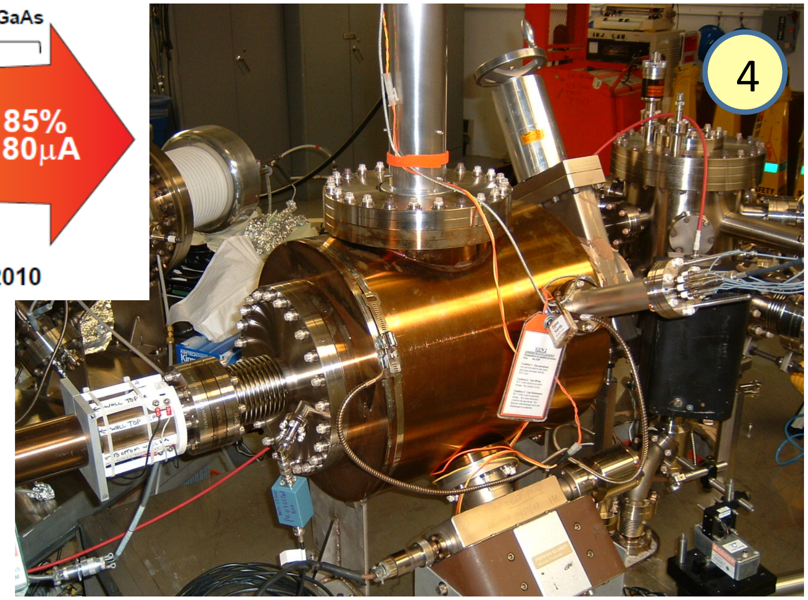
Slide courtesy Georg Hoffstaetter and Bruce Dunham

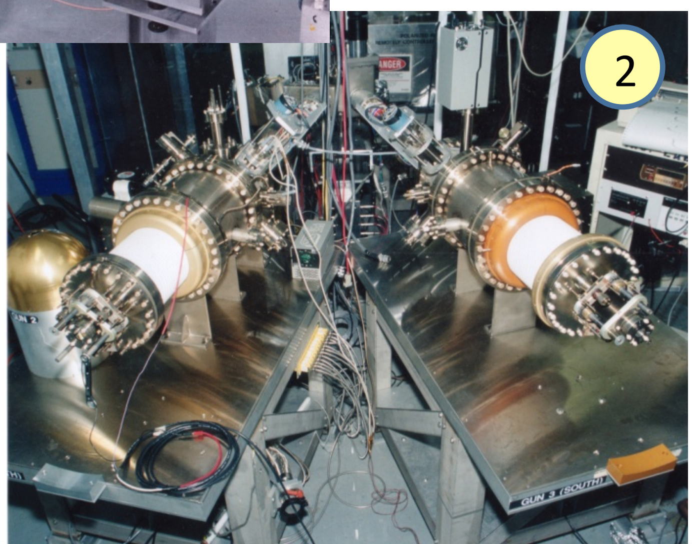
Always Tweaking the Design

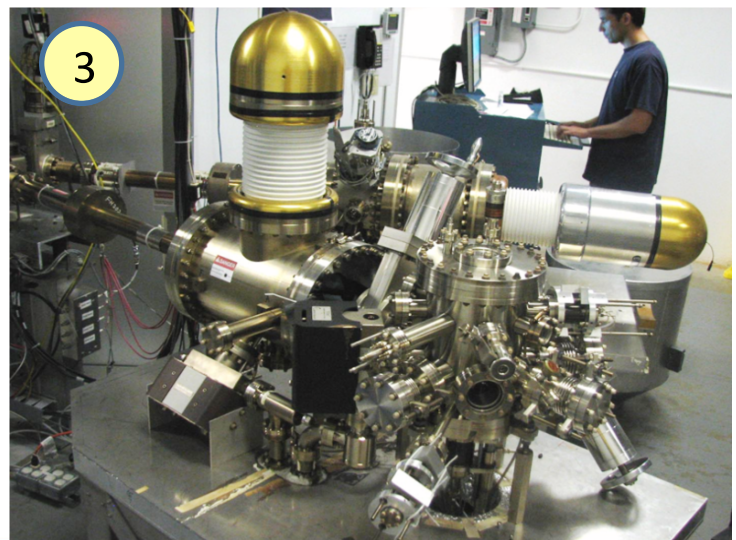




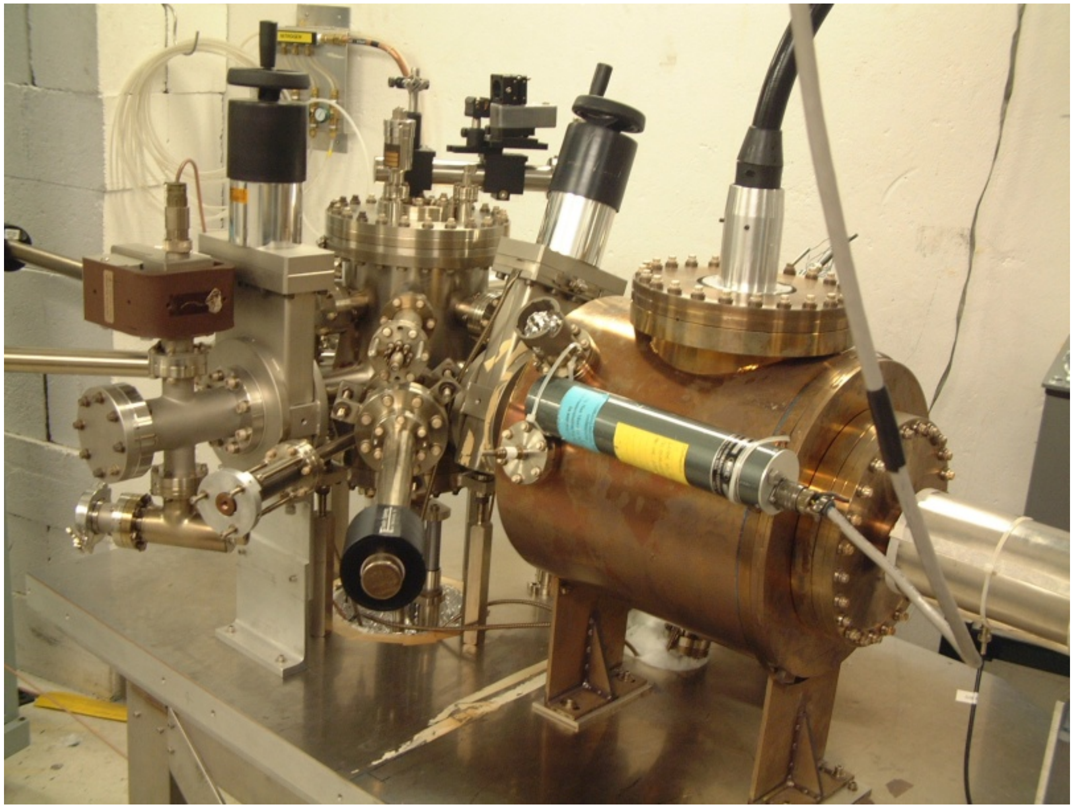
Endless (?) quest for perfection

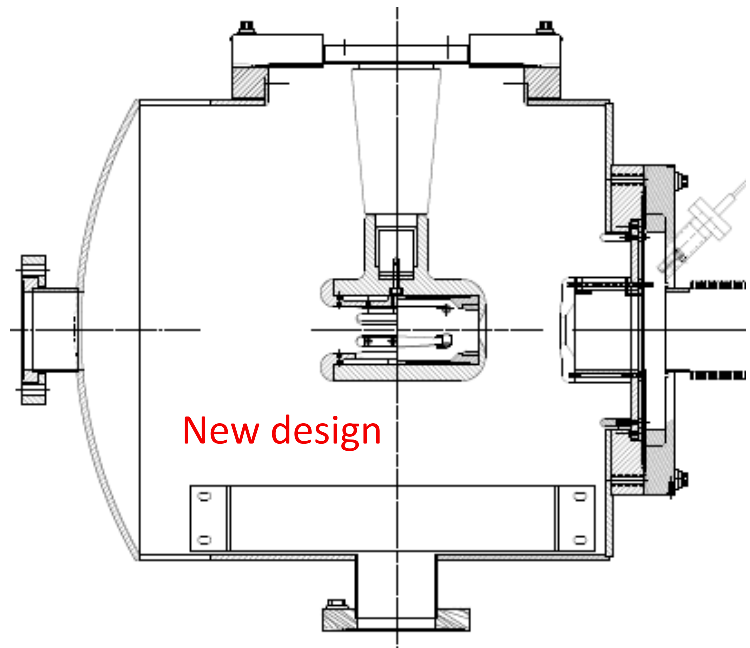






The CEBAF - ILC 200kV Inverted Gun

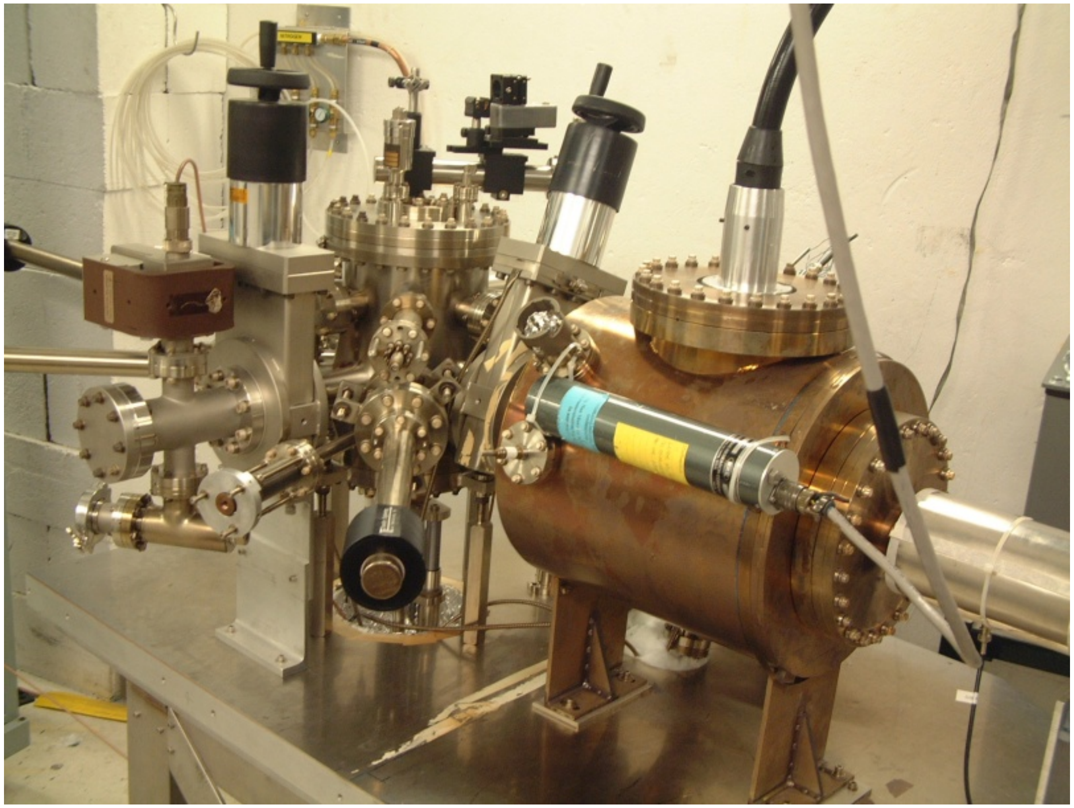


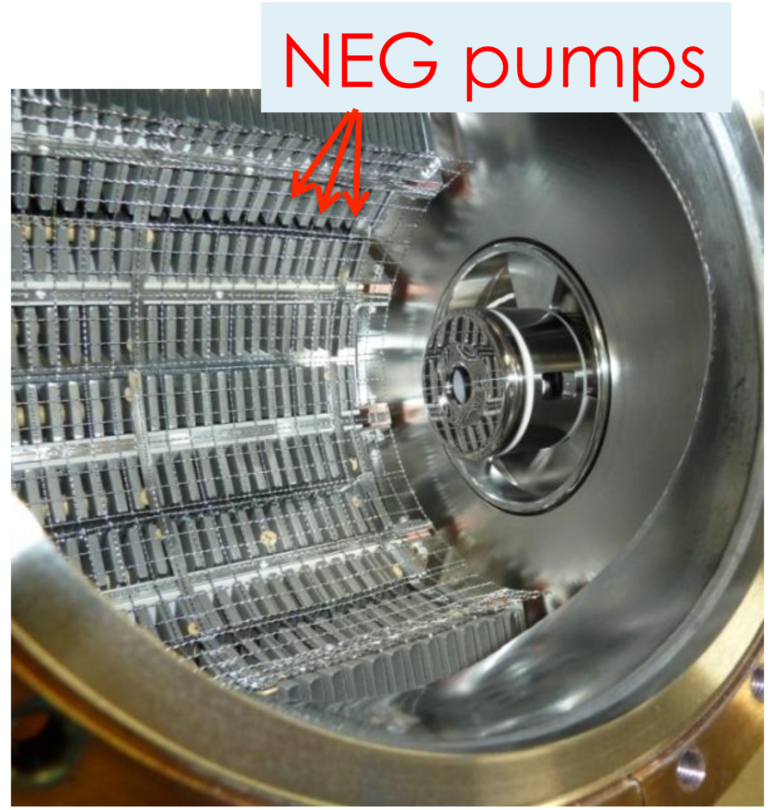


Our "Load-locked" GaAs photogun:

- Gun Vacuum ~ mid to low 10^{-12} Torr
- Beamline vacuum could be improved…

The CEBAF - ILC 200kV Inverted Gun





Our "Load-locked" GaAs photogun:
- Gun Vacuum ~ mid to low 10^{-12} Torr
- Beamline vacuum could be improved…

Benefits of Higher Gun Voltage

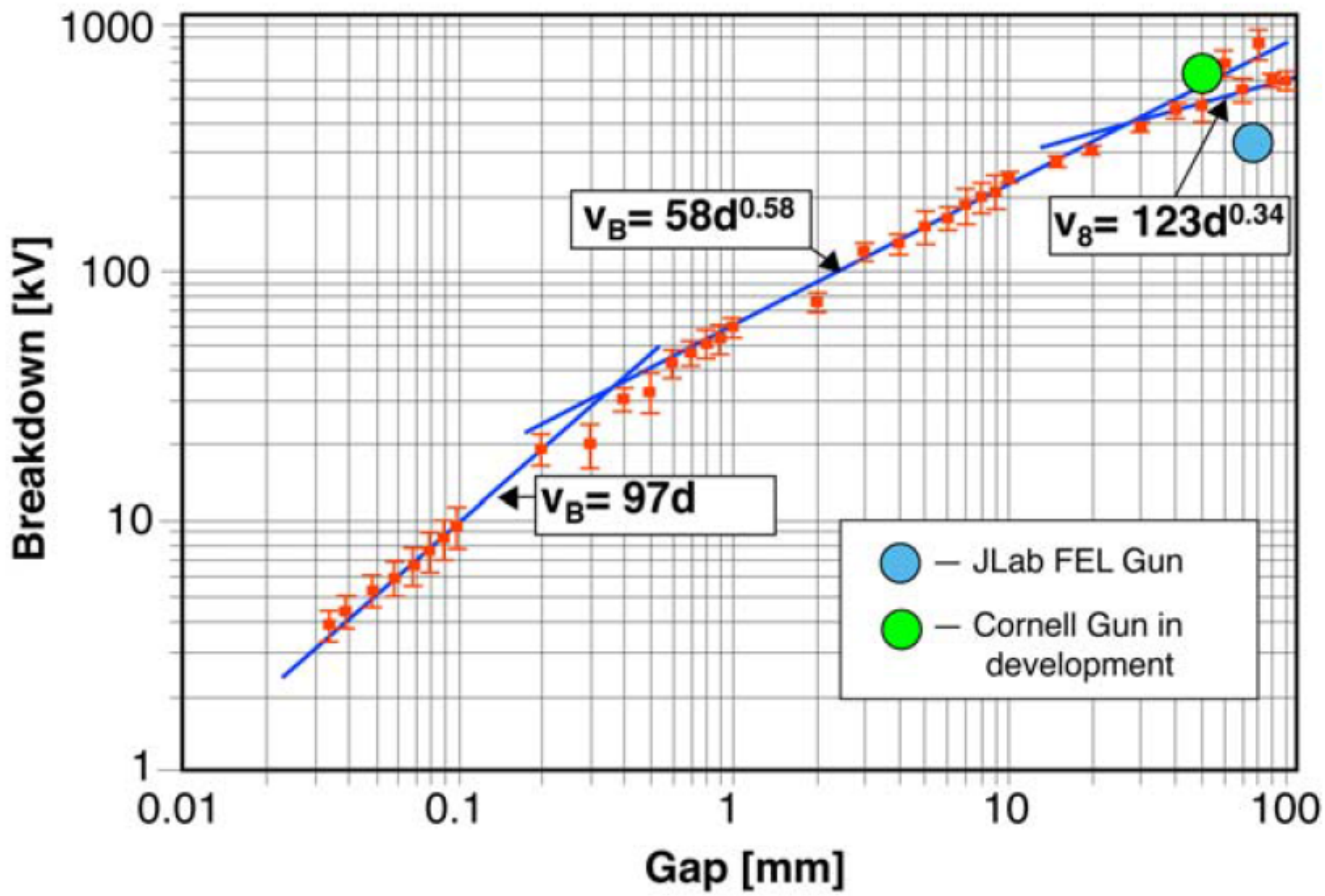
I. Reduce space-charge-induced emittance growth, maintain small transverse beam profile and short bunch-length. In other words, make a "stiff" beam right from the gun
II. Reduce problems associated with Surface Charge Limit (*i.e.*, QE reduction at high laser power)
III. Prolong Charge Lifetime (?)
IV. Compact, less-complicated and less-expensive injector

Biggest Obstacle: Field Emission and HV Breakdown… which lead to bad vacuum and photocathode death

