Electron Sources: an Introduction.

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University of California, Berkeley
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Lecture Outline

1) Who is the electron and how to produce it.

2) Basic information. A brief review and some glossary.

3) How to extract electrons.

4) Characteristics of an electron source.

5) Examples of existing sources.

6) Performance limiting factors.

7) An example of a new source scheme.

1.

Who is the electron and how to produce it.

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.

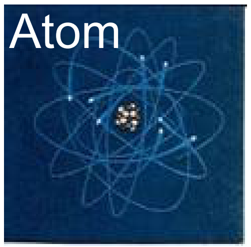
From the Greek ÈLEKTRON that means “Amber”.

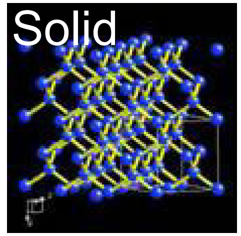
Fundamental particle: lightest lepton.

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

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

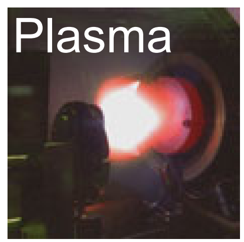
Where it can be found and produced





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

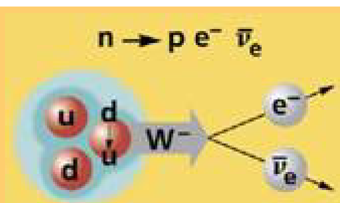
Low current, high quality beams, microscopes, electron holography, inverse photoemission, ...



Very high gradient accelerators research

electron-positron pairs

Commonly used in positrons sources



Heavier Particle Decay Product

Radiation source

2.

Basic Information and Some Glossary

Two Families of particles: Fermions and Bosons

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

Particles with half-integer spin are called **fermions**, 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 fermions are introduced into a system, they will occupy higher energy levels when the lower ones are filled up.
On the contrary, bosons will all occupy the lower energy level allowed by the system

Because of the Pauli principle, the two particle categories follow different energy distributions:

Bosons

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

Bose-Einstein Distribution: photons, mesons

Fermions

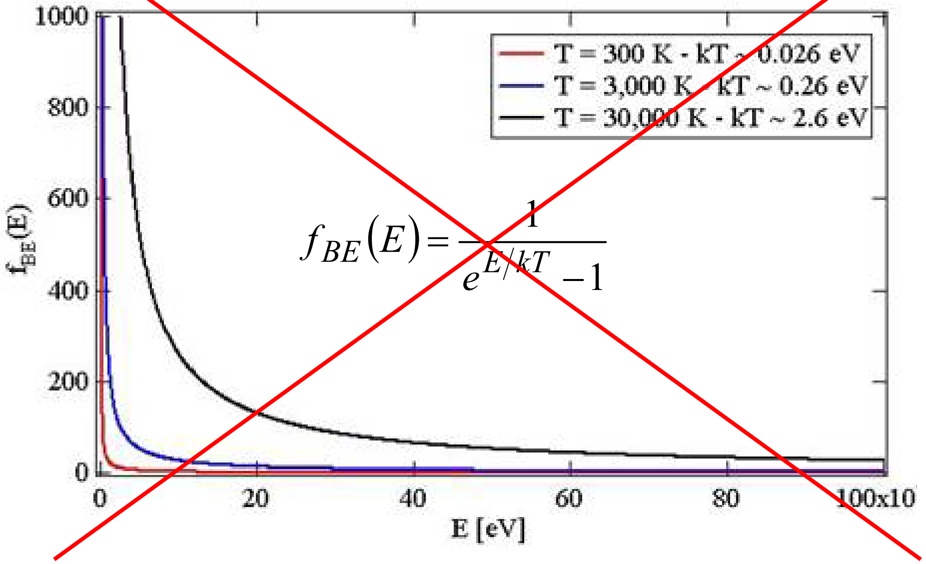
$$f_{FD}(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

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

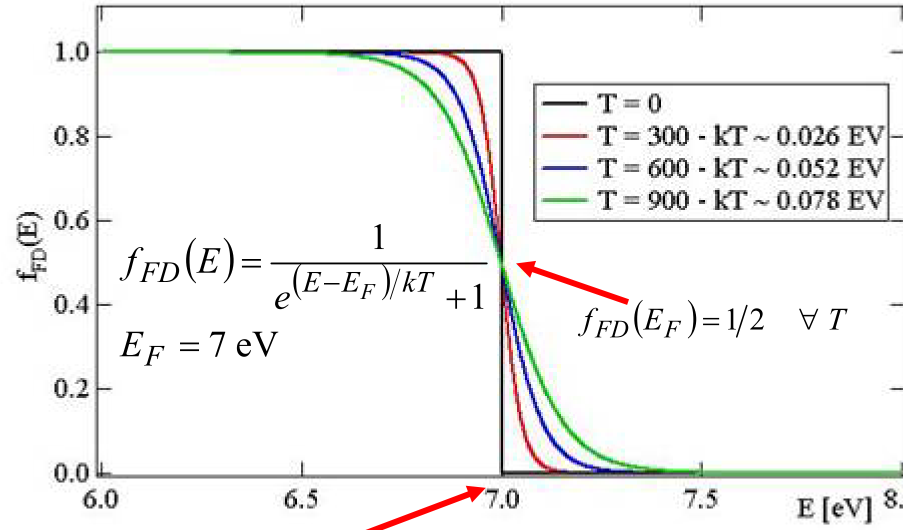
Note that when quantum corrections are not important both distributions are replaced by the classical Maxwell-Boltzmann distribution.

