USPAS Course on Photocathode Physics

John Smedley, BNL and Matt Poelker, TJNAF

Lecture 2

Austin, TX January 16-20, 2011

Lecture 2 Outline:

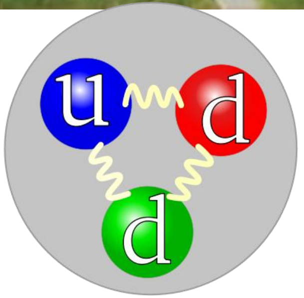
- How to make an electron beam
- History of spin polarized electron sources
- Properties of GaAs

Jefferson Lab

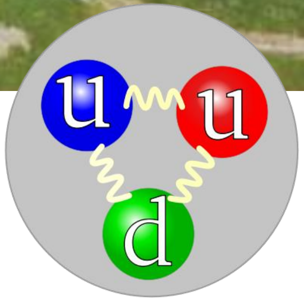
Thomas Jefferson National Accelerator Facility

Exploring the Nature of Matter

Electron

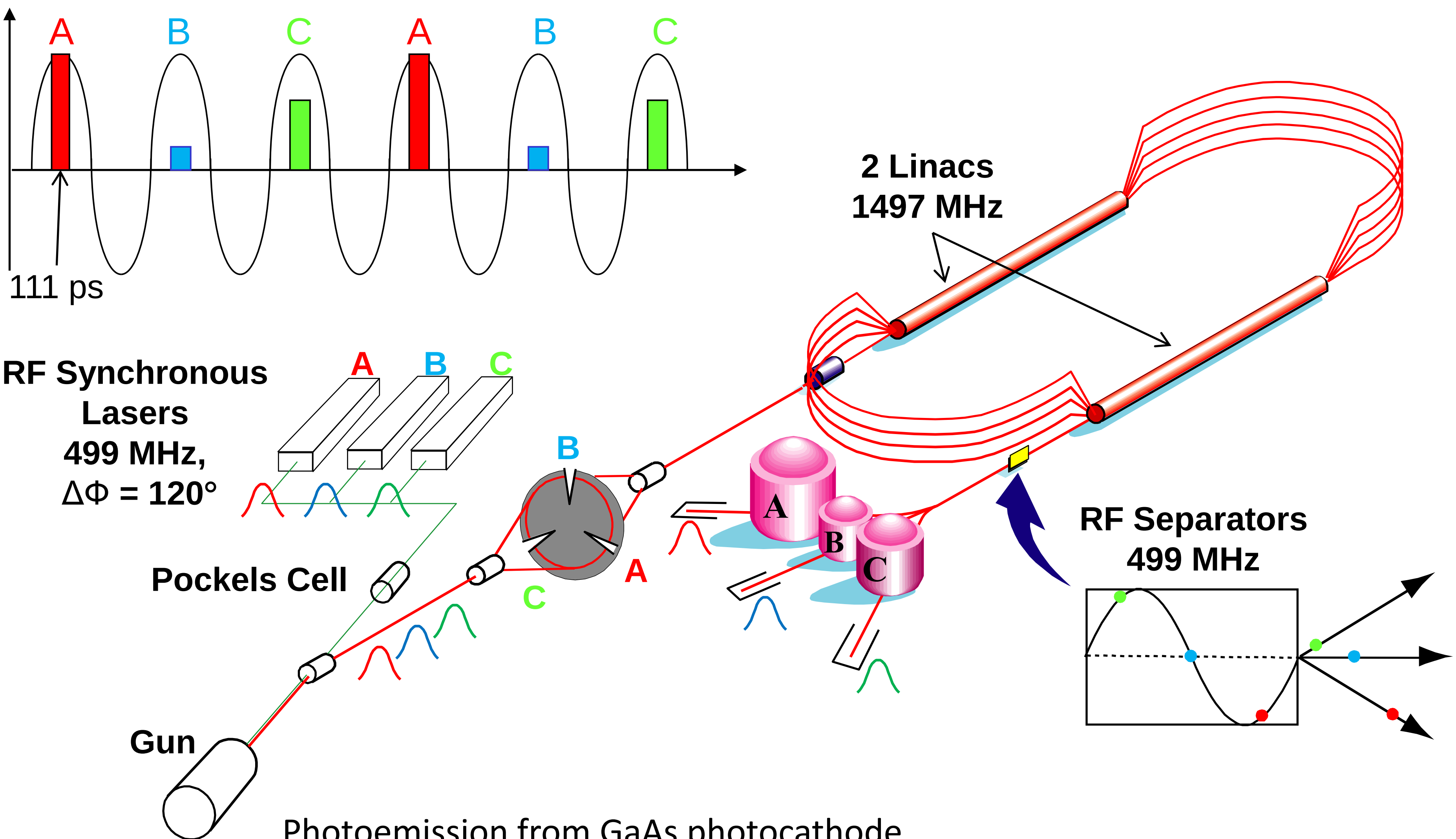


Neutron



Proton

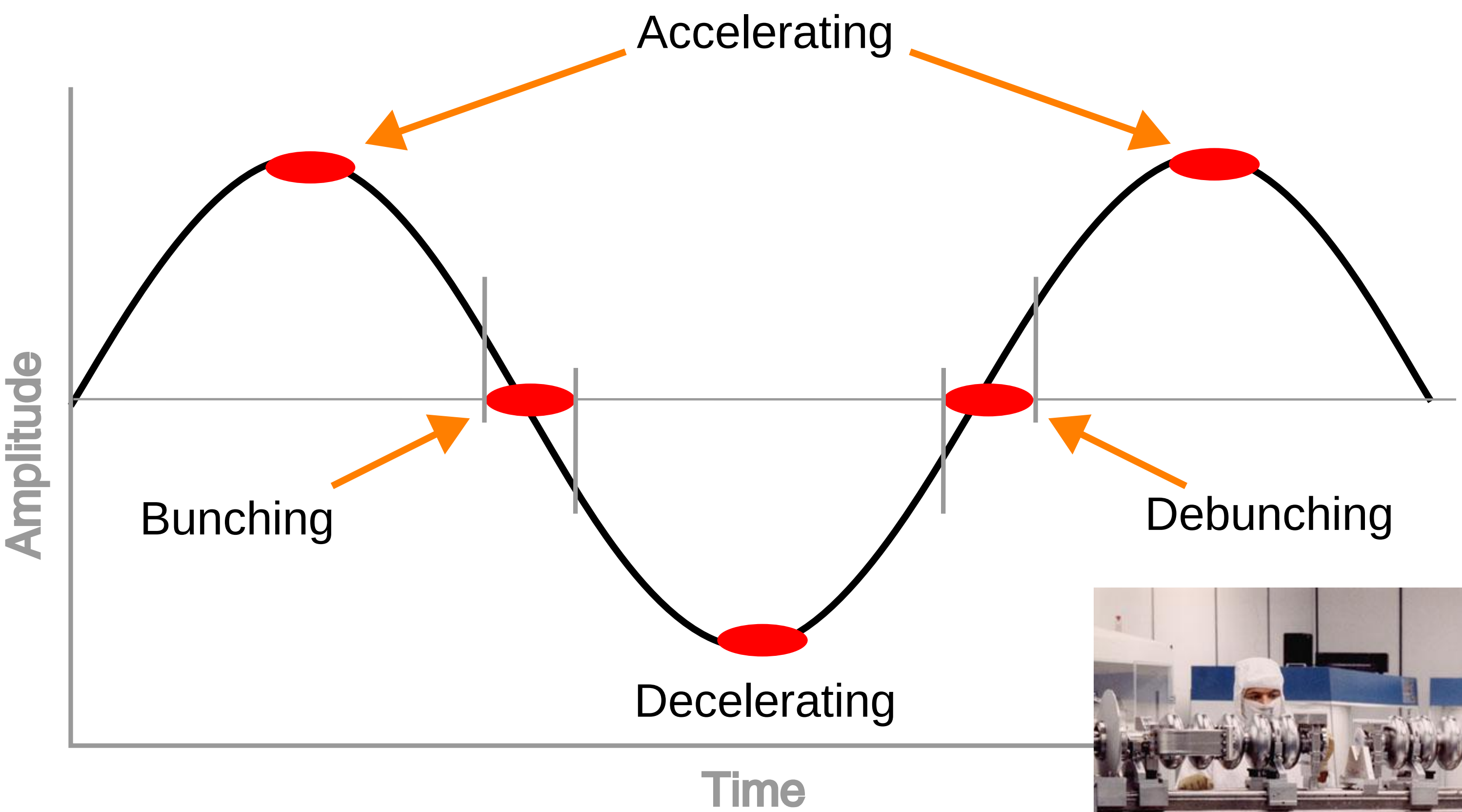
Continuous Electron Beam Accelerator Facility… recall, just a really big microscope



Photoemission from GaAs photocathode

How to make the electrons “powerful” ?

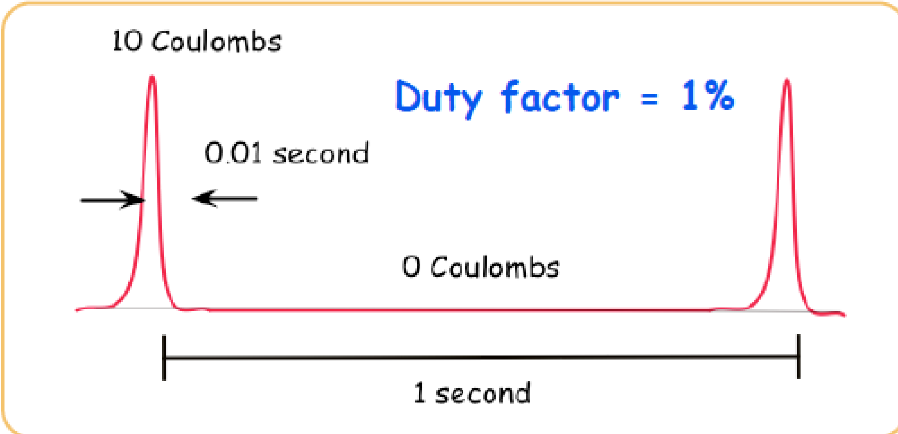
Give them energy using radiofrequency waves !!!



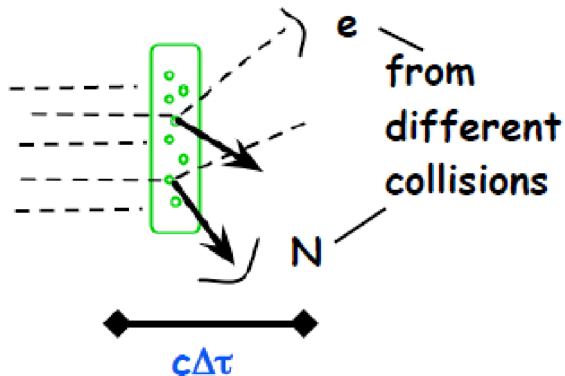
So only a portion of the RF cycle is good for accelerating e-beam

The "C" in CEBAF

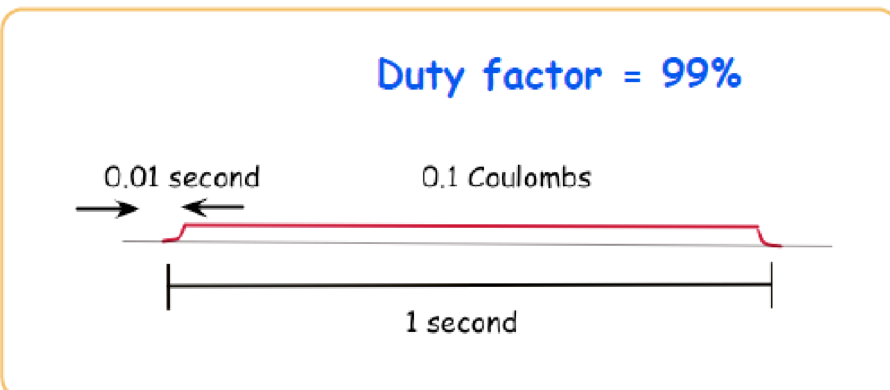
★ Pulsed beams used prior to 1980 (100 mA)



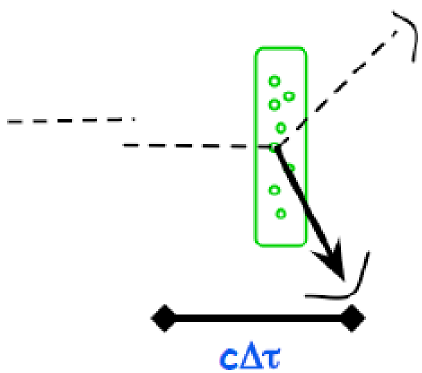
too many electrons in the target over the time interval Δτ
lots of random coincidences



★ Advantages of a continuous beam with the same average current



few electrons in the target --
few random coincidences



No Perfect Electron Source

- Which electron source you choose depends on your accelerator requirements
- Sometimes you can choose between different sources (DC vs RF), sometimes your options are very limited (polarized = photoemission)
- Each source has purported advantages and disadvantages
- Electron source technology is mature, but fortunately many good problems still need be solved

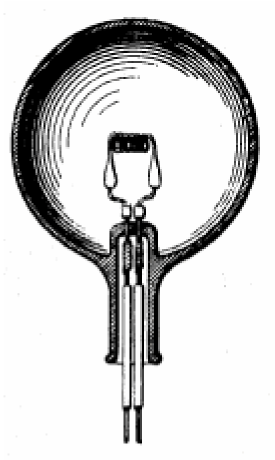
Accelerators Need Electron Beams

How do we make them?

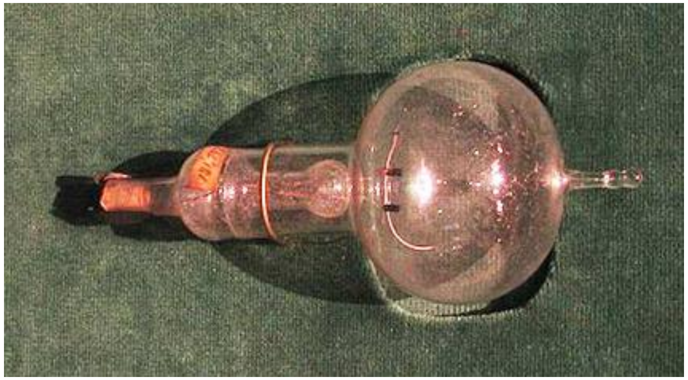
- Field Emission
- Thermionic Emission
- Photoemission
  - Photoionization
- Plasma Source
- Other?

Thermionic Emission

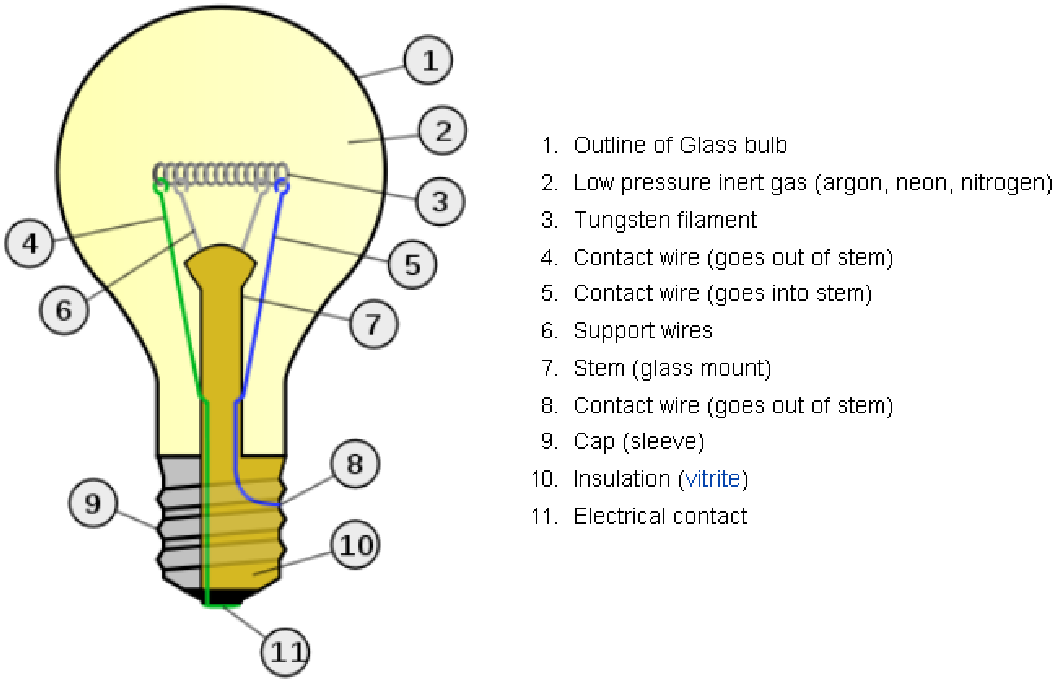
Used to make light….



