Polarized Electron Sources for the ILC and CLIC

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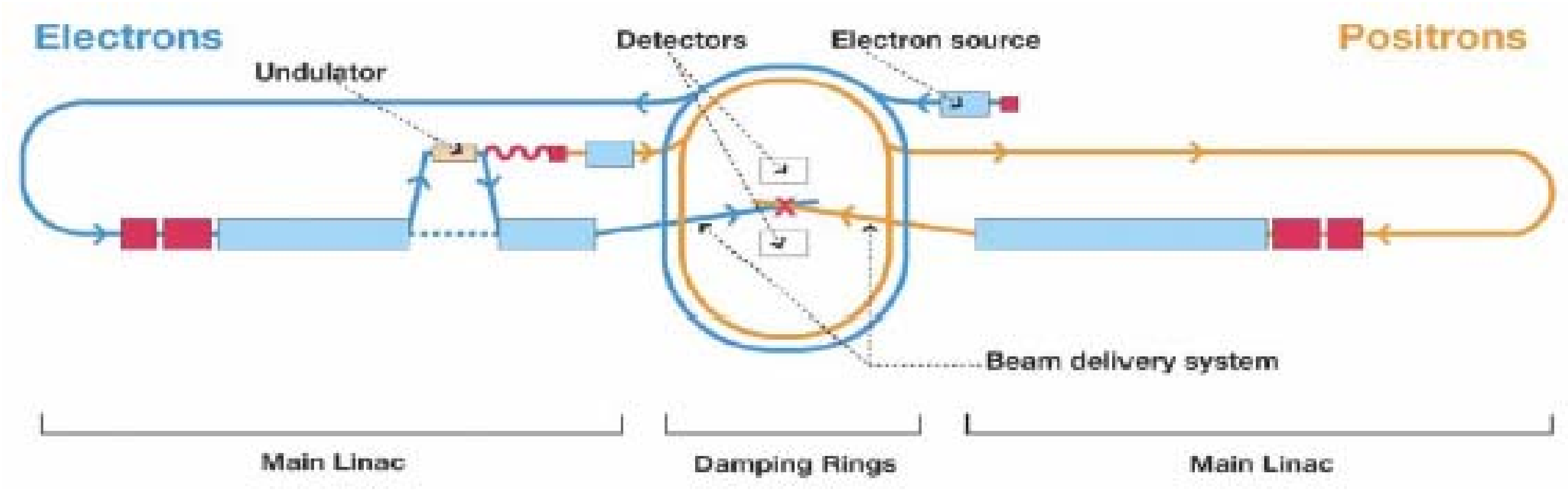
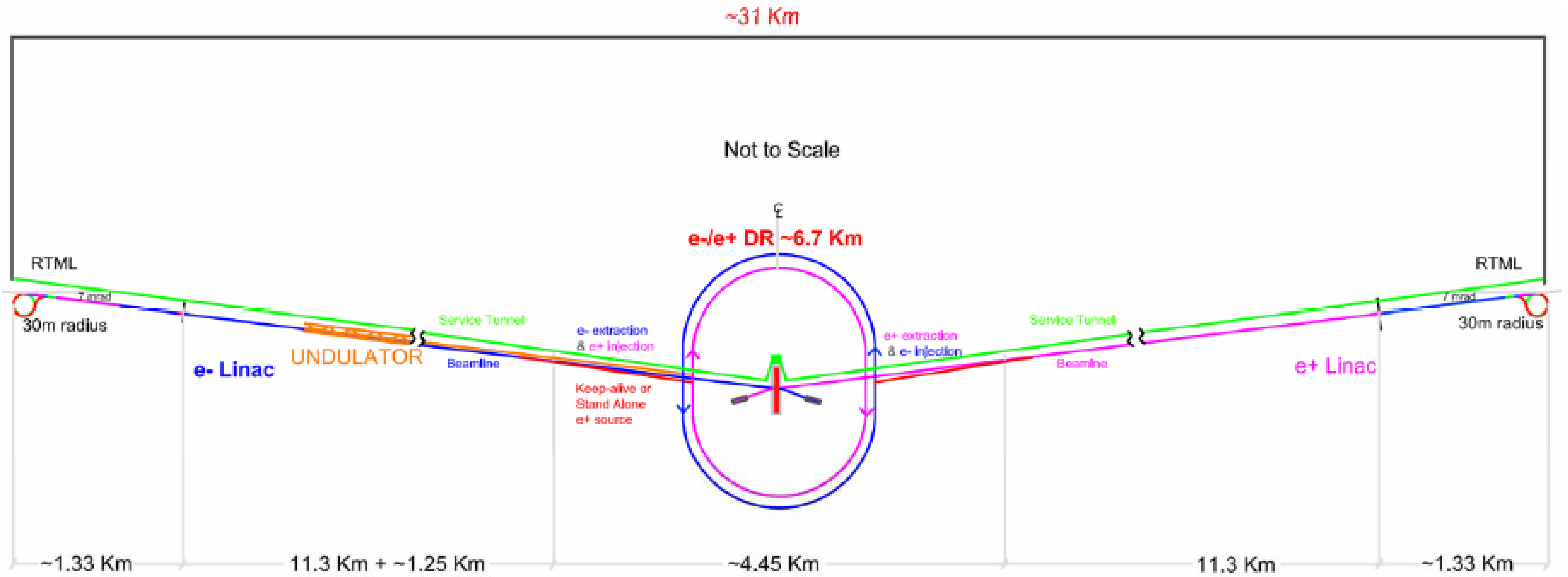
Some perspective: Gun R&D Projects at JLab

Growing into a "Center for Injectors and Sources"…

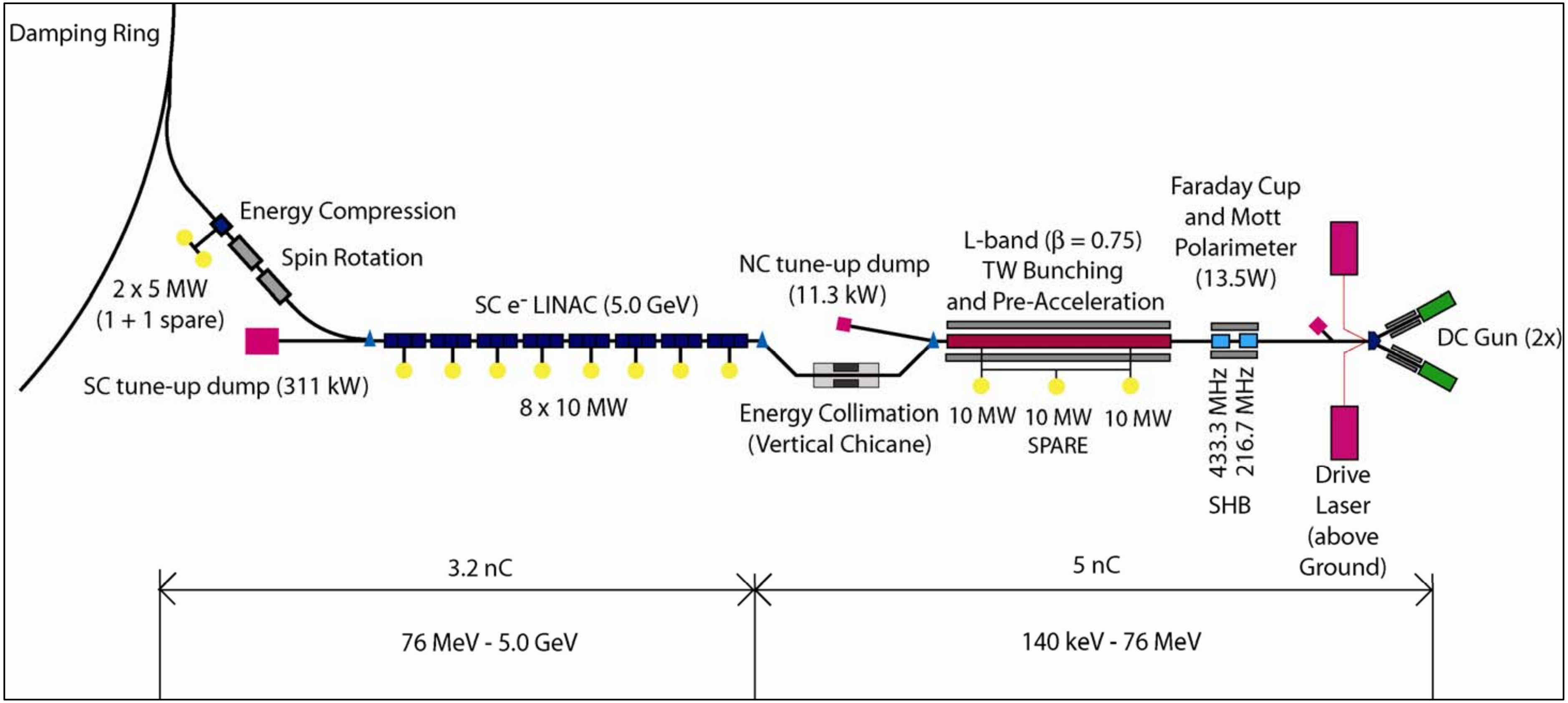
- New and improved CEBAF photoinjector, including gun at ~ 200kV and SRF ¼ cryounit with internal graded-beta capture. (Note: Max gun voltage set by chopper power limitation) Very Expensive
- Design and build gun for ILC: pulsed, high charge/microbunch, 100uA ave. current, polarized $
- Design gun for CLIC: pulsed with high rep rate microstructure, very high peak current and current density, polarized No $, only notoriety
- Continue high current studies (> 1mA at high polarization) with new LL-gun at test cave. EIC application (mostly eRHIC)
- Contribute to FEL Gun development. Shared Challenges, e.g., reliable HV operation, load lock design, etc. Shared Resources
- Positron source: 2mA ave current, 10MeV, high rep rate, small bunch charge Thermionic Gun?
- RF-gun? Polarized and CW – the big challenges

ILC

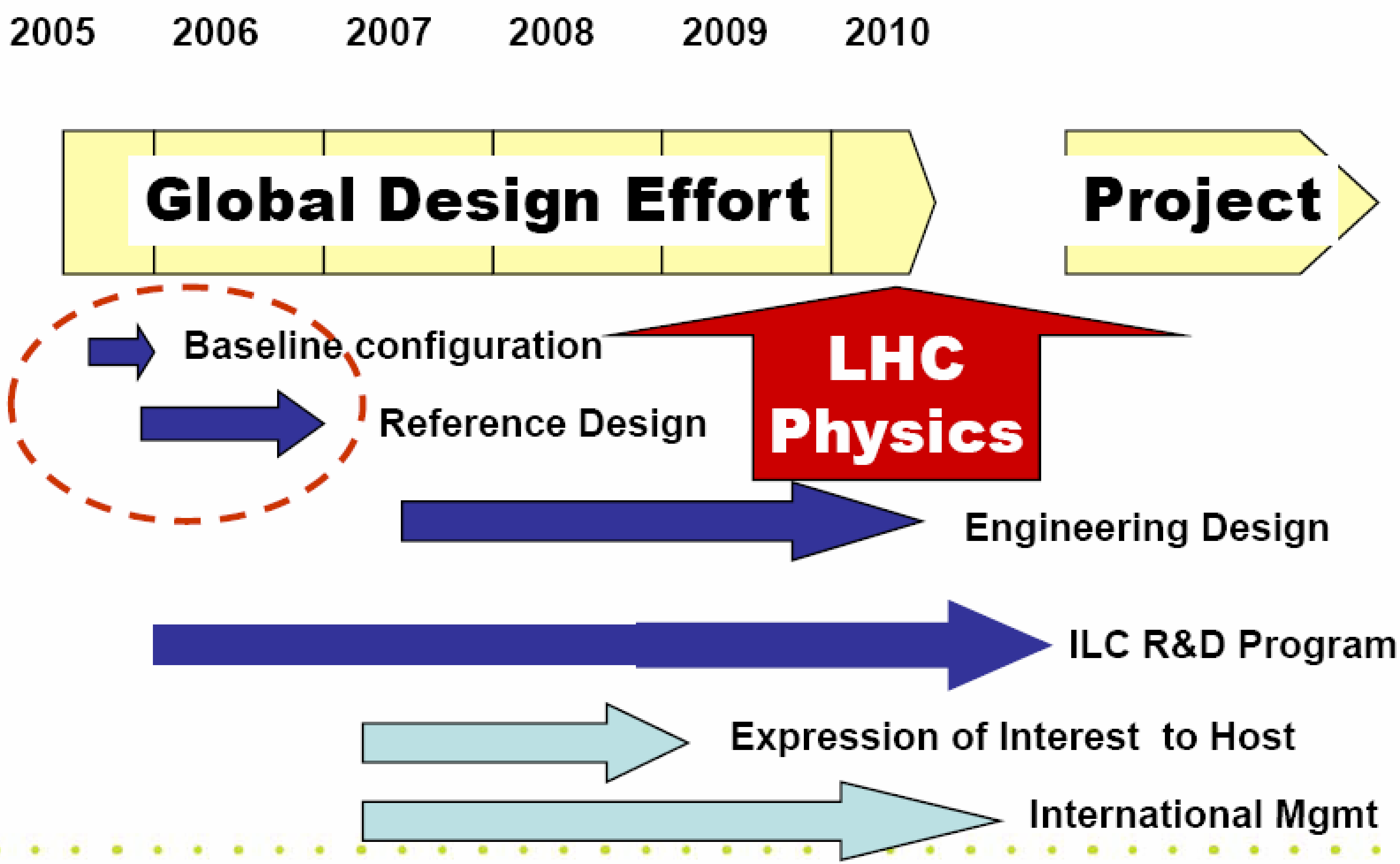

Electrons
Undulator
Detectors
Electron source
Positrons
Beam delivery system
Main Linac
Damping Rings
Main Linac


~31 Km
Not to Scale
e-/e+ DR ~6.7 Km
RTML
RTML
30m radius
30m radius
7 mrad
7 mrad
e- Linac
UNDULATOR
Service Tunnel
Beamline
e- extraction
& e+ injection
Keep-alive or
Stand Alone
e+ source
e+ extraction
& e- injection
Service Tunnel
Beamline
e+ Linac
~1.33 Km
11.3 Km + ~1.25 Km
~4.45 Km
11.3 Km
~1.33 Km

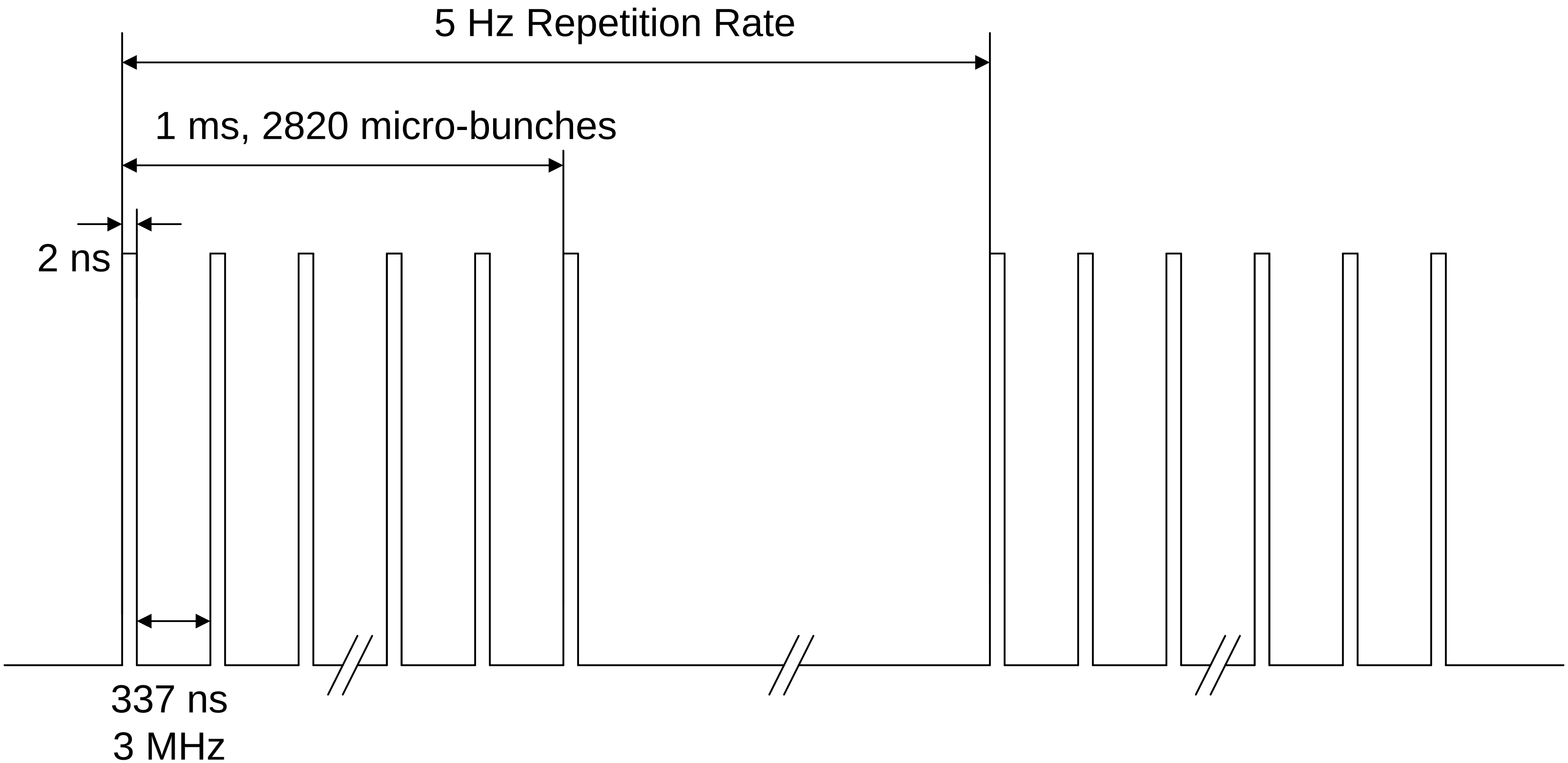
ILC e-Source Photoinjector



The GDE Plan and Schedule



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	3×10^{-3}
Peak current of micropulse (I_B / DF)	I_{peak}	4.8 A

