Polarized Electron Sources at JLab

Joe Grames, Center for Injectors & Sources

OUTLINE

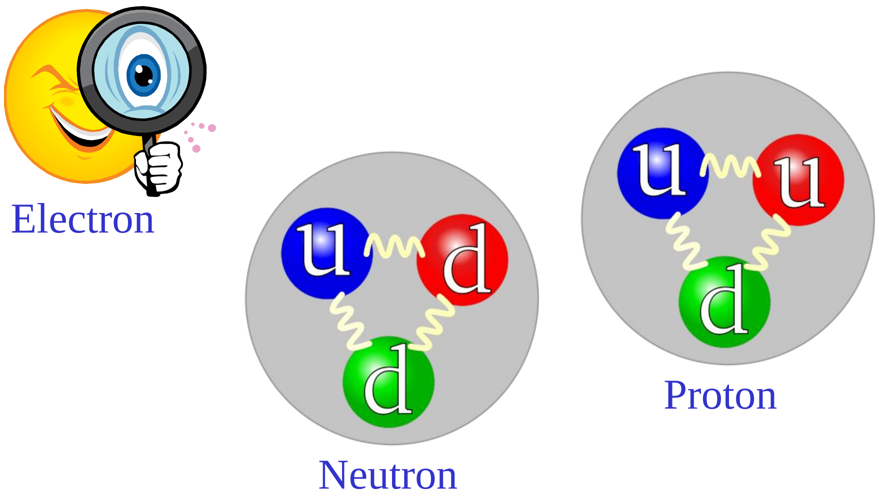
- Motivation
- Photoemission from GaAs
- Spin polarized electrons
- Extreme High Vacuum (XHV)
- High frequency/power lasers
- Electron gun design

www.jlab.org/accel/inj_group

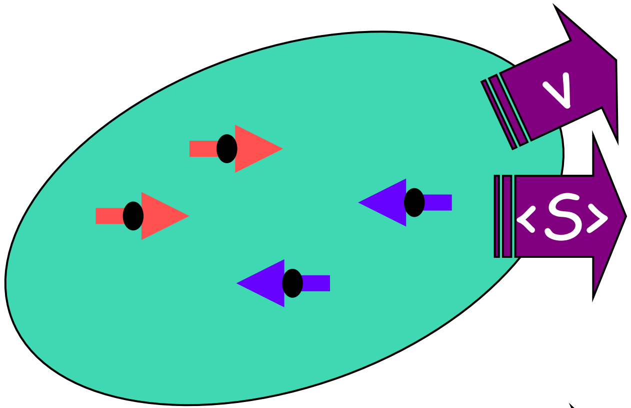
Motivation

Spin Polarized electron beams have wide application in studies which range from materials science to nuclear and high energy physics:

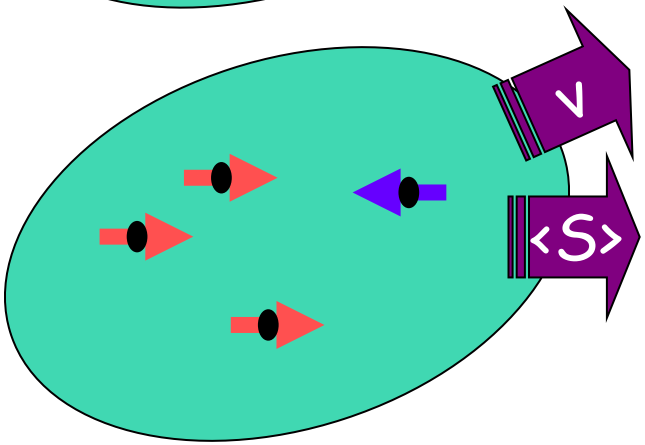
$\Rightarrow$ the latter has driven the development of polarized e- sources



What do we mean by a "Polarized Electron Beam" ?



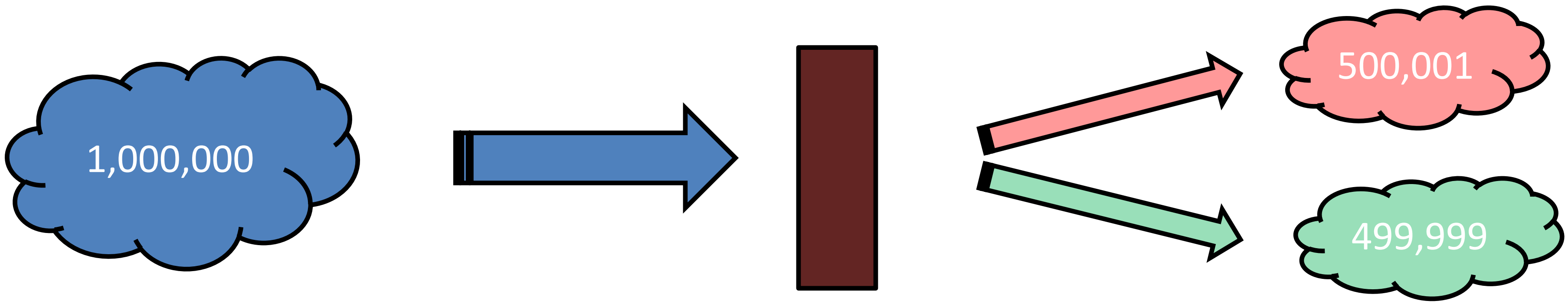
$P_e = (2-2)/(2+2) = 0\%$ ☹



$P_e = (3-1)/(3+1) = 50\%$ ☺

Statistical Precision ~ $1/\sqrt{I \times P^2}$

Precision Experiments Benefit Greatly



Asymmetry = Δ / Σ = (500,001 – 499,999) / (1,000,000) = 2 ppm

Experiment	Hall	Start	Energy	Current	Target	A_{PV}
PV-DIS	A	Oct 09	6.068 GeV	85 uA	^{2}H (25 cm)	63±3 ppm
PREx	A	March 10	1.056 GeV	50 uA	^{208}Pb (0.5 mm)	500±15 ppb
QWeak	C	May 10	1.162 GeV	180 uA	^{1}H (35 cm)	234±5 ppb

A history 30+ years and growing…

Semiconductor sources introduced in 1975 via *optical pumping* of GaAs

First GaAs e- source for an accelerator at SLAC (1978) -> I=1uA, P~35%

Today at Jlab (2010) -> I=100uA, P~85%

Many accelerator facilities have/had polarized e- GaAs sources:

CEBAF, MAMI, Bonn, *SLAC/SLC, MIT-BATES*

R&D for future accelerators have plans for polarized e- GaAs sources:

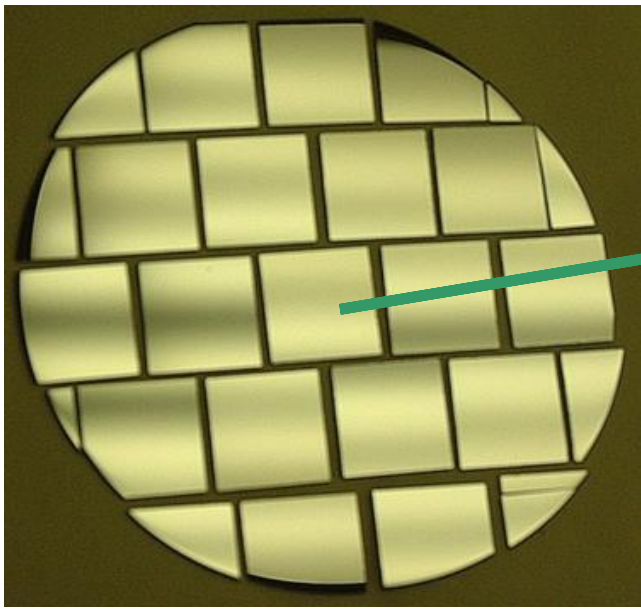
International Linear Collider (ILC) ~ 50 uA

Electron Ion Collider ~ 1 to 500 milliAmps

The present State-of-the-Art for R&D (not on accelerator) have demonstrated only a ~few mA's & for brief periods of time.

Gallium Arsenide “Photocathode”

Buy a wafer, cleave into squares, build some good thermal/electrical/mechanical holder (Mo puck), bond *photocathode* (In foil) and retain (Ta ring).



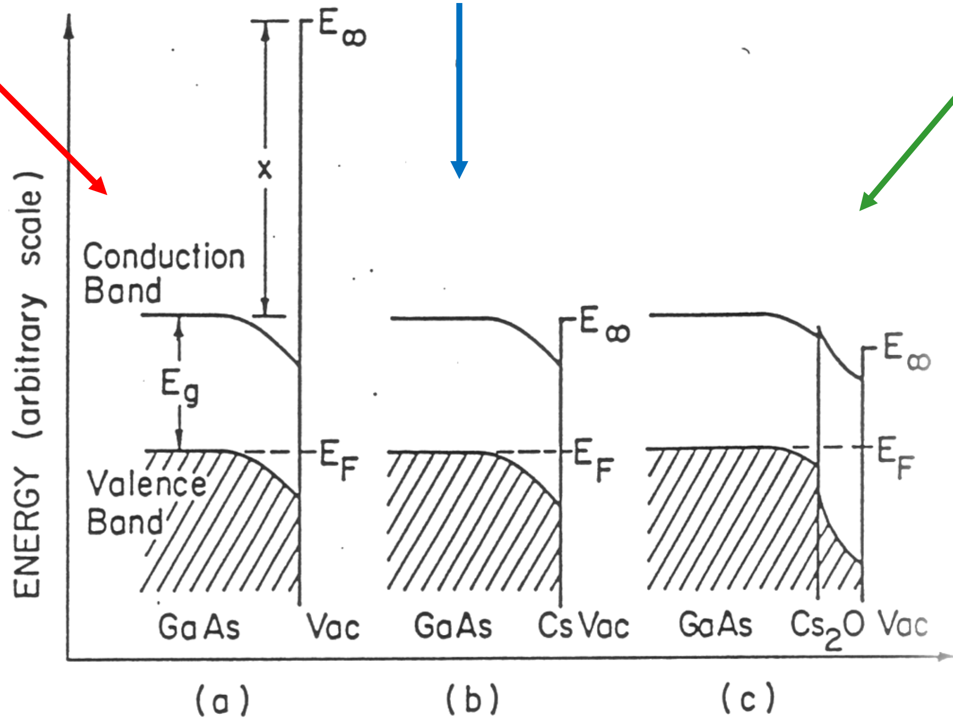
Sounds relatively easy, huh…?

Photo-Emission from GaAs -> $QE = \frac{\# e^{-}\text{'s OUT}}{\# \gamma\text{'s IN}}$

Bare GaAs surface;
Large work function.
No electrons

Alkalai (Cs) reduces
work function.
Some electrons.

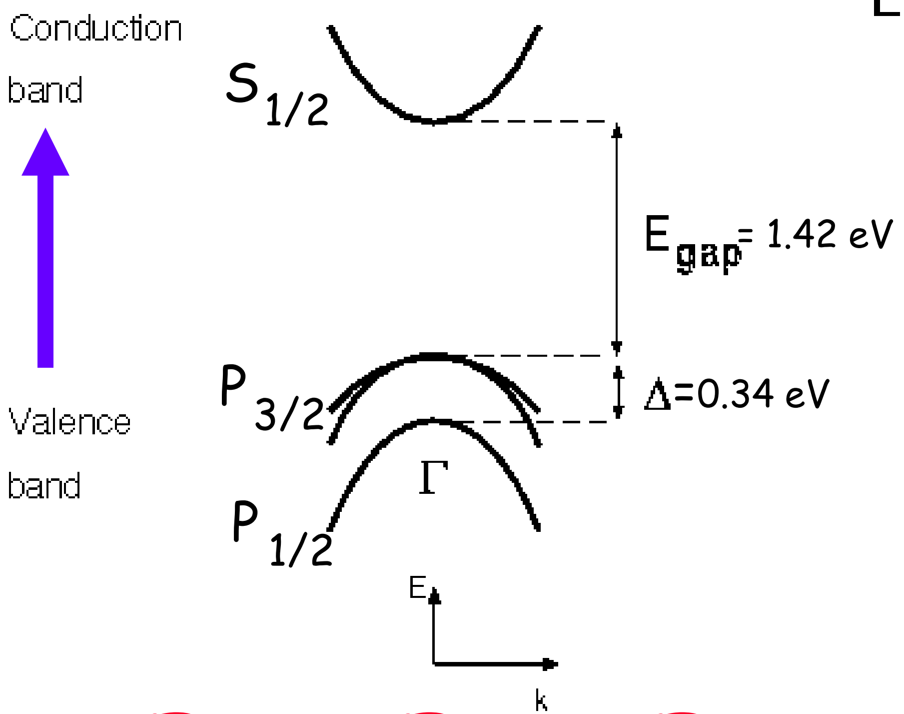
Cesium + Oxidant (O or NF3)
"Negative Electron Affinity".
Many electrons

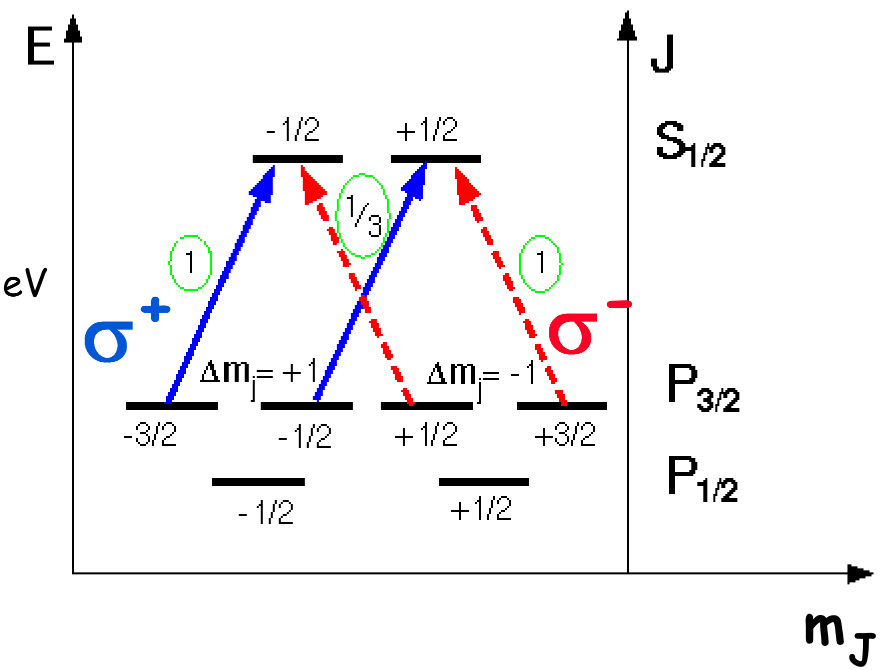


$E_a > 0$ $E_a \approx 0$ $E_a < 0$

Aligning the Spin States in GaAs

Optical pumping between $P_{3/2}$ and $S_{1/2}$





$$E_{gap} < E_{\gamma} < E_{gap+\Delta}$$

(E_{γ} = hc / λ)