The Fermi Energy

~~Bose-Einstein Distribution for Bosons~~



Fermi-Dirac Distribution for Fermions

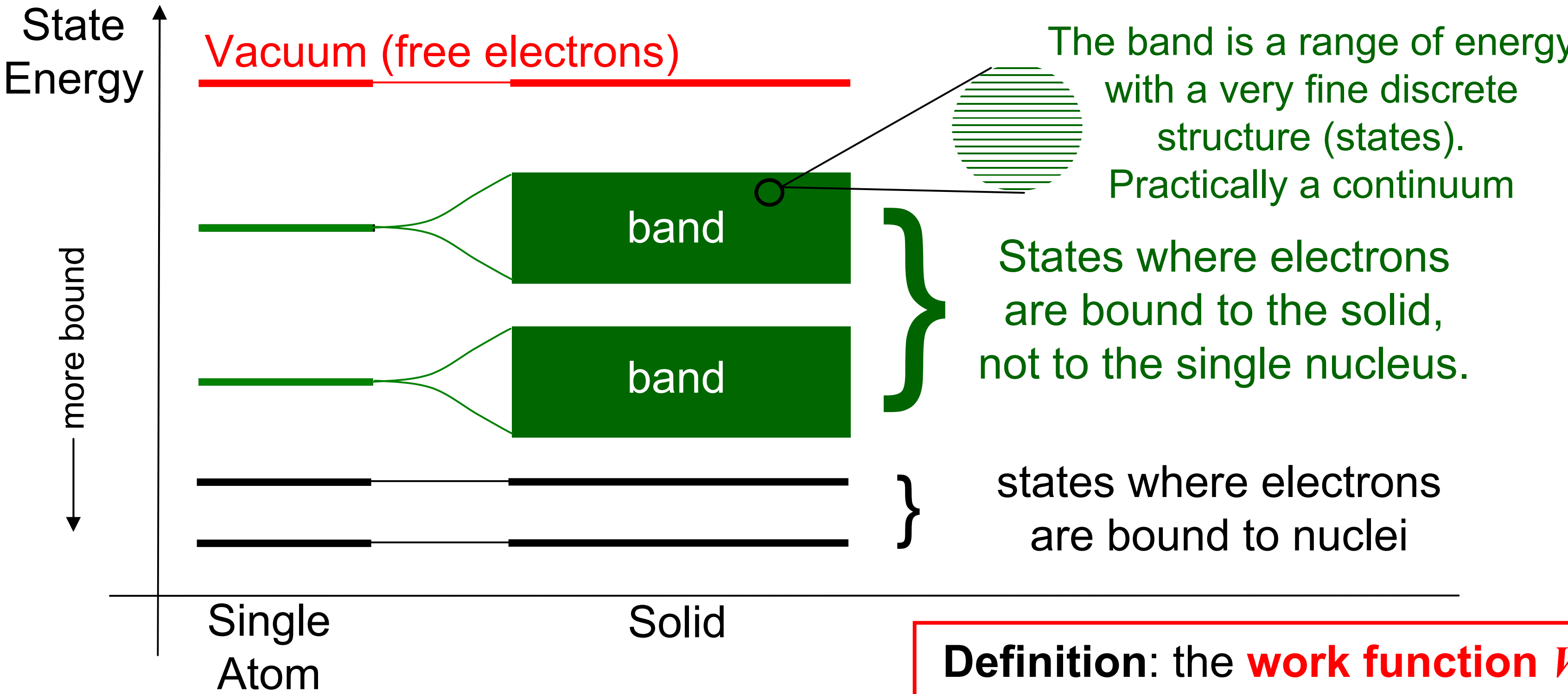


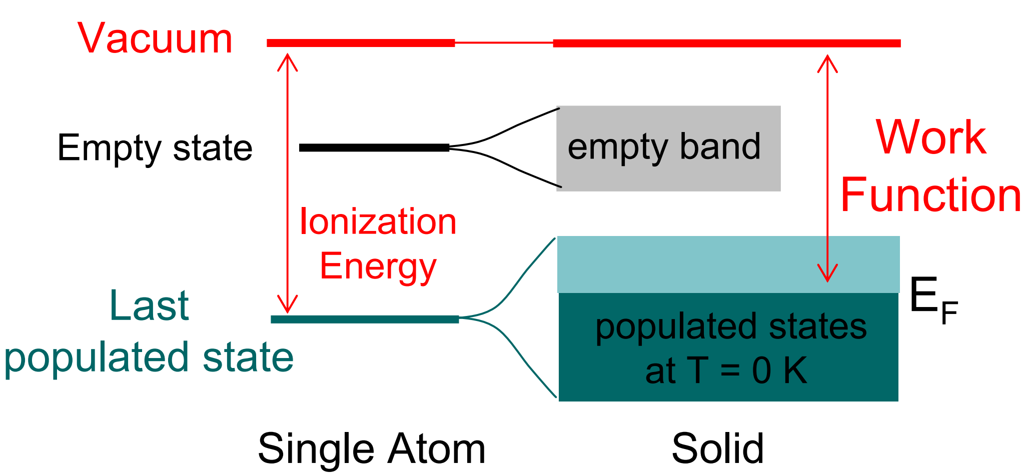
We will deal only with electron sources.
Being electrons fermions (spin 1/2)
we will concentrate our attention in the
Fermi-Dirac distribution

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

We are interested to the case where the system of fermions is **a solid with its electrons**.
The E_F value is a property of the particular material. Example: E_F for copper is 7 eV.

Solids and Work Function





Definition: the **work function** W_F is the energy needed to bring an electron from the Fermi level to the vacuum level (a point at infinite distance away outside the surface).