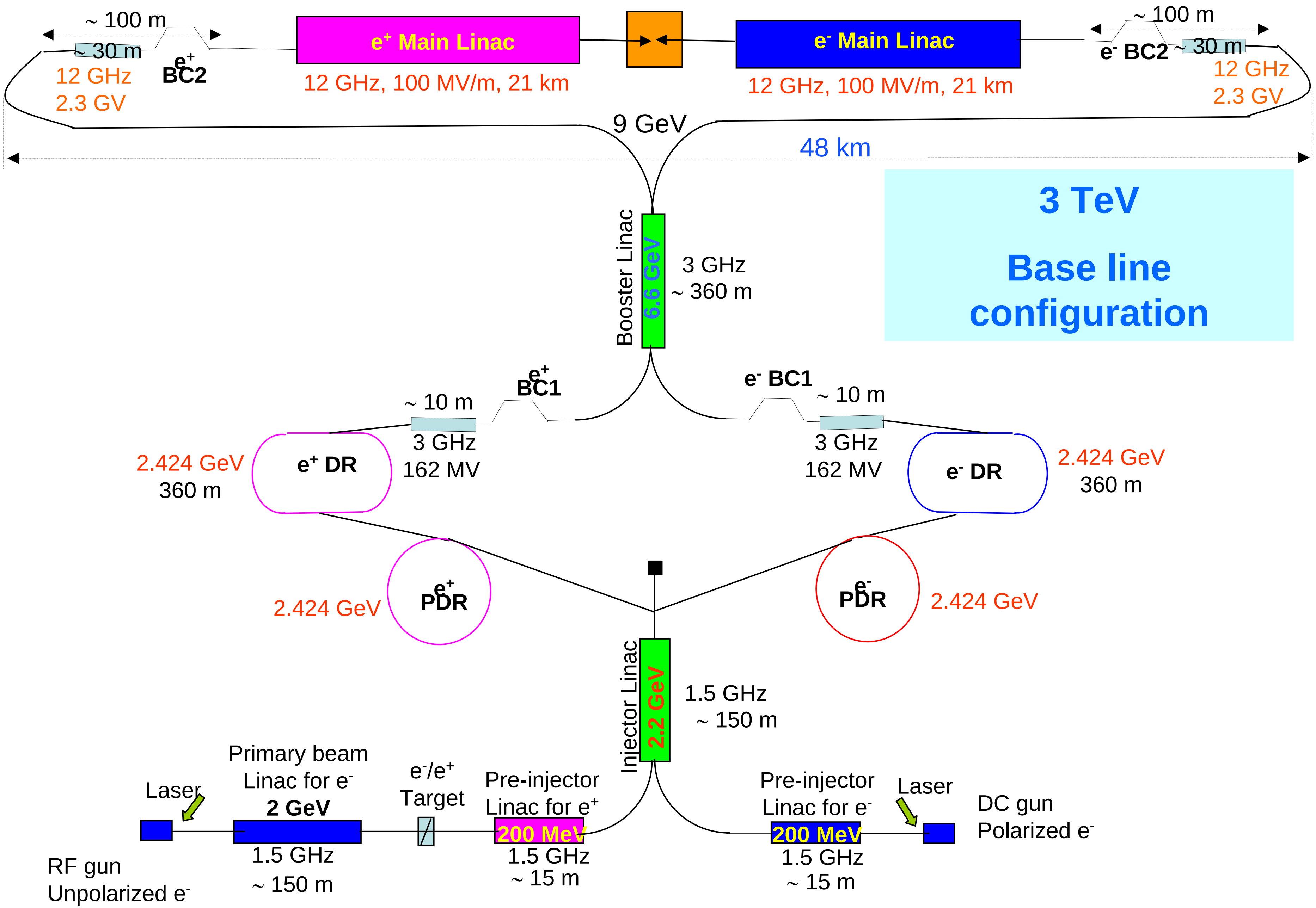
laser

gun

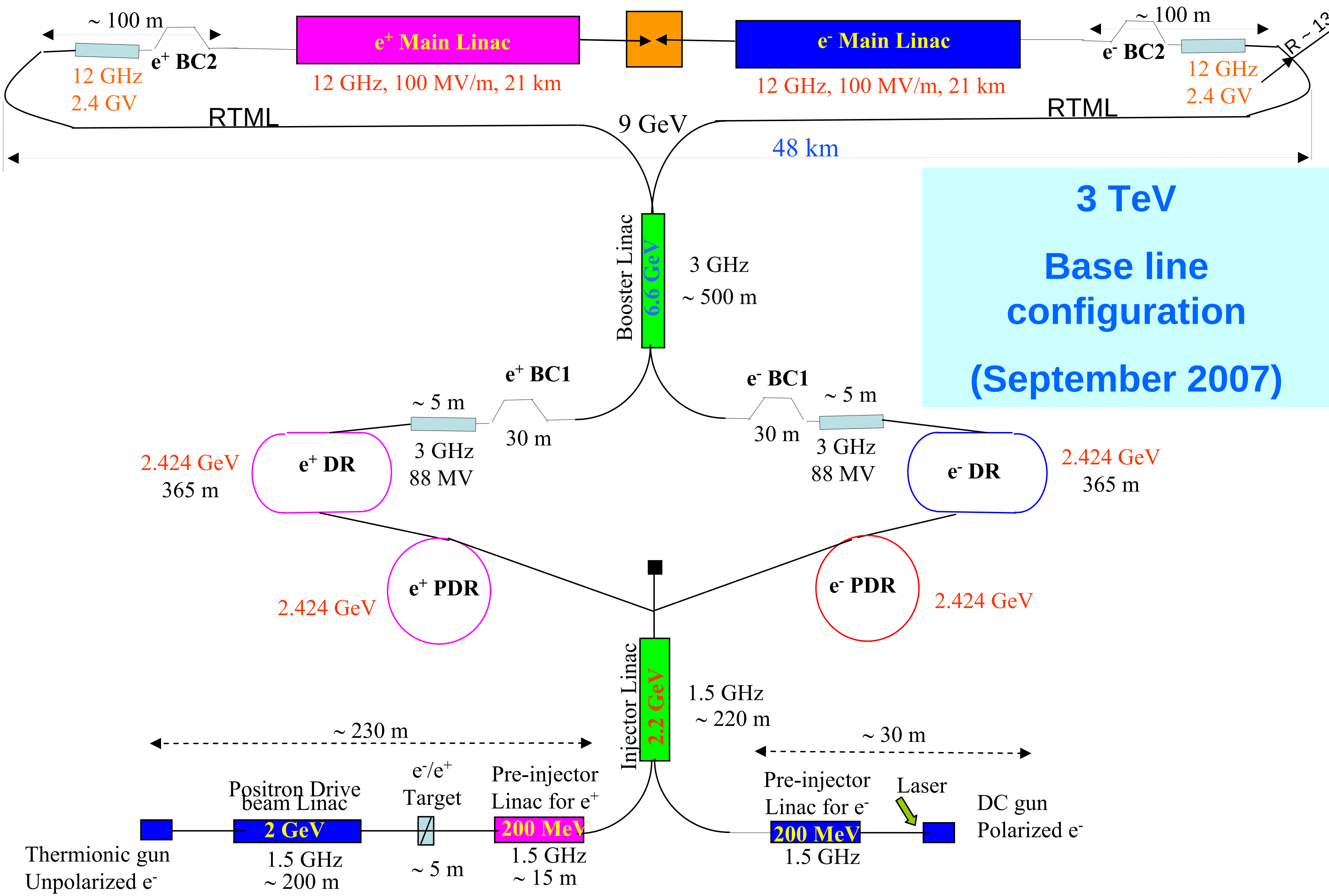
vacuum

photo cathode

The CLIC Injector complex in 2007



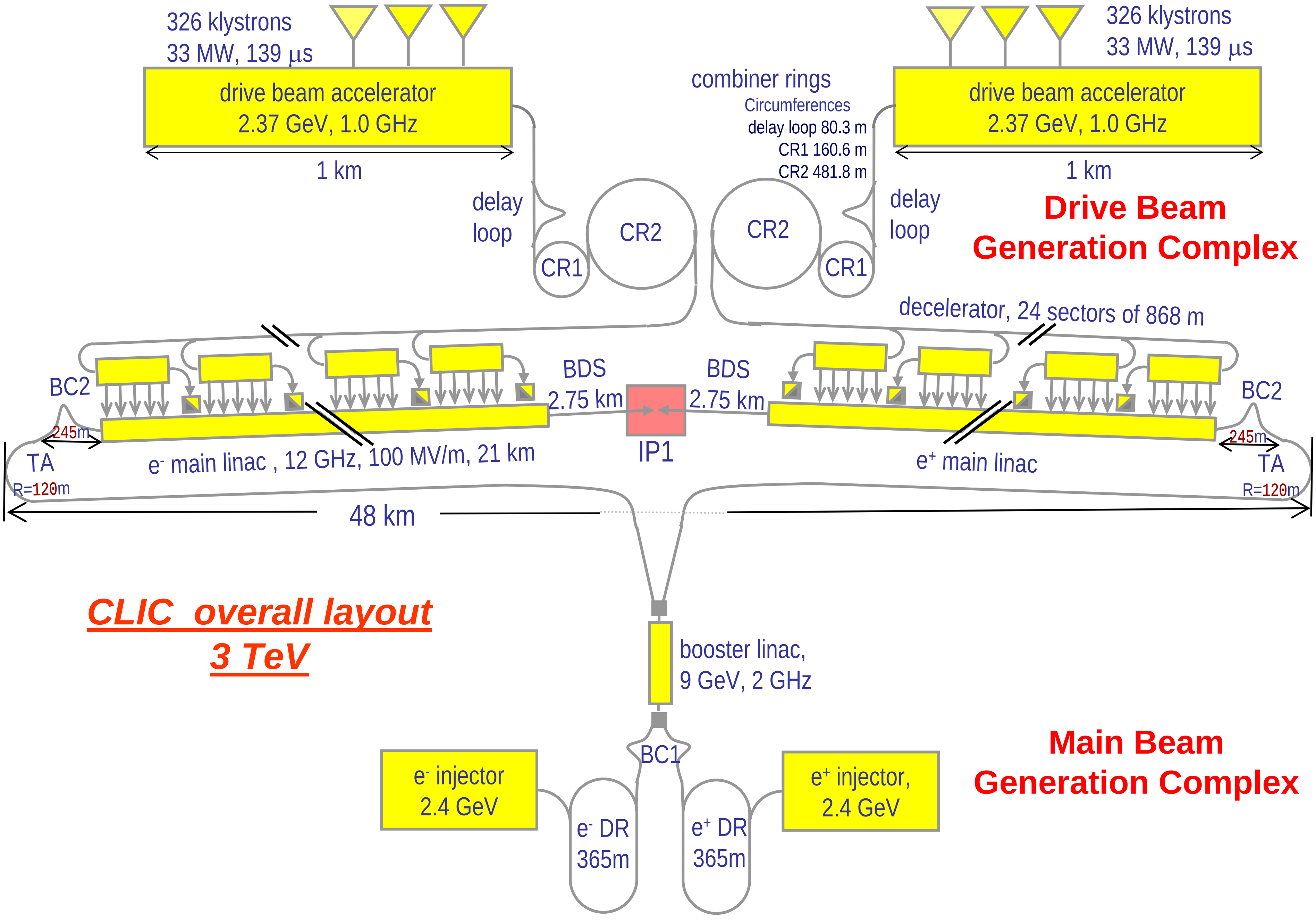
The CLIC Injector complex in 2007



3 TeV

Base line configuration

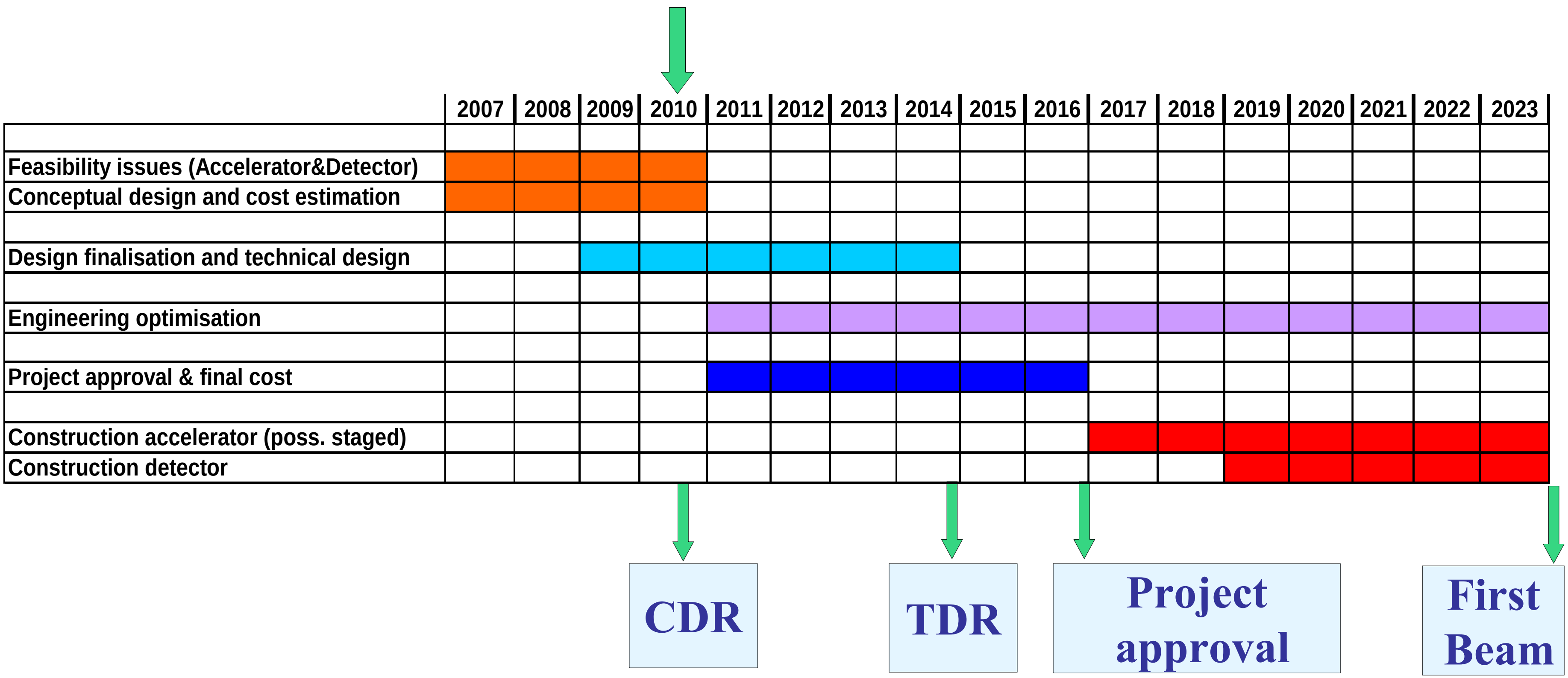
(September 2007)



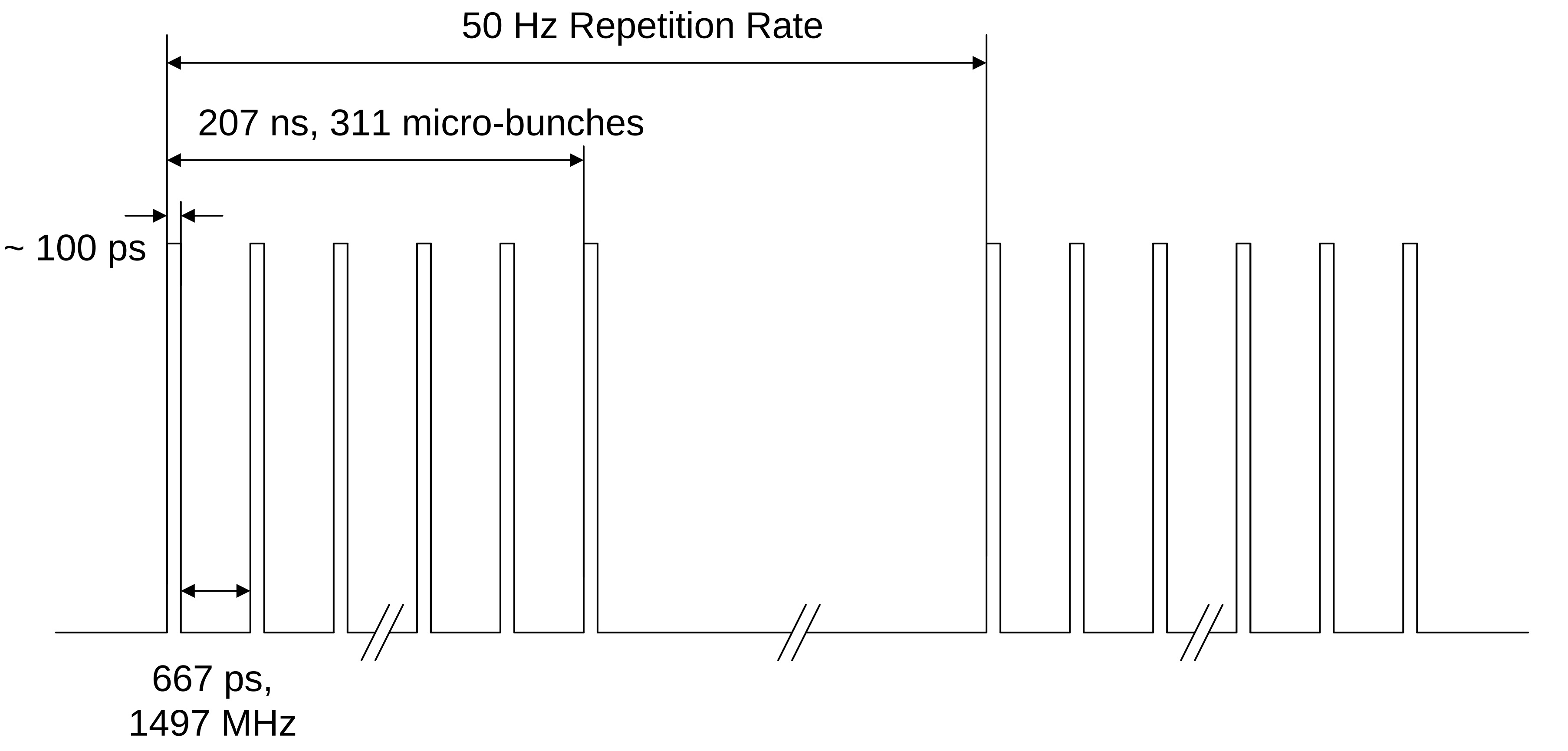
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.37 GeV, 1.0 GHz
1 km
326 klystrons
33 MW, 139 μs
combiner rings
Circumferences
delay loop 80.3 m
CR1 160.6 m
CR2 481.8 m
drive beam accelerator
2.37 GeV, 1.0 GHz
1 km
delay loop
CR1
CR2
CR2
CR1
delay loop
Drive Beam
Generation Complex
decelerator, 24 sectors of 868 m
BC2
245m
TA
R=120m
BDS
2.75 km
IP1
BDS
2.75 km
BC2
245m
TA
R=120m
e- main linac , 12 GHz, 100 MV/m, 21 km
e+ main linac
48 km
CLIC overall layout
3 TeV
booster linac,
9 GeV, 2 GHz
BC1
e- injector
2.4 GeV
e- DR
365m
e+ DR
365m
e+ injector,
2.4 GeV
Main Beam
Generation Complex

