CEBAF/ILC/CLIC Inverted Gun

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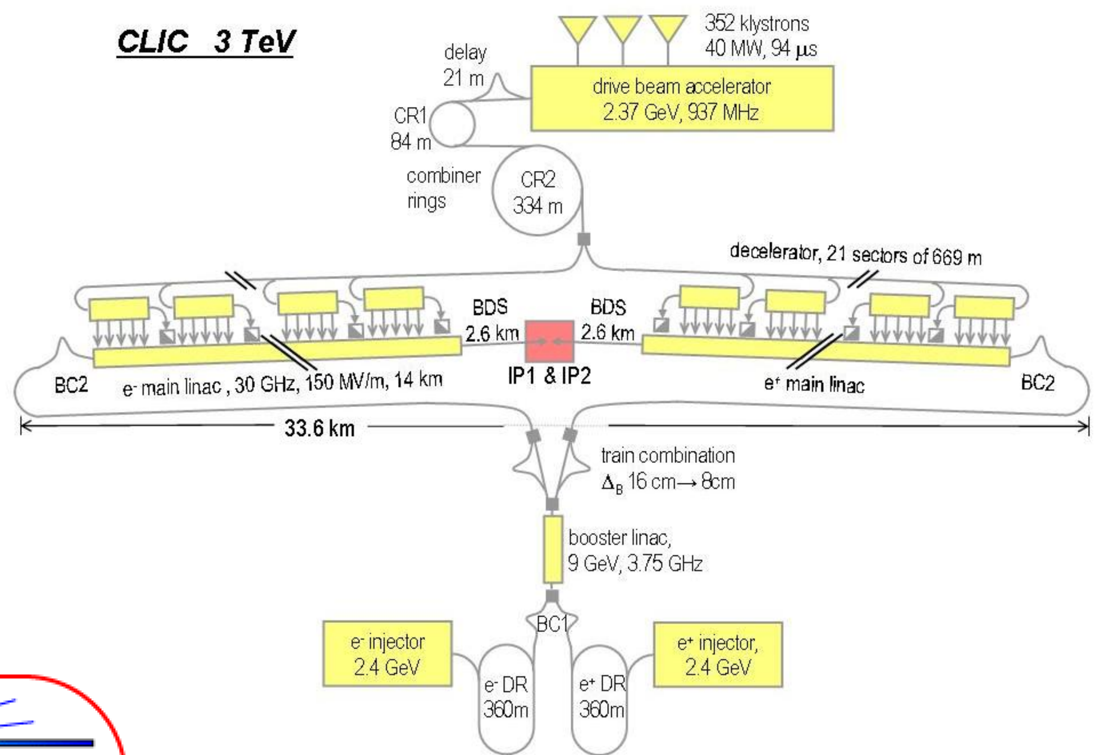
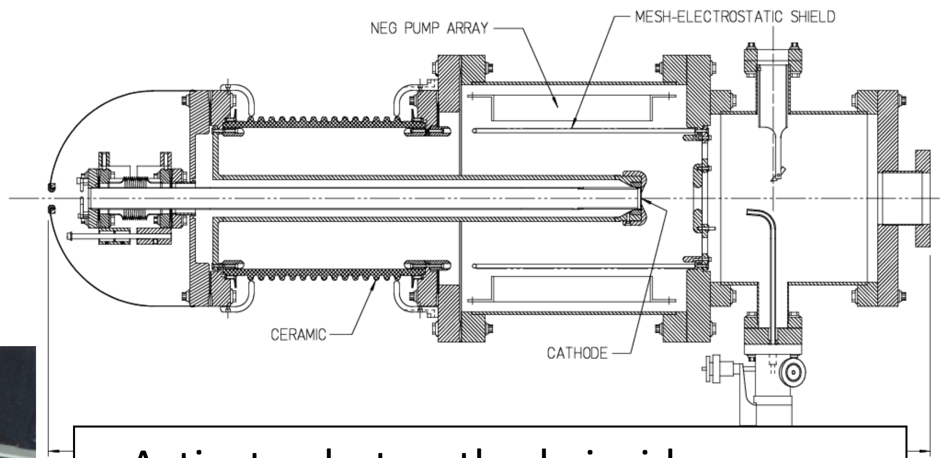
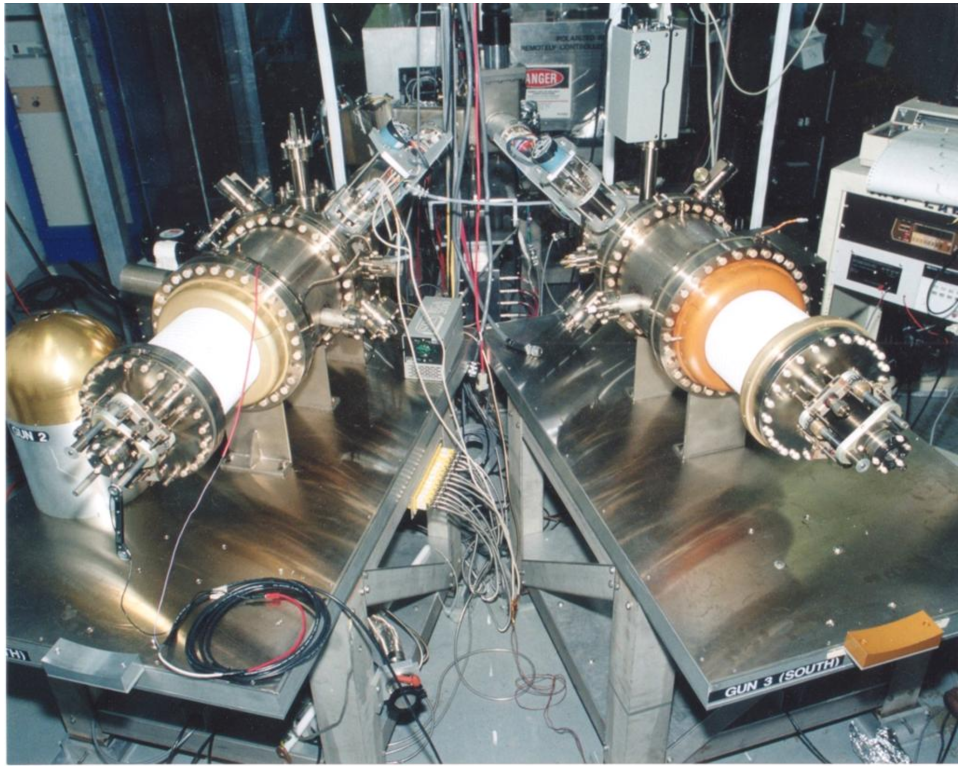


Injector Working Group Mtg., October 15, 2009

CEBAF 100kV vent/bake polarized electron source

- Two-Gun Photoinjector - One gun providing beam, one “hot” spare
- vent/bake guns – 4 days to replace photocathode (can’t run beam from one gun while other is baking)





- Activate photocathode inside gun – no HV breakdown after 7 full activations (re-bake gun after 7th full activation)
- HV breakdown after just 4 activations when Ti-alloy electrodes are used
- Infrared drive laser light: operate at bandgap, 35ps FWHM, 499MHz
- Extract ~ 2000 Coulombs per year
- Beam current ~ 100uA, laser 0.5mm dia., lifetime: ~ 100C, 1x10^5 C/cm^2

Preparing for Demanding New Experiments

Vent/Bake Guns: need improvement

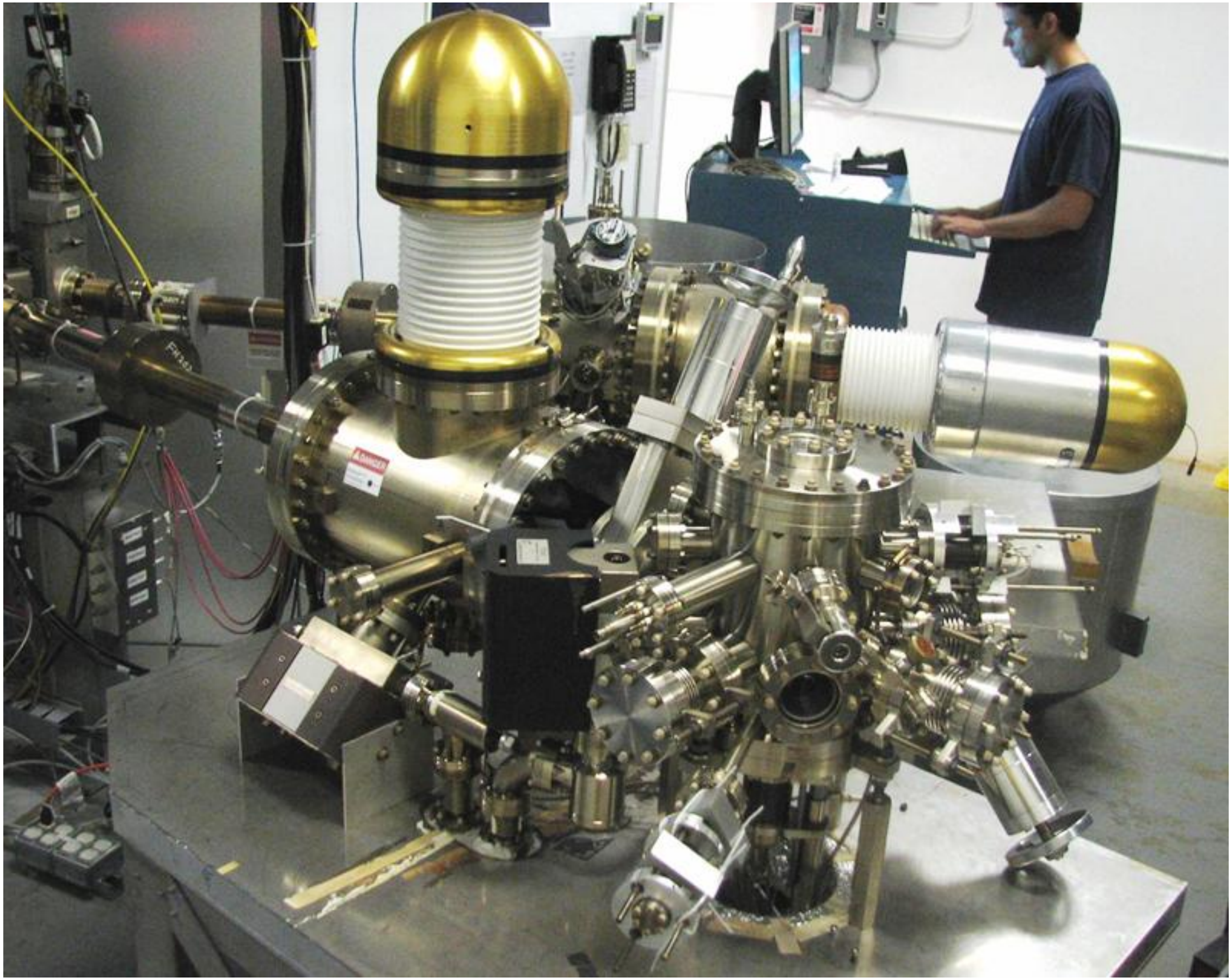
- Difficult to meet demands of approved high current/high polarization experiments like PRex (100uA) and Qweak (180uA and 1-year duration).
- Our vent/bake guns can provide only ~ 1 week operation at 180uA
- 12 hours to heat/reactivate, four days downtime to replace photocathode

Design Goal for New Gun: One Month Uninterrupted Operation at 250uA (~ 150C charge lifetime and 4 "spots"), One Shift to Replace Photocathode

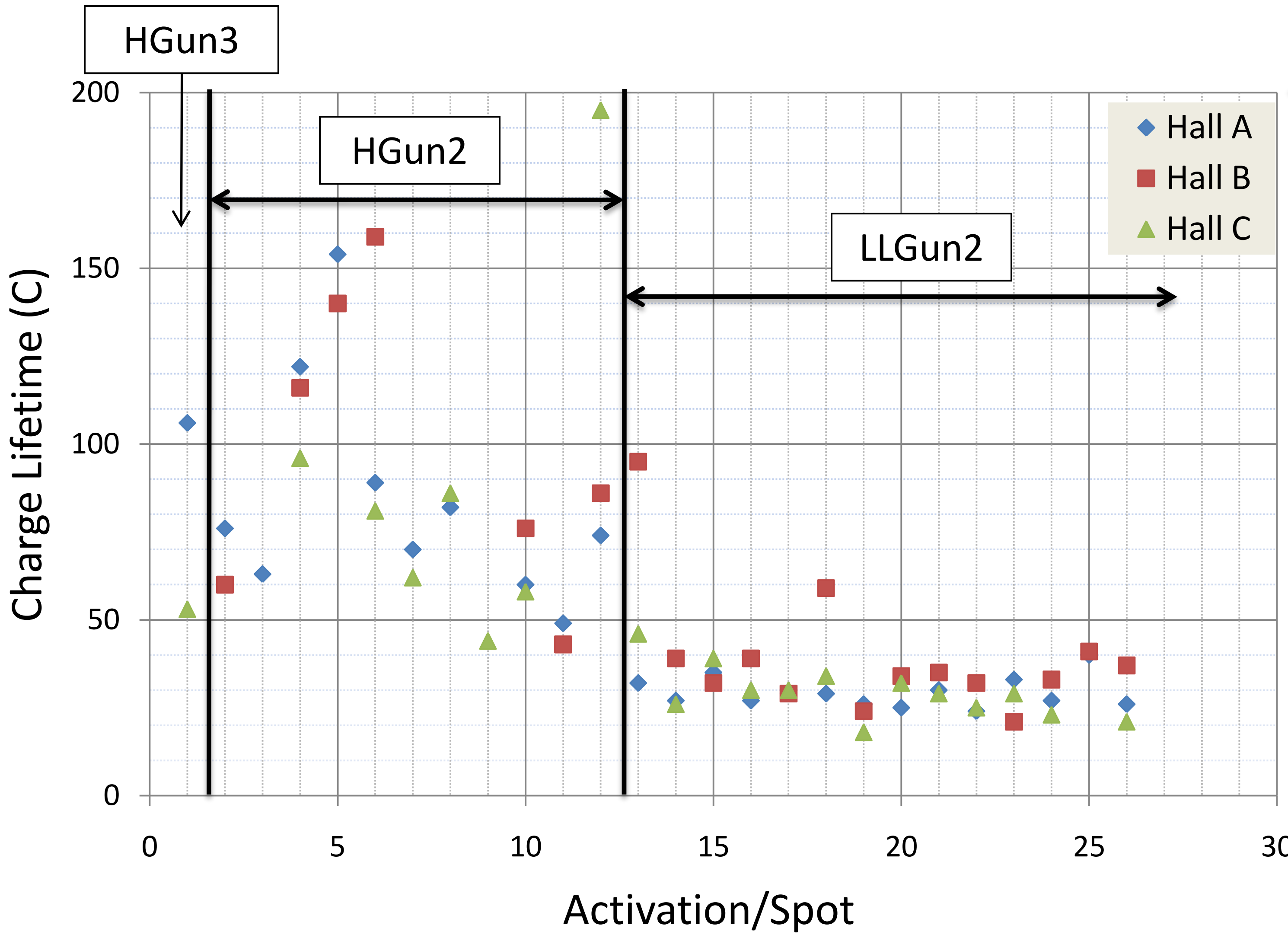
Solution:

(1) LLGun for quick photocathode swap, (2) better vacuum and, (3) higher bias voltage