Example: for Copper (Cu)

E_I = 7.7 eV

W_F = 4.7 eV

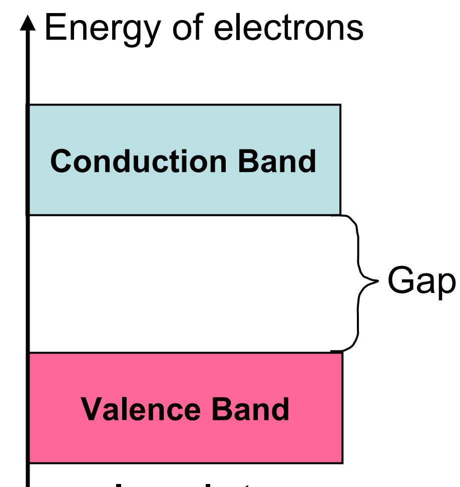
Insulators and Conductors

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. At T = 0 K:

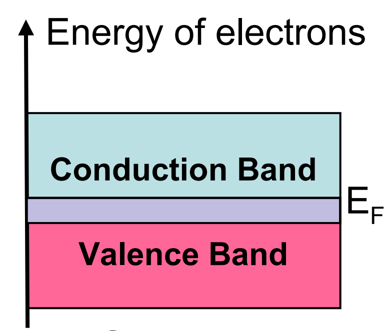
- The valence and the conduction bands are separated by a **gap** with no allowed energy states.
- The valence band is completely filled with electrons.
- The conduction band is totally empty.



a. Insulator

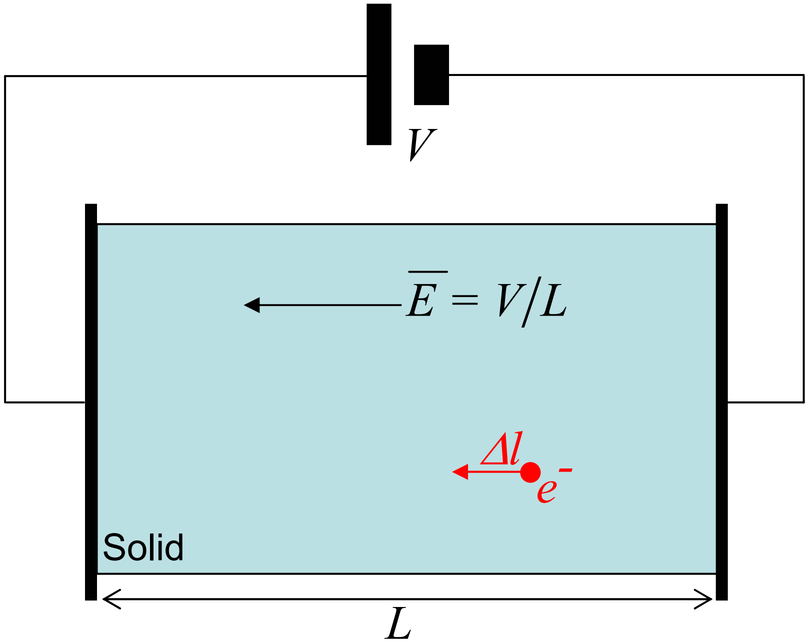
CONDUCTORS. At T = 0 K:

- 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 resulting band are only **partially filled**.

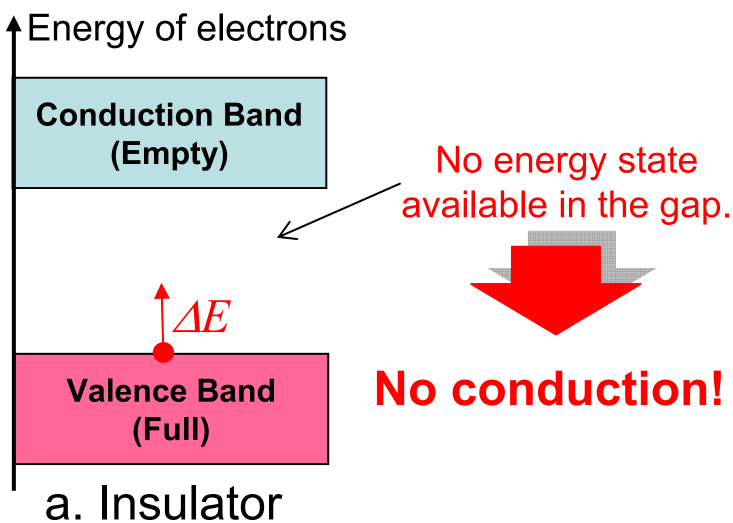


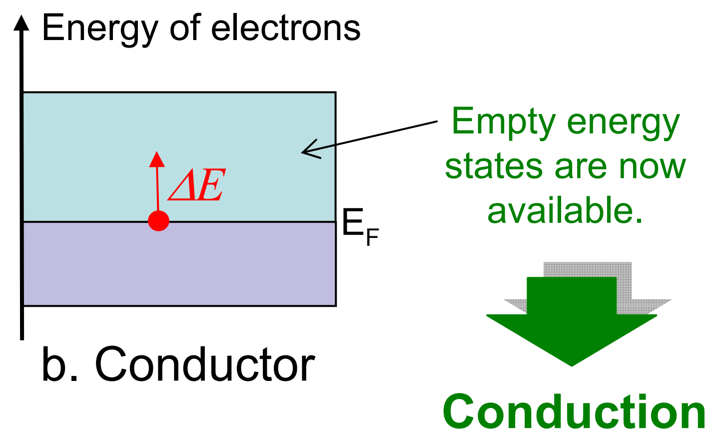
b. Conductor

The Conduction Phenomenon



$$Energy\ Variation = \Delta E = \left|\overline{E}\right|\Delta l = \frac{V}{L}\Delta l$$