Field Emission

- Sources of Field Emission: micro-protrusions, contamination on surface, material defects and impurities, ionization of desorbed gas, etc.,
- Material choices: hardness, work function, grain structures and grain boundaries, electrical conductivity, thermal conductivity
- Surfaces: generally people assume smooth is better than coarse, although experiments indicate smooth does not guarantee "good"
- Mostly, people assume 5 MV/m is "easy" - we want to operate at 10 MV/m or higher

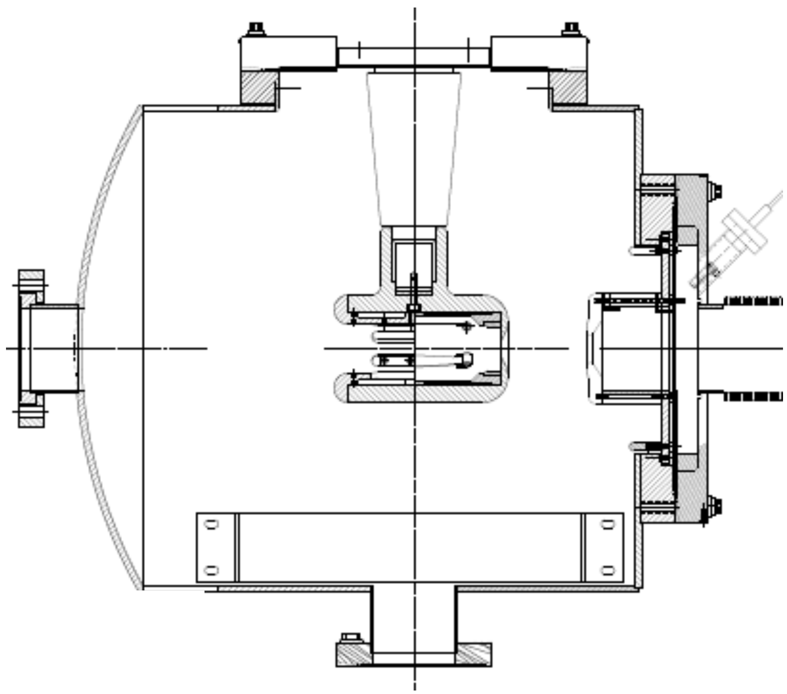
Breakdown in Vacuum



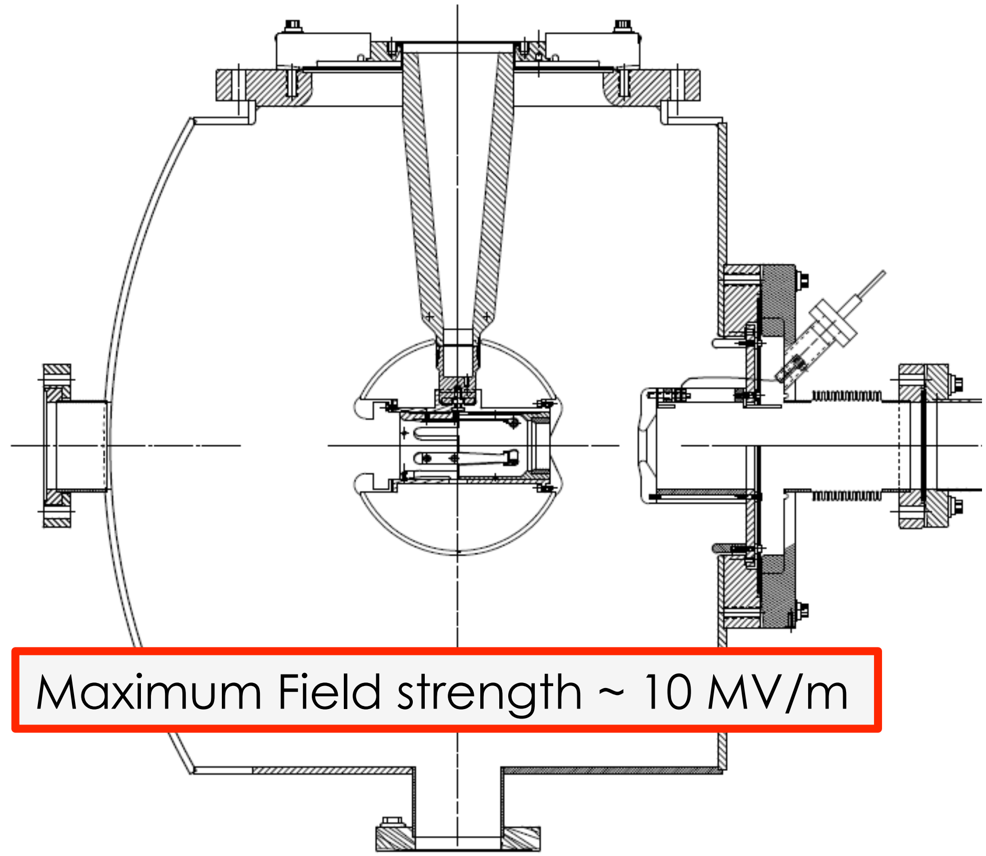
From Paul G. Slade

Figure 7: High voltage holdoff versus vacuum gap dimension.

350 kV PHOTOGUN



CEBAF 200kV
Inverted Gun
"R28" insulator

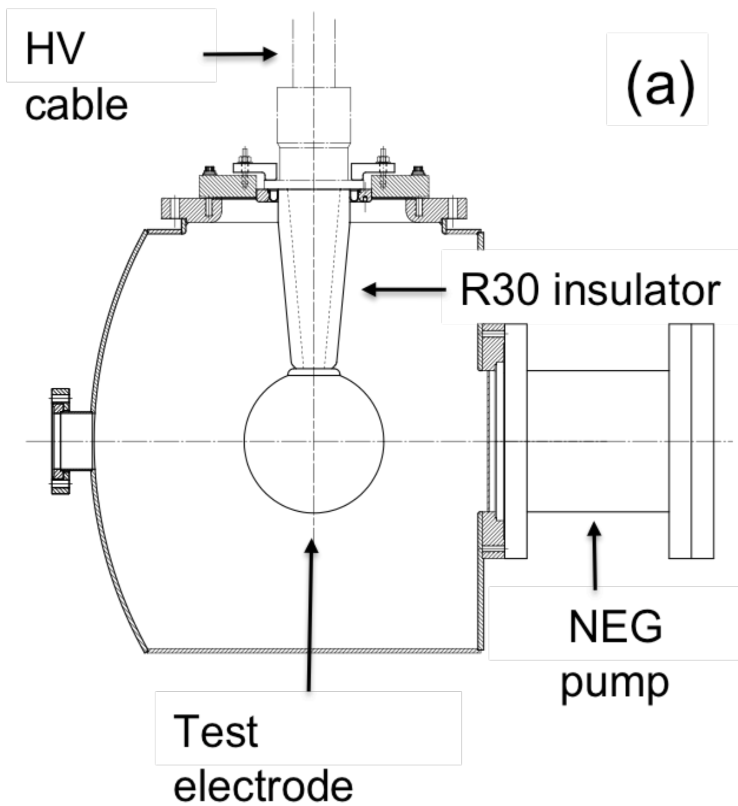


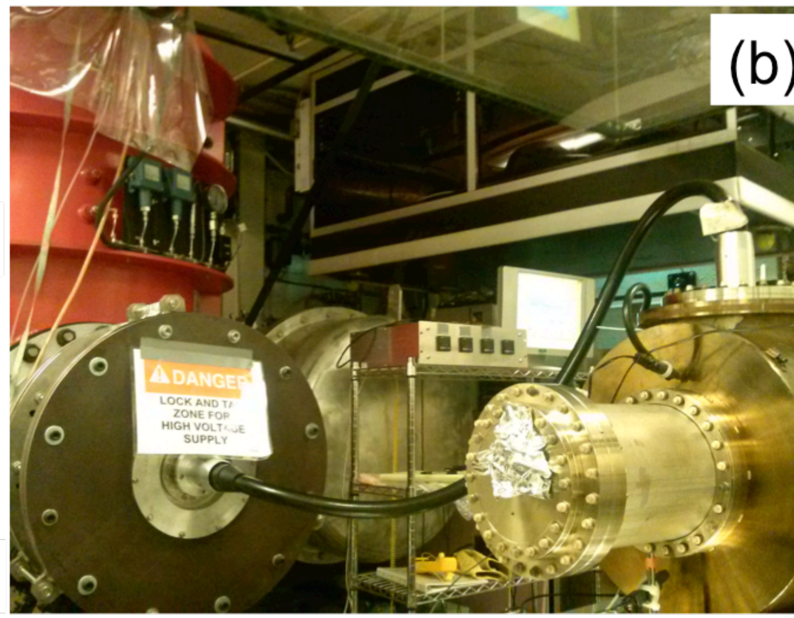
- Longer "R30" insulator
- Spherical electrode
- Thin NEG sheet - move ground plane further away

Slide 16

Building the 350 kV Gun

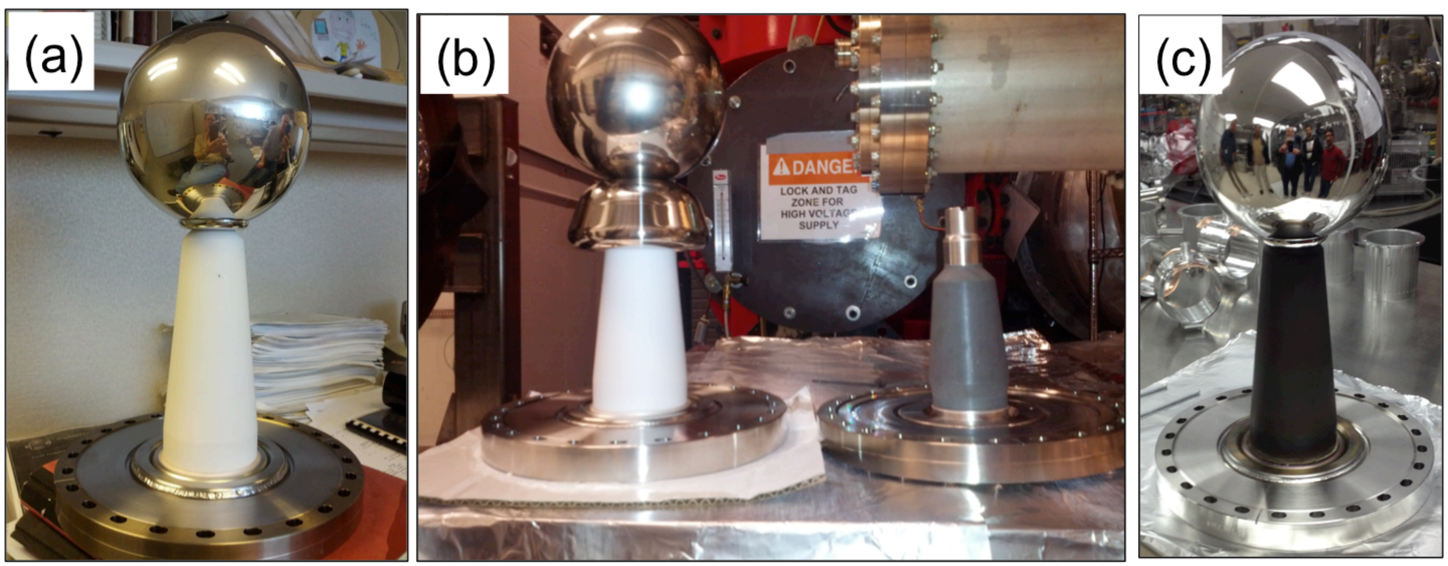
- Start with "dummy" electrodes and test different insulators and cathode screening electrode





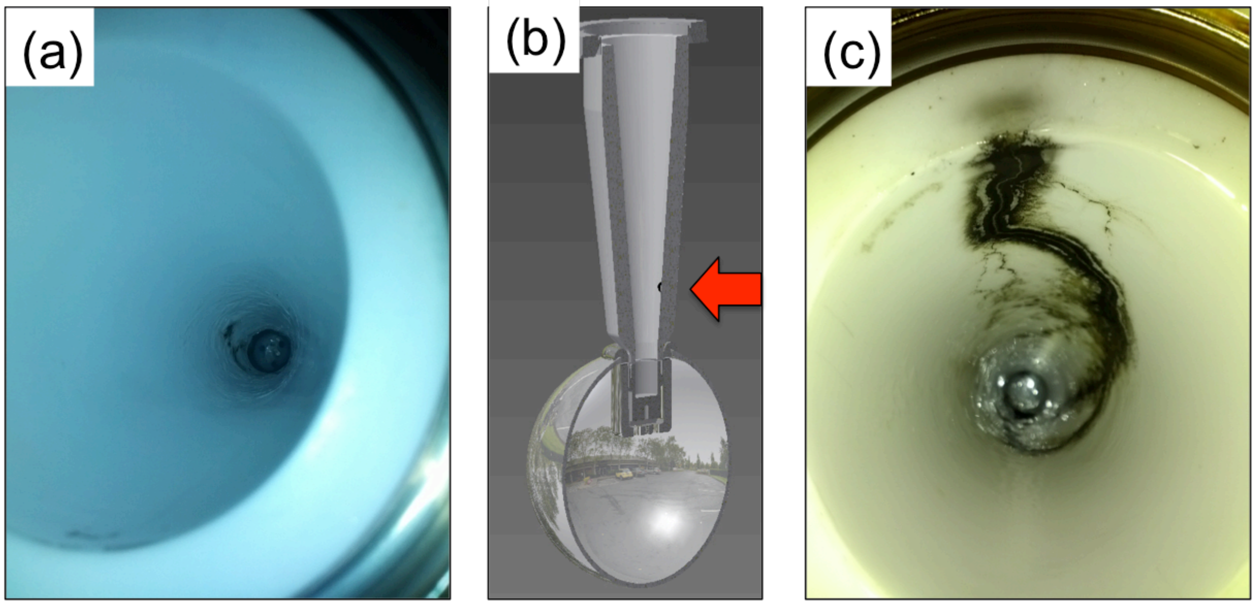
INSULATORS AND SCREENING ELECTRODE

- Longer R30 insulators, conventional alumina
- Short R28 insulator, bulk resistivity, mildly conductive
- Longer R30 insulator, bulk resistivity, mildly conductive
- ZrO-coated R30 insulator, also mildly conductive
- dummy electrode with a screening electrode (shed)



Breakdown at Cable/Insulator Interface

- Problems at the cable junction, atmosphere side



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

SUMMARY OF TESTS

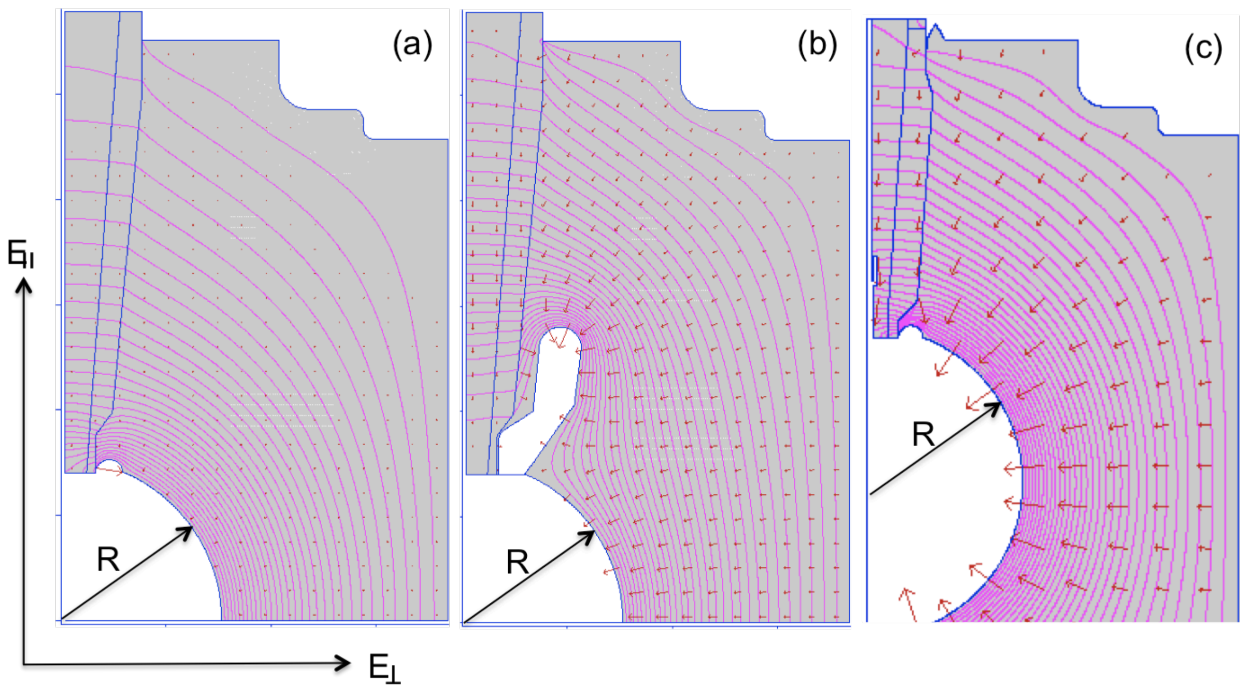
- Two and 1/2 configurations reached our voltage goal

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

Work of Carlos Hernandez-Garcia and the “team”