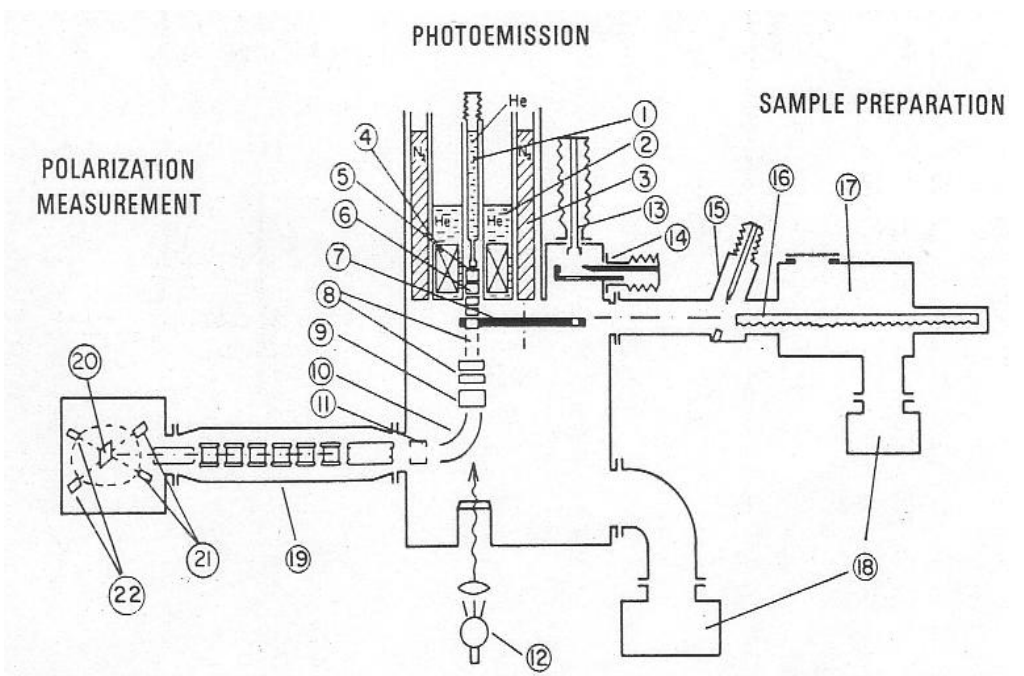
$$P_e = \frac{3-1}{3+1} = 50\%$$

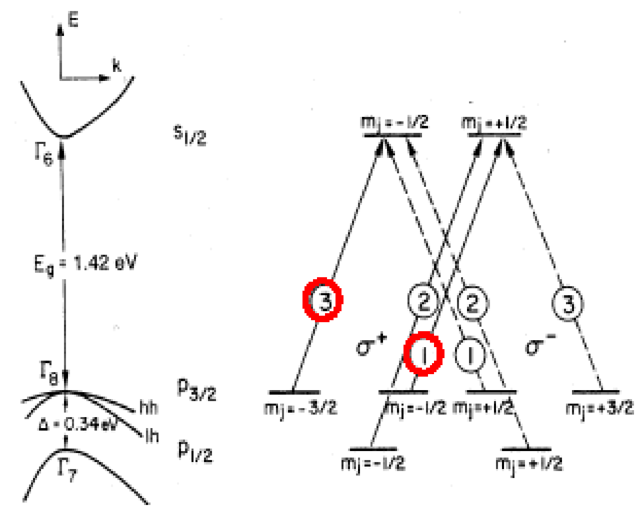
The First GaAs Photoemission Gun

PHYSICAL REVIEW B VOLUME 13, NUMBER 12 15 JUNE 1976

Photoemission of spin-polarized electrons from GaAs

Daniel T. Pierce* and Felix Meier
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule, CH 8049, Zürich, Switzerland
(Received 10 February 1976)





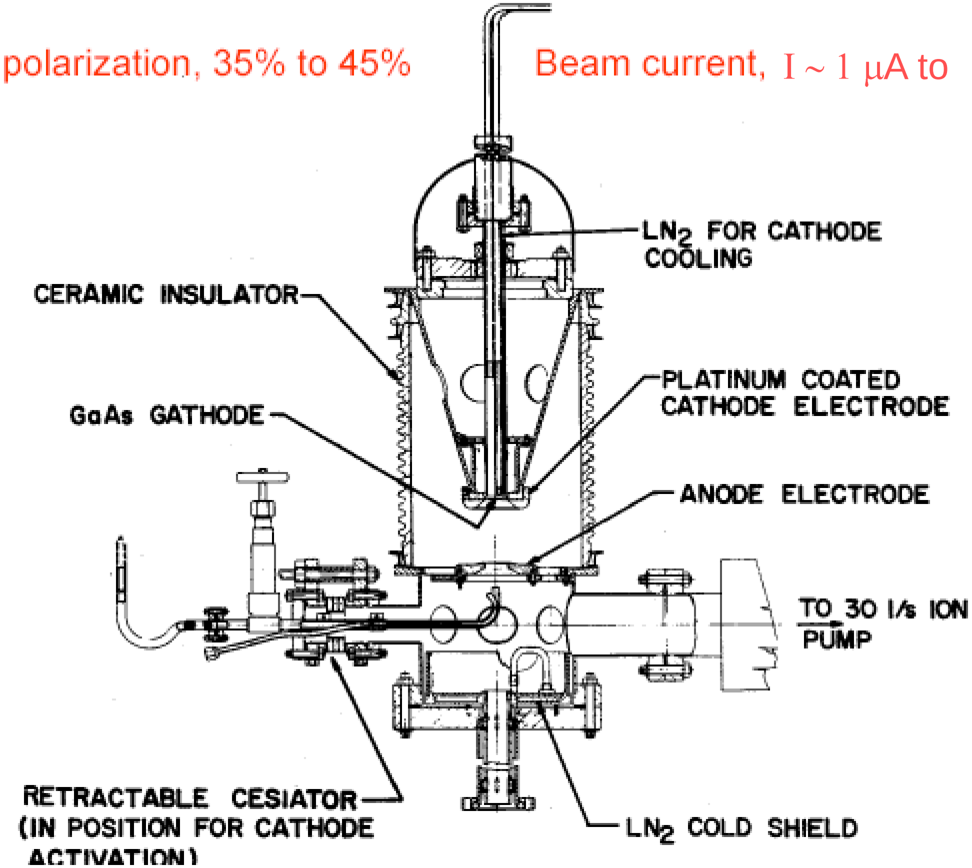
$$P = \frac{3-1}{3+1} = 50\%$$

First High Voltage GaAs Photogun

Polarized e⁻ Gun for SLAC Parity Violation Experiment

Beam polarization, 35% to 45%

Beam current, $I \sim 1\ \mu A$ to 15 A peak



Electrons into the accelerator Dec., 1977

Collaboration announces parity violation June, 1978

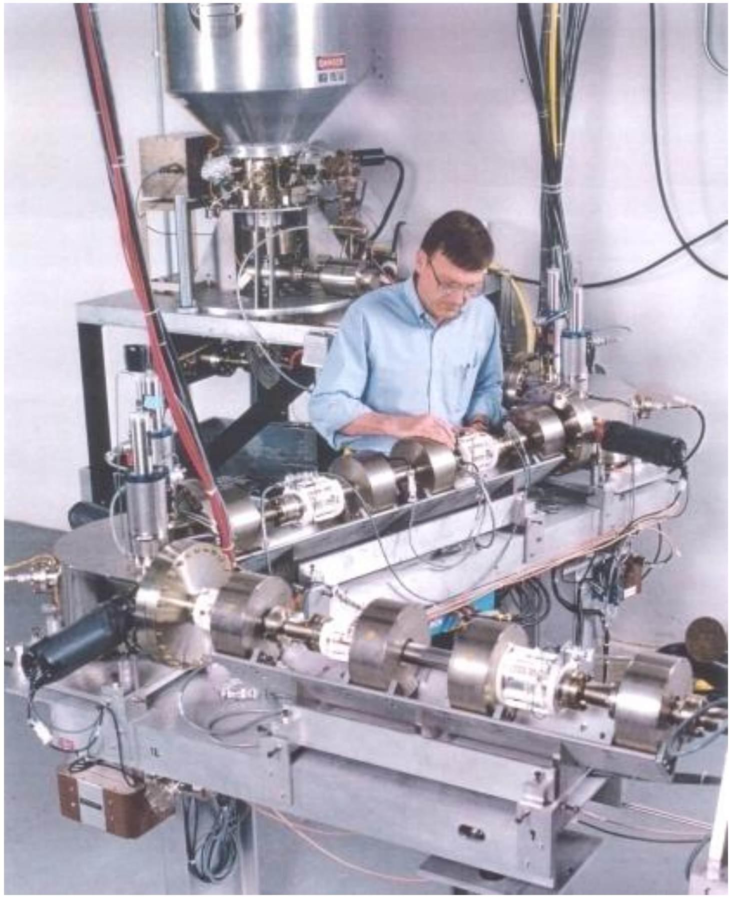
Formation of CEBAF – 1980 to 1996

- ★ 1980 - Formation of the Southeastern Universities Research Association (SURA) and submission of its first NEAL proposal
- ★ 1982 - Five (including second NEAL) proposals submitted to DOE
- ★ 1983 - SURA proposal selected by DOE
  NEAL named the Continuous Electron Beam Accelerator Facility
- ★ 1984 - Newport News site selected and federal funding for R&D
- ★ 1985 - Arrival of Hermann Grunder and the Berkeley team
  Superconducting design developed
- ★ 1986 - J. Dirk Walecka joins CEBAF as Scientific Director
- ★ 1987 - CEBAF construction start
- ★ 1990 - Nathan Isgur becomes Theory Group Leader
- ★ 1994 - first beam on target
- ★ 1995 - Physics program begins in Hall C
- ★ 1996 - CEBAF dedicated by SURA;
  laboratory named Thomas Jefferson National Accelerator Facility

