Electron Sources: an Introduction.

Fernando Sannibale

ALS Accelerator Physics Group
Lawrence Berkeley National Laboratory

Lecture Outline

1) Basic information.

2) How to generate electrons.

3) Characteristics of an electron source.

4) Examples of existing source schemes.

5) Performance limiting factors.

6) Novel electron sources being developed at LBNL.

1. Basic Information.

Electron Story

Discovered by
J.J. Thomson in 1897

For the first time it was proved that the atom is not indivisible and that is composed by more fundamental components.

From the Greek ÈLEKTRON that means “Amber”.

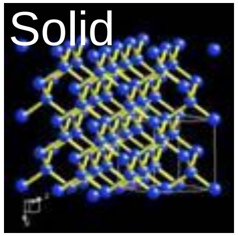
Fundamental particle: lightest lepton.

$m = 9.1095 \times 10^{-31}$ kg or 9.1095×10^{-28} g
(1837 times lighter than a proton)

$e = 1.6022 \times 10^{-19}$ C or 4.803×10^{-10} esu

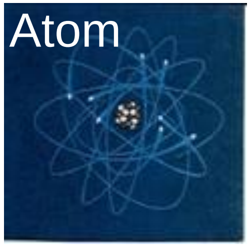
Where It Can Be Found or Generated

☑ **Solid**



Widely used in sources for: accelerators, microscopes, technological applications, ...

☑ **Atom**



Low current, high quality beams, microscopes, electron holography, inverse photoemission, ...

☒ **Plasma**

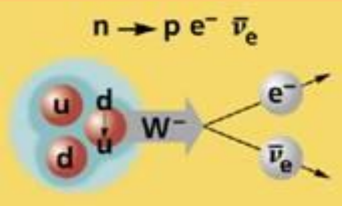
Very high gradient accelerators research

☒

electron-positron pairs

Commonly used in positrons sources

☒



Heavier Particle Decay Product

Radiation source

Two Families of Particles: Fermions and Bosons

In quantum physics, particles can be divided into two main categories according to their **spin**.

Particles with half-integer spin are called **fermions**, while those with integer spin are called **bosons**.

Extremely important difference: only fermions, follow the **Pauli exclusion principle**:

"No two fermions may occupy the same state".

- As a consequence, when more fermions are present in a system, they occupy different states.
- On the contrary, bosons will all occupy the lower energy level allowed by the system
- Because of the Pauli principle, the two categories follow different energy distributions:

Bosons

$$f_{BE}(E)=\frac{1}{e^{E/kT}-1}$$

Bose-Einstein Distribution:
photons, gluons, W, Z^0, …

Fermions

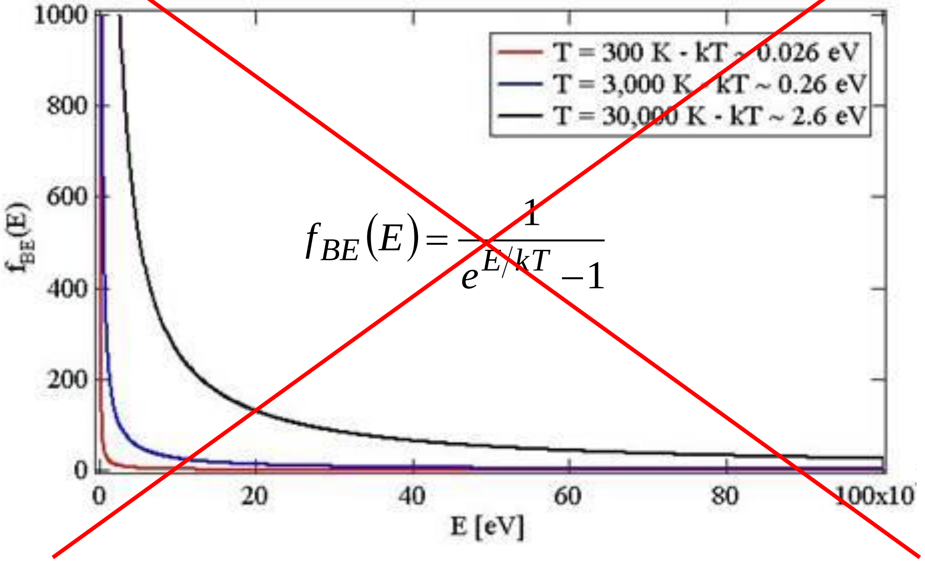
$$f_{FD}(E)=\frac{1}{e^{(E-E_F)/kT}+1}$$

Fermi-Dirac Distribution:
electrons, protons, neutrons, ...

Note that when $E >> kT$, both distributions are approximated by the Maxwell-Boltzmann distribution.