LL Gun#1 at CEBAF, Installed Summer 2007



LLGun#1 Lifetime at CEBAF

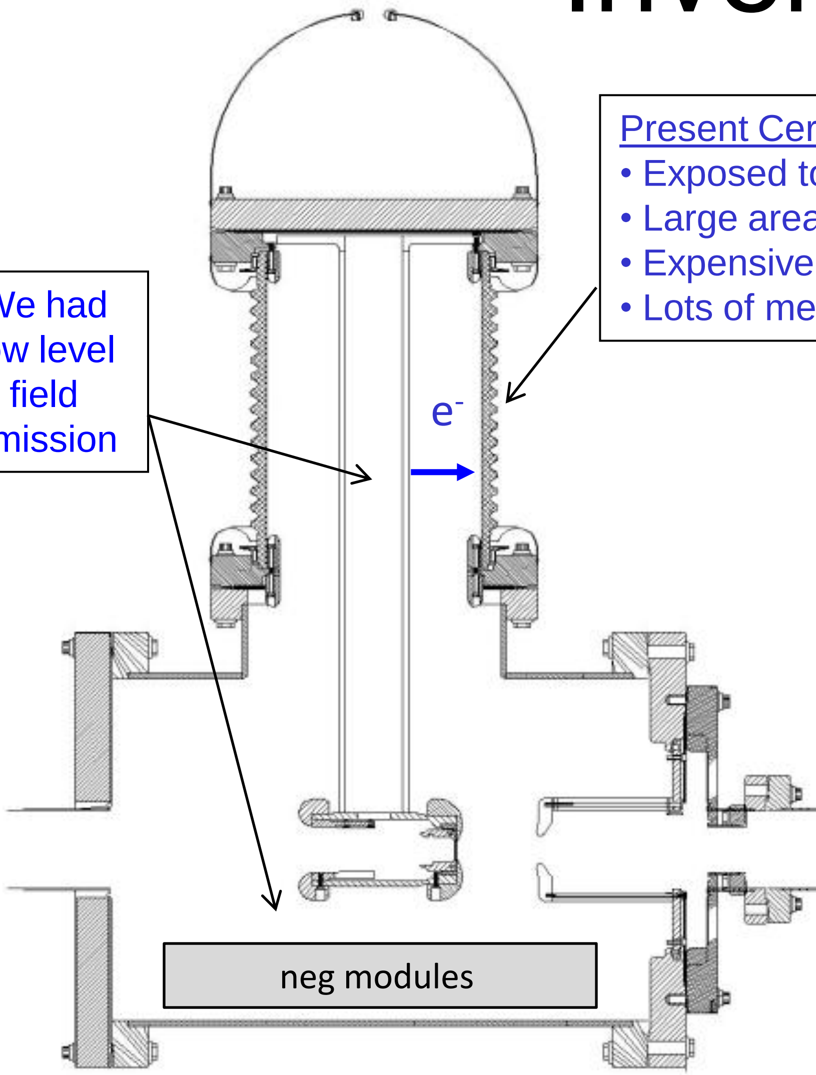


Expected at least 200C based on Test Cave operation

Why only 30C lifetime? Much better performance at Test Cave

“Inverted” Gun

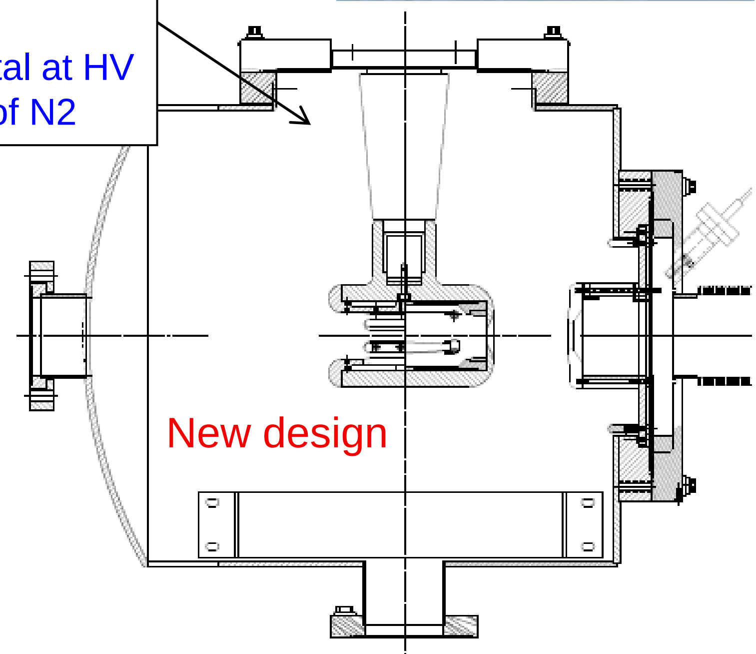
We had low level field emission



Present Ceramic
- Exposed to field emission
- Large area
- Expensive (~$50k)
- Lots of metal at HV

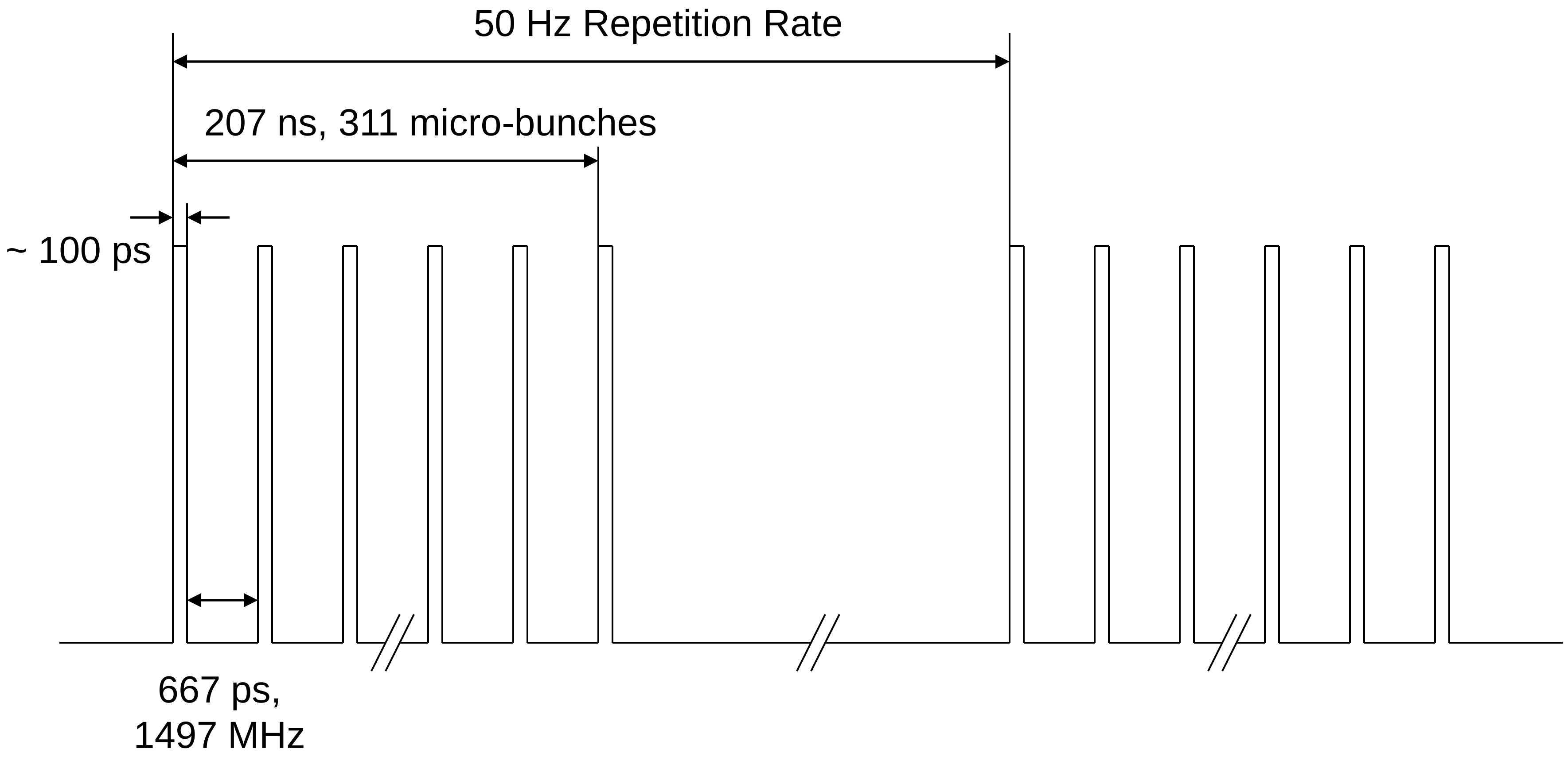
Medical x-ray technology

New Ceramic
- Compact
- ~$5k
- Less metal at HV
- No SF6 of N2



Move away from “conventional” insulator used on most GaAs photoguns today – expensive, months to build, prone to damage from field emission.
High gradient locations not related to beam optics

CLIC e-Beam Time Structure



CLIC e-Beam Source Parameters

Parameter	Symbol	Value
Number Electrons per microbunch	N_e	6×10^9
Number of microbunches	n_b	312
Width of microbunch	t_b	~ 100 ps
Time between microbunches	Δt_b	0.5002 ns
Microbunch rep rate	f_b	1999 MHz
Width of macropulse	T_B	156 ns
Macropulse repetition rate	F_B	50 Hz
Charge per micropulse	C_b	0.96 nC
Charge per macropulse	C_B	300 nC
Average current from gun (C_B x F_B)	I_{ave}	15 uA
Average current in macropulse (C_B / T_B)	I_B	1.9 A
Duty Factor w/in macropulse (100ps/667ps)	DF	0.2
Peak current of micropulse (I_B / DF)	I_{peak}	9.6 A

laser & gun

gun

photo cathode

Source Parameter Comparison

Parameter	CEBAF	JLab/FEL	JLab 100mA FEL	SLC	CLIC	ILC
Number electrons/microbunch	8.3×10^5	8.3×10^8	8.3×10^8	1×10^{11}	6×10^9	3×10^{10}
Number of microbunches	CW	CW	CW	2	312	3000
Width of microbunch	35 ps	35 ps	35 ps	2 ns	~ 100 ps	~ 1 ns
Time between microbunches	0.667 ns	13 ns	1.3 ns	61.6 ns	0.5002 ns	337 ns
Microbunch rep rate	1497 MHz	75 MHz	750 MHz	16 MHz	1999 MHz	3 MHz
Width of macropulse	-	-	-	64 ns	156 ns	1 ms
Macropulse repetition rate	-	-	-	120 Hz	50 Hz	5 Hz
Charge per micropulse	0.13 pC	0.133 nC	0.133 nC	16 nC	0.96 nC	4.8 nC
Charge per macropulse	-	-	-	32 nC	300 nC	14420 nC
Average current from gun	200uA	10mA	100mA	2 uA	15 uA	72 uA
Average current in macropulse	-	-	-	0.064 A	1.9 A	0.0144 A
Duty Factor: beam ON/beam OFF (during macropulse for pulsed machines)	5×10^{-2}	2.6×10^{-3}	2.6×10^{-2}	2.8×10^{-7}	0.2	3×10^{-3}
Peak current of micropulse	3.8 mA	3.8 A	3.8 A	8 A	9.6 A	4.8 A
Current density (for spot size below)	1.9 A/cm^2	19 A/cm^2	19 A/cm^2	10 A/cm^2	12.1 A/cm^2	6 A/cm^2
Laser Spot Size	0.05 cm	0.5 cm	0.5 cm	1 cm	1 cm	1 cm

Existing facilities (CEBAF, JLab/FEL, SLC)

Proposed facilities (JLab 100mA FEL, CLIC, ILC)

Bulk GaAs (JLab/FEL, JLab 100mA FEL)

Increase Gun Voltage: Why?

- Reduce space-charge-induced emittance growth, maintain smaller transverse beam profile and short bunchlength
- Address current density limitation due to Child's Law (not an issue)
- (Maybe?) Reduce problems associated with surface charge limit (i.e., QE reduction at high laser power)
- (Maybe?) Prolong Operating Lifetime

Biggest obstacle: Field emission, HV breakdown…

which lead to Photocathode Death

Historically, Labs have had difficulty operating DC high voltage guns above ~ 100kV and with field gradient > 5MV/m

Increase Gun Voltage: Why?

- Reduce space-charge-induced emittance growth, maintain small transverse beam profile and short bunchlength
  - Make a nice beam, build a rugged and reliable photoinjector (i.e., not complicated)
- (Maybe?) Reduce problems associated with surface charge limit (i.e., QE reduction at high laser power)
  - Mostly, need to have very good vacuum and a good load lock to quickly replace photocathodes

Biggest obstacle: Field emission, HV breakdown…

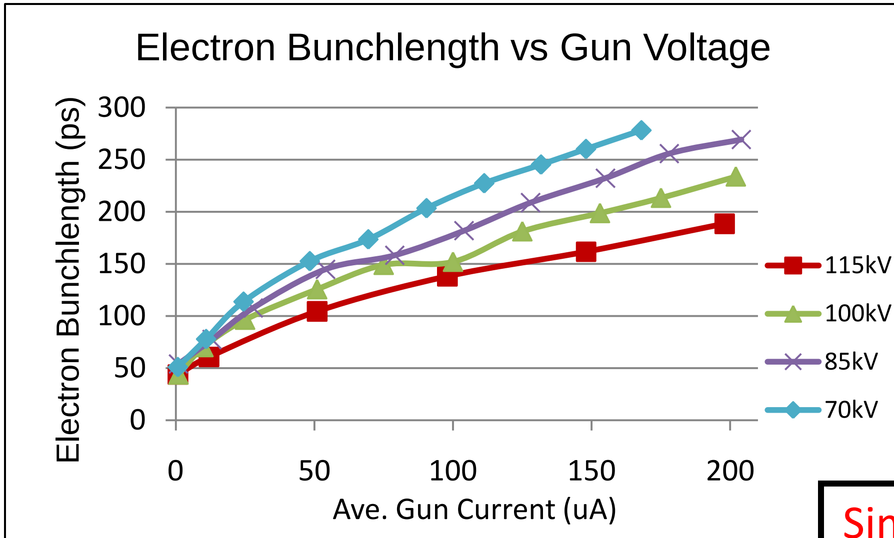
which lead to Photocathode Death

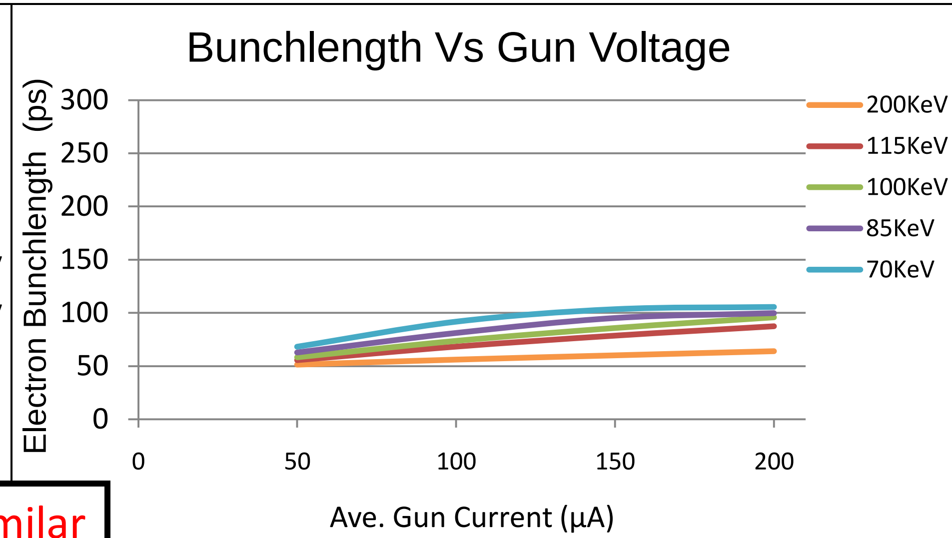
Historically, Labs have had difficulty operating DC high voltage guns above ~ 100kV and with field gradient > 5MV/m