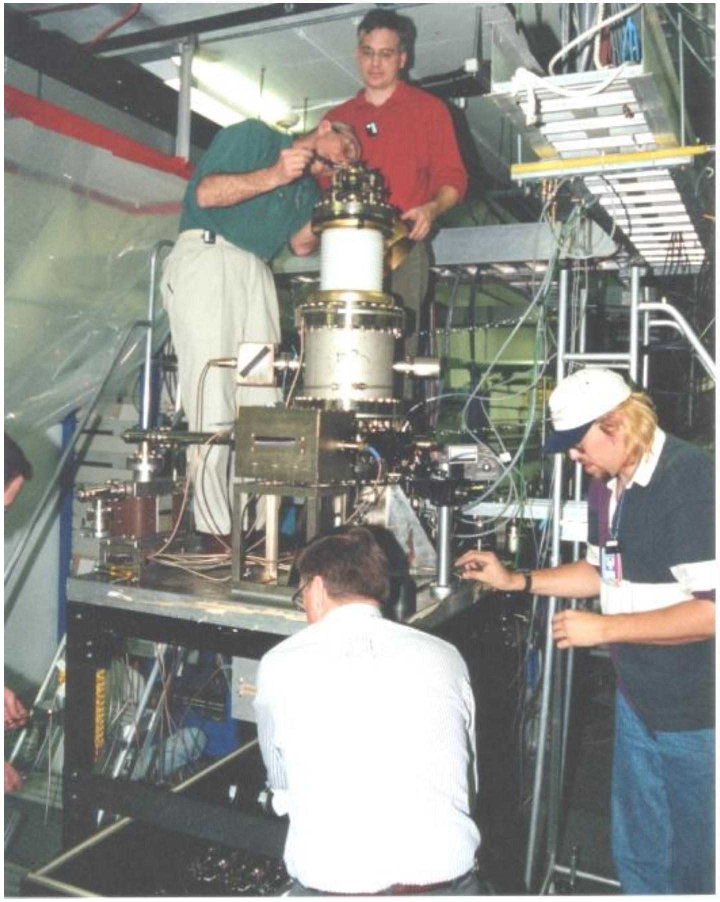
Slide from F. Gross

CEBAF Polarized Source: often in flux

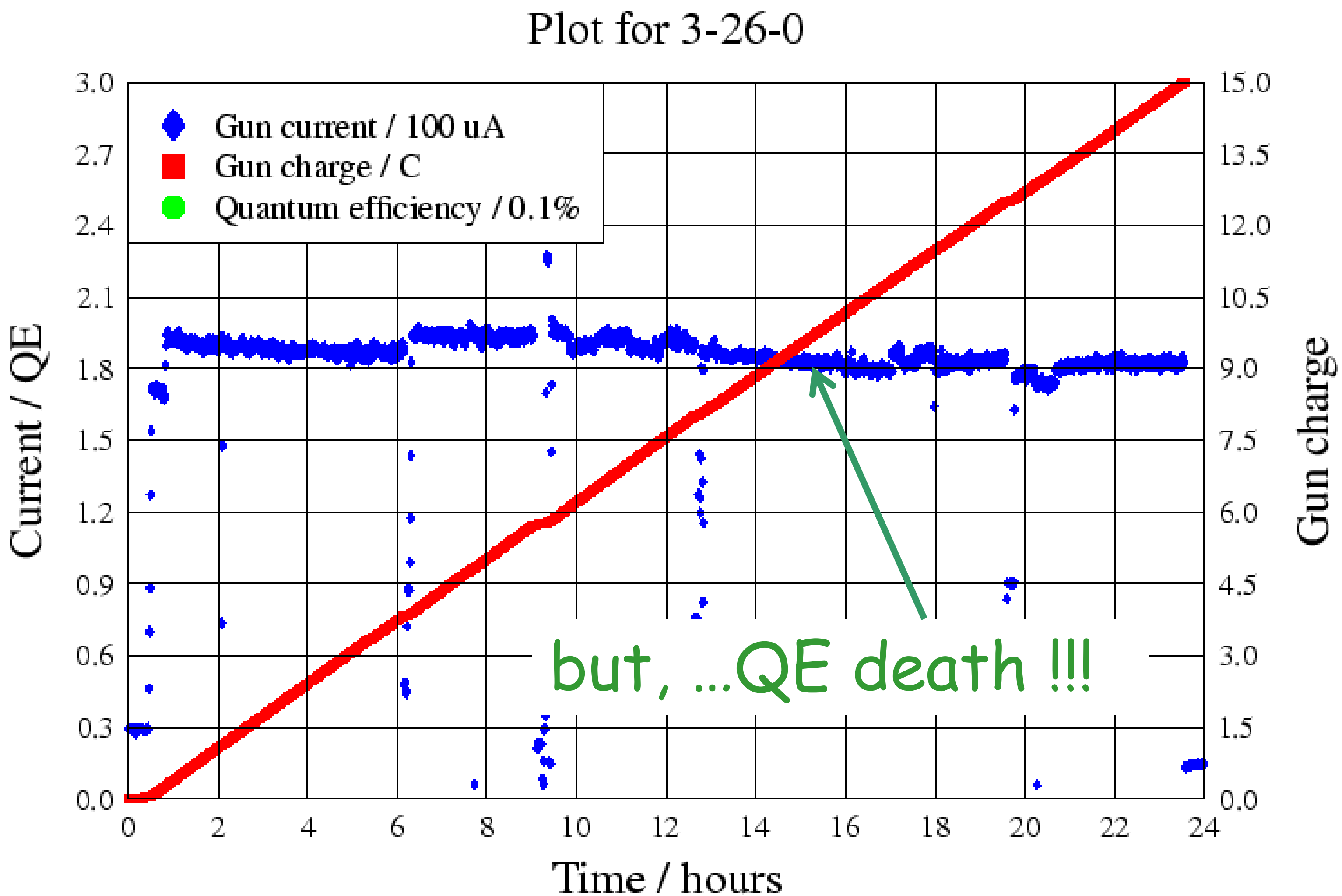
…by 1997



1998, ever changing…



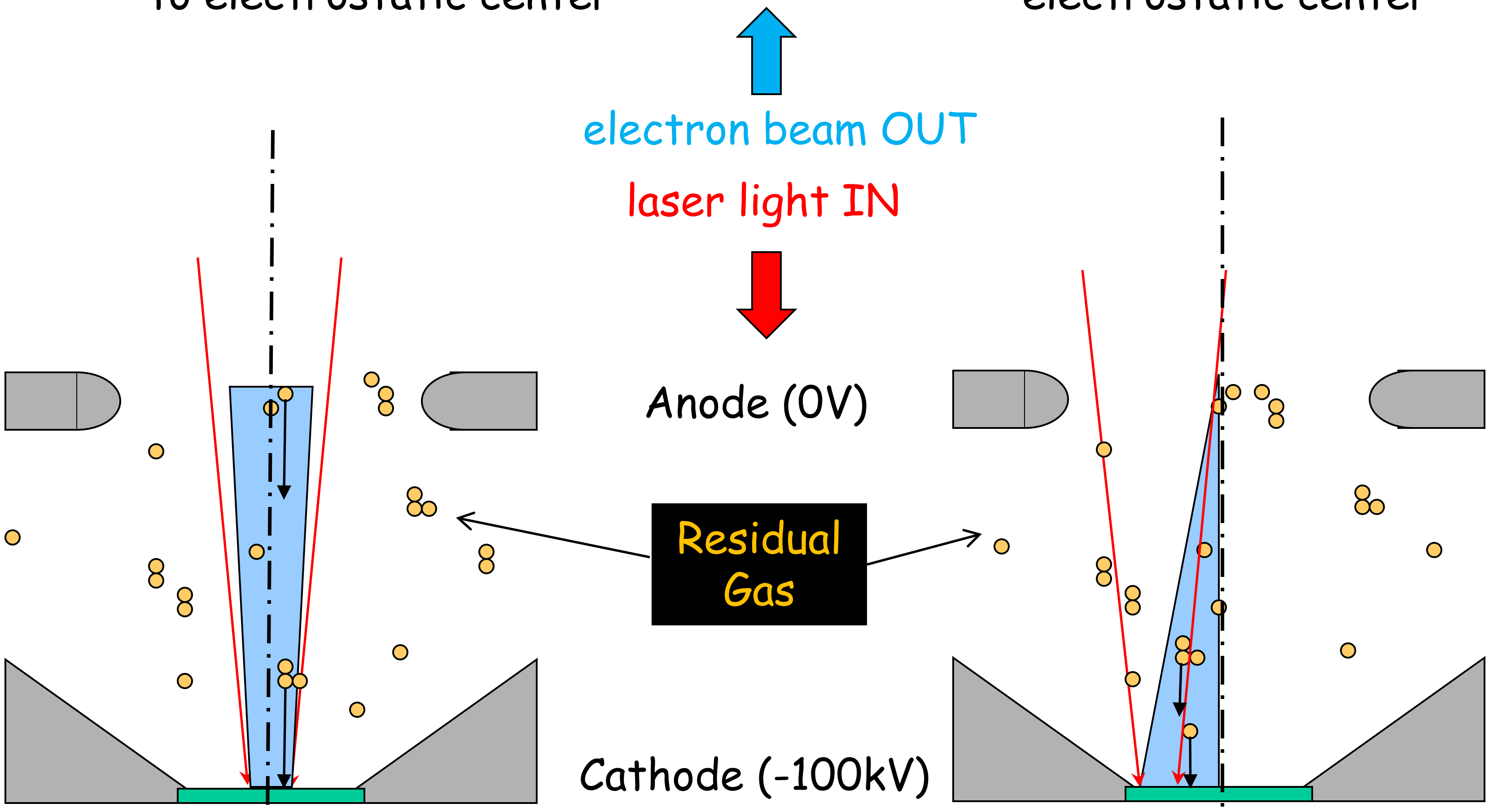
Who wants polarized electrons?



Ion Backbombardment

High energy ions focused to electrostatic center

We don't run beam from electrostatic center

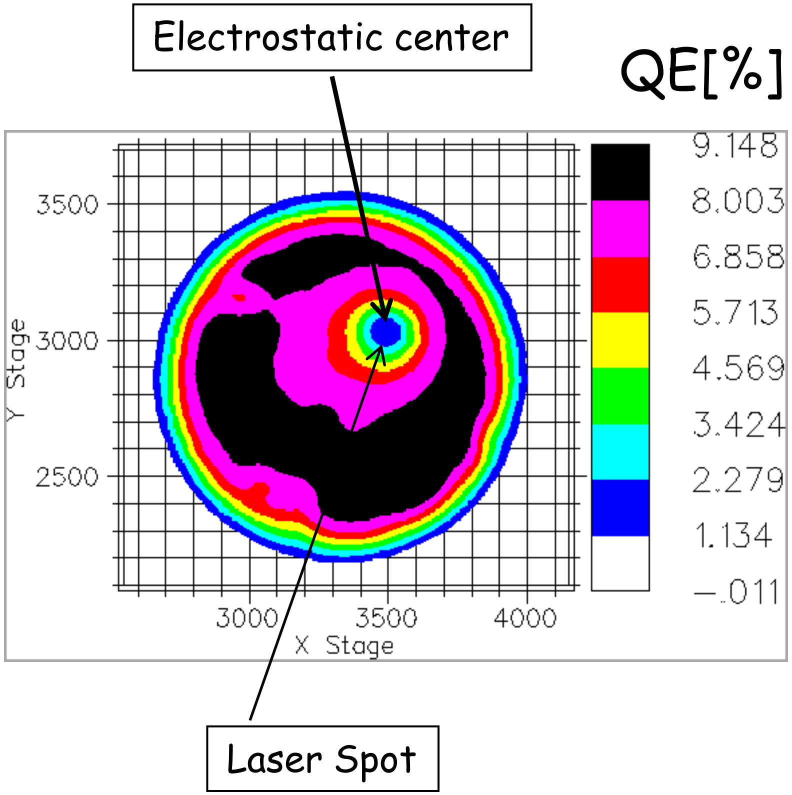


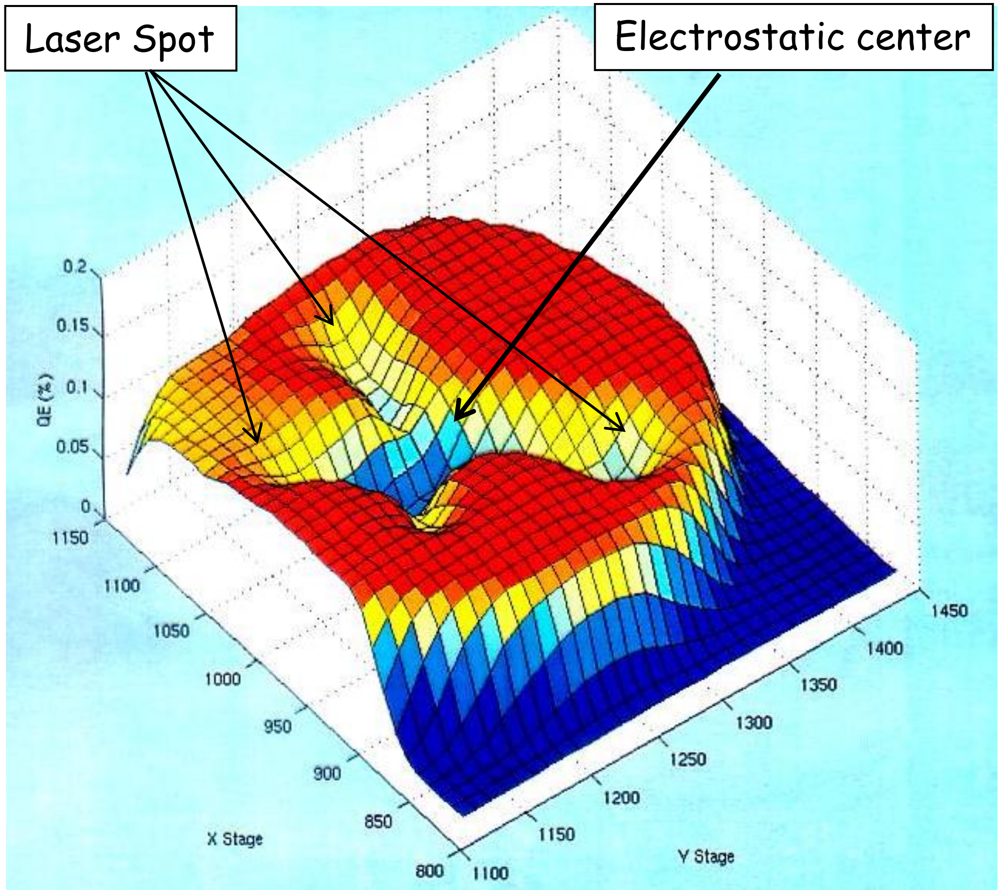
Ions create QE "hole" at the electrostatic center

Ions create QE "trough" to electrostatic center

Bad, bad ions…

Imperfect vacuum => QE degrades via ion backbombardment





Needless to say, we understand Alice's worry…

The woods were dark and foreboding, and Alice sensed that sinister eyes were watching her every step. Worst of all, she knew that Nature abhorred a vacuum.

"The woods were dark and foreboding, and Alice sensed that sinister eyes were watching her every step. Worst of all, she knew that Nature abhorred a vacuum."

– Gary Larson

Air (760 torr) ~ $10^{20}/cm^3$

- Low, Medium Vacuum (>10^{-3} Torr)
  - Viscous flow
    - interactions between particles are significant
  - Mean free path less than 1 mm
- High, Very High Vacuum (10^{-3} to 10^{-9} Torr)
  - Transition region
- Ultra High Vacuum (10^{-9} - 10^{-12} Torr)
  - Molecular flow
    - interactions between particles are negligible
    - interactions primarily with chamber walls
  - Mean free path 100-10,000 km
- Extreme High (<10^{-12} Torr)
  - Molecular flow
  - Mean free path 100,000 km or greater

Vacuum Conditions at CEBAF

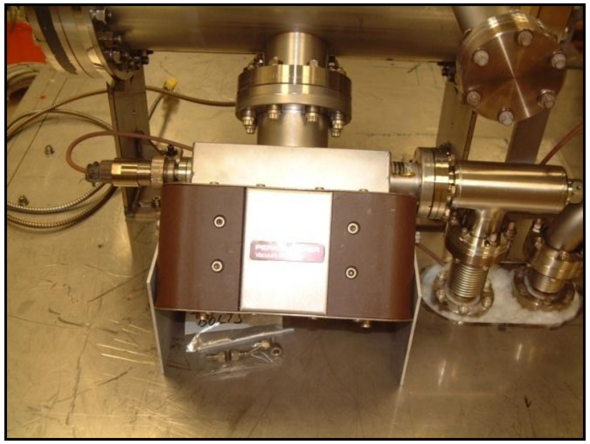
Application	Pressure Range	Location	Vacuum Regime
Beamline to dumps	10^{-5} Torr	Target to dump line	Medium
Cryogenic insulating vacuum	10^{-4} Torr to 10^{-7} Torr	Cryomodules, transfer lines	Medium to high
Targets, Scattering Chambers	10^{-6} to 10^{-7} Torr	Experimental Halls	High to very high
RF waveguide warm to cold windows	10^{-7} to 10^{-9} Torr	Between warm and cold RF windows	High to very high
Warm beamline vacuum	10^{-7} to 10^{-8} Torr or better	Arcs, Hall beamline, BSY, some injector	High to very high
Warm region girders	10^{-9} Torr or better	Girders adjacent to cryomodules	Very high to ultrahigh
Differential pumps	Below 10^{-10} Torr	Ends of linacs, injector cryomodules and guns	Ultrahigh vacuum
Baked beamline	10^{-10} to 10^{-11}Torr	Y chamber, Wien filter, Pcup	Ultra high vacuum
Polarized guns	10^{-11} to 10^{-12} Torr	Inside Polarized guns	Ultra/Extreme high vacuum
SRF cavity vacuum	< 10^{-12} Torr	Inside SRF cavities with walls at 2K	Extreme high vacuum

But, where does the gas come from?

- **Outgassing from the system**
  - Surfaces desorb gas (like a leaky sponge)
  - Primarily water in unbaked systems
  - Primarily hydrogen from steel in baked systems
- **Leaks**
  - Real
    - Gaskets not sealed
    - Cracks in welds, bellows, ceramics, window joints
  - Virtual
    - Small volumes of trapped gas (screw threads) that slowly leak
- **Gas load caused by the beam**
  - Thermal desorption of gas, electrons/photons striking surfaces
- **Engineered Loads**
  - gas added on purpose, e.g., to Cs/NF3
- **Permeation of gas through materials**
  - Hydrogen can permeate through stainless steel!

Ultra & Extreme High Vacuum Pumps

- **Baking to get pressures below 10^{-10} Torr**
  - 250 C for extended time removes water vapor bonded to surface that otherwise limits pressure
- **Ion Pumps**
  - Electric field to ionize gasses
  - Magnetic field to direct gasses into cathodes where they are trapped
    - Has some pumping capability for noble gasses
- **Getter Pumps**
  - Chemically active surface
    - Titanium sublimed from hot filament
    - Non-Evaporative Getters
  - Molecules stick when they hit
    - Does not work well for inert gasses such as Argon, Helium or for methane
- Avoid contamination by oils due to roughing pumps, fingerprints, machining residue.