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



Thermionic Emission

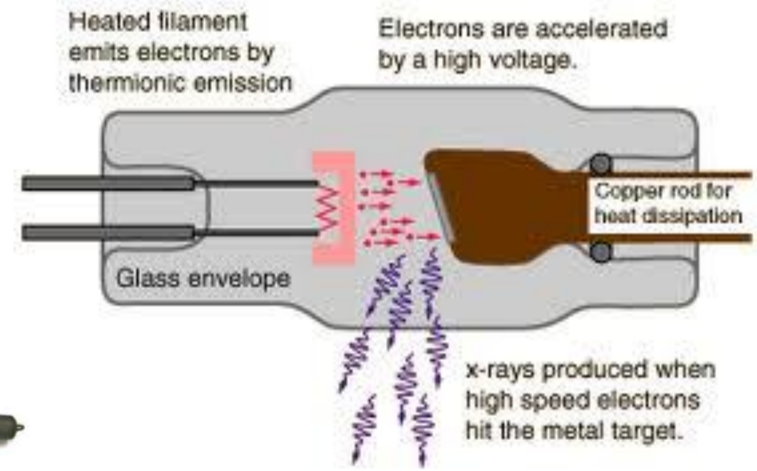
Used to make x-ray light….

bias at high voltage

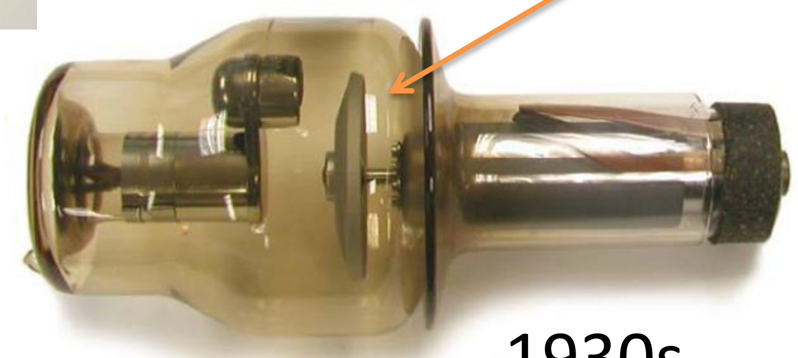
1880s

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



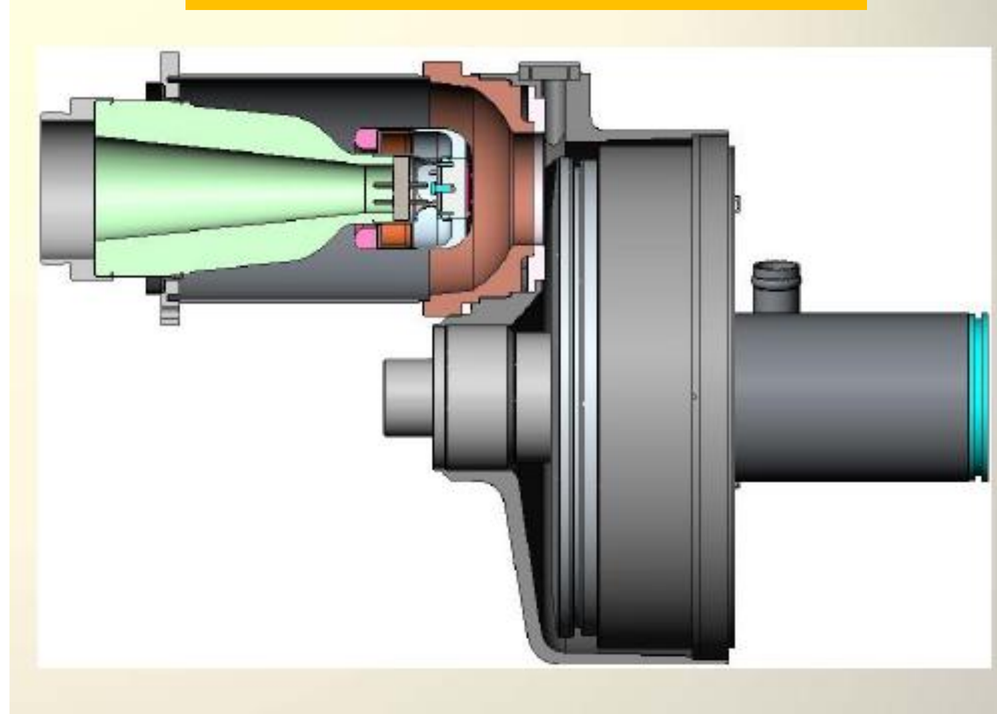
1930s

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

"inverted insulator"…more later

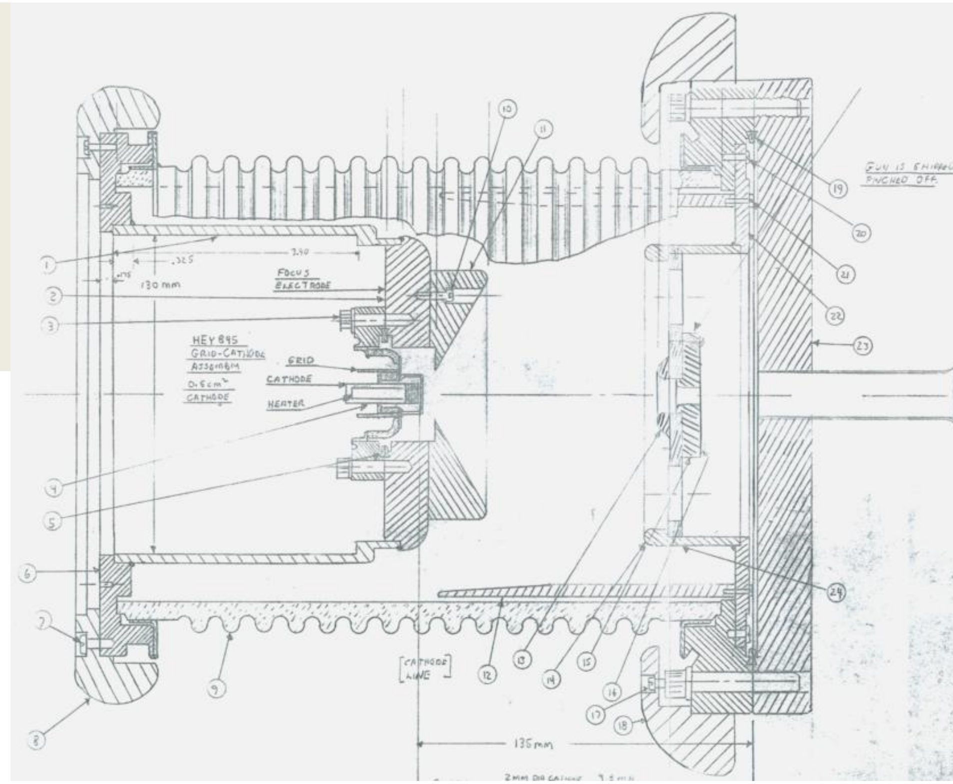


Higher Voltage….
More penetrating
x-ray beam

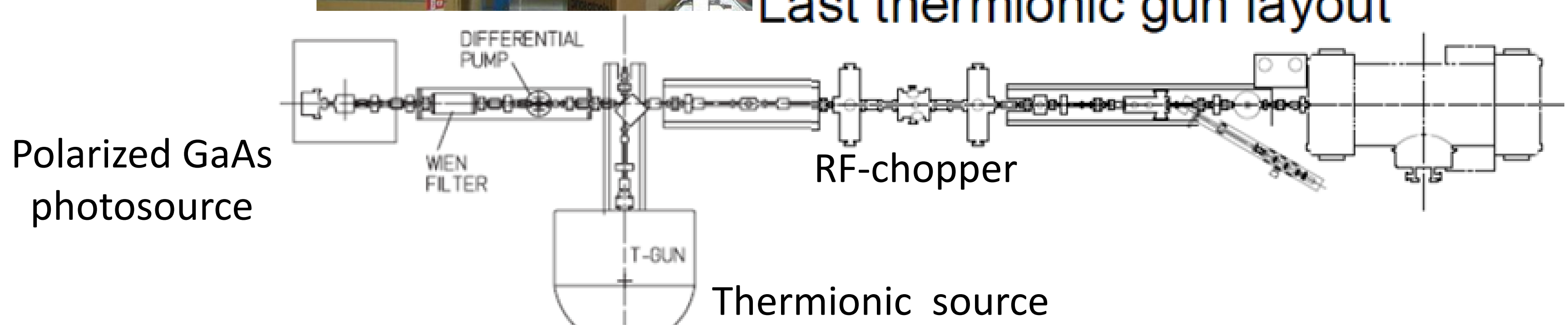
Courtesy Varian

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

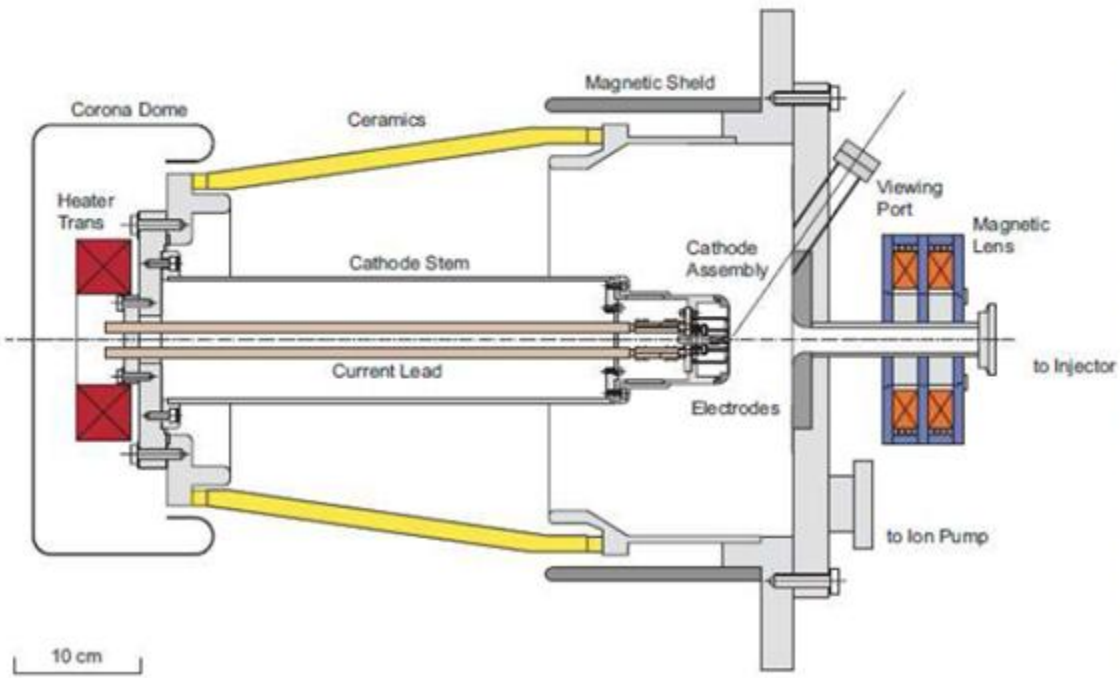


Last thermionic gun layout



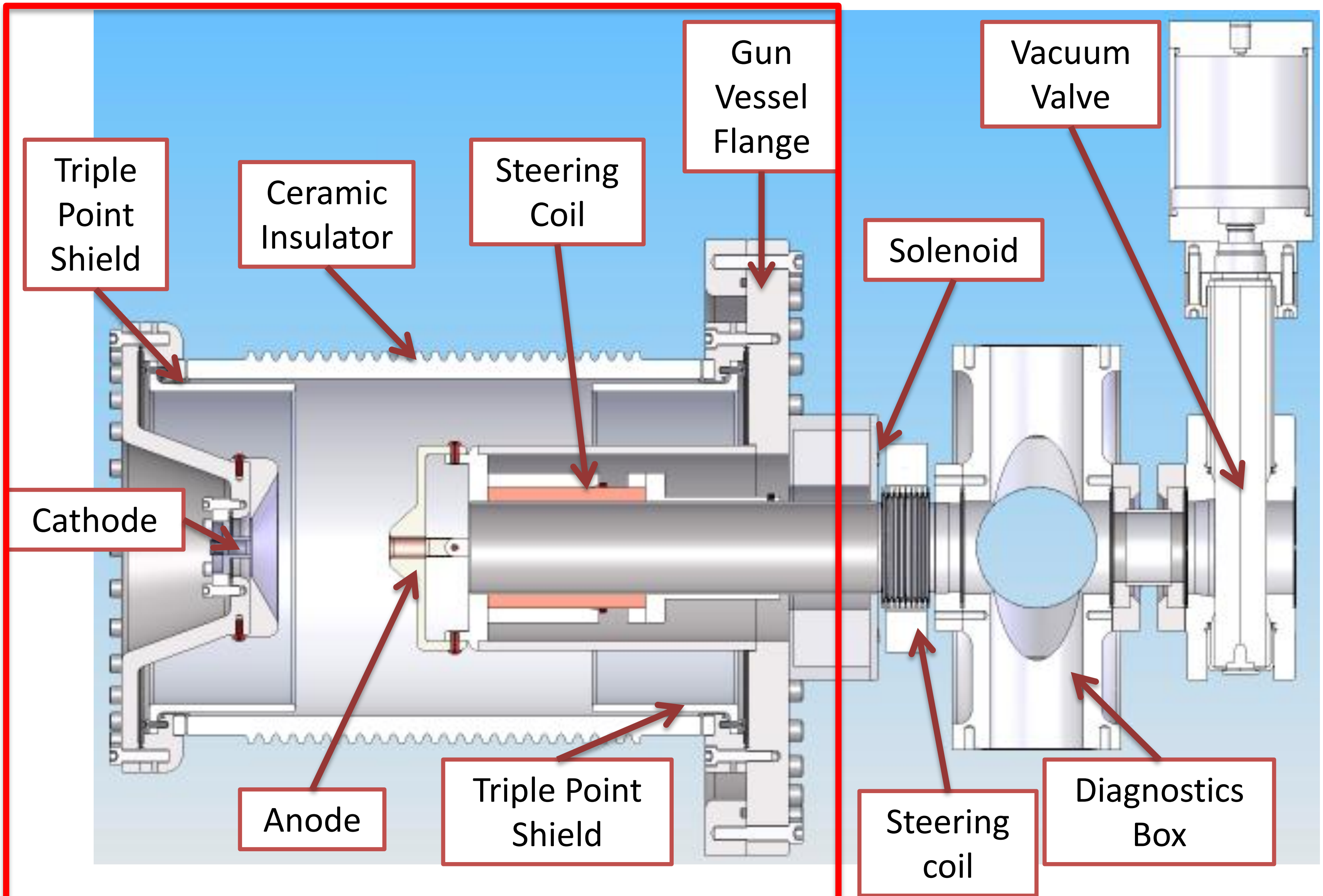
Examples of Thermionic Guns

500kV Electron Gun



Spring 8 SCSS thermionic gun.