Tentative long-term CLIC scenario Shortest, Success Oriented, Technically Limited Schedule

Technology evaluation and Physics assessment based on LHC results for a possible decision on Linear Collider funding with staged construction starting with the lowest energy required by Physics



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)

ILC Polarized e-Source Considerations

Shared Challenges (compared to CEBAF experience)

- Photocathode material – polarization > 80%
- High QE, Ultrahigh vacuum requirement
- Machine-friendly gun design to minimize downtime: reliable load lock
- High voltage and high field gradient: no high voltage breakdown, no field emission + a desire to extend operating voltage beyond 100kV.
- Cathode/anode design: manage ALL of the extracted beam

Unique Challenges (compared to CEBAF experience)

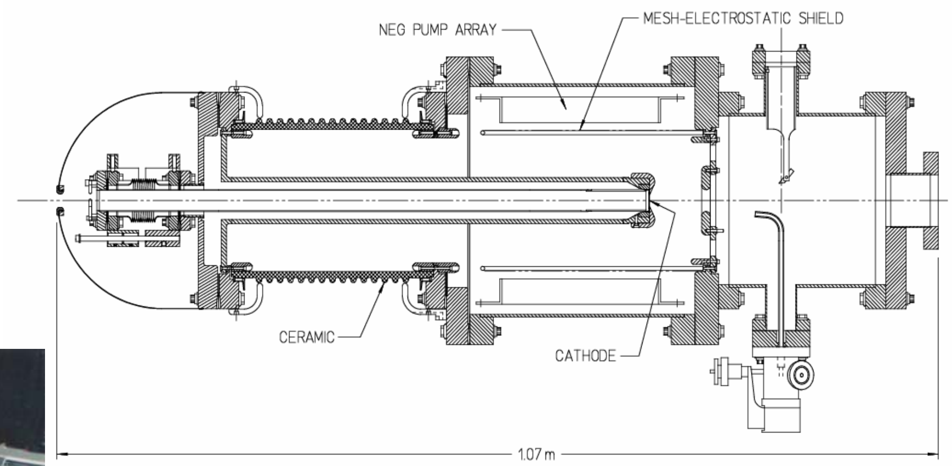
- High bunch charge and high peak current: space charge and surface charge limit
- Injector design with sub-harmonic bunching
- Drive laser, high energy pulses

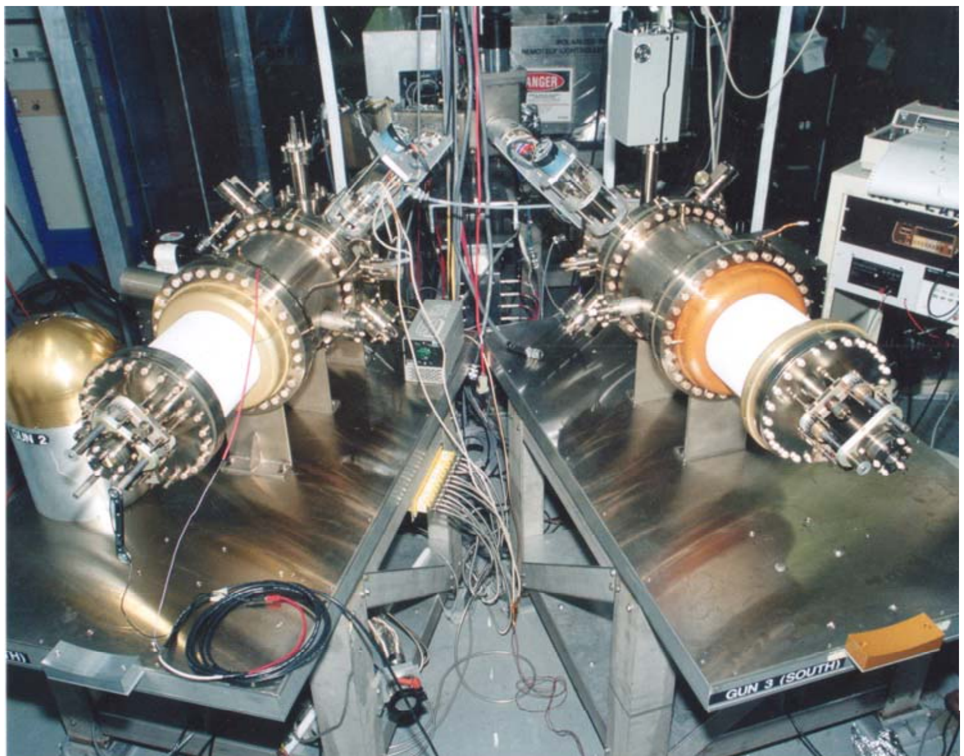
Recent Developments at CEBAF

- CEBAF load-locked gun
  - Improved vacuum and accelerator-friendly ops
- Commercial strained-superlattice photocathode
  - Consistent 85% polarization, ~ 1% QE
  - Demonstration of sustained 1mA operation
- High Voltage R&D (just beginning: K. Surles-Law)
  - Reduce field emission
  - Push value of "routine" operation beyond 100kV
  - Reduce complexity and cost of HV insulator
- Cathode/Anode Design (just beginning: A. Jayaprakash)
  - Optimize geometry to support loss-free beam delivery across entire photocathode surface

CEBAF 100kV 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 7^{th} full activation)
- 13 mm photocathode, but use only center portion, 5 mm dia.
- Extract ~ 2000 Coulombs per year
- Beam current ~ 100uA, laser 0.5mm dia., lifetime: ~ 100C, $1x10^5$ C/cm^2

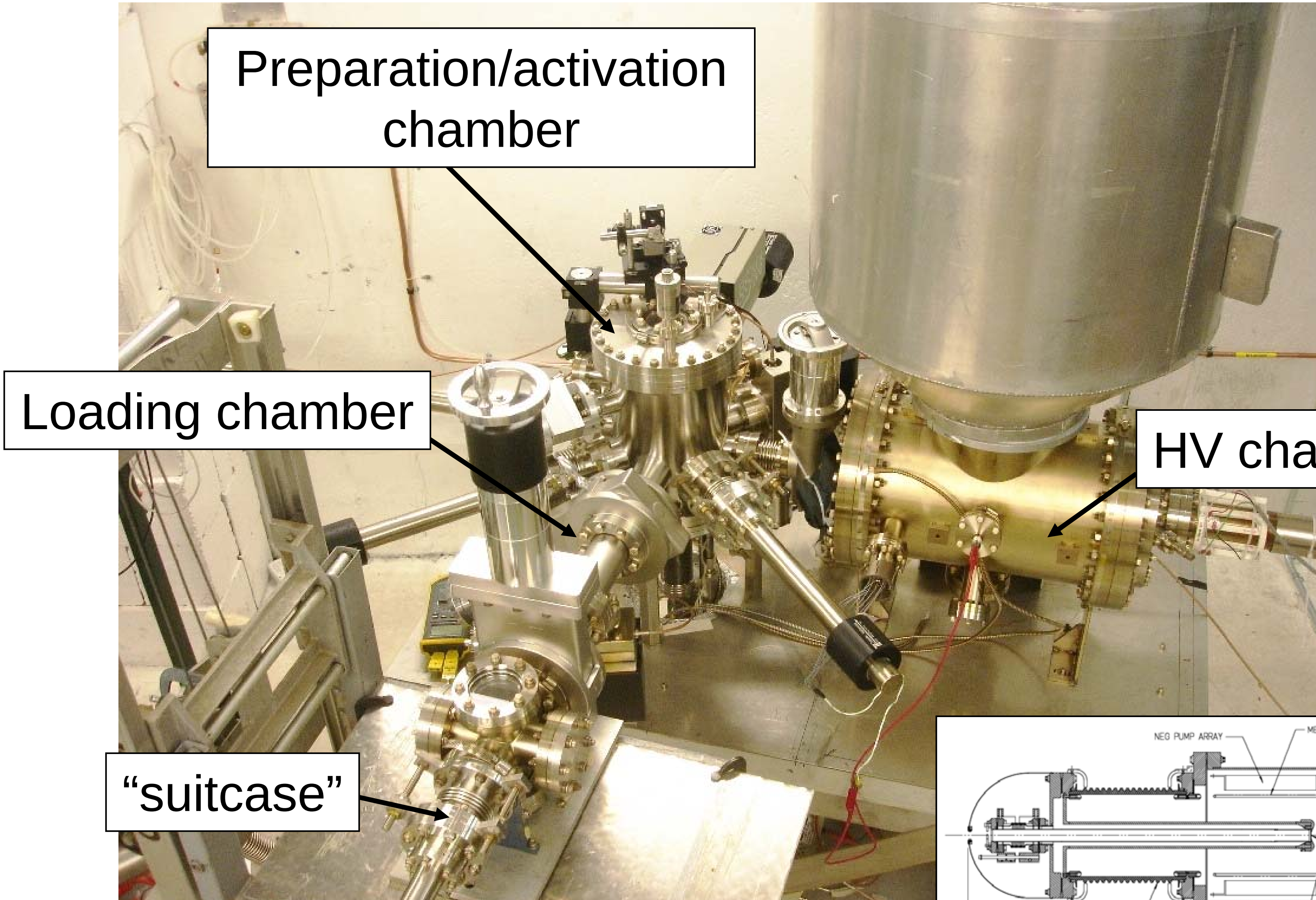
Preparing for Demanding New Experiments

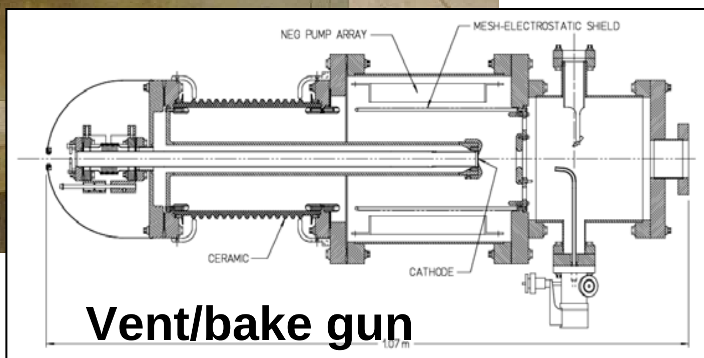
Vent/Bake Guns: need improvement

- 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, One Shift to Replace Photocathode

New CEBAF load-locked gun

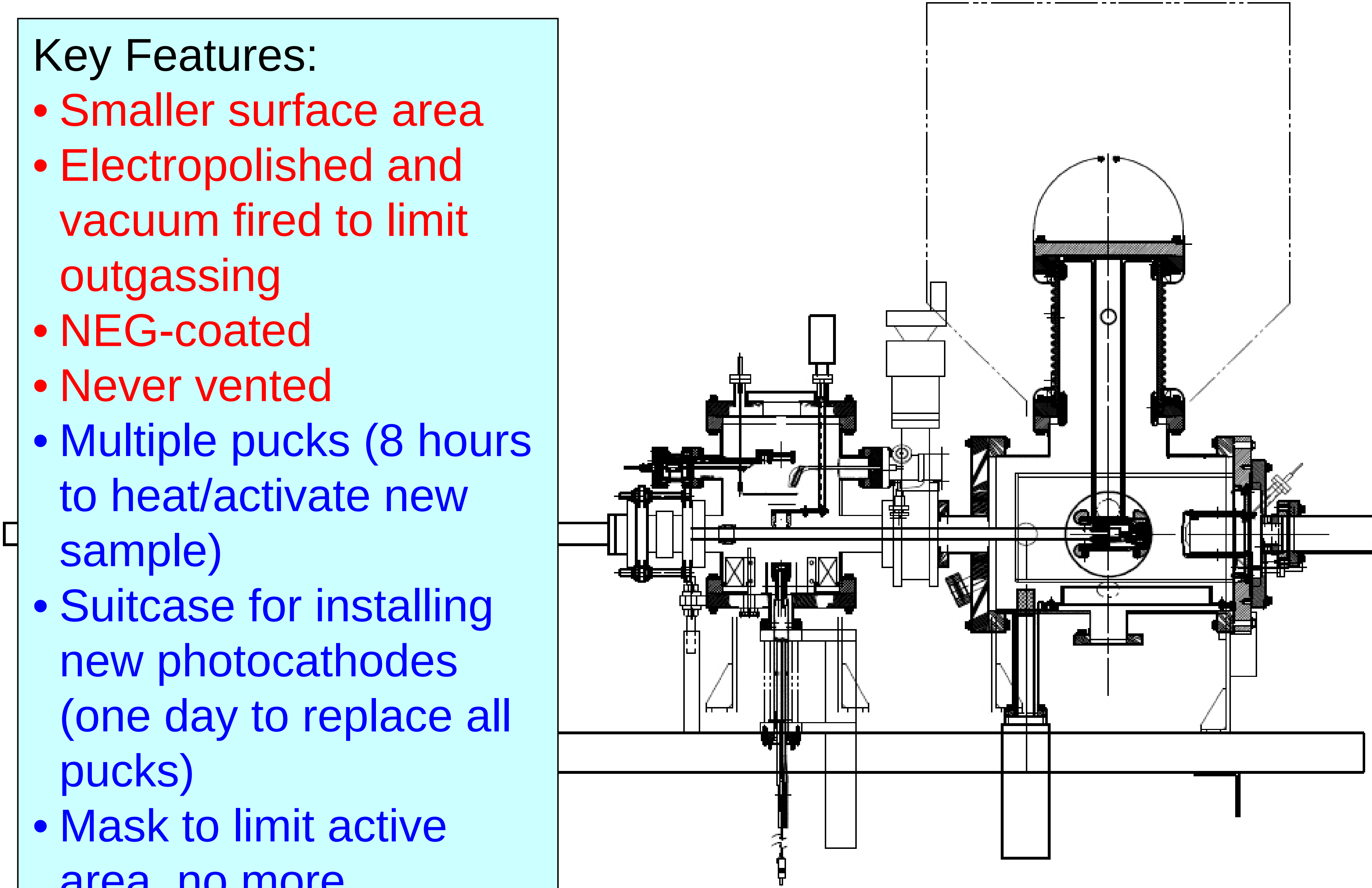




Vent/bake gun

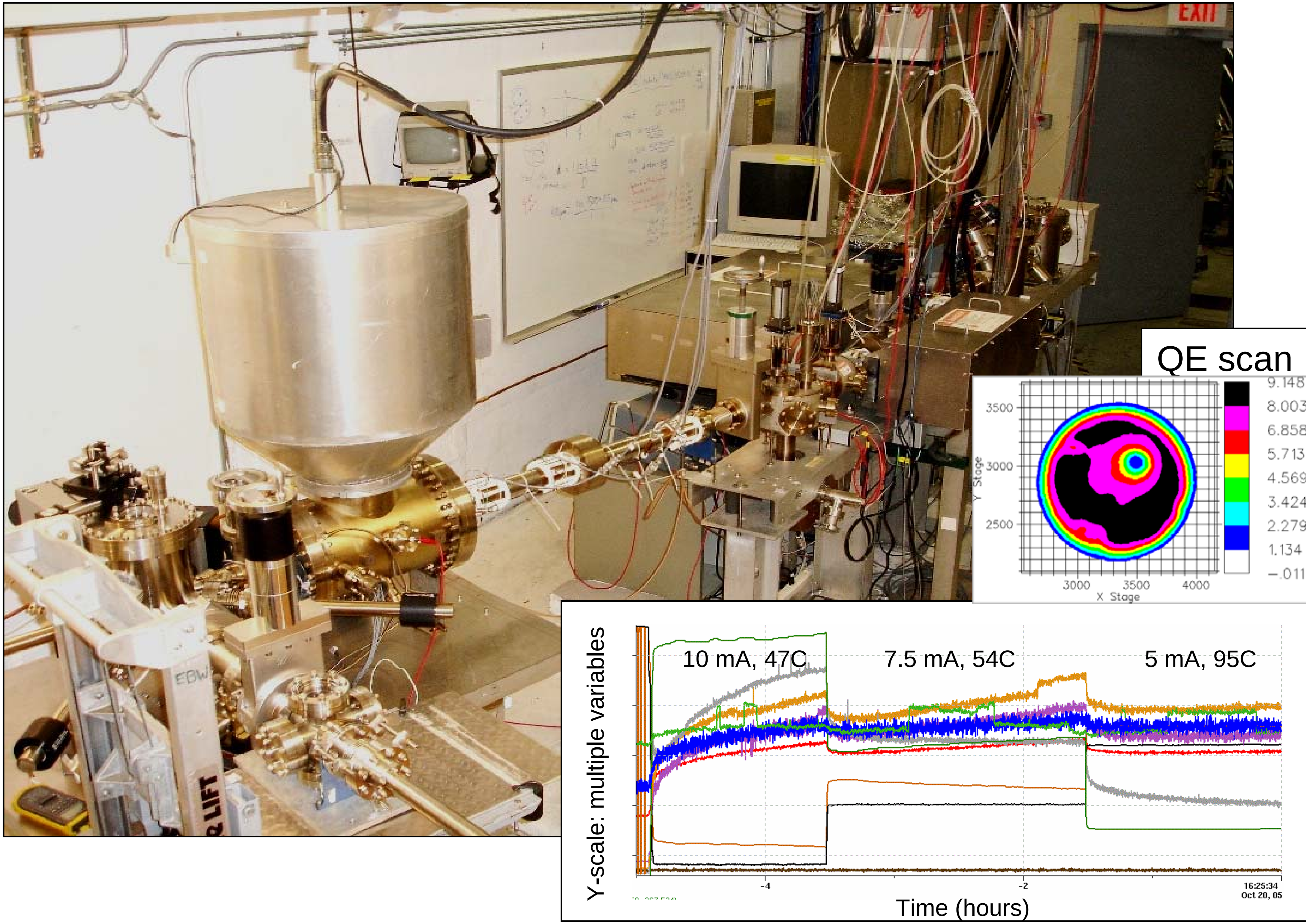
Key Features:

- 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



All new guns based on this basic design

LL Gun and Test Beamline

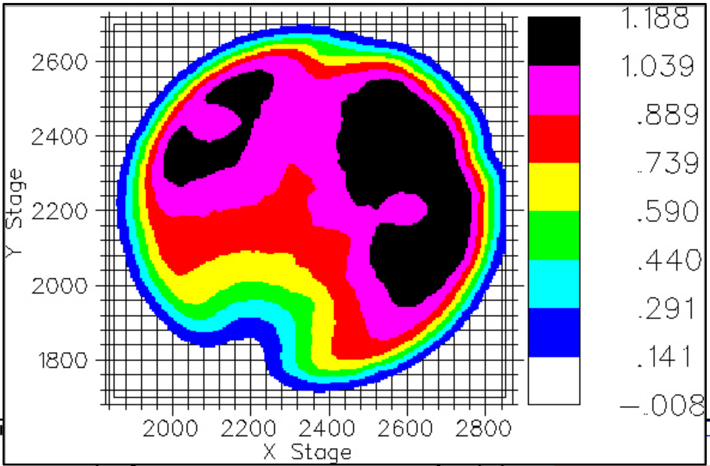


1mA at High Polarization*

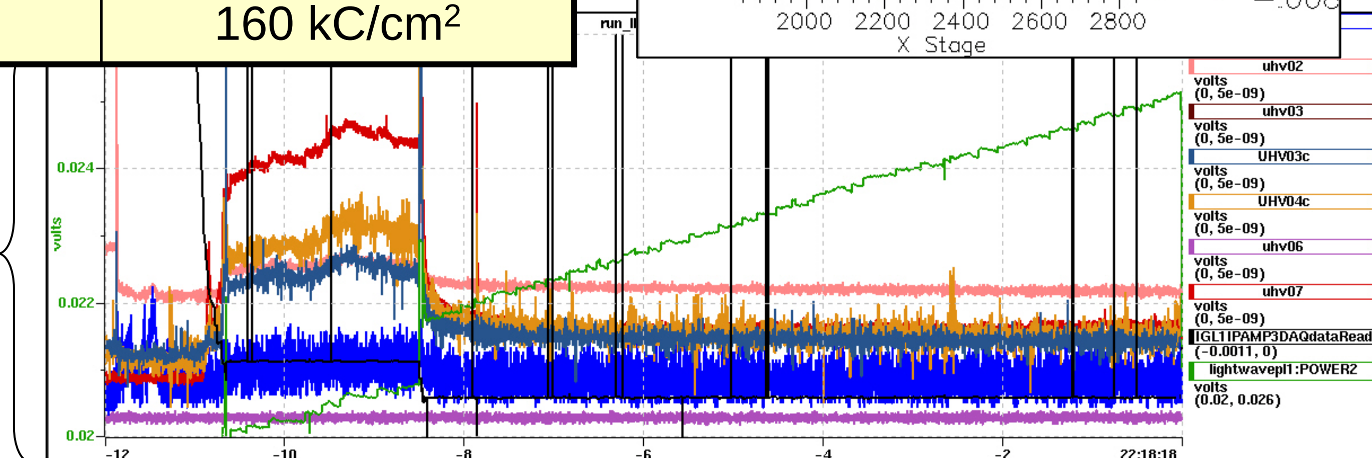
Parameter	Value
Laser Rep Rate	499 MHz
Laser Pulselength	30 ps
Wavelength	780 nm
Laser Spot Size	450 mm
Current	1 mA
Duration	8.25 hr
Charge	30.3 C
Lifetime	210 C
Charge Lifetime	160 kC/cm^2

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

Note High Initial QE

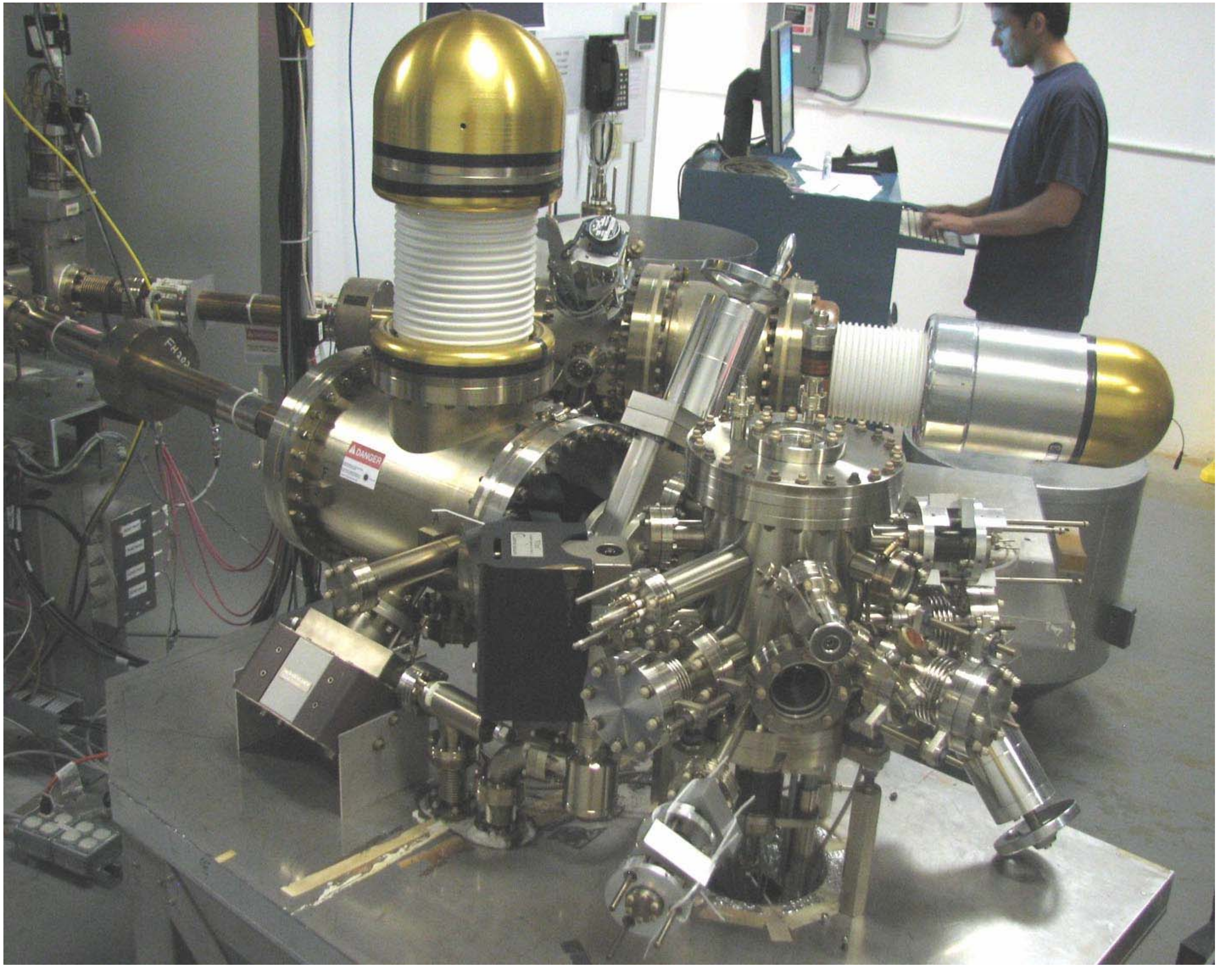


Vacuum signals
Laser Power
Beam Current



"Lifetime Measurements of High Polarization Strained Superlattice Gallium Arsenide at Beam Current > 1 mA Using a New 100 kV Load Lock Photogun", J. Grames et al., Particle Accelerator Conference, Albuquerque, NM, June 25-29, 2007

New LL Gun at CEBAF, Summer 2007



So far, lifetime no better than vent/bake gun. Why?

Possible reasons for short lifetime

- Need to “season” the gun
- We have a leak (gun and/or beamline)
- Beamline vacuum not as good at CEBAF (activate dif-pump NEGs and/or re-bake)
- Field emission from cathode electrode (hi-pot gun to 125kV)
- Gun ion pump exhibits field emission: need to hi-pot
- Wrong magnet (solenoid) settings: beamloss at the bend chamber, Wien filter, etc
- Activate the gun NEG pumps again….

Increase Gun Voltage: Why?

Historically, Labs have had difficulty operating DC high voltage guns above field gradient ~ 5 MV/m and bias voltage ~ 100kV (at least polarized guns).

That said, it would be beneficial to build an ILC gun with higher field gradient and bias voltage to...

- Address current density limitation due to Child's Law
- Reduce space-charge-induced emittance growth, maintain smaller transverse beam profile and short bunchlength
- Reduce problems associated with surface charge limit (i.e., QE reduction at high laser power)
- Prolong Operating Lifetime?

Space Charge Limit

Peak current at ILC photocathode ~ 6 A
Assume laser spot size 1cm
Current density j = 7.6 A/cm^2

Space Charge Limit (Child's Law)

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

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

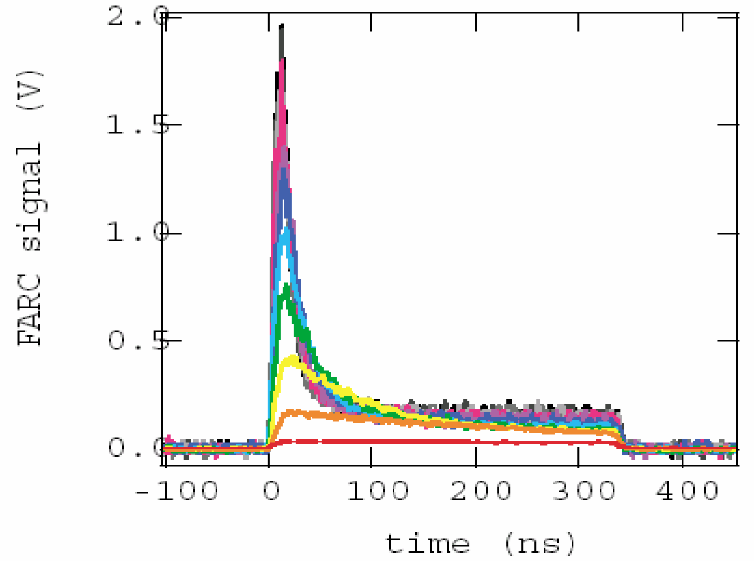
for 3 cm cathode/anode gap

At lower gun voltages, large laser spot is required.
Must also consider charge limit at anode…

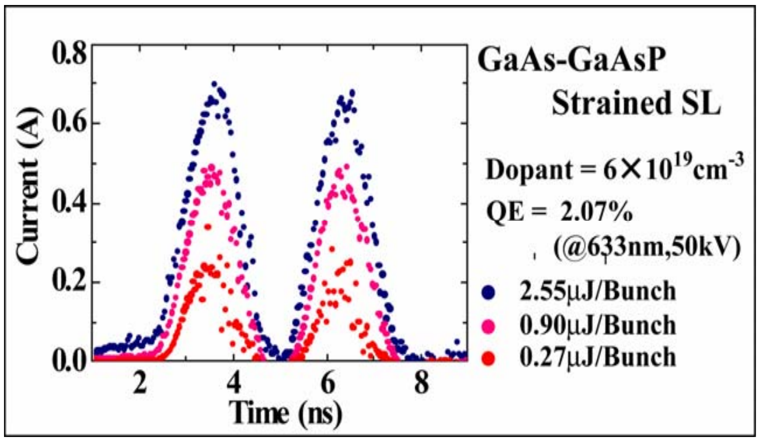
Slide info courtesy Jym Clendenin, SLAC

Surface Charge Limit

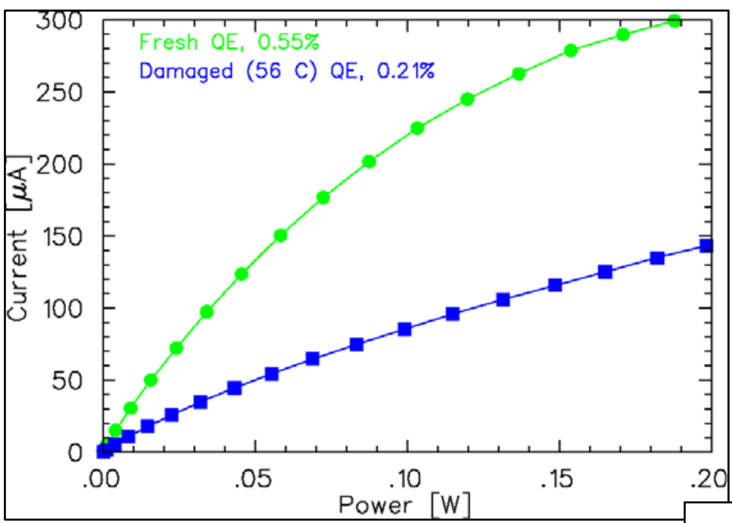
QE reduction at high laser power



Nagoya



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



Heavily doped surface: viable solution?

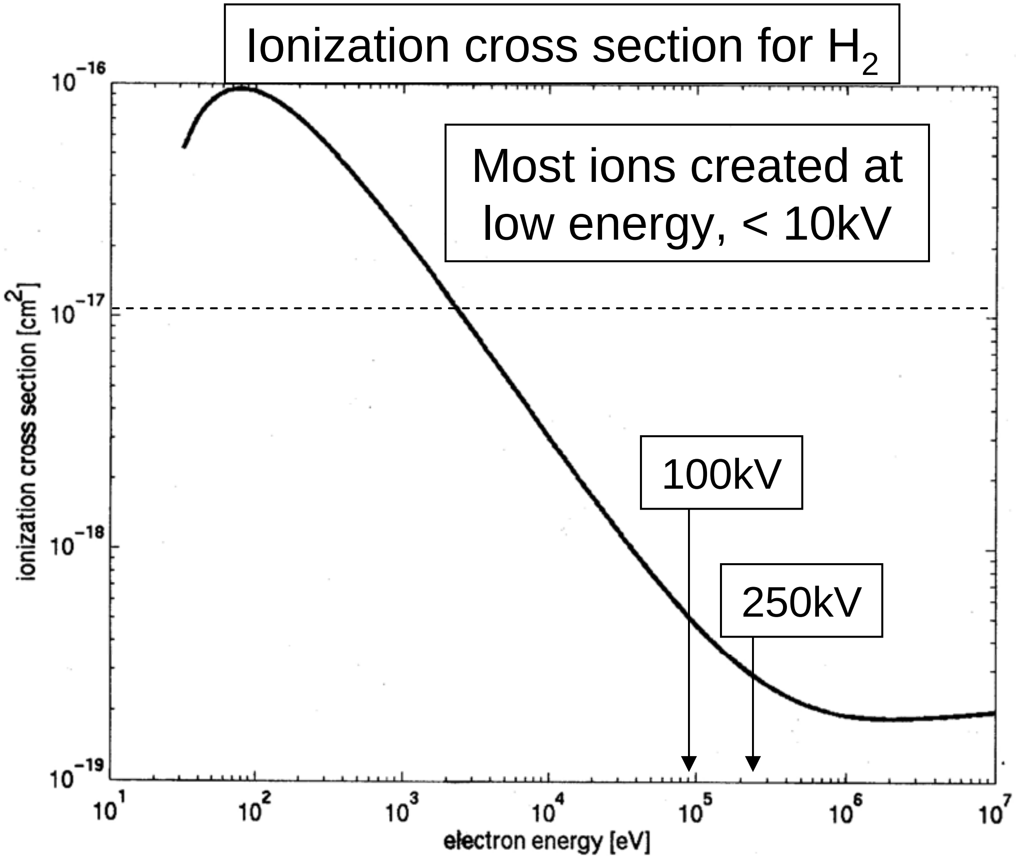
5.5 A/cm2 measured @ SLAC for 780 nm, 75 ns pulse