Ion Pump

NEG pump array

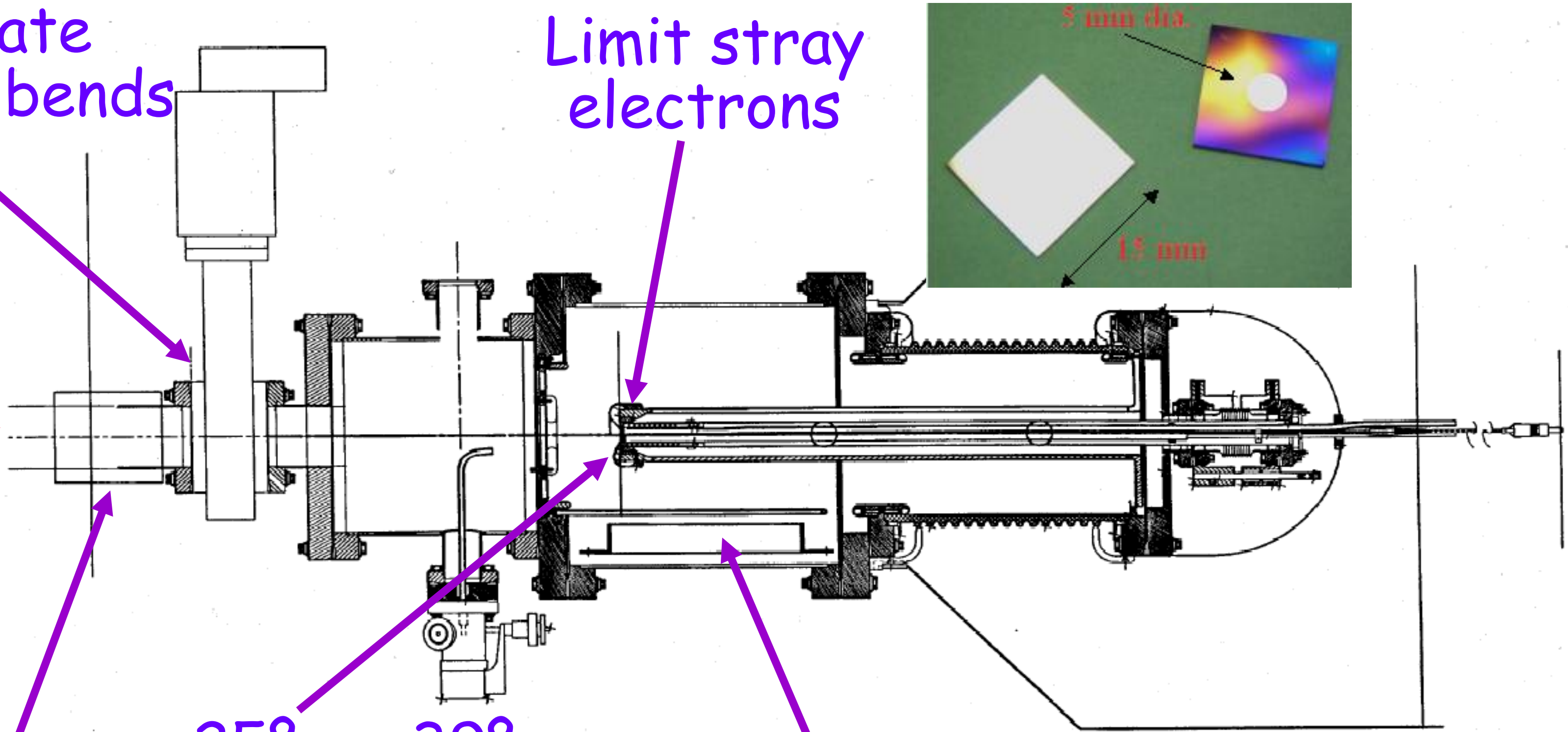
So, by late 90's many gun improvements…

Eliminate sharp bends

Limit stray electrons

Laser

e^-

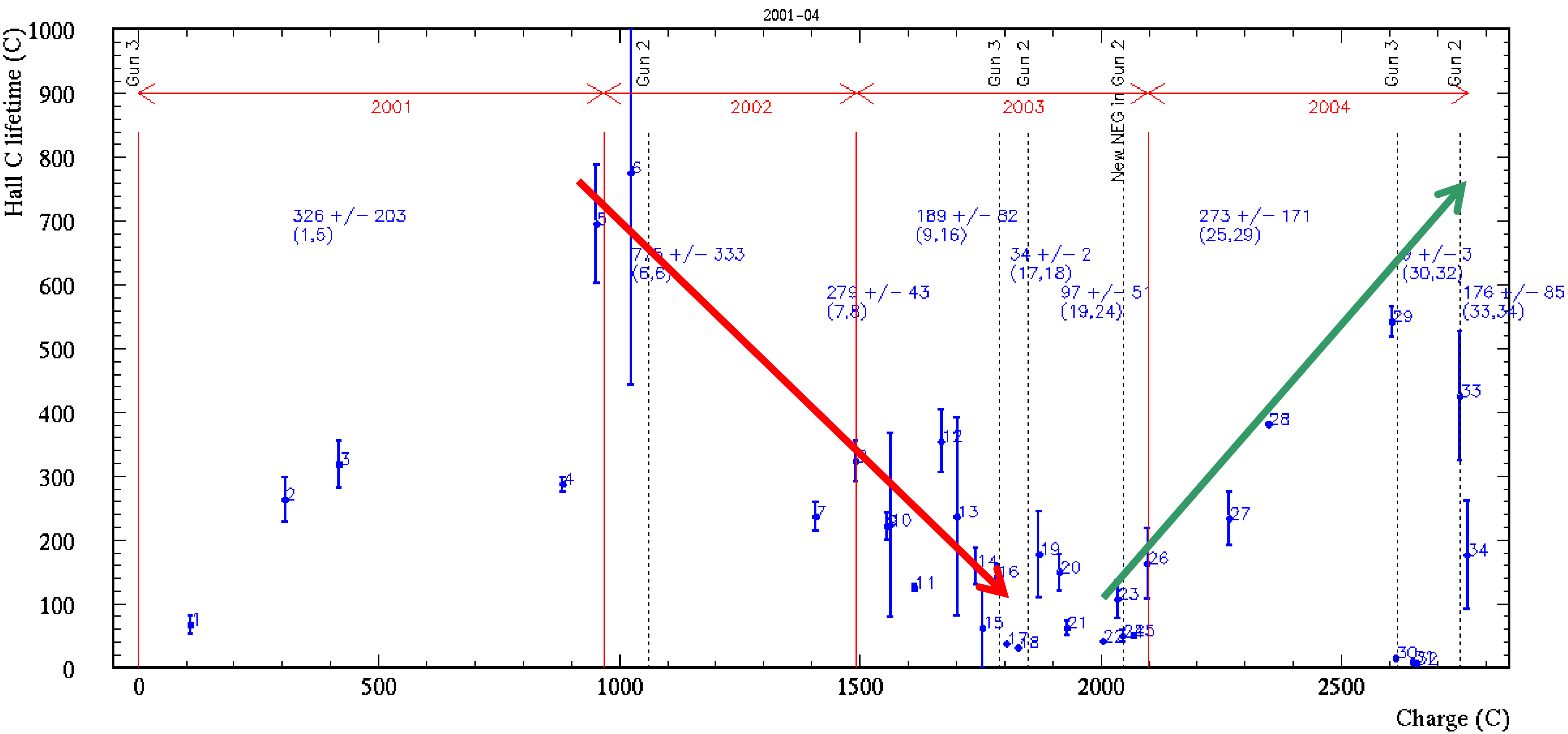


25° vs. 39° Electrode

NEG coated beampipe

Non evaporable getter pumps (NEG)
4,000 liter/s pump speed ⇒ 5E-12 Torr

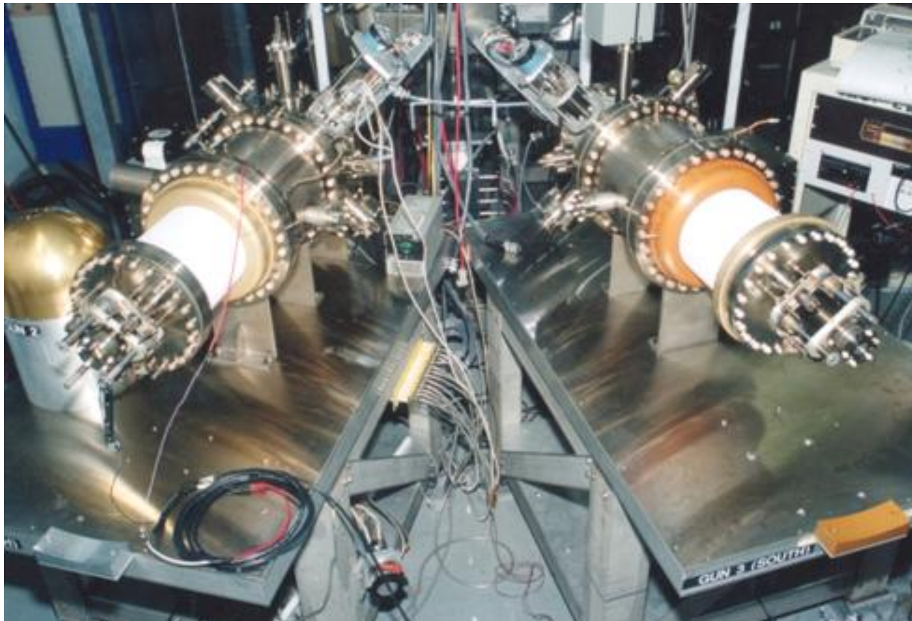
Impact of NEG's on Gun Performance



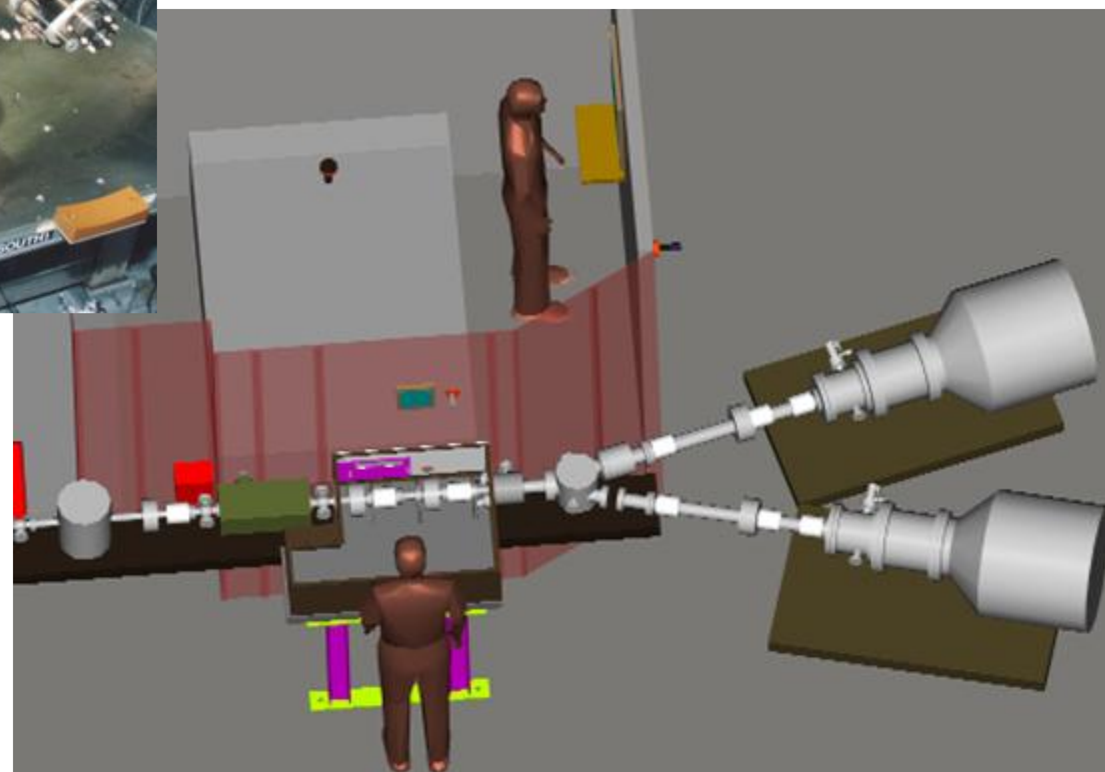
Charge "lifetime" steadily decreasing

NEG replacement improves lifetime

CEBAF Photoinjector: 1999-2007

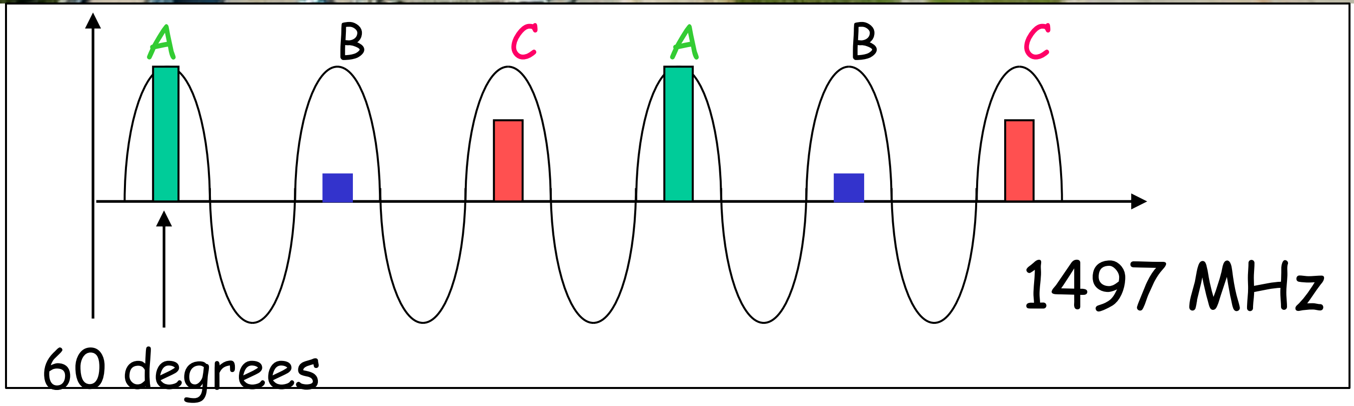


2 identical *vent/bake* electron guns…



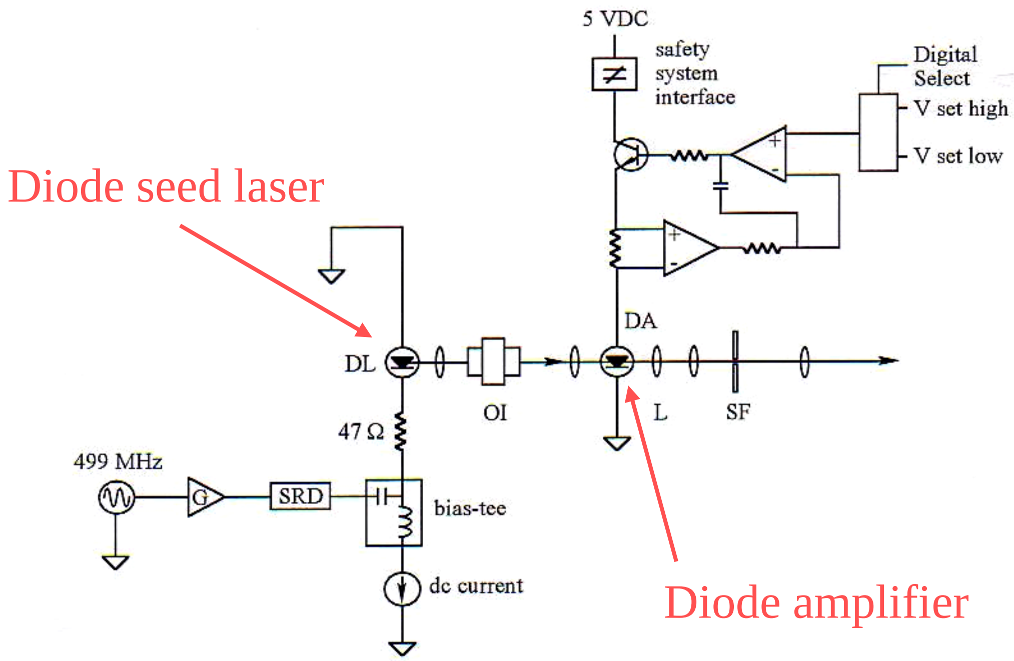
…but, I haven't mentioned our lasers yet!