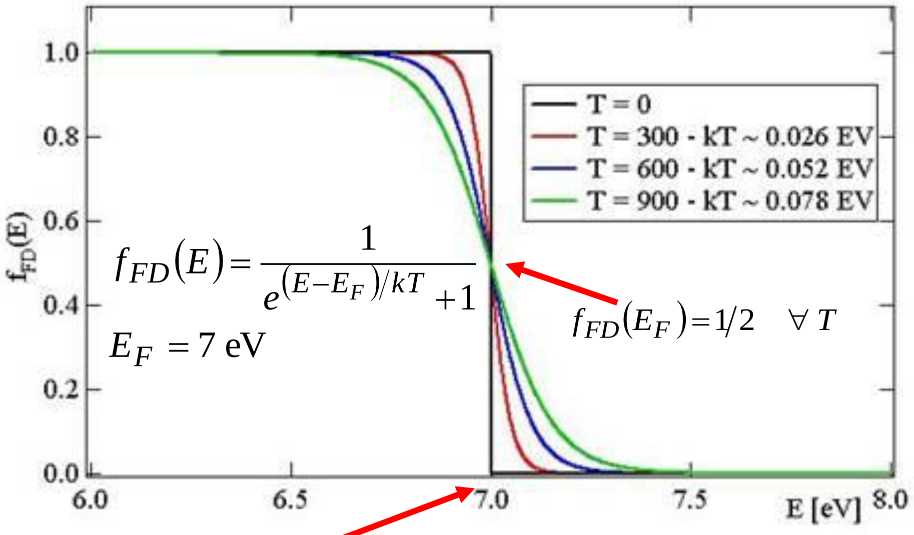
The Fermi Energy

~~Bose-Einstein Distribution for Bosons~~



~~$$f_{BE}(E)=\frac{1}{e^{E/kT}-1}$$~~

Fermi-Dirac Distribution for Fermions



$$f_{FD}(E)=\frac{1}{e^{(E-E_F)/kT}+1}$$

$$E_F = 7\ \mathrm{eV}$$

$$f_{FD}(E_F)=1/2 \quad \forall\, T$$

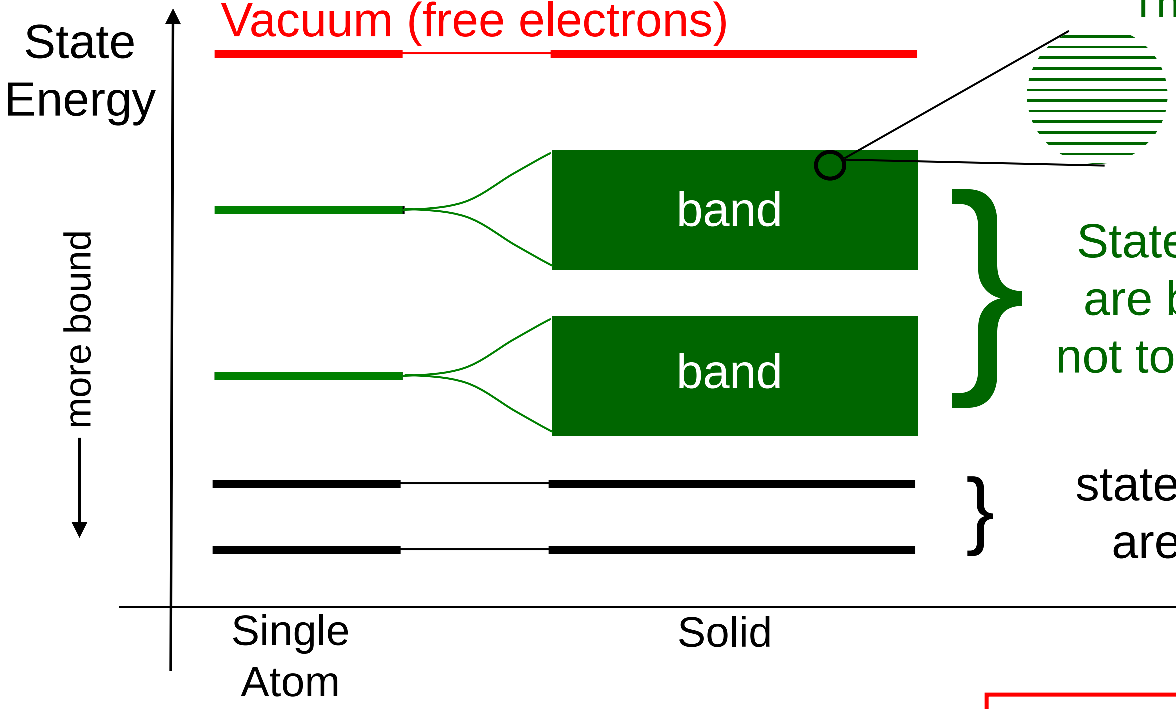
We are dealing with electron sources. Being electrons fermions (spin 1/2) we will concentrate our attention in the Fermi-Dirac distribution

Definition : In a system of fermions the **Fermi energy E_F** is the energy of the highest occupied state at zero temperature.

The system of fermions we are interested to is represented by **the electrons in a solid.**

The E_F value is a property of the particular material. Example: E_F for copper is 7 eV.

Solids and Work Function



State Energy

more bound

Vacuum (free electrons)

band

band

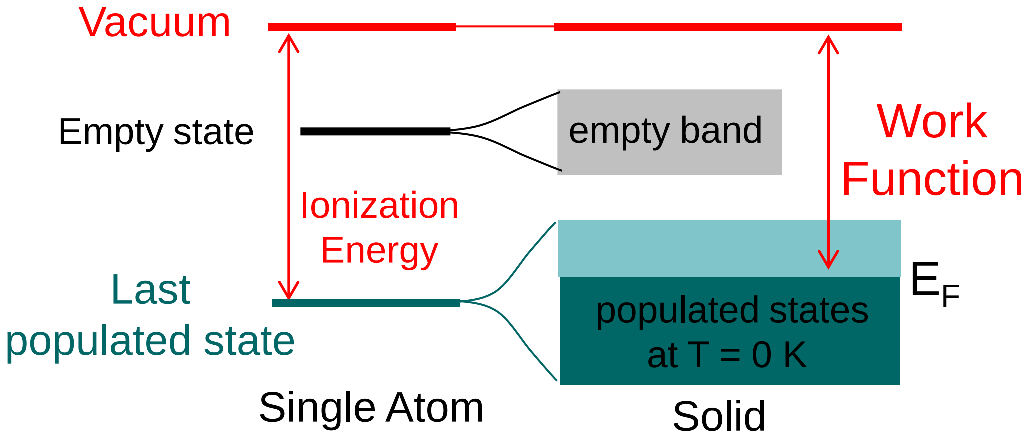
Single Atom

Solid

The band is a range of energy with a very fine discrete structure (states). Practically a continuum

States where electrons are bound to the solid, not to the single nucleus.

states where electrons are bound to nuclei



Vacuum

Empty state

empty band

Ionization Energy

Work Function

Last populated state

populated states at T = 0 K

E_F

Single Atom

Solid

Definition: the **work function W_F** is the energy needed to bring an electron from the Fermi level to the vacuum level

Example: for Copper (Cu)
E_I = 7.7 eV
W_F = 4.7 eV

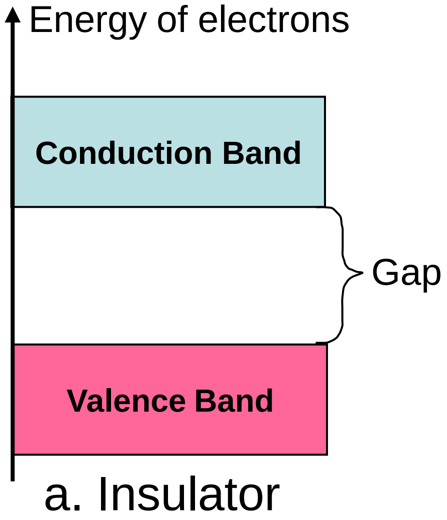
Insulators and Conductors

Definition 1: In solids, the **valence band** is the band that at T = 0 K, is occupied by the highest energy electrons.

Definition 2: The **conduction band** is the higher energy band above the valence band.

INSULATORS:

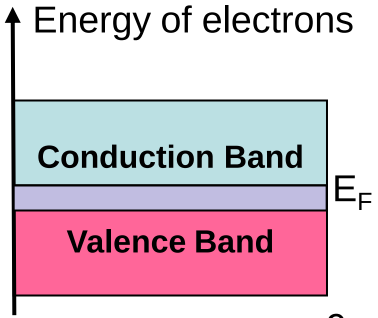
- The valence and the conduction bands are separated by a **gap** with no allowed energy states.
- At T = 0 K, the valence band is completely filled with electrons.
- At T = 0 K, the conduction band is totally empty.



a. Insulator

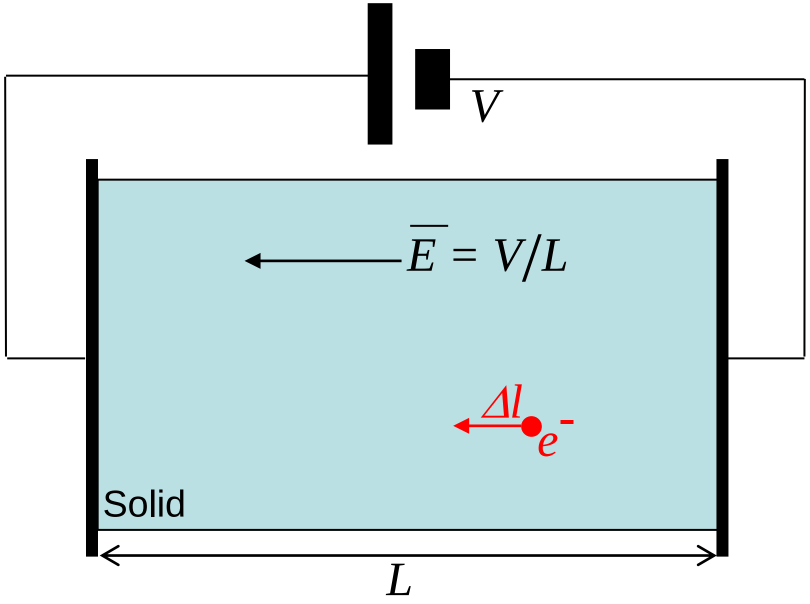
CONDUCTORS:

- The valence and the conduction bands **overlap**. The same band is now at the same time of valence and of conduction.
- The energy states in such a combined band are only **partially filled**.