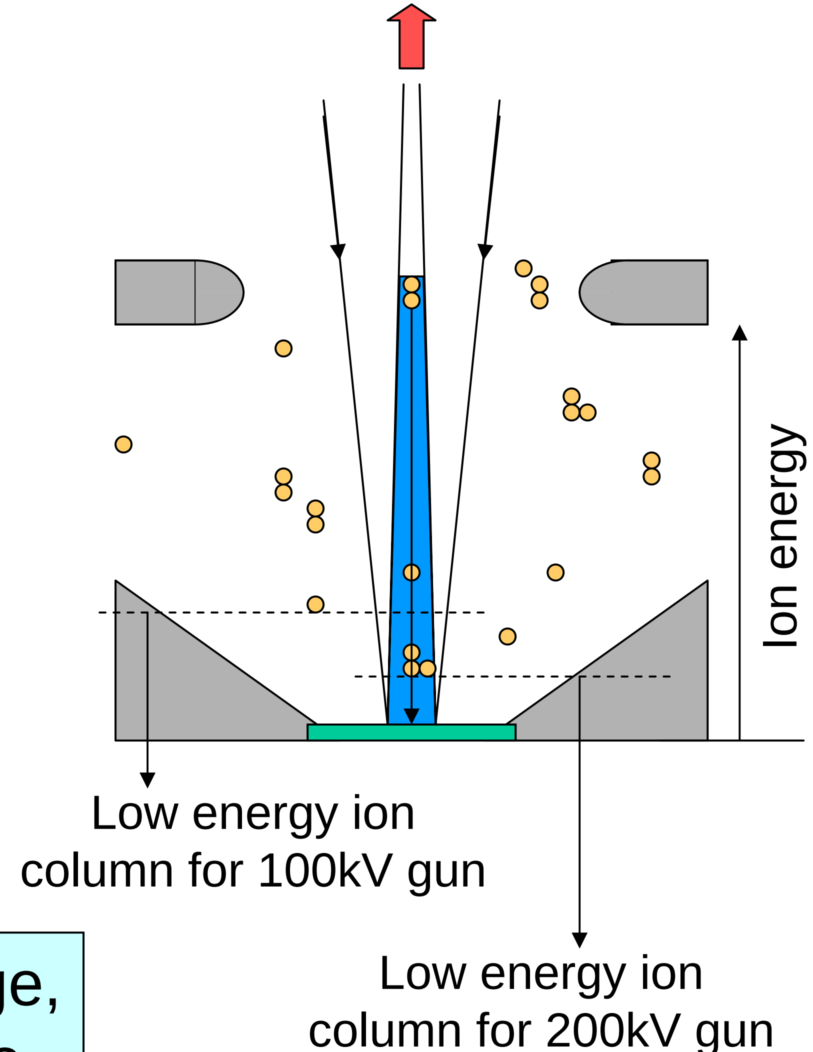
9.7 A/cm2 @ Nagoya for 780 nm, 30 ps

ILC current density comparable to these values…something to worry about

Slide info courtesy Takashi Maruyama, SLAC

Improve Lifetime with Higher Bias Voltage?





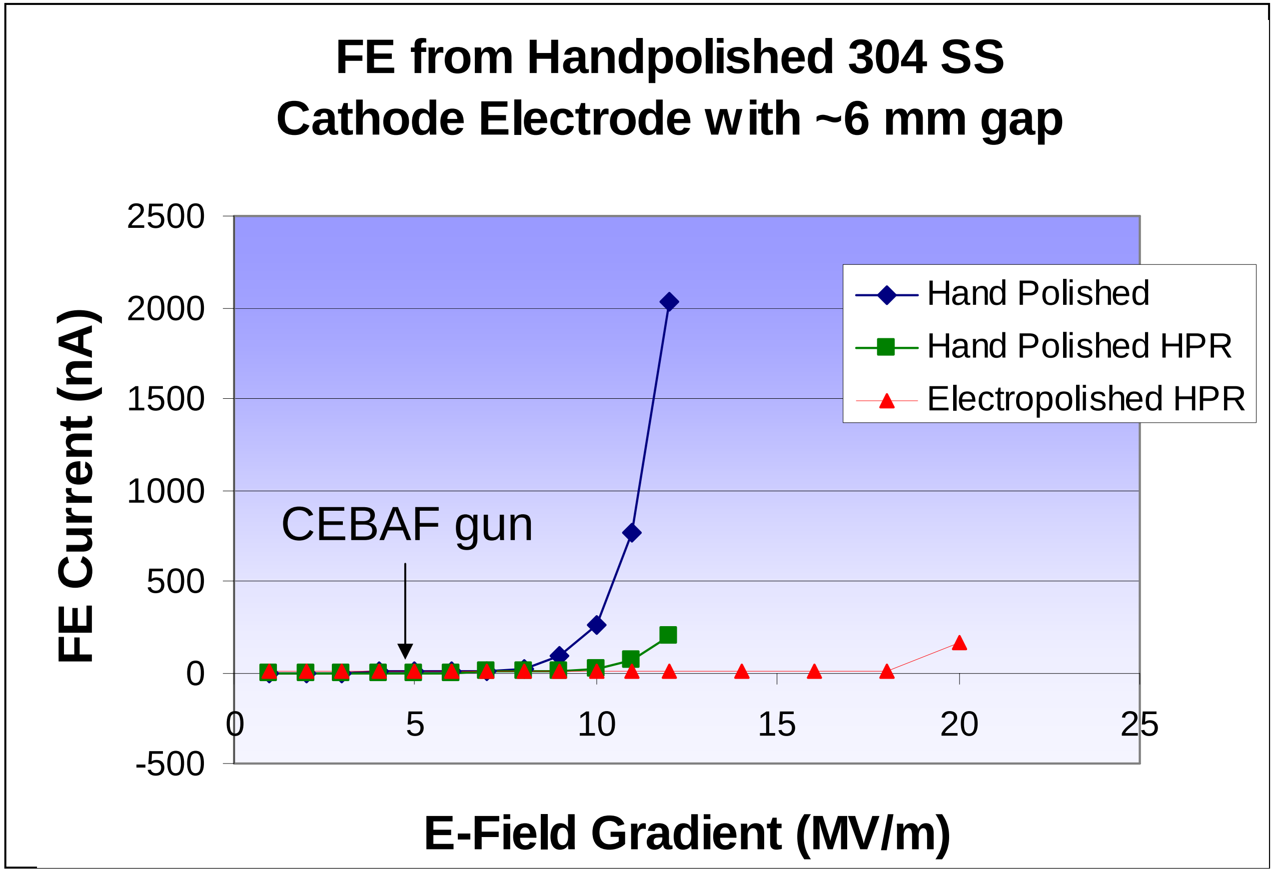
Hypothesis: Double the gun voltage, halve the # of “bad” ions, improve lifetime by 2

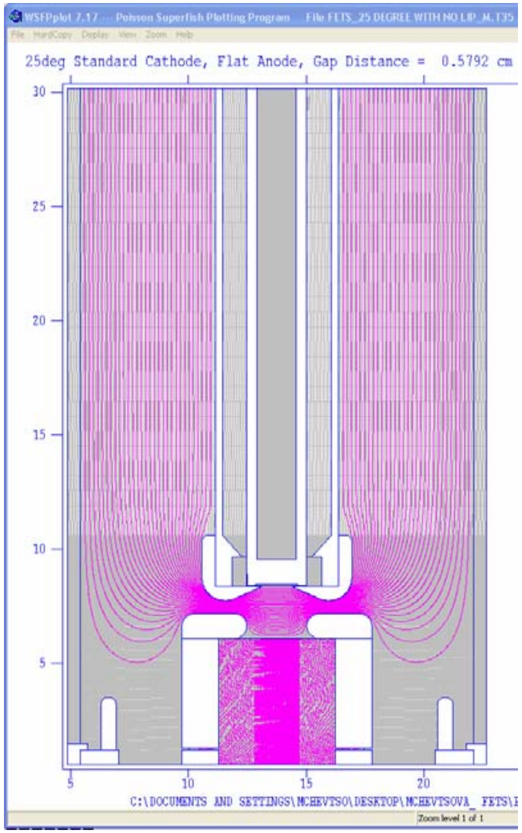
Must Eliminate Field Emission

Investigate the SRF-cavity technique "high pressure rinsing"

Recent tests at JLab with shaped electrodes

Work of M. Chetsova, K. Surles-Law

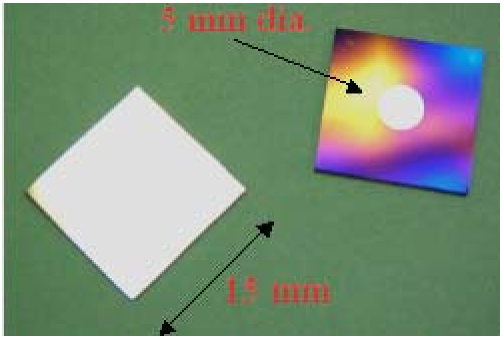




Ken preparing new electrodes, including single crystal Niobium…

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

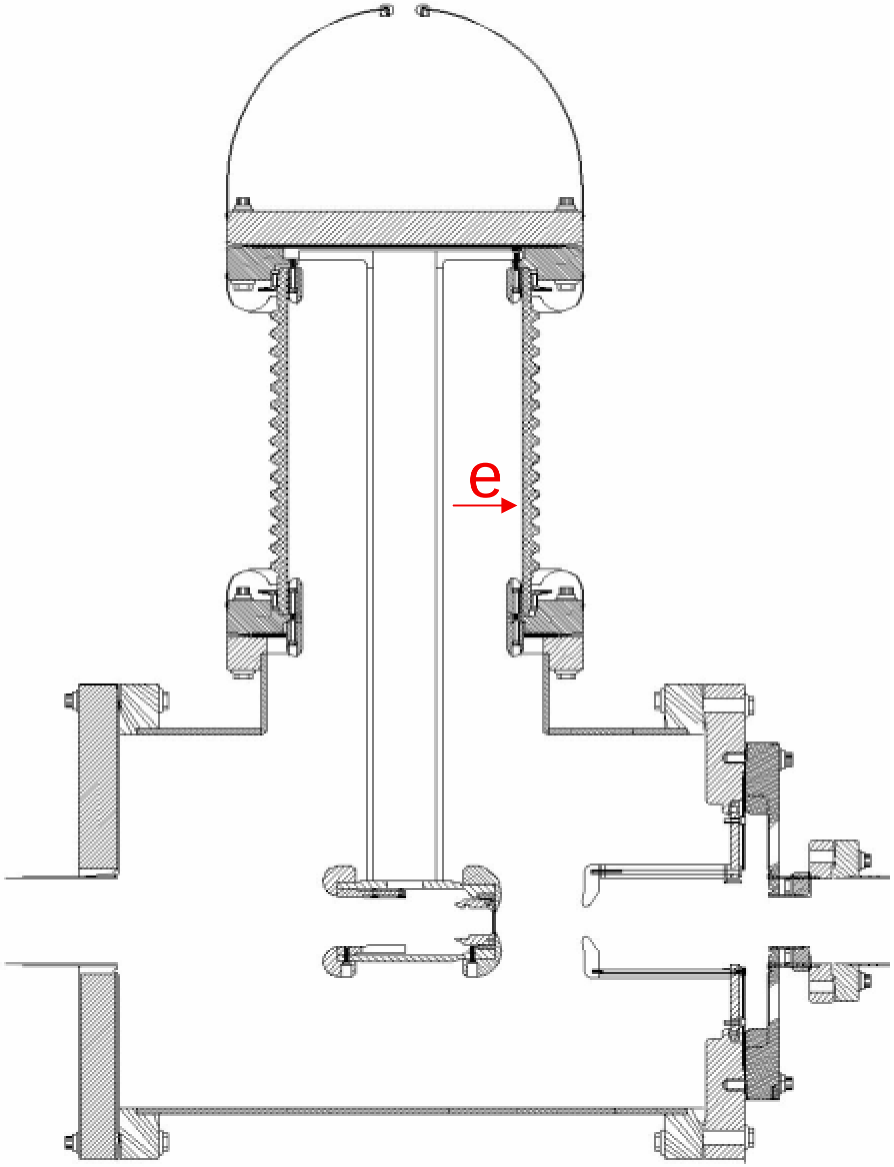


- ILC requires large laser beam to reduce current density and overcome space and surface charge limit
- Suggest detailed modeling of cathode/anode optic and first few meters of beamline
  - Perhaps using multivariate optimization?

Goals of Cathode/Anode Design

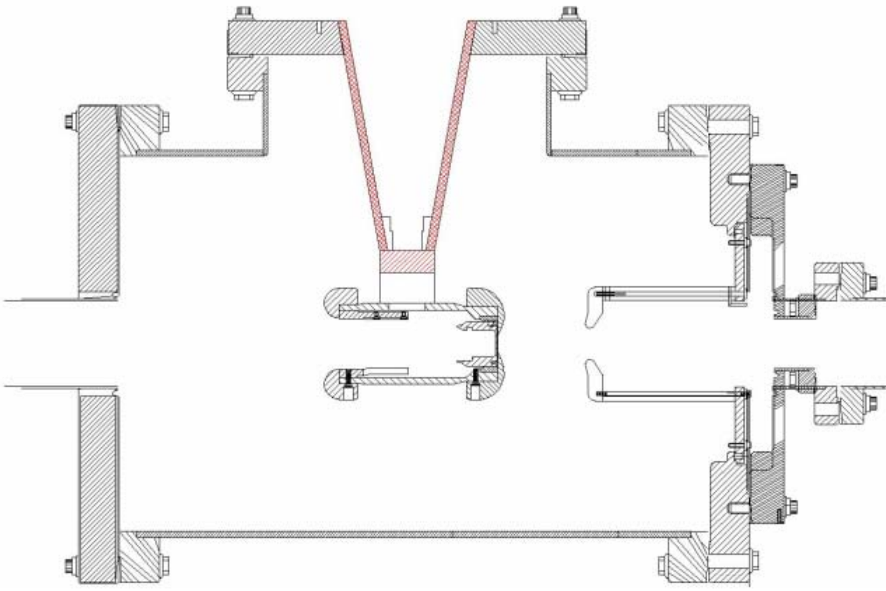
- Create cathode/anode optic with small aberration across large photocathode active area, with very little beam loss. What to optimize?
  - Size of cathode electrode diameter, size of photocathode active area
  - Size of laser beam: lowest possible current density but with adequate emittance
  - Cathode/anode shape for adequate focusing
  - Cathode voltage/gradient: higher voltage to reduce space charge and provide possibility of extracting higher peak current with more narrow laser pulsewidth, to reduce SHB requirements

Inverted Gun Geometry



Present design

- Medical x-ray technology
- Ceramic not exposed to FE
- Compact



New design?

Conclusions: ILC Deliverables

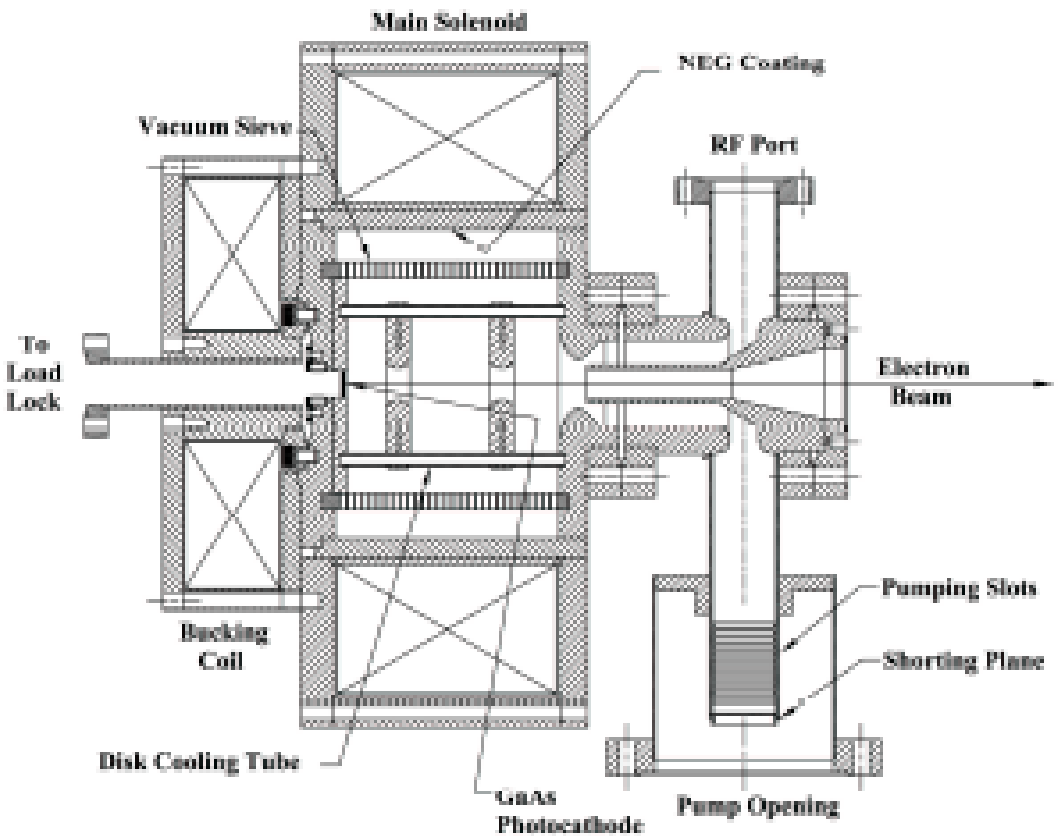
- R&D program to push gun voltage > 120kV to reduce ill effects related to space and surface charge limitations. Empirically determine the reasonable maximum bias voltage for trouble-free operation. Develop an inverted ceramic insulator design.
- Model gun (particularly cathode/anode optic) for 100% transmission of beam. No loss. Set laser beam diameter and pulsewidth to overcome problems associated with space and surface charge limit.
- Engineering design. Incorporate features from bullets above, plus state-of-the art vacuum (small volume, low outgassing rate, NEG pumps and coating), plus reliable load-lock design for quick photocathode replacement (modification of CEBAF load lock design)
- Build and Commission gun

Conclusions: CLIC Deliverables

- Same as ILC Deliverables except we won't build a CLIC gun: paper-study only.
- CLIC gun = ILC gun?
- At the moment, CLIC photoinjector very vague…
- Clearly, ILC gun modeling comes first…
- Then apply the same modeling tools using CLIC beam parameters.