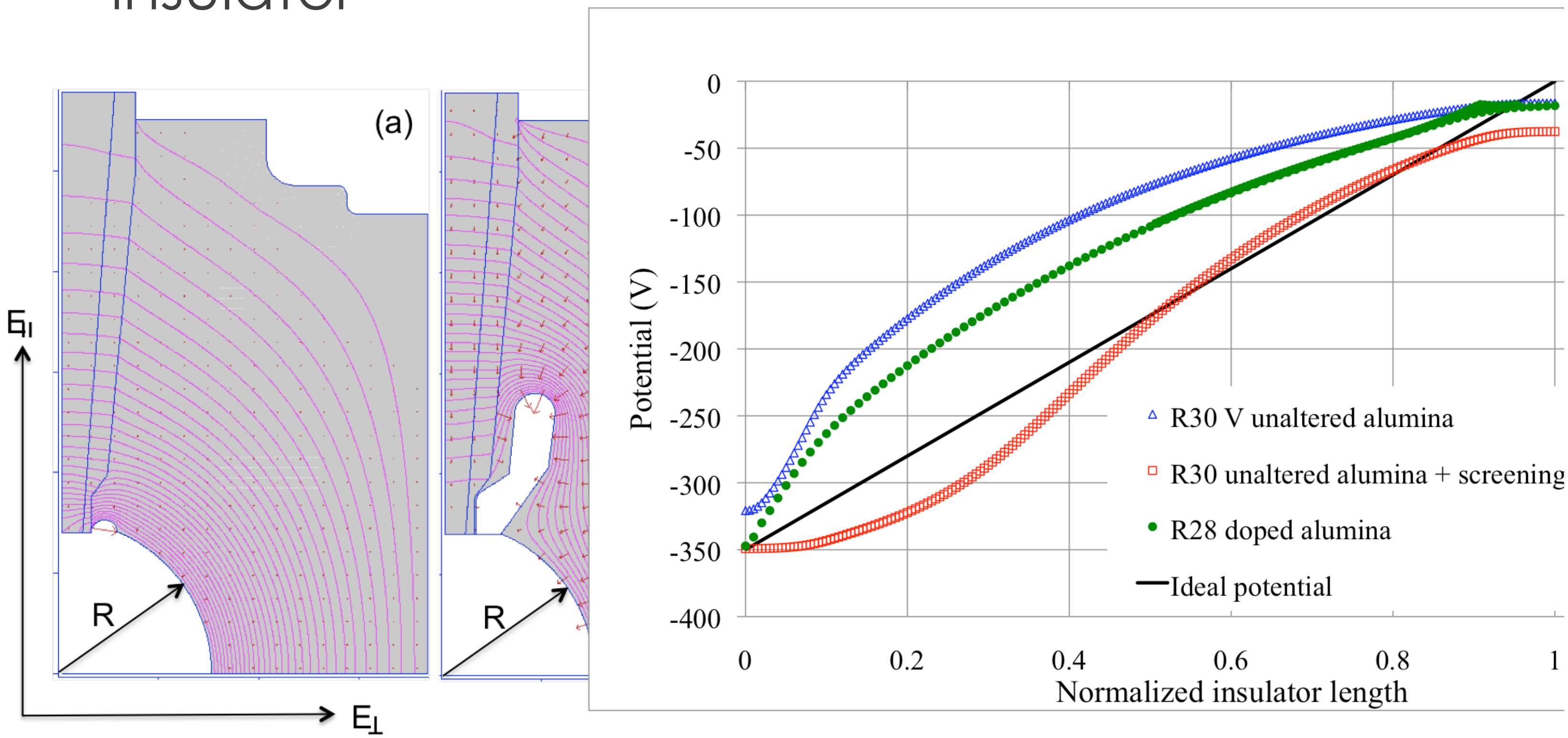
LINEAR POTENTIAL DROP

- Want a linear potential gradient along length of the insulator



Linear Potential Drop

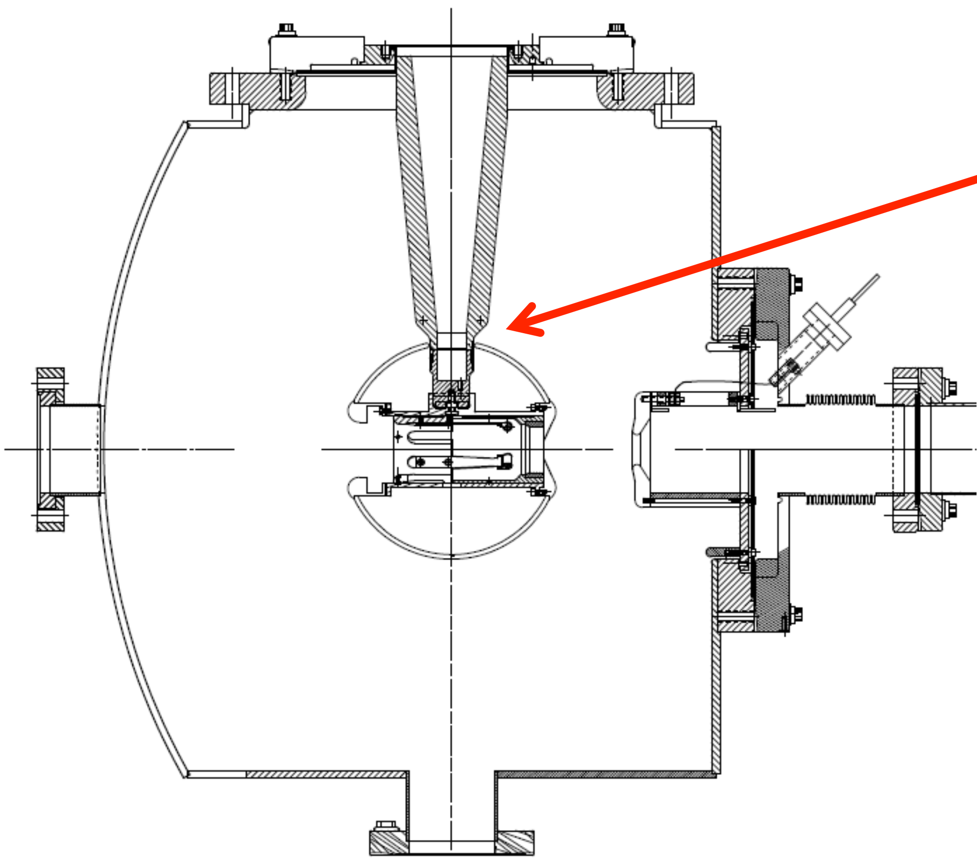
- Want a linear potential gradient along length of the insulator

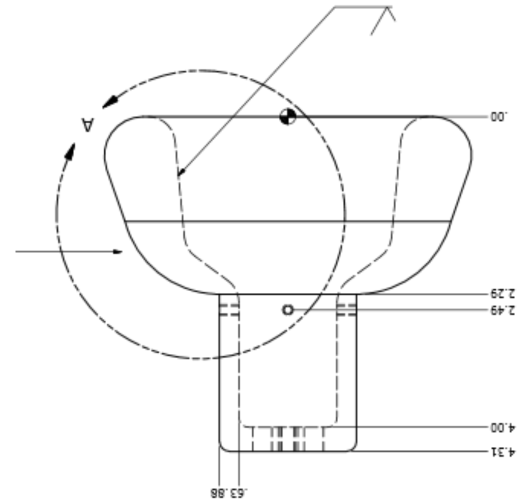


- Note - POISSON does not accurately model the mildly-conductive feature of the black insulator

Work of Carlos Hernandez-Garcia

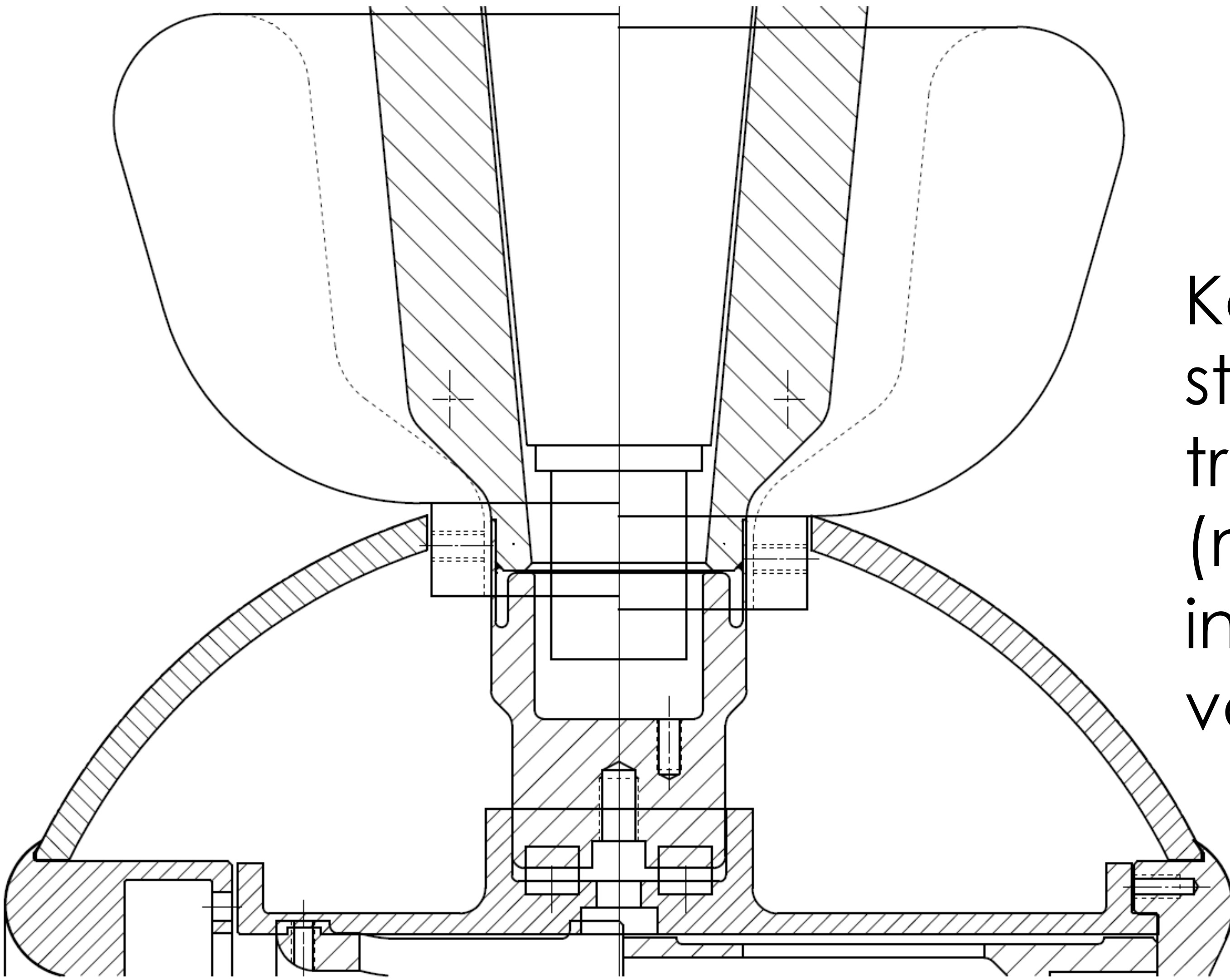
- Plan Y: Combine the two features that provided incremental success: screening electrode and doped black R30 insulator





- Replace dummy ball with electrode that can hold photocathode

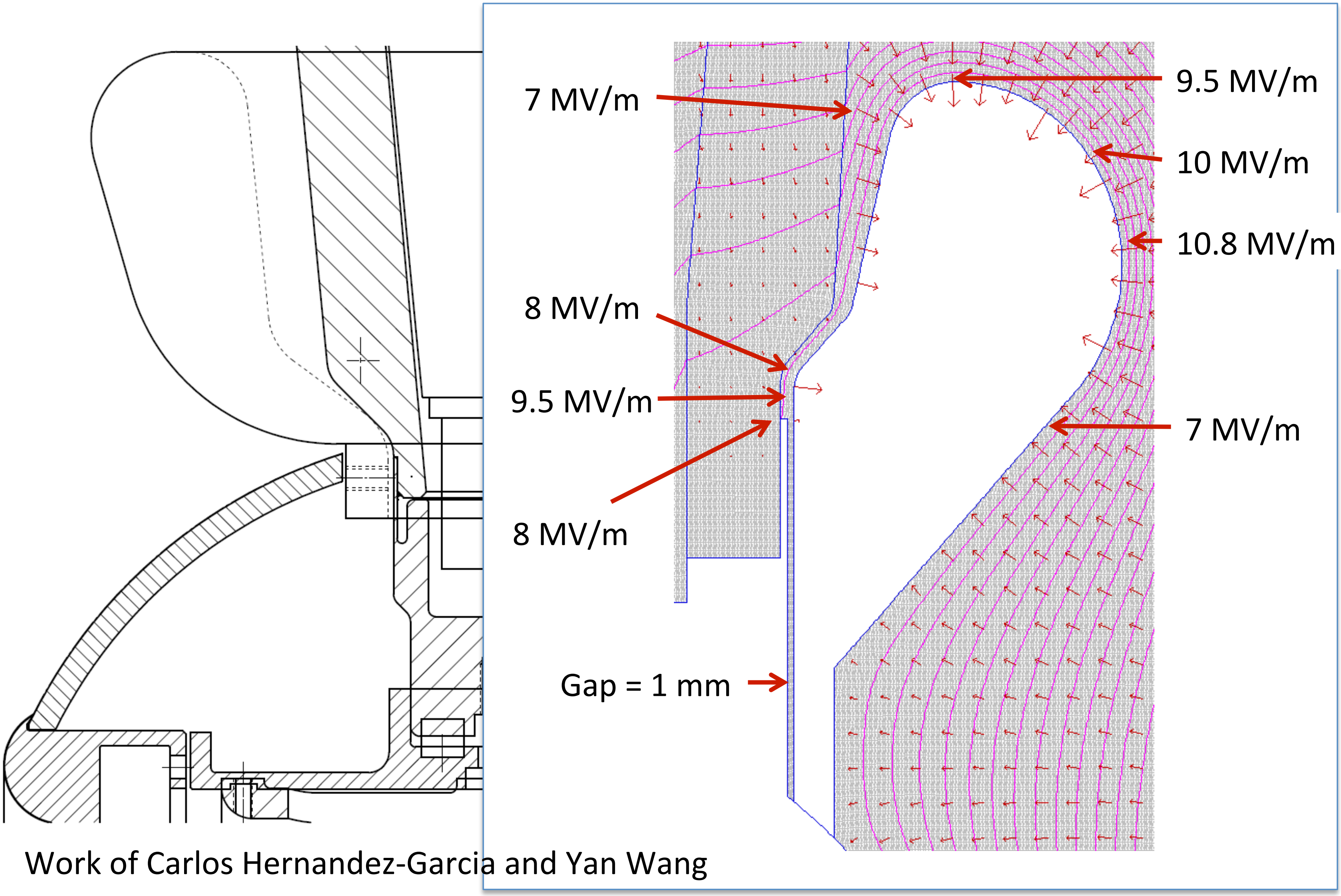
The gap between shed and insulator



Keep field strength low at triple point (metal, insulator, vacuum)

Work of Carlos Hernandez-Garcia and Yan Wang

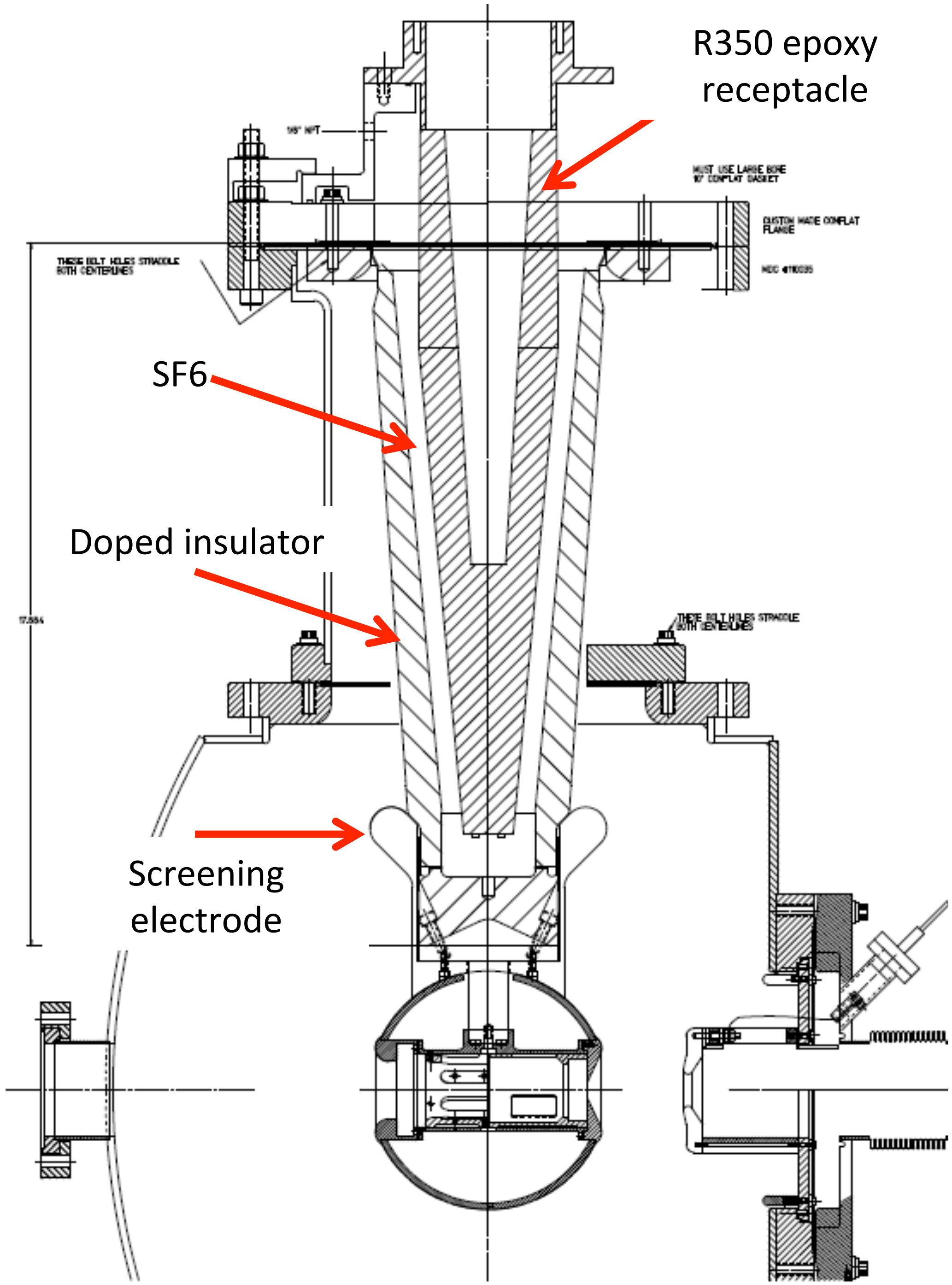
The gap between shed and insulator



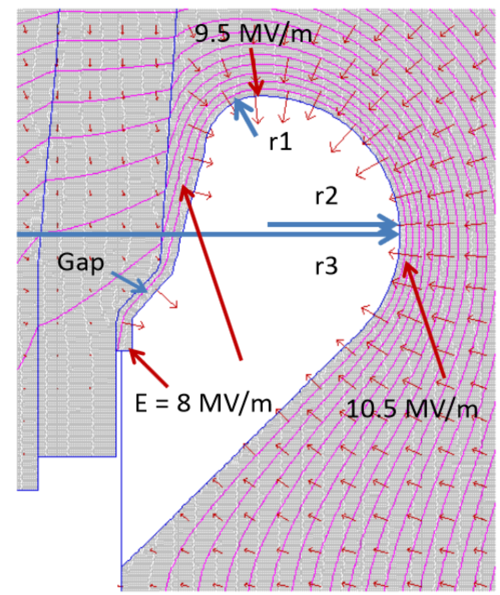
Work of Carlos Hernandez-Garcia and Yan Wang