Semiconductors: a Special Kind of Insulator

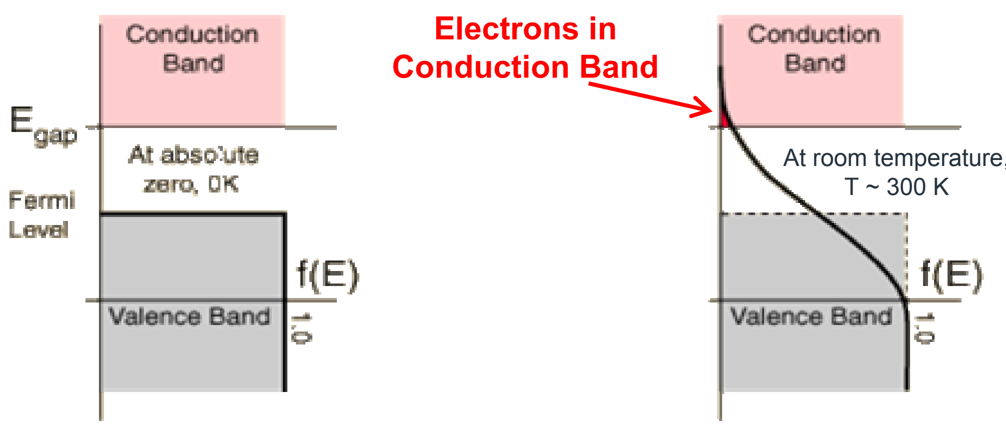
Above absolute zero (T = 0K), the atoms in a crystal (solid) start vibrating.

As a result, some electrons scatter with the atoms gaining extra energy (the larger is T, the larger is the extra energy).

In the valence band of an insulator, if this extra energy is larger than the gap, the electrons are allowed to go in the conduction band.

As a consequence, such a solid undergoes to a **phase transition from insulator to conductor** when the temperature is increased!

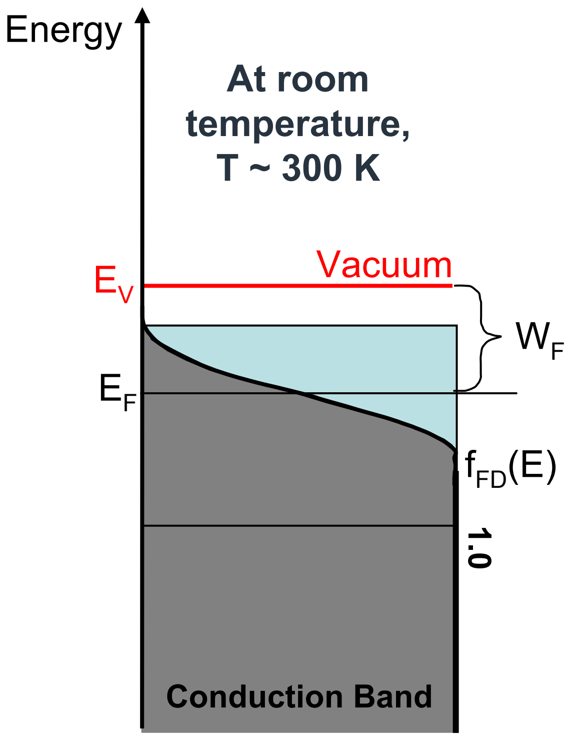
A semiconductor is an insulator with a relatively **small gap** between the valence and conduction bands.
The gap is small enough that at room temperature (T ~ 300K), such a phase transition has already happened.

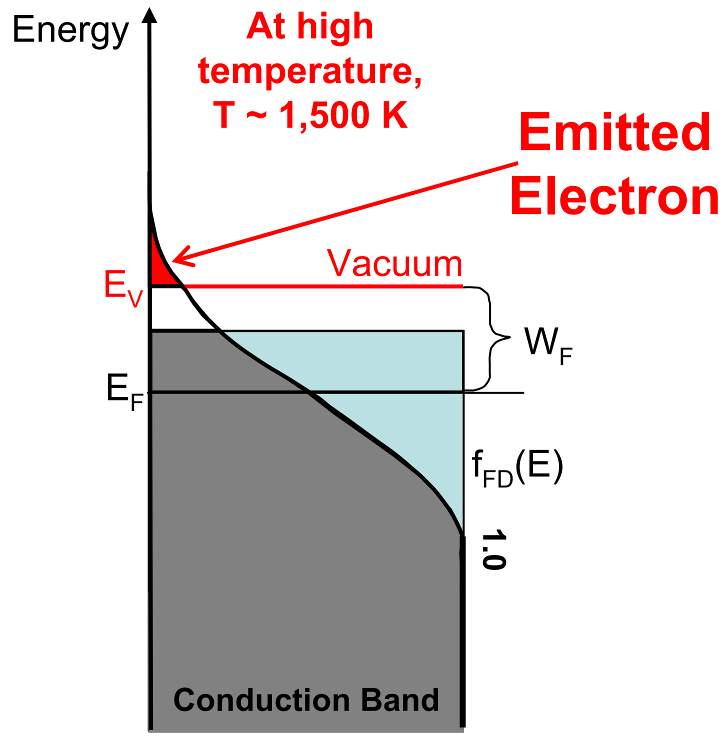


3.

How to extract 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".