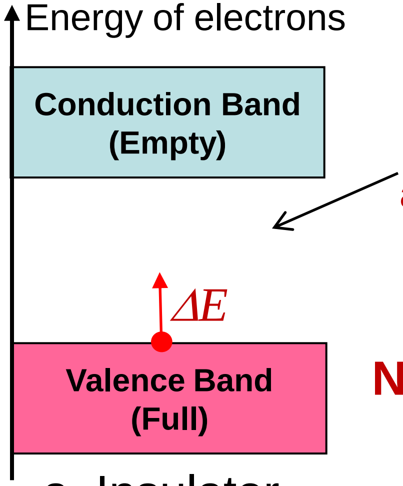


b. Conductor

The Conduction Phenomenon



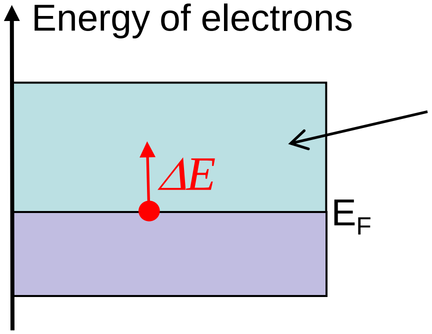
$$\text{Energy Variation} = \Delta W = e\left|\bar{E}\right|\Delta l = e\frac{V}{L}\Delta l$$



a. Insulator

No energy state available in the gap.

No conduction!



b. Conductor

Empty energy states are now available.

Conduction!

Semiconductors: a "Special" Insulator

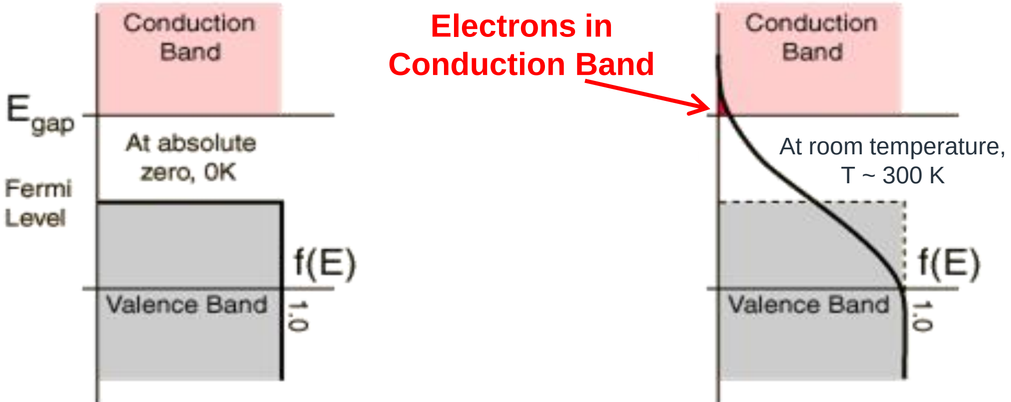
Above absolute zero (T = 0K), the atoms in a solid start vibrating.

As a consequence, some of the electrons in the valence band scatter with the atoms gaining extra energy (the larger is T, the larger can be the extra energy).

If this extra energy is bigger than the energy gap between the bands in an insulator, the scattered electrons will "jump" from the valence to the conduction band.

As a consequence, when the temperature increases a solid can experience a **phase transition from insulator to conductor**.

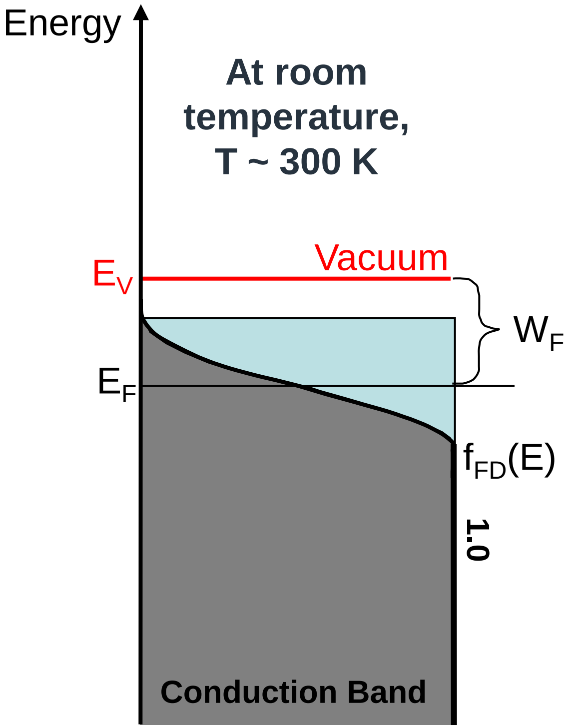
A semiconductor is an insulator with a relatively **small gap** between the valence and conduction bands.
The gap is small enough that at room temperature (T ~ 300K), some of the electrons have been already scattered into the conduction band.

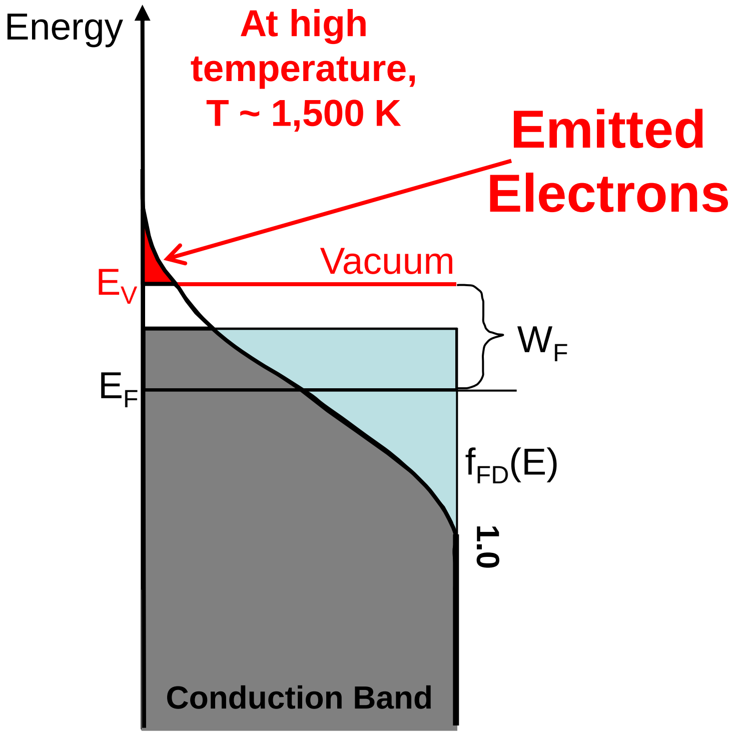


Silicon,
Germanium,
GaAs,
….

2. How to generate electrons.

Thermionic Emission in Conductors





Thermionic emission was initially reported in 1873 by Guthrie in Britain.