TRIUMF 300kV Thermionic Gun

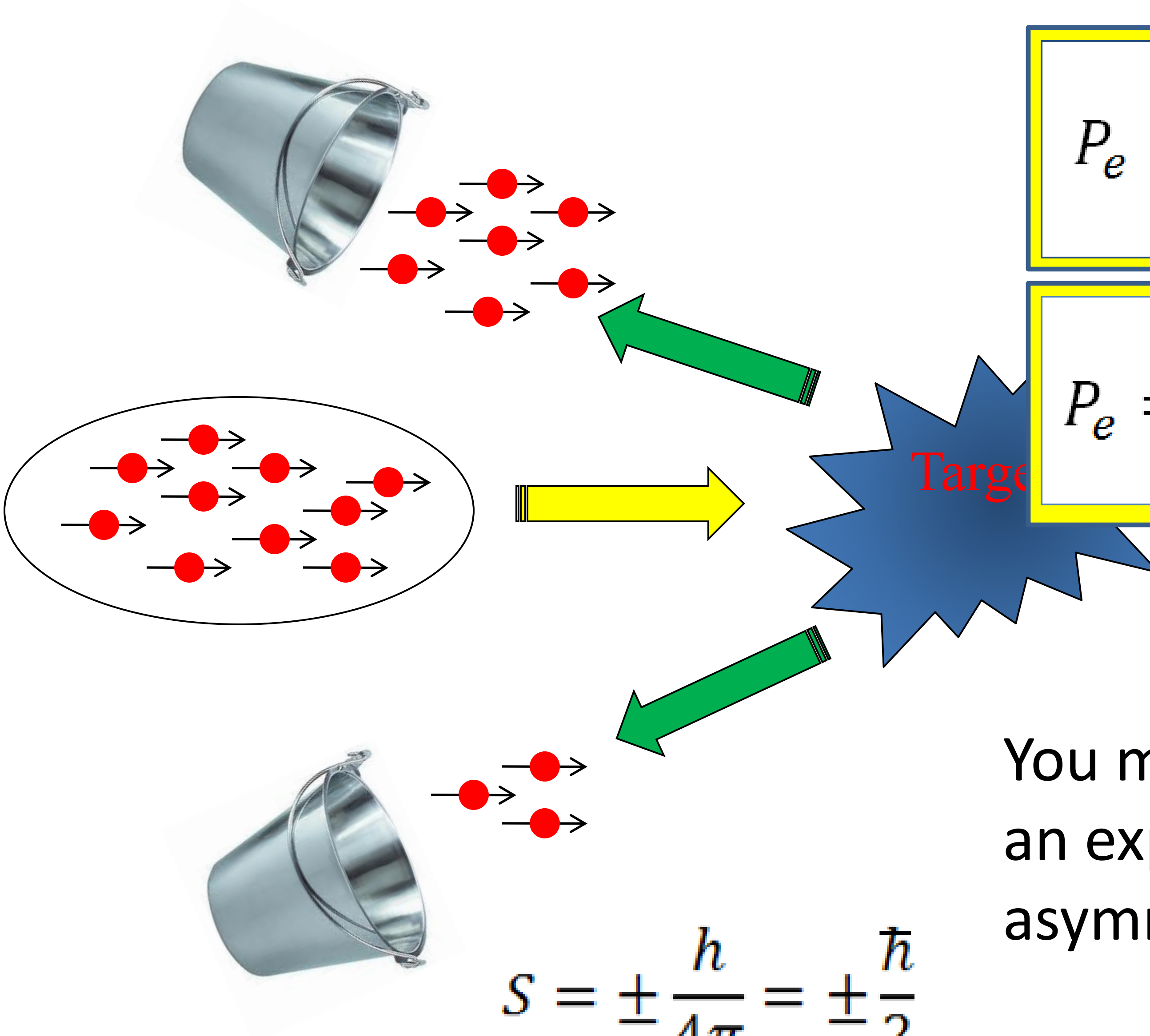


Create RF microstructure by applying modulation to gate

Electron Source Pros and Cons

- CW vs Pulsed, RF vs DC, polarized vs non-polarized
- Thermionic Gun: relatively simple, inexpensive, high up-time, high (DC) current, vacuum not a big issue, large emission region means poor beam quality, might need a "spatial filter", need means to add rf-structure which can be inefficient, bunchers introduce energy spread. No polarization
- Field Emission: bright beam, simple, inexpensive, relatively low current, DC beam, need to add rf-structure, no polarization? Carbon nano-tubes?
- Photoemission: bright beam, RF structure, polarized, vacuum can be demanding, need a laser

Probing with spin tells us something



$$P_e = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

$$P_e = \frac{N_{+} - N_{-}}{N_{+} + N_{-}}$$

You measure
an experimental
asymmetry

$$S = \pm\frac{h}{4\pi} = \pm\frac{\hbar}{2}$$

What Does "Polarized" Mean?

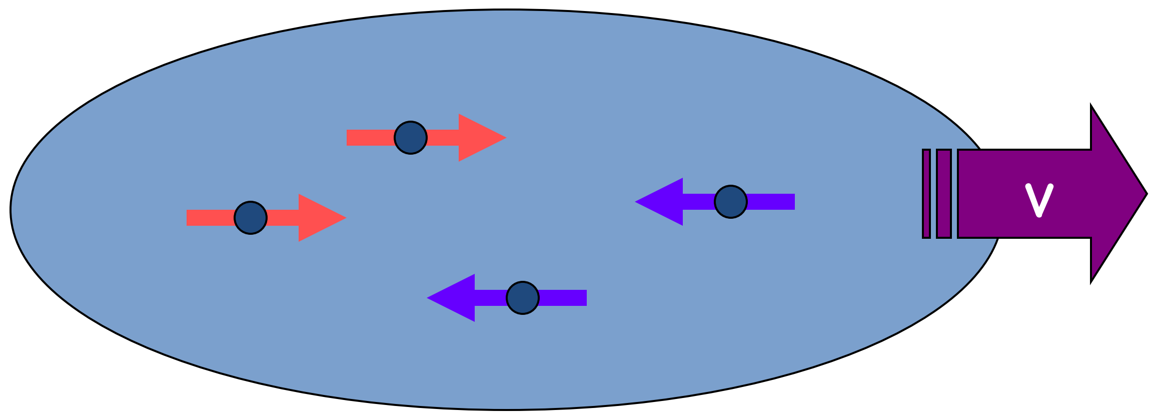
People with very different opinions

Light: a preference for the electric field vector to be oriented a certain way

Electrons: a preference for electrons to spin in one direction

0% Polarization

☹

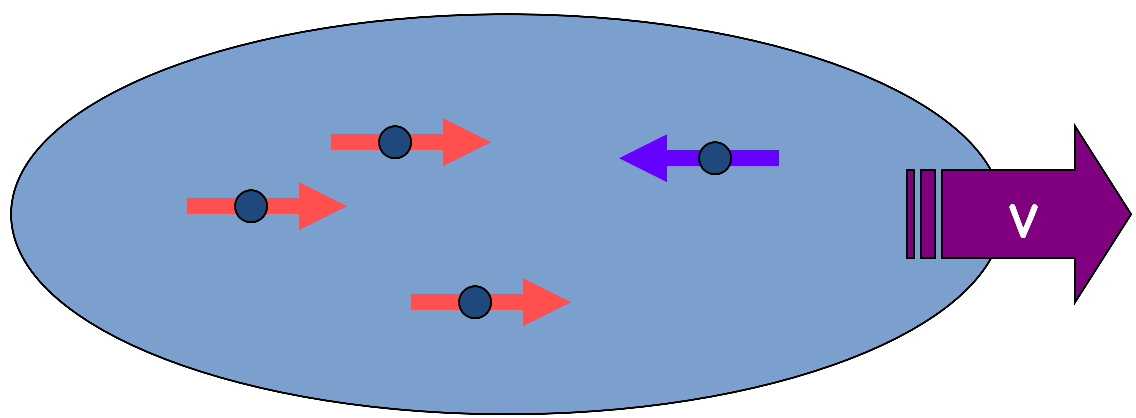


$$P_e = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Getting all the spins to point in the same direction…that's the hard part

50% Polarization

☺



Polarized Source Landscape 1970s

Self-polarization via Sokolov-Ternov Effect

Electron Scattering (Mott)

Photoinonization: Fano Effect

Photoionization of State Selected alkali atoms

Optically Pumped He Discharge

Field Emission from EuS

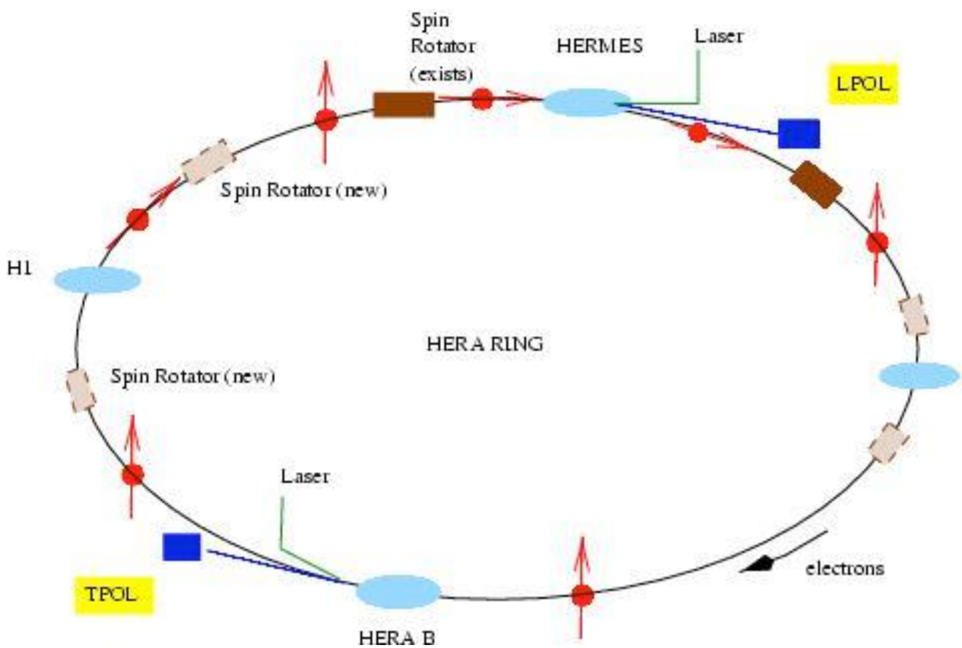
Photoemission from GaAs

Sokolov-Ternov Effect

- Electrons (and positrons) in storage rings self-polarize due to spin-flip synchrotron radiation: there's a slightly higher preference for one spin state direction than the other
- Process is slow, need storage lifetime to be longer than self-polarization time
- Polarization is out of plane
  - VEPP-2 Ring at Budker Institute, Novosibirsk, Russia first observation 1971
  - DESY Hamburg, Germany

Sokolov-Ternov Effect

- Need Siberian Snakes to create longitudinal polarization
- Depolarizing resonances make life complicated
- Happy to end up with ~ 70% polarization



$$P_{ST} = \frac{\omega_{\uparrow\downarrow} - \omega_{\downarrow\uparrow}}{\omega_{\uparrow\downarrow} + \omega_{\downarrow\uparrow}} = \frac{8}{5\sqrt{3}} \approx 92.4\%$$

$$P_Y(t) = -P_{ST}(1 - e^{-t/\tau_{ST}})$$

$$\tau_{ST} = \frac{1}{\omega_{\uparrow\downarrow} + \omega_{\downarrow\uparrow}} = \frac{8\rho^3}{5\sqrt{3}c\lambda_c r_0 \gamma^5}$$

~ 1 hour at HERA

reference

What if you need a Direct Source of Polarized Electrons?

TABLE III. Comparison of some sources of spin-polarized electrons.

Method	Ref.	$\|P\|$	Reversal of $\vec{P}$	I_{dc} (A)	I_{pulse}	E (eV)	ΔE (eV)	H (kOe)	Emittance	Brightness
1. Photoemission from NEA GaAs	3	0.40	$\Delta\vec{L}$	10^{-6} [10^{-3}]	[10^{12} electrons/ 1.5 μsec]	0.2	0.2	0	2 mrad-cm at 1 eV	very high
2. Photoemission from EuO	27	0.61 [0.80]	$\Delta\vec{H}$	10^{-6}	3×10^{9} electrons/ 1.5 μsec	2	2	21 [30]		medium
3. Photoionization of polarized Li atomic beam	53	0.76	$\Delta\vec{H}$		3×10^{9} electrons/ 1.5 μsec		1500	0.2	7 mrad-cm at 70 keV	medium
4. Fano effect, photoionization of Cs atoms	55	0.90	$\Delta\vec{L}$		3×10^{9} electrons/ 0.5 μsec		500	0	0.6 mrad-cm at 115 keV	high
5. Optically pumped He discharge	56	0.30	$\Delta\vec{L}$	10^{-6}		500 [30]	0.5	0	10 mrad-cm at 500 eV	high
6. Field emission (EuS)	57	0.89	$\Delta\vec{H}$	[10^{-6}]			0.1	2–20		very high
7. Electron scattering from Hg atomic beam	58	0.27	$\Delta\theta$	2×10^{-8}		7	0.2	0		medium
8. Electron scattering from W	62	0.40	$\Delta\theta, \Delta E$	5×10^{-8} [10^{-4}]		80	0.2	0		high

Table comes from this paper….

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)

But first, more History Review….jeez!

By 1927: People like Uhlenbeck, Goudsmit, Bohr, Dirac, and others explore the notion of electron spin, and people start to accept the idea….

1929: Mott wonders if we can observe electron spin directly? Stern-Gerlach experiment? Proposes scattering electrons from nuclei, observing scattering asymmetry due to electron spin-orbit coupling

1942: Schull verifies Mott's predictions… yes, electron spin is real

>1950's Emphasis shifts away from verifying electron spin to the production of spin-polarized beams, as a physics tool

Mott Scattering

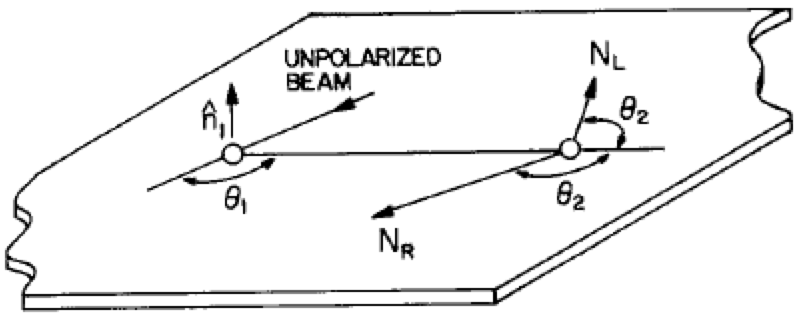
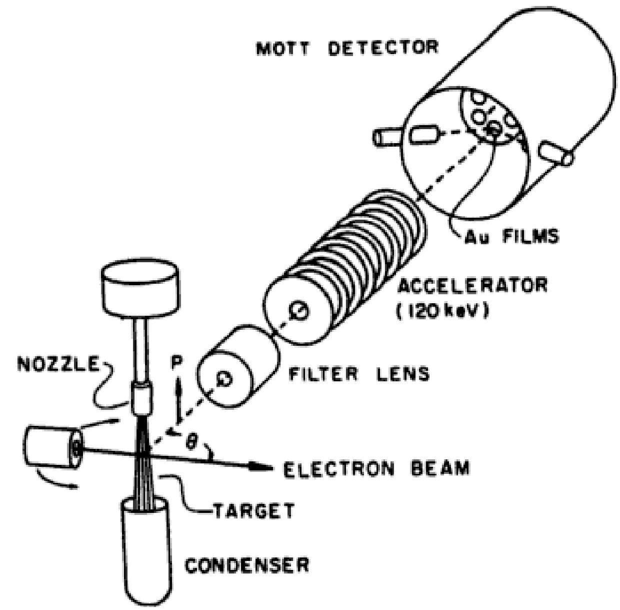


FIG. 1. Schematic diagram of a double-scattering experiment.