Parameter	CLIC	ILC
Number electrons/microbunch	6×10^{9}	3×10^{10}
Number of microbunches	312	3000
Width of microbunch	~ 100 ps	~ 1 ns
Time between microbunches	0.5002 ns	337 ns
Microbunch rep rate	1999 MHz	3 MHz
Width of macropulse	156 ns	1 ms
Macropulse repetition rate	50 Hz	5 Hz
Charge per micropulse	0.96 nC	4.8 nC
Charge per macropulse	300 nC	14420 nC
Average current from gun	15 uA	72 uA
Average current in macropulse	1.9 A	0.0144 A
Duty Factor: beam ON/beam OFF (during macropulse for pulsed machines)	0.2	3×10^{-3}
Peak current of micropulse	9.6 A	4.8 A
Current density (for spot size below)	12.1 A/cm^2	6 A/cm^2
Laser Spot Size	1 cm	1 cm

Warm RF Gun for ILC? for CEBAF?

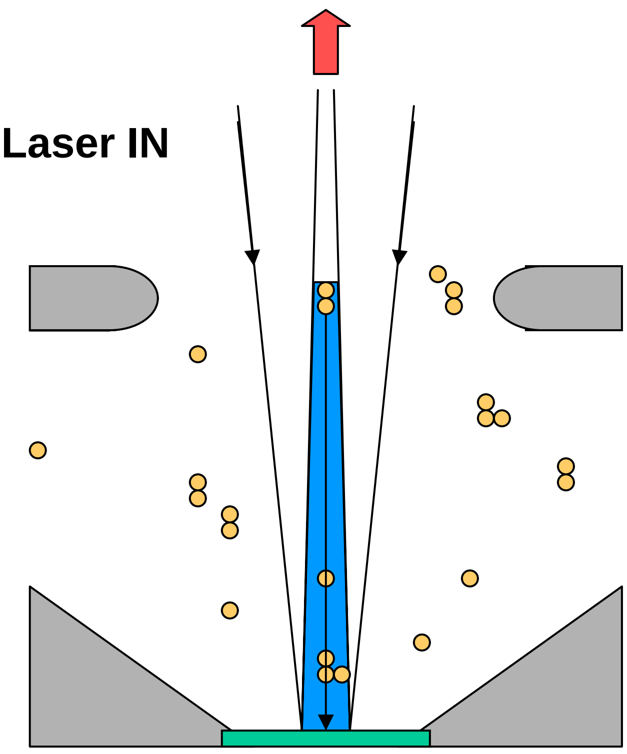


SBIR proposal from David Yu, Duly Research and Fermi Lab, for ILC gun

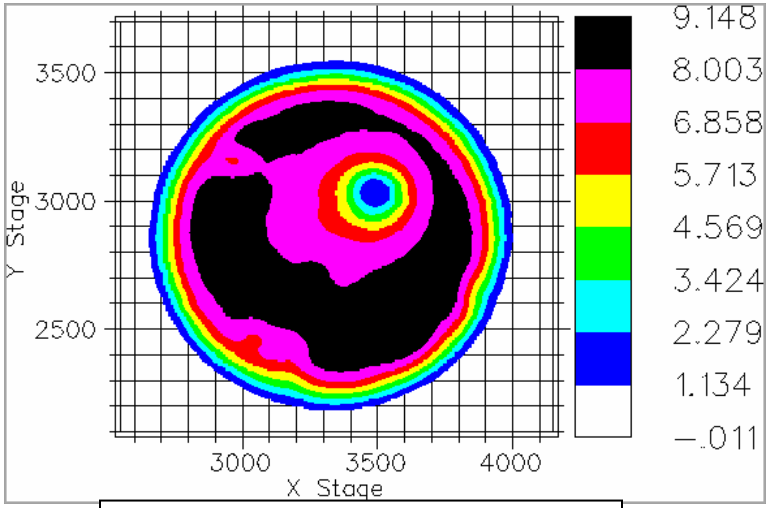
- PWT gun: open geometry for adequate UHV
- Low Q, but 1 MeV energy possible
- Pulsed-RF so cooling not so problematic
- Something similar for CEBAF? Need 200 to 500kV beam
- Use CEBAF load lock
- Be the first to demonstrate GaAs QE and lifetime in RF gun
- “Cheap” way to get into RF gun business.

What limits photogun lifetime?

Imperfect vacuum and Ion Backbombardment



QE (%)

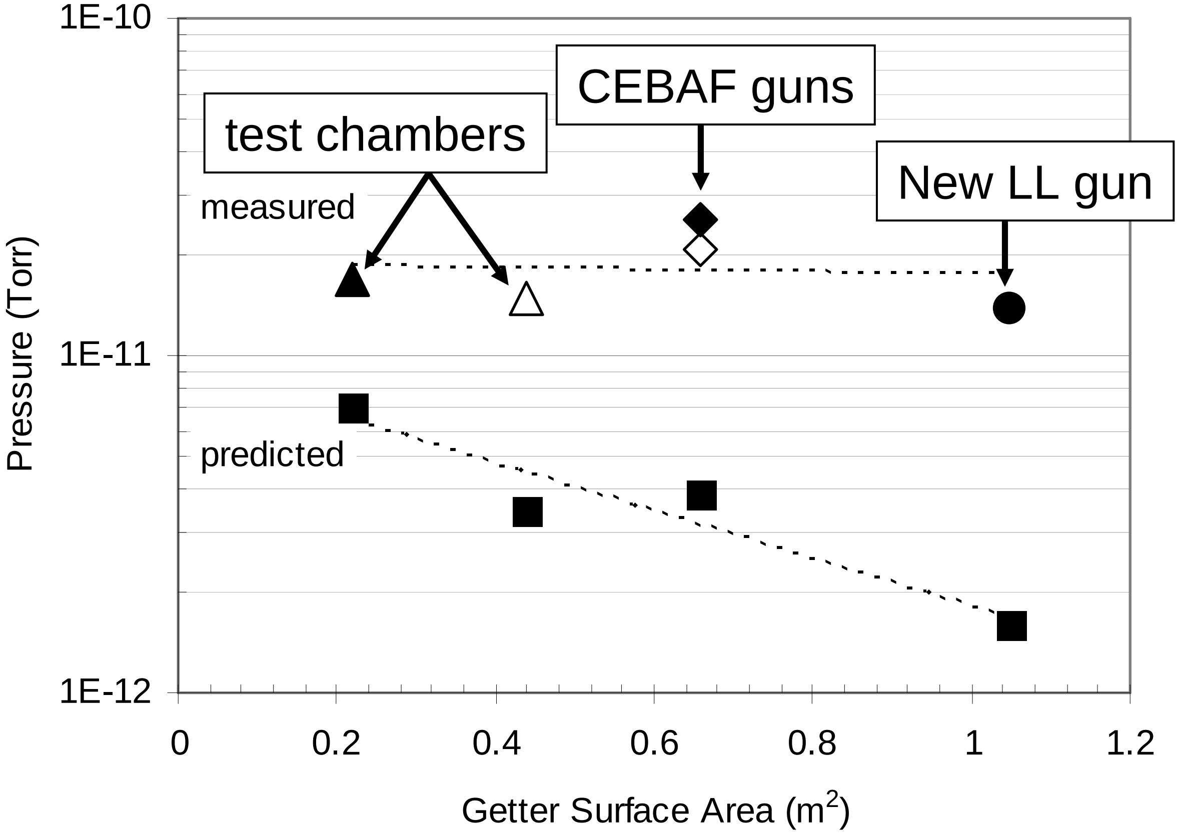


QE scan of photocathode

Note, other factors can limit lifetime: Field emission, photocathode material, laser wavelength, laser radial position at photocathode, beam optics, gun voltage, gap size,….. (i.e., many ways to get a bad result)

Improving Gun Vacuum

$$\text{Ultimate Pressure} = \frac{\text{Outgassing Rate} \times \text{Surface Area}}{\text{Pump Speed}}$$

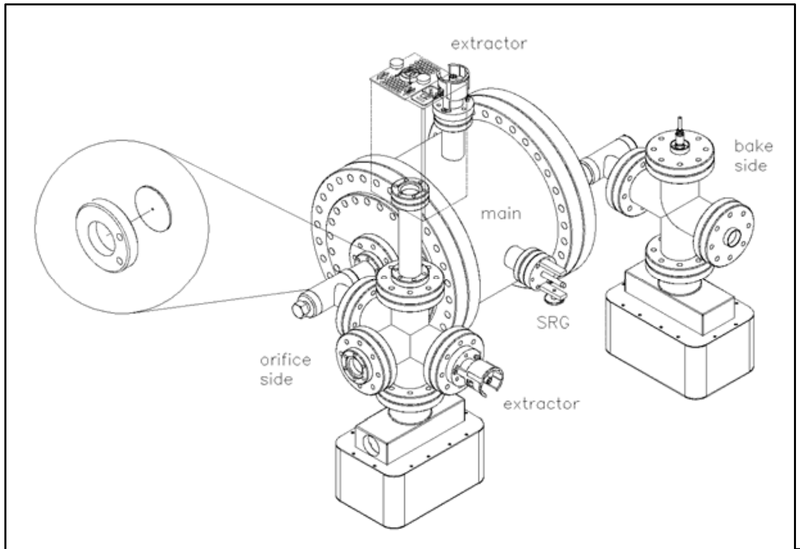


How to explain this discrepancy?

- Outgassing rate higher than assumed “standard” value; $1\text{x}10^{-12}$ Torr·L/s·cm^2?
- NEG pump speed smaller than SAES says?

Measured pressure always much greater than predicted

Outgassing Rate

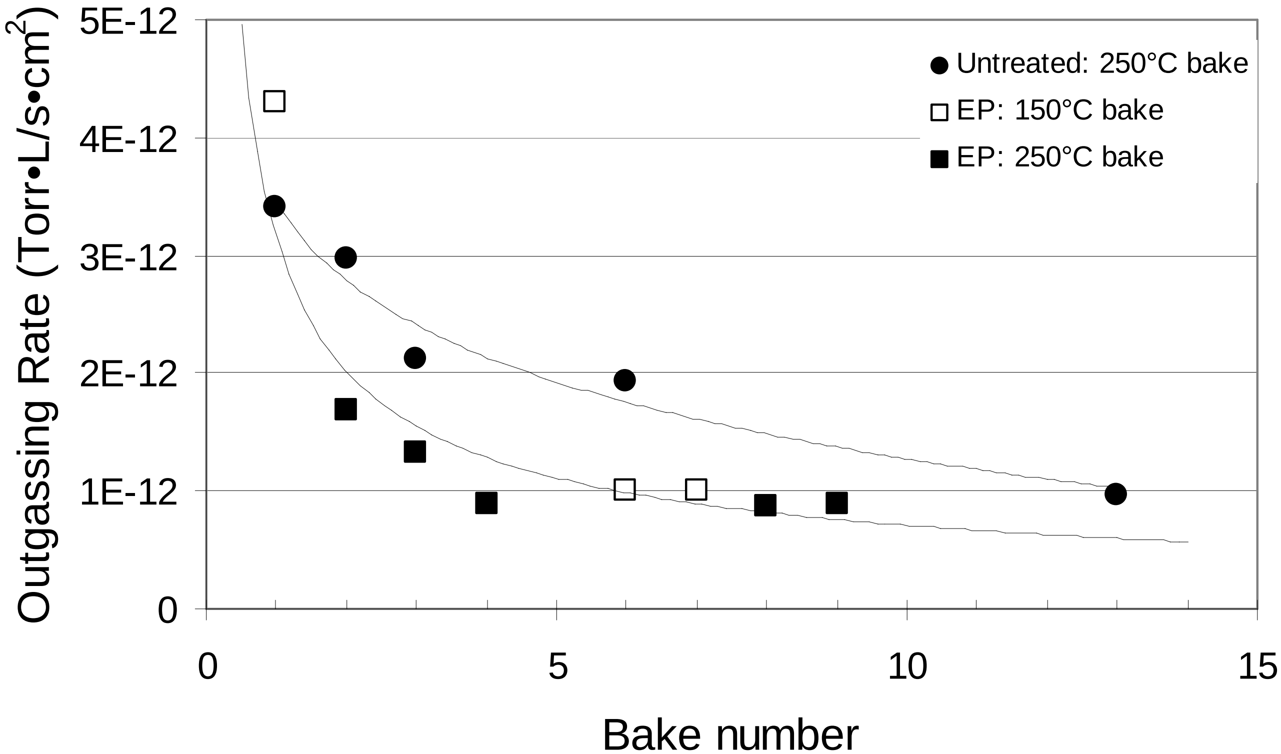


- Orifice and Rate of Rise Methods
- Studied 304, 316L and 6061 Al
- Degreasing and solvent cleaning vs EP and vacuum firing

	Preprocessing				In situ bake parameters		Outgassing Rate (Torr·L/s·cm²)	
Chamber	t(h)	T(°C)	EP	Surface roughness	t(h)	T(°C)	Orifice Method	Rate of Rise Method
Old 304			no	3.7 µm	400	250	9.7×10^{-13}	1×10^{-12}
New 304			no	3.7 µm	180	250	1.9×10^{-12}	2.5×10^{-12}
EP 304	4	900	yes	2.1 µm	30 then 90	150 250		8.9×10^{-13}

"Characterization of the CEBAF 100 kV DC GaAs Photoelectron Gun Vacuum System," M.L. Stutzman, et al., Nucl. Instrum. Meth. A, 574 (2007) p. 213-220

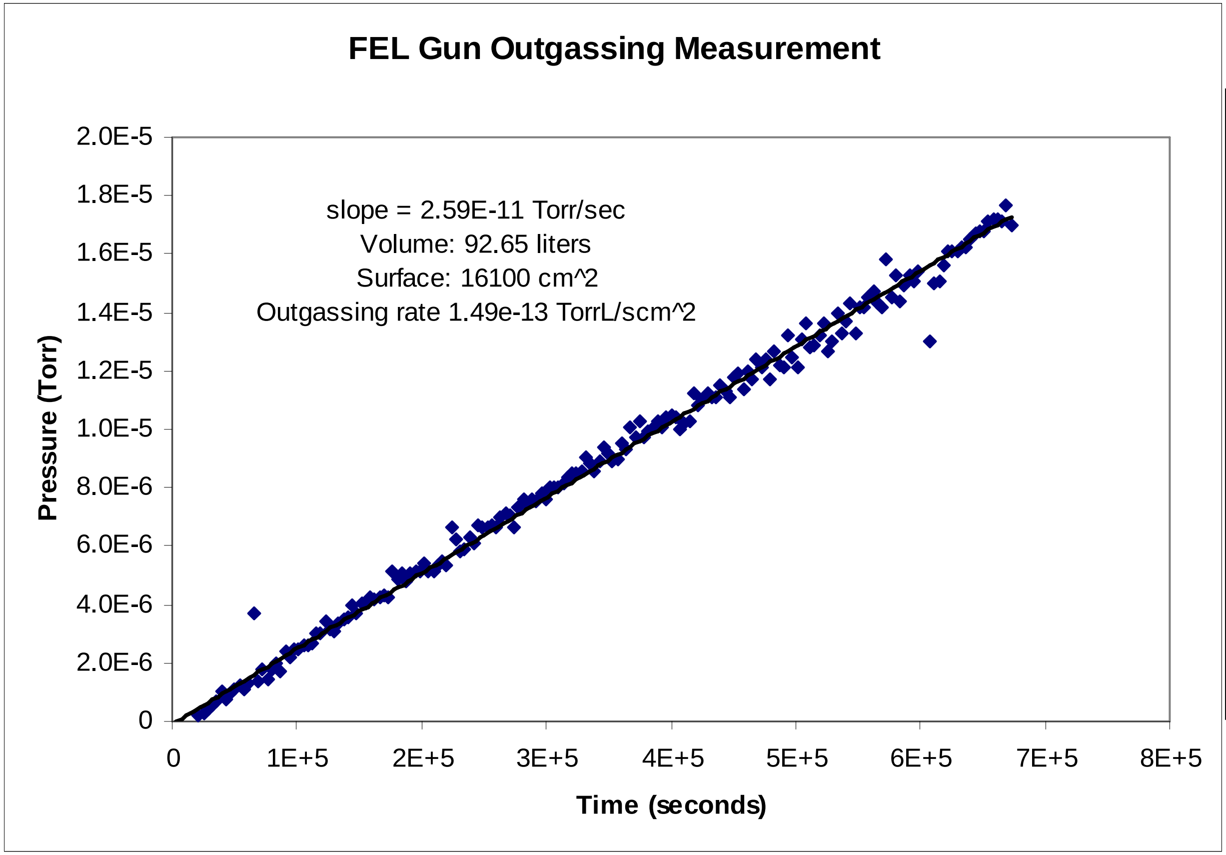
Benefit of EP and Vacuum Firing



- Electropolishing and vacuum firing provides low rate with fewer bakes
- Extremely low values (e.g., 10^{-14} to 10^{-15}) reported in literature elude us
- Conclusion: We have the "industry-standard" outgassing rate ~ 1×10^{-12} Torr·L/s·cm^2