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

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

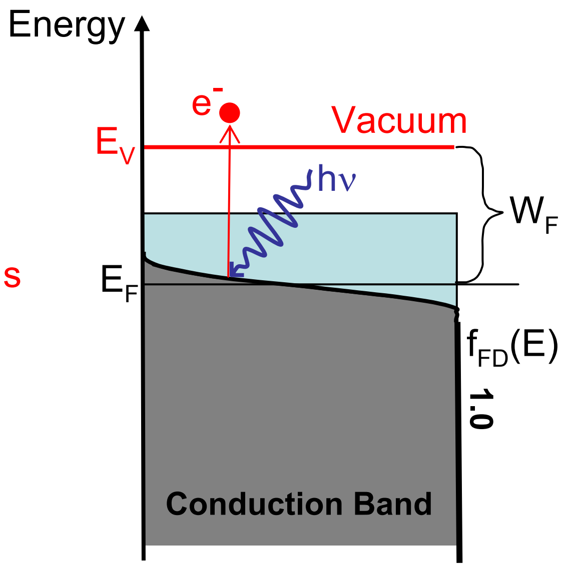
$$w \equiv work \;\; function$$

Photoelectric Effect

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

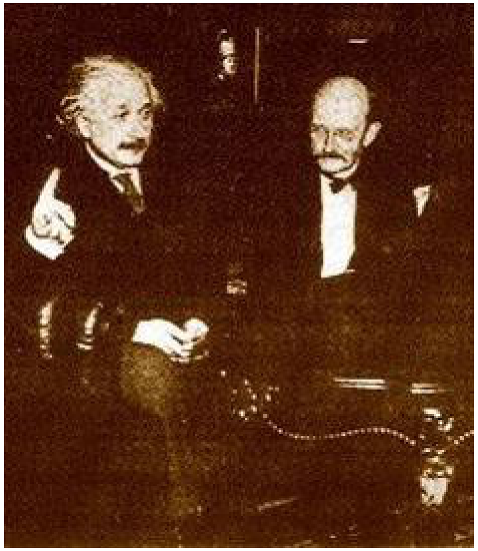
photon frequency

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



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

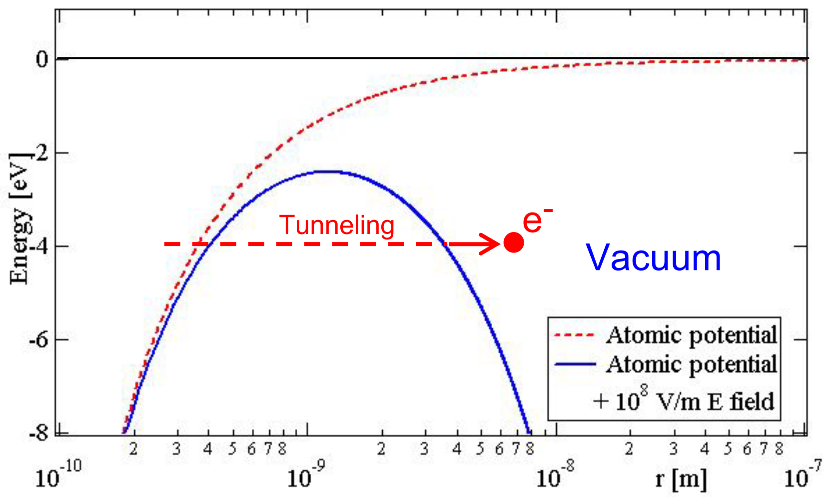
$$T_{e-} = E_{ph} - W_F$$



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



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

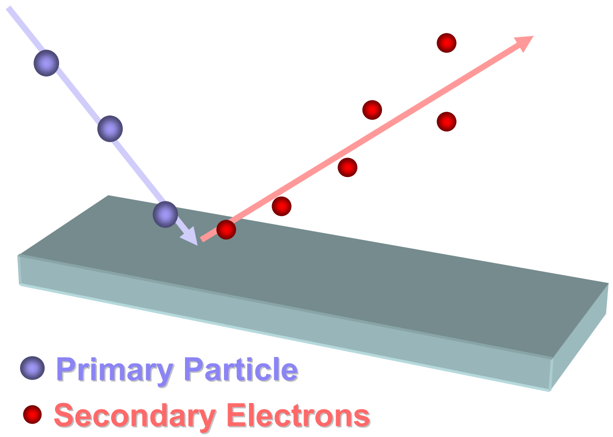
$$\left|\overline{E}\right| = \text{constant}$$

Quantum 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 application of the quantum mechanics theory.

Secondary Emission



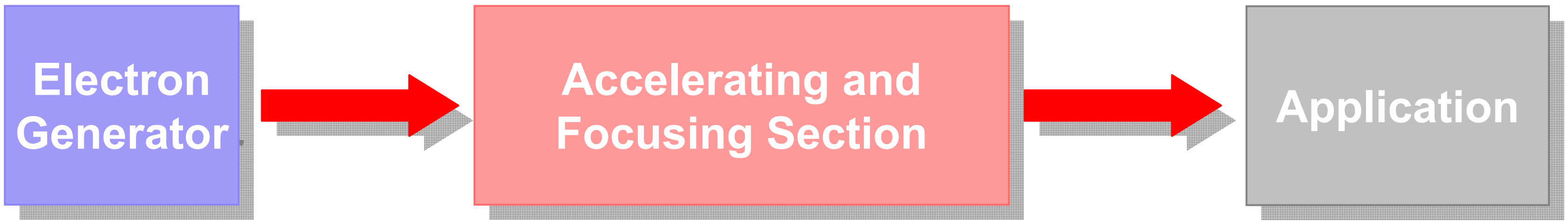
Primary Particles: photons, electrons, protons, neutrons, ions, ...

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

4.

Characteristics of an Electron Source.

The Typical Electron Source



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

Focusing: usually by stationary magnetic fields.

Acceleration: by electric fields.

- Electrostatic
- Pulsed
- Radio Frequency
- "Wakefields"

} Higher gradients (Pulsed, Radio Frequency, "Wakefields")

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.