Plan Z

- Combination of doped insulator and shed, SF6 and epoxy receptacle, plus added length
- the screening electrode, a good design…



- r1 = 1 cm
- r2 = 2.5 cm
- r3 = 9.5 cm
- 3 mm gap

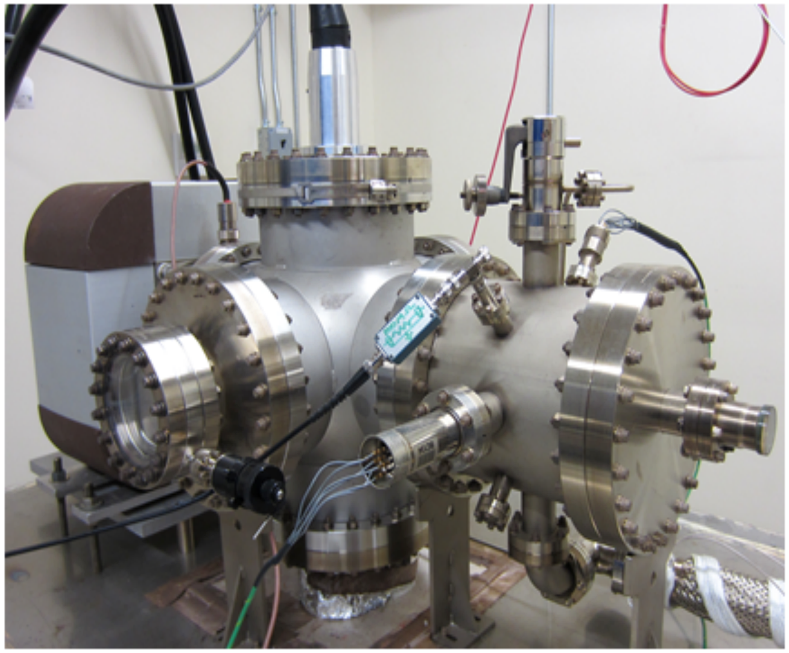


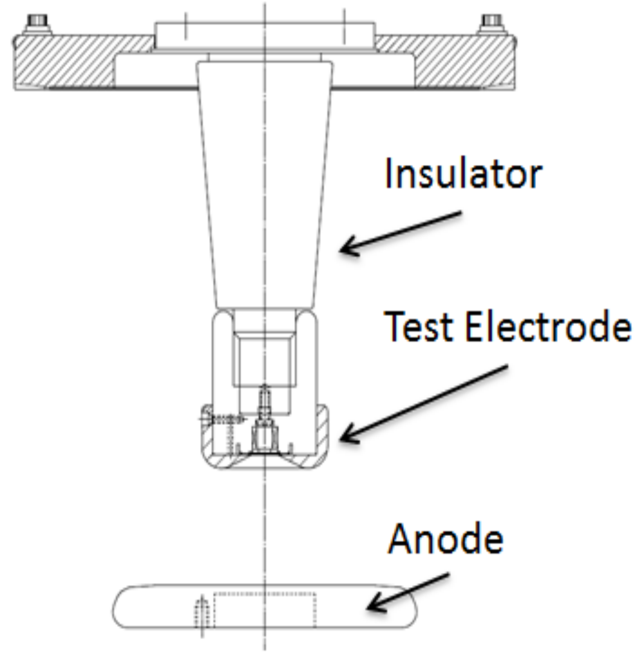
Work of Yan Wang

Field Emission: Things we've been Studying

- Fowler-Nordheim Theory: a good place to start, but it will disappoint …
- Diamond-paste polished stainless steel
  - Is it necessary to have such a smooth surface?
- Gas conditioning: an essential tool
- Electropolished stainless steel: speed the process?
- Barrel-polished stainless steel: another option
- BCP-d niobium: expensive
- TiN-coated aluminum: promising…
- 900 $^{\circ}$C degas, CO_2 snow, high pressure rinsing…

Field Emission Test Stand





- Spellman -225kV supply, small “R28” inverted insulators, variable cathode/anode gap from to 10 to 50mm, field strength to ~ 20 MV/m
- Build a test stand that resembles an actual gun (tests with small gaps and high field strength but low voltage, don’t appear to be very useful)

Diamond-Paste Polishing

- Receive the electrode from the machine shop with "32" surface finish
- Silicon carbide polishing with 300 grit paper to remove obvious visible scratches
- Solvent cleaning in ultrasonic bath of alkali solution
- Silicon carbide polishing with 600 grit paper
- Solvent cleaning in ultrasonic bath of alkali solution
- Polish with 6mm grit
- Ultrasonic clean
- Polish with 3mm grit
- Ultrasonic clean
- High pressure rinsing (1200 psi) for 20 minutes with ultrapure de-ionized water with resistivity > 18 MWcm.
- High temperature (900°C) vacuum degas for one hour

DIAMOND-PASTE POLISHING

- Receive the electrode from the machine shop with “32” surface finish
- Silicon carbide polishing with 300 grit pa… …ve obvious visible scratches
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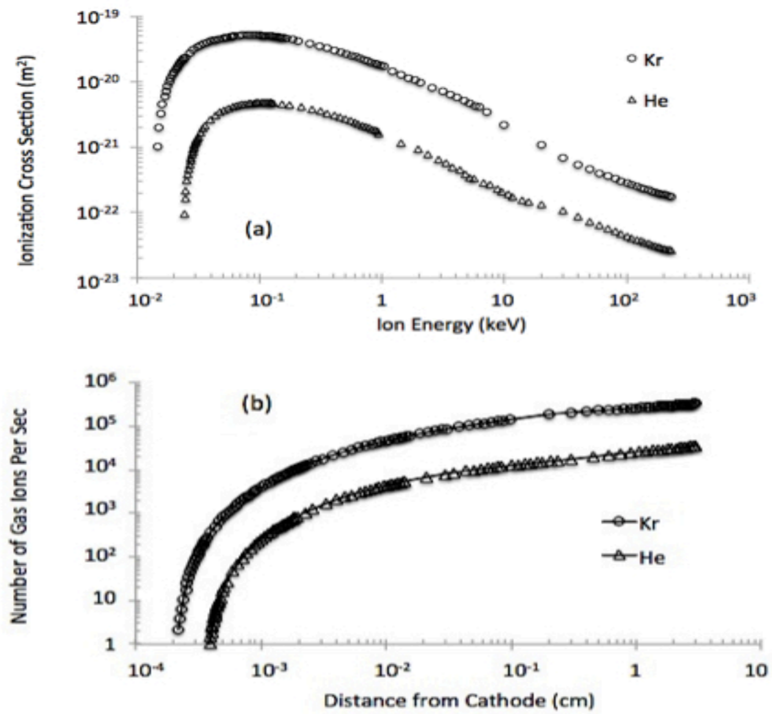
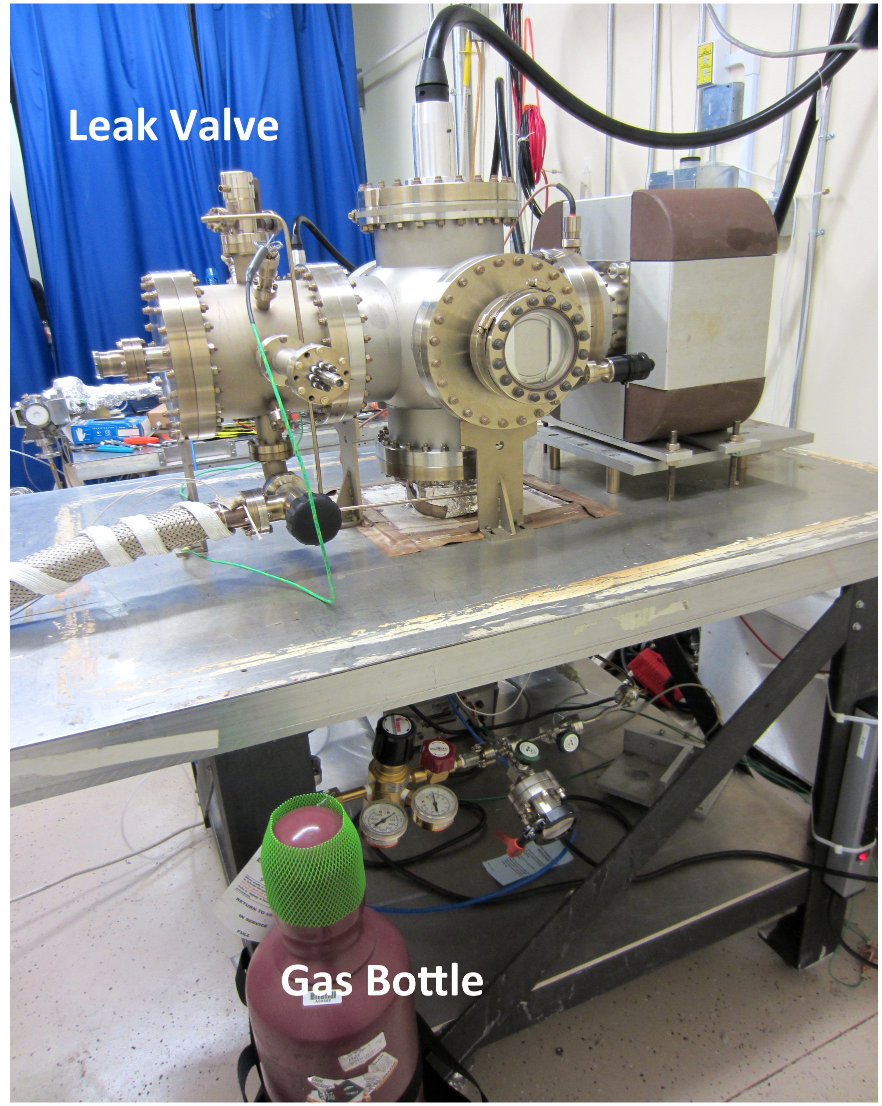
- Silicon carbid…
- Solv…
- …
- …
- …
- …
- H… …ssure rinsing (1200 psi) for 20 minutes with ul…rapure de-ionized water with resistivity > 18 MWcm.
- High temperature (900°C) vacuum degas for one hour

Two months later and the electrode is ready for high voltage!
Maybe it will work!?

Gas Conditioning

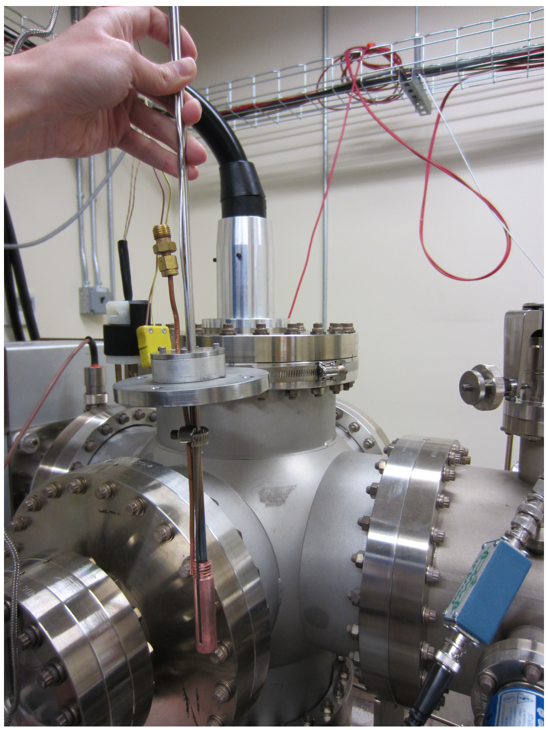


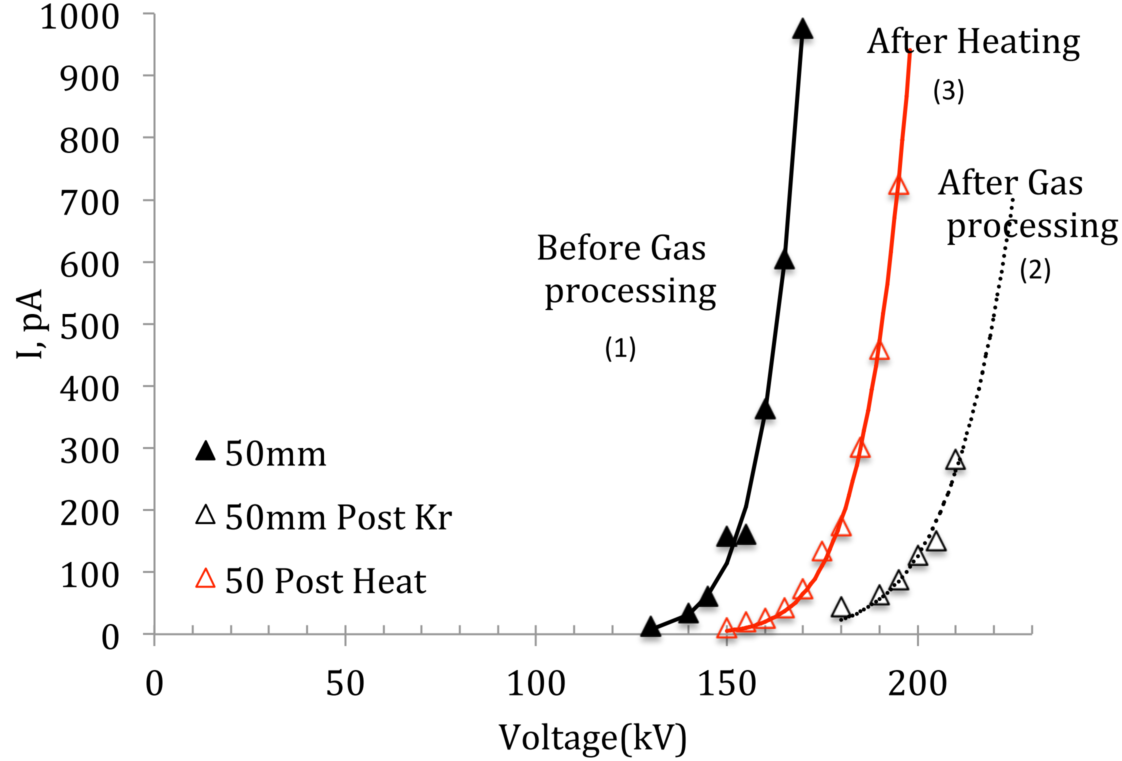


- Field emission ionizes inert gas
- Ions bombard electrode, hopefully near field emitter, which can be sputtered away
- And ions get implanted, increasing work function

What Does Gas Conditioning Do?

Benefits of implantation are reversible

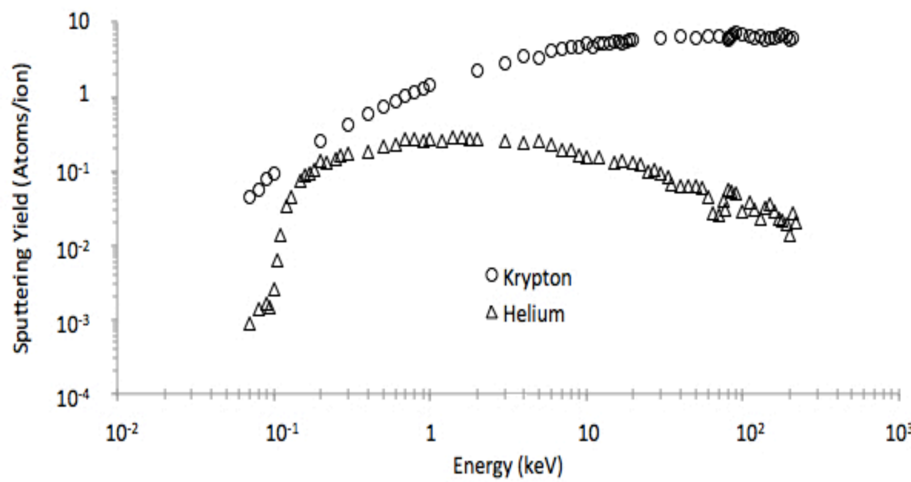




Work of M. BastaniNejad, E. Forman, C. Hernandez-Garcia

What Does Gas Conditioning Do?

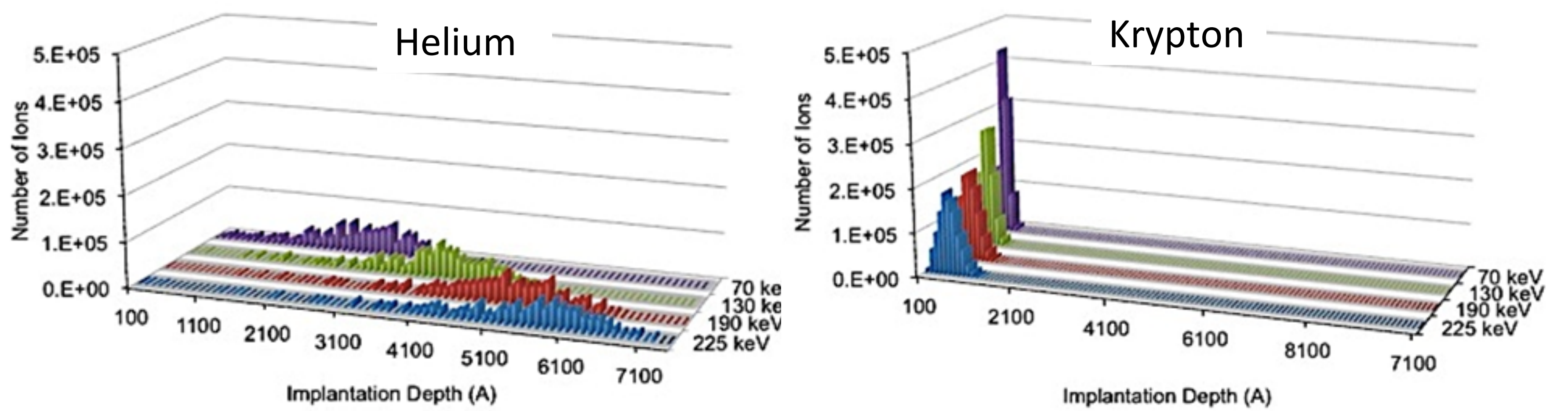
Sputtering and Implantation



Sputtering Yield

WHAT DOES GAS CONDITIONING DO?

