Polarized Electron Sources

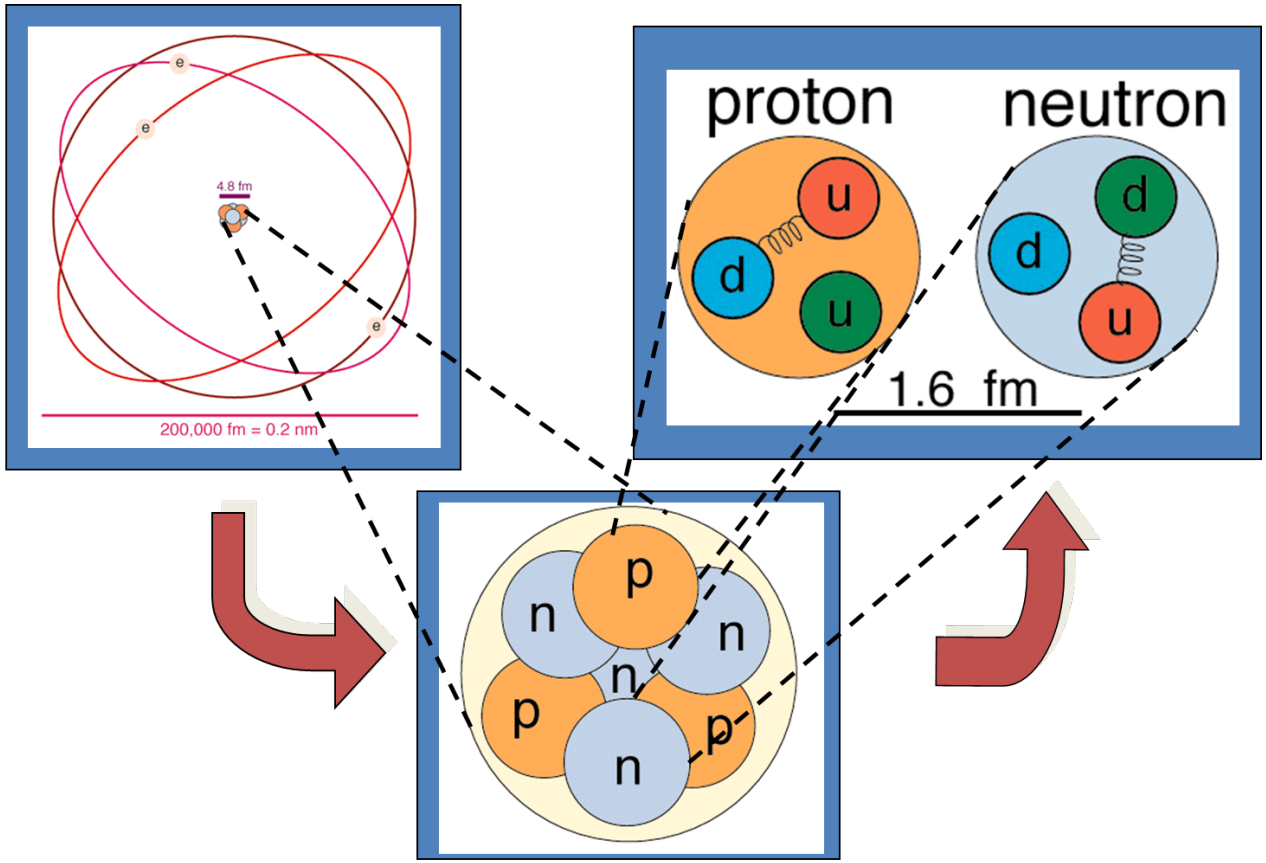
Joe Grames

JLAB Summer Lecture Series, July 17, 2014

Who needs electrons?

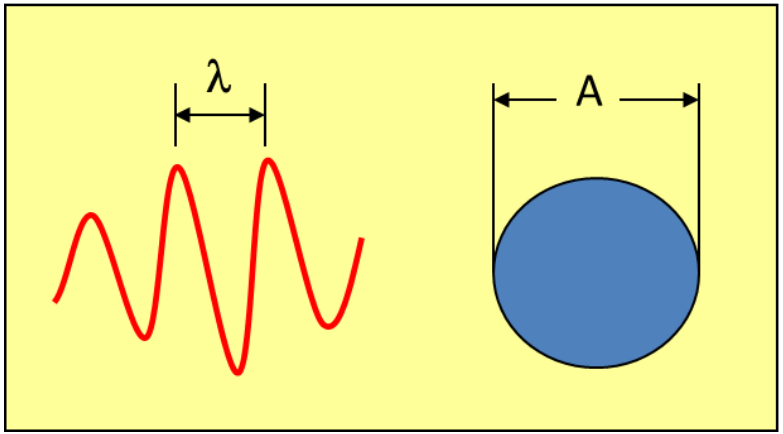
Storage batteries, man-made and natural power generators, power grids and distribution circuits, and… the “free” electrons used in particle accelerators…..

^{7}Li

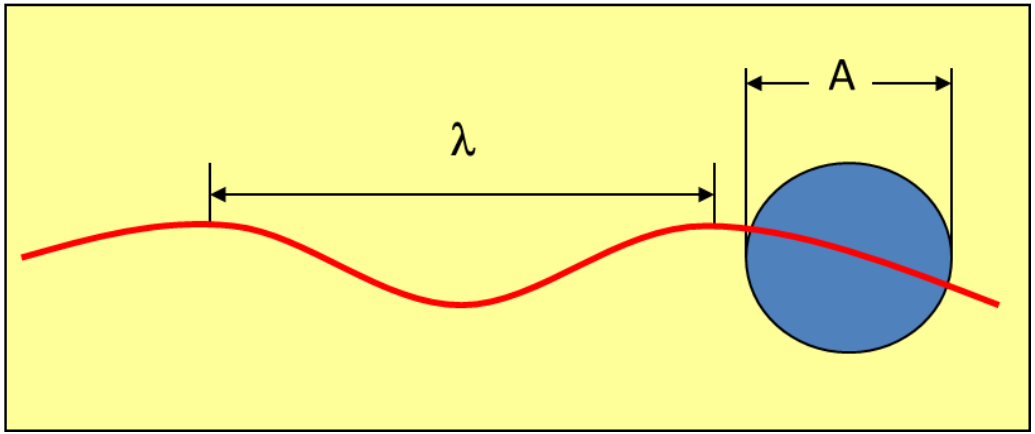


Slide courtesy Prof. Steven Blusk, Syracuse University

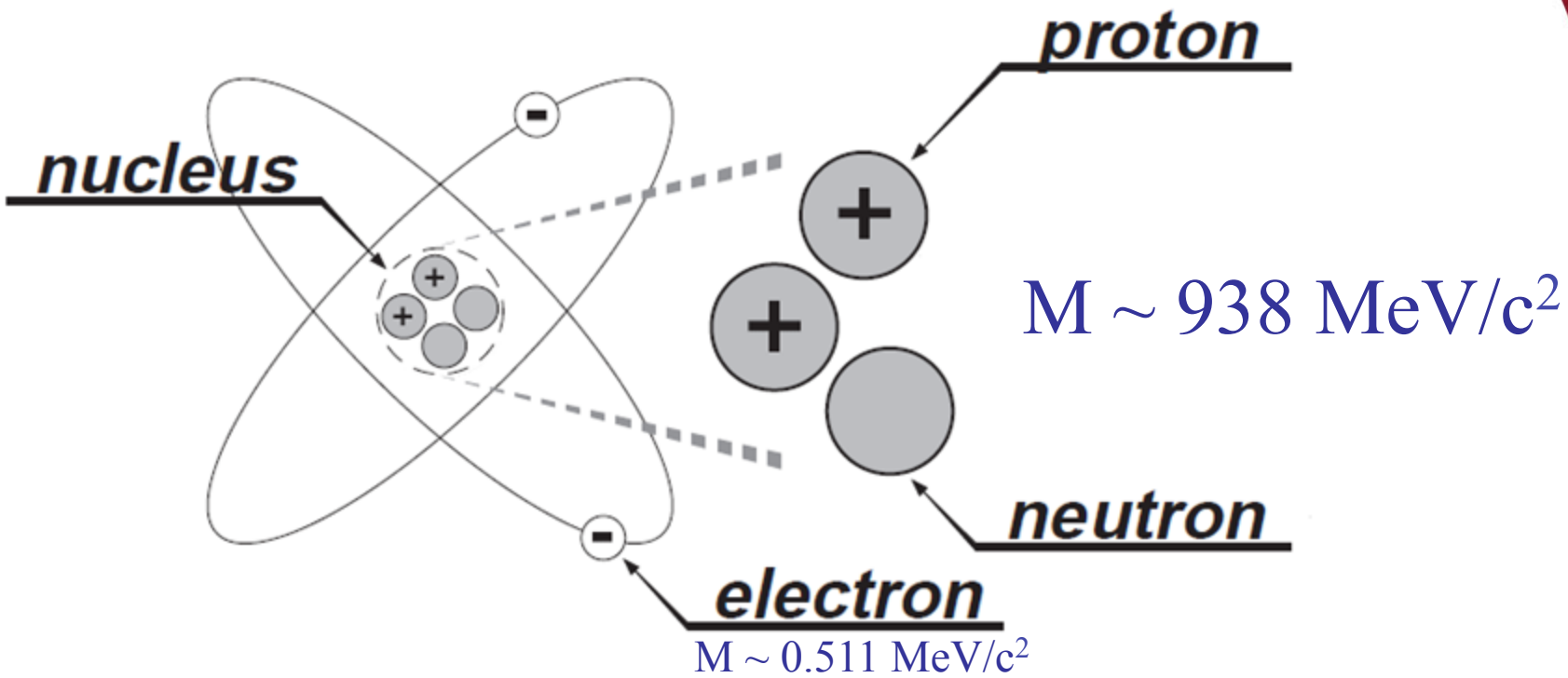
YES, this works !



NO, this doesn't really work !



What you "are" is what you "see"…



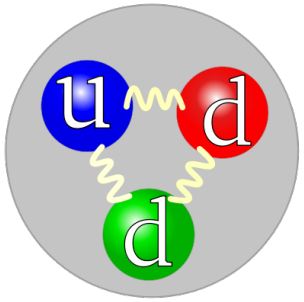
mass ~ 1/λ ~ energy

$$E=mc^2$$

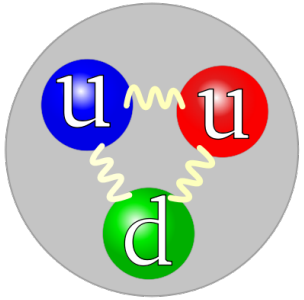
What to do?

Build a 5 mile long electron microscope!

Electron



Neutron

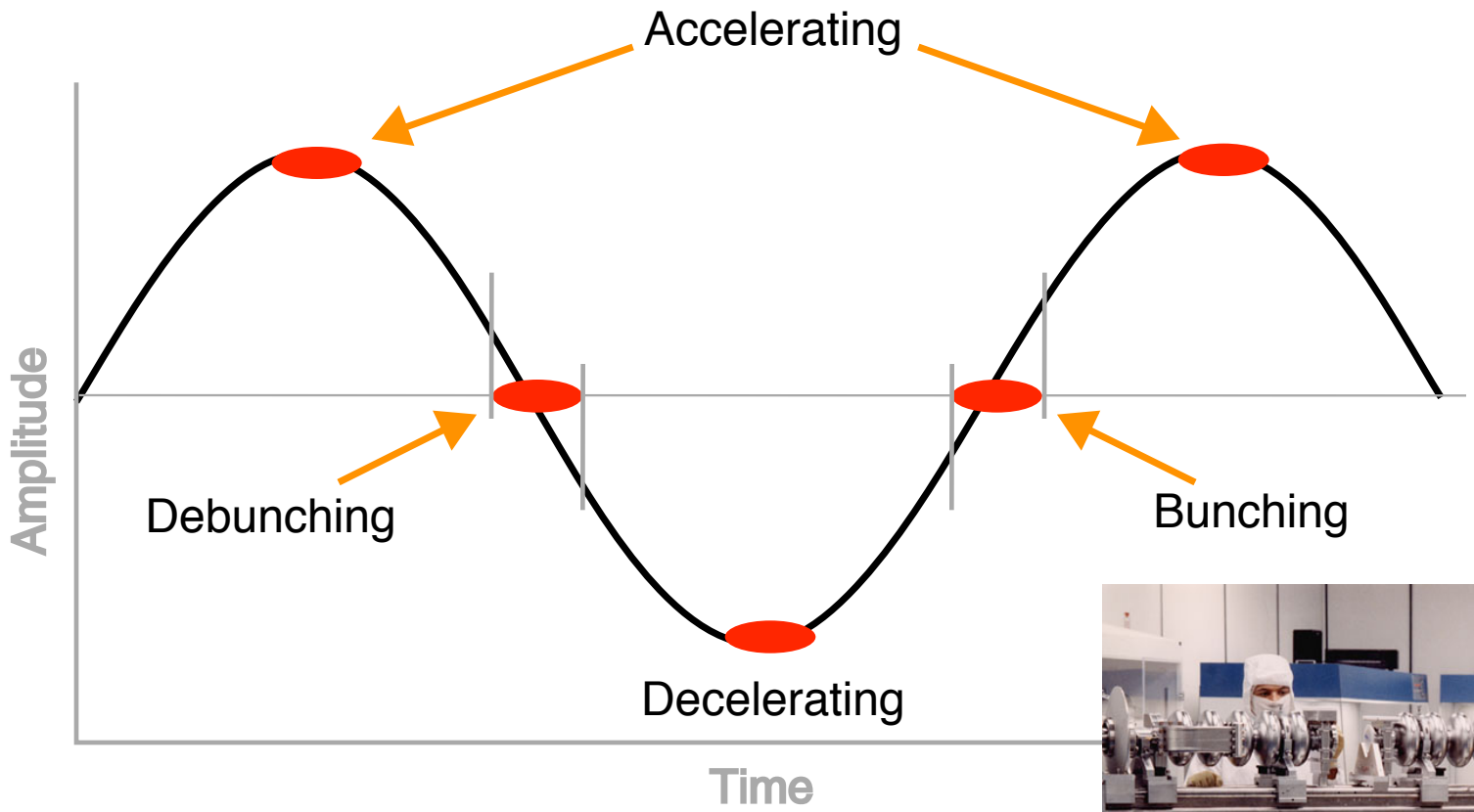


Proton

Make electrons energetic enough (E_{beam}) to peek inside proton or neutron ($M_{nucleon}$).

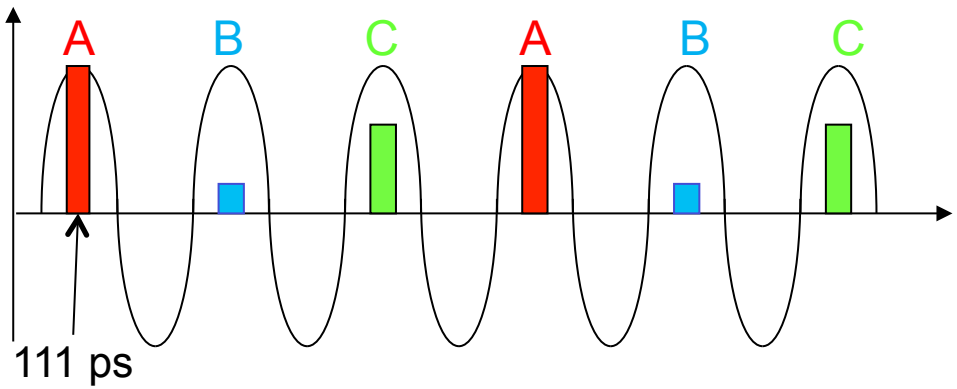
How to make the electrons "powerful" ?

Use radio(frequency) waves !!!



Electrons gain energy on each crest!