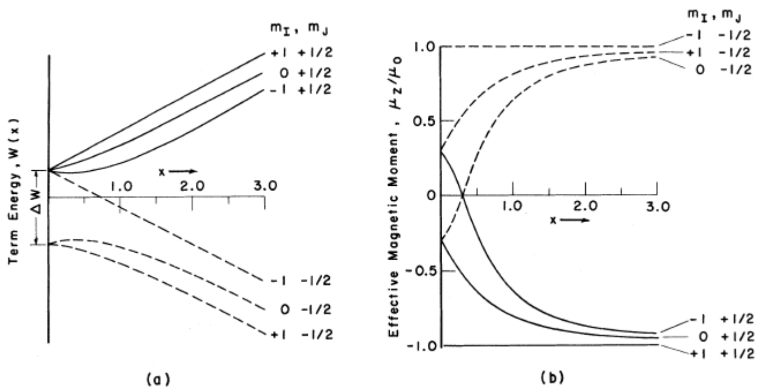
- Spin-orbit coupling introduces a scattering asymmetry
- First scattering event makes the polarized beam, second scattering event used to measure polarization
- Degree of polarization depends on Sherman Function
- Not much beam current (or polarization)
- Mostly used for polarimetry (more later)



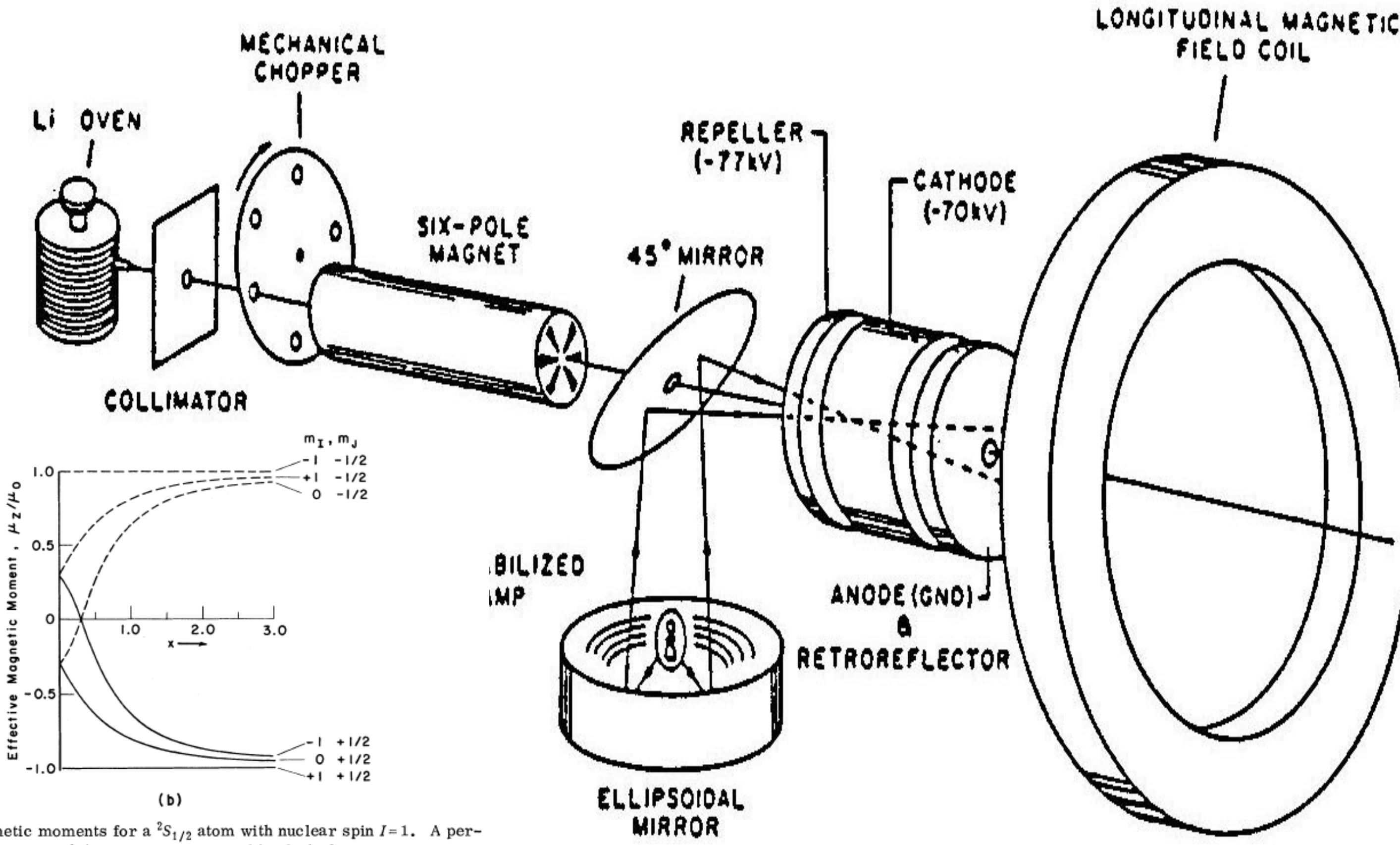
$$\frac{N_l - N_r}{N_l + N_r} = S(\theta, E_0)S(120°,\ 120\ \text{keV})$$

From the book “Polarized Electrons” by J. Kessler Springer Verlag, 1st ed. 1976

Photoionization



Breit-Rabi diagram and plot of the effective magnetic moments for a $^2S_{1/2}$ atom with nuclear spin $I=1$. A perfect high-field state separation leads to the elimination of the terms represented by dashed curves.



Yale Photoionization Source “PEGGY”
“State selected” Li^6 atoms

NUCLEAR INSTRUMENTS AND METHODS 163 (1979) 29-59 ; © NORTH-HOLLAND PUBLISHING CO.

Yale Li^6 Photoionization Source

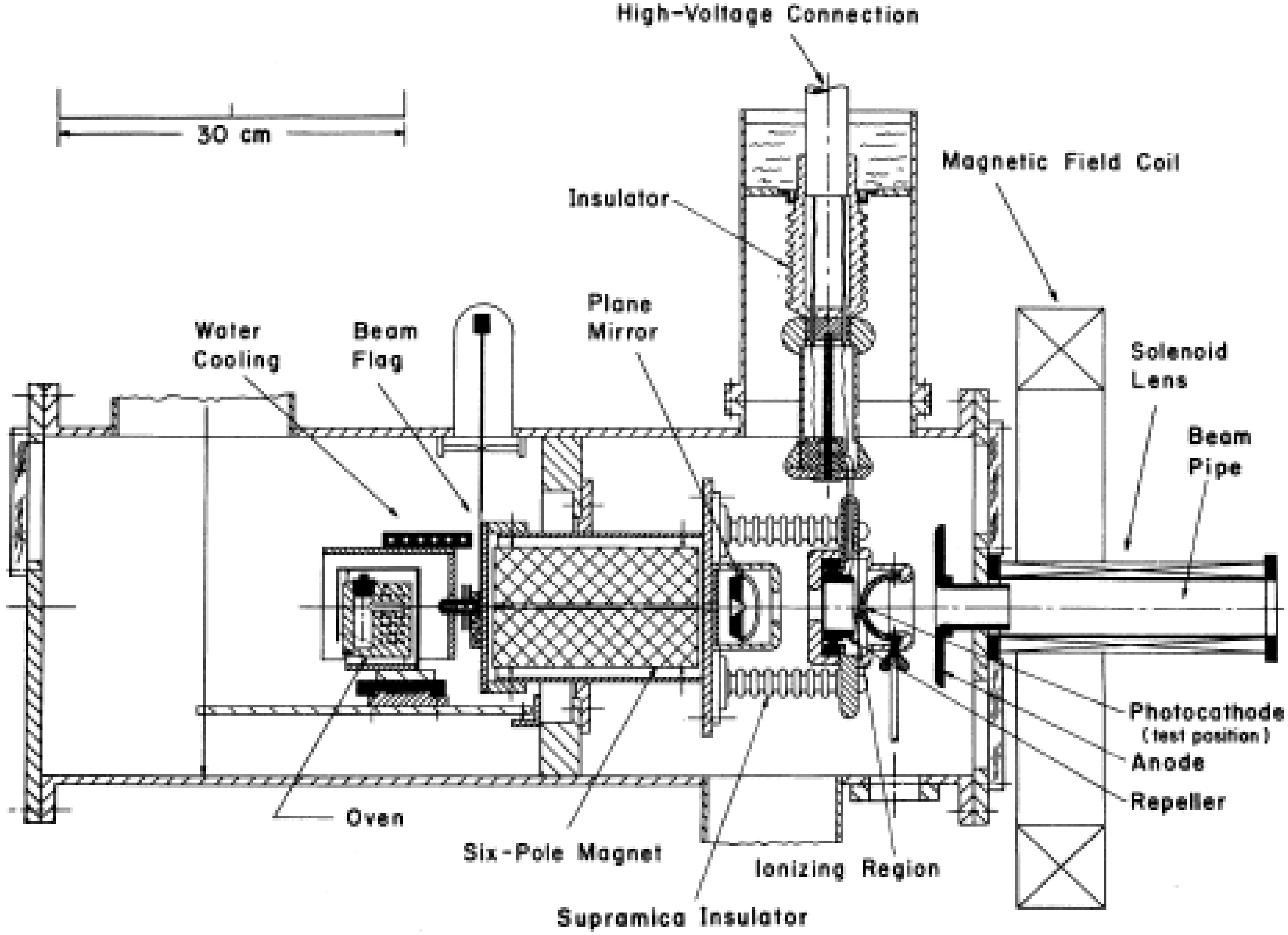
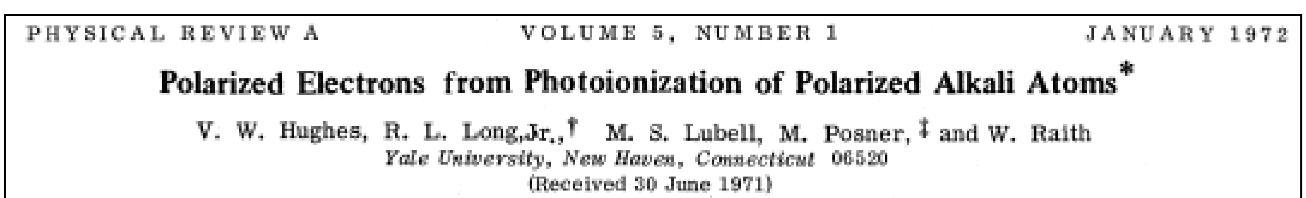


FIG. 18. Scale drawing of the polarized electron source assembly.



PHYSICAL REVIEW A VOLUME 5, NUMBER 1 JANUARY 1972

Polarized Electrons from Photoionization of Polarized Alkali Atoms*

V. W. Hughes, R. L. Long, Jr.,† M. S. Lubell, M. Posner,‡ and W. Raith
Yale University, New Haven, Connecticut 06520
(Received 30 June 1971)