Sputtering and Implantation



Implantation

What Does Gas Conditioning Do?

Sputtering and Implantation

- Helium: want a shallow implantation depth, so helium works best when FE turns ON at lower voltages, and/or with small gaps (10 to 20mm), don't expect much sputtering
- Krypton: can work at any voltage, good for larger gaps (30 to 50mm), sometimes too much sputtering creates a new field emitters

A POWERFUL TECHNIQUE

- Gas conditioning can turn a BAD electrode into a GOOD electrode
- TURN OFF ion pump
- NEG pumps don't pump inert gas
- Set voltage to excite field emitter
- Add gas at 10^{-5} Torr, apply voltage and watch for sharp decrease in FE current

Turn on Field Strength (MV/m) at 100pA , Before Gas Processing vs. Gaps

Gap (mm)	304L#1	304L#2	316LN#1	316LN#2
50	6.4	4.9	>12.6	8.7
40	6.6	5.4	>13.8	8.1
30	6.2	5.5	>15	9.1
20		6.6	15	10.5

Turn on Field Strength (MV/m) at 100pA , After Gas Processing vs. Gaps

Gap (mm)	304L#1	304L#2	316LN#1	316LN#2
50	>12.6	>12.6	>12.6	>12.6
40	>13.8	>13.8	>13.8	>13.8
30	13.6	13.5	>15	12.9
20		14.4	17.3	14.1

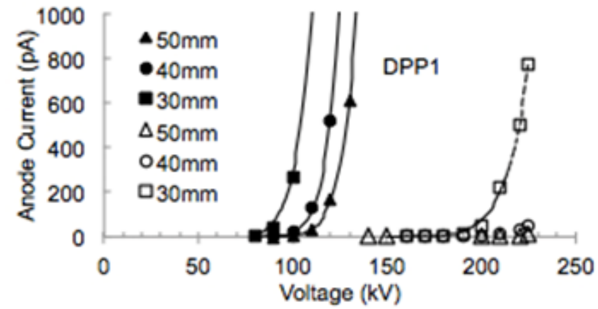
Perhaps 316L is better than 304L?

BACKUP SLIDES

- Thank You

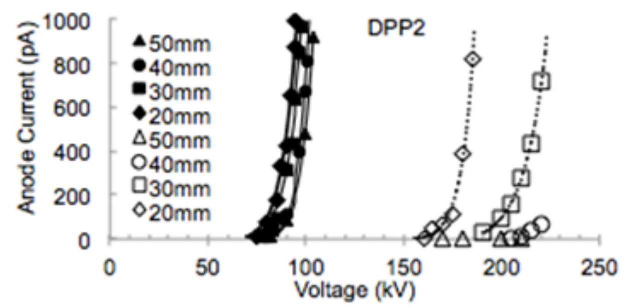
DIAMOND-PASTE POLISHED STAINLESS STEEL

- Variable performance is common
- Favorable response to gas conditioning



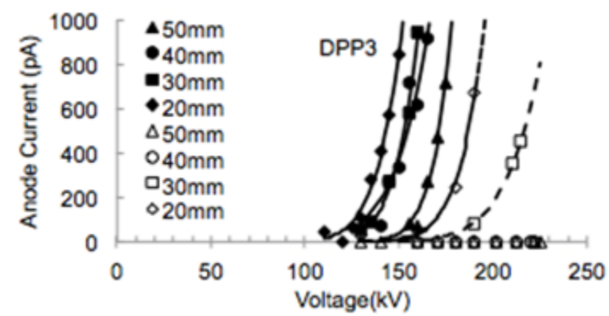
Turn on Field Strength (MV/m) at 100pA, Before Gas Processing vs. Gaps

Gap(mm)	EP1	EP2	EP3	DPP1	DPP2	DPP3
50	10.9	7.3	>12.6	6.4	4.9	8.7
40	11.1	8.1	>13.8	6.6	5.4	8.1
30	11.4	8.7	14.8	6.2	5.5	9.1
20	11.3	10.5	17.5		6.6	10.5

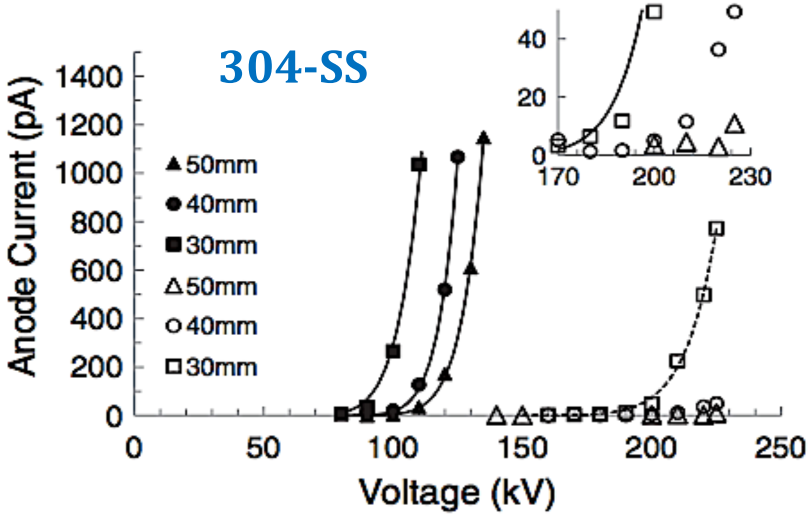


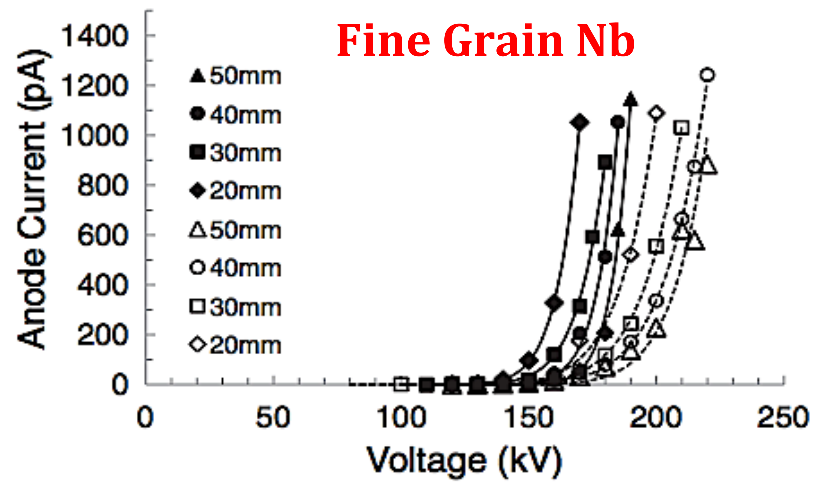
Turn on Field Strength (MV/m) at 100pA, After Gas Processing vs. Gaps

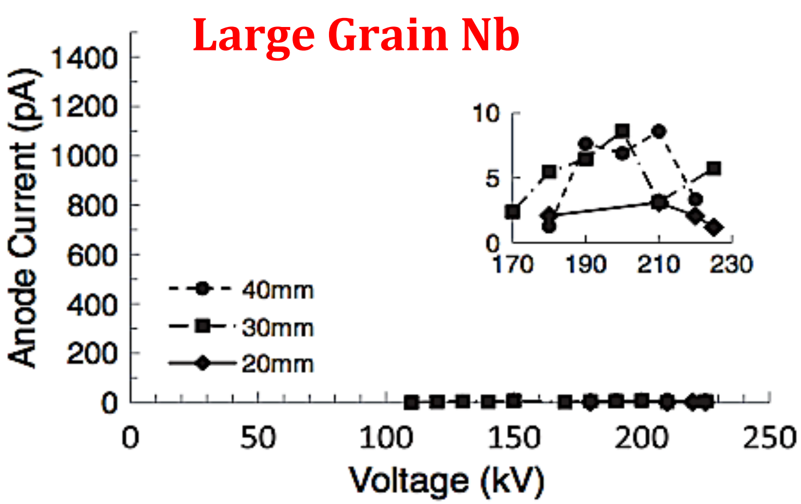
Gap(mm)	EP1	EP2	EP3	DPP1	DPP2	DPP3
50	8.2	9.2	>12.6	>12.6	>12.6	>12.6
40	9.1	9.9	>13.8	>13.8	>13.8	>13.8
30	9.8	10.5	>15.1	13.6	13.5	12.9
20	11.3	12.8	>18.7		14.4	14.1

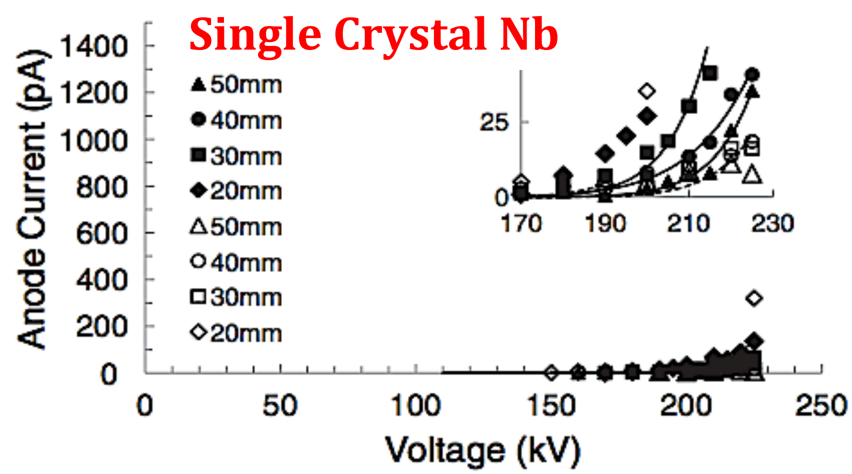


I to V curves for Niobium









Buffered Chemical Polishing of Niobium

- Receive the electrode from the machine shop with "32" surface finish
- Silicon carbide polishing with 600 grit paper, if necessary, to remove obvious visible scratches
- Solvent cleaning in ultrasonic bath of alkali solution
- Buffered-chemical polishing to remove ~ 100 mm material
- High pressure rinsing (1200 psi) for 20 minutes with ultrapure de-ionized water with resistivity > 18 MWcm.
- High temperature (900°C) vacuum degas for one hour

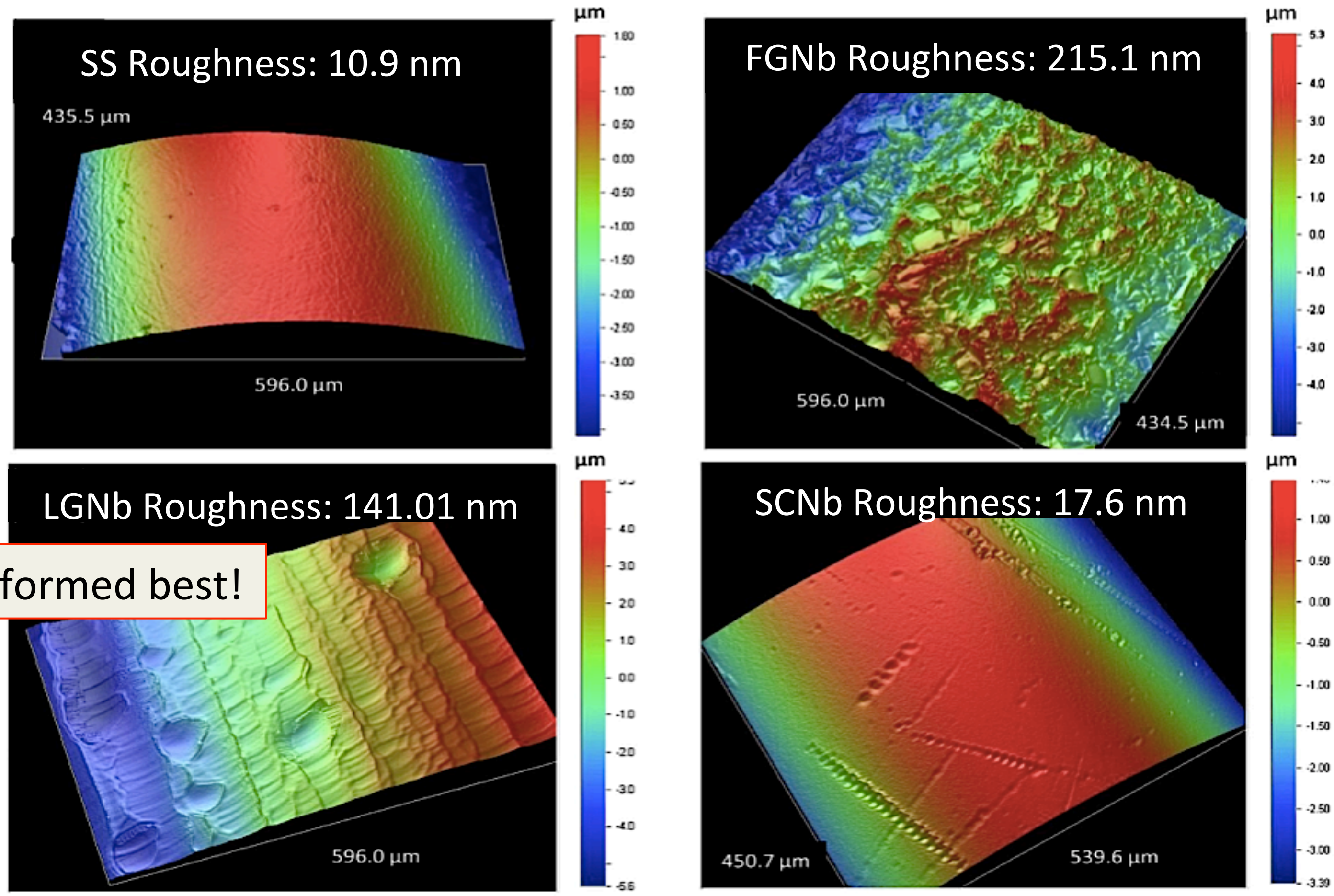
FE RESULTS OF BCP-ED NIOBIUM

- Field strength at which the electrode exhibited 100pA of field emission, post krypton gas conditioning
- “>” symbol….the electrode did not produce 100pA of field emission

	FGNb1	FGNb2	SCNb1	SCNb2	LGNb1	LGNb2	DPP-SS1	DPP-SS2
50mm	11.8	10.7	>12.6	>12.6	>12.6	>12.6	>12.6	10.7
40mm	11.5	11.2	>13.8	>13.8	>13.8	>13.8	>13.8	10.0
30mm	10.8	12.0	>15.0	13.1	>15.0	15.0	13.6	9.9
20mm	10.4	14.1	>18.7	12.3	>18.7	17.5	No data	No data

NIOBIUM ELECTRODES

- More evidence that there’s more to field emission than topography

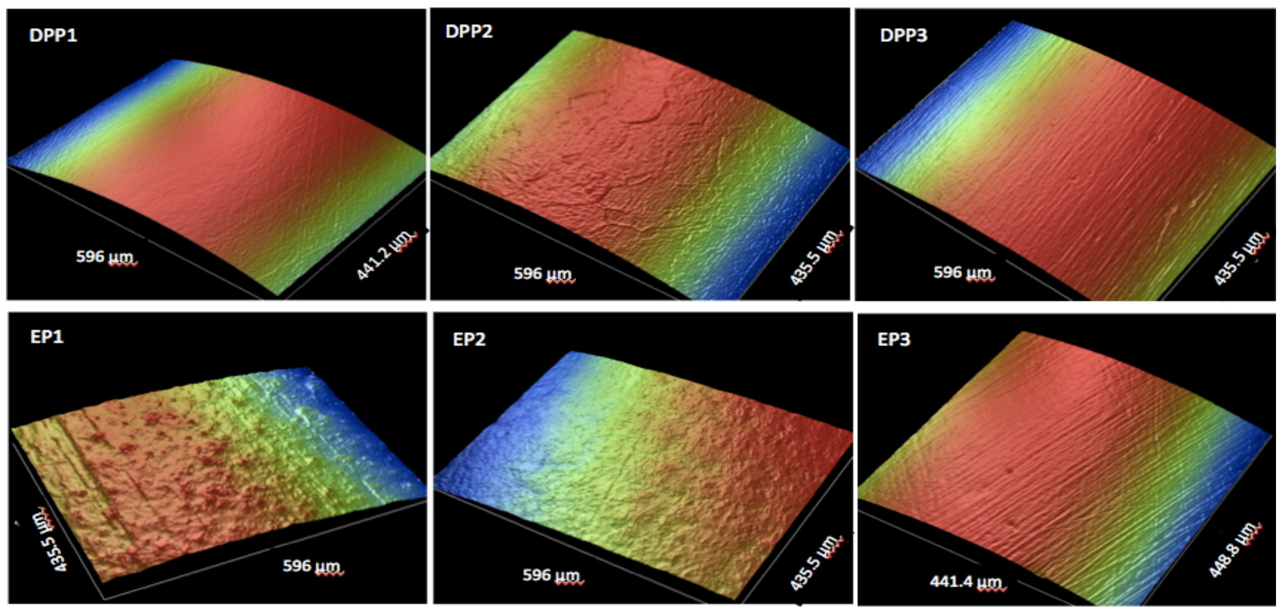


This one performed best!