Continuous Electron Beam Accelerator Facility



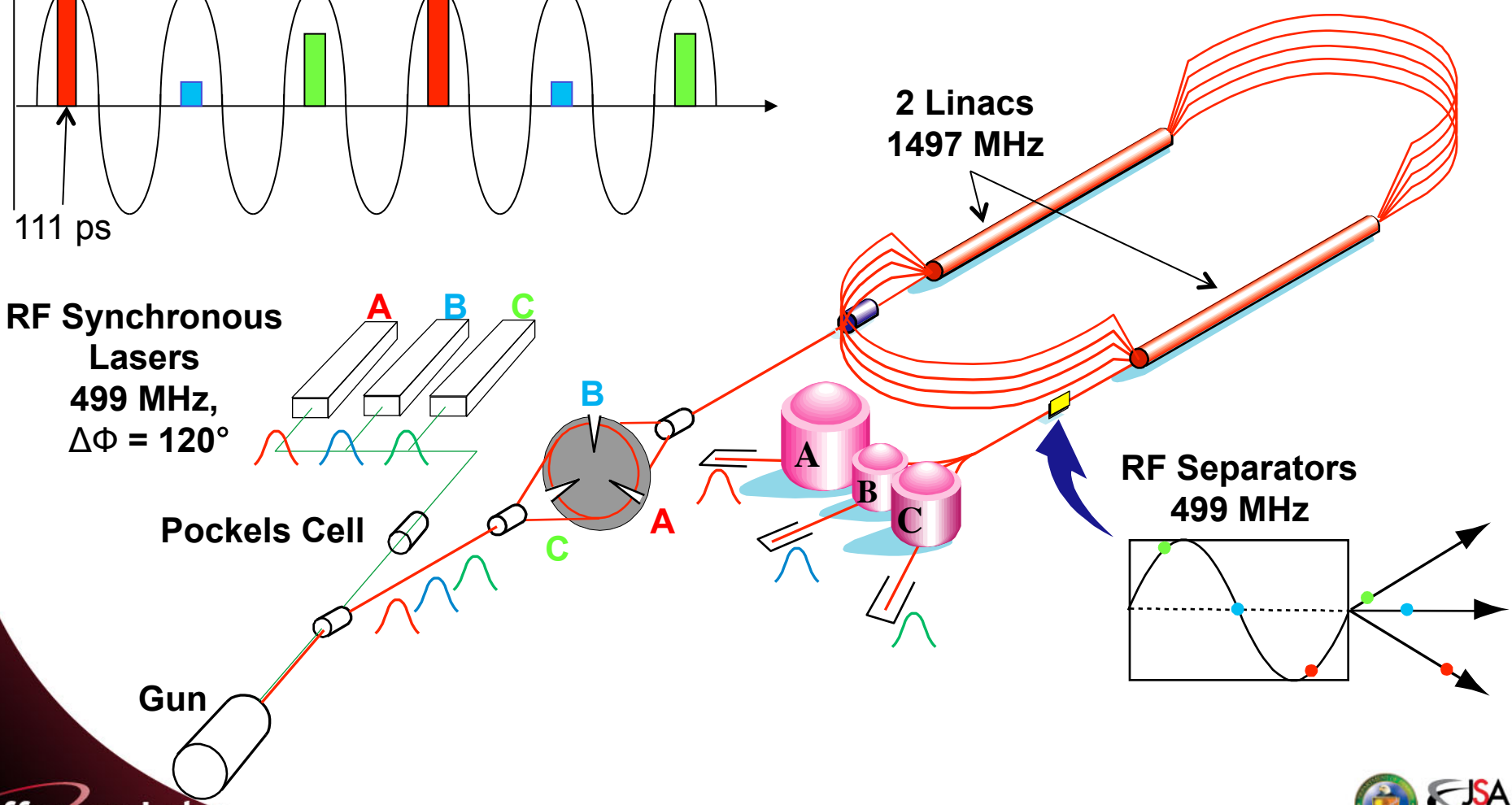
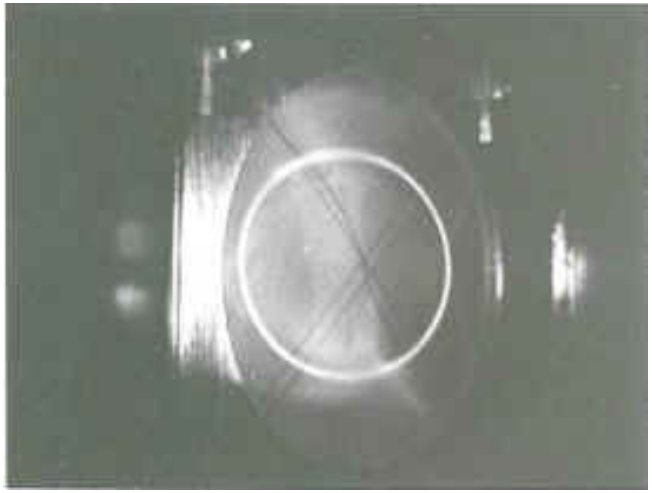
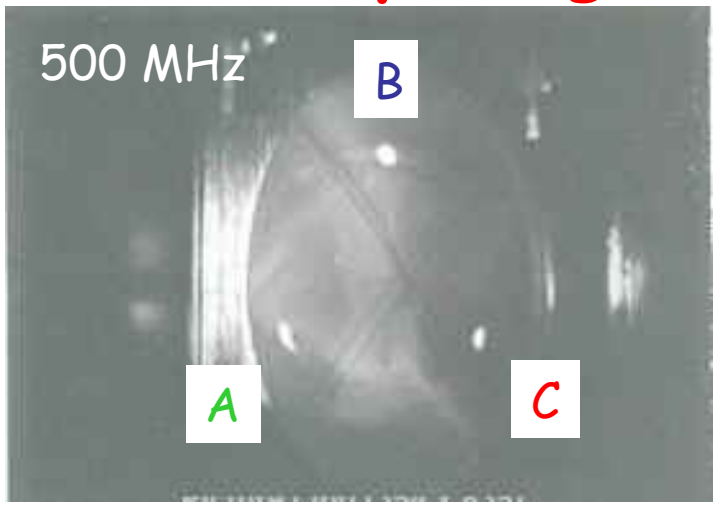


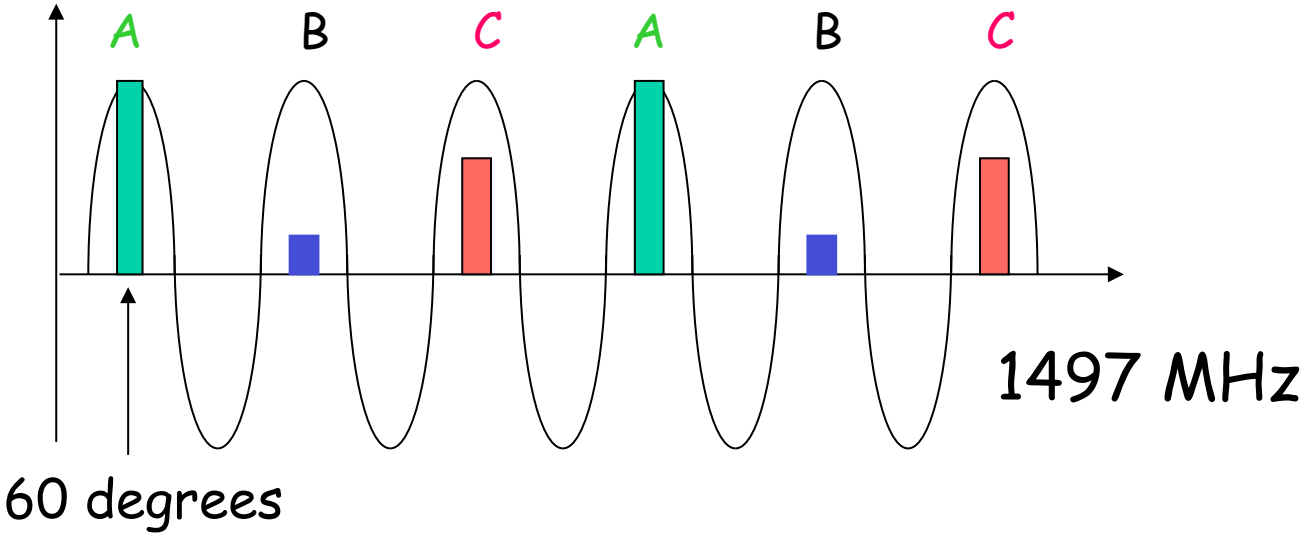
Photo Finish, but at 2 billionths of a second !!!

DC beam, not so useful



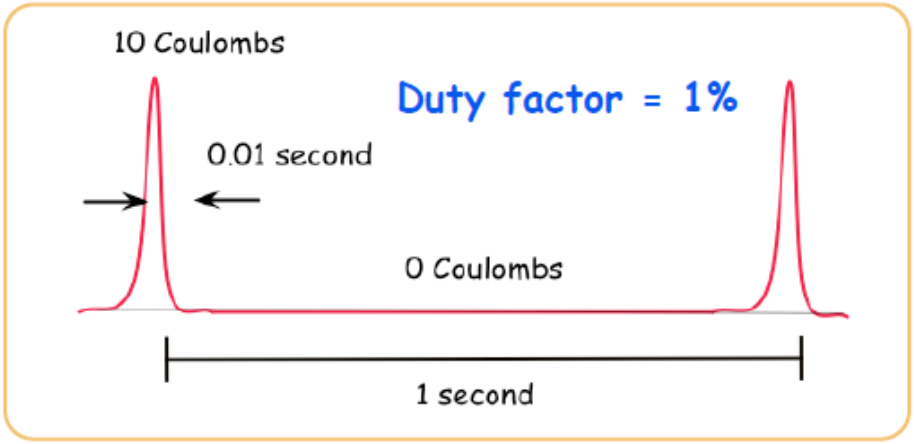
3 lasers pulsing



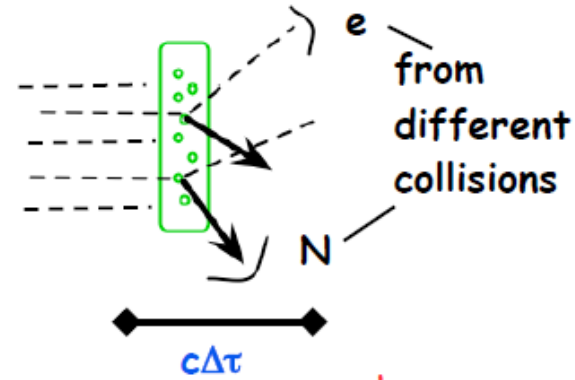


The "C" in CEBAF

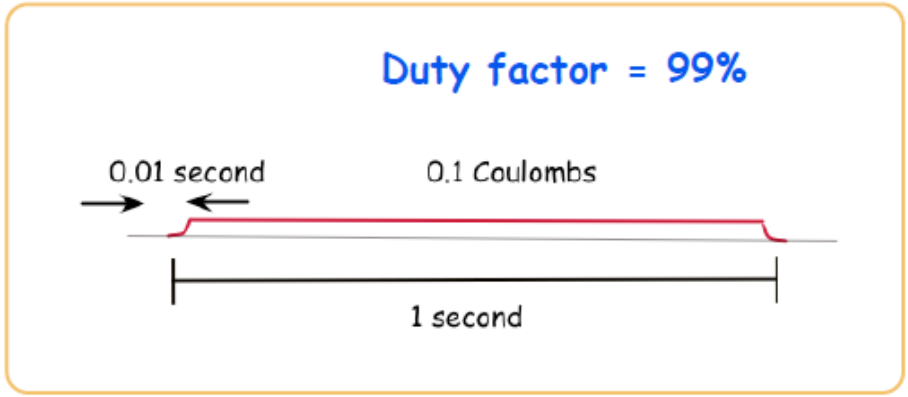
★ Pulsed beams used prior to 1980 (100 mA)



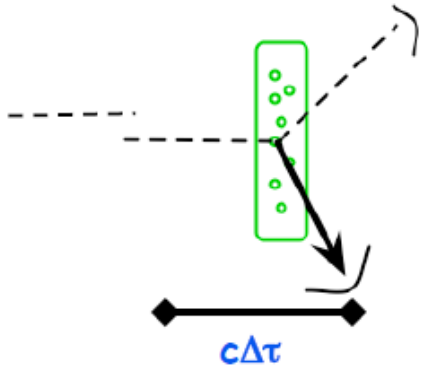
too many electrons in the target over the time interval $\Delta\tau$
lots of random coincidences



★ Advantages of a continuous beam with the same average current



few electrons in the target -- few random coincidences



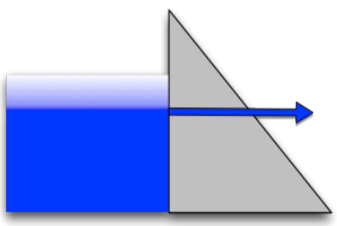
Accelerators Need Electron Beams

How do we make them?

- Field Emission
- Thermionic Emission
- Photoemission

The Canonical Emission Equations

(slide courtesy of Dr. K. Jensen, Naval Research Laboratory)

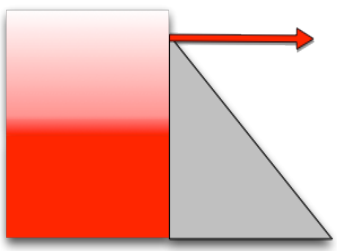


- **Field Emission**

  Fowler Nordheim

  E.L. Murphy, and R.H. Good, Physical Review 102, 1464 (1956).

$$J_{FN}(F) = A_{FN} F^2 \exp\left(-\frac{B\Phi^{3/2}}{F}\right)$$

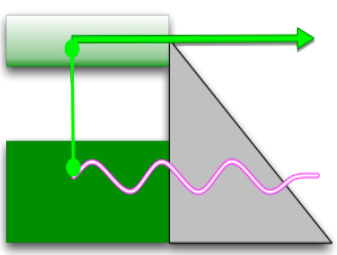


- **Thermal Emission**

  Richardson-Laue-Dushman

  C. Herring, and M. Nichols, Reviews of Modern Physics 21, 185 (1949).

$$J_{RLD}(T) = A_{RLD} T^2 \exp\left(-\frac{\Phi}{k_B T}\right)$$



- **Photoemission**

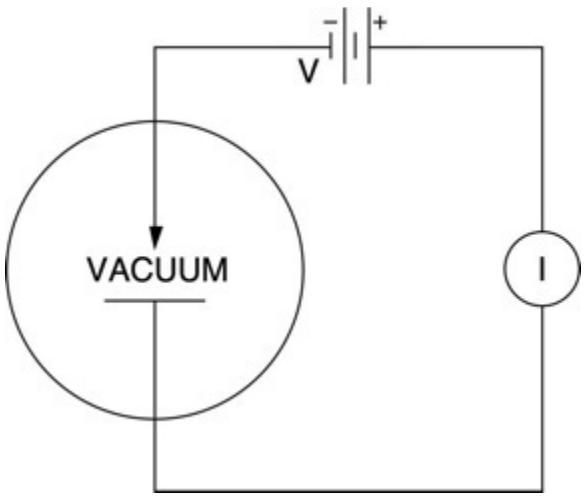
  Fowler-Dubridge

  L.A. DuBridge Physical Review 43, 0727 (1933).

$$J_{MFD}(\lambda) = \frac{q}{\hbar\omega}(1-R)F_\lambda(\omega)\{\hbar\omega - \Phi\}^2 I_\lambda$$

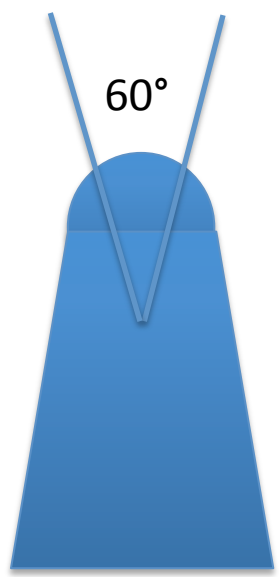
Listed chronologically

Field Emitter Sources



$I = BV^2 \exp(-C/V)$
Vacuum diode

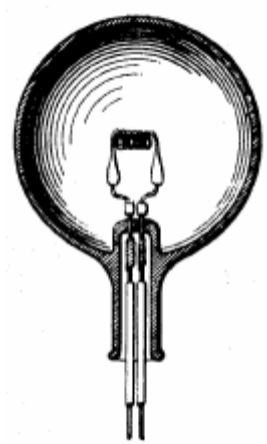
- Explained by Fowler-Nordheim, 1928: a quantum mechanical tunneling effect
- "bright" e-beam, good for surface science



$$I \approx A \times 1.54 \times 10^{-6} \frac{F^2}{\phi} \exp\left[-6.83 \times 10^9 \frac{\phi^{3/2}}{F}\right]$$

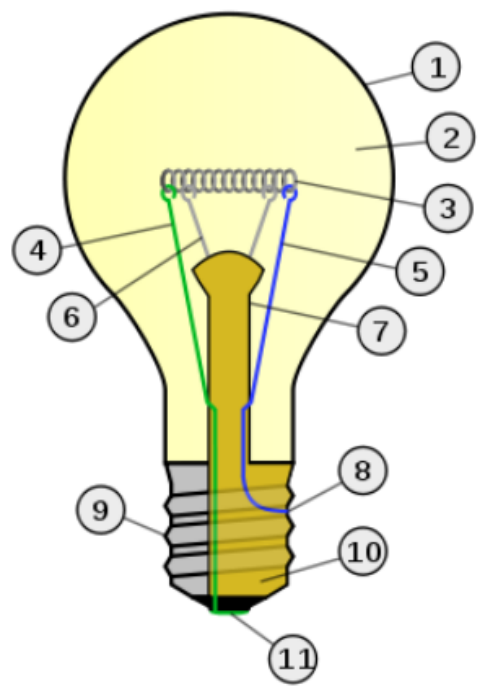
Thermionic Emission

Used to make light….