Benchmarking PARMELA Simulation Results Against Beam-Based Measurements at CEBAF/Jefferson Lab – work of Ashwini Jayaprakash, JLab

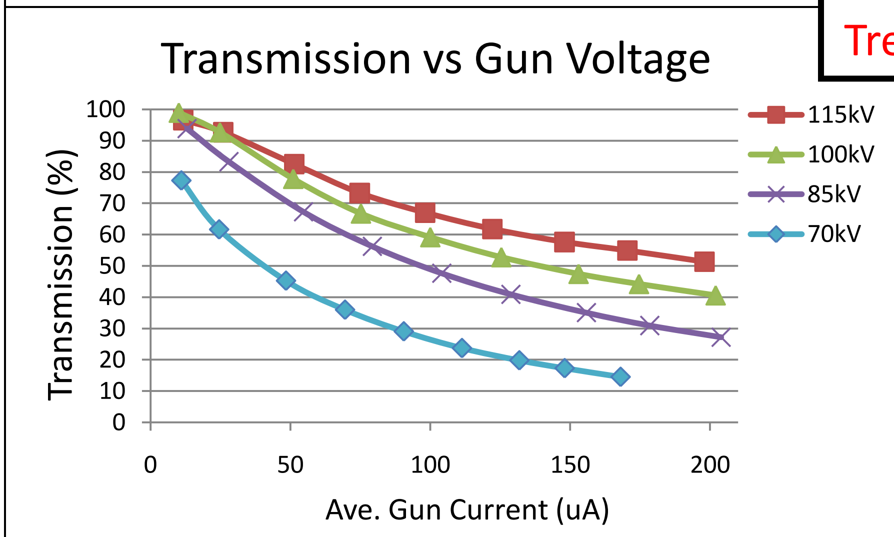
Measurements at CEBAF/JLab

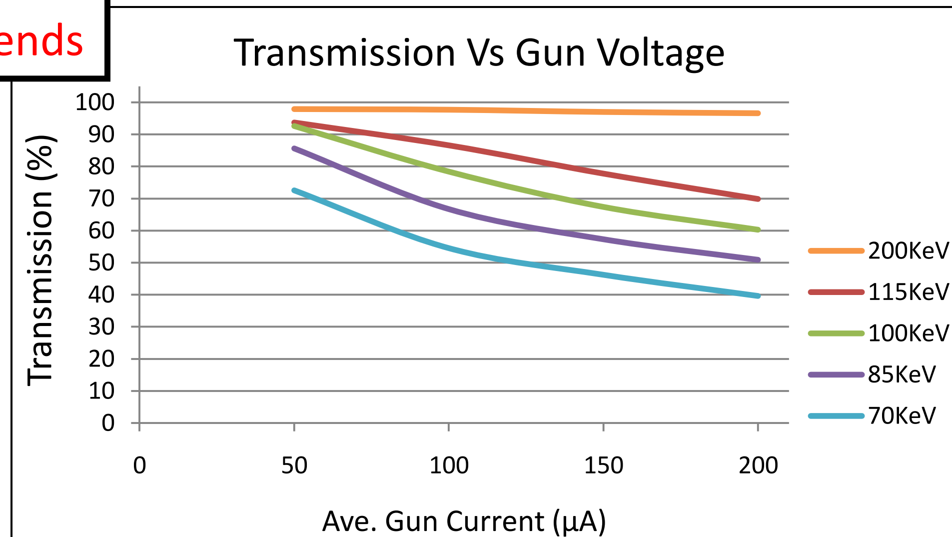
PARMELA Simulation Results





Similar Trends





Message: Beam quality, including transmission, improves at higher gun voltage

Space Charge Limit (my old slide)

Child's Law

$$j_0 = \left(2.33\times10^{-6}\right) V_0^{3/2} / d^2$$

V (kV)	j_0 (A/cm^2)
100	7
140	14
200	23
350	53

Comparable to CLIC current density…

Assume 3cm cathode/anode gap
CLIC peak current ~ 10A and Current density j = 6 A/cm^2 for 1cm diameter laser

Suggests CLIC current density comparable to Child's Law current limit…. but not to worry…..

Space Charge Limit

Child's Law (1D): $j_1 = \left(2.33\times10^{-6}\right)V^{3/2}/d^2$

Child's Law (2D) (PRL **87**, 278301) : $j_2 \cong j_1\left(1+\frac{1}{4}\frac{d}{r}\right)$

Short Pulse (PRL **98**, 164802): $j_{SCL} = j_2\left(2\frac{1-\sqrt{1-3X_{CL}^2/4}}{X_{CL}^3}\right),$

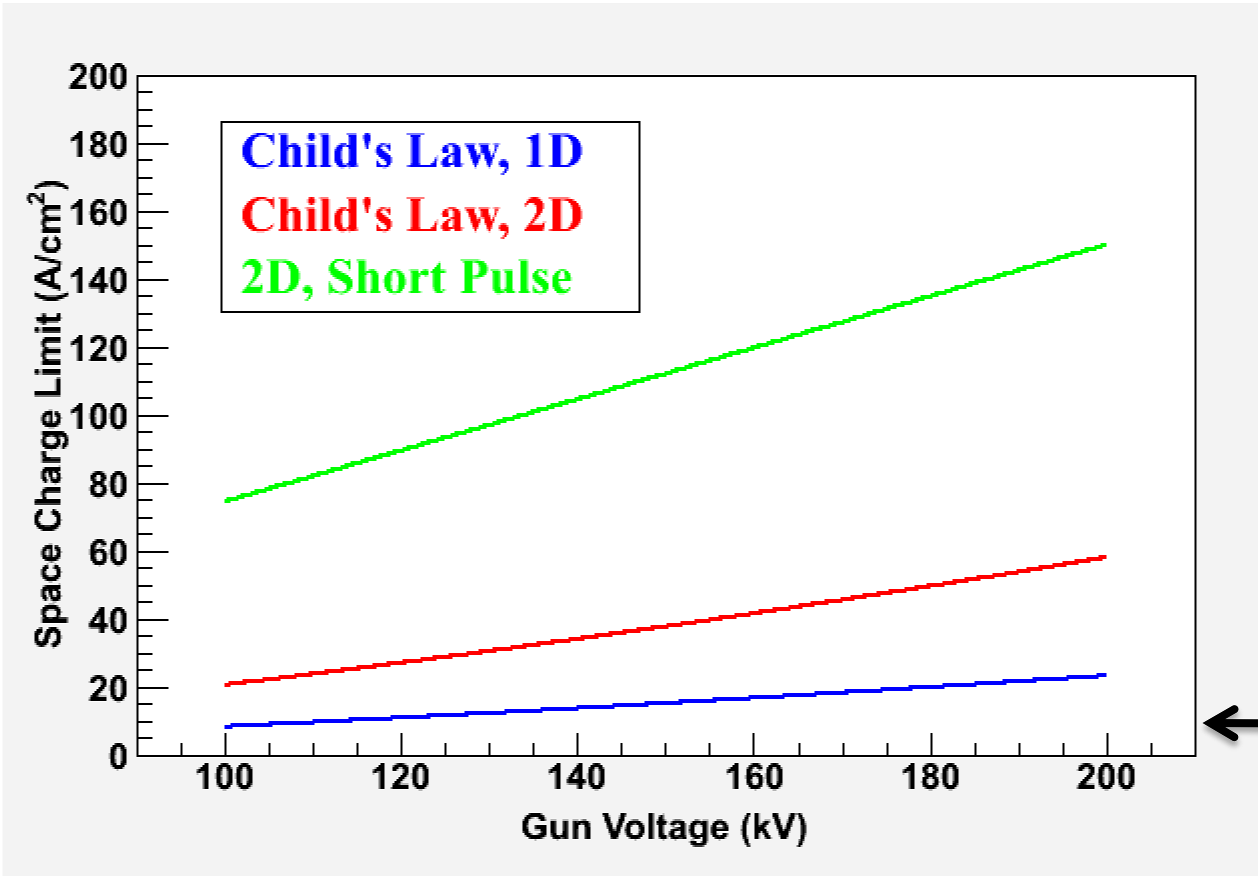
$$X_{CL} = \frac{t_b}{\tau}$$

V	Gun voltage
d	Cathode/anode gap (3 cm)
r	Laser spot size (1 cm = 2*r*)
t_b	microbunch length (100 ps)
τ	Gap transit time (0.48 ns @ 100 kV)

ILC with long microbunch…
won't reap "short pulse" benefit

Space Charge Limit – Not an Issue

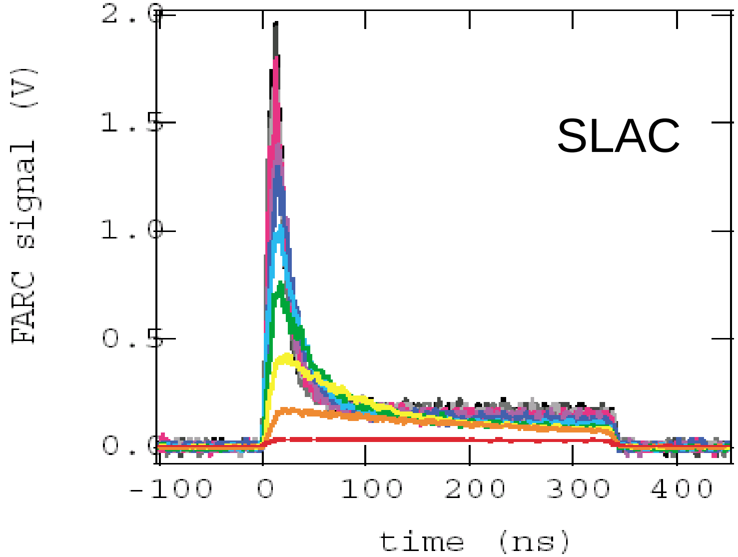
1D SCL does not apply (i.e. we don't have infinite charge plane)
CLIC conditions – with finite beam size 2D, and short pulses - push Child's Current Limit higher…..



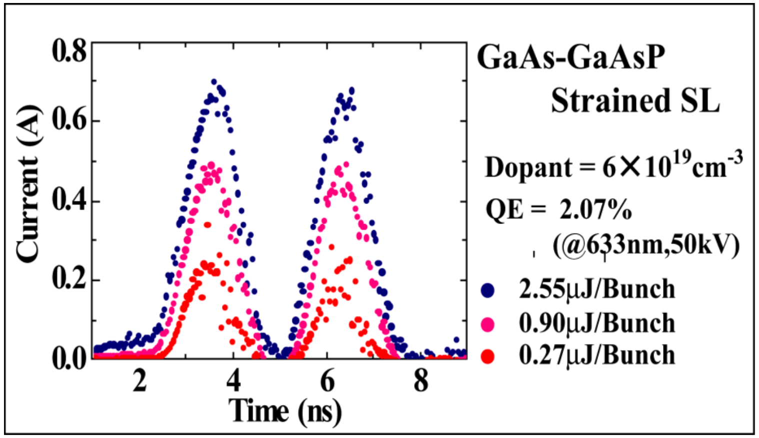
CLIC/ILC current density

Surface Charge Limit

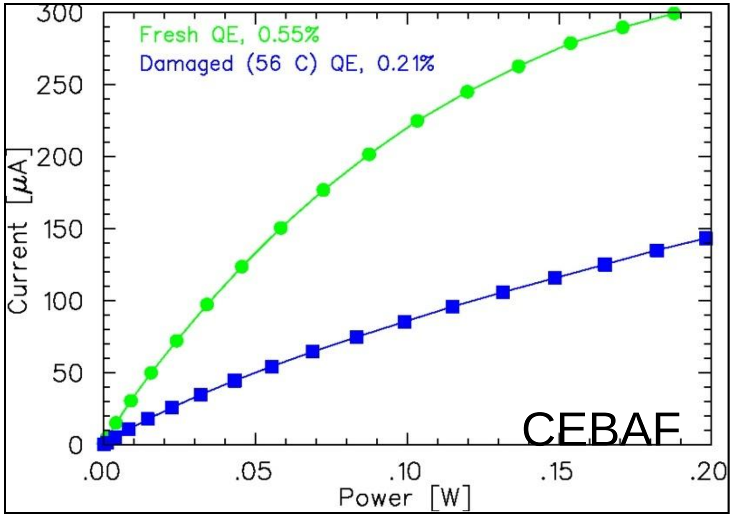
QE reduction at high laser power



Nagoya



Peak to peak spacing 2.8ns,
bunchwidth 0.7ns, Charge: 1nC/bunch



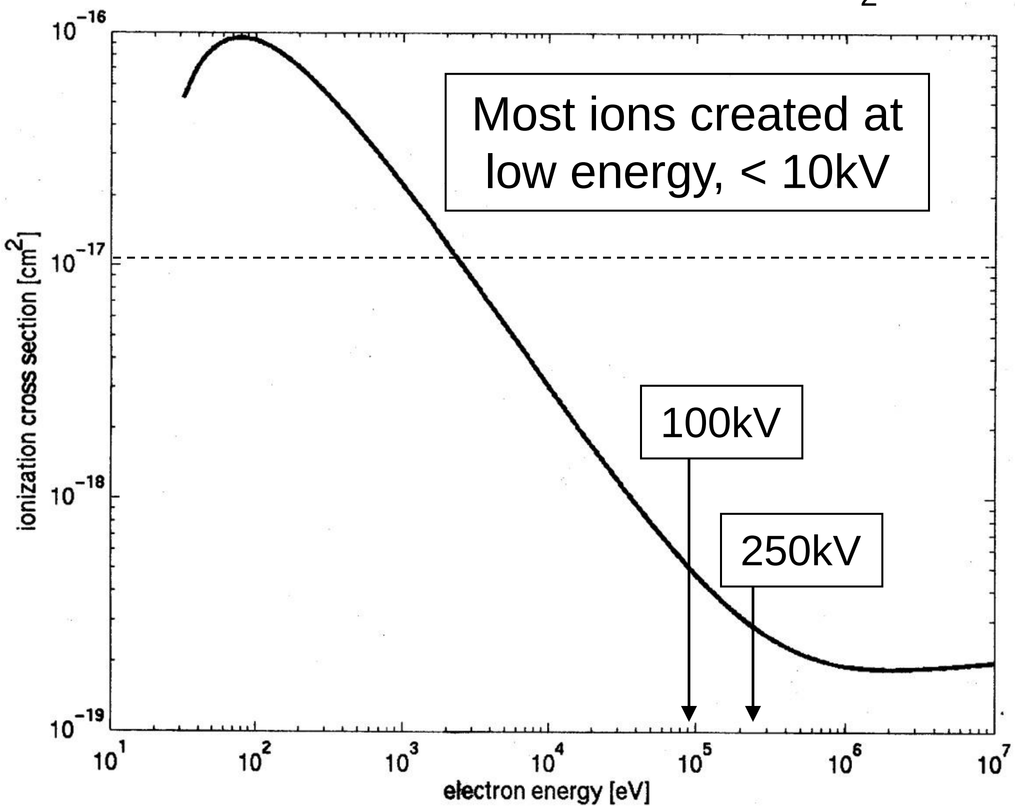
Heavily doped surface: viable solution?