Electropolished Stainless Steel

- Can we avoid time-consuming diamond-paste polishing?
- Start with three test electrodes having different surface finish, and send them to commercial electropolishing company

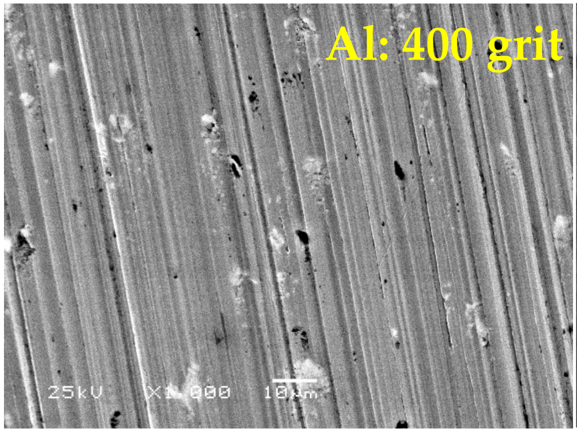
	DPP1	DPP2	DPP3	EP1	EP2	EP3
Waviness (nm)	25	30	73	312	385	76
Roughness (nm)	11	29	31	163	140	37

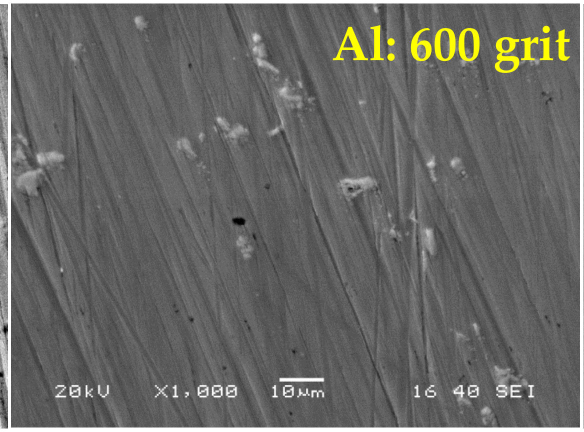


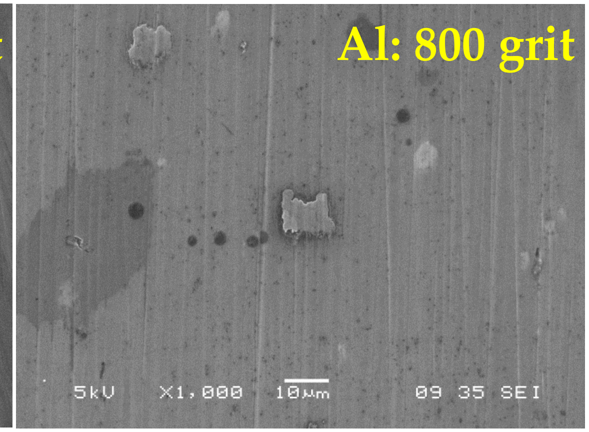
TiN-COATED ALUMINUM

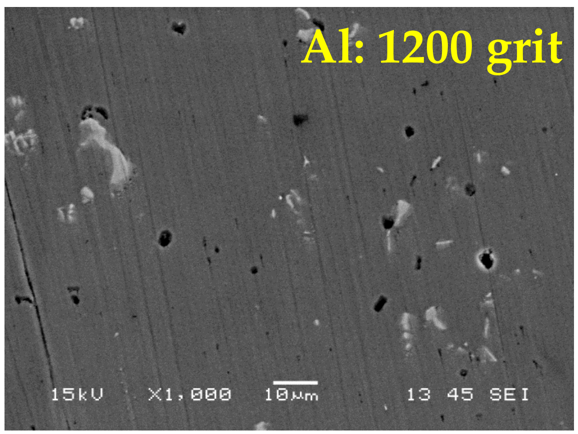
- Aluminum is cheap and easy to machine
- Takes just hours to polish to mirror-like finish with silicon-carbide paper
- Good thermal conductor, compared to steel, a nice feature when gun provides high current
- We used a “boutique” vendor to coat our small electrodes
- Can an industrial TiN-coating provide the same benefit? Need to test

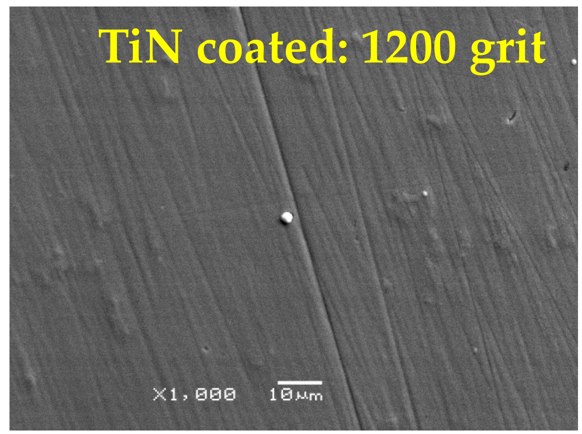
SURFACE IMAGES AL AND TIN-AL





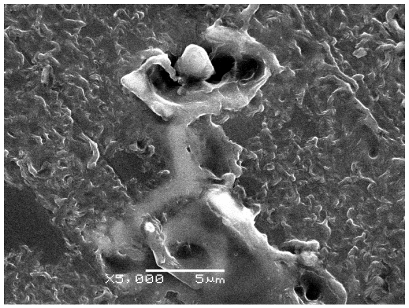




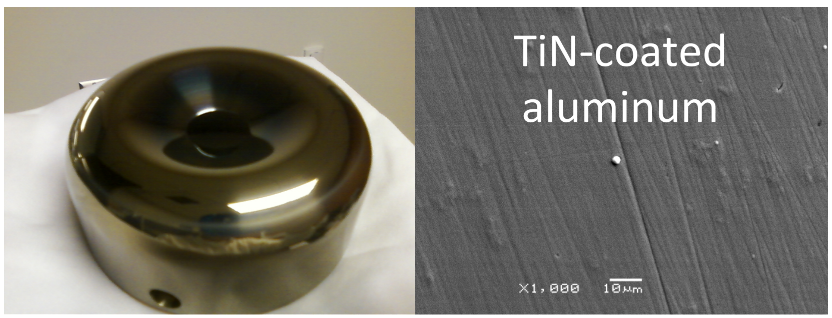


Note, the black spots are voids and defects, not particulate contamination from sand paper polishing

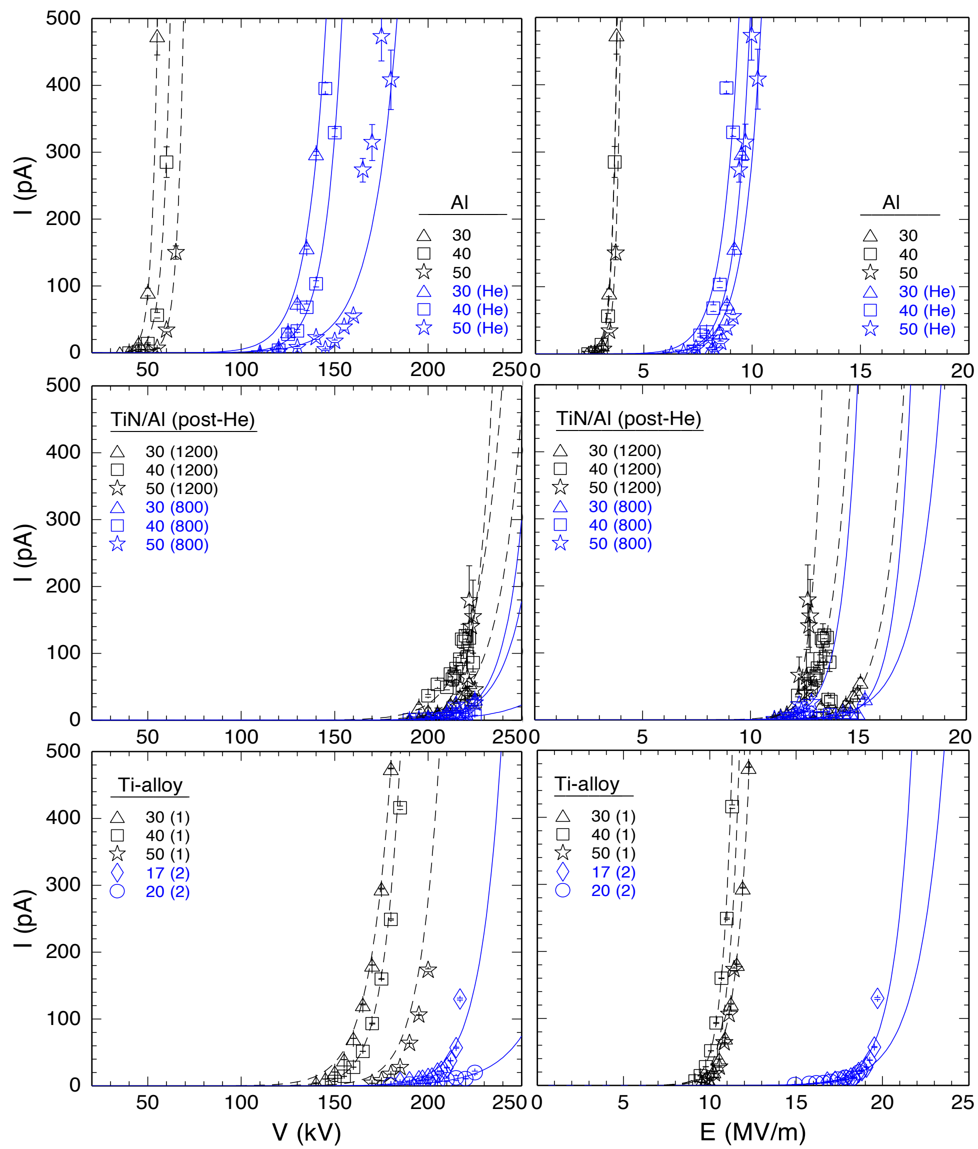
TiN-coated aluminum



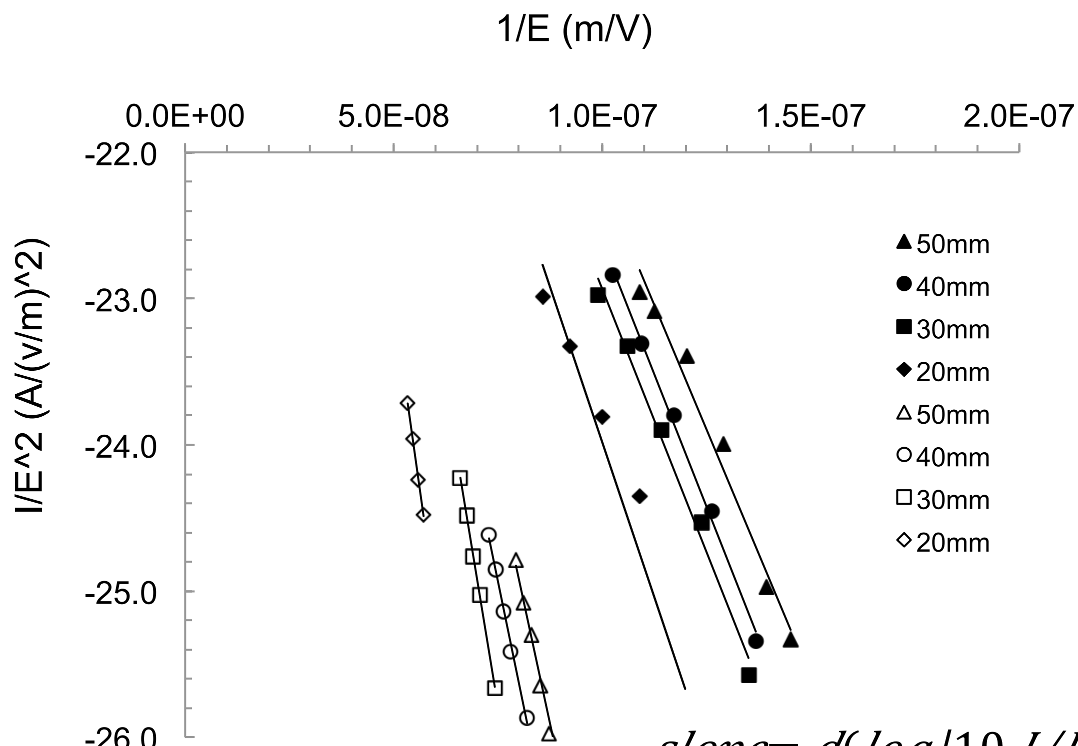
Bare aluminum: easily damaged



Diamond-paste polished Ti-alloy: a traditional "hard" electrode



Fowler-Nordheim Line Plots



$$\boxed{I = C_1 A_e \beta^2 E^2 e^{-C_2/\beta E}}$$

$$C_1 = 1.54x10^{-6} \cdot 10^{4.52 \cdot \phi^{-0.5}}/\phi$$

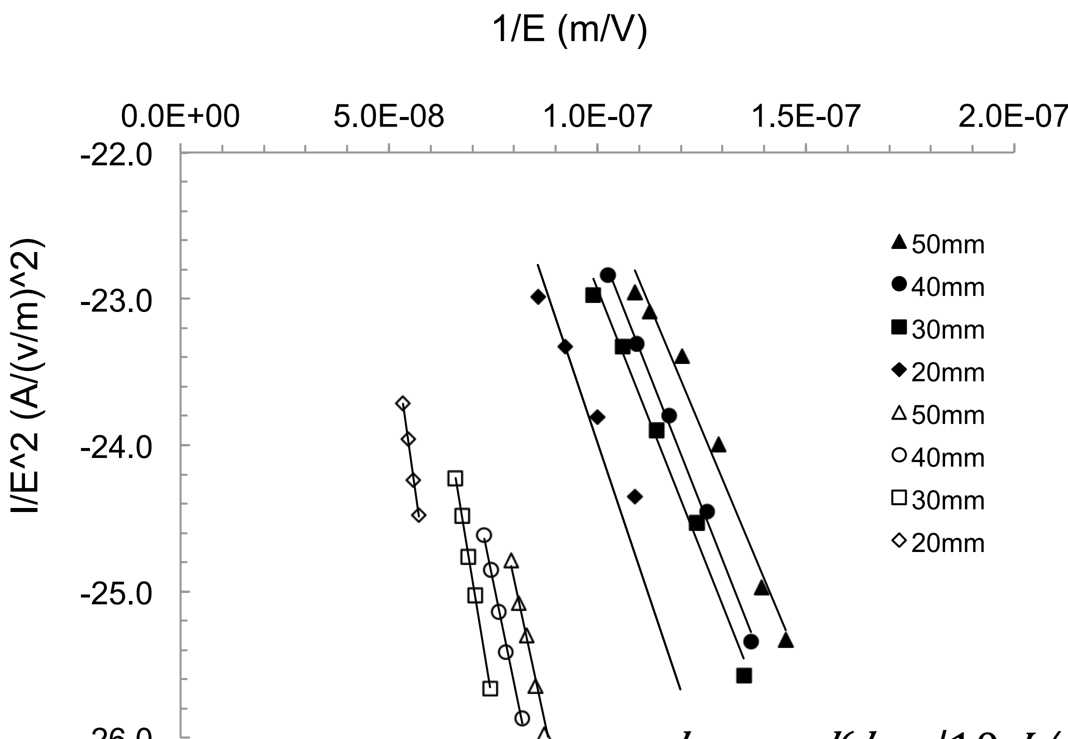
$$C_2 = 6.53x10^{9}\, \phi^{1.5}$$

$$slope = d(\log_{10} I/E^2)/d(1/E) = -\,2.84\times10^{9}\, \varphi^{1.5}/\beta$$

$$intercept = \mathrm{Log}_{10}\,(I_F/E^2)_{E\to\infty} = \mathrm{Log}_{10}\,[1.54\times10^{-6} A_e \beta^2 \times 10^{4.52\varphi^{-0.5}}/\varphi]$$

- These plots tell you *b*, the field enhancement factor, and A_e, the field emitter area

Fowler-Nordheim Line Plots



$$\boxed{I = C_1 A_e \beta^2 E^2 e^{-C_2/\beta E}}$$

$$C_1 = 1.54x10^{-6} \cdot 10^{4.52 \cdot \phi^{-0.5}}/\phi$$

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$$slope = d(\log_{10} I/E^2)/d(1/E) = -2.84\times10^{9}\, \varphi^{1.5}/\beta$$

$$intercept = Log_{10}(I_F/E^2)_{E\to\infty} = Log_{10}\left[1.54\times10^{-6} A_e \beta^2 \times 10^{4.52\varphi^{-0.5}}/\varphi\right]$$

- But it's wrong to assume work function, *F* , is a constant
- With three variables, there are an infinite number of solutions that provide a good fit

FOWLER-NORDHEIM LINE PLOTS

Electrodes	β , Pre-Gas Conditioning	β , Post-Gas Conditioning	A_e (m^2), Pre-Gas Conditioning	A_e (m^2), Post-Gas Conditioning
EP1	413	413	1.2E-18	1.2E-18
EP2	485	362	8.5E-19	2.4E-18
EP3	501	456	5.3E-23	1.2E-22
DPP1	228	134	9.7E-19	1.1E-17
DPP2	972	299	8.4E-20	7.1E-17
DPP3	475	171	2.5E-20	1.4E-19