Edison's patent,
Long-lasting filament

- Studied since early 1800's and perfected over 100 years, by many inventors (why does Edison get so much credit?)
- Thermionic emission from Tungsten filaments and metalloids like LaB6 operating at >1000K are common
- ~ 90% of consumed power simply generates heat



Melts 3695K

1. Outline of Glass bulb
2. Low pressure inert gas (argon, neon, nitrogen)
3. Tungsten filament
4. Contact wire (goes out of stem)
5. Contact wire (goes into stem)
6. Support wires
7. Stem (glass mount)
8. Contact wire (goes out of stem)
9. Cap (sleeve)
10. Insulation (vitrite)
11. Electrical contact

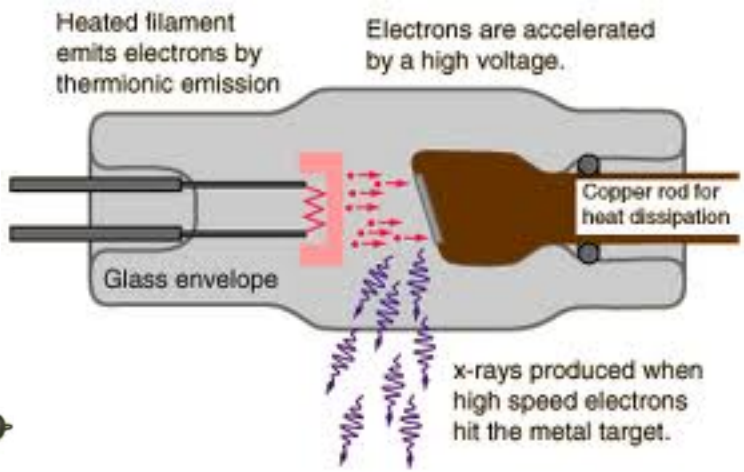
Thermionic Emission

Used to make x-ray light….

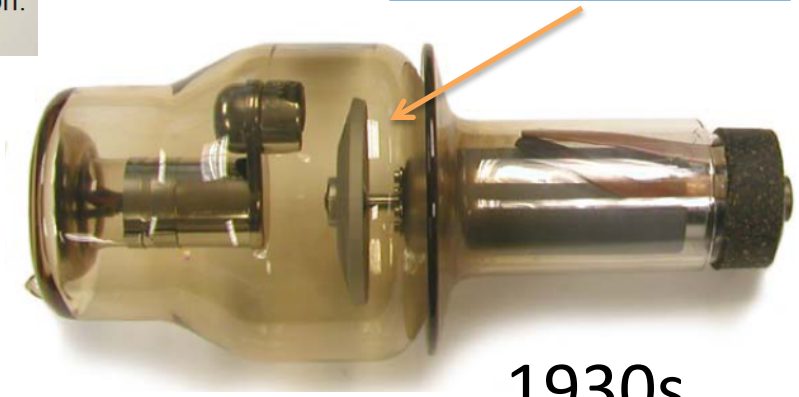
1880s

bias at high voltage

In 1913, William Coolidge invented an x-ray tube with high vacuum, a heated filament as electron source, and an x-ray producing anode. The tube, shown here, was produced in the 1920s by General Electric Corporation.
Photo: www.orau.org Oak Ridge Associated Universities



Rotating anode to distribute heat

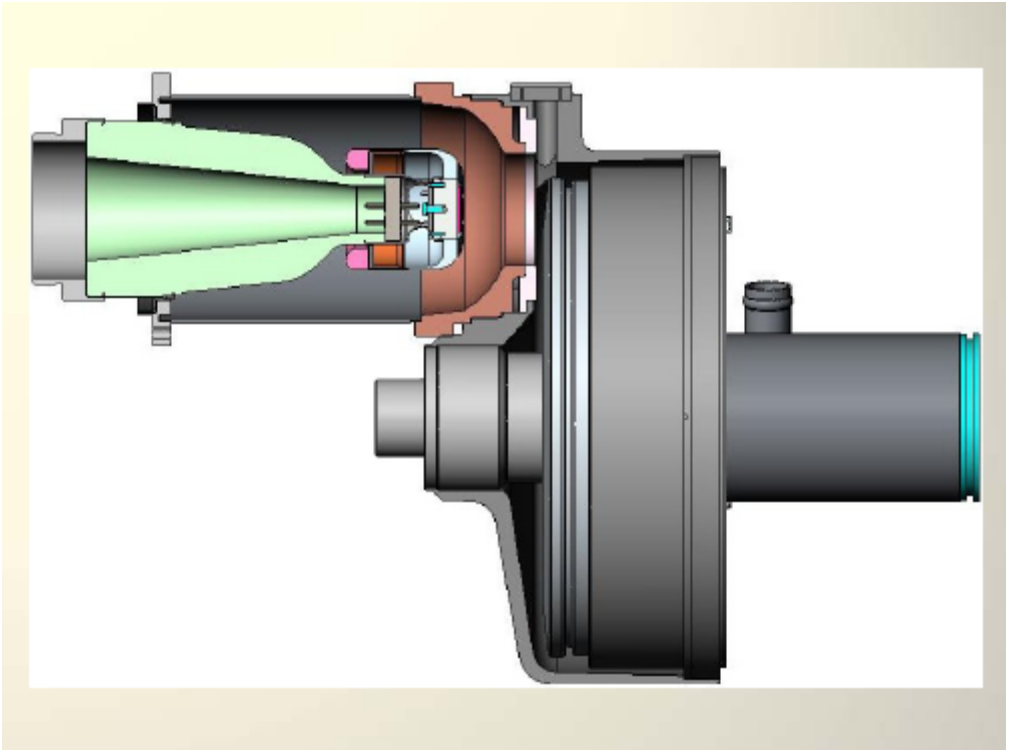


1930s

X-rays are generated when a DC electron beam, typically a few mA, strikes a tungsten target at 60-200 keV. e-Beam quality is not a big concern

Modern X-Ray Sources

Higher e-beam current.....
Higher x-ray flux

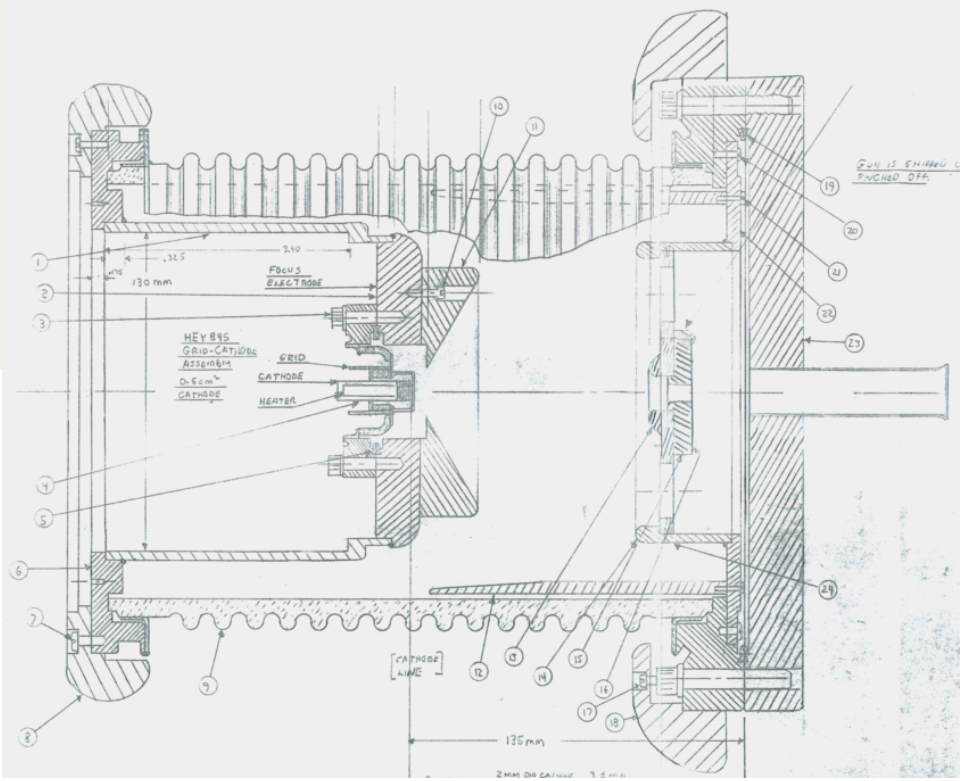


Higher Voltage....
More penetrating
x-ray beam

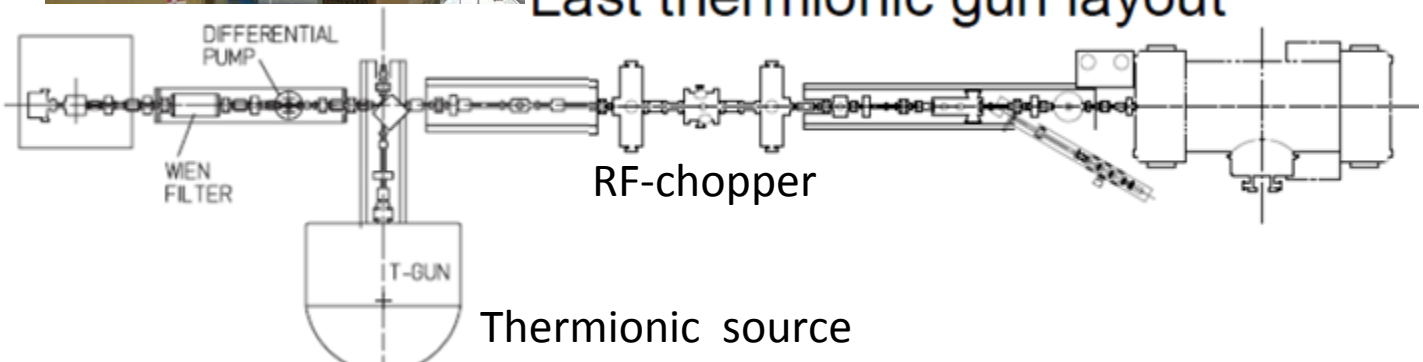
Courtesy Varian

CEBAF's First Electron Source

- Make beam by running current through the filament biased at 100kV
- Use "grid" to turn beam ON/OFF, i.e., create machine-safe macropulses
- Apertures to improve emittance
- Use RF "chopper" to create RF structure



Last thermionic gun layout



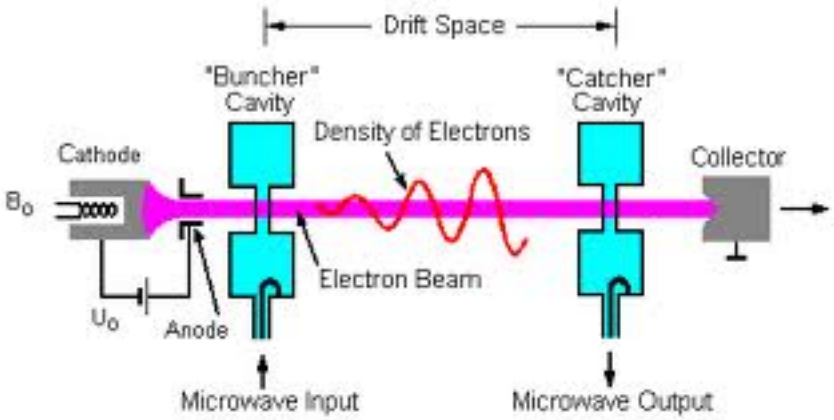
Polarized GaAs photosource

RF-chopper

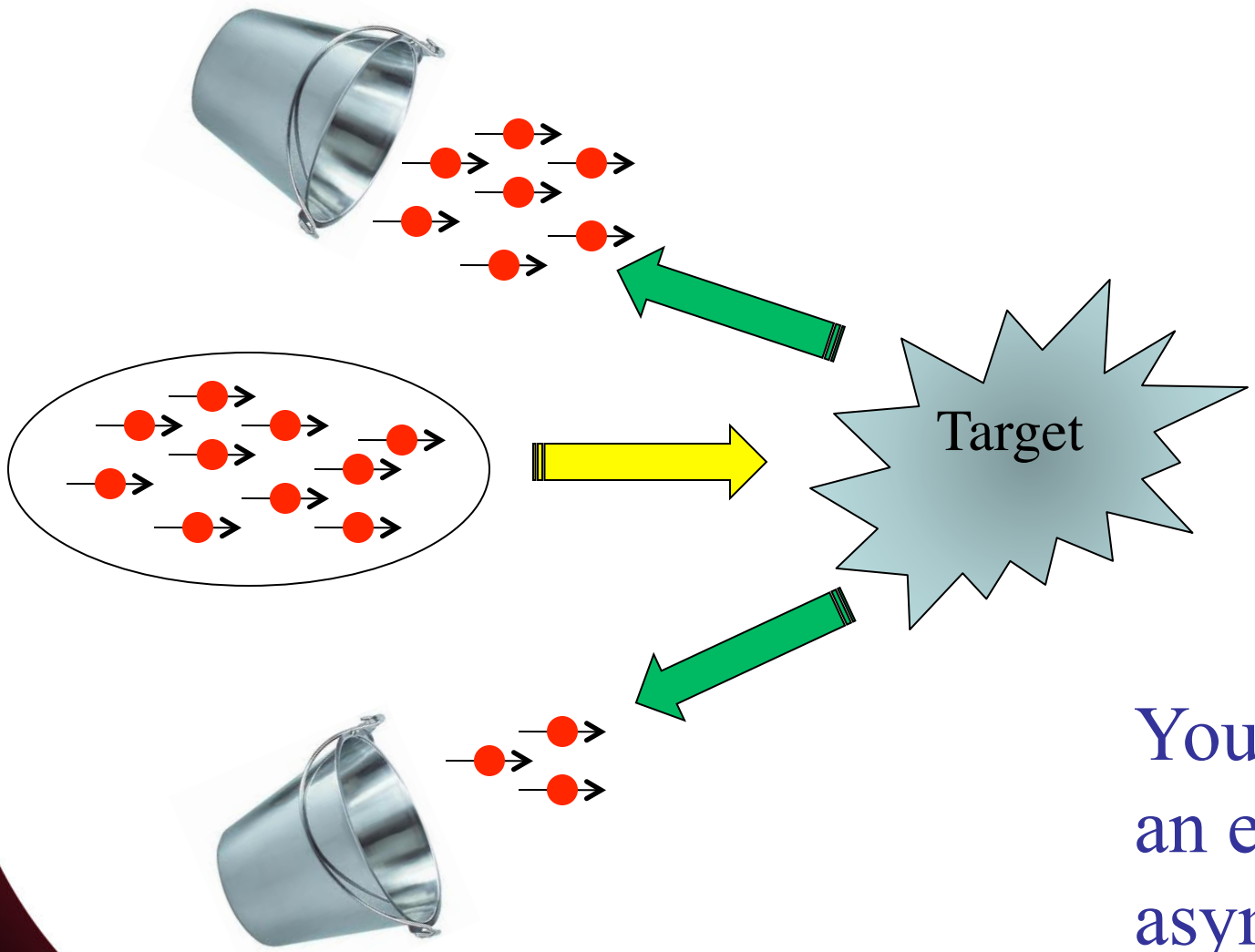
Thermionic source

Klystrons — RF generators

- Electrons make RF-energy…
- Klystrons use a DC electron beam at a few mA to generate/amplify microwaves by velocity modulation.
- Klystrons use thermionic cathodes to generate the required electron beam.