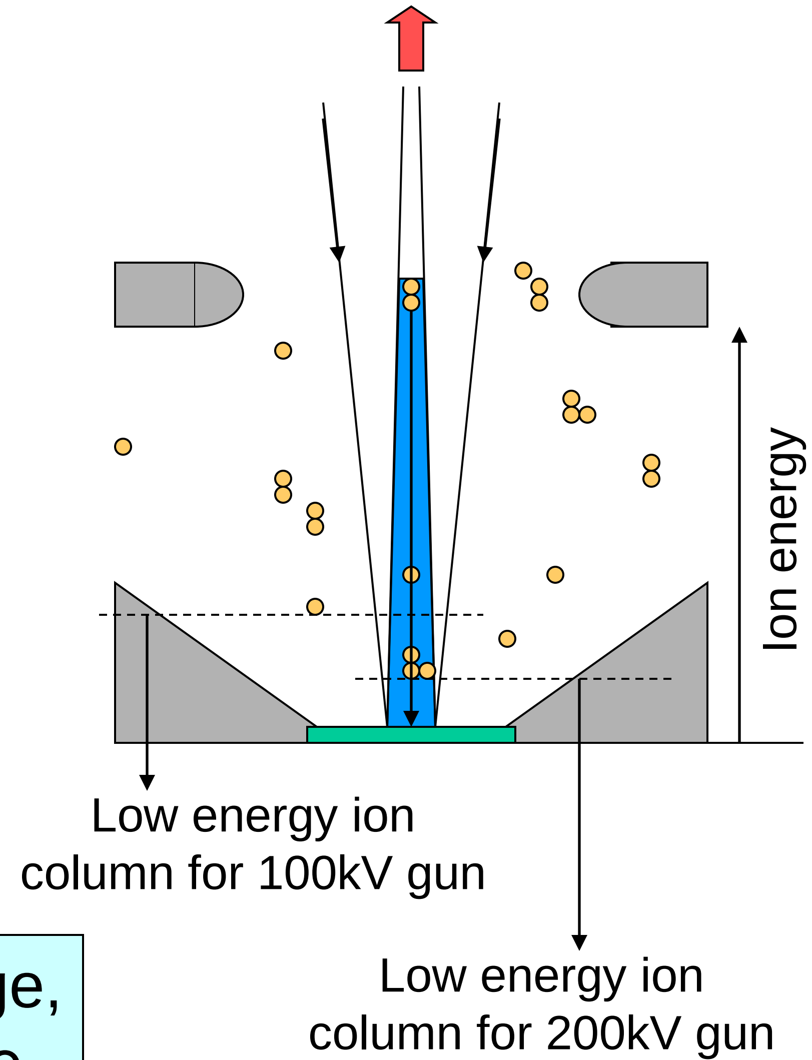
5.5 A/cm2 @ SLAC for 780 nm, 75 ns pulse
9.7 A/cm2 @ Nagoya for 780 nm, 30 ps

CLIC current density comparable to these values…something to worry about. Need to identify factors that lead to SCL,
Will higher voltage help?

Improve Lifetime with Higher Bias Voltage?

Ionization cross section for H_2

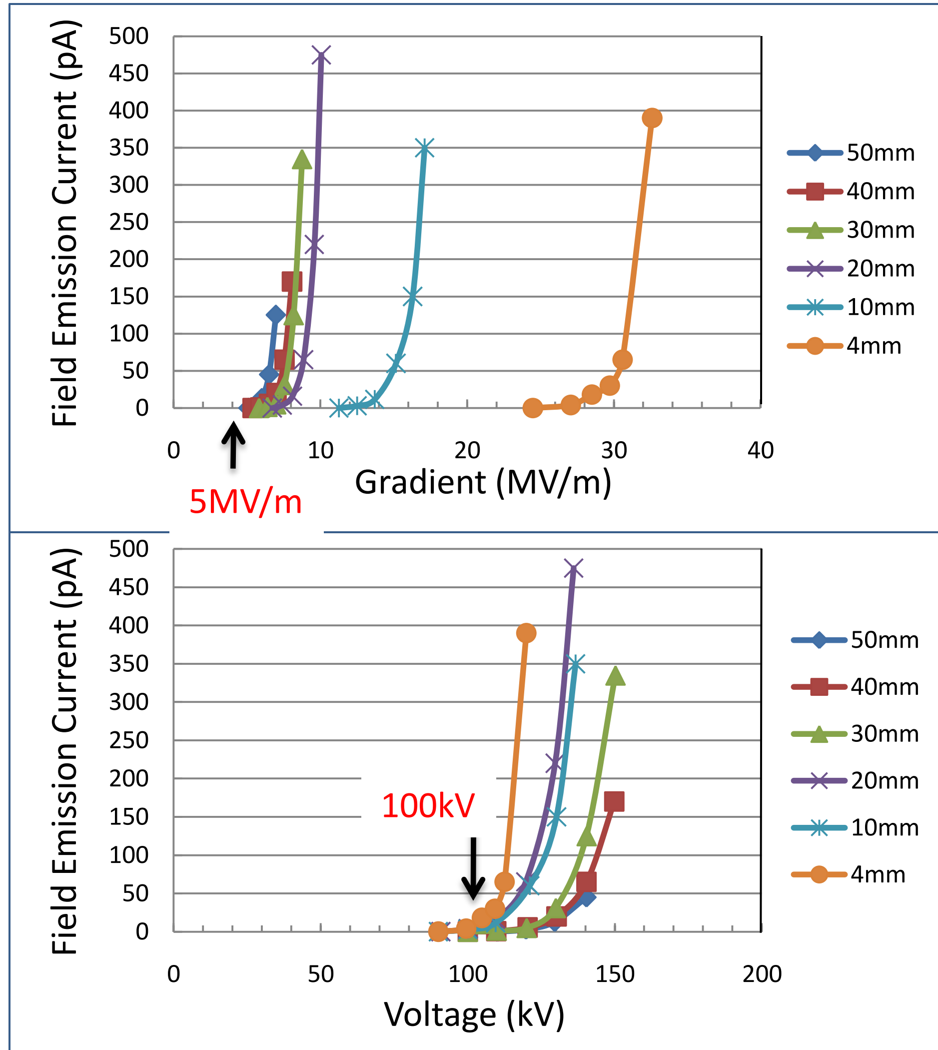




Hypothesis: Double the gun voltage, halve the # of “bad” ions, improve lifetime by 2

Field Emission – Most Important Issue

Stainless Steel and Diamond-Paste Polishing Good to ~ 5MV/m and 100kV.

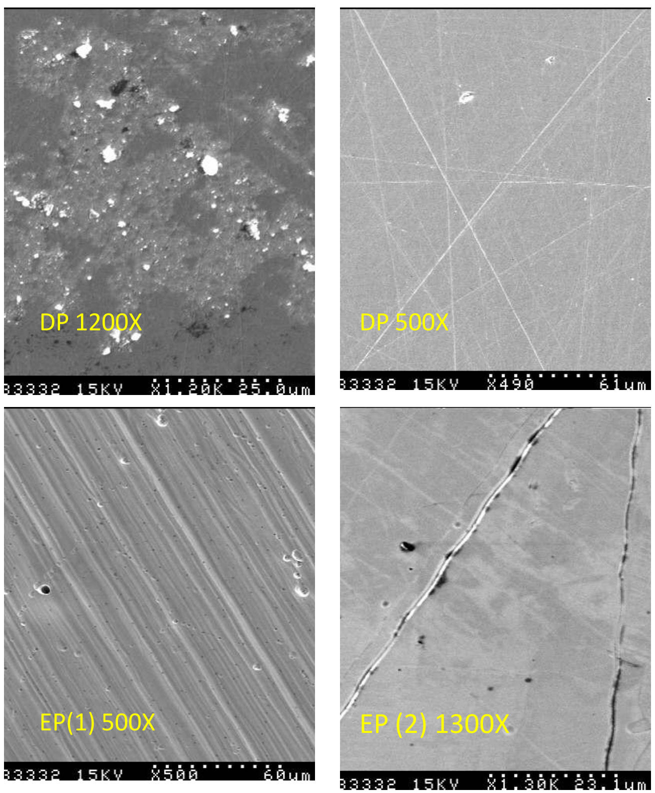


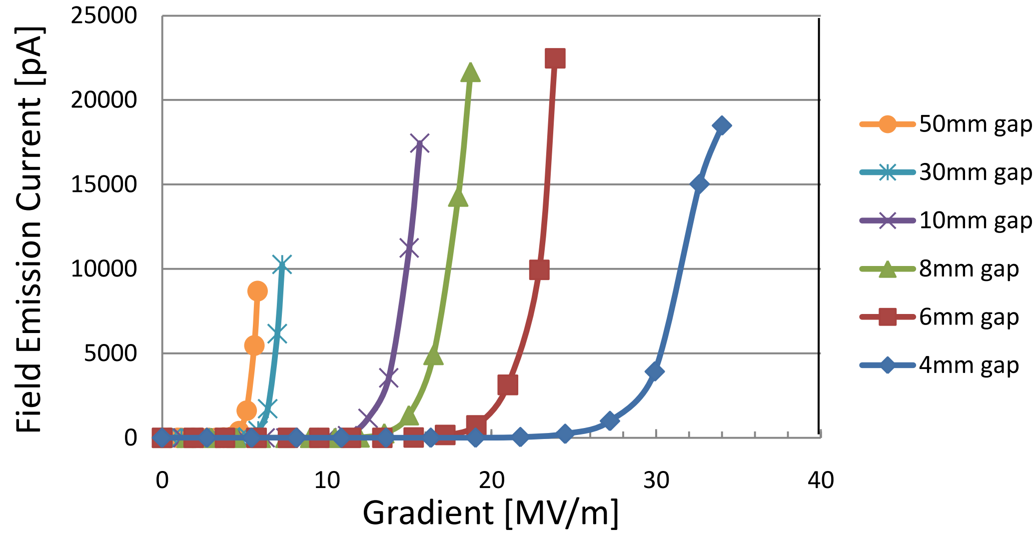
- Flat electrodes and small gaps not very useful
- Want to keep gun dimensions about the same – suggests our 200kV gun needs "quiet" electrodes to 10MV/m

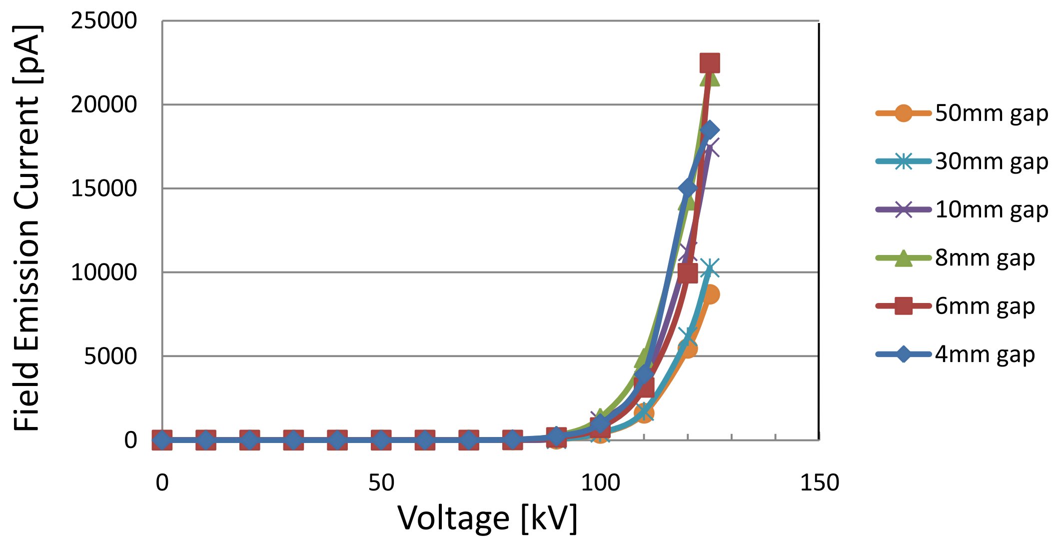
Work of Ken Surles-Law, Jefferson Lab

Electropolished Stainless Steel

- Results similar to diamond-paste polishing: limiting gradient 5MV/m
- Considerable time saving
- Perhaps better results if we start with smoother surface



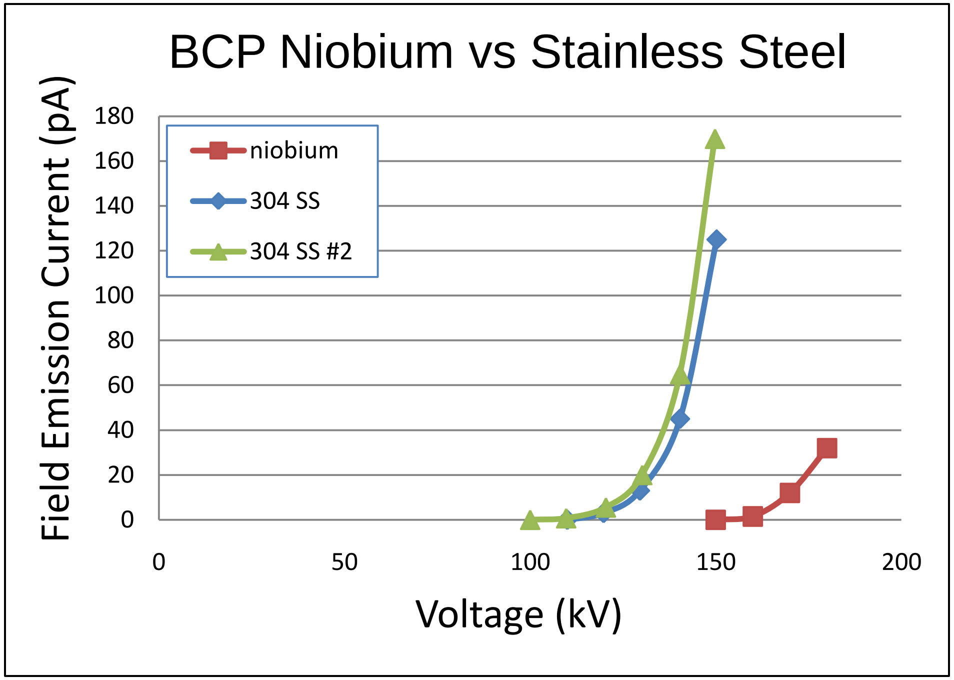




Work of Ken Surles-Law, Jefferson Lab

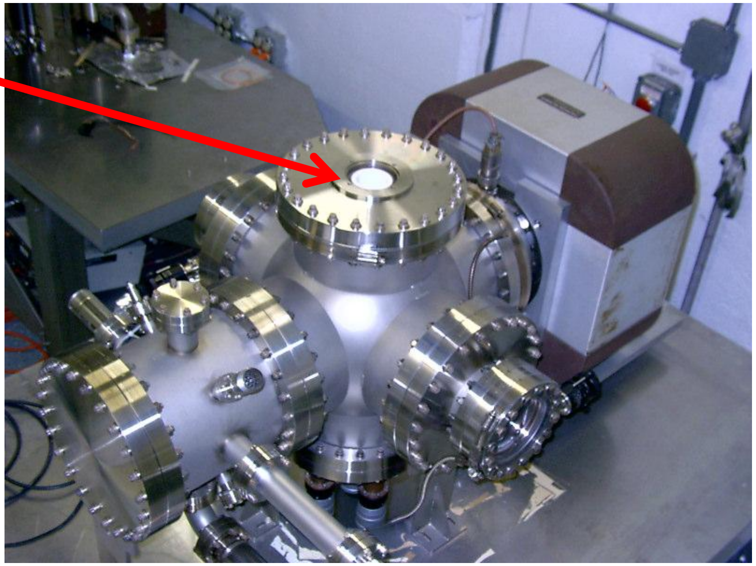
Single Crystal Niobium:

- Capable of operation at higher voltage and gradient
- Buffer chemical polish (BCP) much easier than diamond-paste-polish



Conventional geometry: cathode electrode mounted on metal support structure

Replace conventional ceramic insulator with “Inverted” insulator: no SF6 and no HV breakdown outside chamber