1 electron gun + 2 rf linacs + 3 experiments

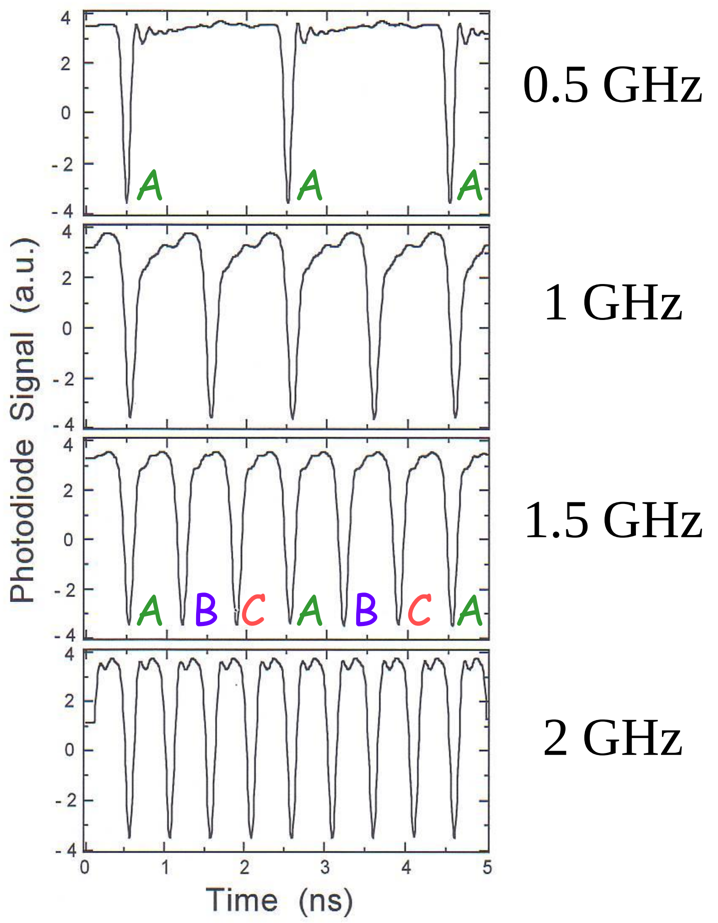


Radio Frequency Synchronous Lasers

RF Gain Switching



M. Poelker, Appl. Phys. Lett. **67**, 2762 (1995).



Continuous Electron Beam Accelerator Facility

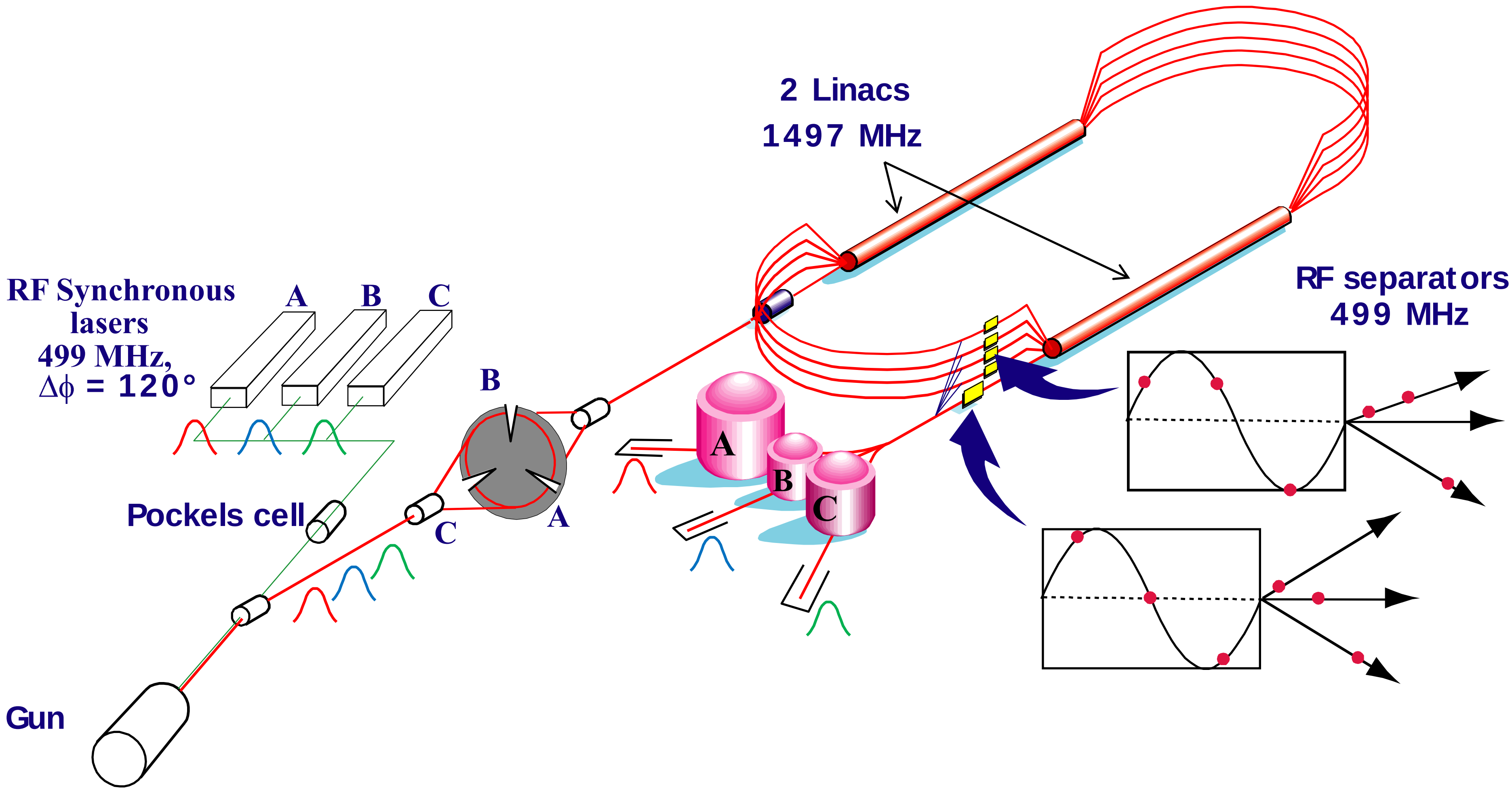
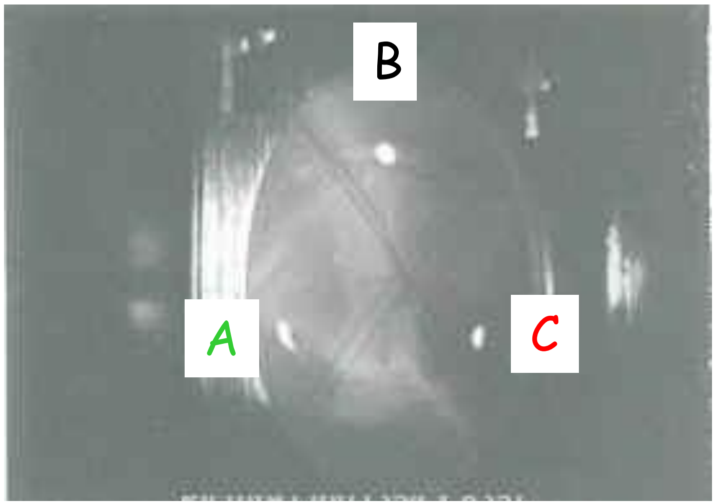
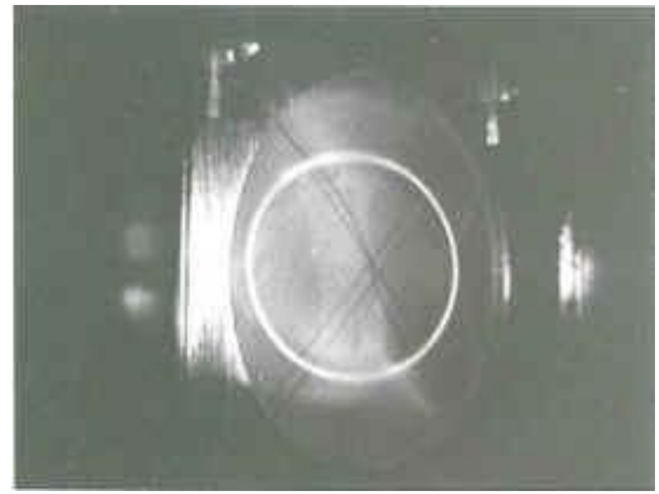


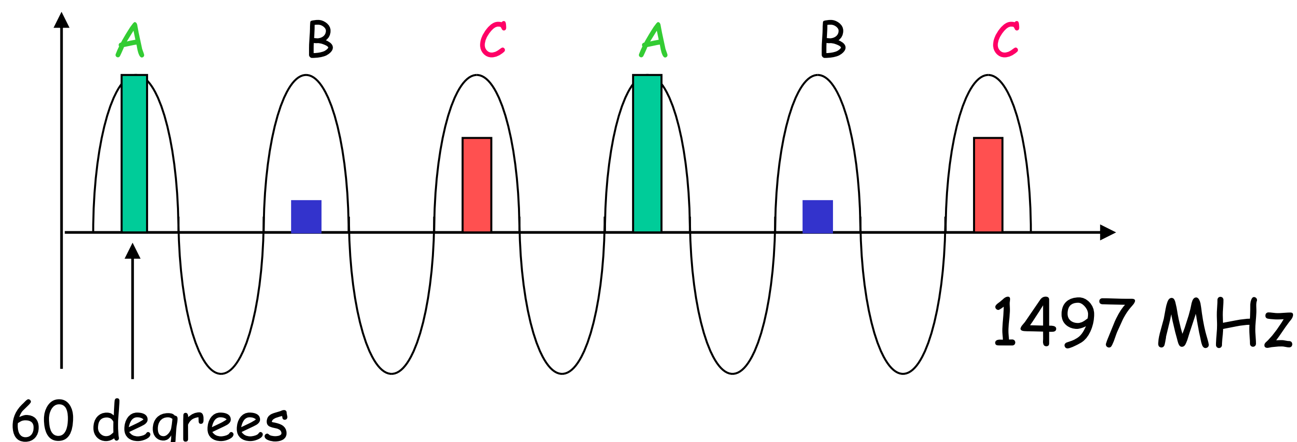
Photo Finish, but at 2 billionths of a second !!!

3 lasers pulsing



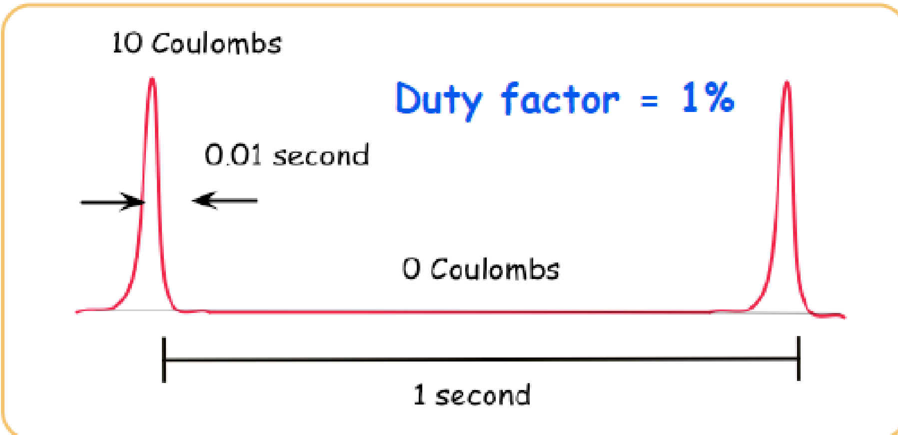
DC beam, not so useful



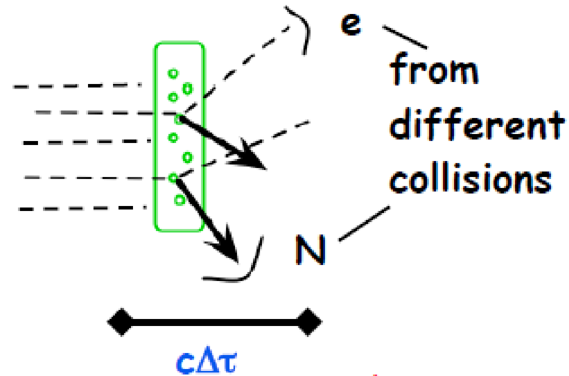


The "C" in CEBAF

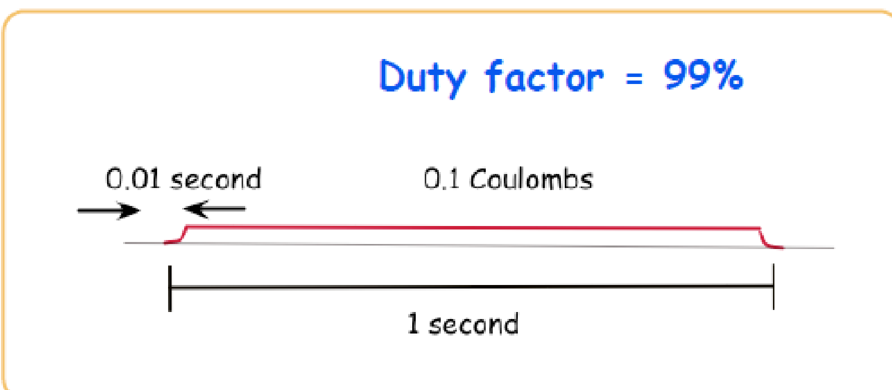
★ Pulsed beams used prior to 1980 (100 mA)



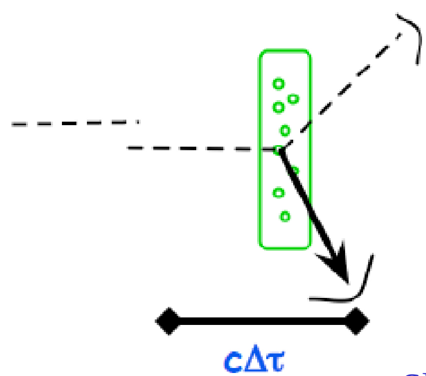
too many electrons in the target over the time interval $\Delta\tau$ lots of random coincidences