What about the probing with spin ?



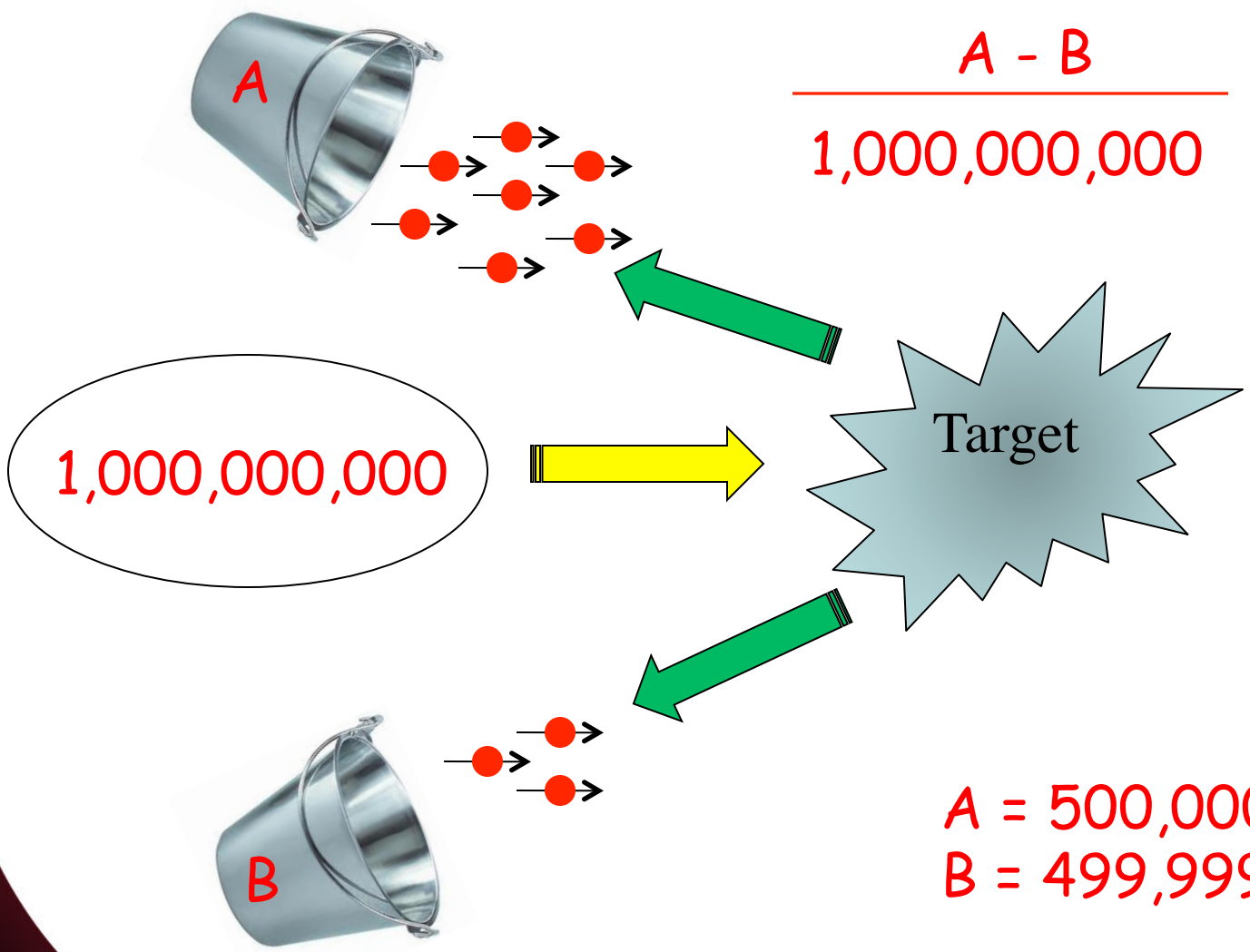
You measure an experimental asymmetry

Parity Violation Experiments at CEBAF

Experiment	Energy (GeV)	I (μA)	Target	A_{pv} (ppb)	Maximum Charge Asym (ppb)	Maximum Position Diff (nm)	Maximum Angle Diff (nrad)	Maximum Size Diff (δσ/σ)
HAPPEx-II (Achieved)	3.0	55	^{1}H (20 cm)	1400	400	1	0.2	Was not specified
HAPPEx-III (Achieved)	3.484	100	^{1}H (25 cm)	16900	200±100	3±3	0.5±0.1	10^{-3}
PREx	1.063	70	^{208}Pb (0.5 mm)	500	100±10	2±1	0.3±0.1	10^{-4}
QWeak	1.162	180	^{1}H (35 cm)	234	100±10	2±1	30±3	10^{-4}
Møller	11.0	75	^{1}H (150 cm)	35.6	10±10	0.5±0.5	0.05±0.05	10^{-4}

PV experiments motivate polarized e-source R&D

What does “234 ppb” even mean?

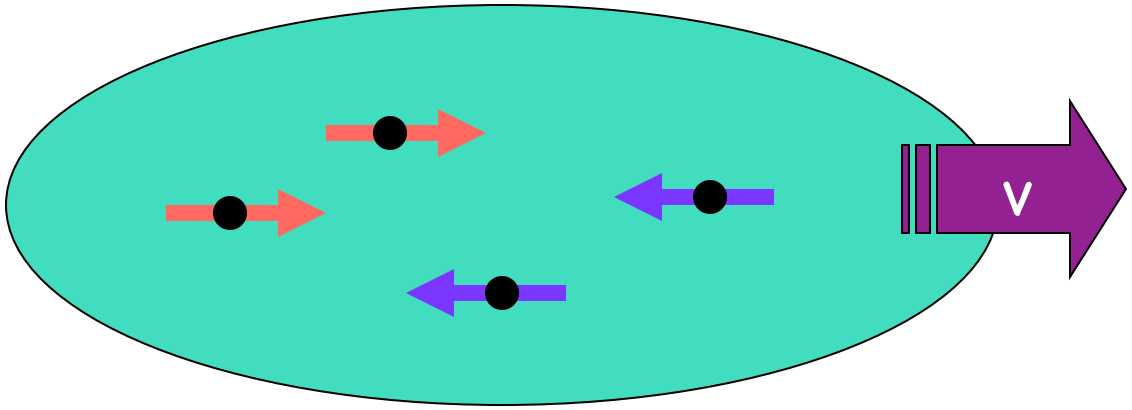


$$\frac{A - B}{1{,}000{,}000{,}000}$$

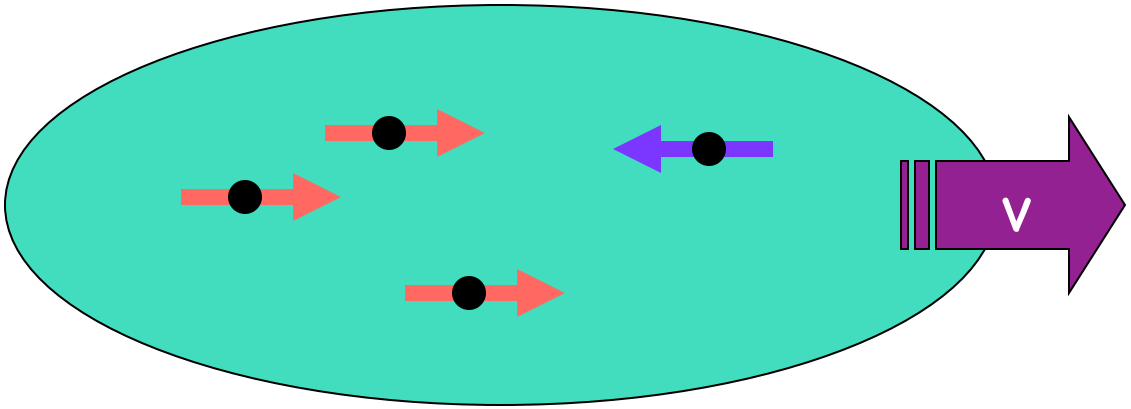
A = 500,000,117
B = 499,999,883

Electron Bunch Spin & Polarization

0% Polarization
(thermionic)



50% Polarization



Polarized Source Landscape 1970s

Self-polarization via Sokolov-Ternov Effect

Electron Scattering (Mott)

Photo-ionization: Fano Effect

Photo-ionization of State Selected alkali atoms

Optically Pumped He Discharge

Field Emission from EuS

Photoemission from GaAs

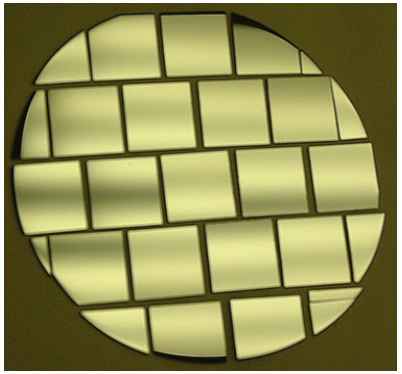
Sources can be problematic !

- Fast spin reversal; some methods difficult to reverse spin greater than 1Hz second (present day experiments want >1kHz)
- It would be nice to make RF-time structure directly, instead of DC beam
- Most accelerators require reasonably small emittance
- Maximize feasability; lasers, pounds of alkali metal, hot and cold things very near each other, strong magnetic fields, very high voltage, challenging vacuum issues can kill a concept
- Long term reliability can be an issue (24/7 ops)
- Reproducibility, getting the same result twice

Polarized Source "Musts"

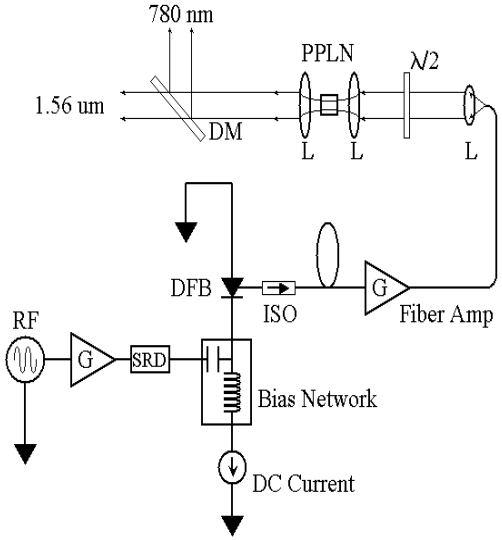
Good Photocathode

- Many electrons/photon
- High Polarization
- Fast response time



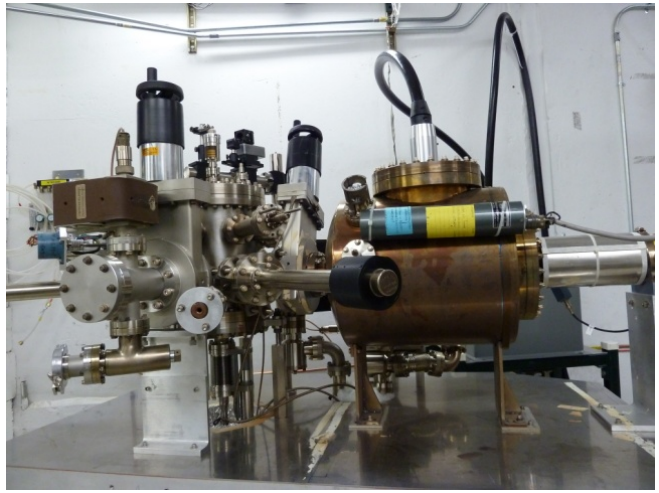
Good Laser

- Lots of Photons
- CW Pulses
- High Polariztion



Good Electron Gun

- Accelerate Electrons
- Happy Photocathode
- Integrate Laser



GaAs….the method that caught on

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)

The spin polarization of electrons photoemitted from (110) GaAs by irradiating with circularly polarized light of energy $1.5 < \hbar\omega < 3.6$ eV was measured by Mott scattering. The GaAs surface was treated with cesium and oxygen to obtain a negative electron affinity (NEA). The spectrum of spin polarization $P(\hbar\omega)$ exhibits a peak ($P = 40\%$) at threshold arising from transitions at Γ, and positive ($P = 8\%$) and negative ($P = -8\%$) peaks at 3.0 and 3.2 eV, respectively, arising from transitions at L (Λ). Anomalous behavior, consisting of a depolarization at threshold and an increase and shift in the peak polarization to 54% at 1.7 eV, is attributed to a small positive electron affinity (PEA) characteristic of some samples. Restriction of the photoelectron emission angle by the PEA leads directly to the anomalously high P. Results of calculations show that P cannot be increased above 50% for emission arising from transitions at Γ in NEA GaAs. Our detailed interpretation of the spectra indicates how spin-polarized photoemission can be used to study the spin-dependent aspects of electronic structure. The outstanding qualities of NEA GaAs as a source of spin-polarized electrons are discussed and compared with other sources.

Photoemission from GaAs

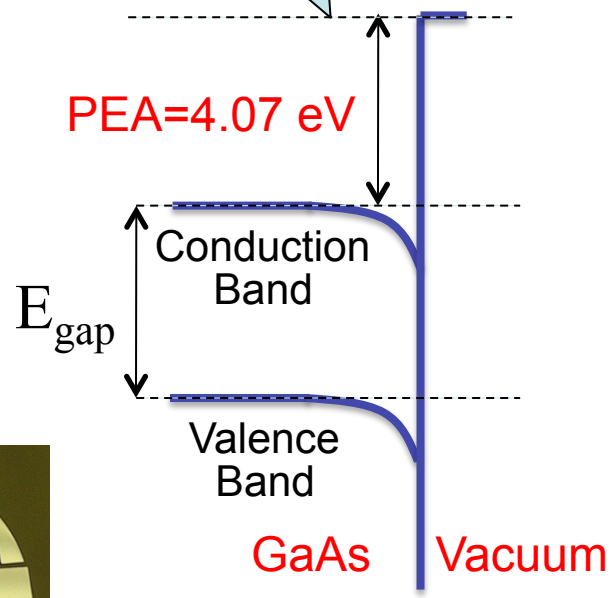
Bare GaAs surface

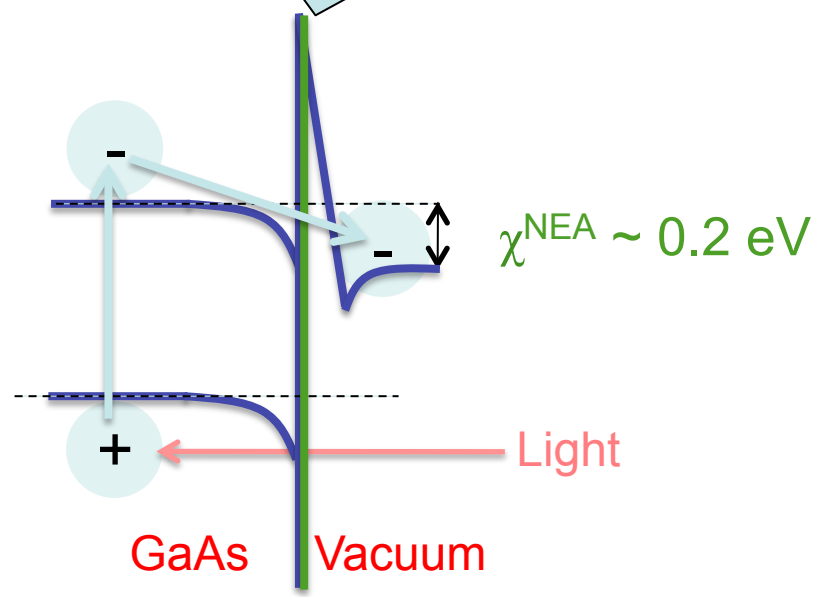
- Large Work Function
- Positive Electron Affinity (PEA)