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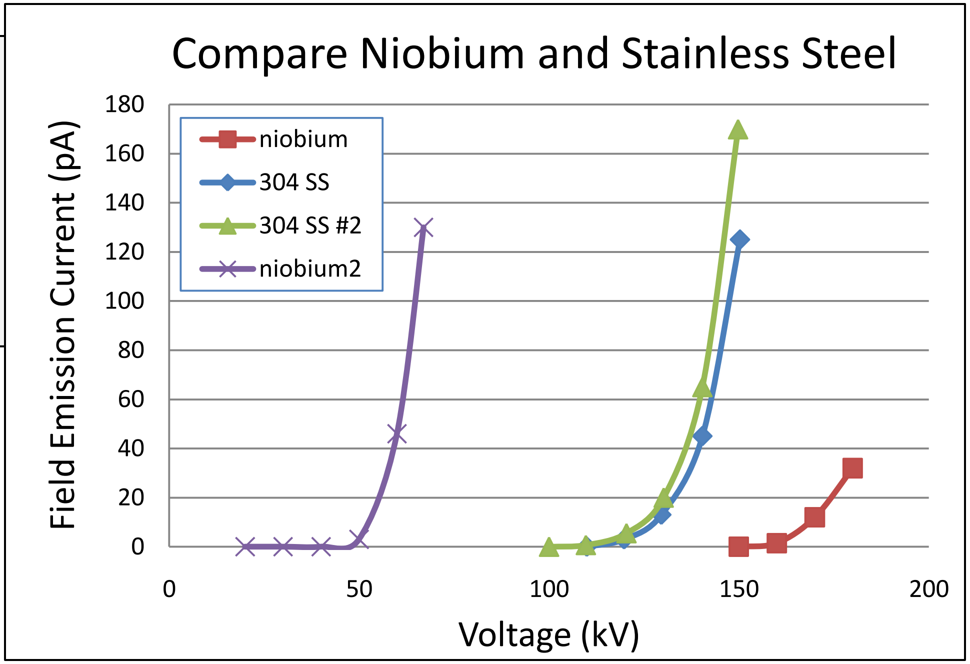

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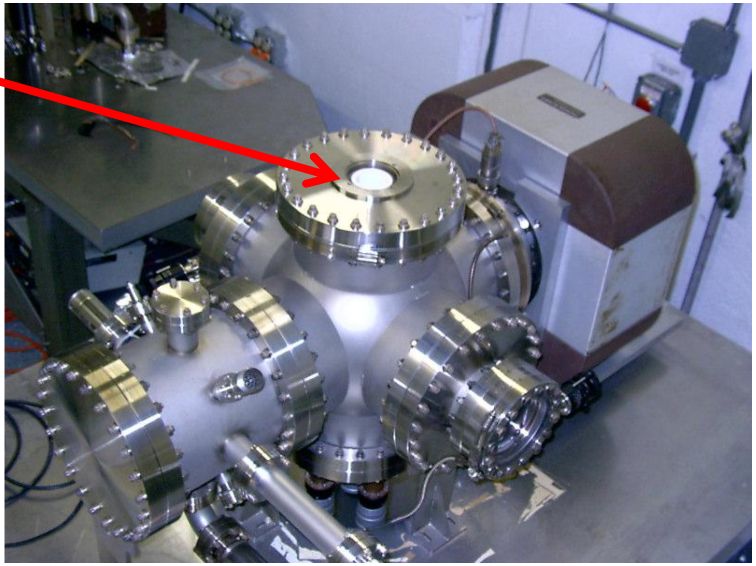

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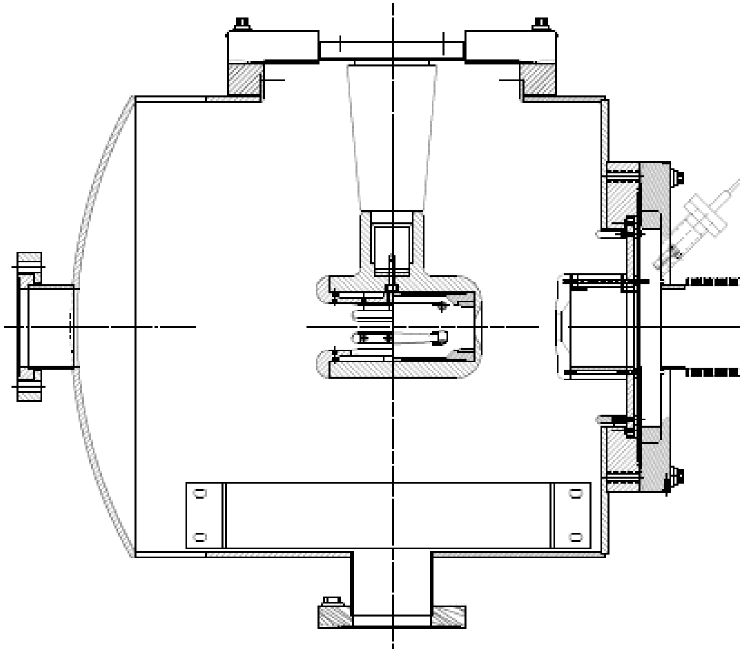
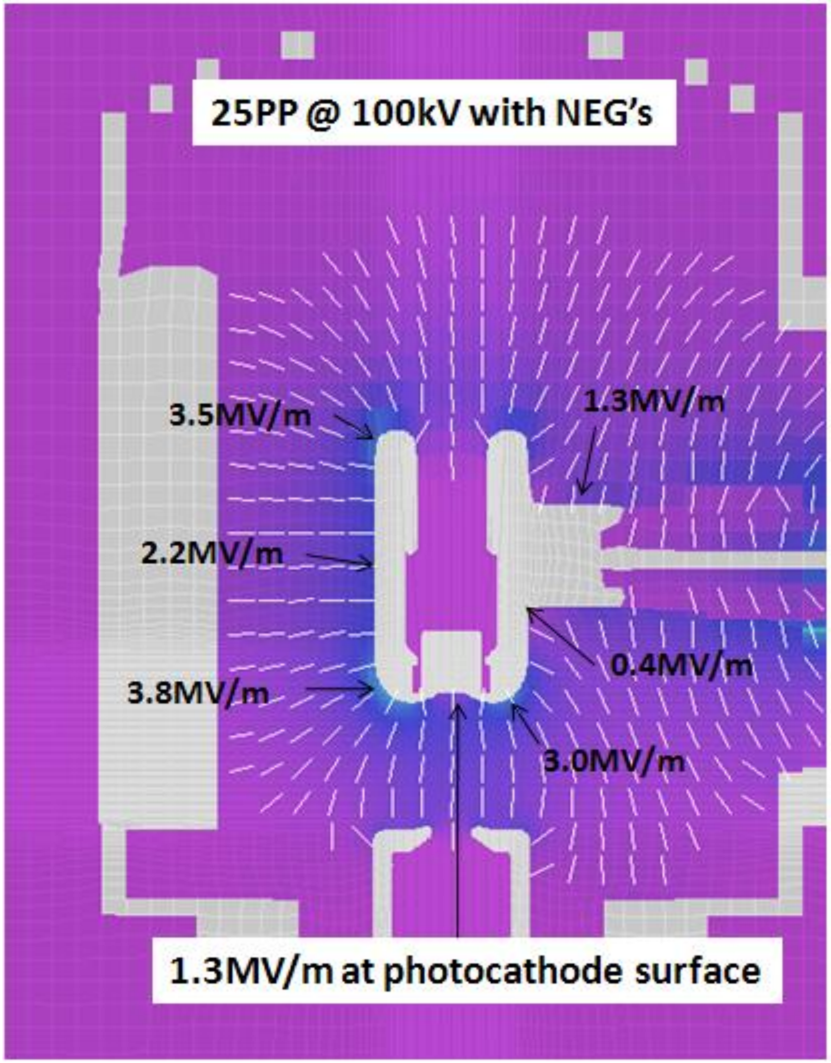
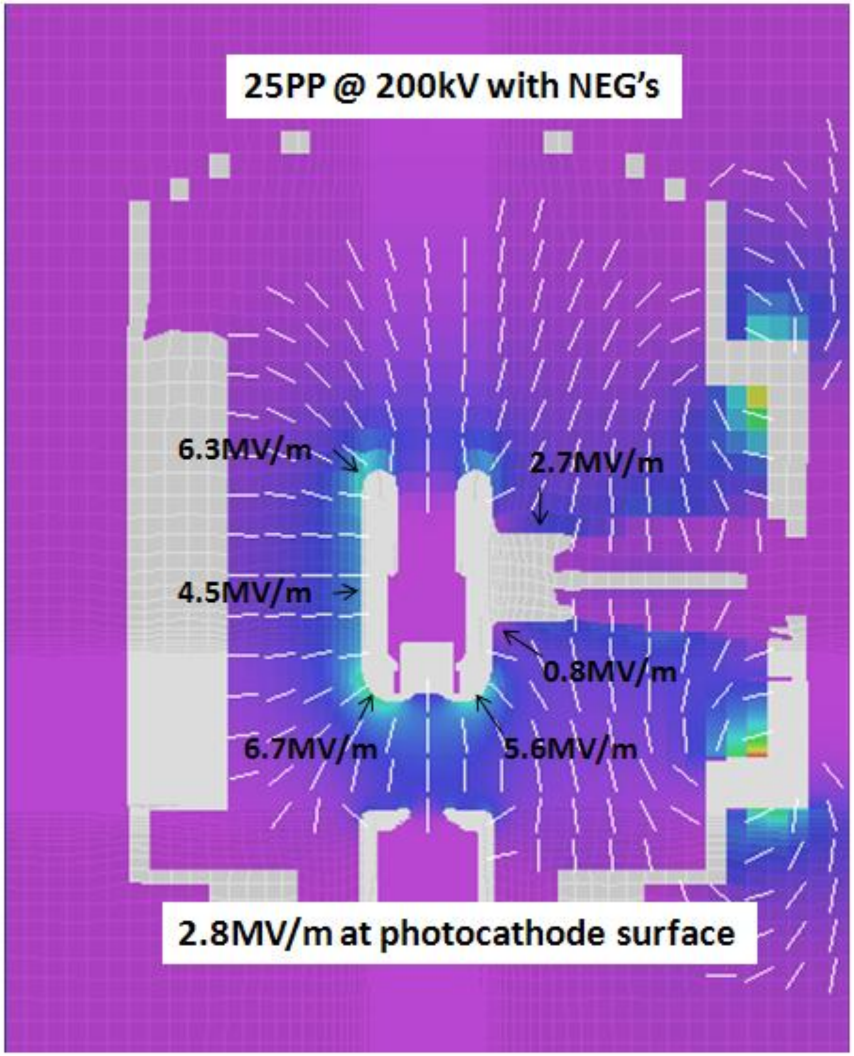


Inverted Gun at voltage > 100kV?

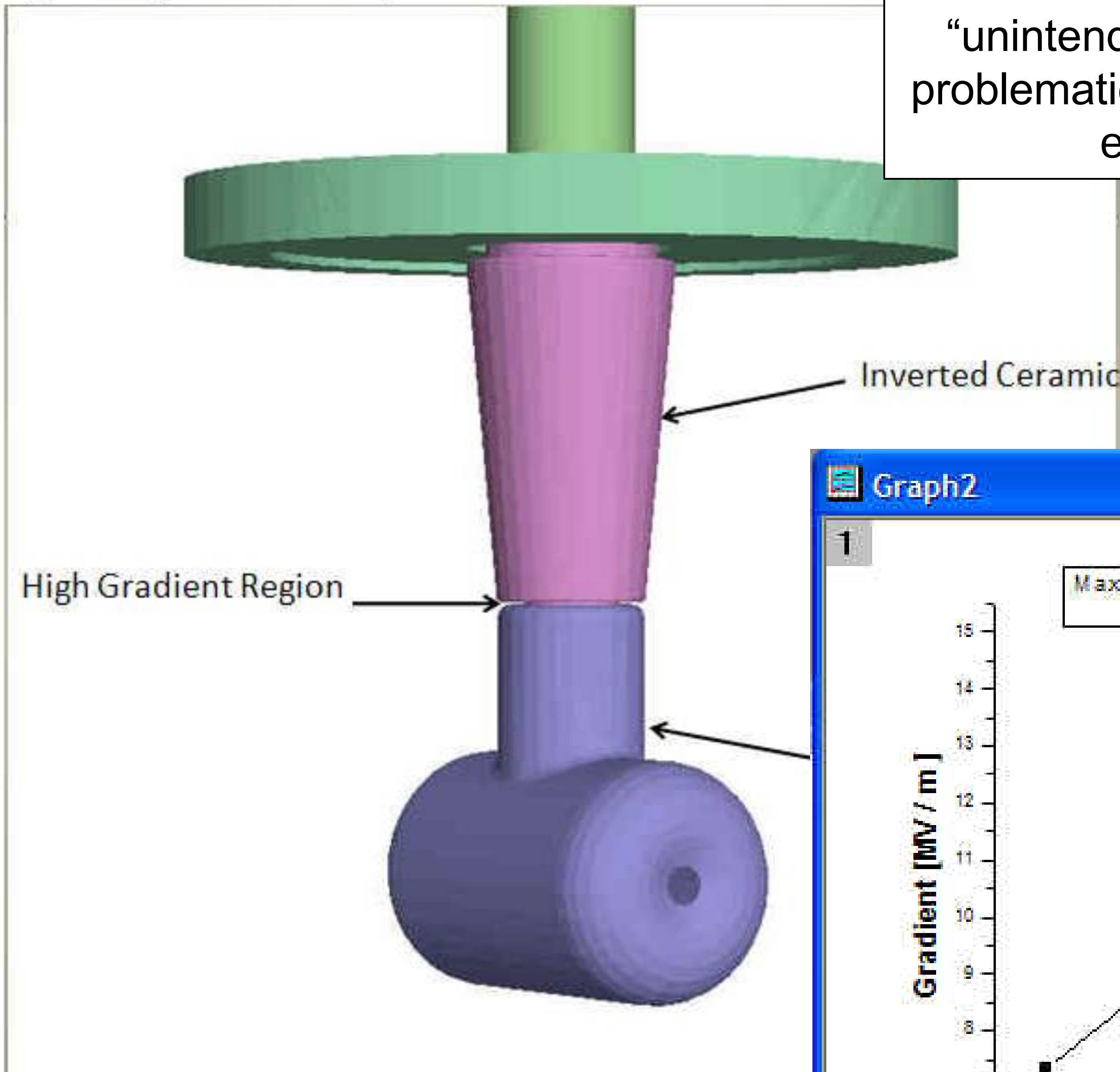




Presently limited to 150kV at CEBAF (system compatibility, e.g., pss, blue tank): 150 kV would provide "safe" gradient and likely markedly better transmission, And still get two Wien beamline…

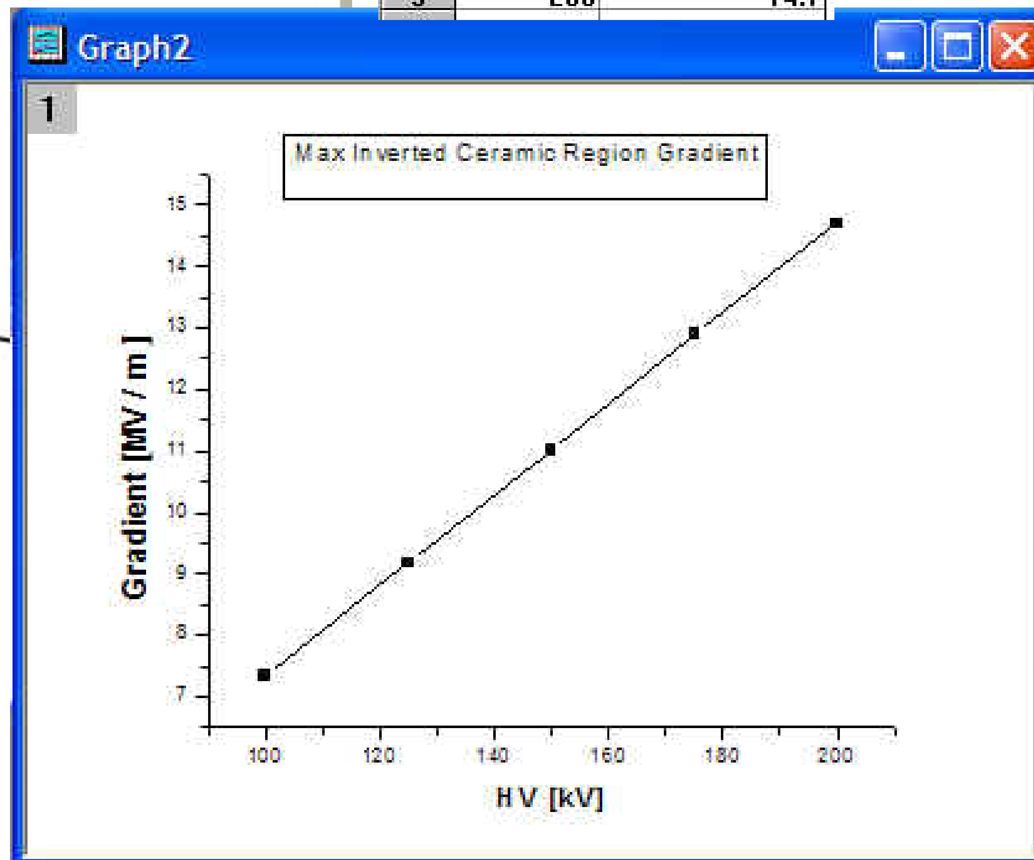
Our design has one region of “unintended” high gradient – could be problematic…..exploring new designs via electrostatic modeling

Figure 1: Highest Gradient Region



Data2 - InvCeramic Region Max ...