Recent High Temperature Bake of JLab FEL Gun

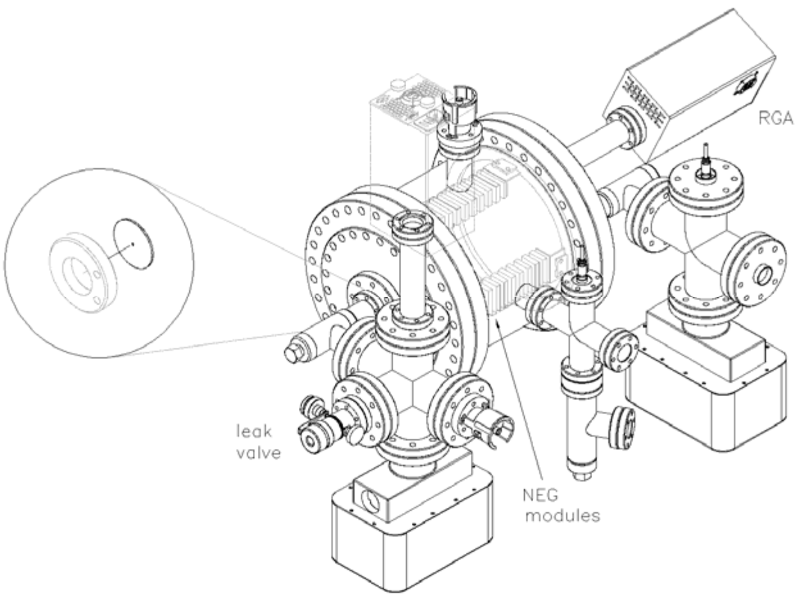
316 LN Stainless Steel, Baked at 400°C for 10 days
Vacuum inside, hot air outside, Strip heaters instead of hot air guns
Outgassing rate: 1.49×10^{-13} Torr L/s cm^2

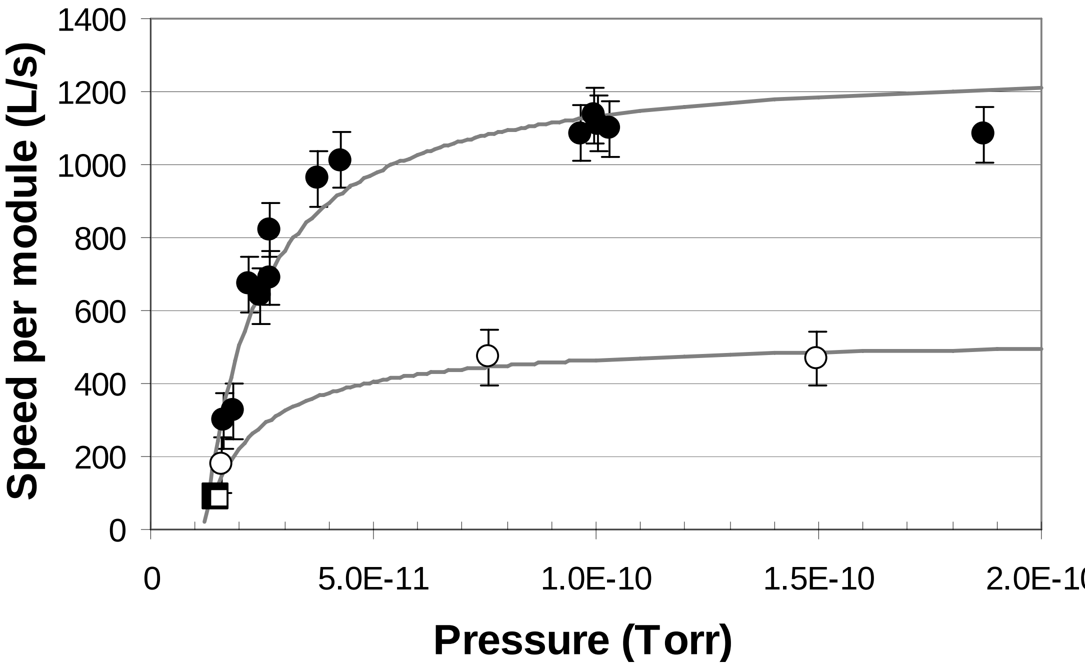


Lessons for CEBAF/ILC?

- We should have vacuum fired our end flanges
- Welding introduces hydrogen
- 250C for 30 hours not adequate

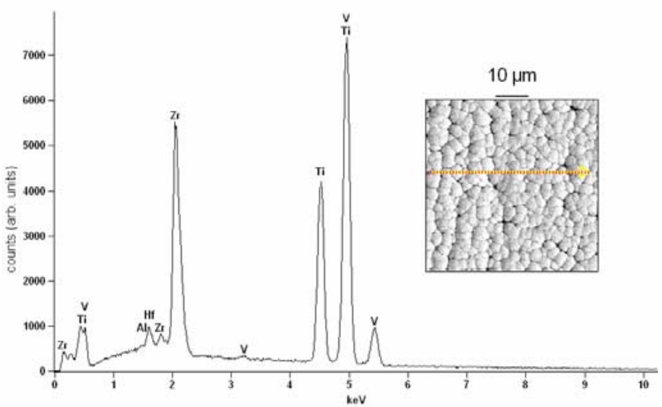
NEG Pump Speed

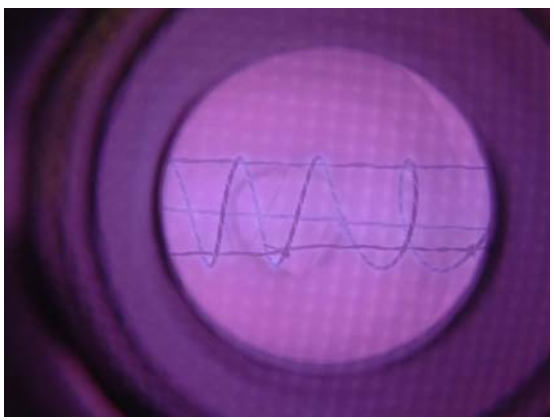


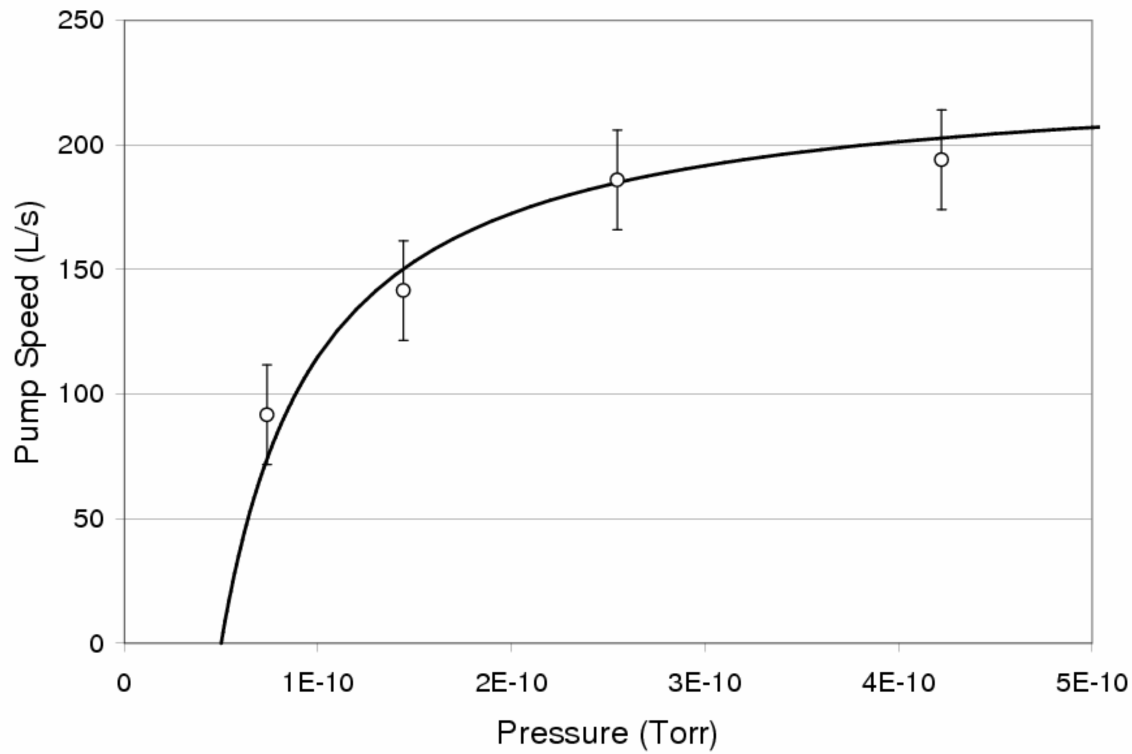


- Full NEG activation better than passive activation via bake
- NEG pump speed very good, at least at high pressure
- Conclusion: Can't explain reduced pump speed at low pressure – a real effect? More likely an indication of gauge limitations

NEG Coating



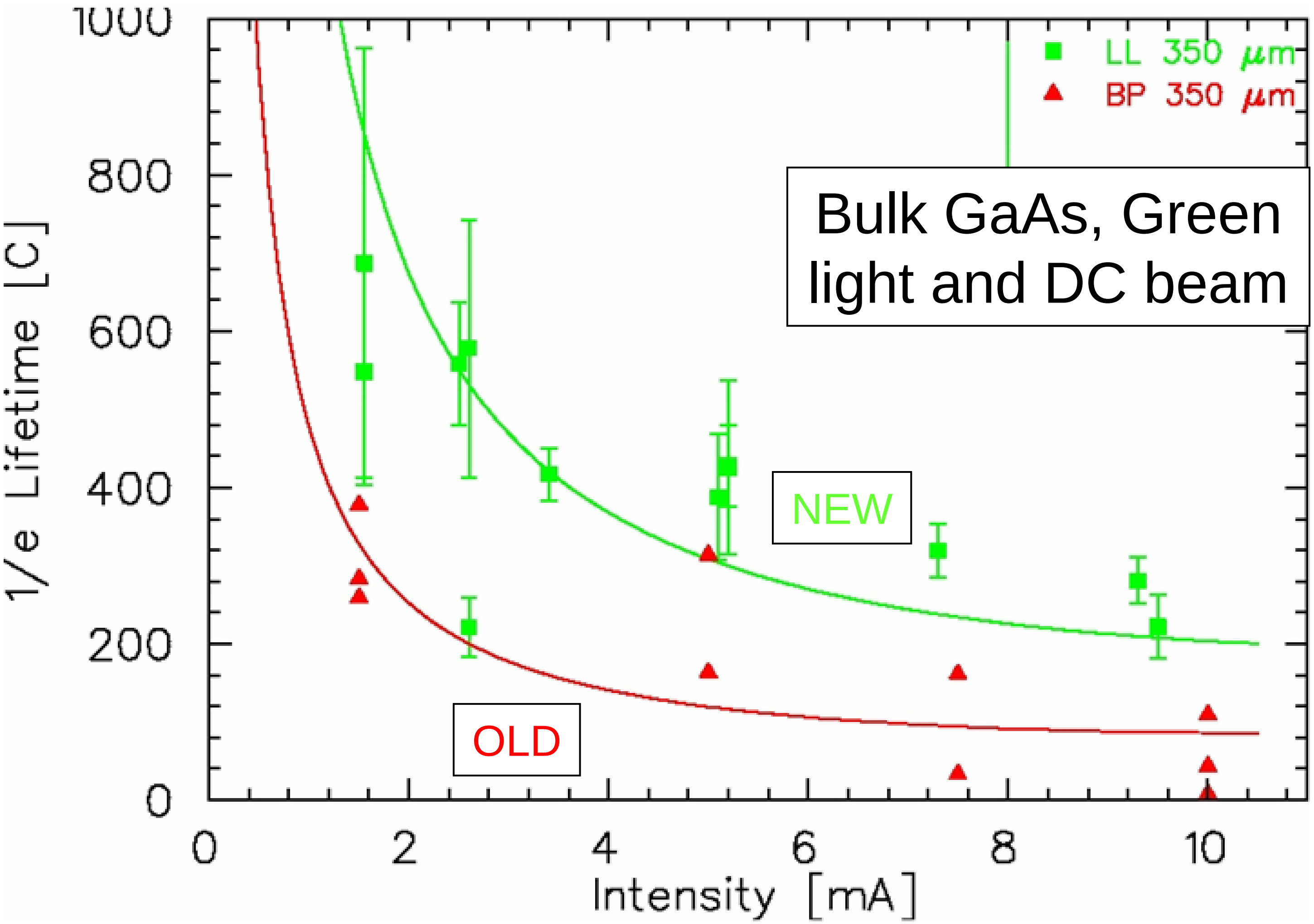




NEG coating turns a gas source into pump
~0.02 L/s·cm^2 : Modest pump speed can be improved

SAES claims > 5 L/s·cm^2
for a chamber with 4000 cm^2, that would be a big pump!

Compare NEW and OLD load locked guns



Vacuum gauges indicated same pressure in both guns, suggesting our gauges don't work below 1.5×10^{-11}Torr

Photogun Lifetime - the best vacuum gauge

"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

Future R&D Toward Improved Vacuum

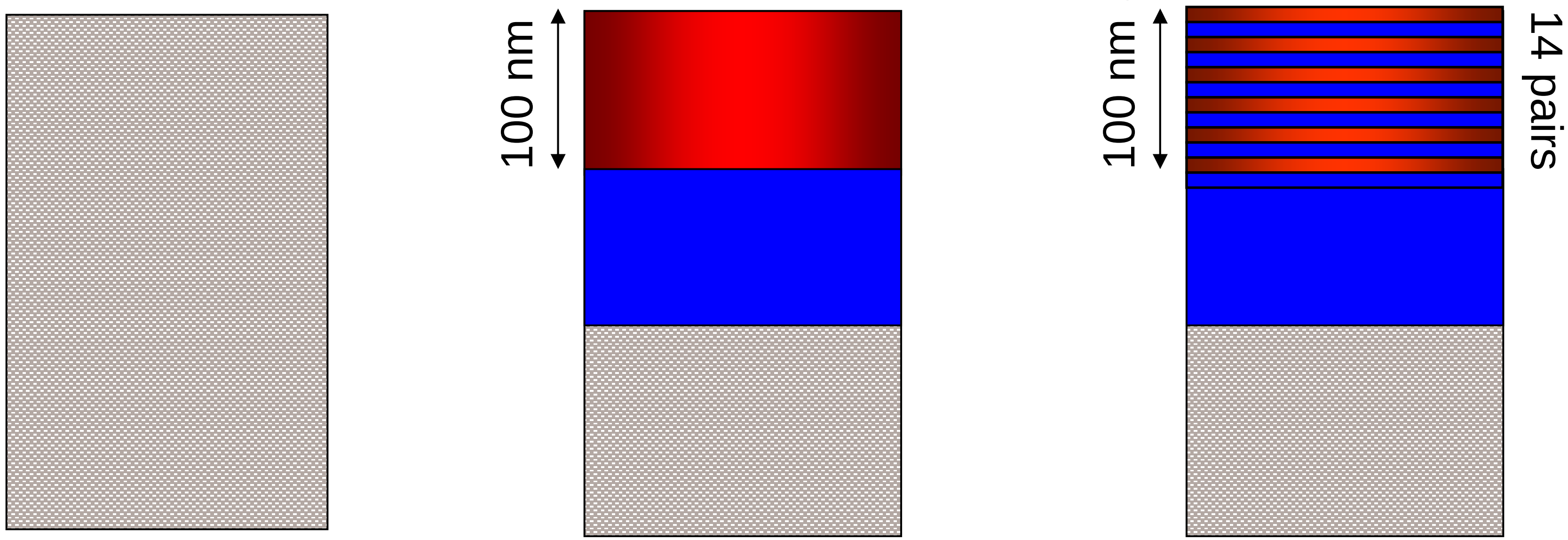
- Ion pump studies (do ion pumps limit our vacuum?)
- 400C heat treatment: does outgassing remain low following venting?
- A better vacuum gauge? SBIR with ElVac
- Do NEGs really quit pumping at low pressure?
- If so, we need different pumps: Ti-sublimators, cryo-pumps…

Photocathode Material

Bulk GaAs

Strained GaAs:
GaAs on GaAsP

Superlattice GaAs:
Layers of GaAs on GaAsP



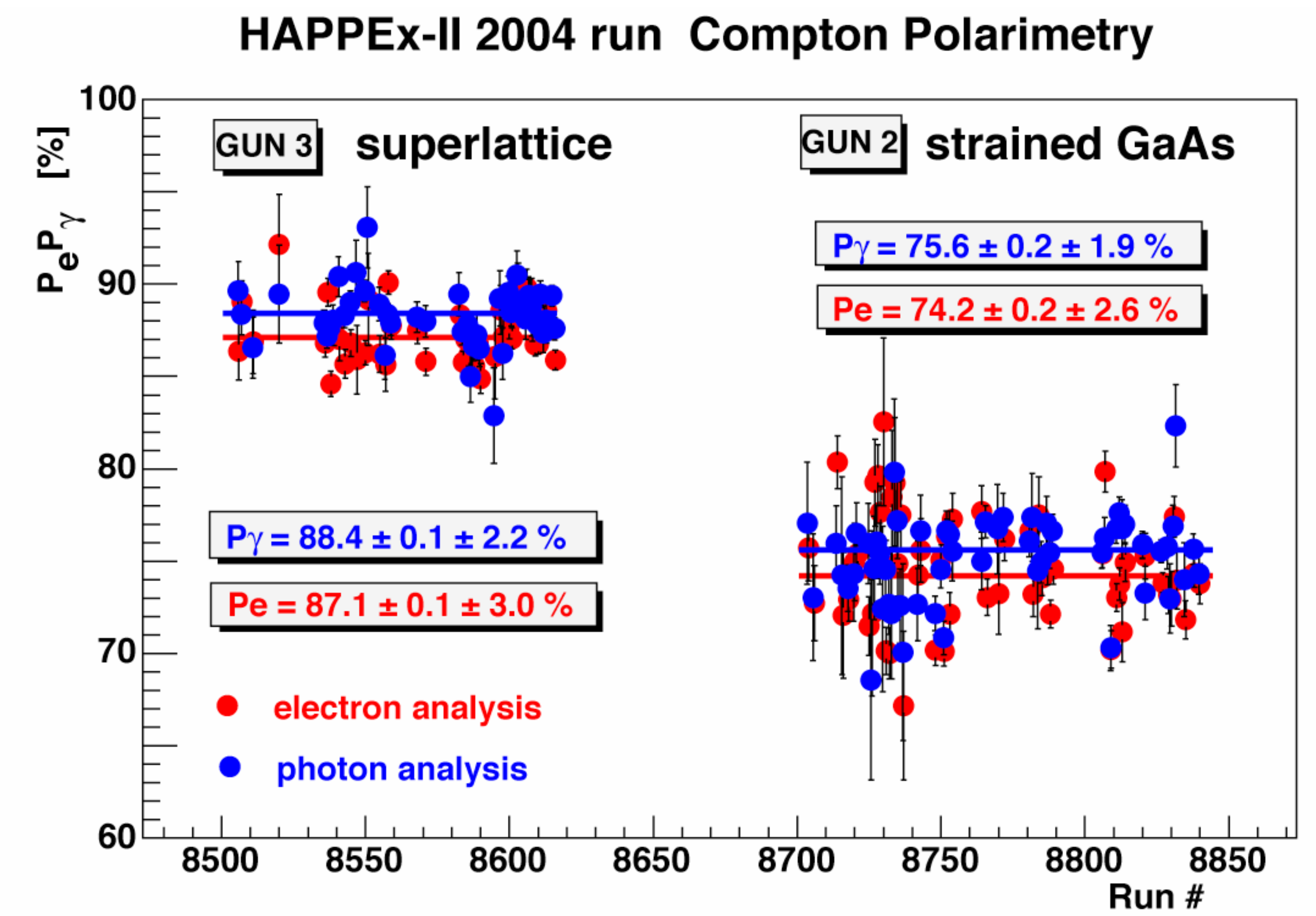
High QE ~ 20%
Pol ~ 35%

“conventional” material
QE ~ 0.15%
Pol ~ 75%
@ 850 nm

No strain relaxation
QE ~ 1%
Pol ~ 85%
@ 780 nm

Commercial Products

Significant FOM Improvement



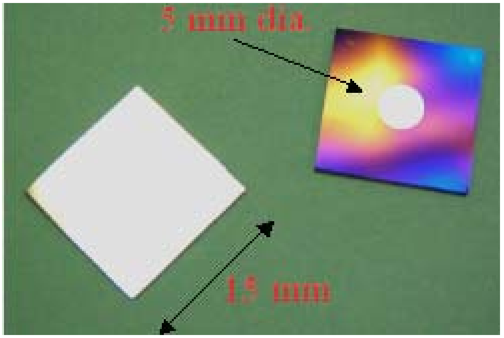
$$\frac{P^2_{sup.} I}{P^2_{str.} I} = 1.38$$

But we could not operate with long lifetime….