Owen Richardson received a Nobel prize in 1928 "for his work on the thermionic phenomenon and especially for the discovery of the law named after him".

$$\boxed{J = AT^2 e^{-w/kT}}$$

$$A = \frac{4\pi m k^2 e}{h^3} = 1.20173 \times 10^6 \quad A m^{-2} K^{-2}$$

$$w \equiv work \quad function$$

Emission by Photoelectric Effect

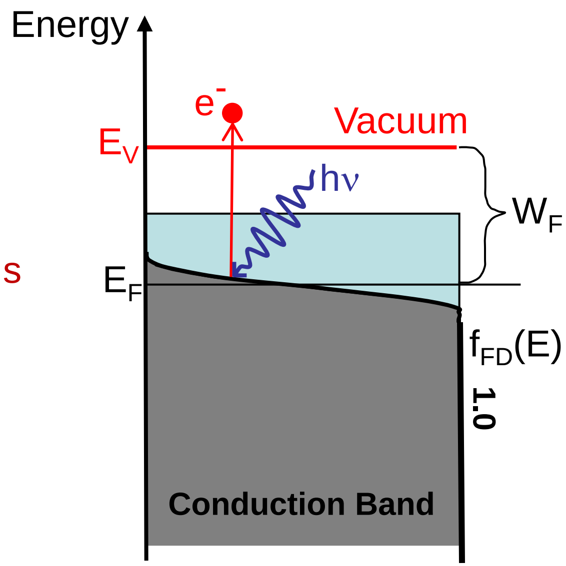
$$\boxed{Photon\ Energy = E_{ph} = h\nu}$$

photon frequency

Planck Constant= 6.626068 × 10^{-34} m^2 kg / s

$$\boxed{If\quad E_{ph} \geq W_F}$$

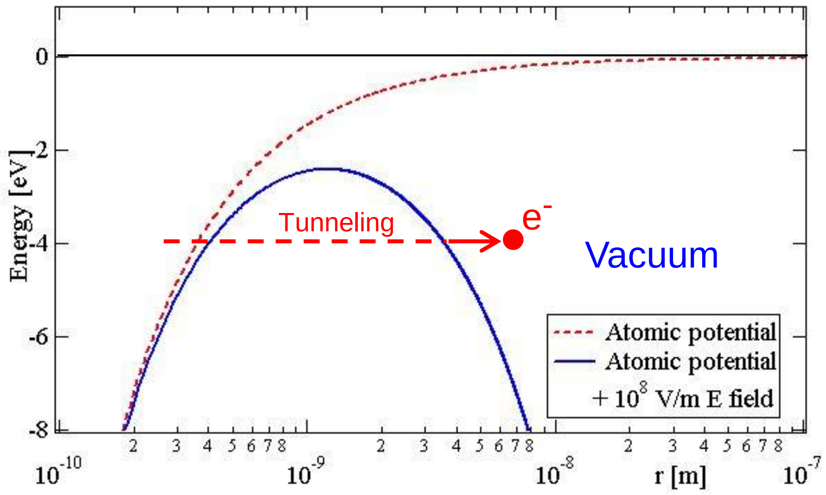
$$\boxed{T_{e-} = E_{ph} - W_F}$$



Albert Einstein received the 1921 prize in Physics for work that he did between 1905 and 1911 on the Photoelectric Effect.

Max Planck received the 1919 Nobel for the development of the Quantum Theory of the photon.

Field Emission



$$U_p = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r} + e\left|\bar{E}\right|r$$

$$\left|\bar{E}\right| = \text{constant}$$

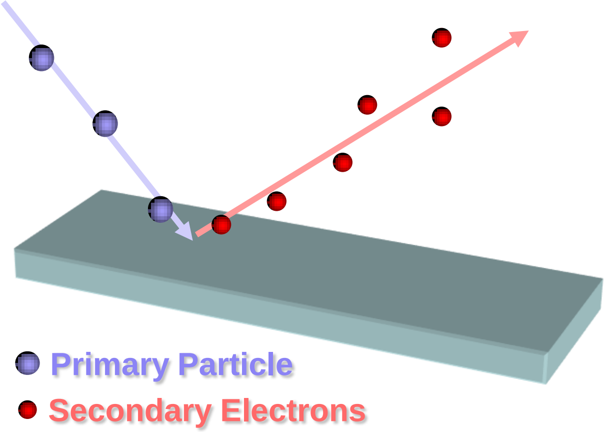
$$\left|\bar{E}\right| > \quad \sim 10^9\, V/m$$

Tunneling is the quantum-mechanical effect of transitioning through a classically-forbidden energy state.

Field emission was first observed in 1897 by Robert Williams Wood.

But only in 1928, Fowler and Nordheim gave the first theoretical description of the phenomenon. It was one of the first applications of the quantum mechanics theory.

Secondary Emission



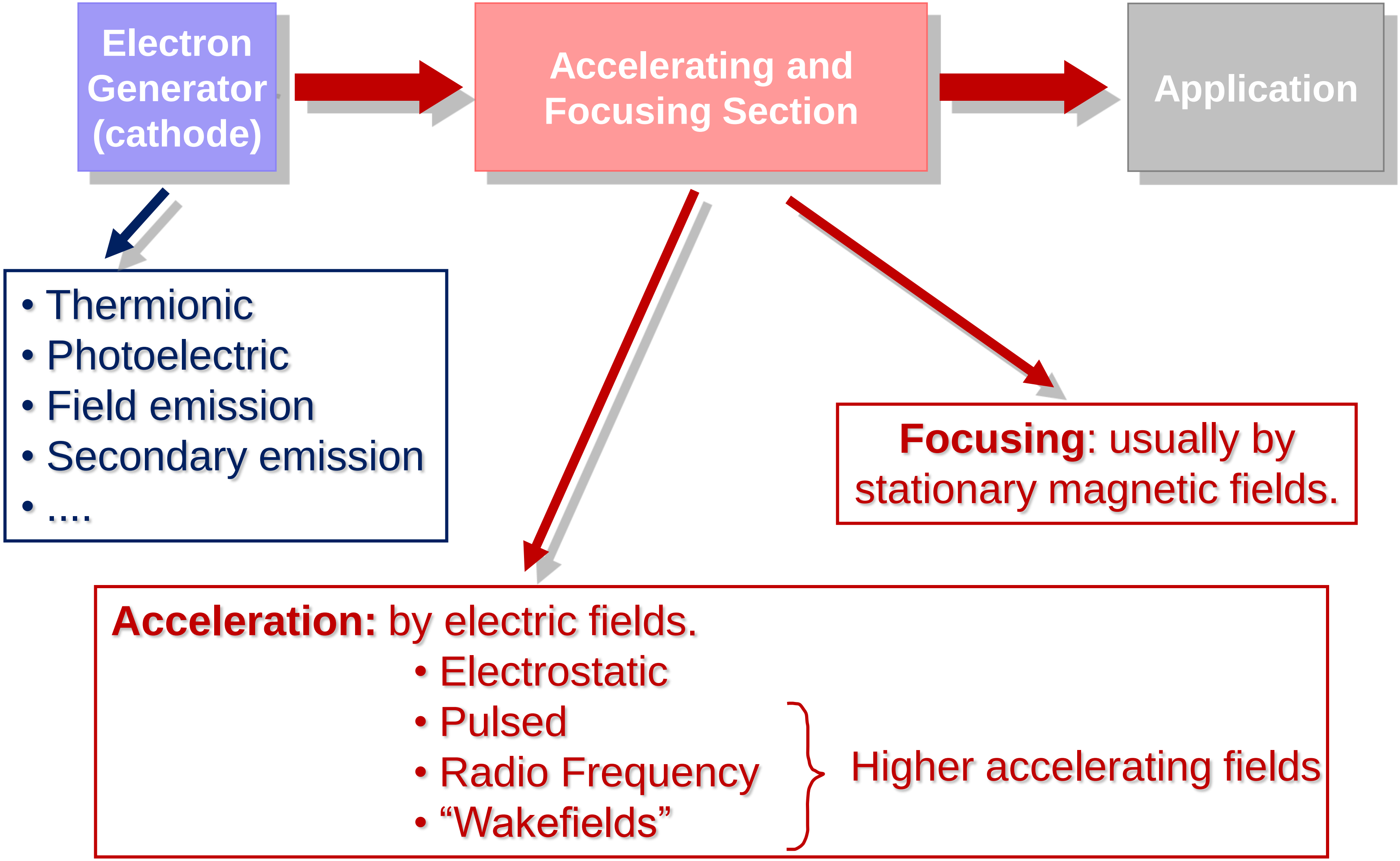
Primary Particles: photons, electrons, protons, neutrons, ions, ...