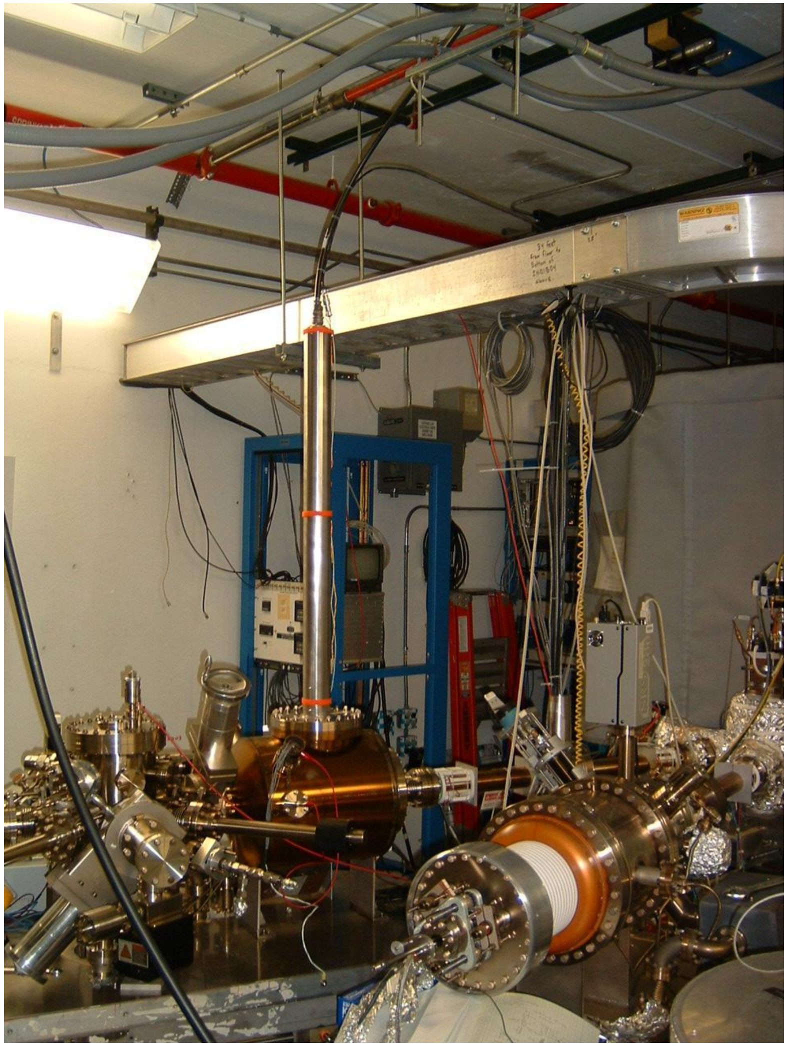
	A1(X)	A2(Y)
	HV [kV]	Gradient [MV/m]
1	100	7.35
2	125	9.18
3	150	11
4	175	12.9
5	200	14.7

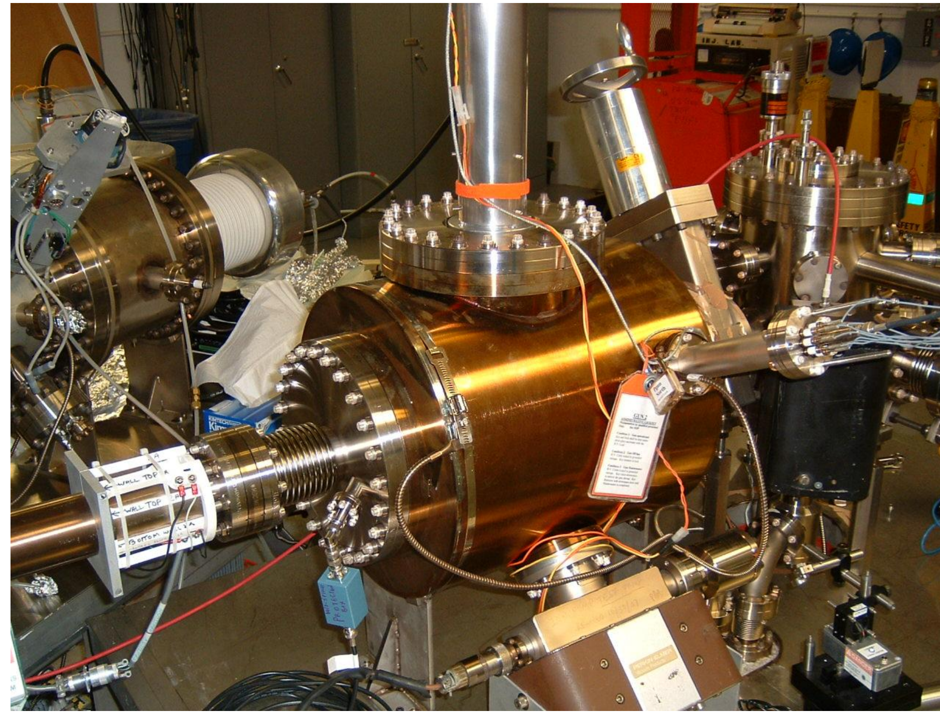


High Temperature Bake to Reduce Outgassing Rate

- As much "thin-wall" material as possible
- 316LN (L= low carbon, N= nitrogen added for hard knife edges)
- Manufactured and electropolished by NorCal
- 400C bakeout for 9 days, under vacuum
- Pumped by oil-free turbo, then added ion pump, while monitoring "effluent" with RGA
- At 9^{th} day, vacuum still improving by ~15% per 24 hours
- RGA shows H2, methane, CO and HCl (from electropolishing)
- Rate of Rise method, with spinning rotor gauge, outgassing rate 10^{-13}TL/scm^2, one order of magnitude improvement
- Vented and remeasured good rate, on test chamber
- Now working to de-gas internal components…


DuPont
Tyvek
DuPont
Tyvek



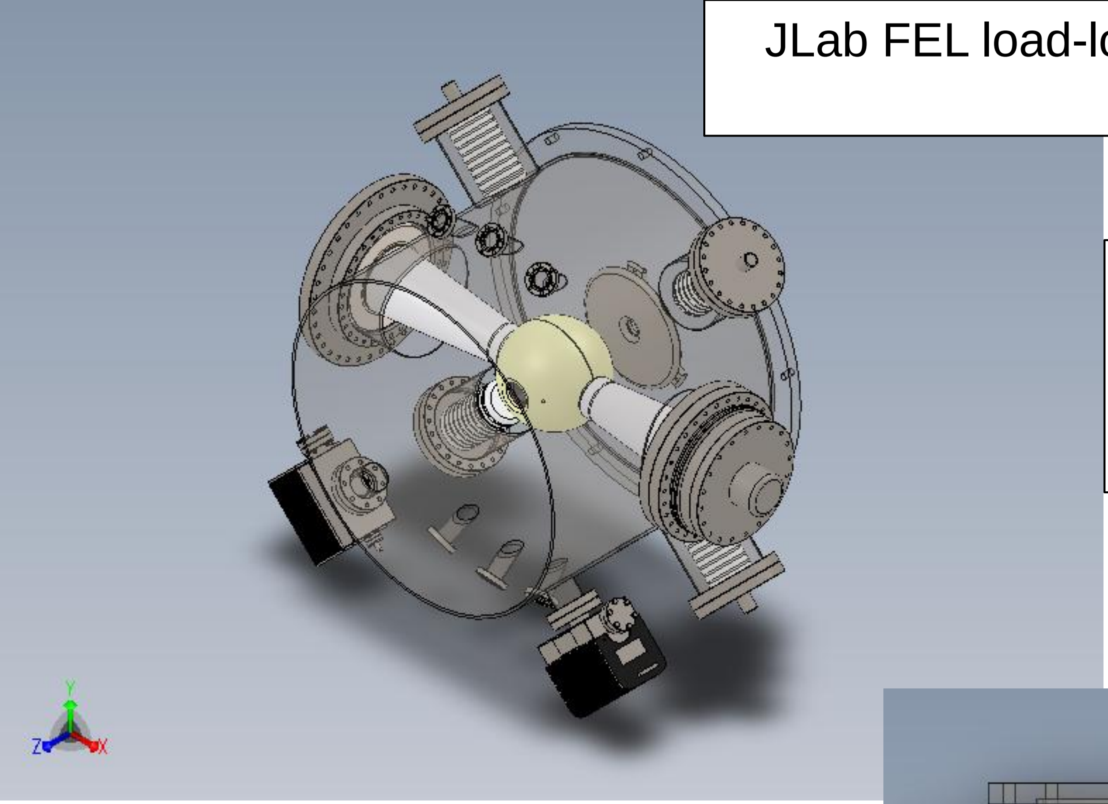


- Inverted Gun installed at CEBAF, operational since July 23, 2009
- Happy at 100kV, conditioned to 110kV, briefly went to 125kV
- Opportunity at CEBAF for operation > 100kV
- Lifetime ~ 75C at 130uA ave. current
- Aggressive commissioning of 2nd InvGun at Test Cave. Should be under vacuum - with Nb electrode - by end October

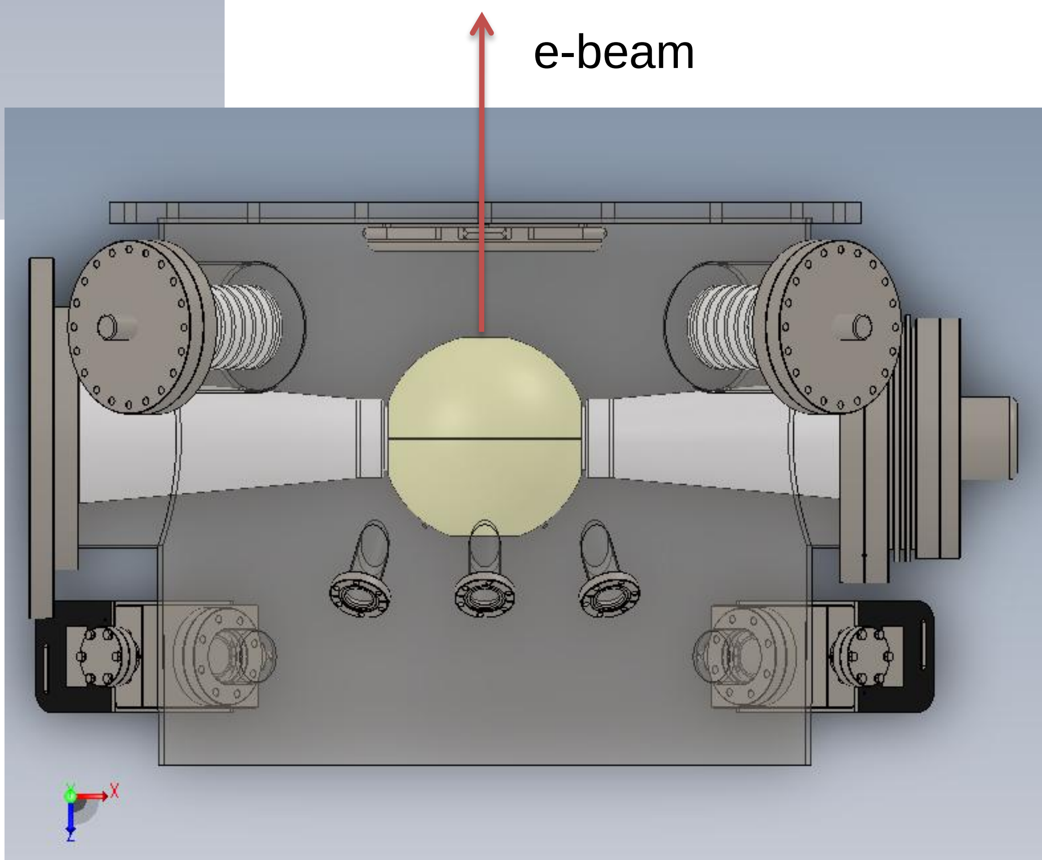
To-do List for CLIC, ILC and JLab

- Demonstrate Higher Voltage > 100kV with new inverted gun
  - 200kV for CEBAF, 350kV for ILC
  - Field emission measurements, materials and polishing techniques
  - New gun design if necessary: reduce gradient where possible, symmetric design
- Cathode/Anode Design for large laser beam
  - Uniform emittance across beam profile
  - No beam loss
- Improve Vacuum
  - NEG/ion pump limitations
  - Gauges at -13Torr
  - Cryopumping

JLab FEL load-locked gun at very high voltage, with inverted insulators



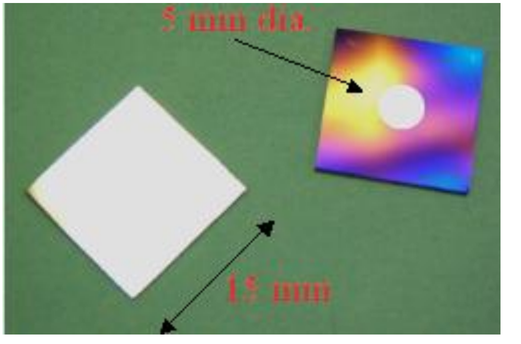
Courtesy: M. Marchlick, G. Biallis, C. Hernandez-Garcia, D. Bullard, P. Evtushenko, F. Hannon, and others from JLab-FEL



- Condition to 600kV, operate at 500kV
- 3x bigger inverted insulators
- One insulator for HV: one for cooling
- Niobium electrode – no diamond paste polishing
- Work in-progress