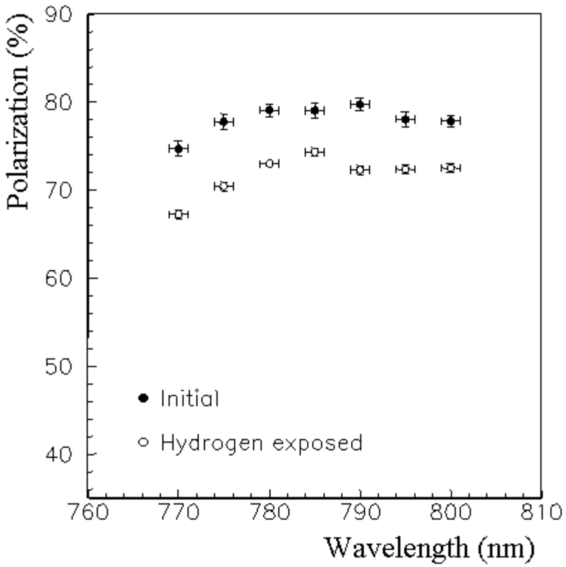
Commercial Superlattice Photocathodes

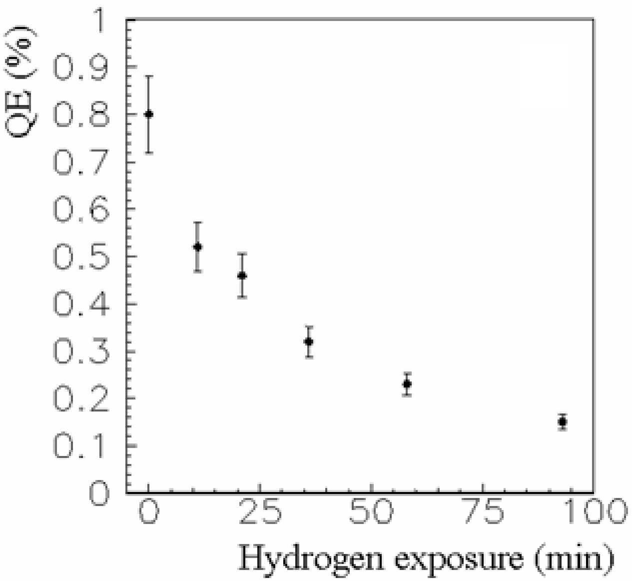
- Success required ~ 1 year of effort
- Cannot be hydrogen cleaned
- Arsenic capped (worked with vendor SVT)
- No solvents during preparation!

M. Baylac et al., "Effects of atomic hydrogen and deuterium exposure on high polarization GaAs photocathodes" PRST-AB 8, 123501 (2005)



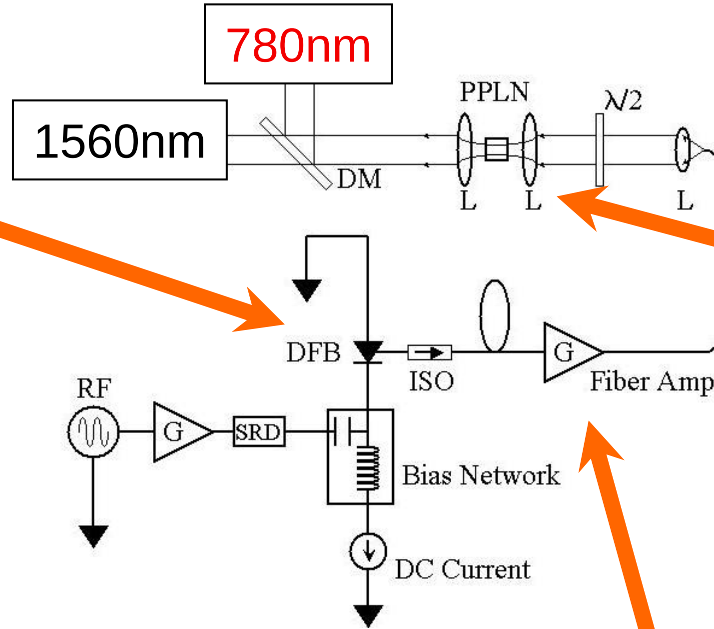
Anodized edge: a critical step. Eliminates electrons that hit beampipe walls



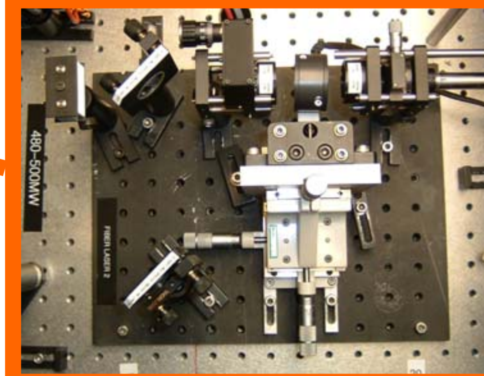


Fiber-Based Drive Laser

Gain-switched seed

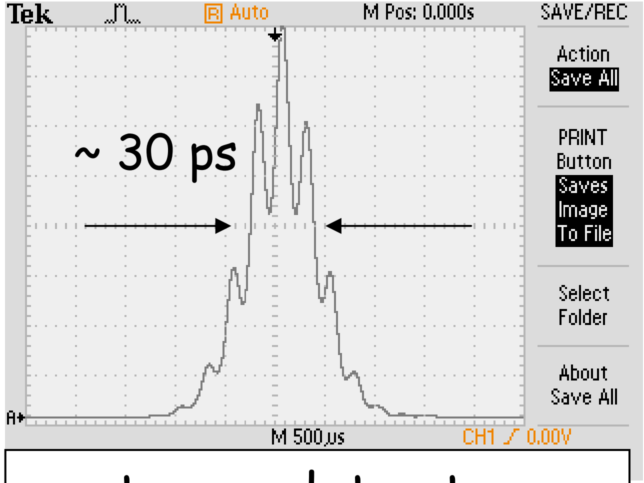


Frequency-doubler

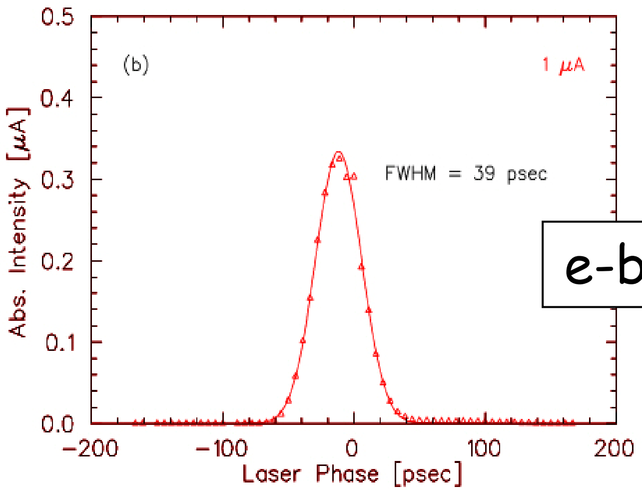


ErYb-doped fiber amplifier

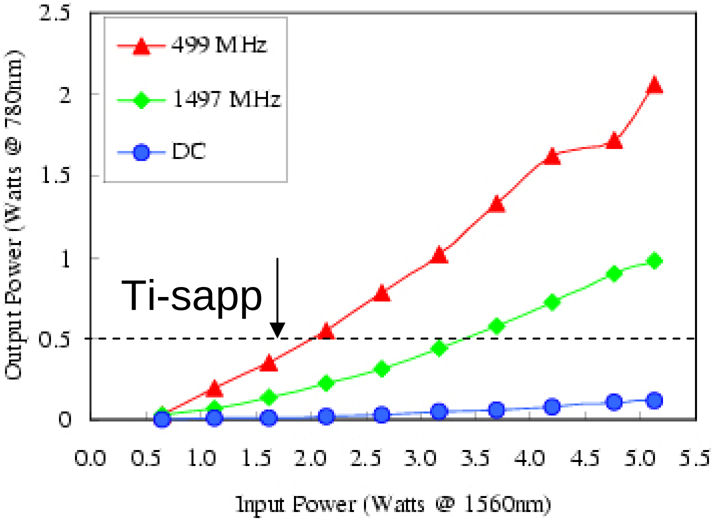
Fiber-Based Drive Laser



autocorrelator trace



e-bunch

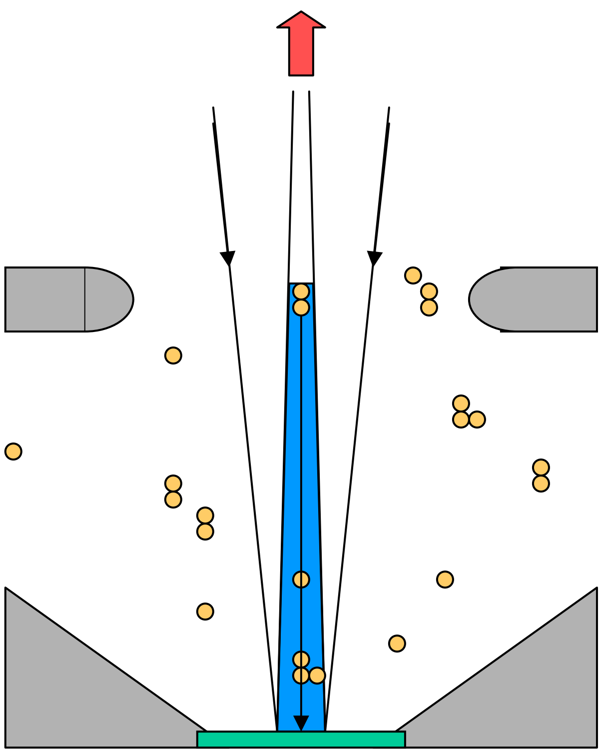


- CEBAF's last laser!
- Gain-switching better than modelocking; no phase lock problems, no feedback
- Very high power
- Telecom industry spurs growth, ensures availability
- Useful because of superlattice photocathode (requires 780nm)

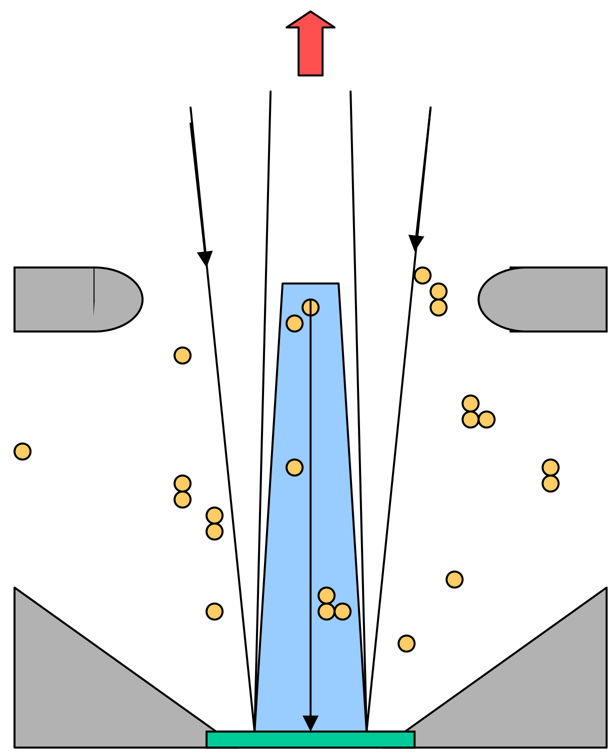
Improve Lifetime with Larger Laser Spot?

(Best Solution – Improve Vacuum, but not easy)

Bigger laser spot, same # electrons, same # ions



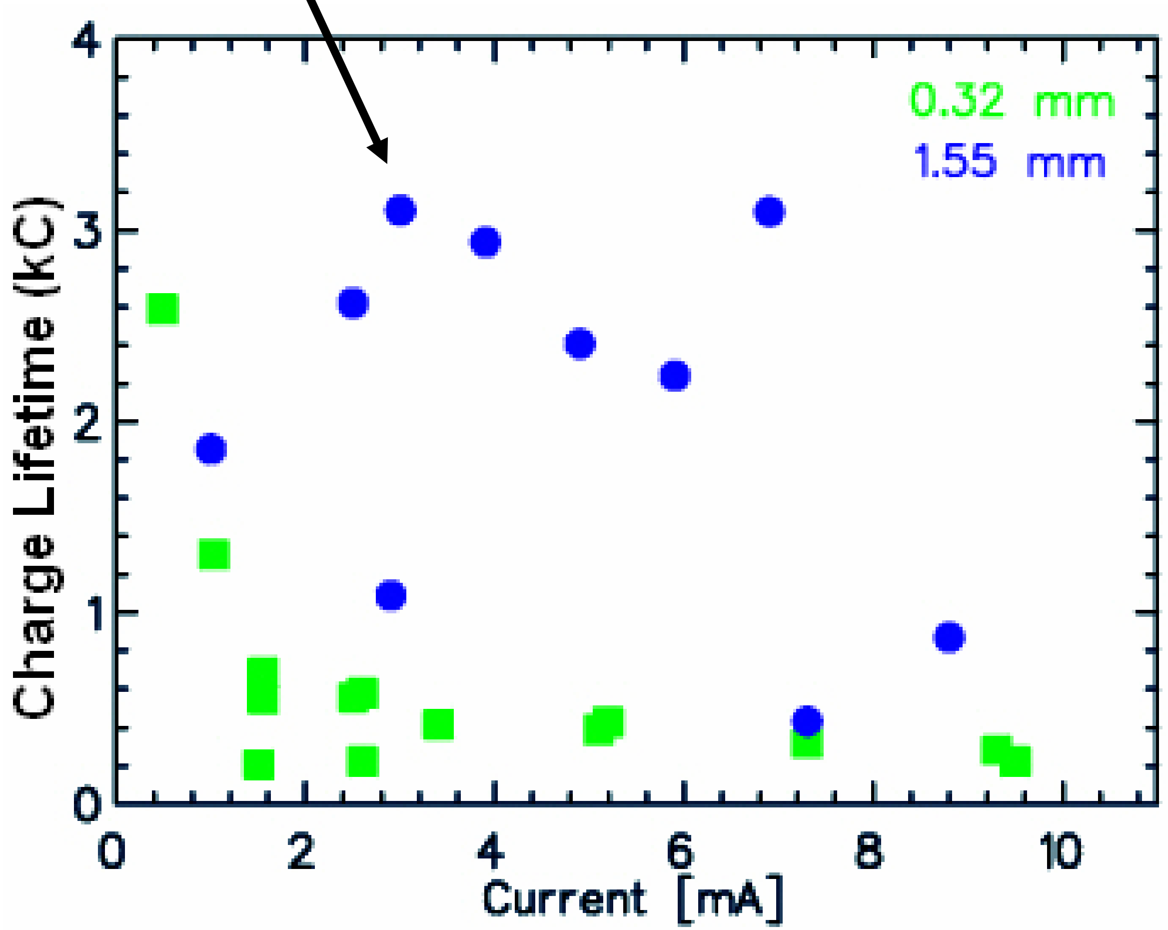
Ionized residual gas
strikes photocathode



Ion damage distributed
over larger area

Lifetime with Large/Small Laser Spots

Tough to measure large Coulomb lifetimes with only 100-200 C runs!



Factor of 5 to 10 improvement with larger laser spot size

Expectation:

$$\left(\frac{1500}{350}\right)^2 \approx 18$$

"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