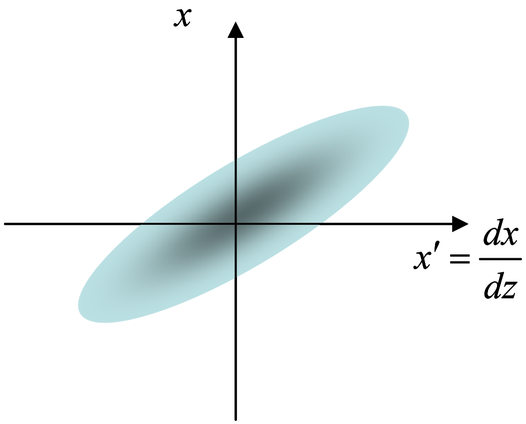
Time Structure:

DC
Pulsed: from single shot to hundreds of kHz
CW: from hundreds of MHz to several GHz

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

Polarization: orientation of the electron spin

The Concept of Emittance



Emittance: volume of the phase space occupied by the beam particles

The emittance is generally a 6D quantity, but in most cases planes can be decoupled and the 2D cases 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

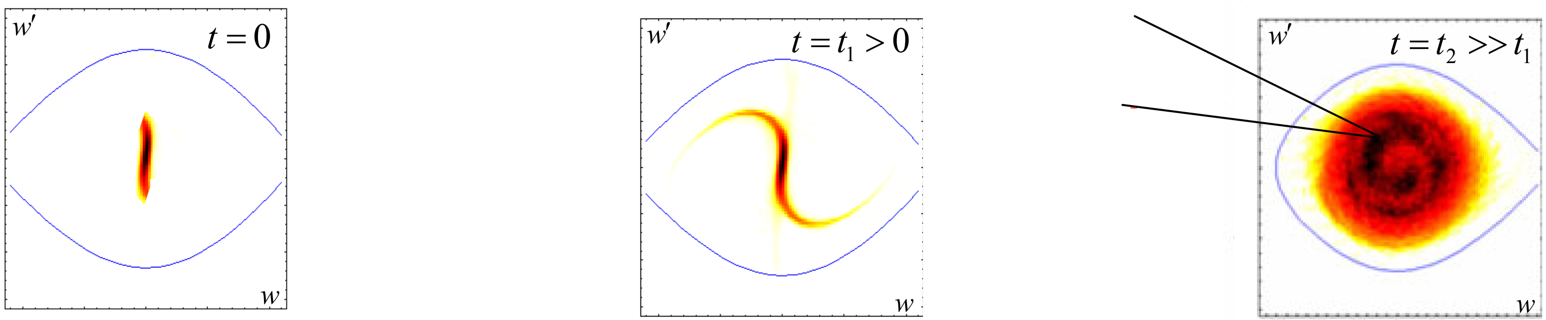
A statistical definition: the r.m.s. Emittance:

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

• For 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 fileds, …)

• This is **not** true for the case of the <u>rms emittance</u>.
In the presence of nonlinear forces the rms emittance is not conserved

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



• The emittance according to Liouville is still conserved.
But the rms emittance calculated for increasing times **increases**.

Brightness and Degeneracy Factor

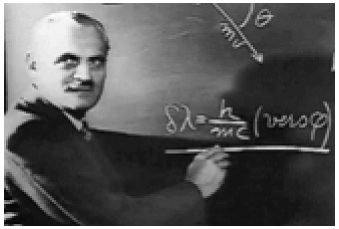
Brightness: phase space density of particles. I.e. number of particles per unit of phase space volume.

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

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

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

This can be interpreted as the fact that the phase space volume occupied by a particle is given by: **$(\lambda_c/2\pi)^3$ =** elementary phase space volume



Degeneracy Factor, δ : brightness in units of elementary phase space volume. Number of particles per elementary volume.

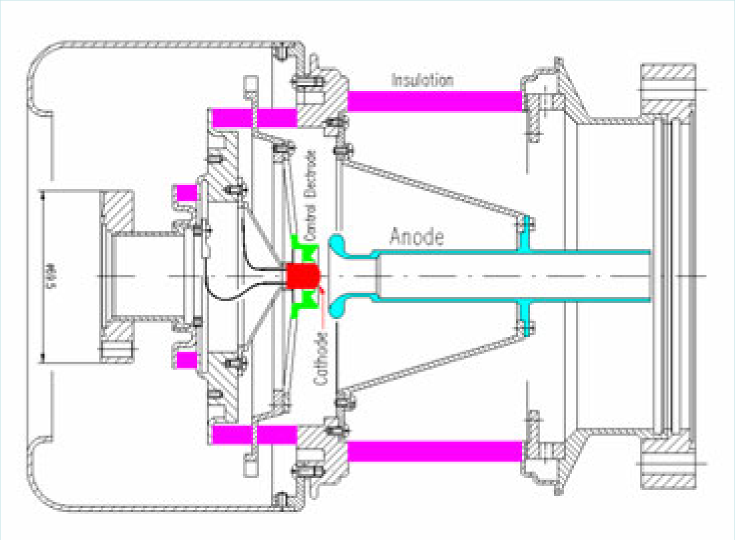
Because of the Pauli exclusion principle the **limit value of δ** is: infinity for bosons and **1 for non polarized fermions**.

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

5.

Examples of Existing Sources.