Cathode/Anode Design

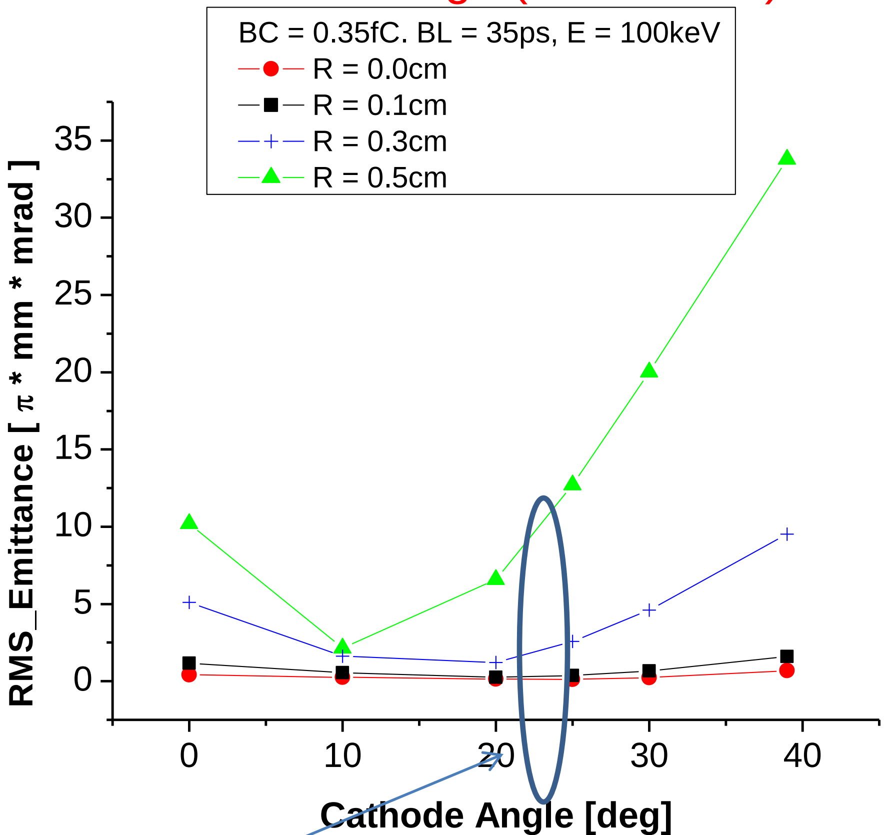
- We learned at CEBAF that it is extremely important to manage ALL of the extracted beam
  - Anodized edge: beam from outside 5 mm active area can hit beampipe walls, degrade vacuum, reduce operating lifetime



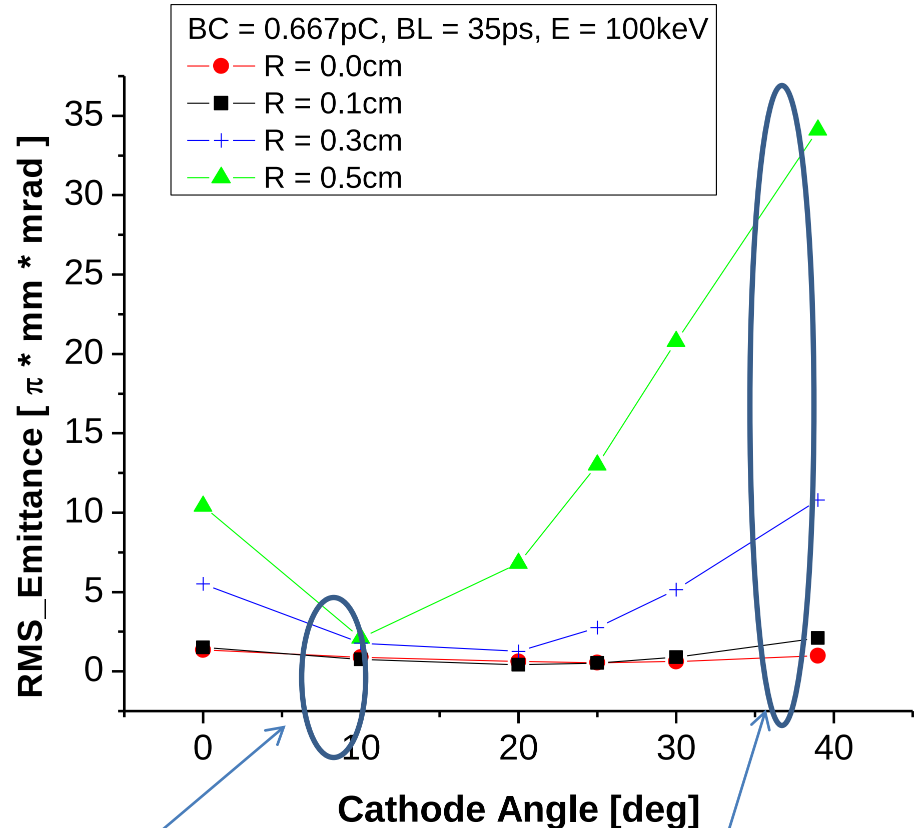
- ILC/CLIC requires large laser beam to reduce current density and overcome space and surface charge problems
- Need a cathode/anode design that ensures uniform emittance across beam profile. A beam that can be easily managed/transported, with *ZERO* beam loss.

Emittance vs. radial distance from electrostatic center
Choosing the best cathode focusing angle….

Low Bunch Charge (i.e. CEBAF)



High Bunch Charge (i.e. CLIC/ILC)

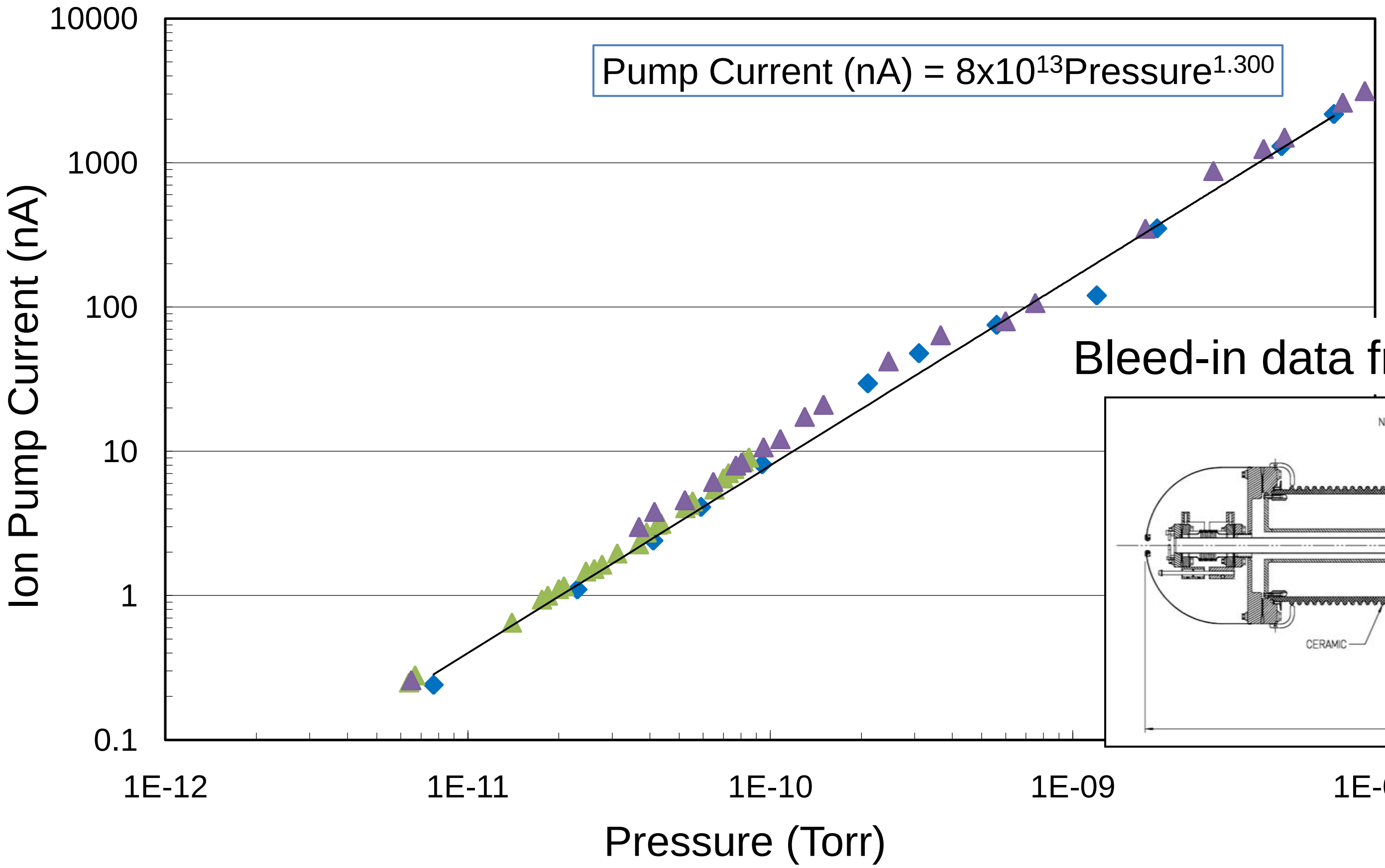


Why we can't use all of photocathode

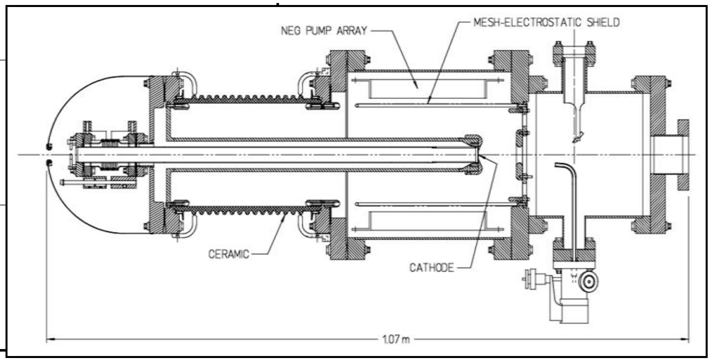
"one" beam from gun

"many" beams from gun

Do Ion Pumps Limit Ultimate Pressure?

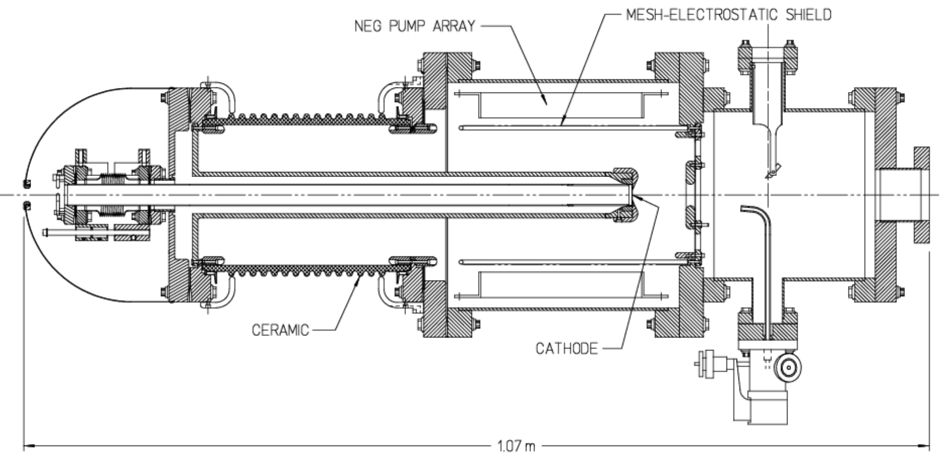


Bleed-in data from vent-bake guns



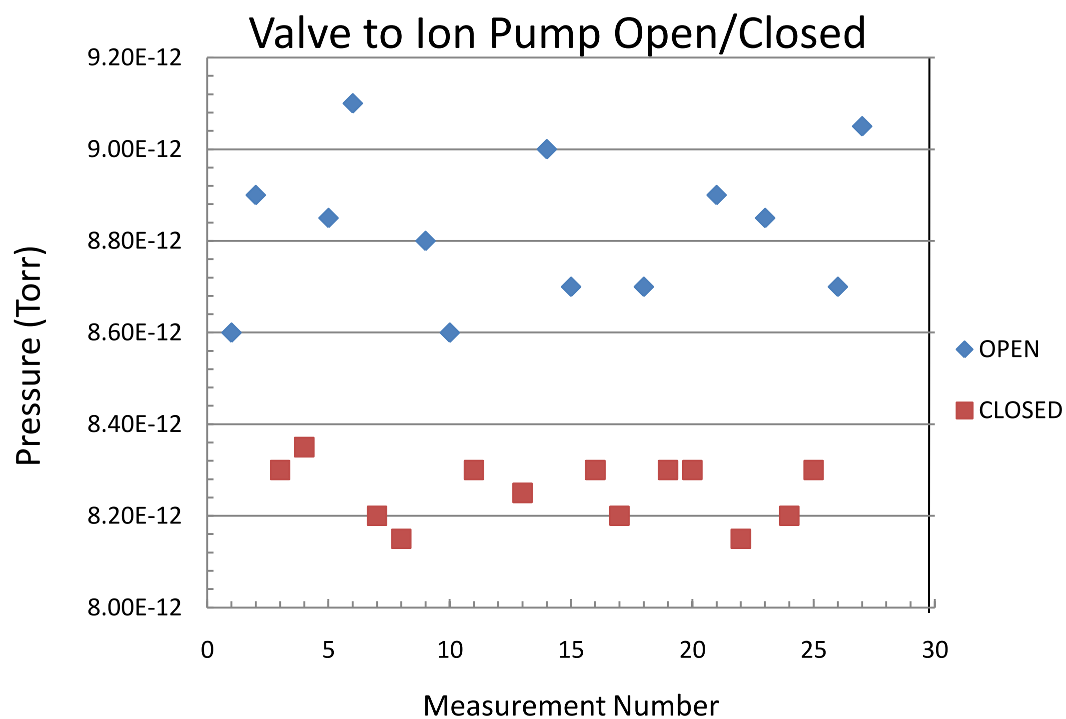
- We build guns and test stands and always measure pressure higher than expected: ~ 3e-12 to 8e-12Torr. Why?
- Pinched-off and baked ion pumps have current 0.1nA or lower. Does this mean ion pump in -12Torr range, or OFF?
- Do NEG pumps quit pumping at low pressure?
- Do gauges lie?

Vacuum Studies: Ion Pump Limitation?