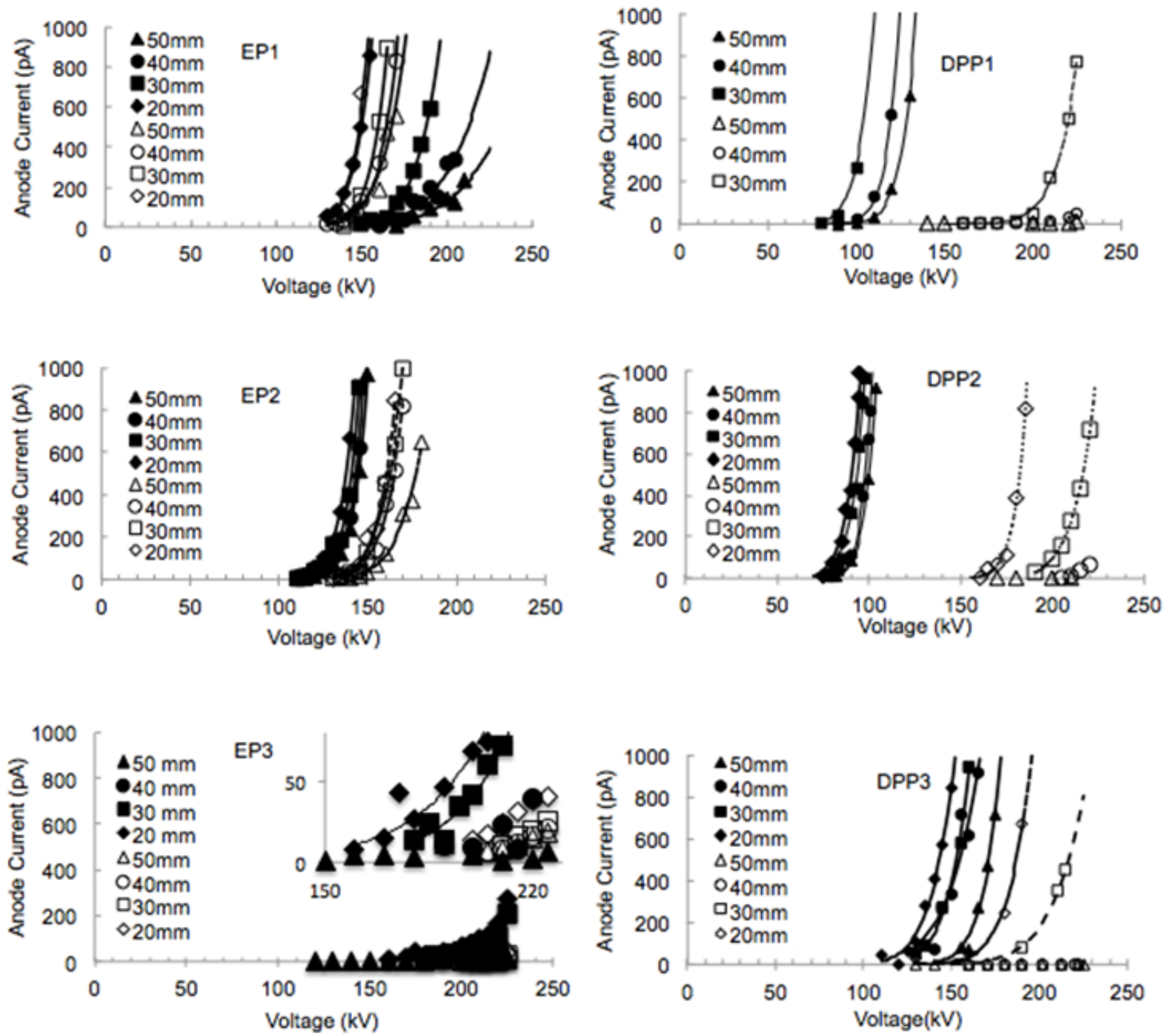
Why not identical here?

	DPP1	DPP2	DPP3	EP1	EP2	EP3
Waviness (nm)	25	30	73	312	385	76
Roughness (nm)	11	29	31	163	140	37

Identical here

Electropolished Stainless Steel

- EP-d electrodes exhibited less variability
- EP-d electrodes did not respond favorably to gas conditioning
- Best electrodes were DPP-d



ELECTROPOLISHED STAINLESS STEEL

- EP-d electrodes exhibited less variability
- EP-d electrodes did not respond favorably to gas conditioning
- Best electrodes were DPP-d

Turn on Field Strength (MV/m) at 100pA , Before Gas Processing vs. Gaps

Gap(mm)	EP1	EP2	EP3	DPP1	DPP2	DPP3
50	10.9	7.3	>12.6	6.4	4.9	8.7
40	11.1	8.1	>13.8	6.6	5.4	8.1
30	11.4	8.7	14.8	6.2	5.5	9.1
20	11.3	10.5	17.5		6.6	10.5

Turn on Field Strength (MV/m) at 100pA , After Gas Processing vs. Gaps

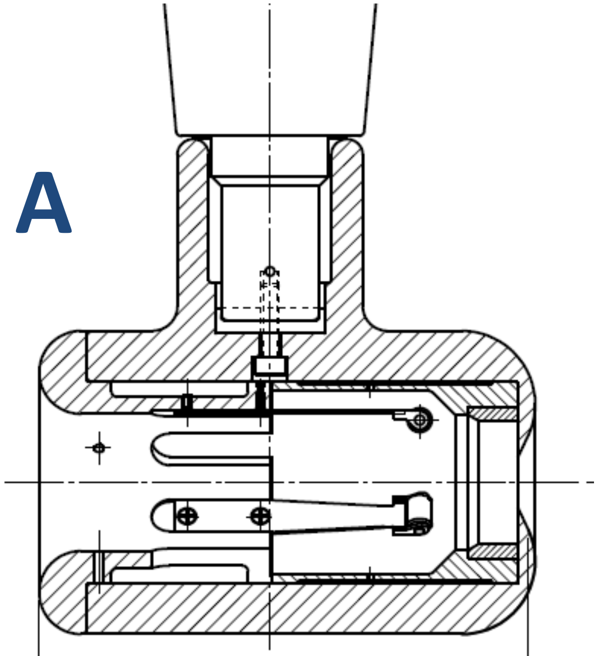
Gap(mm)	EP1	EP2	EP3	DPP1	DPP2	DPP3
50	8.2	9.2	>12.6	>12.6	>12.6	>12.6
40	9.1	9.9	>13.8	>13.8	>13.8	>13.8
30	9.8	10.5	>15.1	13.6	13.5	12.9
20	11.3	12.8	>18.7		14.4	14.1

BARREL POLISHING OF STAINLESS STEEL

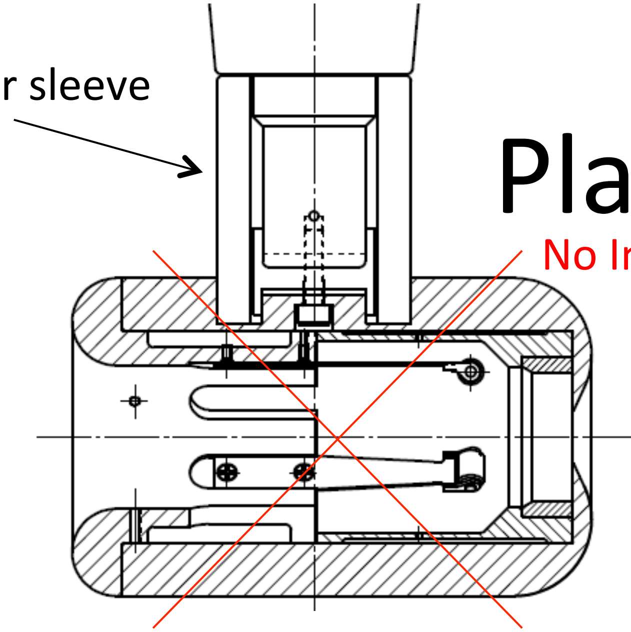
Barrel Polishing of Stainless Steel

On our to-do list for testing

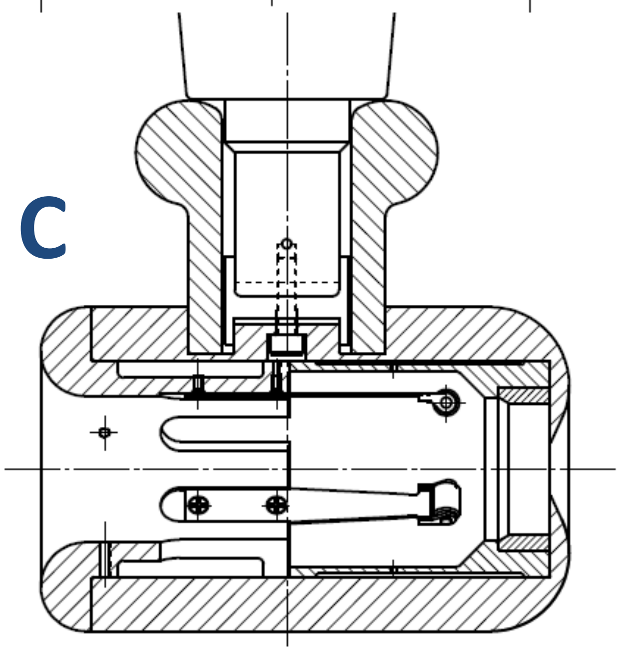
Plan A



Plan B

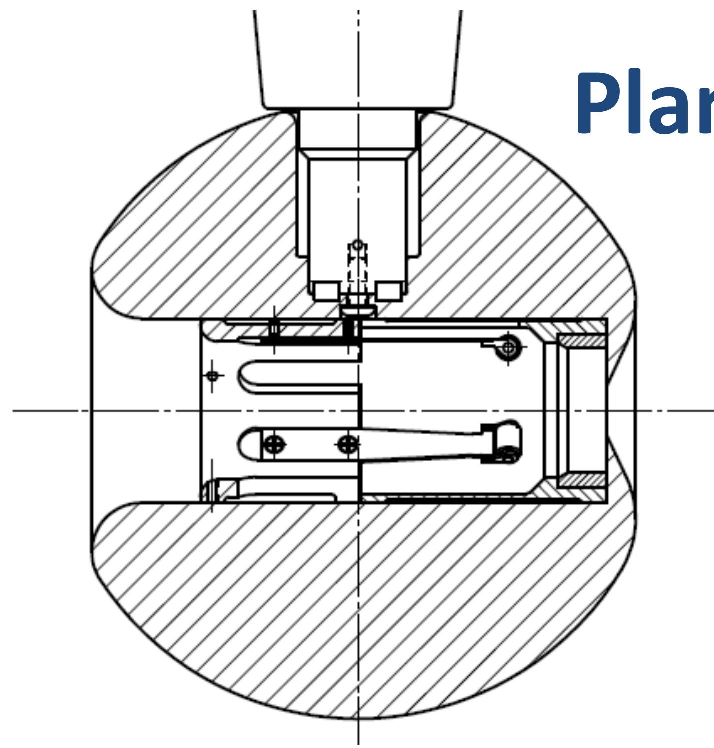


Plan C

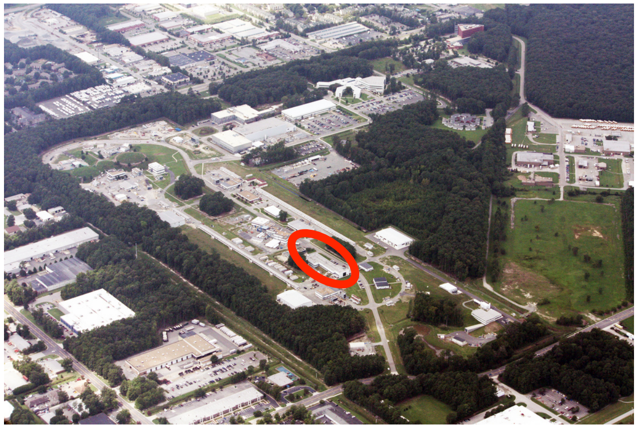


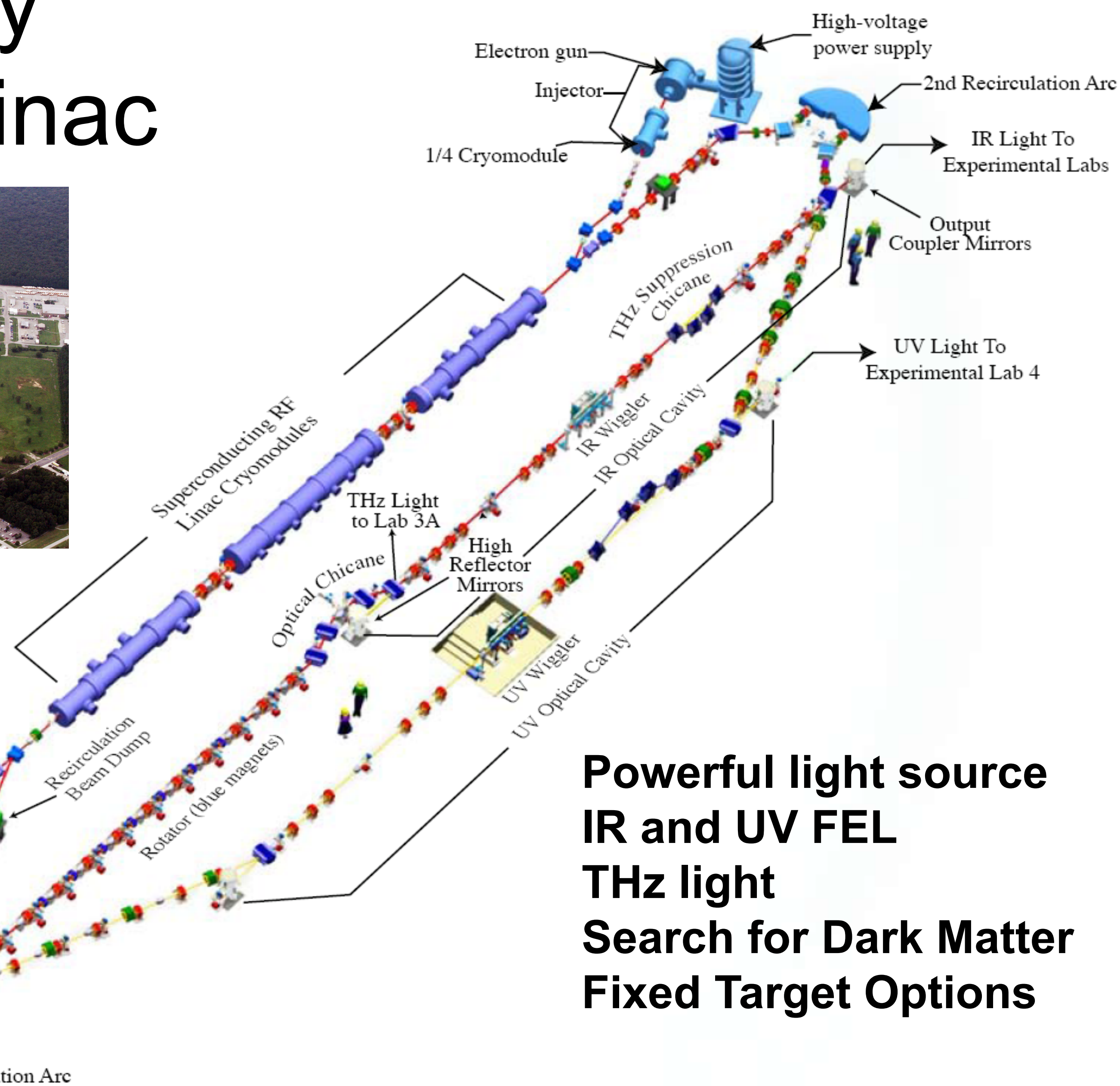
Screening electrode, or “shed”

Plan D



JLab Energy Recovery Linac

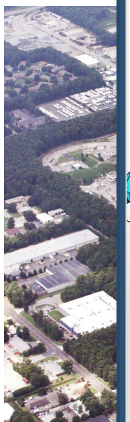


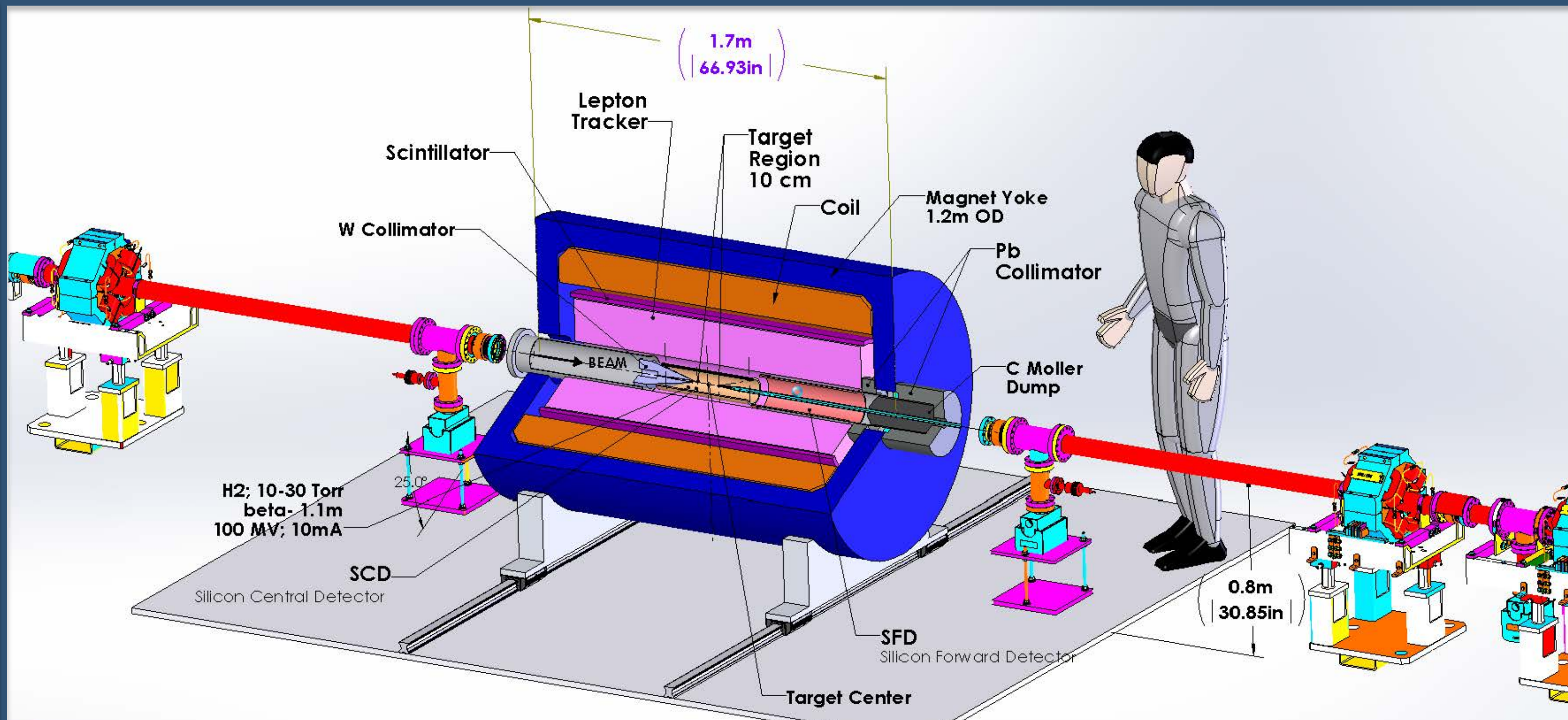


Beam accelerated from 5 to 100 MeV and then decelerated back to 5 MeV, to recover the energy