Physical Processes: ionization, elastic scattering, Auger electrons, bremsstrahlung and pair formation, Thomson scattering, ...

3.

Characteristics of an Electron Source.

The Typical Electron Source



Electron Generator (cathode) → **Accelerating and Focusing Section** → **Application**

- Thermionic
- Photoelectric
- Field emission
- Secondary emission
- ....

Focusing: usually by stationary magnetic fields.

Acceleration: by electric fields.

- Electrostatic
- Pulsed
- Radio Frequency
- "Wakefields"

} Higher accelerating fields

Electron Sources
Main Parameters

Energy: from few eV to several MeV (~ GeV plasma source)
Energy Spread: from ~ 0.1 eV and up.

Current: - Average: from less than a pA to several tens of A.
- Peak: from μA to thousands of A.

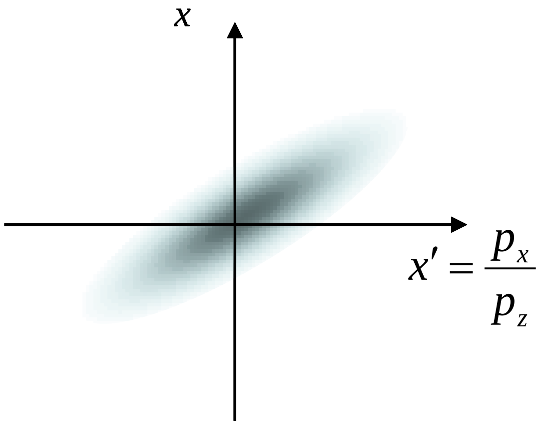
Time Structure: - DC
- Pulsed: from single shot to hundreds of MHz
- CW: from hundreds of MHz to several GHz

Bunch Length: from hundreds of fs to seconds.
Single electron.

Polarization: controlled orientation of the electron spin

And few more important quantities …

The Concept of Emittance



Emittance: quantity proportional to the volume of the phase space occupied by the beam particles

The emittance is generally a 6D quantity but quite often, the planes can be decoupled and the 2D individual planes can be investigated independently.

Liouville Theorem: in a Hamiltonian system (non-dissipative system) the emittance is conserved

For most applications, smaller emittances are preferred.
It is very easy to increase this quantity, but very hard to preserve it!

Emittance and r.m.s. Emittance

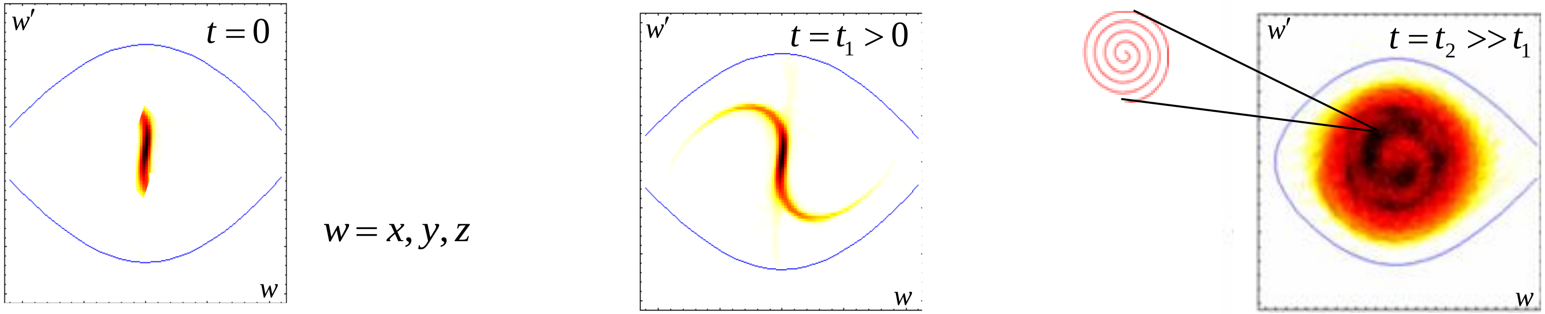
A statistical definition: the r.m.s. Emittance:

$$\varepsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\, x'\rangle^2}$$

- **According to the Liouville theorem, in a Hamiltonian system the emittance is conserved. This is true even when the forces are nonlinear (space charge, nonlinear magnetic and/or electric fields, …)**

- **This is not true for the case of the rms emittance.**
In the presence of nonlinear forces the rms emittance is not conserved

- **Example: *filamentation*. Particles with different phase space coordinates, because of nonlinear forces can move with different phase space velocity**



- **The emittance according to Liouville is still conserved.**
But the rms emittance increases with time.

Brightness and Degeneracy Factor

Brightness: density of particles in the phase space.
I.e. number of particles per unit of phase space volume.

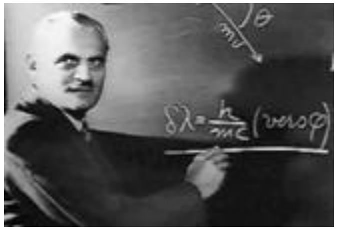
$$B = \frac{N}{\varepsilon_x \varepsilon_y \varepsilon_z}$$

Heisenberg uncertainty principle: *“it is impossible to determine with precision and simultaneously, the position and the momentum of a particle”*.Applied to emittances:

$$\varepsilon_w \geq \lambda_c / 4\pi \qquad w = x, y, z$$

$$\lambda_c \equiv Compton\ \ wavelength = h / m_0 c = 2.426\ \ pm\ \ for\ \ electrons$$

This can be interpreted as the fact that the phase space volume occupied by a particle is given by: **$(\lambda_c/4\pi)^3$ =** elementary phase space volume



Degeneracy Factor, δ: if the phase space is expressed in elementary phase space volume units, the brightness becomes a dimensionless quantity δ representing the **number of particles per elementary volume.**

$$\delta = B\left(\frac{\lambda_C}{4\pi}\right)^3$$

Because of the Pauli exclusion principle the **limit value of δ** is: infinity for bosons and **1 for non polarized fermions**.