Used old gun as test bed: “flapper” valve installed between gun and ion pump

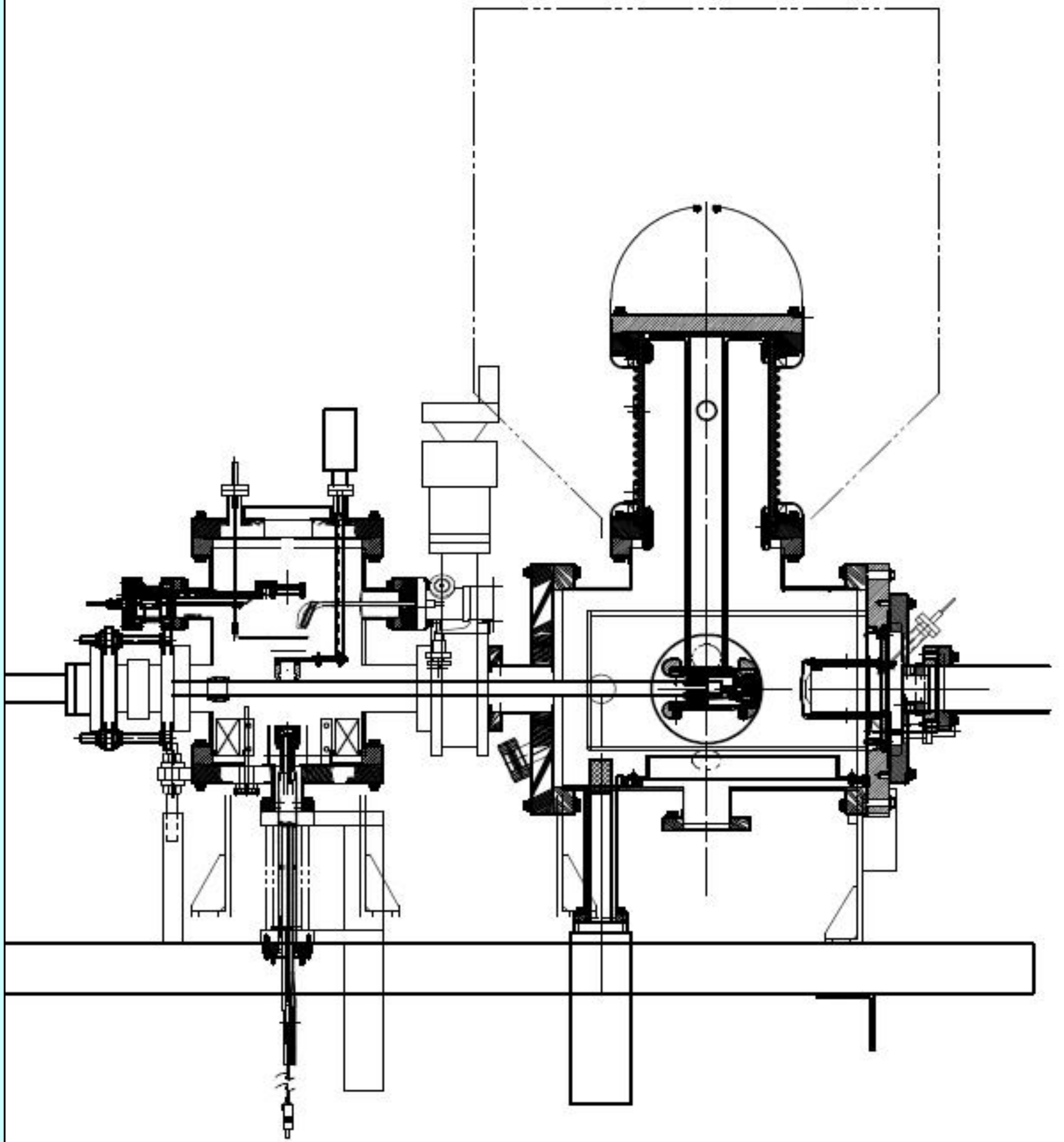
- Conventional wisdom: Ion pumps required for gasses not pumped by NEGs – but might be limiting our ultimate pressure.
- Beam tests so far inconclusive
- Stutzman with test stand to explore these issues……



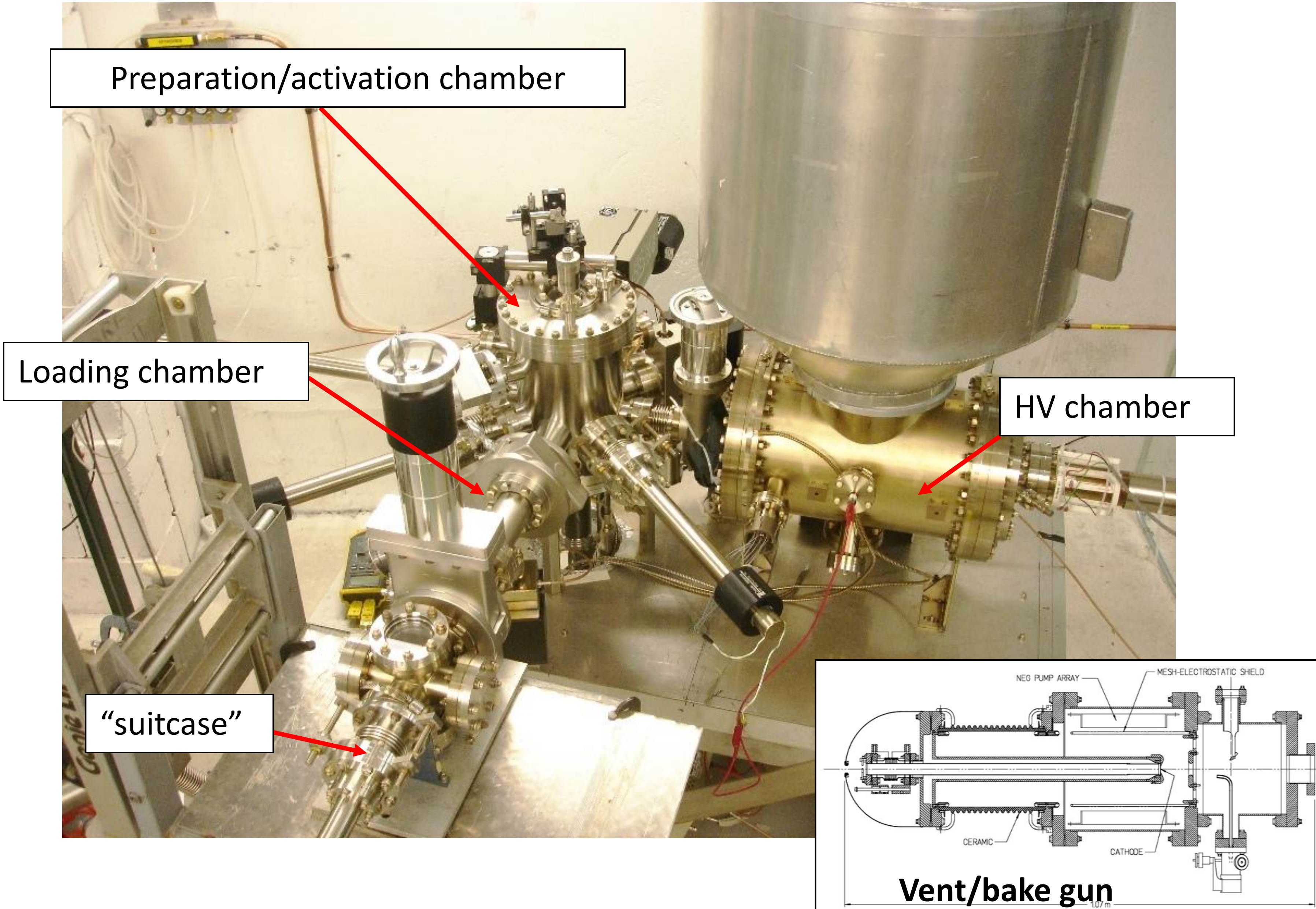
BACK-UP SLIDES

Key Features:

- Smaller surface area
- Electropolished and vacuum fired to limit outgassing
- NEG-coated
- Never vented
- Multiple pucks (8 hours to heat/activate new sample)
- Suitcase for installing new photocathodes (one day to replace all pucks)
- Mask to limit active area, no more anodizing

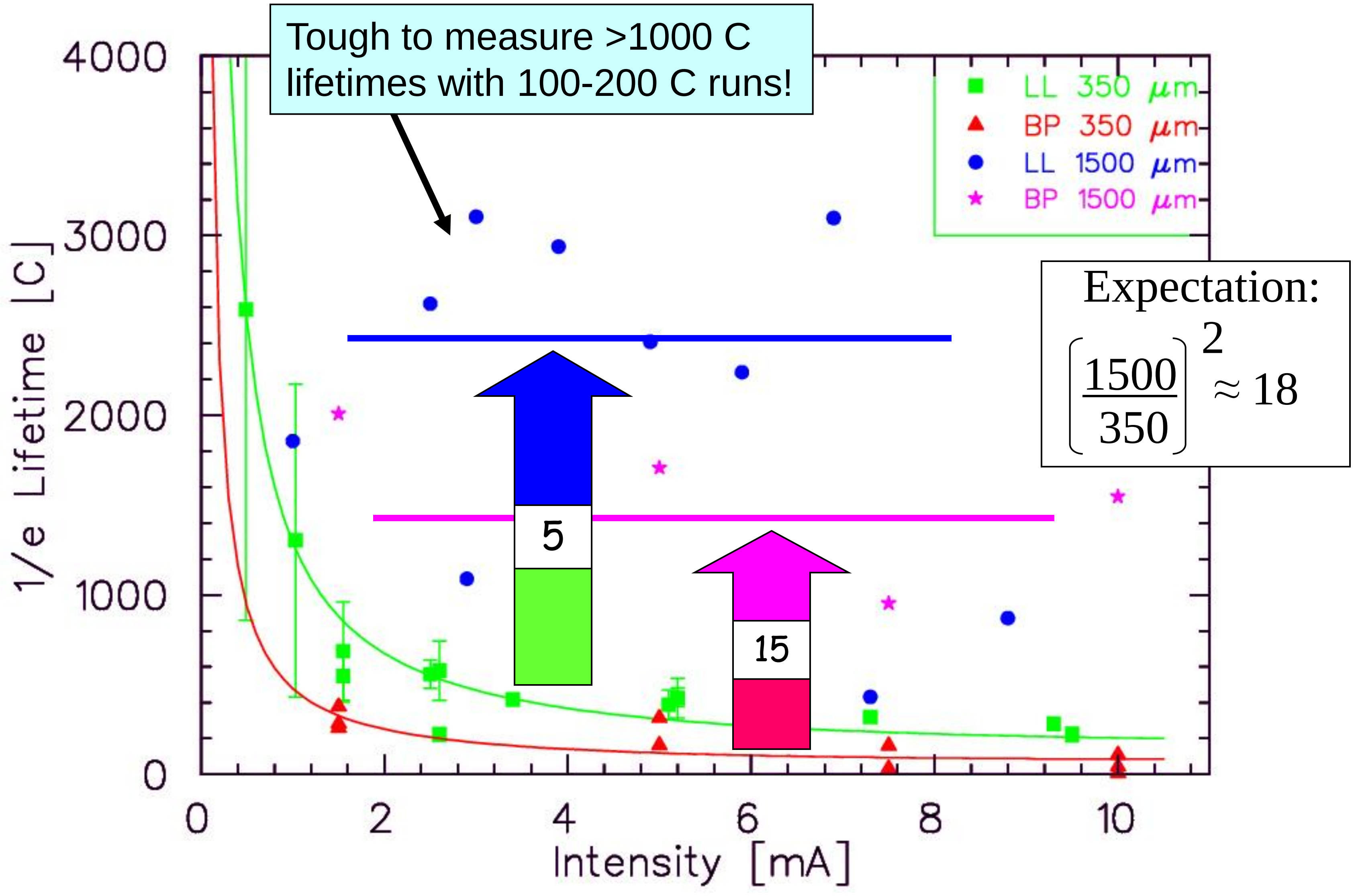


New CEBAF load-locked gun



Vent/bake gun

Lifetime with Large/Small Laser Spots



"Further Measurements of Photocathode Operational Lifetime at Beam Current > 1mA using an Improved 100 kV DC High Voltage_GaAs Photogun," J. Grames, et al., Proceedings Polarized Electron Source Workshop, SPIN06, Tokyo, Japan

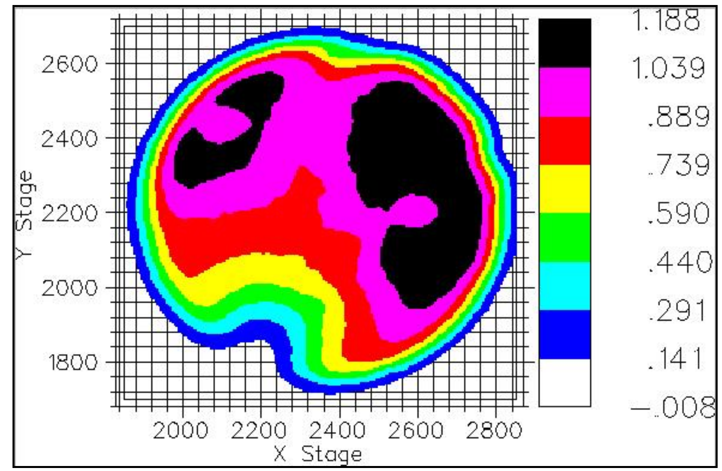
1mA at High Polarization*

Parameter	Value
Laser Rep Rate	499 MHz
Laser Pulselength	30 ps
Wavelength	780 nm
Laser Spot Size	450 mm
Current	1 mA
Duration	8.25 hr
Charge	30.3 C
Lifetime	210 C
#How long at 1mA?	10.5 days

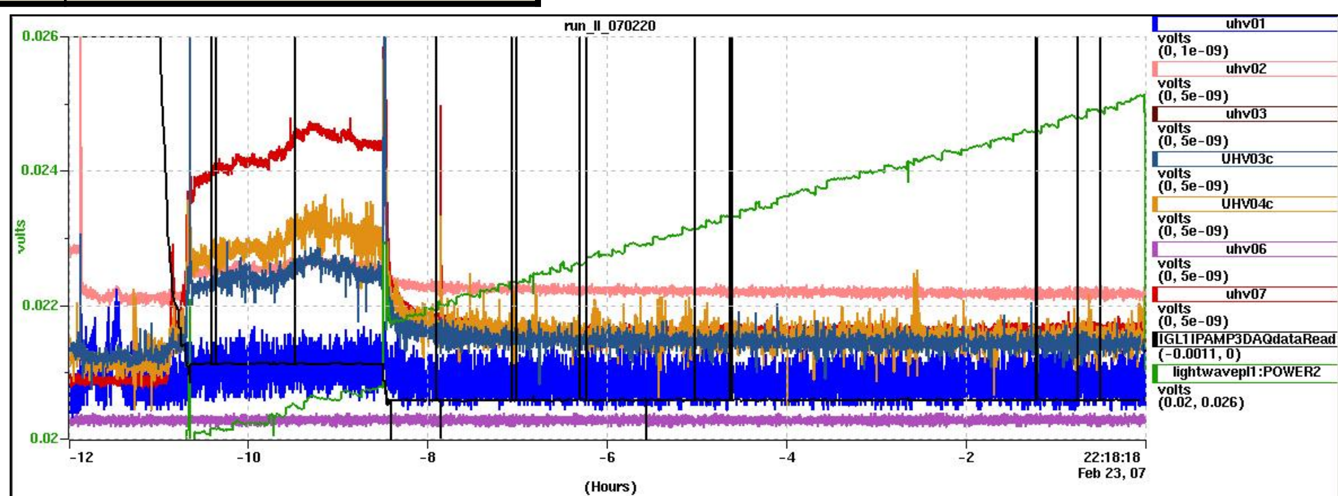
prediction with 10W laser

*** Note: did not actually measure polarization**

High Initial QE



Vacuum signals
Laser Power
Beam Current



ILC e- Beam Time Structure

ILC e-Beam Source Parameters

Parameter	Symbol	Value
Number Electrons per microbunch	N_e	3×10^{10}
Number of microbunches	n_b	3000
Width of microbunch	t_b	~ 1 ns
Time between microbunches	Δt_b	337 ns
Microbunch rep rate	f_b	3 MHz
Width of macropulse	T_B	1 ms
Macropulse repetition rate	F_B	5 Hz
Charge per micropulse	C_b	4.8 nC
Charge per macropulse	C_B	14420 nC
Average current from gun (C_B x F_B)	I_{ave}	72 uA
Average current macropulse (C_B / T_B)	I_B	14.4 mA
Duty Factor within macropulse (1ns/337ns)	DF	$3\text{x}10^{-3}$
Peak current of micropulse (I_B / DF)	I_{peak}	4.8 A

laser ←

gun ←

vacuum ←

photo cathode ←

Comparison between different bunch charge