★ Advantages of a continuous beam with the same average current



few electrons in the target -- few random coincidences



Slide from F. Gross

So, a nice story, *but…*

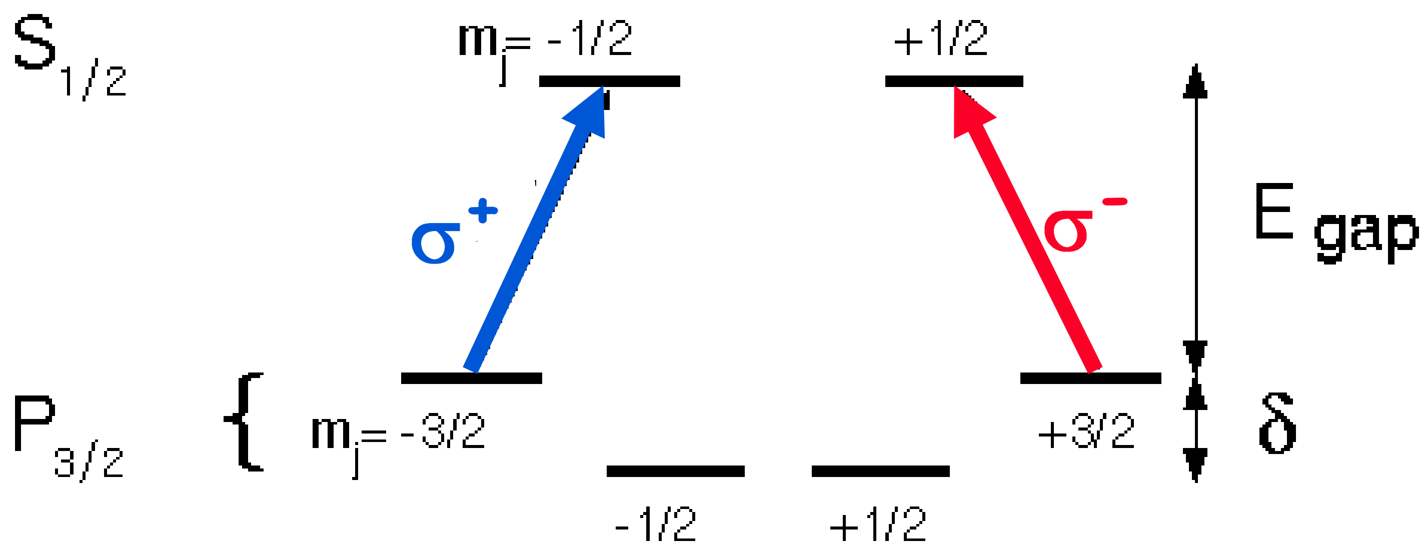
…now that you are all properly "deputized" for polarized electron source technology, let's take things to the next level…

- photocathodes with higher polarization & QE
- high power rf lasers that can make milliAmps
- higher current, higher voltage GaAs photoguns

Higher P: breaking the GaAs degeneracy…

Split degeneracy of $P_{3/2}$

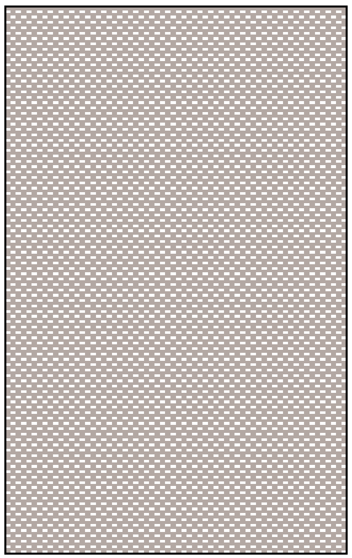
& optical pumping between $P_{3/2}$ and $S_{1/2}$



P_e = +/- 100%, with $E_{gap} < E_\gamma < E_{gap+\delta}$

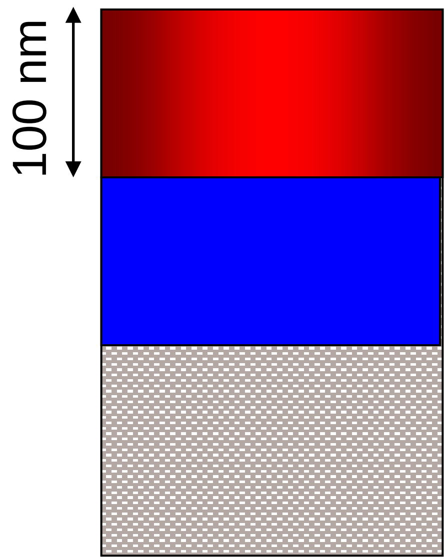
Spin Polarized GaAs Photocathode Evolution

Bulk GaAs



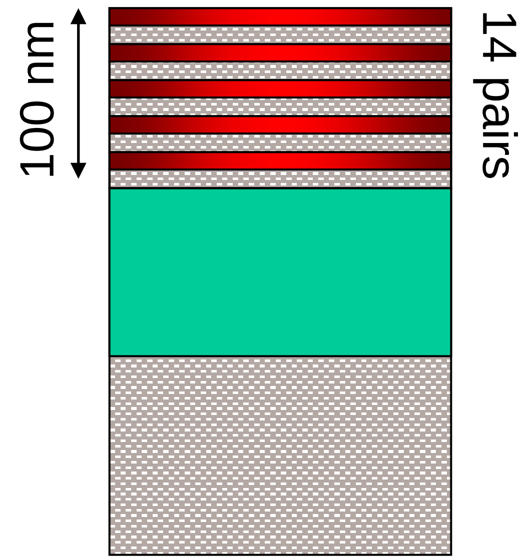
High QE ~ 20%
Pol ~ 35%

Strained GaAs:
GaAs on GaAsP



"conventional" material
QE ~ 0.2%
Pol ~ 75%
@ 850 nm

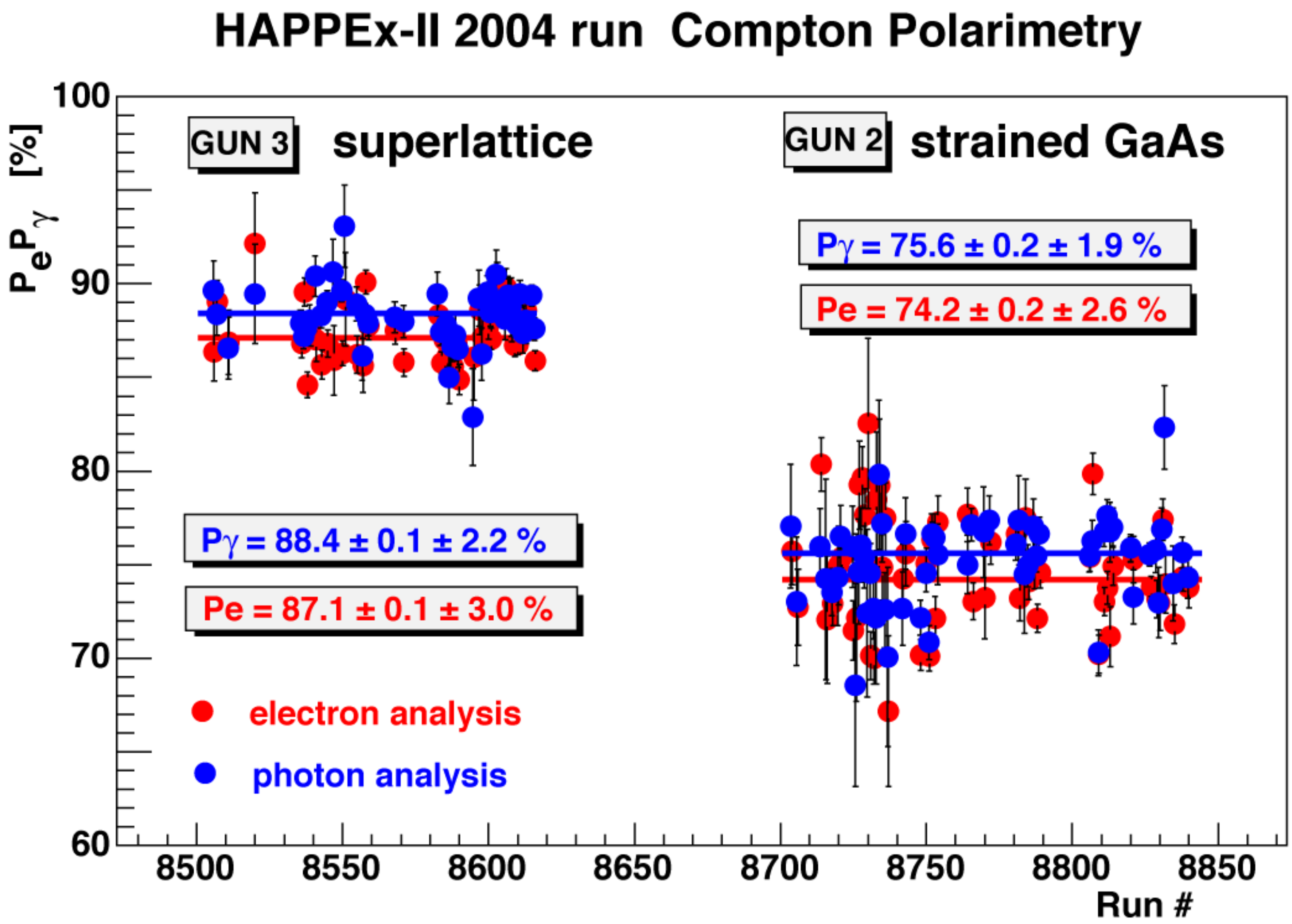
Superlattice GaAs:
Layers of GaAs on GaAsP



No strain relaxation
QE ~ 1.0 %
Pol ~ 85%
@ 780 nm

FOM ∝ I P^2

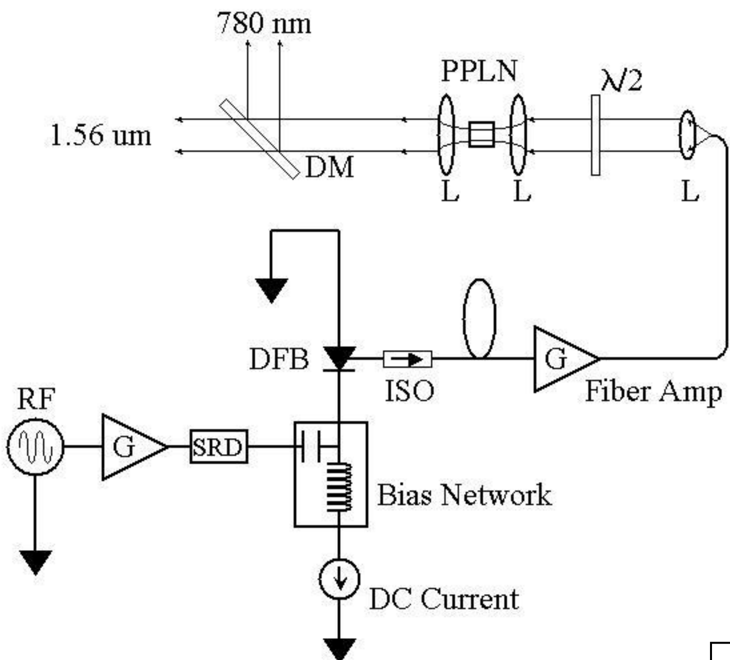
And, it really works!

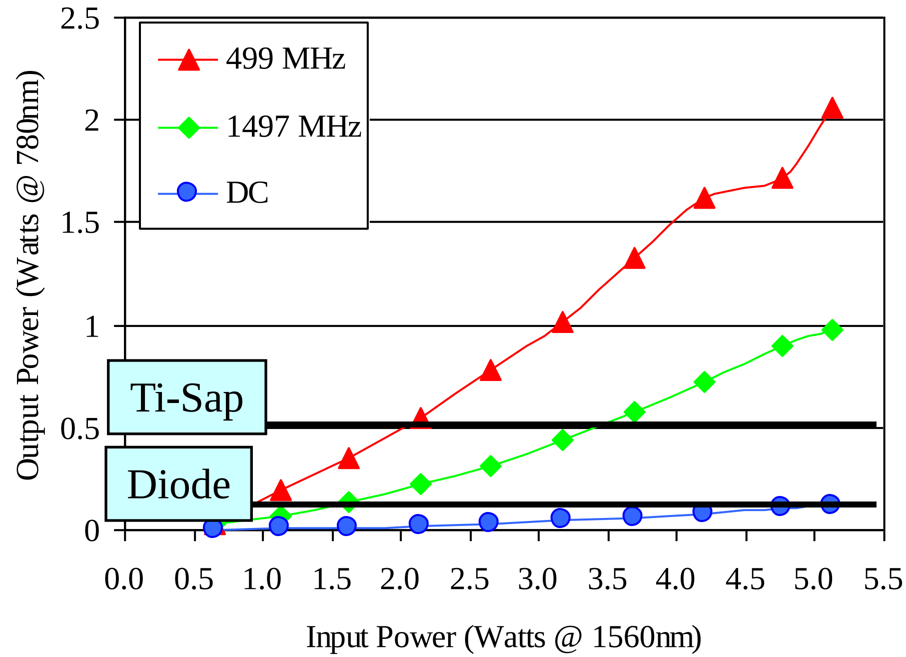


Experiment Figure of Merit

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

Fiber-Based Drive Laser





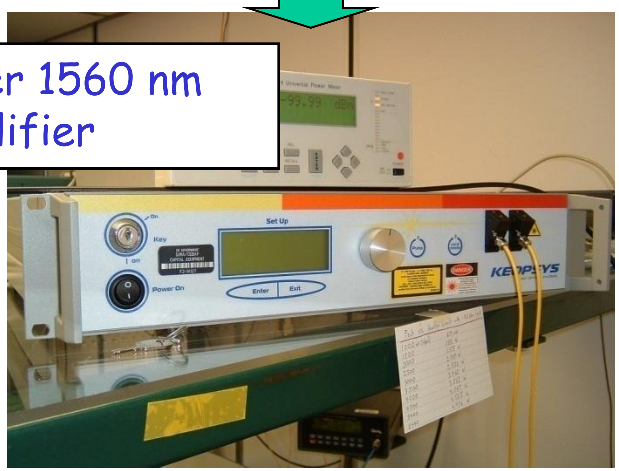
J. Hansknecht and M. Poelker, Phys. Rev. ST Accel. Beams 9, 063501 (2006)