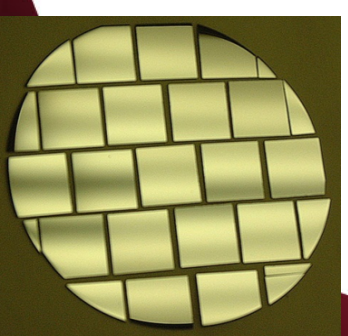
NEA Surface Activation

Dipole layers of Cesium + NF_3

- Reduces Work Function
- Negative Electron Affinity (NEA)



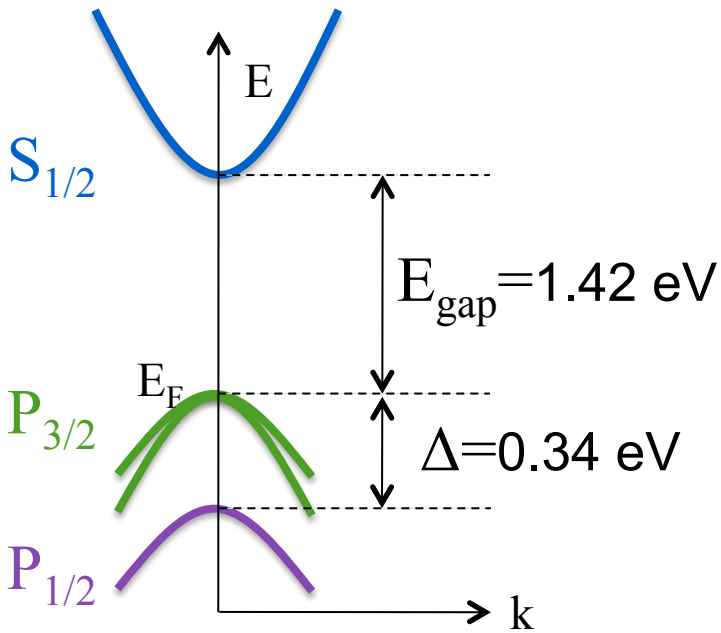


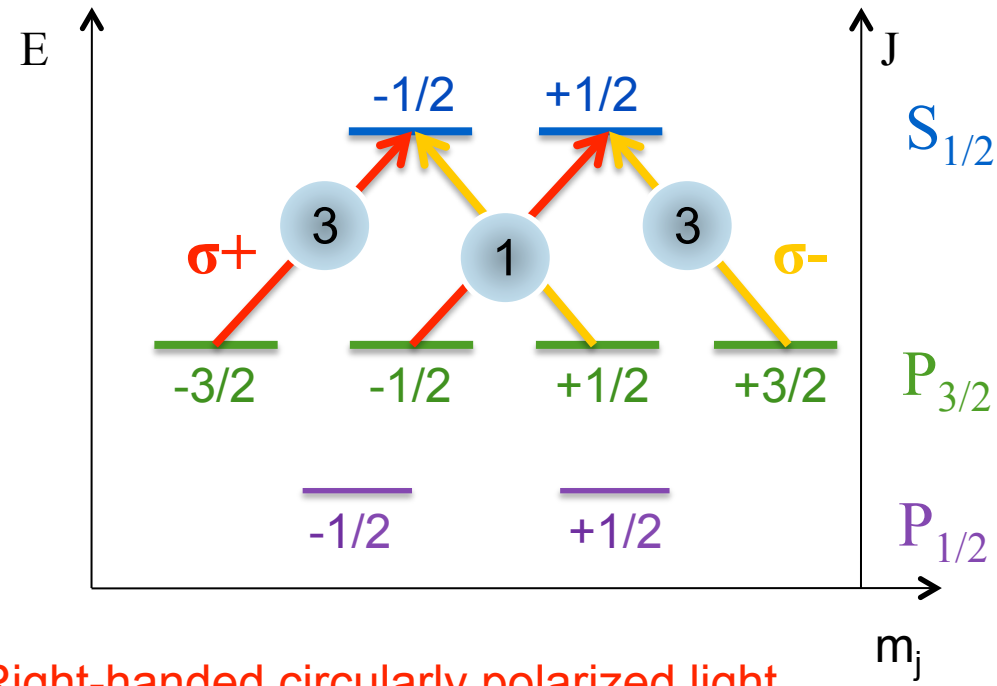


Quantum Efficiency = N_{e-} / N_{γ}

Bulk GaAs

- Laser excitation from $P_{3/2}$ to $S_{1/2}$: $E_{gap} < E_{\gamma} < E_{gap}+\Delta$
- Electron Polarization: $P_e < \frac{3-1}{3+1} = 50\%$



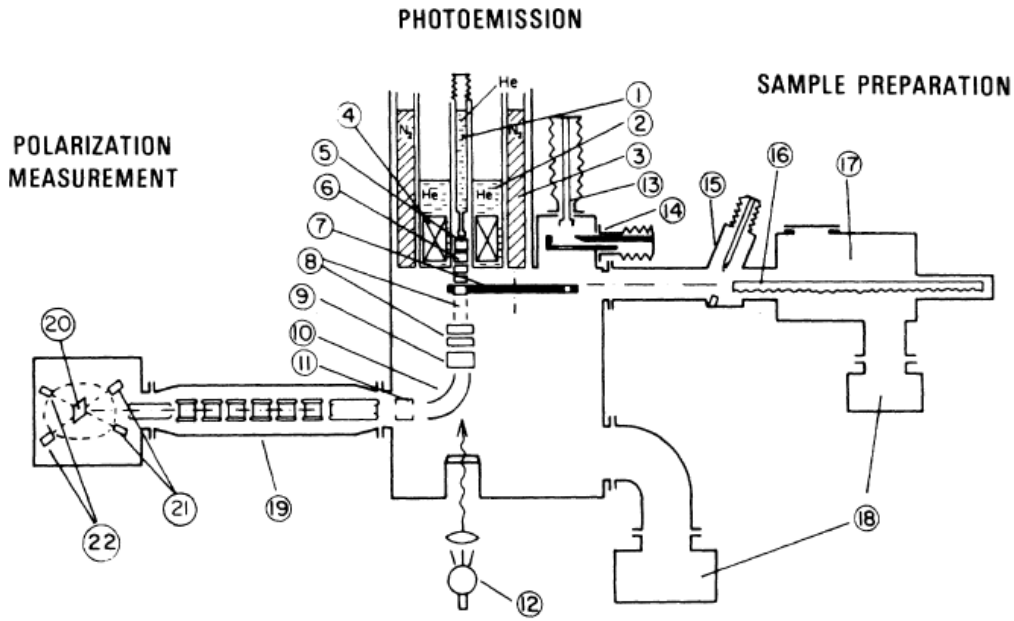


σ+: Right-handed circularly polarized light

σ- : Left-handed circularly polarized light

- Reverse electron polarization by reversing light polarization

First Observation of Polarization from GaAs



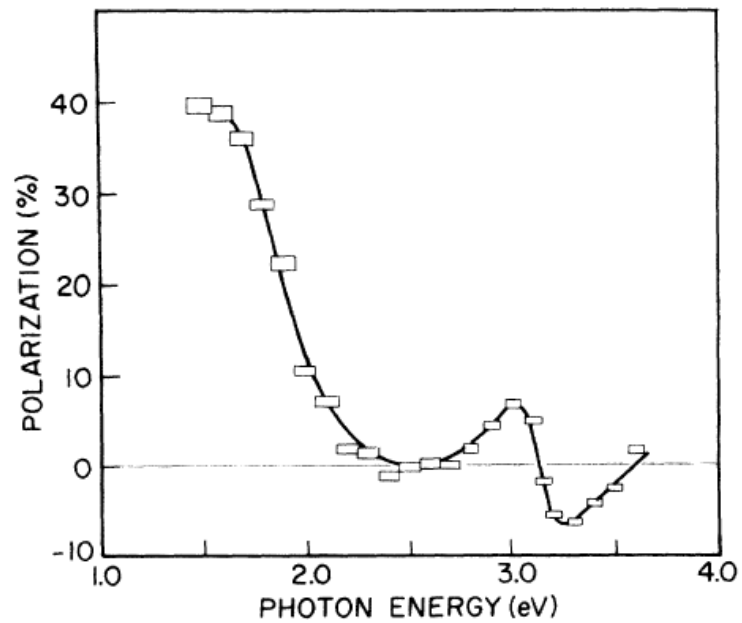


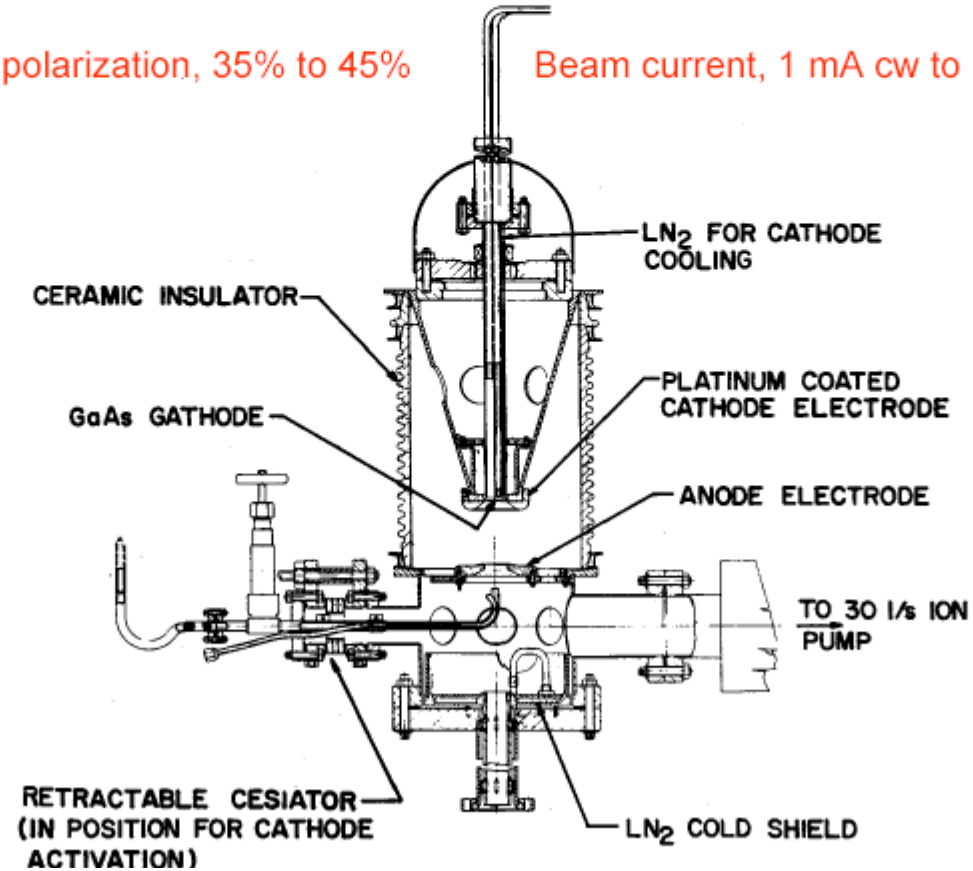
FIG. 6. Spectrum of spin polarization from GaAs + CsOCs at $T \leq 10$ K [the same sample and conditions as curve (a) of Fig. 5] . Note the high value of $P = 40\%$ at threshold ($\hbar\omega \sim 1.5$ eV) and positive and negative peaks at $\hbar\omega = 3.0$ and 3.2 eV.

First High Voltage GaAs Photogun

Polarized e⁻ Gun for SLAC Parity Violation Experiment

Beam polarization, 35% to 45%

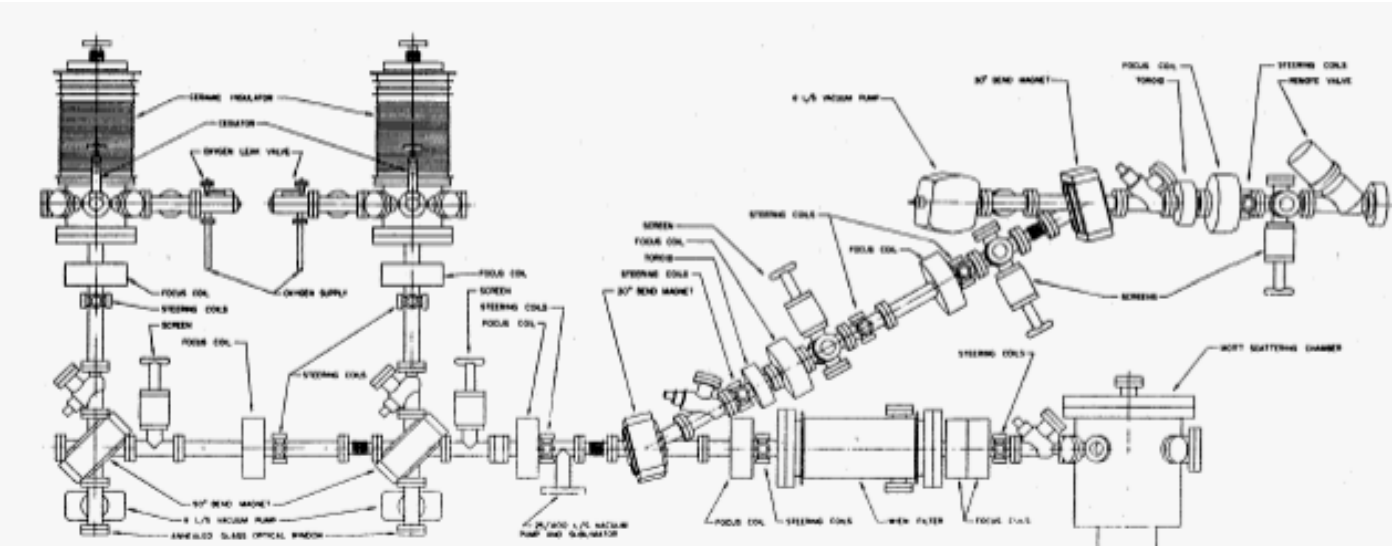
Beam current, 1 mA cw to 15 A peak

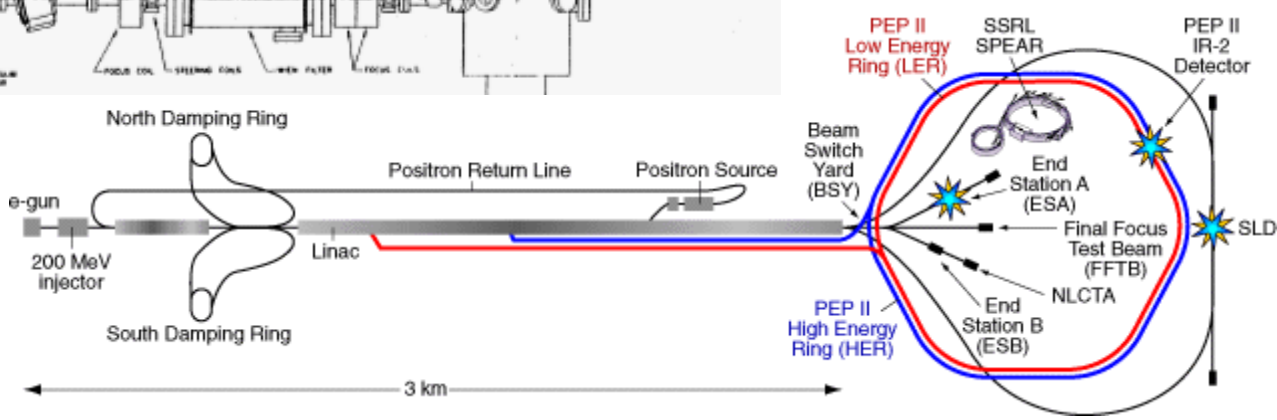


Started with a thermionic gun housing

First GaAs Photoinjector

- Built for SLAC parity-violation experiment E122
- Polarized electrons accelerated December, 1977
- E122 announces parity violation June, 1978 - an important verification of the Standard Model