Yale Li^6 Photoionization Source at SLAC

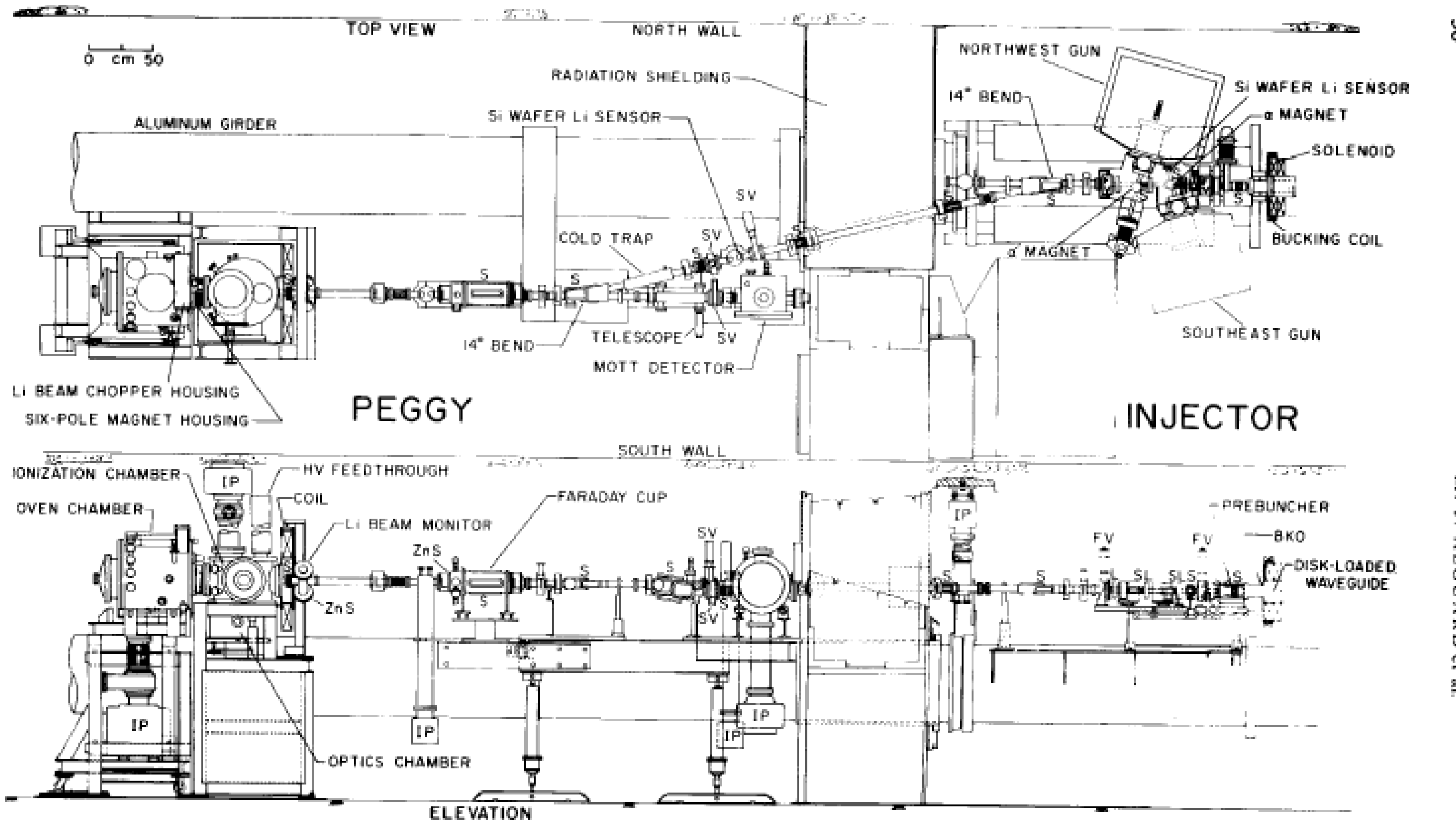


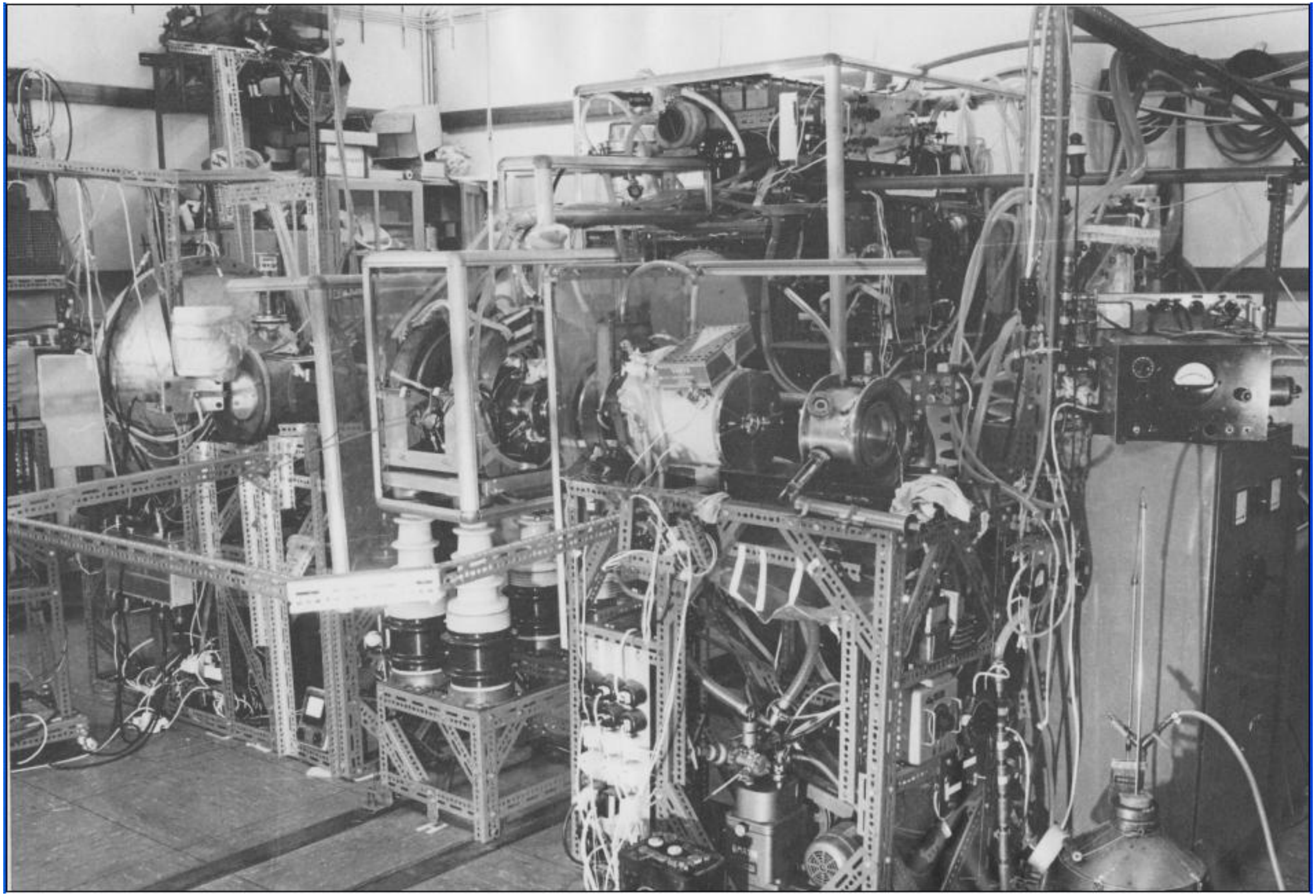
Fig. 9. Scale drawing of PEGGY showing a top view and an elevation. The parallel offset of the PEGGY beam line from the injector beam line can be seen in the top view. Abbreviations which have been used are as follows: BKO, beam knock out for changing pulse duration and separation; FV, fast valve; IP, ion pump; L, magnetic lens; S, magnetic steering; SV, slow valve; T, toroid beam current monitor; and ZnS, zinc sulfide screen for visual monitoring of the beam.

NUCLEAR INSTRUMENTS AND METHODS 163 (1979) 29-59 ; © NORTH-HOLLAND PUBLISHING CO.

A SOURCE OF HIGHLY POLARIZED ELECTRONS AT THE STANFORD LINEAR ACCELERATOR CENTER*

Alguard, Clendenin, Hughes, et. al.,

Bonn Li^6 Photoionization source



Courtesy Dr. Walther v. Drachenfels, Bonn University

Fano-Effect

Ionization cross section using circularly polarized light at the right wavelength can be very different for two spin states of atom

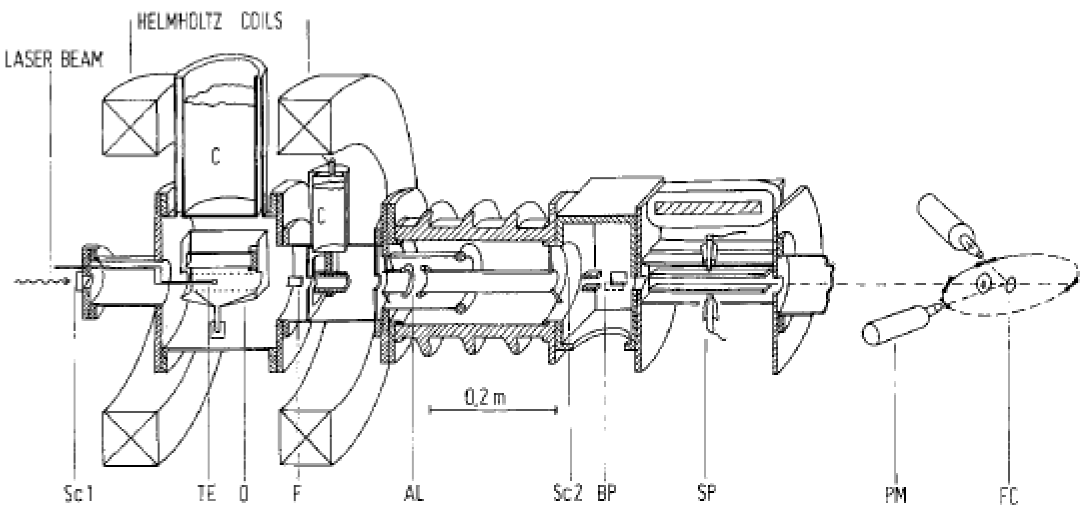
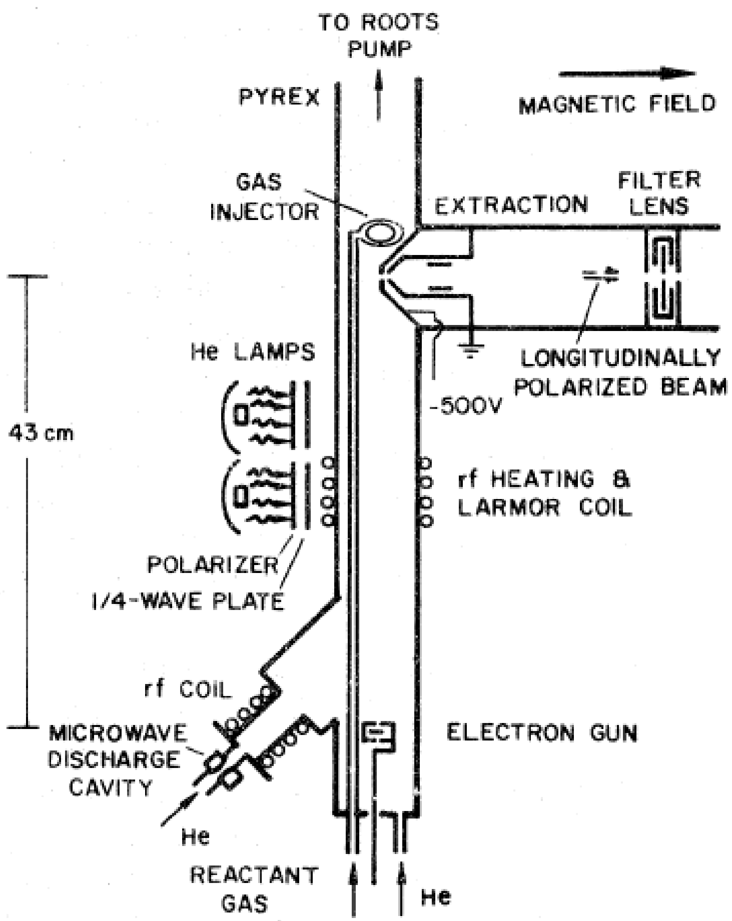


Fig. 3. Longitudinal section of electron source and polarization analyzer. *O* oven system, *F* Faraday cup, *AL* accelerating lens, *SP* spin precessor (Wien filter), *FC* foil carrier (details are not shown), *PM* photo-multipliers, *TE* test electron source, *BP* beam steering plates, Sc_1 and Sc_2 positions of scintillators for laser beam adjustment, *C* cold traps

Bonn Cs Fano-effect Source, ~ 1974

NUCLEAR INSTRUMENTS AND METHODS 140 (1977) 47–55;

Optically Pumped Helium Afterglow



$$He(2^3S_1)\uparrow\uparrow + CO_2\uparrow\downarrow \rightarrow He(1^1S_0)\uparrow\downarrow + CO_2^{+}\uparrow + e^{-}\uparrow$$

Step1: Create metastable He using rf discharge, put electrons in 2^3S state

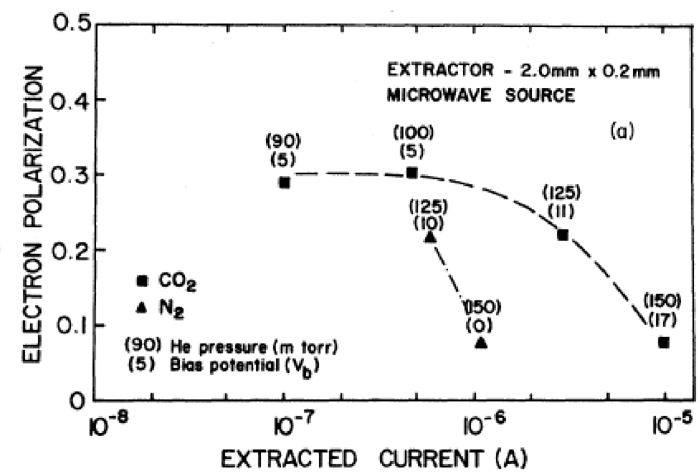
Step2: Optically pump to populate just one of the 2^3S levels: 100% electron spin polarization

Step3: Combine with CO2, chemi-ionization liberates a polarized electron

PHYSICAL REVIEW A VOLUME 11, NUMBER 4 APRIL 1975

Intense polarized electron beams from chemi-ionization reactions with optically pumped $He(2\,^3S)$†

P. J. Keliher,* R. E. Gleason, and G. K. Walters
Department of Physics, Rice University, Houston, Texas 77001
(Received 9 December 1974)

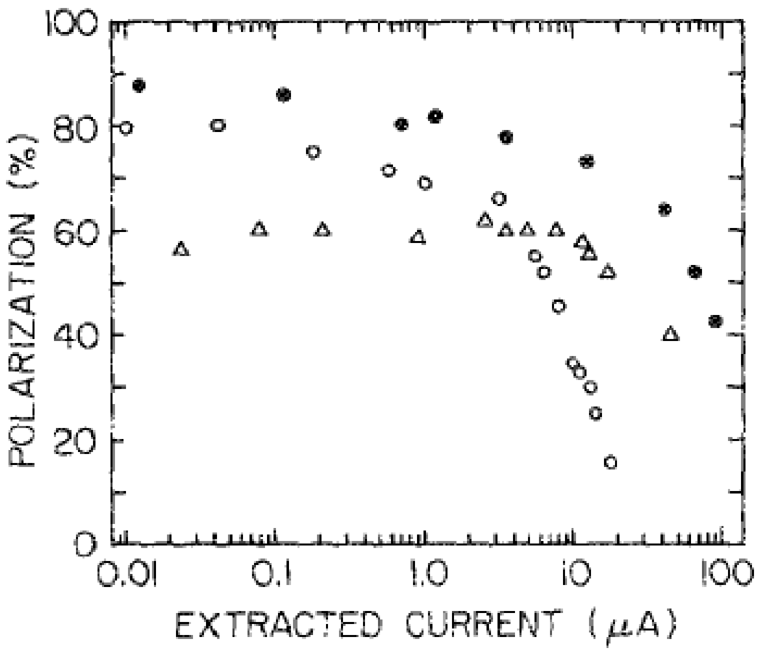


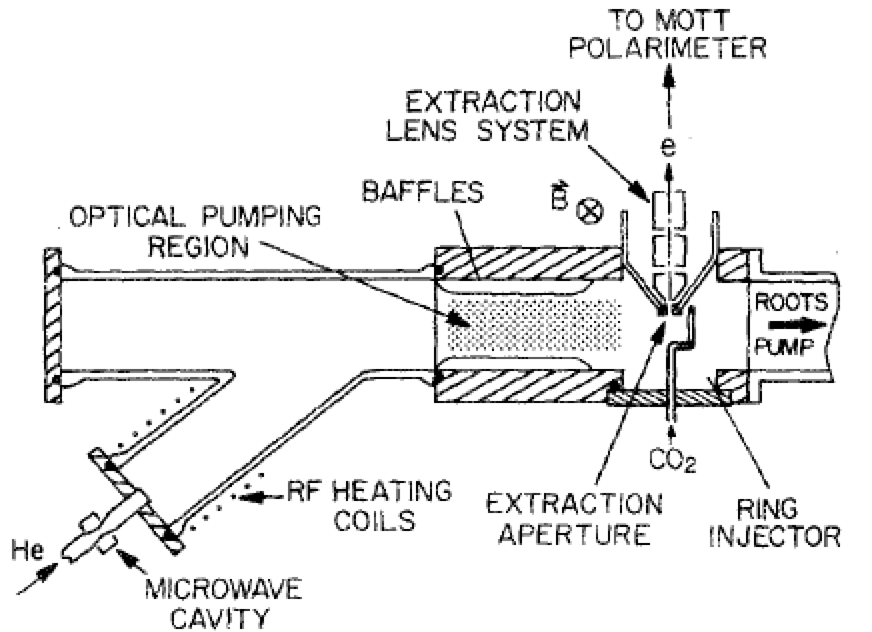
Optically Pumped Helium Afterglow

Improved source of polarized electrons based on a flowing helium afterglow

G. H. Rutherford, J. M. Ratliff, J. G. Lynn, F. B. Dunning, and G. K. Walters
Department of Physics and the Rice Quantum Institute, Rice University, Houston, Texas 77251

(Received 27 December 1989; accepted for publication 15 January 1990)





$$He(2^3S_1)\uparrow\uparrow + CO_2\uparrow\downarrow \rightarrow He(1^1S_0)\uparrow\downarrow + CO_2^{+}\uparrow + e^{-}\uparrow$$

Rice Helium Afterglow Source, ~ 1990

Optically Pumped Helium Afterglow

Nuclear Instruments and Methods in Physics Research A 337 (1993) 1–2
North-Holland

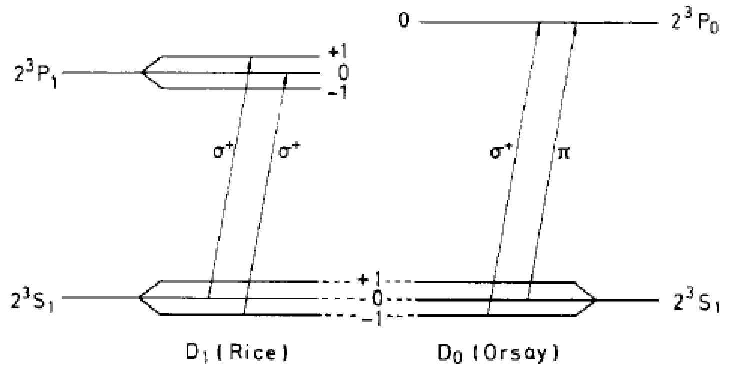


Fig. 2. Helium optical pumping process via D_0 and D_1 transitions.