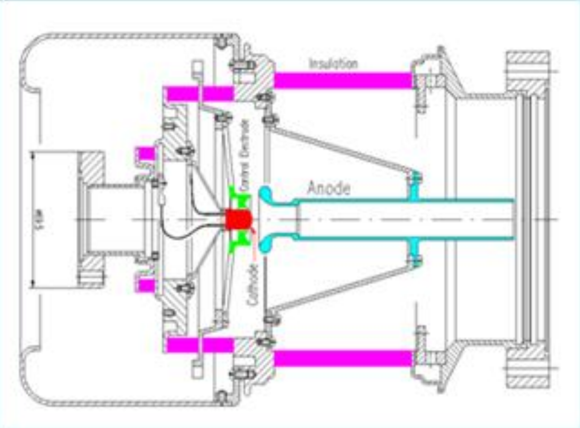
Short pulses, low energy spread, small emittances, high current densities, all lead to a **high degeneracy factor.**

4.

Examples of Existing Source Schemes.

Examples of Electron Sources

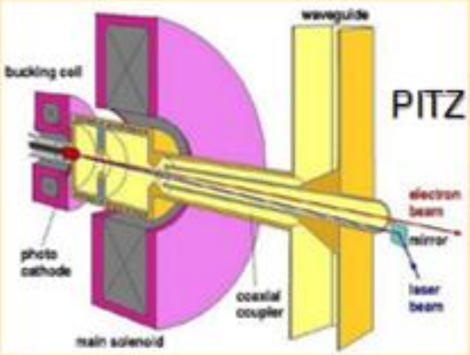
Thermionic Electron Gun



LINAC LAB Gun (Fermi Lab):
E = 100 keV
Current = 2 A max
Application: LINAC Injector

Current densities
~ 10-100 A/cm^2

RF Gun with Photo-Cathode

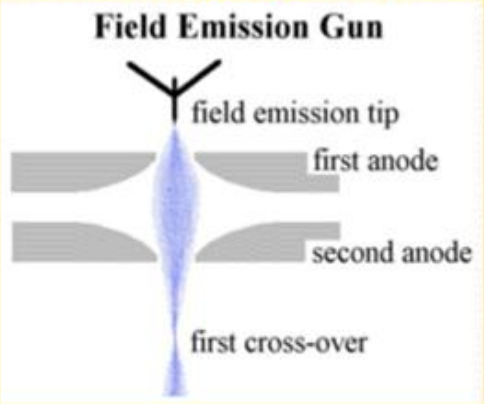


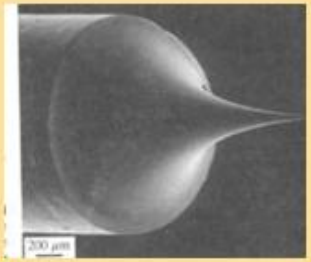
PITZ

LCLS RF Gun
3 GHz
6 MeV
20 -1000 pC
ε_n ~ 0.1 – 1 μm
120 Hz reprate
150 MV/m field

Examples of Electron Sources

Field Emission Electron Gun





THERMO Electro Corporation:
- Field at the cathode tip > 1 MV/cm
- 100 nm spot size at 5 nA sample current
- Average current density ~ 50 A/cm^2
- Application: Electron microscopes

A Secondary Emission (SEM) Source

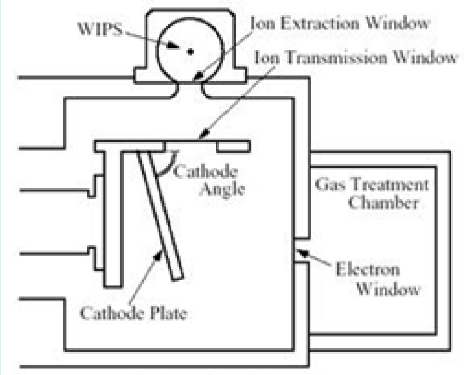


Fig. 1. Secondary emission electron gun.

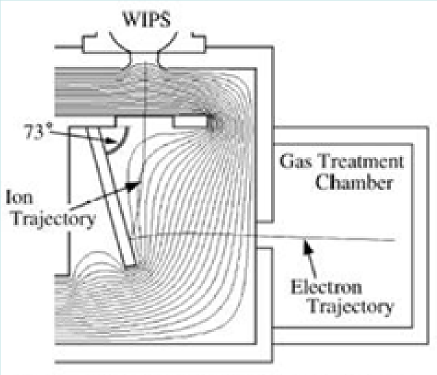


Fig. 4. Equipotential lines, ion and electron trajectories.

Electron energy = 40-80 kV
Current density: 6.4 mA/cm^2
Ion source energy = 10 kV
Large and uniform beam through the window
Application: pollutant gas treatment.

P.R Chalise et al., Jpn. J. Appl. Phys. 40, 1118 (2001)

5.

Performance Limiting Factors.

Some Examples of Limitations

Thermionic guns.

- Continuous emission. Difficult to obtain short pulses.
- Difficult to control the bunch distribution

Photo-emission guns.

- High repetition rate limitations by laser and cathodes technologies.
- Cathode lifetime issues.

Field emission guns.

- Max electric field at the tip. Limits in the minimum size of the tip.
- Best brightness but low average current.
- Tip damage, lifetime

Secondary Emission Gun.

- Low current densities.
- High energy spread, poor emittance, very low brightness.

Common to most technologies

- Max electric field. Field emission limits. Dark current.

Degeneracy Parameter in Nowadays Electron Guns

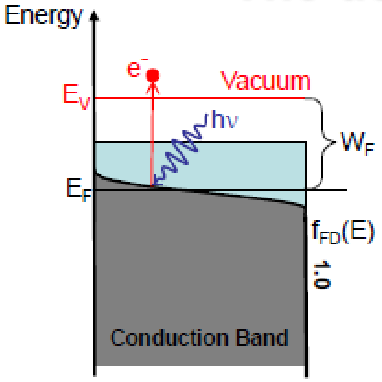
Most of the edge electron beam applications (accelerators, free electron lasers, microscopes, ...) push the performance of the electron source:

- **Lowest emittance**
- **Smallest energy spread**
- **Highest brightness**

Highest Degeneracy Factor δ

- **Conv. thermionic: $\delta \sim 10^{-14}$**
- **SEM: $\delta < 10^{-14}$**
- **Photo-RF guns: $\delta \sim 10^{-11}$**
- **Field emission: $\delta \sim 10^{-5}$**

The degeneracy factor inside a metal cathode is ~ 1. !!!



How do we lose all of that?

Extraction Mechanism

Coulomb interaction

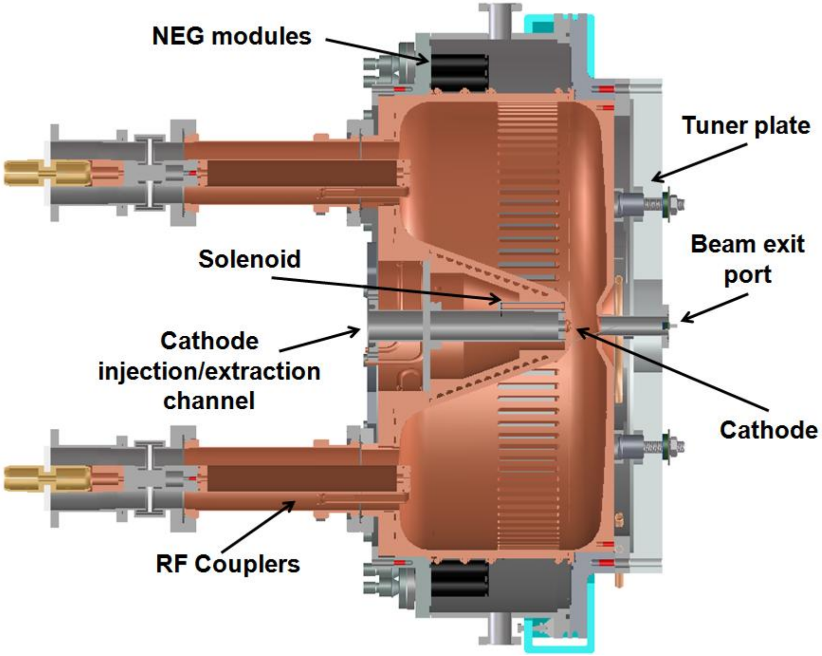
4th generation light sources require high charge/bunch sources for high photon flux. For those charges a $\delta \sim 10^{-11}$ is the best that can be presently obtained.