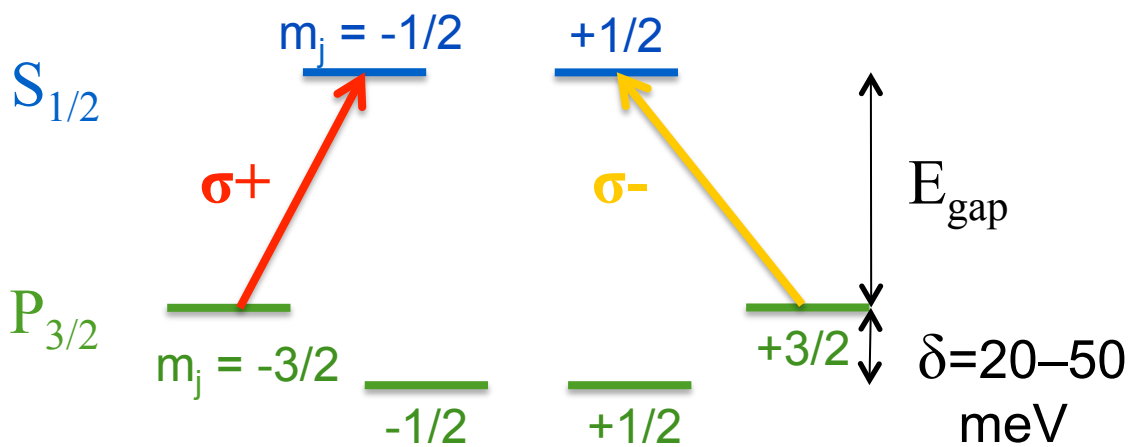




Higher P: Breaking GaAs Degeneracy

- Split degeneracy of $P_{3/2}$: Introduce strain on GaAs crystal by growing it on substrate (GaAsP) with different lattice constant

- High polarization by laser excitation from $P_{3/2}$ to $S_{1/2}$:
  $E_{gap} < E_{\gamma} < E_{gap}+\delta$



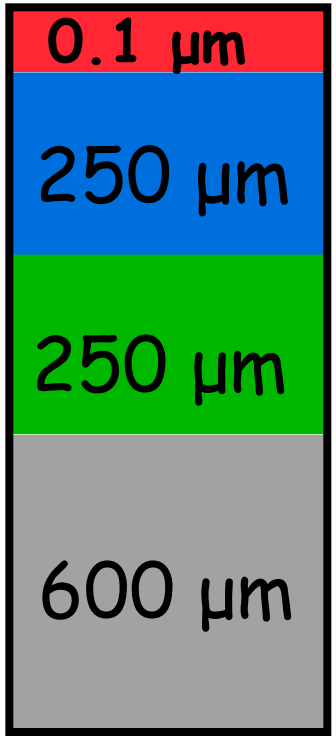
- Higher QE: Alternating layers of GaAs and GaAsP – **Superlattice GaAs**

Strained layer GaAs

Bandwidth Semiconductor (formerly *SPIRE*)

- MOCVD-grown epitaxial spin-polarizer wafer
- Lattice mismatch

$\Rightarrow$ split degeneracy of $P_{3/2}$



Strained GaAs

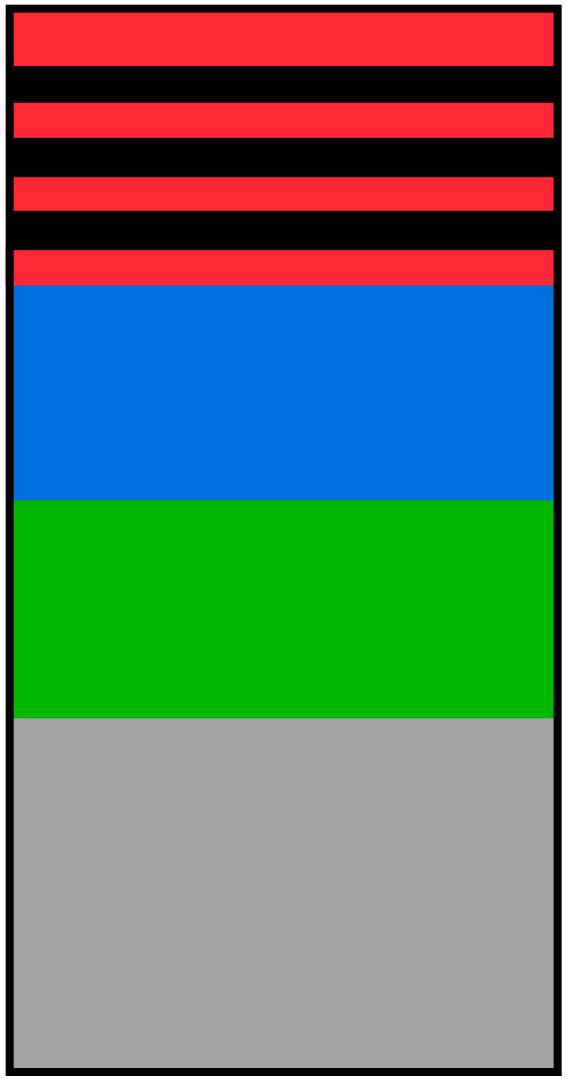
$GaAs_{1-x}P_x$ $x=0.29$

$GaAs_{1-x}P_x$ $0<x<0.29$

p-type GaAs substrate

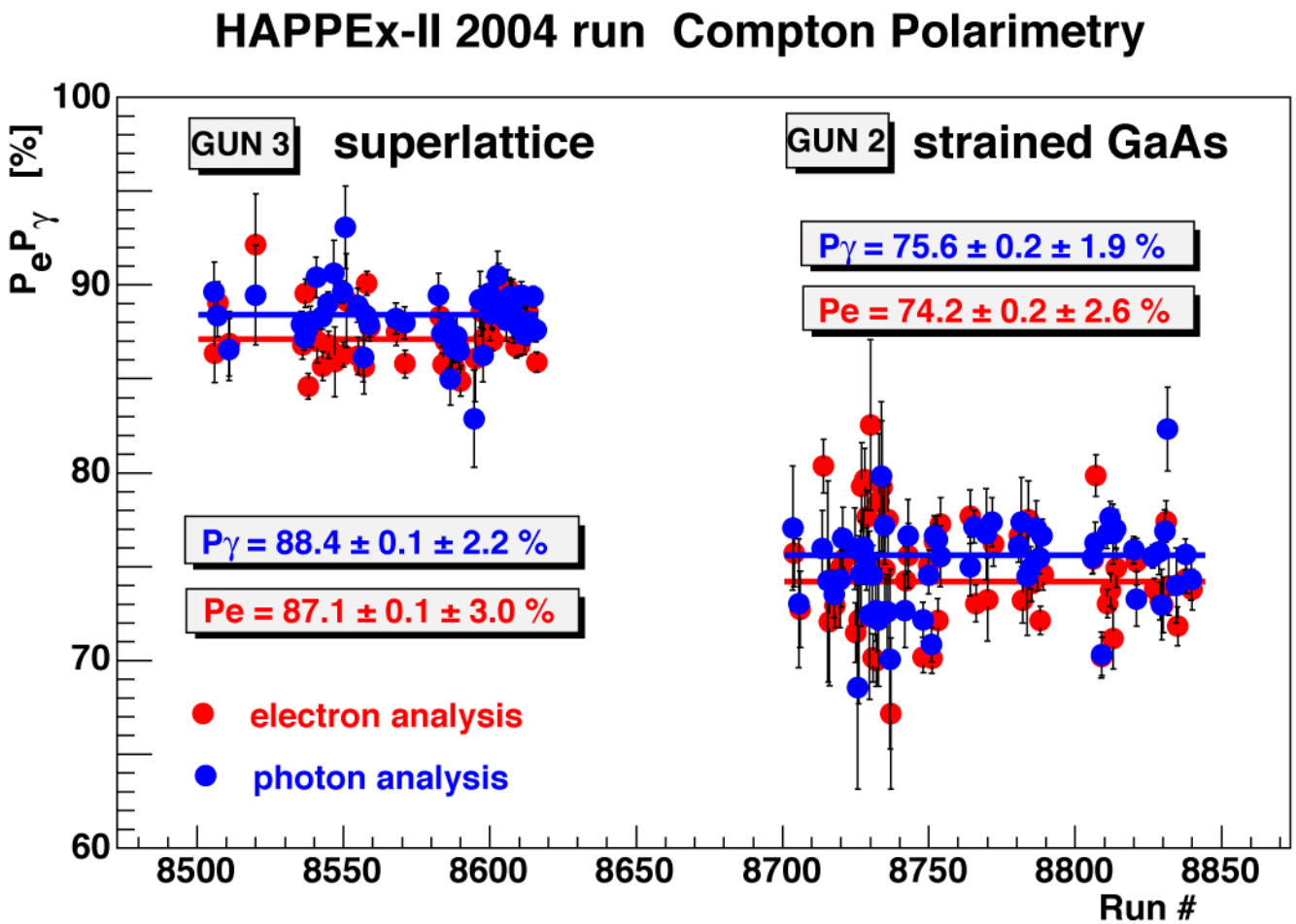
Strained Layer - Superlattice GaAs

Be doping (cm^{-3})



SVT associates, per SLAC specs.

And, it really works!



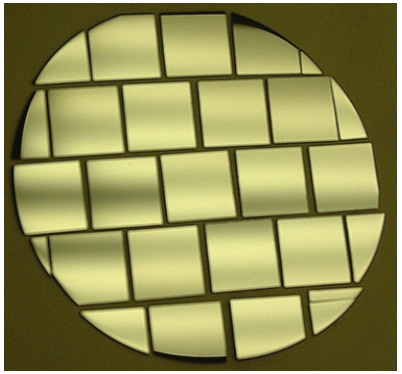
Experiment Figure of Merit

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

Polarized GaAs Source "Musts"