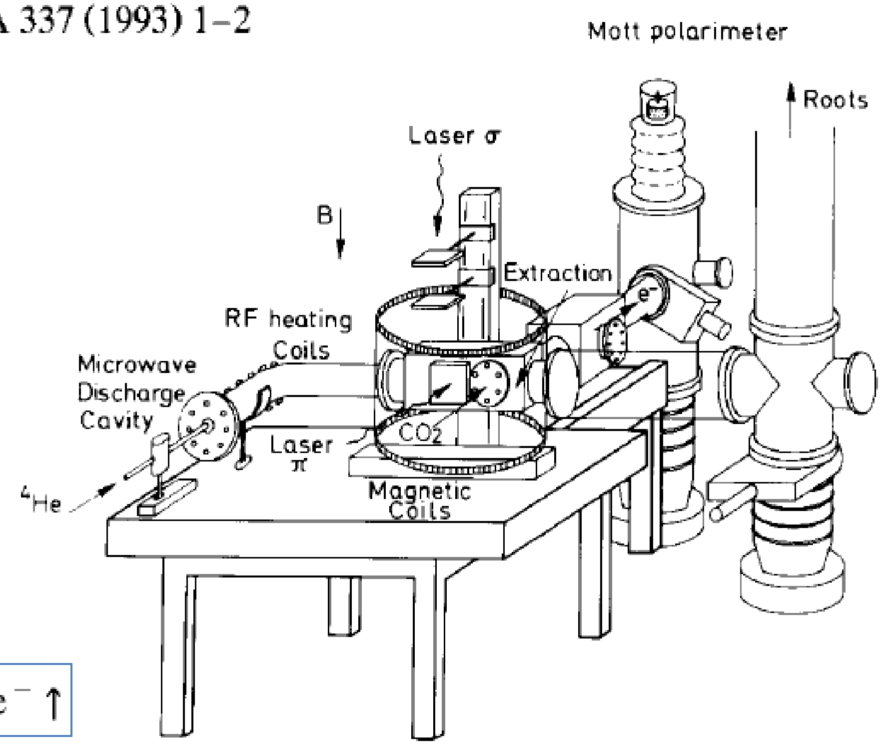


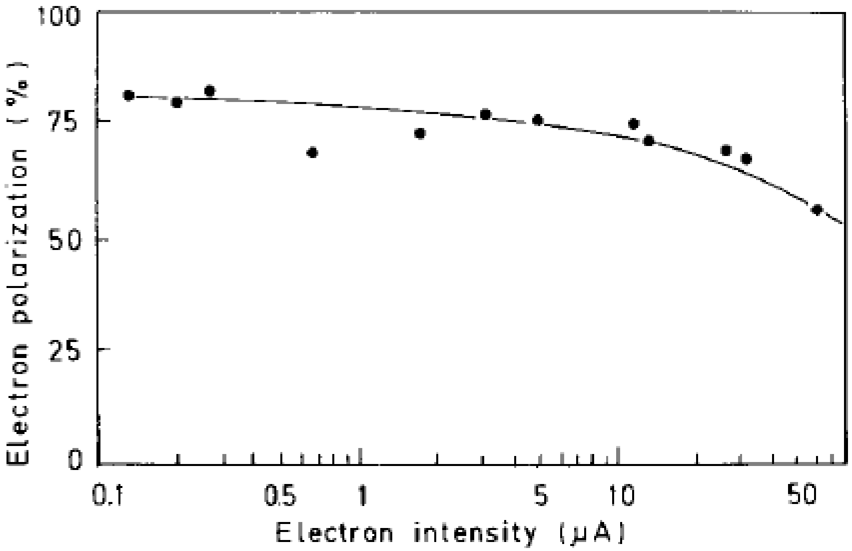
Fig. 1. Diagram of the Orsay source.

$$\mathrm{He}(2^3\mathrm{S})\uparrow\uparrow + \mathrm{CO_2} \rightarrow \mathrm{He}(1^1\mathrm{S})\uparrow\downarrow + \mathrm{CO_2^+}\uparrow + e^-\uparrow$$

Step1: Create metastable He using rf discharge, electrons in 2^3S state
Step2: Optically pump to populate just one of the 2^3S levels: 100% polarization
Step3: Combine with CO2, chemi-ionization liberates polarized electron

Orsay Helium Afterglow Source

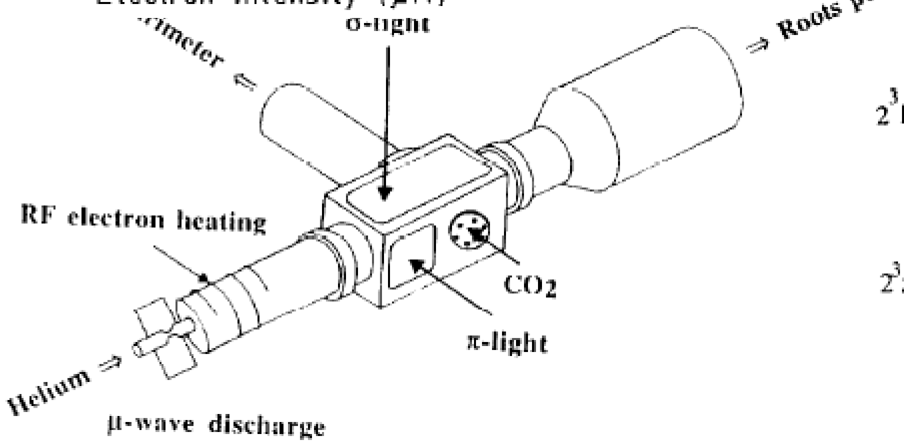
Optically Pumped Helium Afterglow



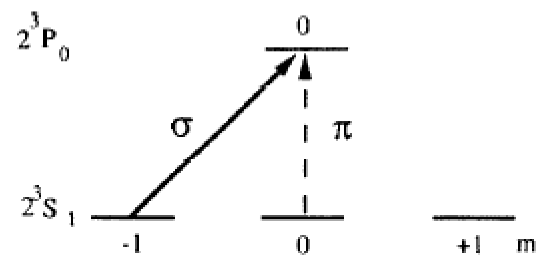
DEVELOPMENT OF A POLARIZED ELECTRON SOURCE BASED ON HELIUM AFTERGLOW.

J. Arianer, S. Cohen, S. Essabaa, R. Frascaria and O. Zerhouni
Institut de Physique Nucleaire, 91406 Orsay Cedex, France

$$He(2^3S_1)\uparrow\uparrow+\bar{CO}_2\uparrow\downarrow\rightarrow He(1^1S_0)\uparrow\downarrow+CO_2^+\uparrow+e^-\uparrow \quad (1)$$



(a)

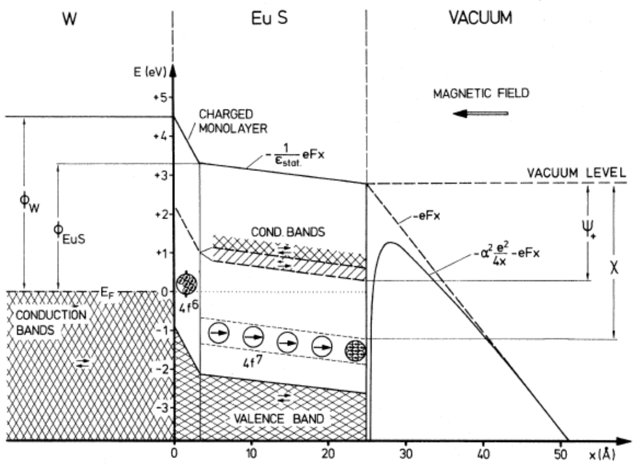


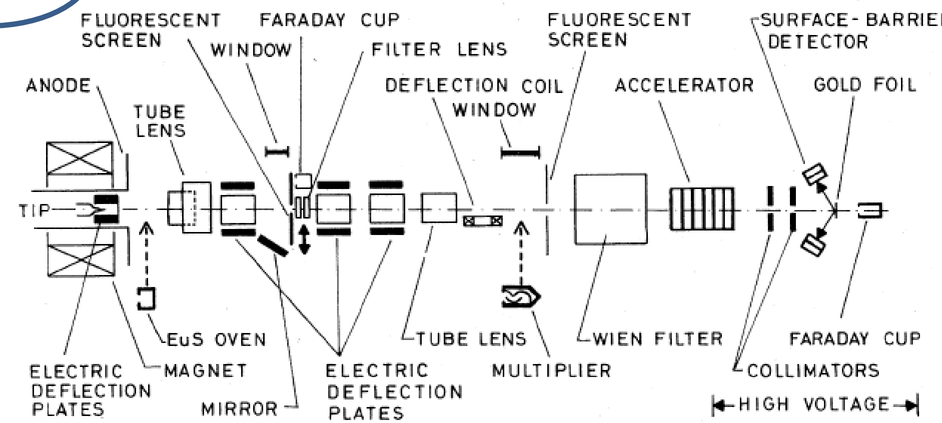
(b)

Orsay Helium Afterglow Source, 1990s

Spin Polarized Field Emission

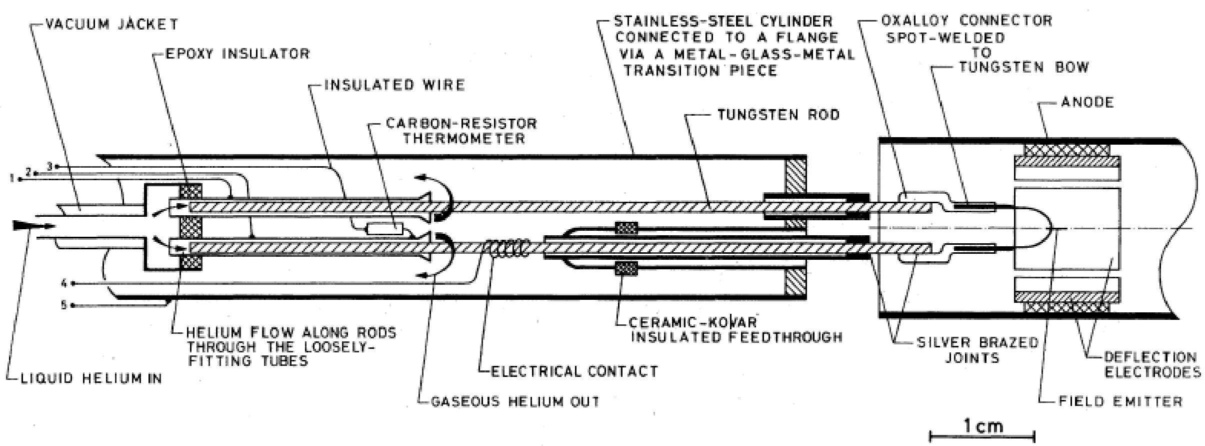
Volume 29, Number 25 PHYSICAL REVIEW LETTERS 18 December 1972





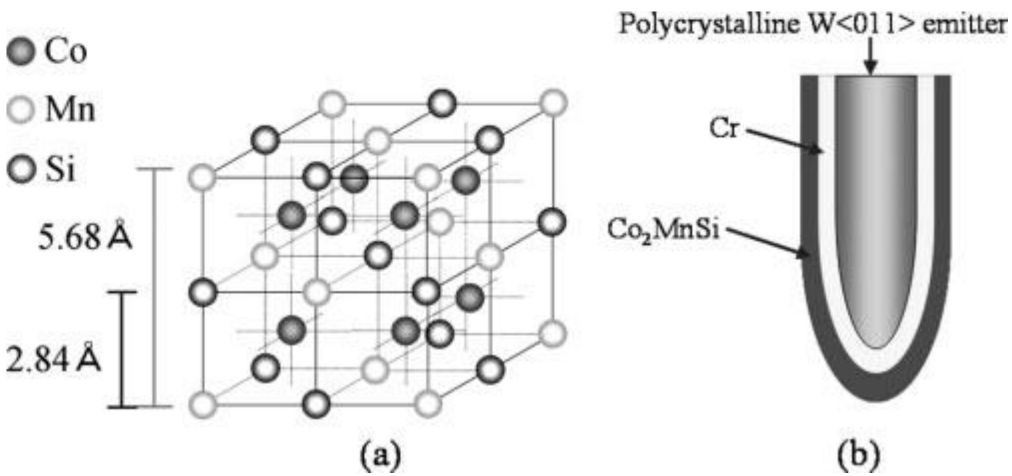
The EuS film acts like a spin filter

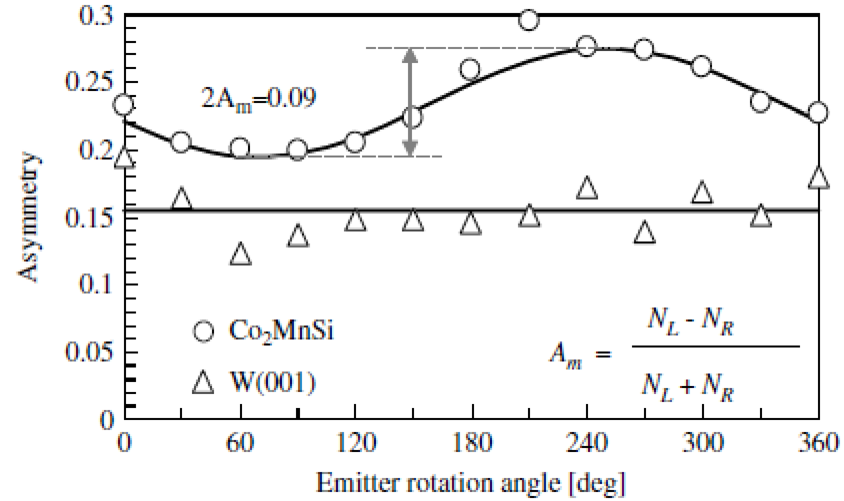
2258 KISKER, BAUM, MAHAN, RAITH, AND REIHL 18

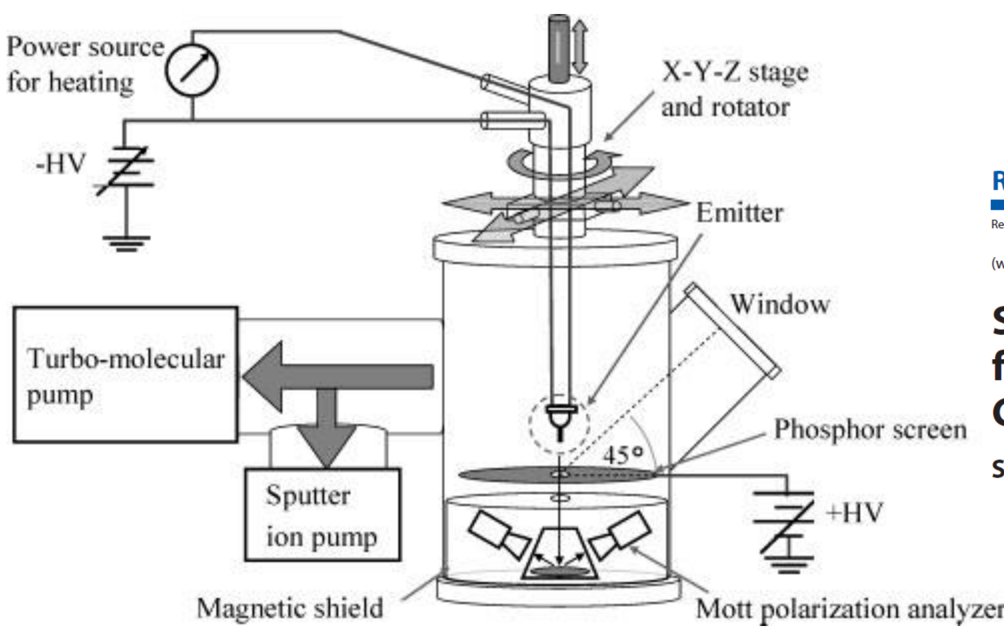


Strong magnetic field and cryogenic temps

Spin Polarized Field Emission







Research Article

SURFACE and INTERFACE ANALYSIS

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Spin polarization of field-emitted electrons from ferromagnetic half-metallic Heusler alloy Co_2MnSi

Shigekazu Nagai,*,† Yuji Fujiwara and Koichi Hata

2007

What are the Problems with these Sources?