6.

Novel Electron Sources Being Developed at LBNL.

The LBNL VHF Photo-Injector

The Berkeley normal-conducting scheme satisfies all the LBNL FEL requirements simultaneously.



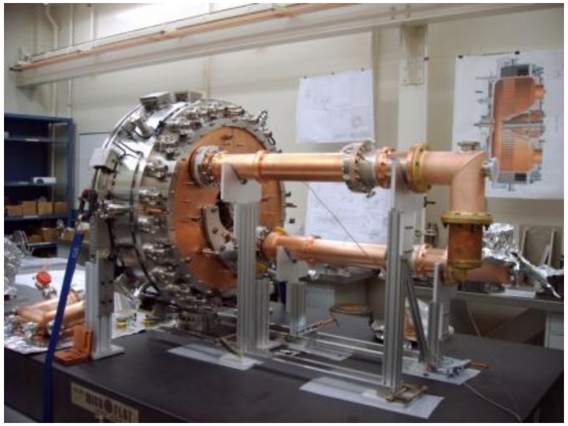
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

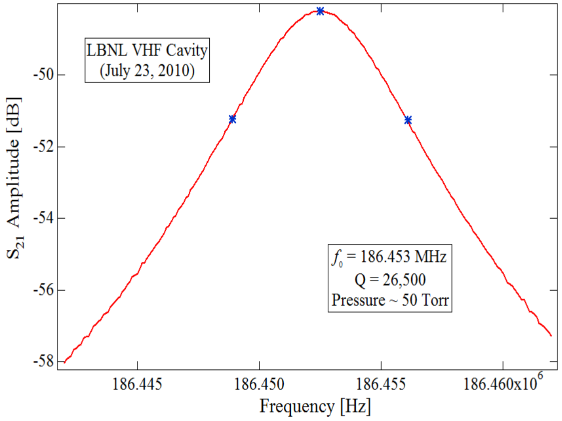
Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter	69.4 cm
Total length	35.0 cm

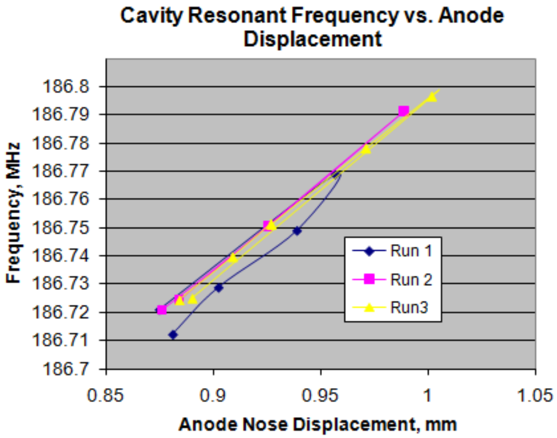
- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.
- 187 MHz compatible with both 1.3 and 1.5 GHz super-conducting linac technologies.

The LBNL VHF Photo-Injector



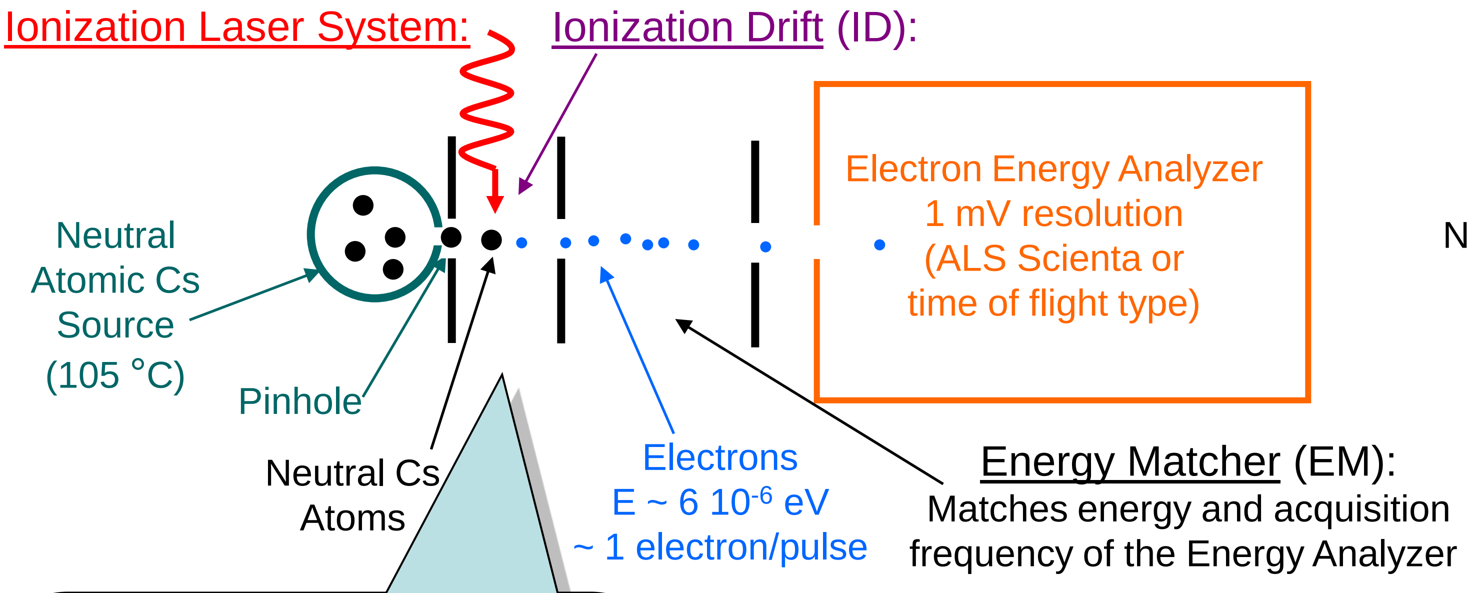
Successful low power RF test





High power RF conditioning under way. Successful vacuum leak test.
1.2 10^{-9} Torr achieved with 1 (out of 20) NEG pump and no baking.