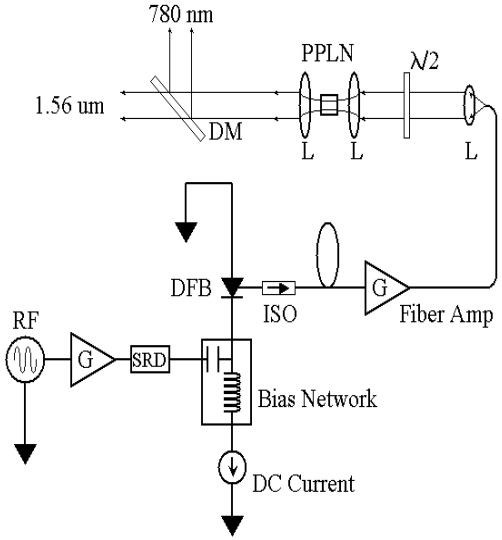
Good Photocathode

- Many electrons/photon
- High Polarization
- Fast response time



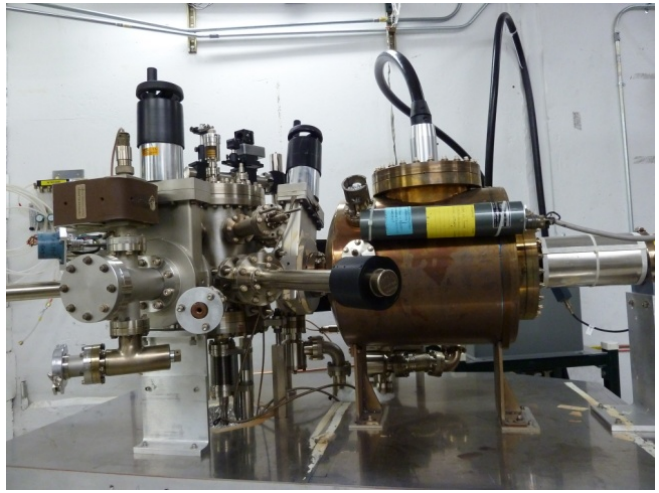
Good Laser

- Lots of Photons
- CW Pulses
- High Polariztion

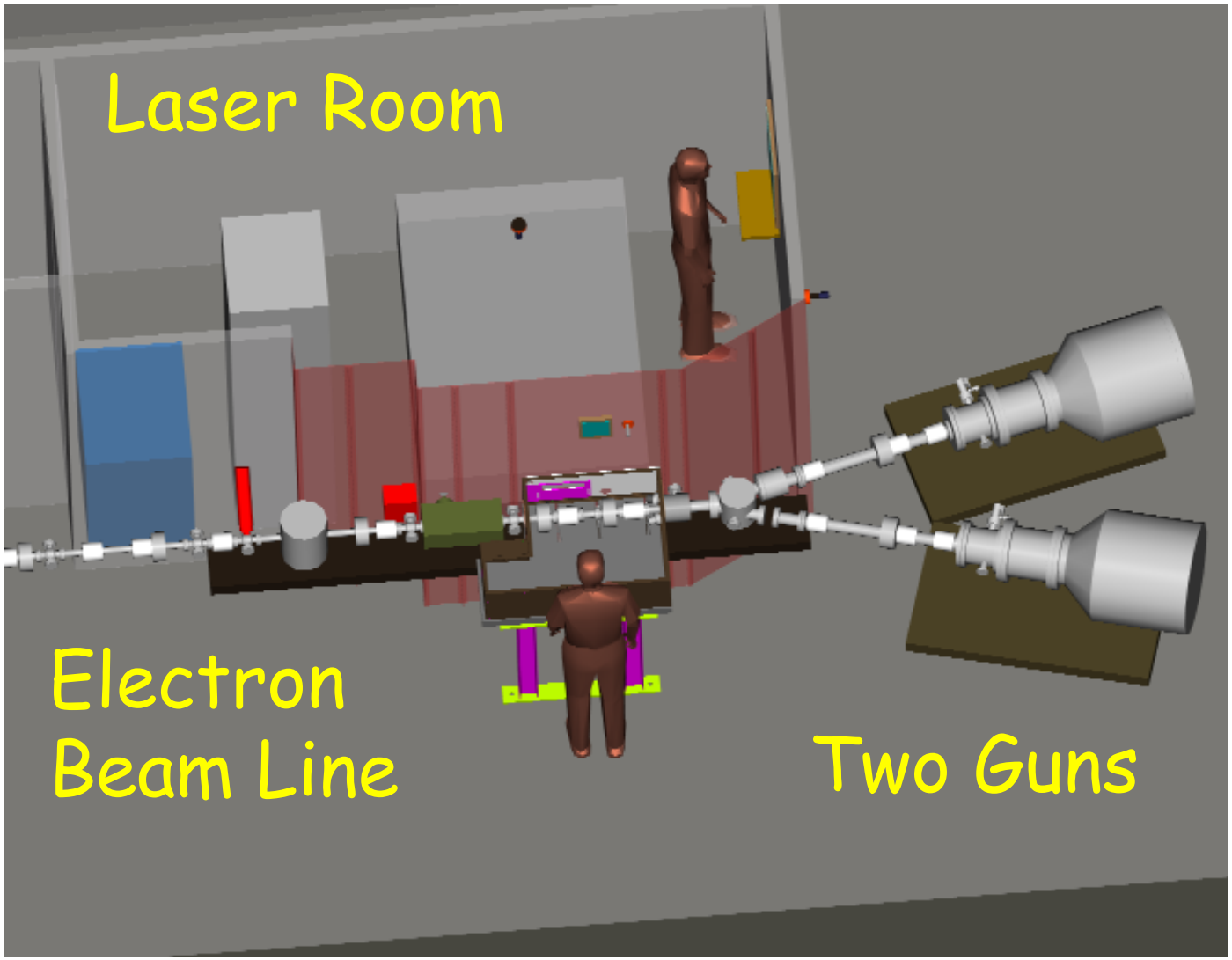


Good Electron Gun

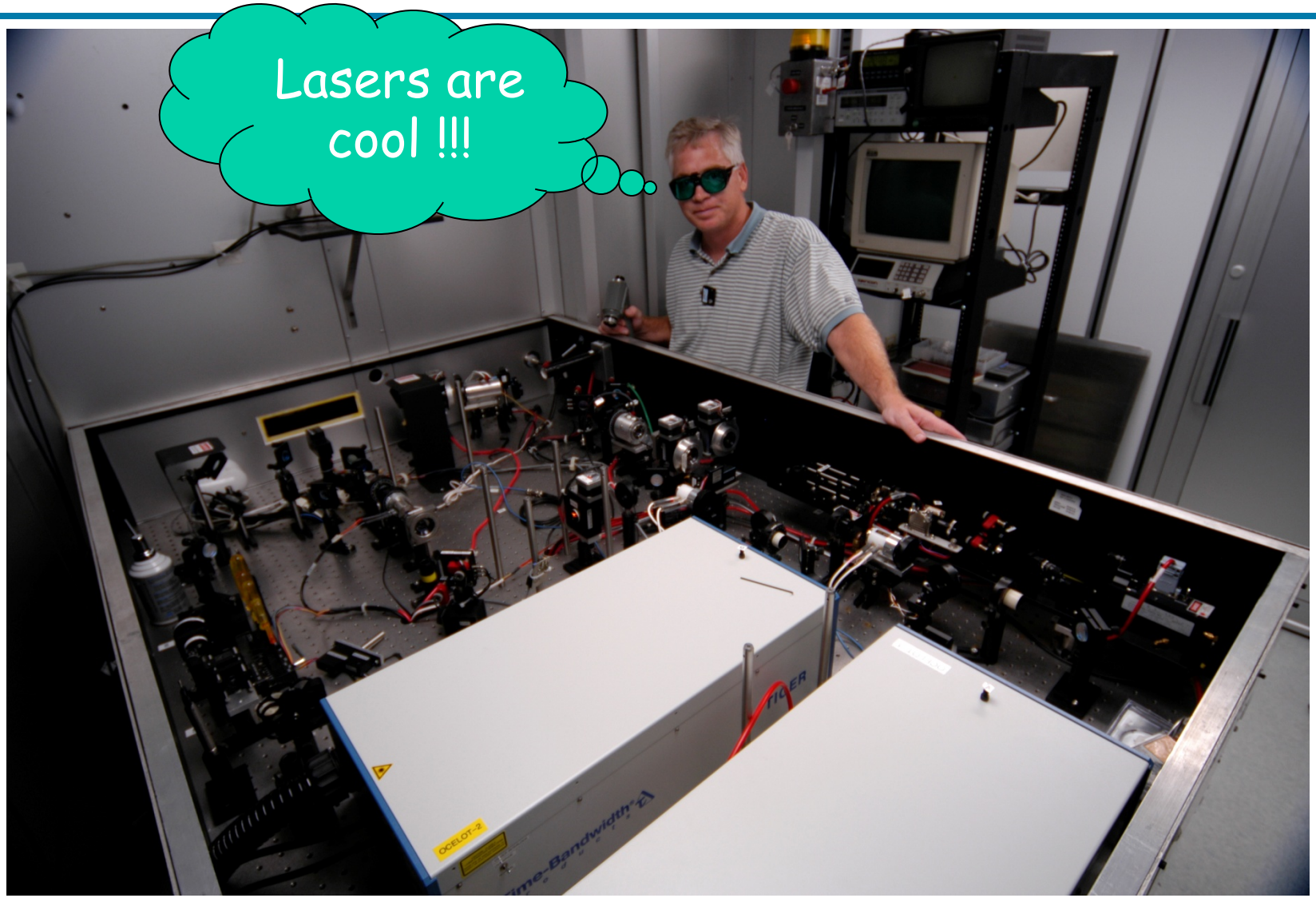
- Accelerate Electrons
- Happy Photocathode
- Integrate Laser

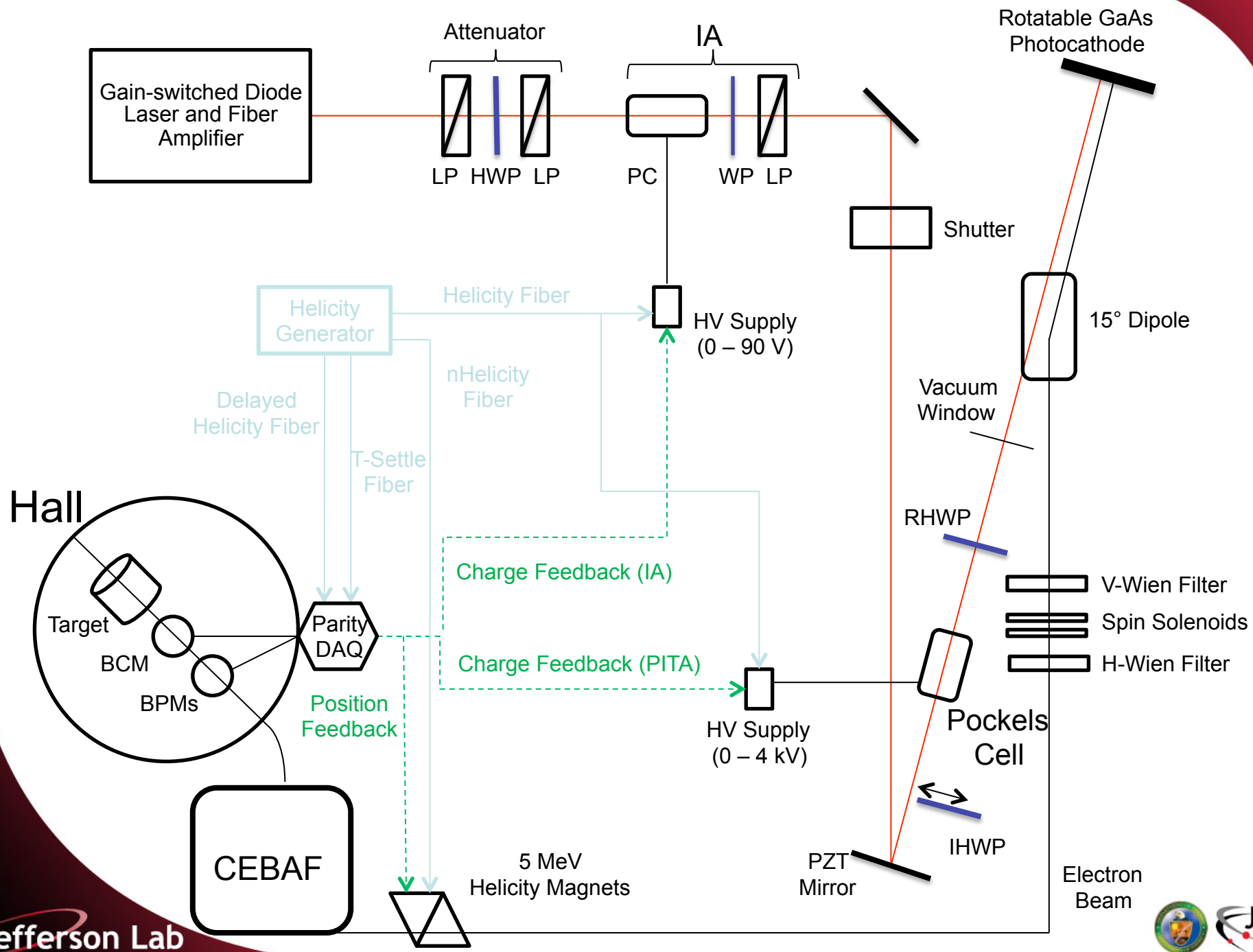


Bird's Eye View



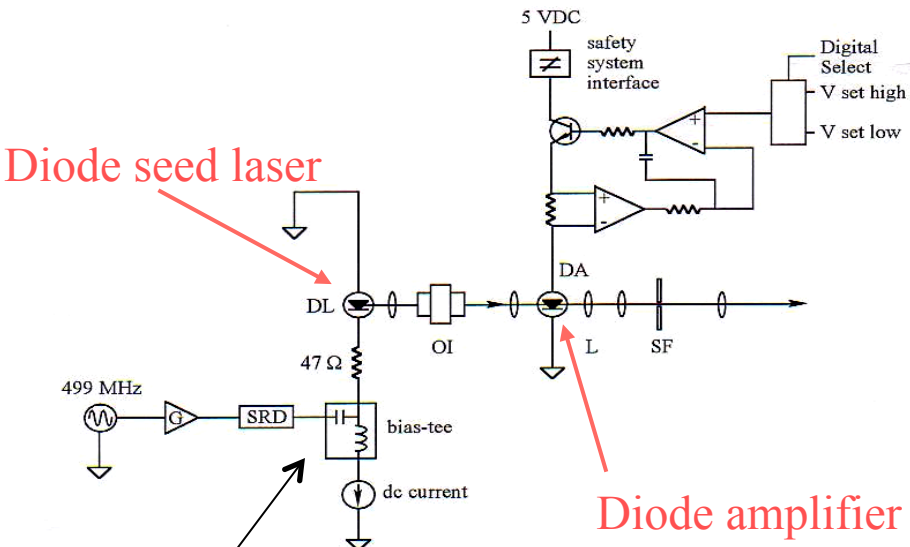
Laser Room for Dust & Climate Control

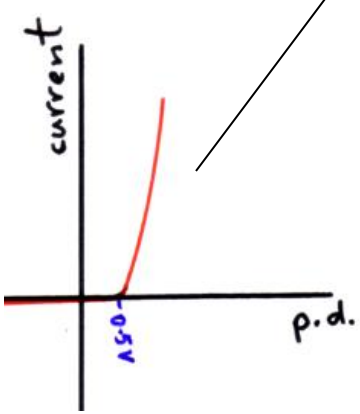


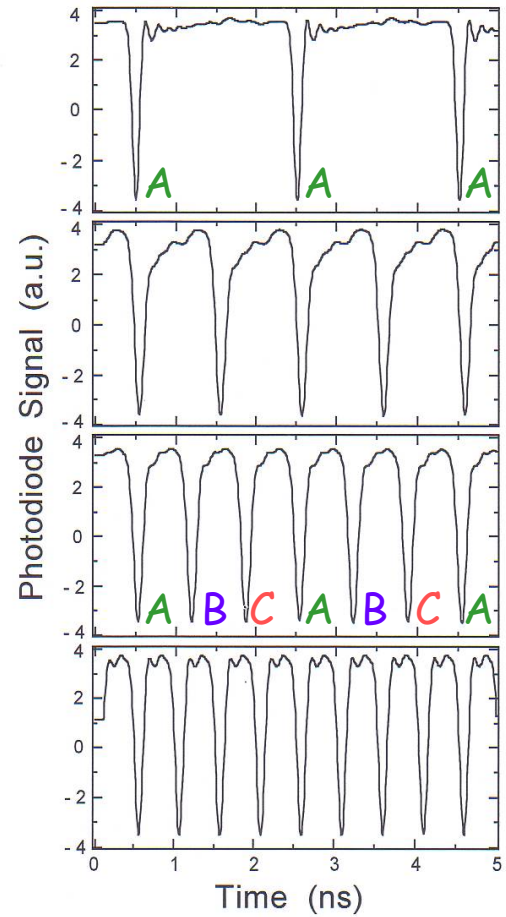

Gain-switched Diode Laser and Fiber Amplifier
Attenuator
LP HWP LP
IA
PC
WP LP
Rotatable GaAs Photocathode
Shutter
Helicity Generator
Helicity Fiber
HV Supply (0 – 90 V)
15° Dipole
nHelicity Fiber
Delayed Helicity Fiber
T-Settle Fiber
Vacuum Window
Hall
RHWP
Charge Feedback (IA)
V-Wien Filter
Spin Solenoids
H-Wien Filter
Target
BCM
BPMs
Parity DAQ
Charge Feedback (PITA)
Position Feedback
HV Supply (0 – 4 kV)
Pockels Cell
IHWP
CEBAF
5 MeV Helicity Magnets
PZT Mirror
Electron Beam

Radio Frequency Pulsed Lasers

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







0.5 GHz

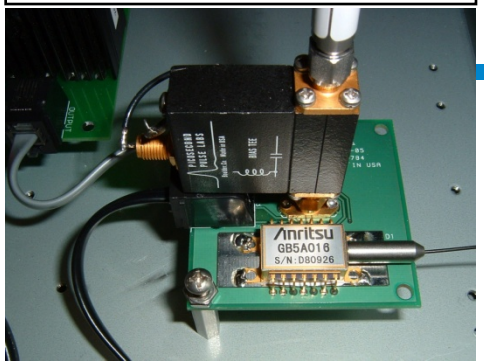
1 GHz

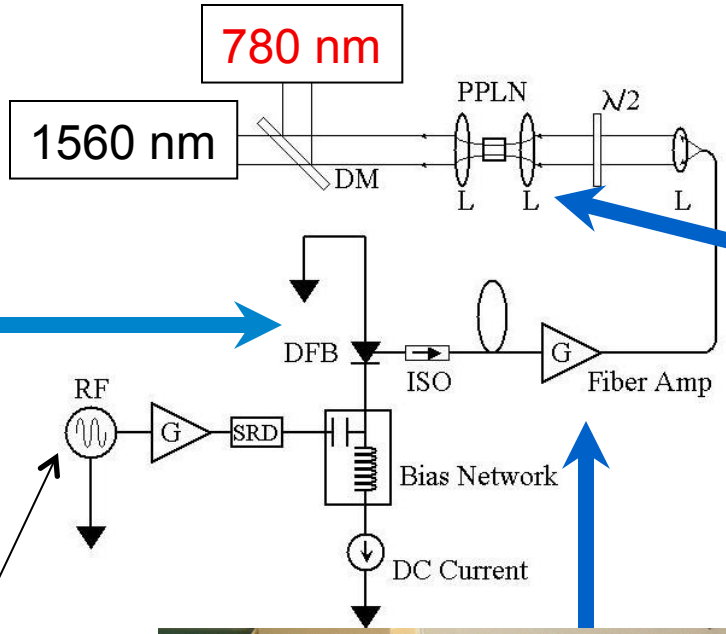
1.5 GHz

2 GHz

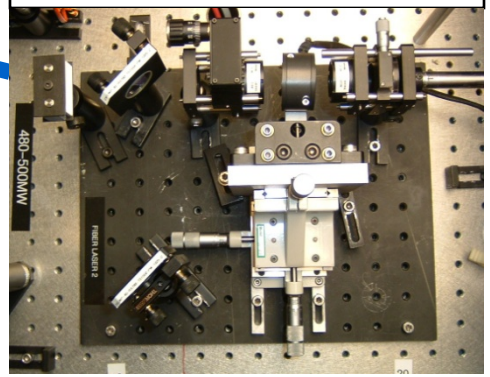
Fiber-based Drive Laser

RF Locked Low-Power
(1 mW)
1560 nm Fiber Diode





Frequency-doubler
1560 nm to 780 nm
30% Efficiency (2 W)



499 MHz

High Power (6 W) 1560 nm Fiber Amplifier

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 9, 063501 (2006)

Synchronous photoinjection using a frequency-doubled gain-switched fiber-coupled seed laser and ErYb-doped fiber amplifier

J. Hansknecht* and M. Poelker

Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA

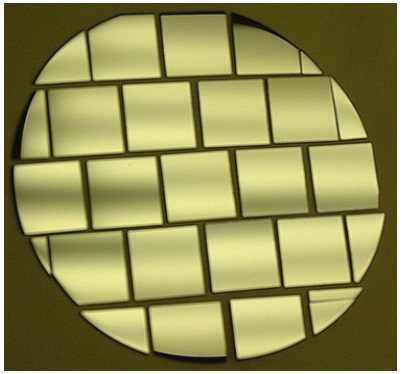
(Received 12 April 2006; published 21 June 2006)

Light at 1560 nm from a gain-switched fiber-coupled diode laser and ErYb-doped fiber amplifier was frequency doubled to obtain over 2 W average power at 780 nm with ~40 ps pulses and pulse repetition rate of 499 MHz. This light was used to drive the 100 kV DC high voltage GaAs photoemission gun at the