- For some of these sources, tough to flip the sign of the polarization fast, time scale < 1 second (very important for nuclear physics experiments)
- It would be nice to make RF-time structure directly, instead of DC beam
- Most accelerators require reasonably small emittance
- Lots of overhead: lasers, pounds of alkali metal, hot and cold things very near each other, strong magnetic fields, low and high voltage, vacuum issues
- Long term reliability can be an issue (24/7 ops)
- Reproducibility: getting the same result twice

GaAs….the method that caught on

PHYSICAL REVIEW B VOLUME 13, NUMBER 12 15 JUNE 1976

Photoemission of spin-polarized electrons from GaAs

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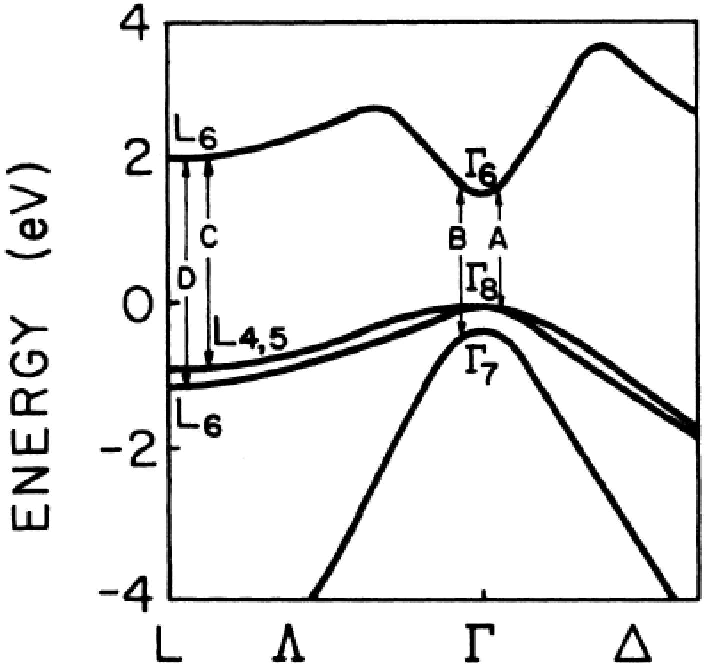
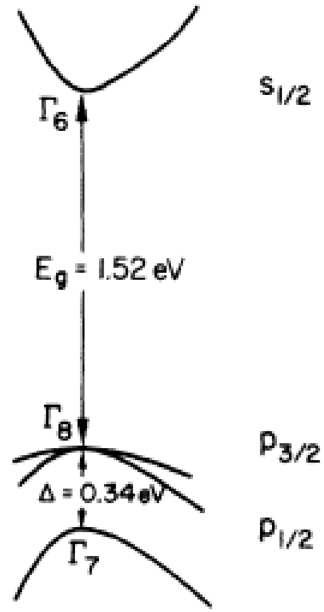
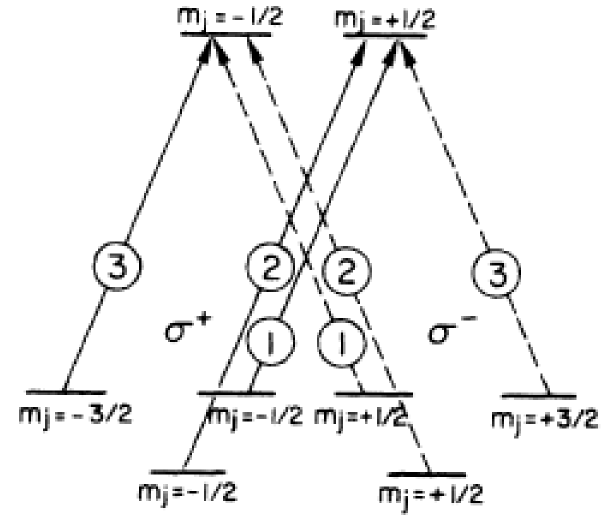
(Received 10 February 1976)

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.

GaAs Energy Levels







$$P_e = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Use light to selectively populate the conduction band with electrons of a particular spin state

Photoemission: a three step process

old

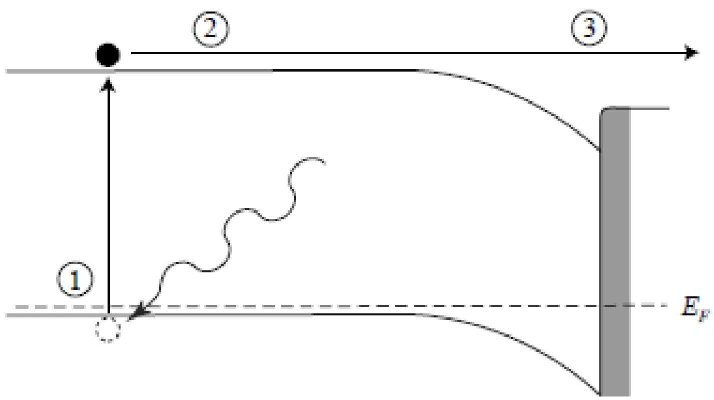
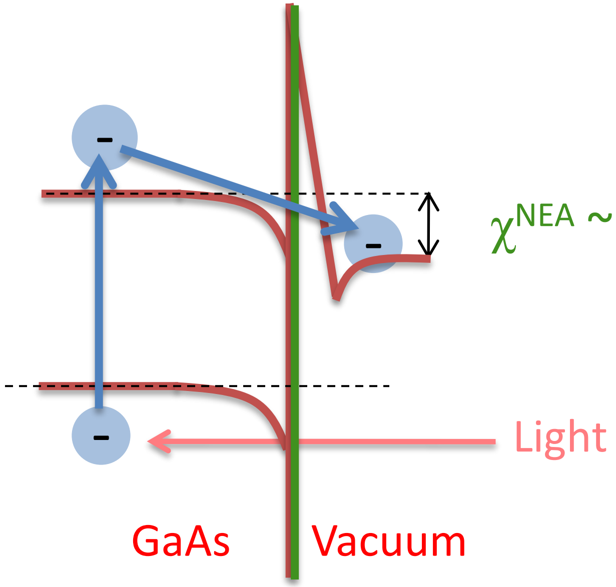


Figure 2.6: Spicer's Three–Step Photoemission Process: 1– photoexcitation of valence electrons into the conduction band (creation of electron–hole pair), 2– transport of electrons to the surface, 3– emission of electrons into the vacuum.

new



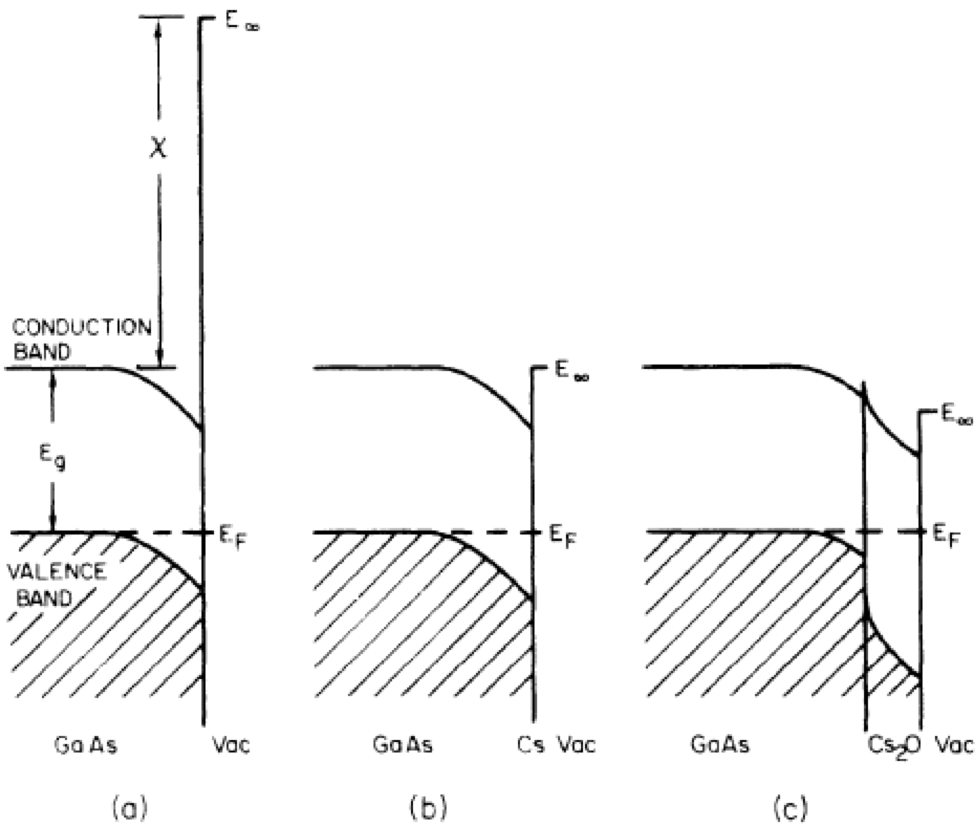
Step 1: Electrons are excited to conduction band by absorbing light

Step 2: (some) Electrons diffuse to the surface

Step 3: (some) Electrons leave material

From Pablo Saez PhD thesis, Stanford University, 1997

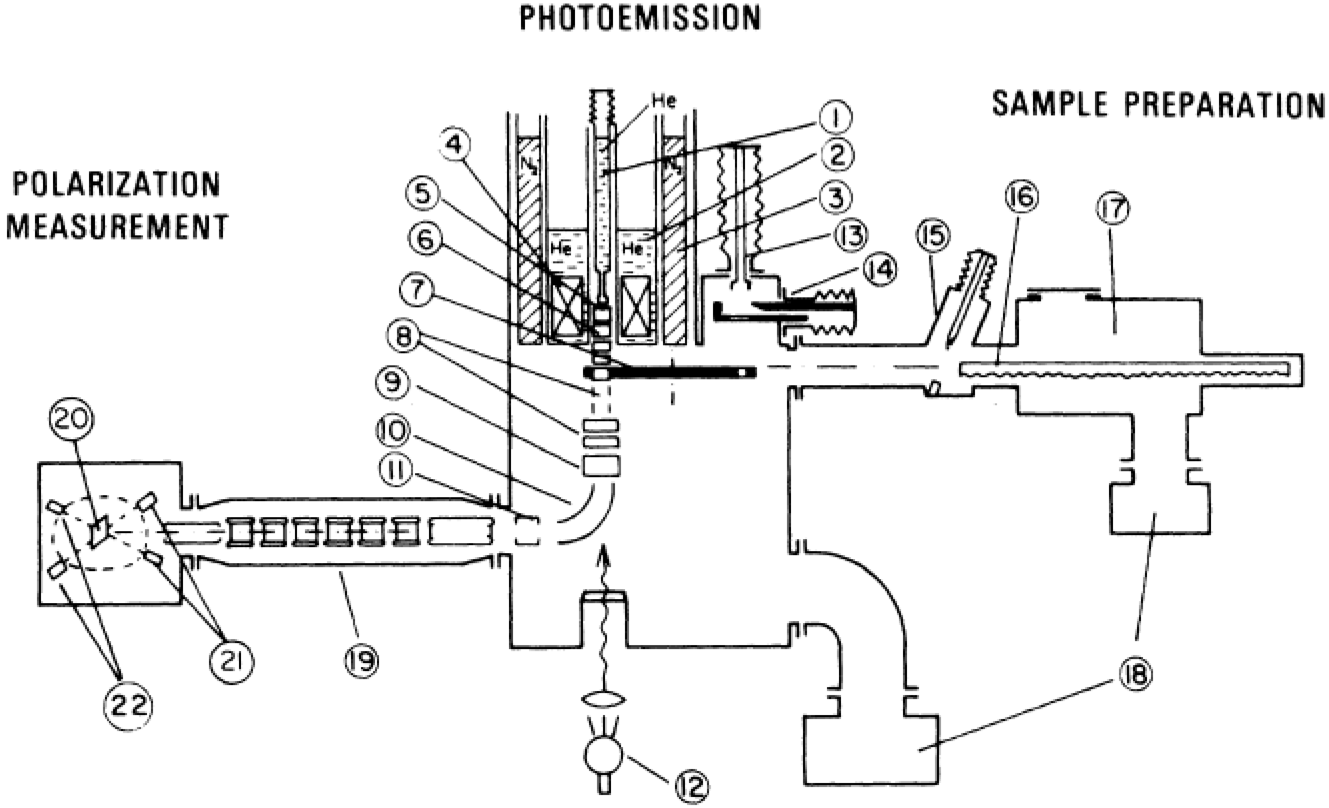
Reducing the Work Function



- Negative Electron Affinity
- P-doped GaAs reduces work function at surface, creates band bending region
- Approximately one monolayer of Cs and Oxidant reduces work function below that of conduction band

From Bruce Dunham PhD thesis, University of Illinois, 1993

Pierce-Meier Apparatus



First Observation of Polarization

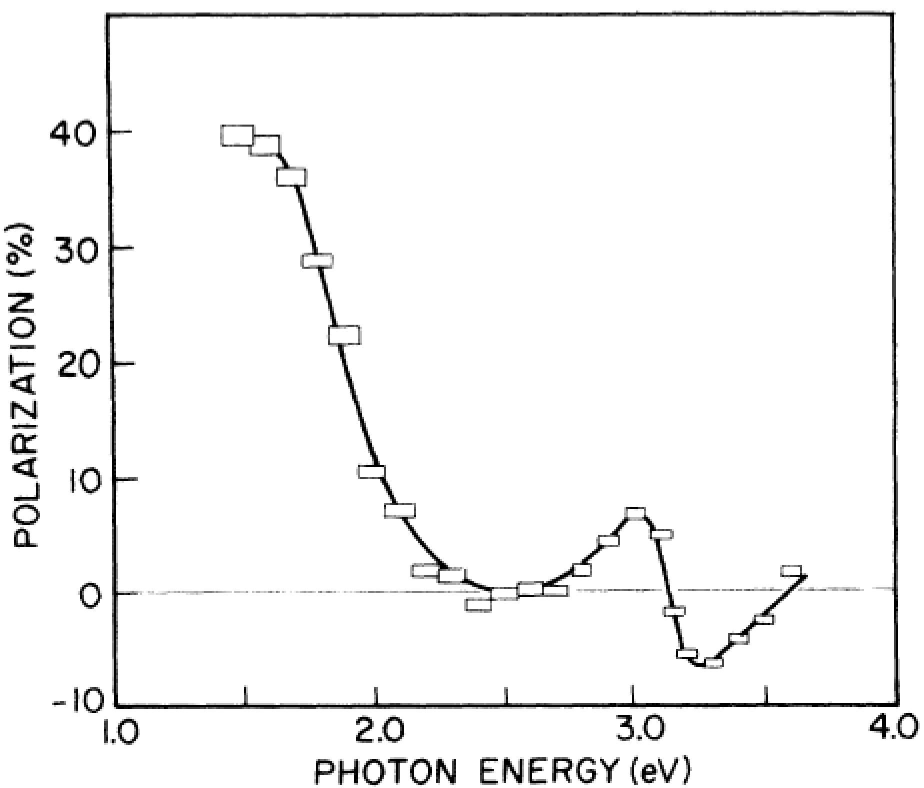


FIG. 6. Spectrum of spin polarization from GaAs + CsOCs at $T \leq 10$ K [the same sample and conditions as curve (a) of Fig. 5]. Note the high value of $P = 40\%$ at threshold ($\hbar\omega \sim 1.5$ eV) and positive and negative peaks at $\hbar\omega = 3.0$ and 3.2 eV.