A Quantum-Limited Brightness Electron Source



Ionization Laser System:

Ionization Drift (ID):

Electron Energy Analyzer
1 mV resolution
(ALS Scienta or
time of flight type)

NOT TO SCALE

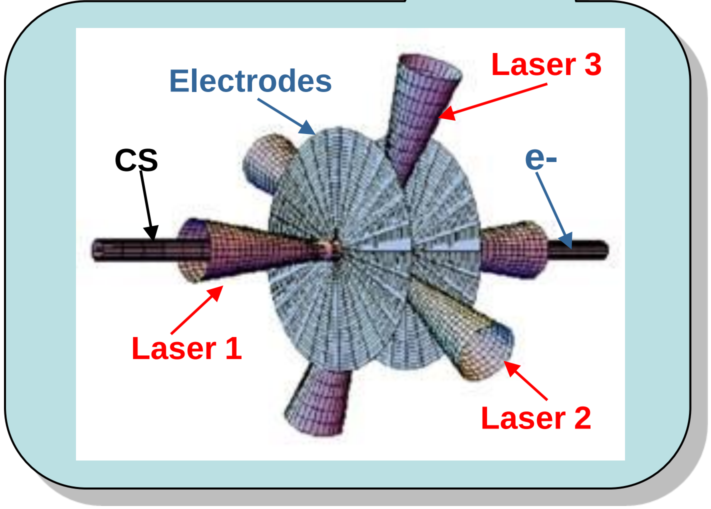
Neutral
Atomic Cs
Source
(105 °C)

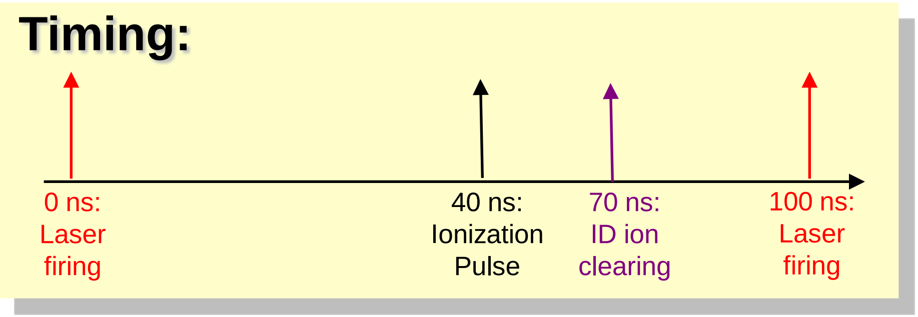
Pinhole

Neutral Cs
Atoms

Electrons
E ~ 6 10^{-6} eV
~ 1 electron/pulse

Energy Matcher (EM):
Matches energy and acquisition frequency of the Energy Analyzer





Timing:

M.S. Zolotorev, E. D. Commins, F.Sannibale. Physical Review Letters **98**, 184801 (2007).

Fundamental Concepts

1) Atom Excitation. In the interaction region defined by the overlap of three lasers (2 CW and one pulsed), we excite on average one alkali atom per laser pulse to a very high Rydberg level (n~ 800). The electron in the excited atom will have a total energy close to zero and will start to drift away from the ion on a Kepler-like orbit.

2) Waiting Period. After the laser pulse, we wait the time necessary (~ 40 ns) for the electron to arrive at the apogee of the orbit where its kinetic energy is practically zero (~ 10^{-5} eV), and we apply a short pulsed voltage to finally ionize the atom and to give the electron a kinetic energy (~ 1 eV) sufficient for leaving the interaction region area.

3) Electron Acceleration. In this step, the electron is accelerated up to the energy required by the application and leaves the gun.

4) Ion Clearing. After the electron acceleration, we apply a “cleaning” field in order to remove the residual ion before the beginning of the following cycle. In this way we avoid that the residual ion will interact with the electron produced in the next pulse.

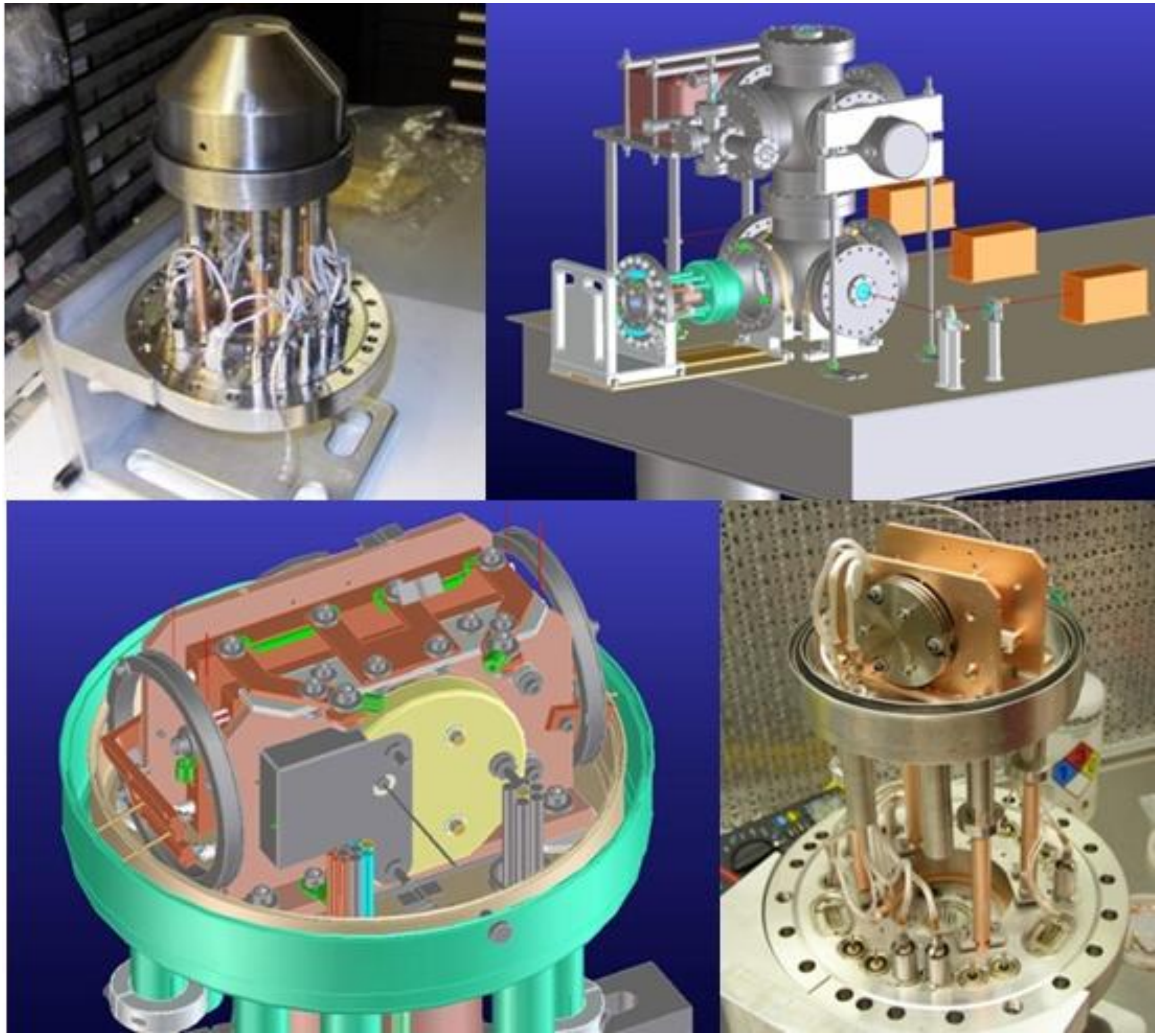
The application of all such concepts allows to eliminate the Coulomb interaction between electrons (a single electron per cycle is produced) and to properly control the interaction between the electron and ions (parent and residual ones).

The theoretical degeneracy factor for this source is expected to be: $\delta \sim 0.6$

If the source is operated at 10 MHz repetition rate, can produce an average current of ~ 1 pA with densities of up to ~ 10^4 A/cm^2.

Main applications include Angstrom resolution scanning microscopes, electron holography, inverse photemission, lens-less imaging at nm scale, ...

DEGAS: a Proof of Principle Experiment at LBNL



Construction finished, source performance under characterization