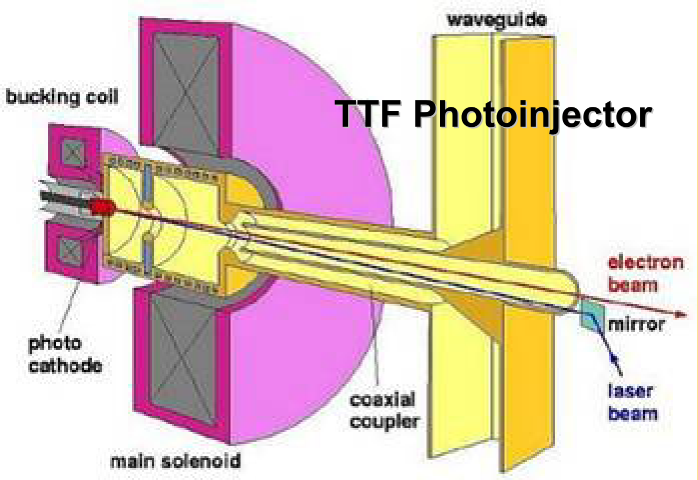
Thermionic Electron Gun



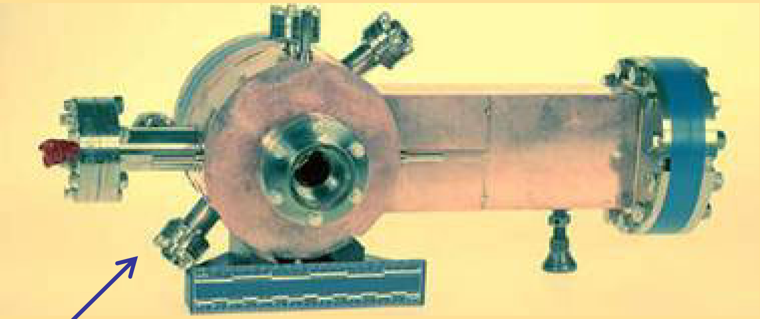
LINAC LAB Gun (Fermi Lab):
E = 100 keV
Current = 2 A max
Application: LINAC Injector

Charge densities ~ 10 A/cm^2

RF Gun with Photocathode



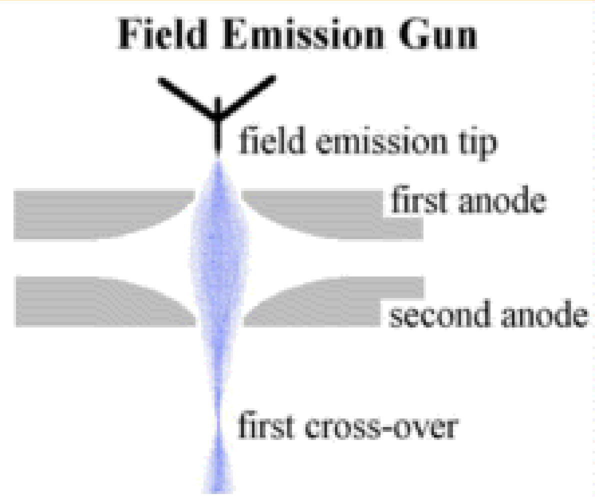
Charge densities up to 10^5 A/cm^2



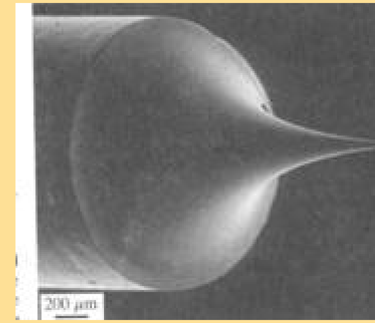
ATF (BNL) Gun III (LINAC Injector):

- Energy ~ 2 MeV
- Normalized rms emittance of 2.6 mm mrad
- Charge of 1 nC
- Pulse length of 10 ps
- RF = 2856 MHz (100 MV/m)

Field Emission Electron Gun



Charge densities up to 10^5 A/cm^2



THERMO Electro Corporation:

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

A Secondary Emission (SEM) Source

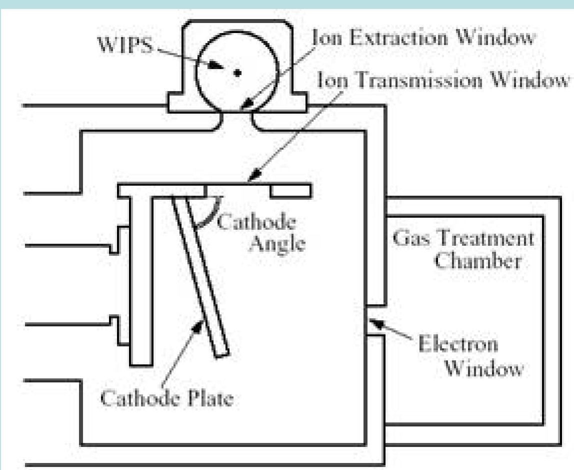


Fig. 1. Secondary emission electron gun.

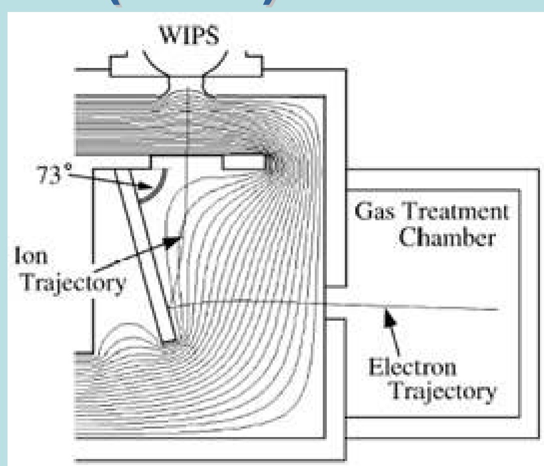


Fig. 4. Equipotential lines, ion and electron trajectories.

E = 80 kV

Current density: 6.4 mA/cm^2

Ion source energy = 10 kV

Very compact

Application: gas treatment.