Polarized GaAs Source "Musts"

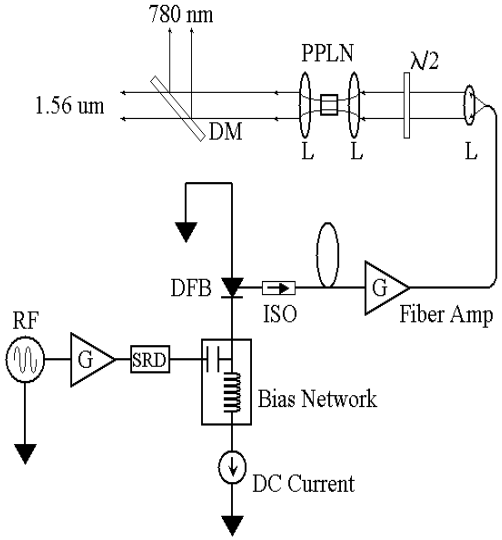
Good Photocathode

- Many electrons/photon
- High Polarization
- Fast response time



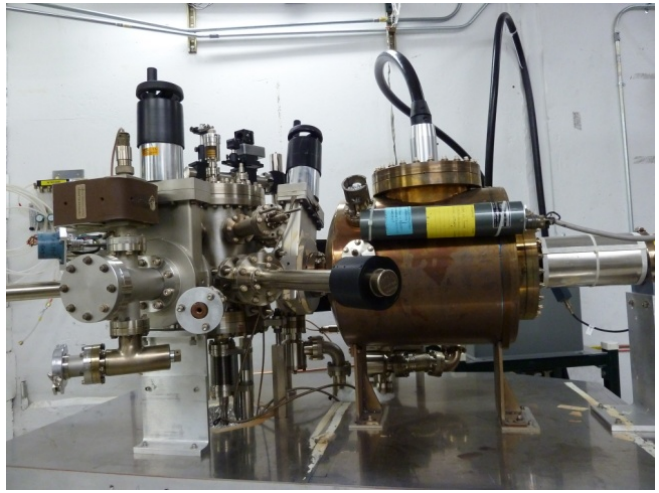
Good Laser

- Lots of Photons
- CW Pulses
- High Polarization



Good Electron Gun

- Accelerate Electrons
- Happy Photocathode
- Integrate Laser



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

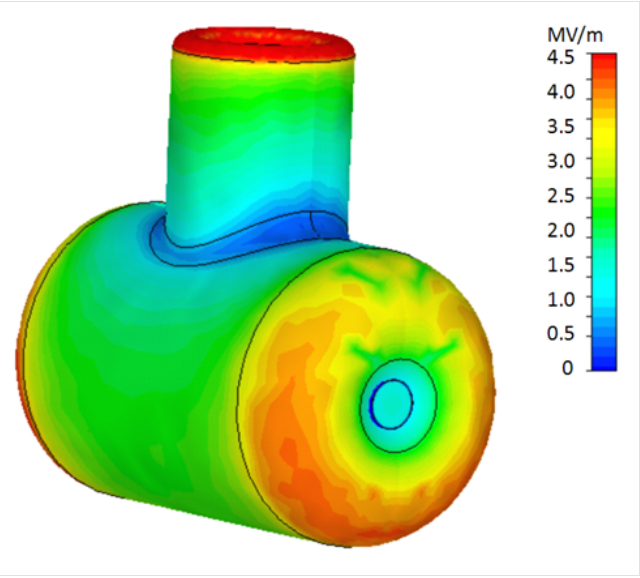
Load-locked dc high voltage GaAs photogun with an inverted-geometry ceramic insulator

P. A. Adderley, J. Clark, J. Grames, J. Hansknecht, K. Surles-Law, D. Machie, M. Poelker,*
M. L. Stutzman, and R. Suleiman

Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA

(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.



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" – Gary Larson

Vacuum regimes

Air ~ 10^{16} / Torr-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
Insulating vacuum for cryogens	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

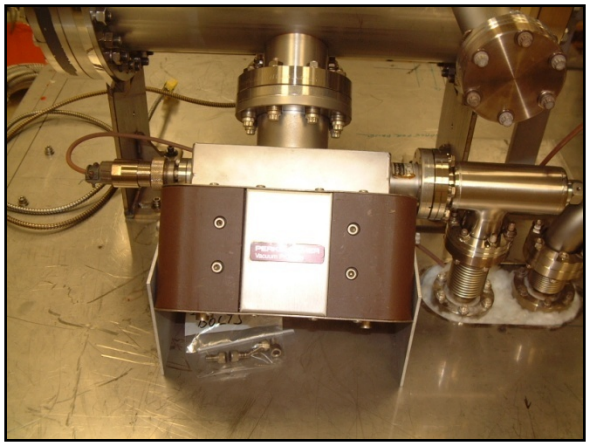
Where does the gas come from?

- **Outgassing from the system**
  - Metal and non-metal (viton o-rings, ceramics) all outgas
  - Primarily water in unbaked systems
  - Primarily hydrogen from steel in baked systems
- **Leaks**
  - Real
    - Gaskets not sealed
    - Cracks in welds, bellows, ceramics, window joints
    - Superleaks that only open at very low temperatures
  - Virtual
    - Small volumes of gas trapped inside system (screw threads, etc.) that pump out slowly over time
- **Gas load caused by the beam**
  - Desorption of gases by elevated temperatures, electrons or photons striking surfaces, etc.
- **Engineered Loads** (targets, etc.) where gas is added
- **Permeation of gasses through materials**
  - Viton gaskets worse than metal seals
  - Hydrogen can permeate through stainless steel!

Ultra High Vacuum Pumps

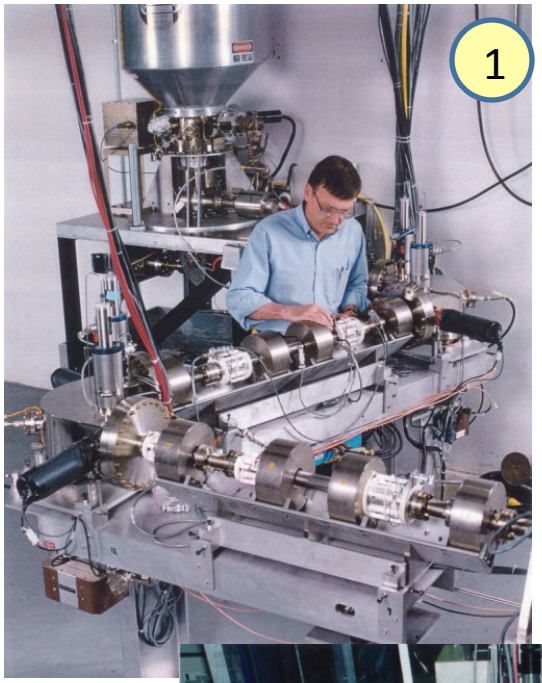
- **Getter Pumps**
  - Chemically active surface
    - Titanium sublimed from hot filament
    - Non-Evaporative Getters
  - Molecules stick when they hit
    - Does not work well for inert gasses such as Argon, Helium or for methane
- **Ion Pumps**
  - Electric field to ionize gasses
  - Magnetic field to direct gasses into cathodes where they are trapped
    - Has some pumping capability for noble gasses
- **Baking used to get pressures below 10^{-10} Torr**
  - 250°C for 30 hours removes water vapor bonded to surface that otherwise limits pressure
- Avoid contamination by oils due to roughing pumps, fingerprints, machining residue.

NEG pump array

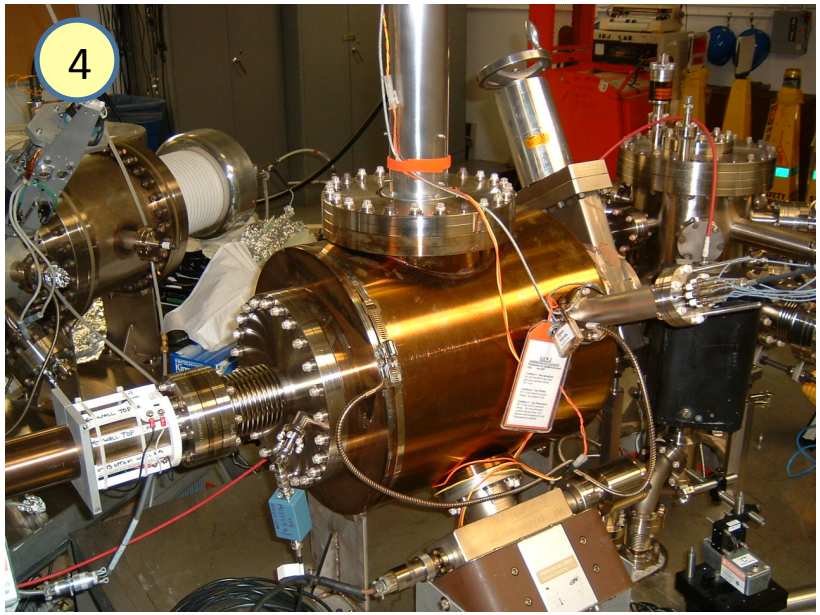


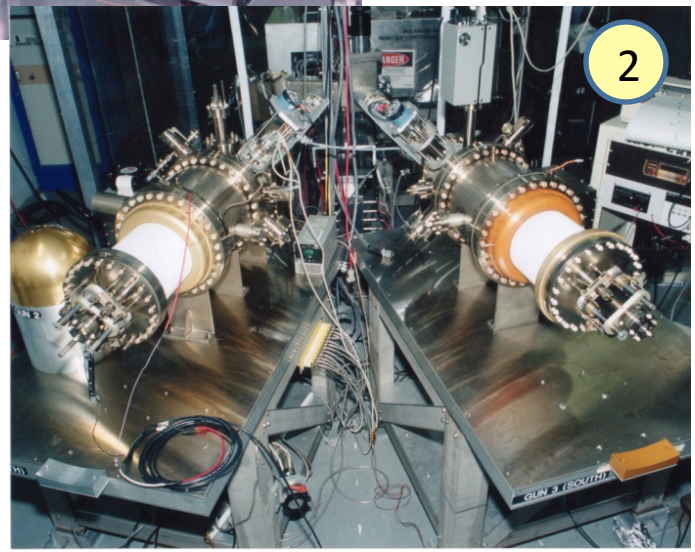
Ion Pump

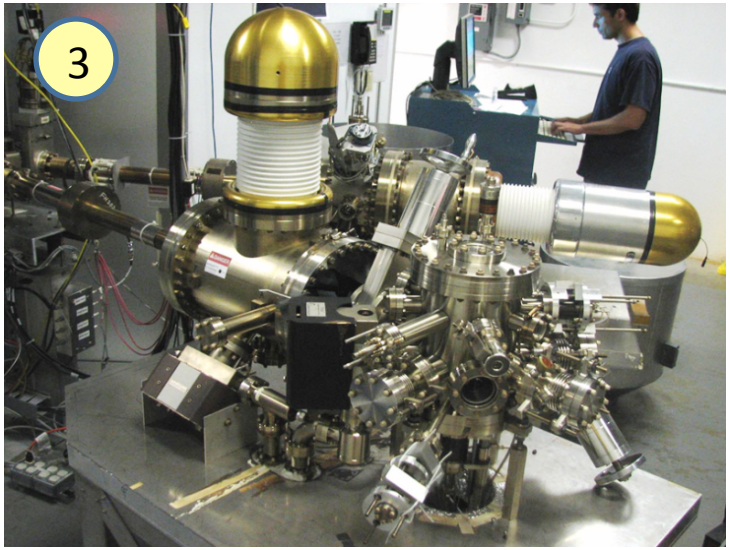
Always Tweaking the Design



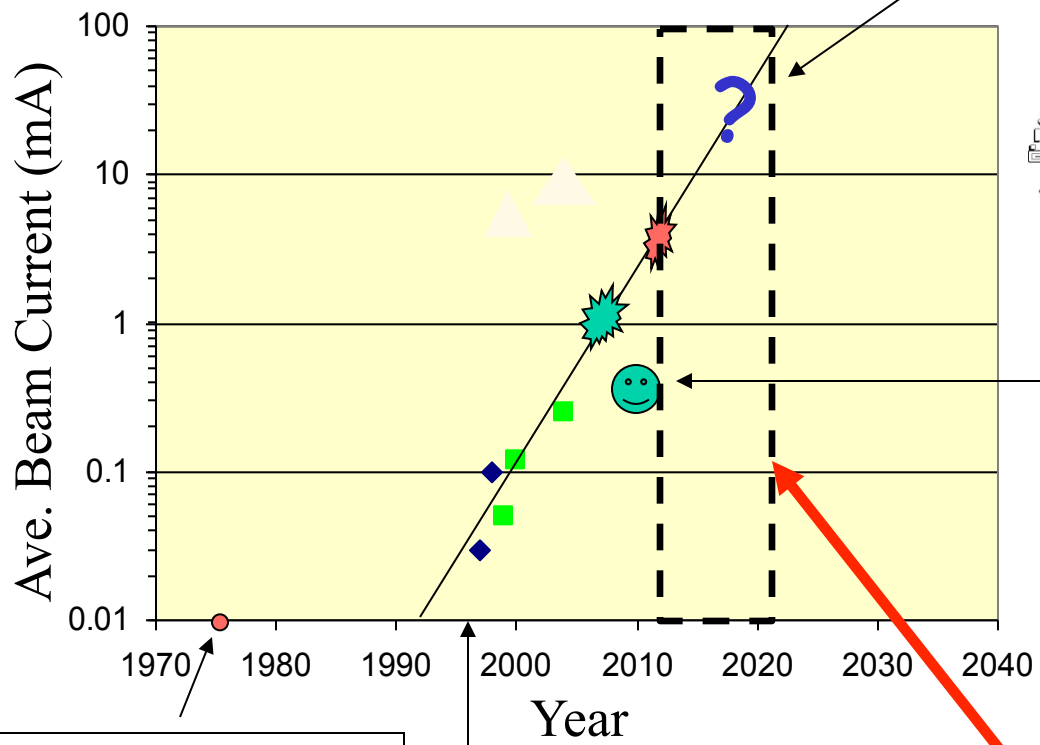
Endless (?)
quest for
perfection



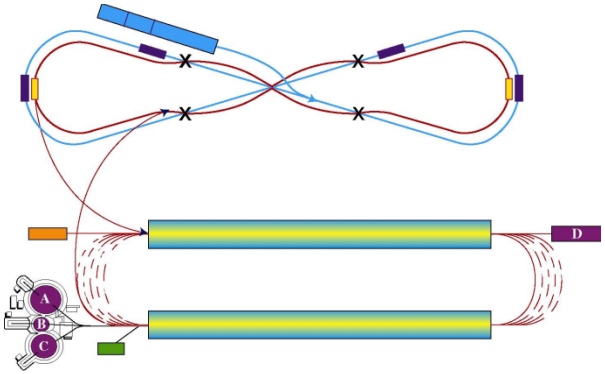


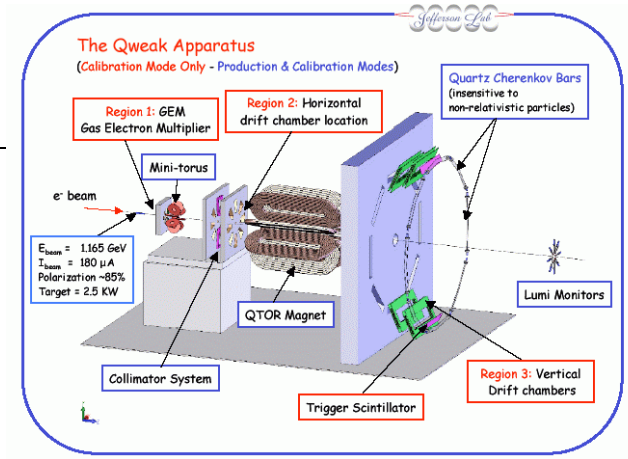


High Polarization from GaAs: Trending toward higher current…



E(L)IC





First polarized beam from GaAs photogun

First low polarization, then high polarization at CEBAF

(Insert your name) breaks world record !!!