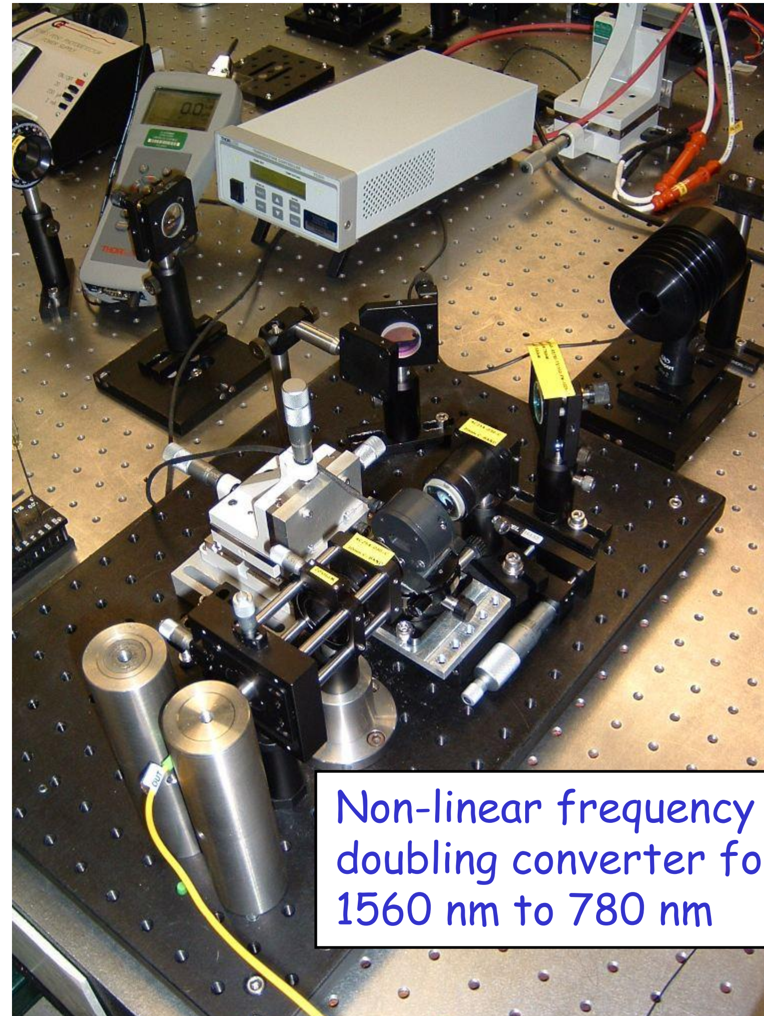
- Gain-switching better than modelocking; no phase lock problems
- Very high power
- Telecom industry spurs growth, ensures availability
- Useful because of superlattice photocathode (requires 780nm)

fiber technology-based laser system

RF locked low-power
1560 nm fiber diode

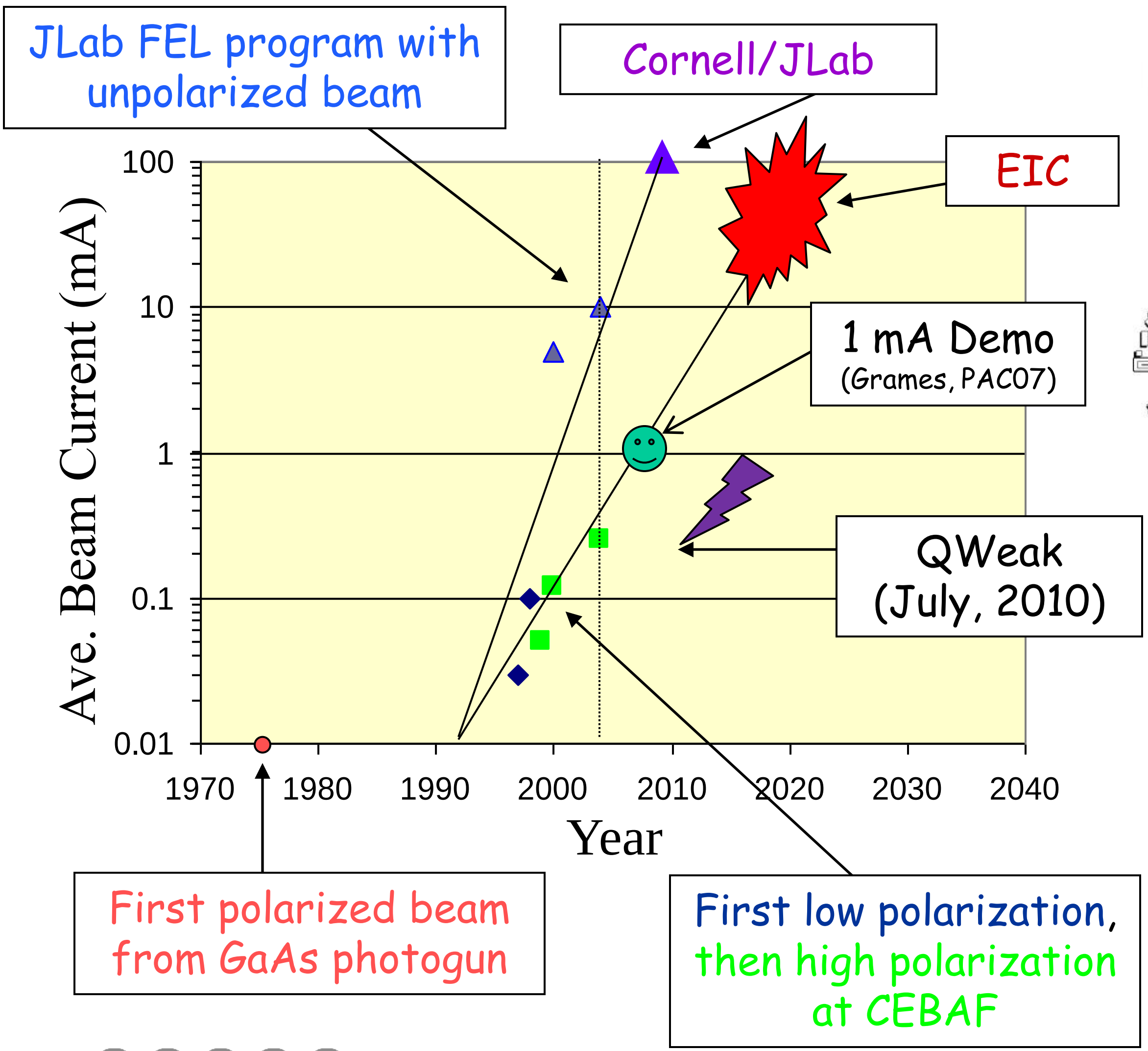
High power 1560 nm
fiber amplifier

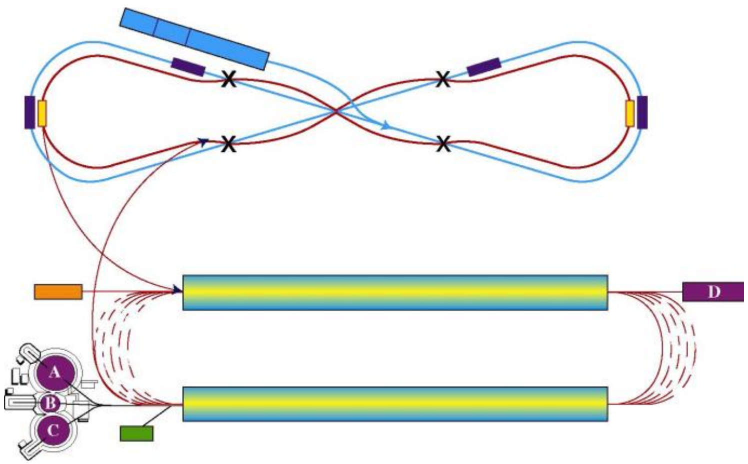


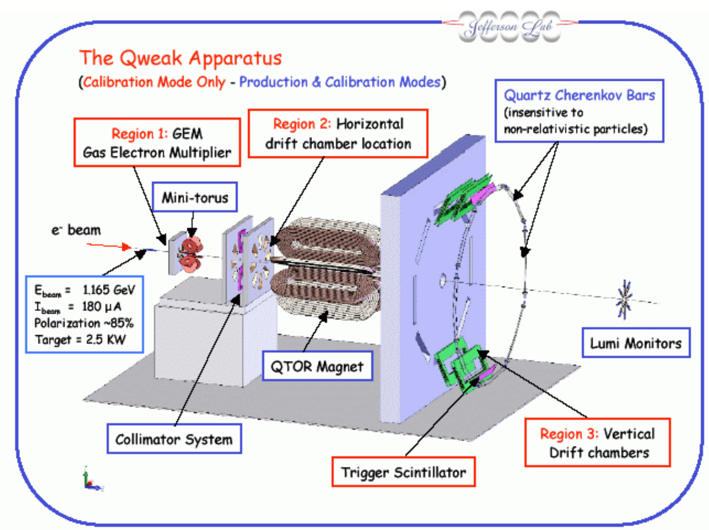


Non-linear frequency
doubling converter for
1560 nm to 780 nm

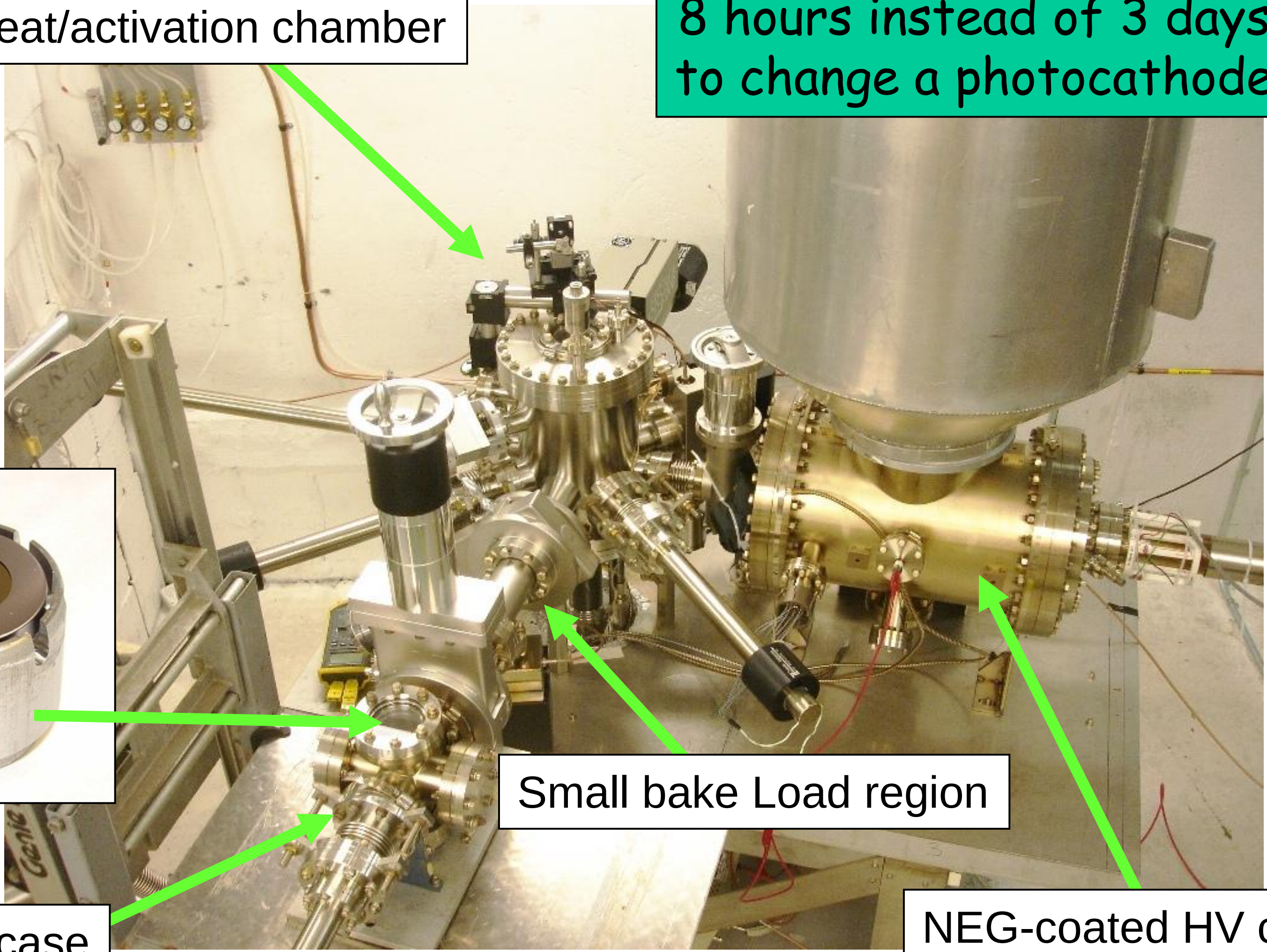
Demands for higher-er-er current !!!







Development of JLab "load lock" photoguns



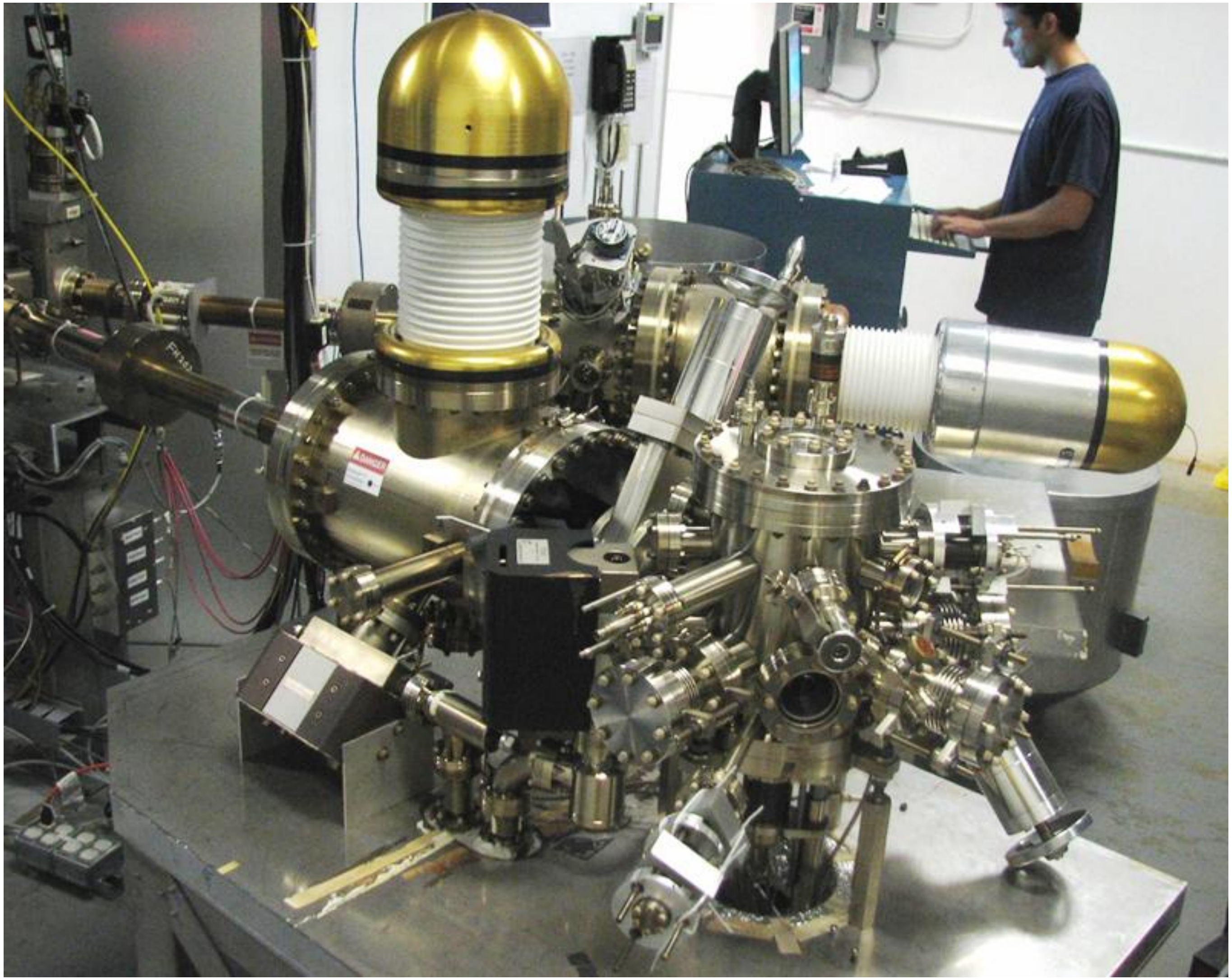
CEBAF Load Lock Photogun (2007)….