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

6.

Performance Limiting Factors.

Some Examples of Limitations

High power thermionic guns.

- Average Current. Limits in the cathodes current density.
- Cathode lifetime.
- Cathode thermal emittance limit

RF Guns.

- Repetition Rate. Heat load in the RF structures limits.
- Max electric field. Field emission limits. Dark current.

Field emission guns.

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

Secondary Emission Gun.

- Low current densities.
- High energy spread.

The Ultimate Limit

Practically, most of the edge applications (accelerators, free electron lasers, microscopes, inverse photoemission, ...) are limited by the performance of the electron gun in:

- Emittance
- Energy spread
- Brightness

} Degeneracy factor δ ⇒

- Thermionic: $\delta \sim 10^{-14}$
- SEM: $\delta \sim 10^{-14}$
- Photo-RF guns: $\delta \sim 10^{-12}$
- Field emission: $\delta \sim 10^{-5}$

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

How do we loose all of that ?

Extraction Mechanism

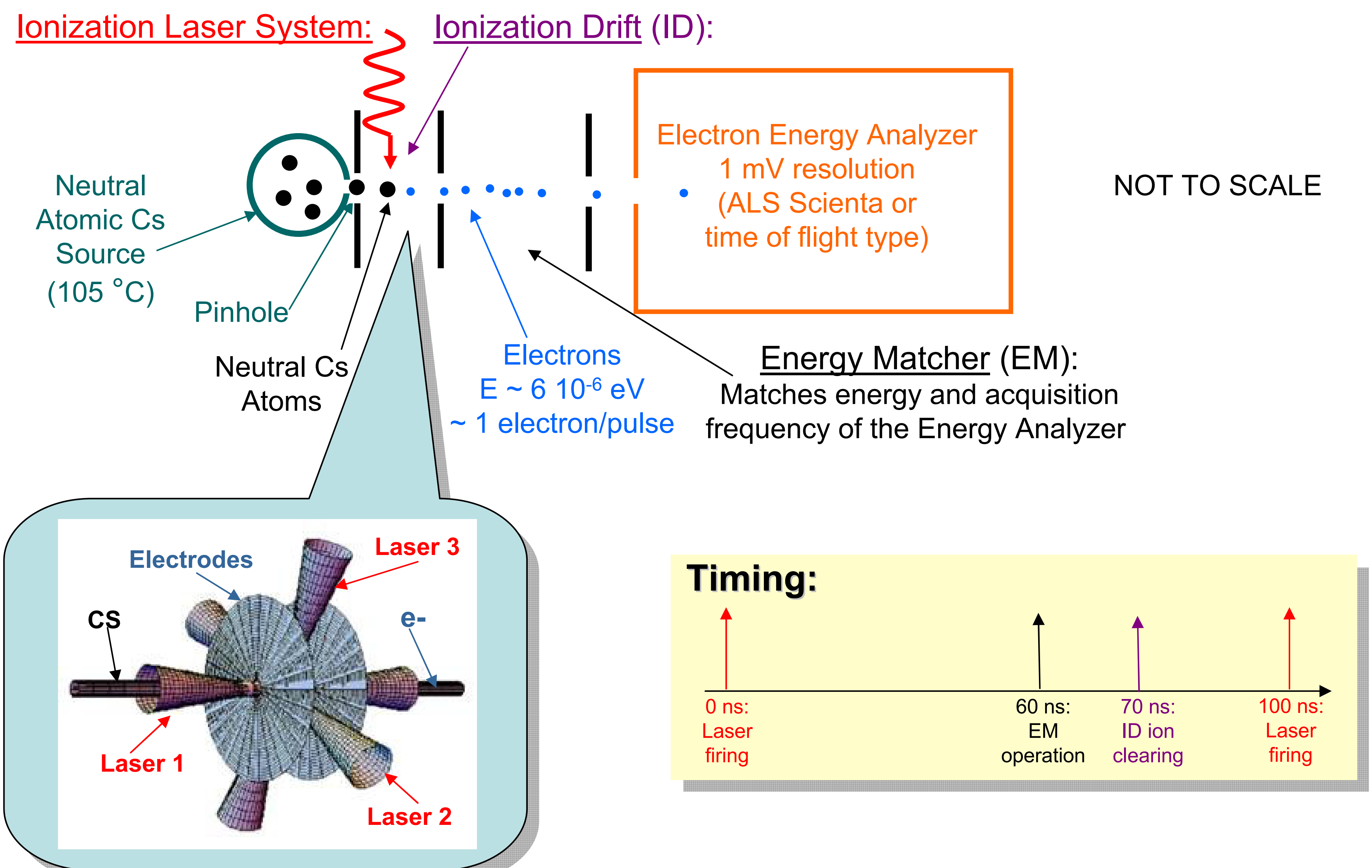
Coulomb interaction

7.

An Example of a new Source Scheme.

High Degeneracy Electron Source

M. Zolotorev, E. D. Commins, J. Oneill, F. Sannibale, W. Wan.
(Lawrence Berkeley National Laboratory and UCB)



Fundamental Concepts

1) Electron Excitation. In the region of well defined and controlled volume (defined by the overlap of the lasers) we ionize on average one alkali atom per laser pulse. The electron in the excited atom will have a total energy close to zero and will start to drift away from the ion.
2) Waiting Period. After the laser pulse, we wait the time necessary for the electron to go far enough from the ion loosing most of its kinetic energy and we apply a short pulsed voltage to extract the electron from the ionization region.
3) Electron Acceleration. In this step, we accelerate the electron up to the energy required by the considered application.
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 it is avoided 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 degeneracy factor for this source is expected to be: $\delta \sim 0.5$