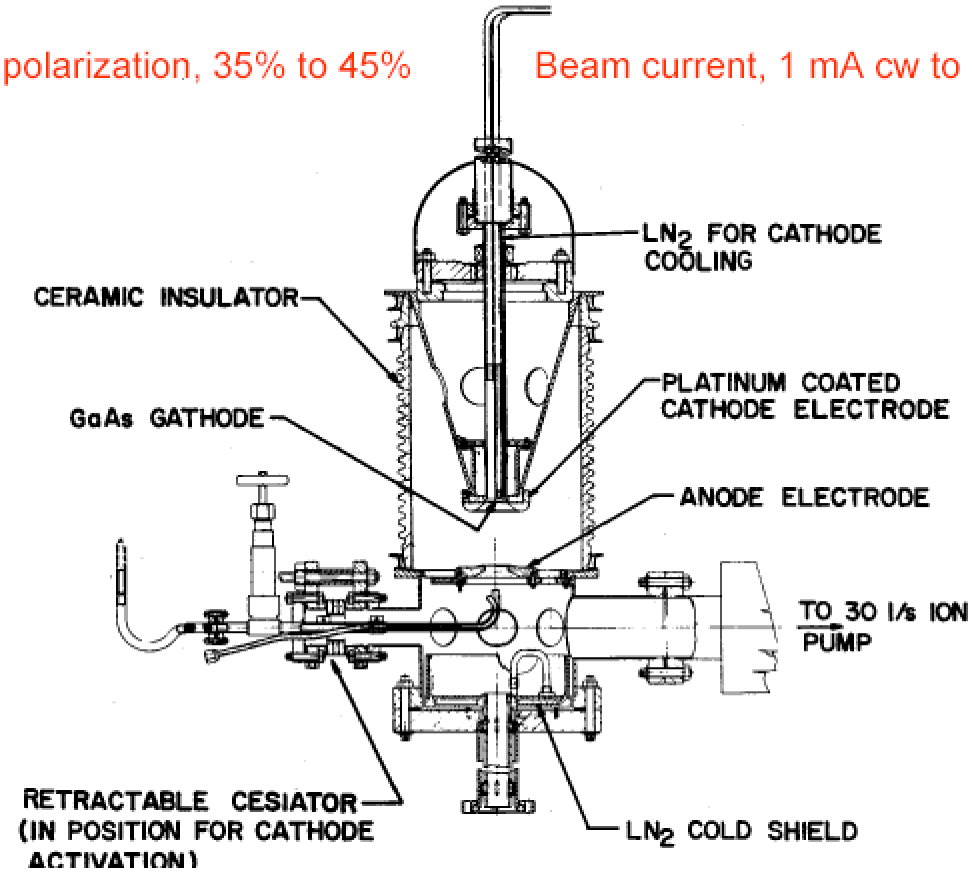
Flip sign of e-beam polarization by changing the helicity of the circularly polarized light

First High Voltage GaAs Photogun

Polarized e- Gun for SLAC Parity Violation Experiment

Beam polarization, 35% to 45%

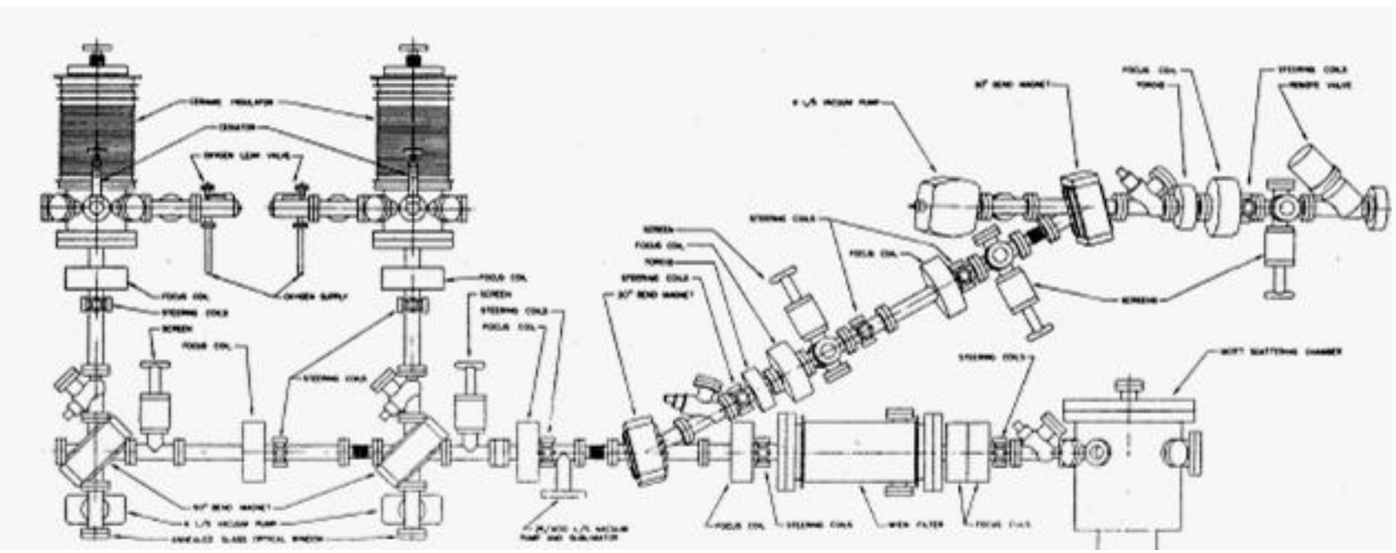
Beam current, 1 mA cw to 15 A peak

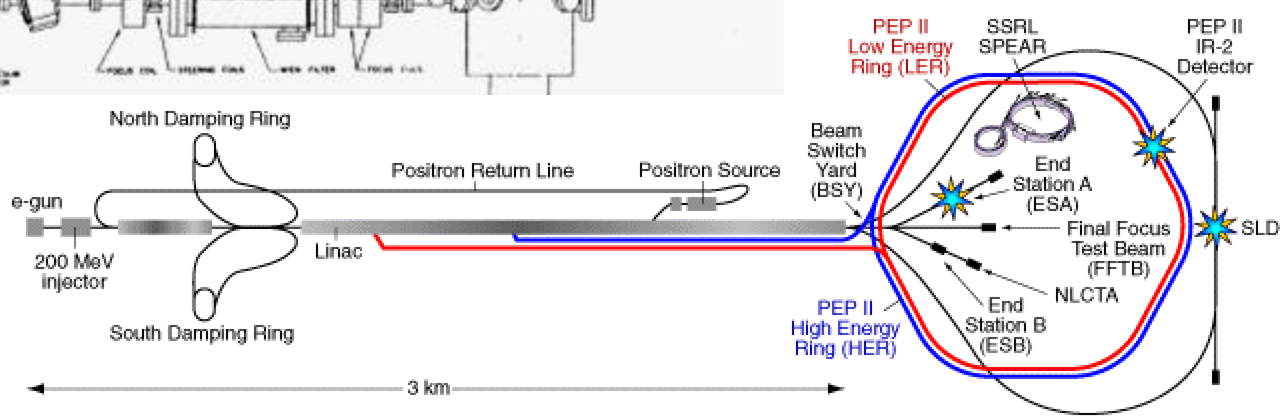


Started with a thermionic gun housing?

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

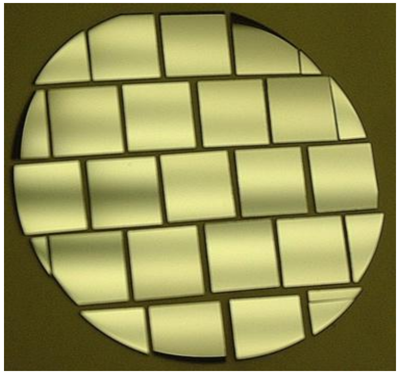




Polarized Electron Source "Musts"

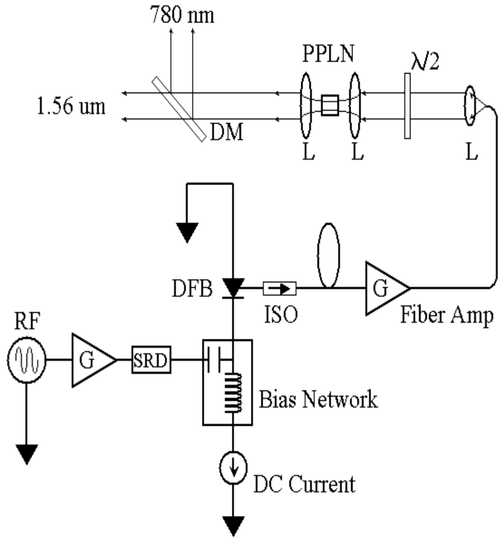
Good Photocathode

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



Good Laser

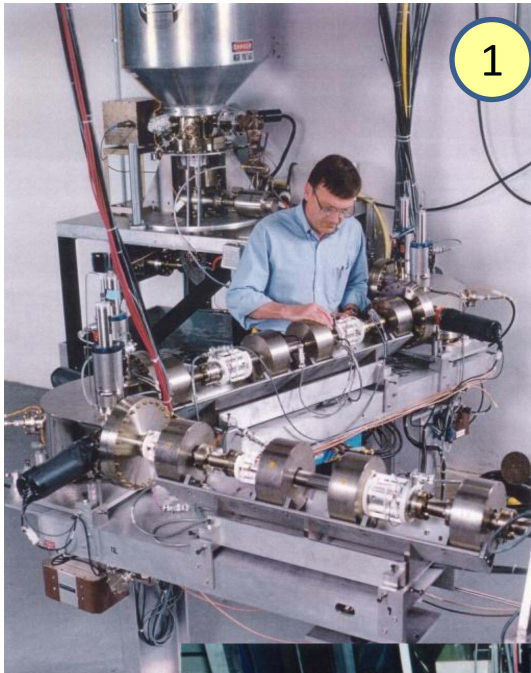
- "Headroom"
- Suitable pulse structure
- Low jitter



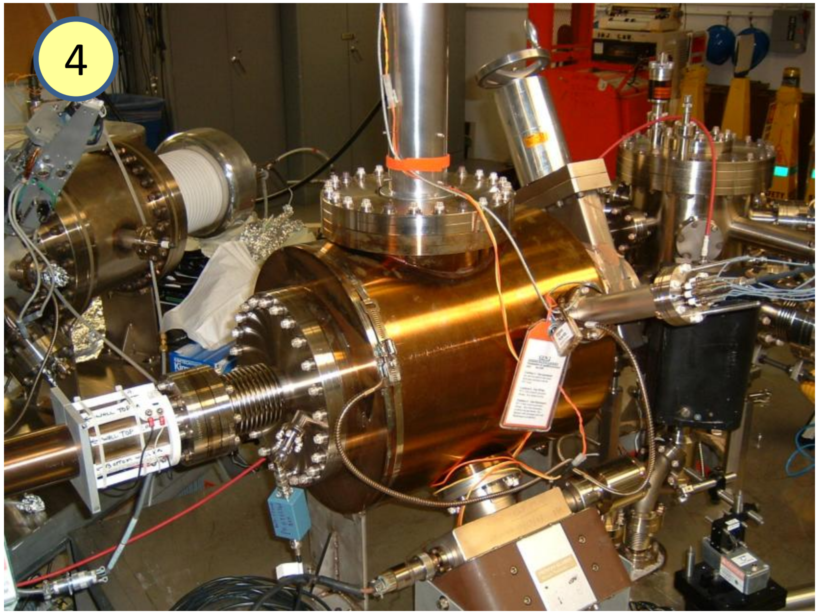
Good Electron Gun

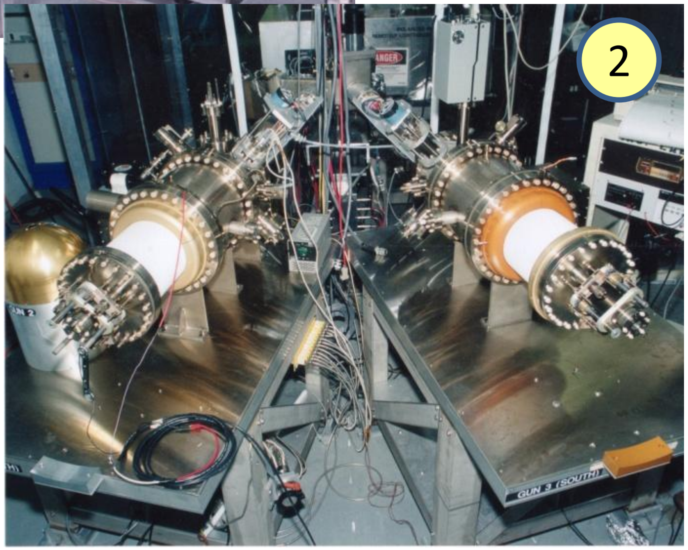
- Ultrahigh vacuum
- No field emission
- Maintenance-free

Always Tweaking the Design



Endless (?)
quest for
perfection



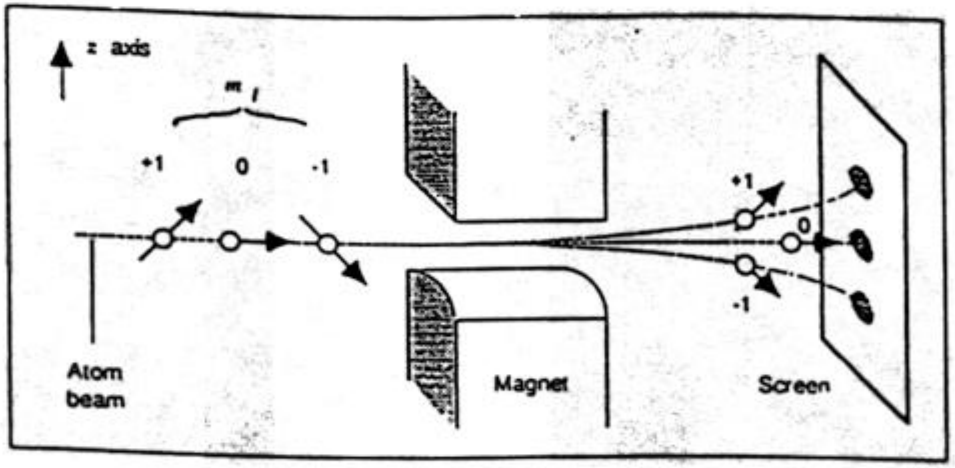


Backup Slides

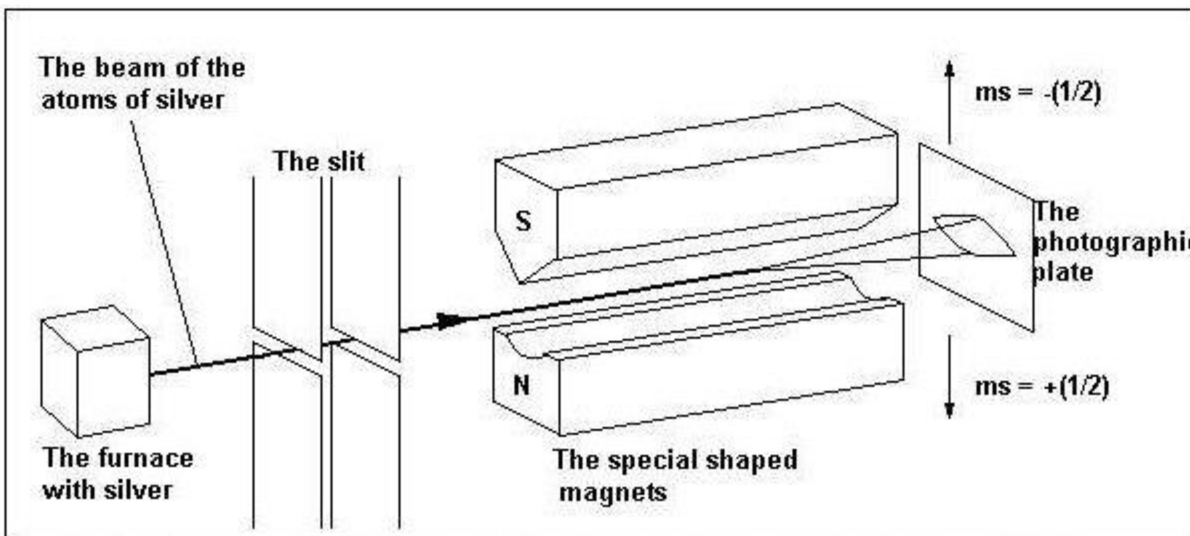
Homework

Why not use a sextupole to polarize the e-beam?

Stern-Gerlach Experiment



Electrons have total angular momentum J = L + S, orbital and spin angular momentum terms. Spin angular moment = +/- $h/4\pi$



The Stern-Gerlach experiment. On the photographic plate are two clear tracks.