Powerful light source
IR and UV FEL
THz light
Search for Dark Matter
Fixed Target Options

JLab Energy
Re

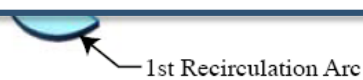




Bean
5 to
dece
MeV
ener

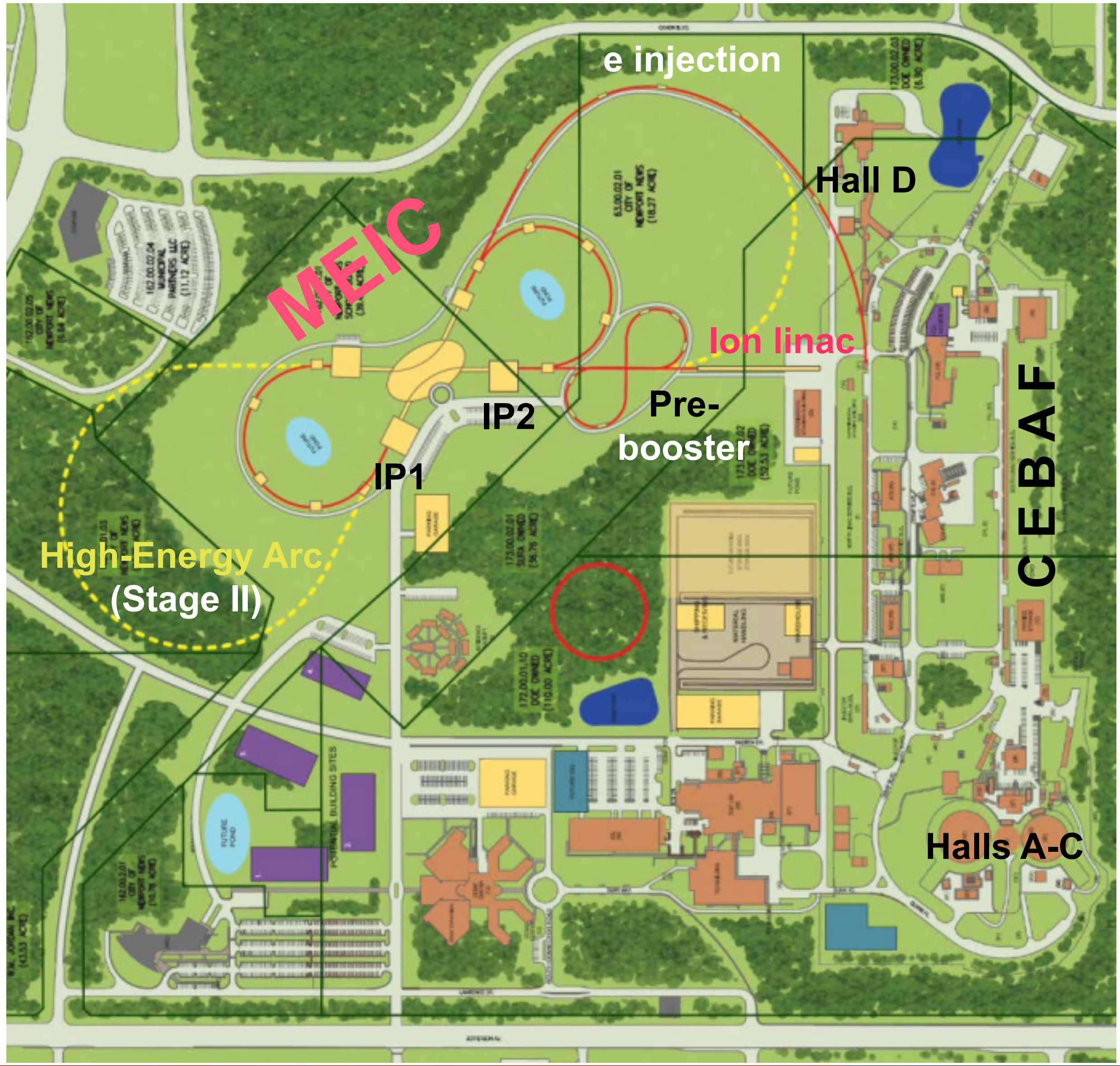
- 10 mA at 100 MeV : 1 MW beam power!!
- Energy Recovery Linac, with internal target, makes this experiment possible
- But with CsK2Sb photocathode…

r

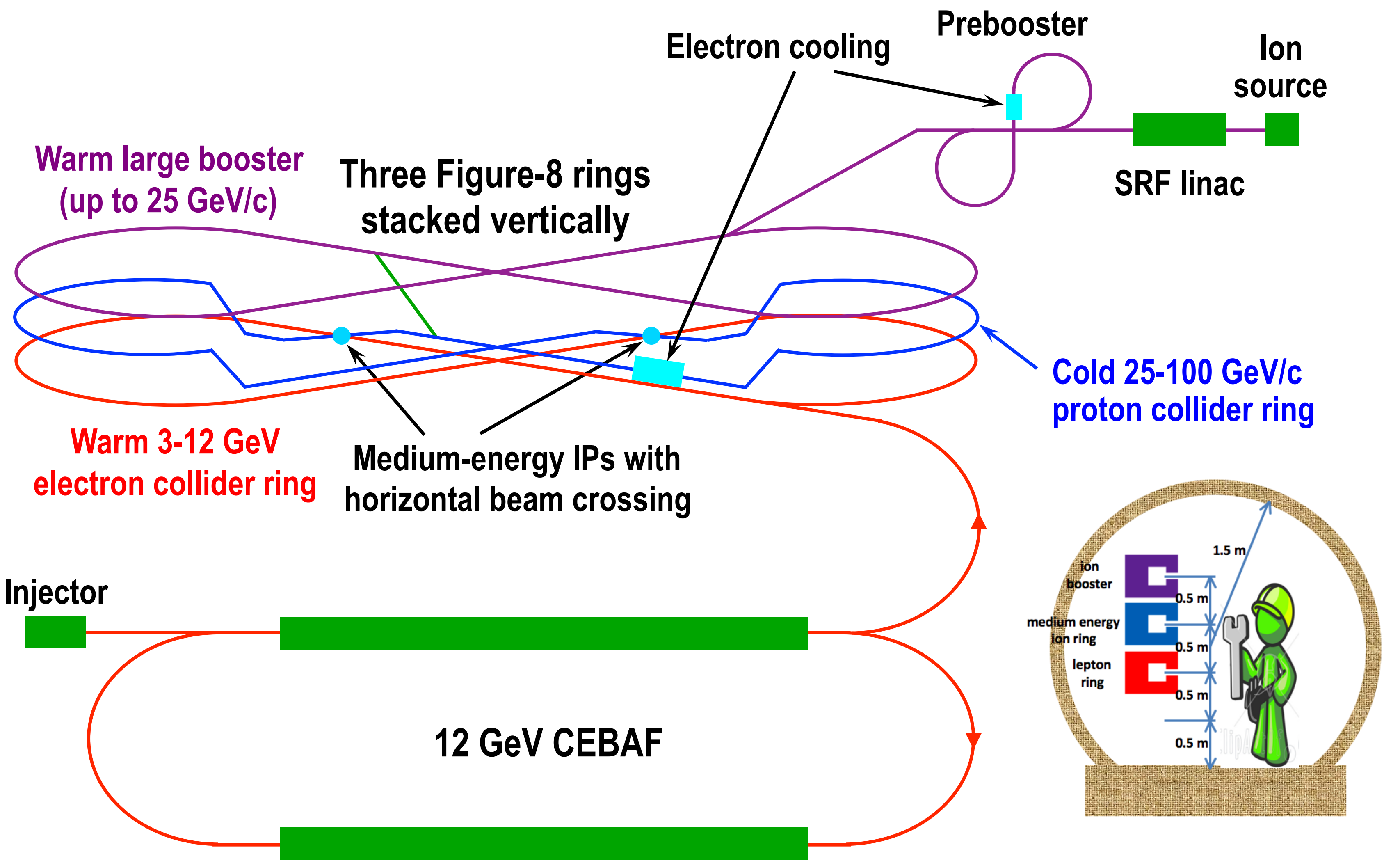


Electron Ion Collider at JLab

- Stage I MEIC
  - CEBAF as full-energy e^-/e^+ injector
  - 3 to12 GeV e^-/e^+
  - 25 to100 GeV protons
  - 12 to40 GeV/u ions
- Stage II EIC
  - up to 20 GeV e^-/e^+
  - up to 250 GeV protons
  - up to 100 GeV/u ions
- Two independent but complementary detectors



MEIC Layout



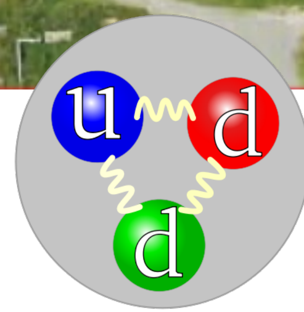
Cross sections of tunnels for MEIC

Jefferson Lab

Thomas Jefferson National Accelerator Facility

Exploring the Nature of Matter

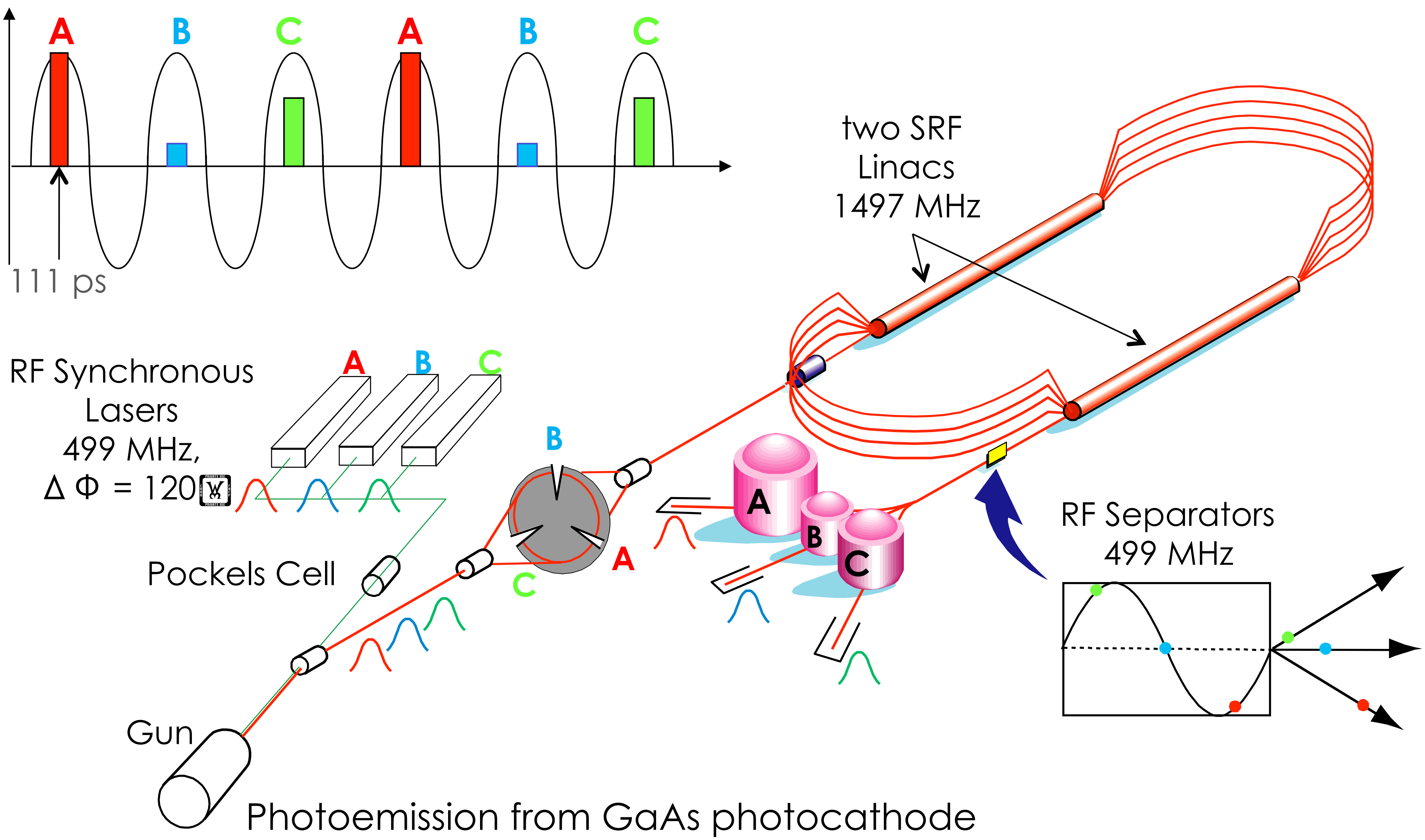
Electron



Neutron

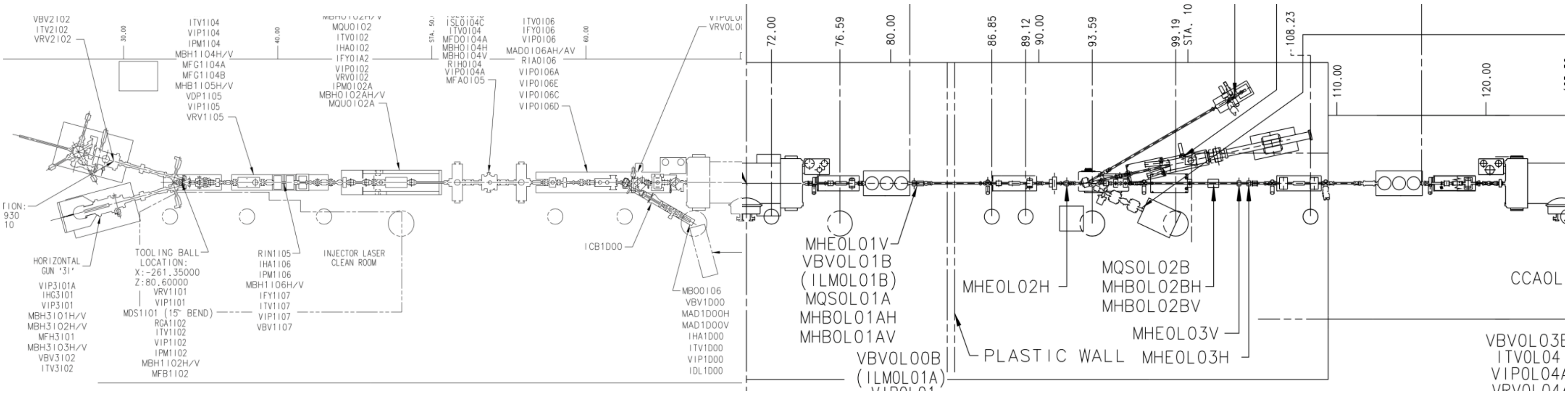
Proton

Continuous Electron Beam Accelerator Facility



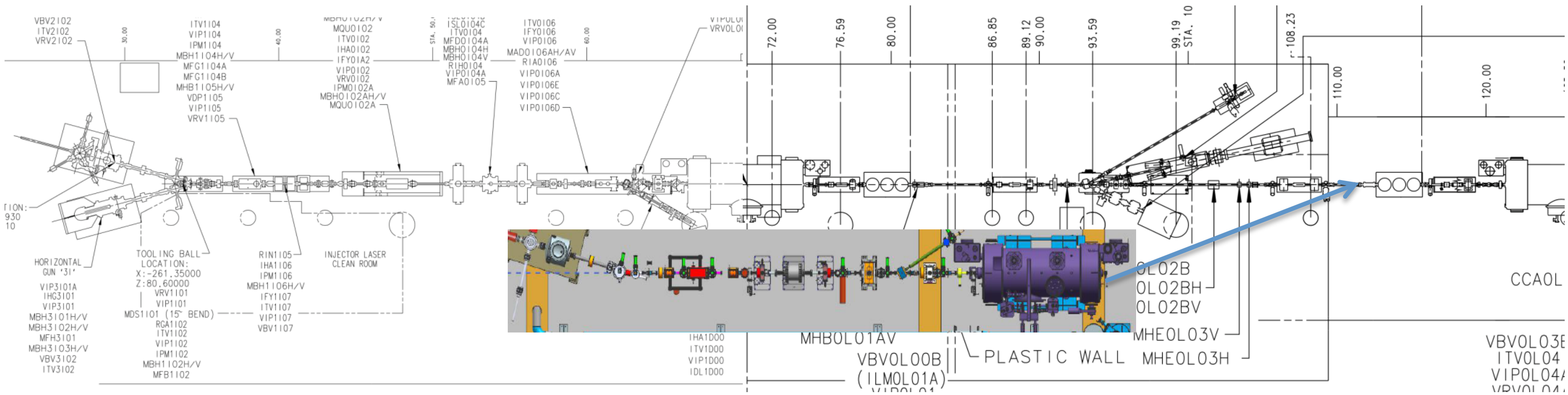
Photoemission from GaAs photocathode

Preparing for the next generation Parity-Violation Experiment



Proposed by Joe Grames

Preparing for the next generation Parity-Violation Experiment



1) deliver 100% long polarization to two halls simultaneously - each gun/ beamline has spin manipulators
2) parity violation experiments can monitor helicity correlated beam properties directly from gun. No other superimposed beams from gun to merger point
3) apertures at injector are good for non-parity users, they keep them. Apertures are bad for parity Users, the new line could eliminate them, hopefully even the chopper
4) Parity violation experiments get a laser "clean-up polarizer" to provide near perfect circular polarization, which helps reduce helicity correlated beam asymmetries

Proposed by Joe Grames