10 mA from with 1000C lifetimes

1 mA from High-P photocathode

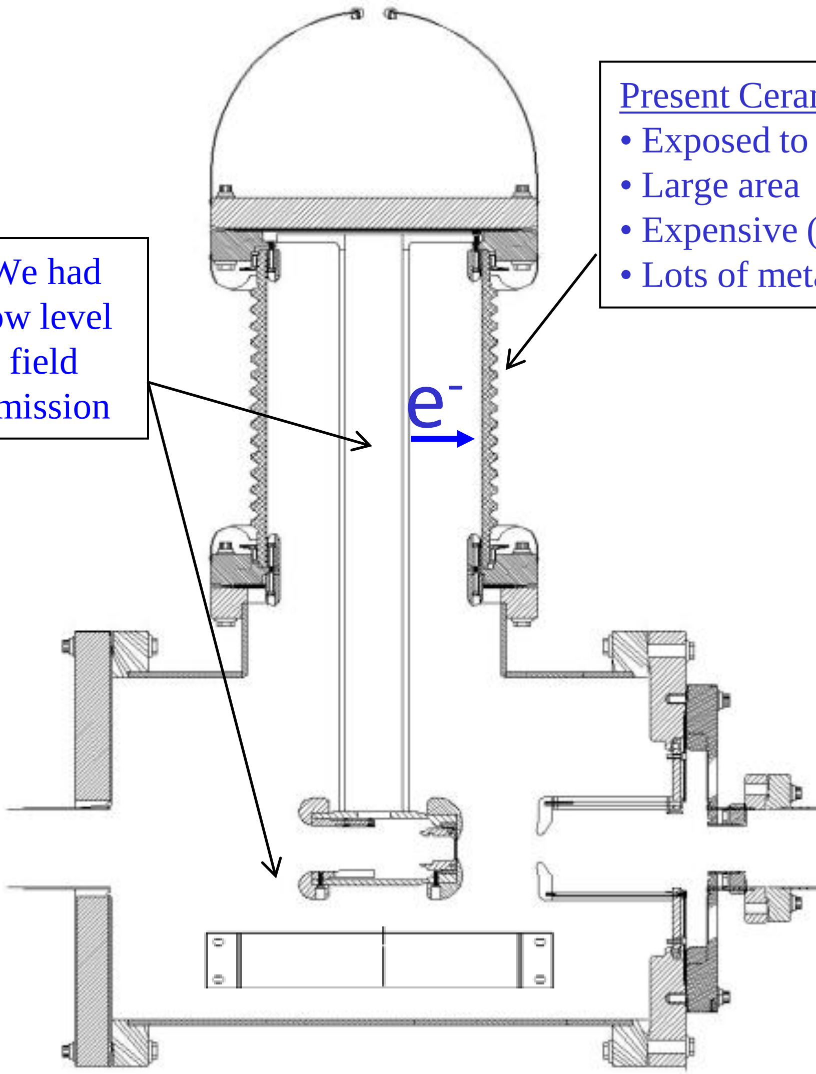
Into the tunnel…

But, Field Emission strikes !!!



Higher Voltage Inverted Gun (Jlab & ILC)

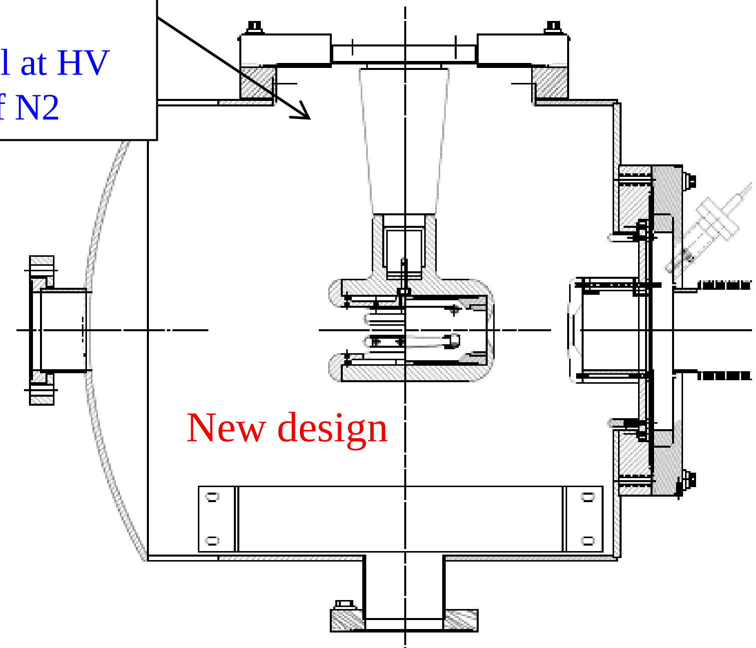
We had low level field emission



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



“New” Inverted Photogun (2009)….

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 010101 (2010)

Load-locked dc high voltage GaAs photogun with an inverted-geometry ceramic insulator

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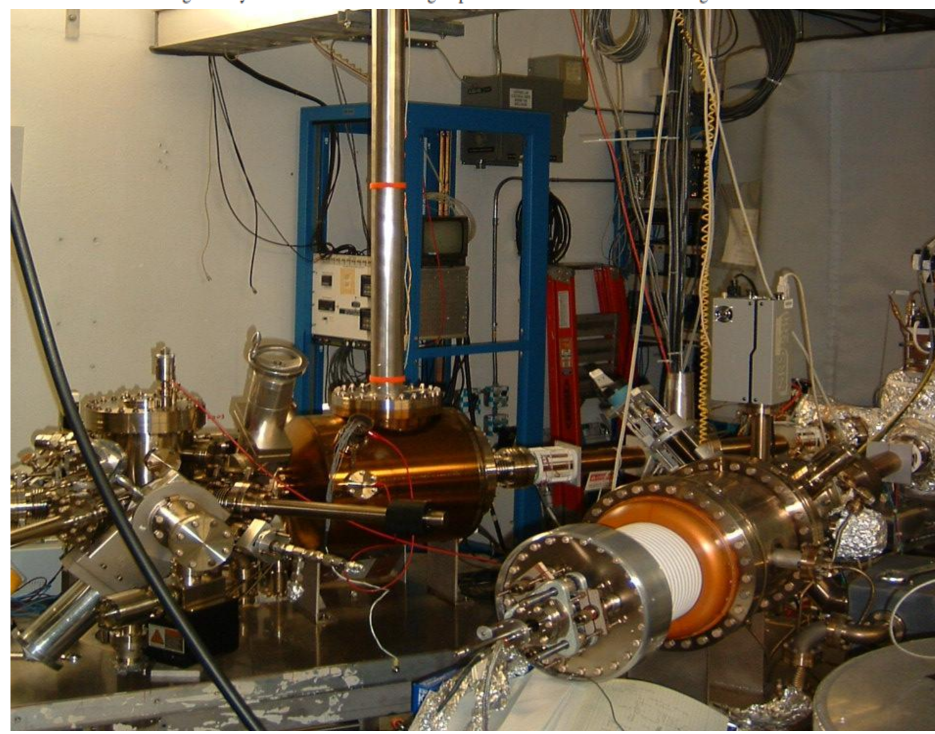
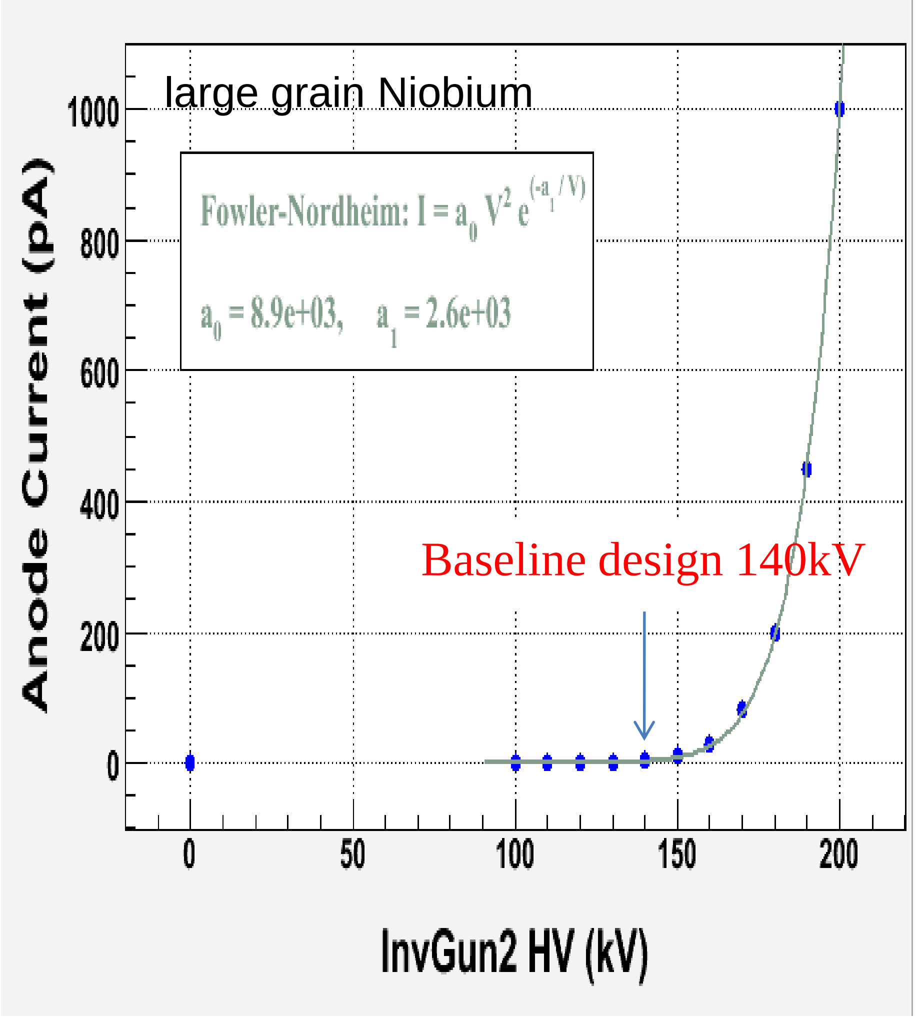
(Received 24 November 2009; published 26 January 2010)

A new dc high voltage spin-polarized photoelectron gun has been constructed that employs a compact inverted-geometry ceramic insulator. Photogun performance at 100 kV bias voltage is summarized.

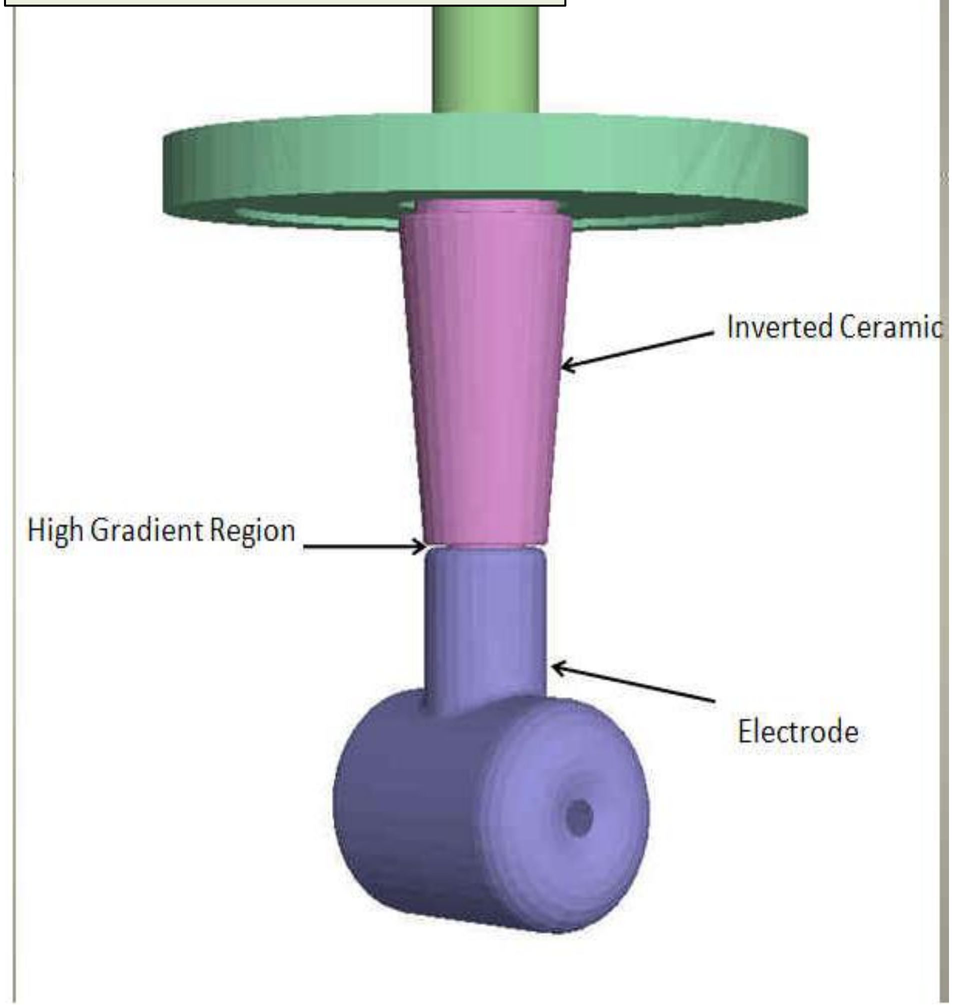


New(er) Inverted Photogun (2010)….

Work of Riad Suleiman



Work of Ken Surles-Law



Polarized Electron Sources at JLab

Joe Grames, Center for Injectors & Sources

Thanks for your attention !!!

Summary

- Motivation
- Photoemission from GaAs
- Spin polarized electrons
- Extreme High Vacuum (XHV)
- High frequency/power lasers
- Electron gun design

www.jlab.org/accel/inj_group