Particle Sources

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Lecture Outline

- Electron Sources
- Protons and Heavy Ions Sources
- Anti-particles Sources
- Neutron Sources
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 "Elektron" that means "Amber".

Fundamental particle: lightest lepton.

\[ m = 9.1095 \times 10^{-31} \text{ kg} \]
(1837 times lighter than a proton)

\[ e = 1.6022 \times 10^{-19} \text{ C} \quad \text{or} \quad 4.803 \times 10^{-10} \text{ esu} \]
Spin 1/2
Atom

Solid

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

Widely used in sources for:

Plasma

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

Very high gradient accelerators research.

Largely used in proton and ions sources

Commonly used in positrons and antiproton sources

electron-positron pairs

Heavier Particle Decay Product

Radiation source
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 \( E \gg kT \), both distributions are approximated by the Maxwell-Boltzmann distribution.
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.

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

**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)
- $E_i = 7.7 \text{ eV}$
- $W_F = 4.7 \text{ eV}$
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.

**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**.
The Conduction Phenomenon

Energy Variation = $\Delta W = e|\overline{E}| \Delta l = e \frac{V}{L} \Delta l$

- **Conduction Band (Empty)**
- **Valence Band (Full)**

Energy of electrons

- **a. Insulator**
  - No energy state available in the gap.
  - No conduction!

Energy of electrons

- **b. Conductor**
  - Empty energy states are now available.
  - Conduction!
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. As a consequence, when the temperature increases a solid can experience a phase transition from insulator to conductor.
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".

\[ J = AT^2 e^{-\frac{w}{kT}} \]

\[ A = \frac{4\pi nk^2e}{h^3} = 1.20173 \times 10^6 \text{ Am}^{-2} \text{ K}^{-2} \]

\( w \equiv \text{work function} \)
Emission by Photoelectric Effect

**Photon Energy**

\[ E_{ph} = h\nu \]

**If** \[ E_{ph} \geq W_F \]

\[ T_{e^-} = E_{ph} - W_F \]

Planck Constant: \( 6.626068 \times 10^{-34} \text{ m}^2 \text{ kg} / \text{s} \)

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

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.

\[ U_p = -\frac{e^2}{4\pi\varepsilon_0 r} + e|E|r \]

where \(|E| = \text{constant}\) and \(|E| > 10^8 \div 10^9 \text{ V/m}\)
Primary Particles: photons, electrons, protons, neutrons, ions, ...

Physical Processes: ionization, elastic scattering, Auger electrons, bremsstrahlung and pair formation, Thomson scattering, ...
The Typical Electron Source

Electron Generator → Accelerating and Focusing Section → Application

Focusing: usually by stationary magnetic fields.

Acceleration: by electric fields.
- Electrostatic
- Pulsed
- Radio Frequency
- “Wakefields”

Higher accelerating fields

Particle Sources

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The Typical Electron Source

Thermionic
Photoelectric
Field emission
Secondary emission

- ....
**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

- **Emittance** and another important quantity …
**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:

\[ \varepsilon_w \geq \frac{\lambda_c}{4\pi} \quad w = x, y, z \]

\[ \lambda_c \equiv \text{Compton wavelength} = \frac{h}{m_0 c} = 2.426 \, \text{pm for electrons} \]

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

**Degeneracy Factor, \(\delta\)**: if the phase space is expressed in elementary phase space volume units, the brightness becomes a dimensionless quantity \(\delta\) 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 \(\delta\)** 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.**
Examples of Electron Sources

Thermionic Electron Gun

LINAC LAB Gun (Fermi Lab):
- $E = 100$ keV
- Current = 2 A max
- Application: LINAC Injector
- Current densities
  - $\sim 10$-100 A/cm$^2$

RF Gun with Photo-Cathode

LCLS RF Gun
- 3 GHz
- 6 MeV
- 20 - 1000 pC
- $\epsilon_n \sim 0.1 - 1 \mu m$
- 120 Hz replate
- 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/cm²
  - Application: Electron microscopes

**A Secondary Emission (SEM) Source**

- Electron energy = 40-80 kV
- Current density: 6.4 mA/cm²
- 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)
Some Examples of Limitations

**Thermionic guns.**
- Average Current. Limits in the cathodes current density.
- Cathode lifetime ("dispenser" cathodes overcome the problem).
- Difficult to control the bunch distributions (especially longitudinally)

**Photo-emission guns.**
- High repetition rate with high gradient limitations. Heat load in the NC RF structures; SRF still in R&D; Break-down in DC guns.
- 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.
- Best brightness but low average current.
- Tip damage, lifetime

**Secondary Emission Gun.**
- Low current densities.
- High energy spread, poor emittance, low brightness.
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

The degeneracy factor inside a metal cathode is \( \sim 1 \). !!!

How do we lose all of that?

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.
In most protons and ion sources a gas of neutral atoms or molecules is “heated” into a plasma state were ions and electrons are dissociated and move independently as free particles.

Heating mechanism can be of various kind: thermal, electrical, electromagnetic (RF, ultraviolet light or intense visible light from a laser).

In a source, the ions are then extracted from the plasma and accelerated.

Neutral gas of practically any specie of atoms can be produced and used in sources. For example, neutral gas of metals can be obtained by heating the solid element inside an oven with an exit aperture.
From the Greek πρωτον that means “first”.

One of the main components of nuclei.

\[ m = 1.672621637(83) \times 10^{-27} \text{ kg} \]
(1837 times heavier than an electron)

\[ e = 1.6022 \times 10^{-19} \text{ C} \quad \text{or} \quad 4.803 \times 10^{-10} \text{ esu} \]

Spin 1/2

Discovered by E. Rutherford in 1919
In Penning discharge sources, Magnetrons and Plasmatrons a high voltage discharge (arc) in a gas at 0.001 to 1 Torr is used for generating the plasma.

In hot cathode sources thermionic emission generates electrons that then ionize the atoms and create the plasma.

In cold cathodes sources a higher voltage is sufficient for sustaining lower density plasmas.

The electric field accelerates the electrons and a magnetic field makes them move on spiraling orbits inside the plasma ionizing more atoms along their trajectory.

The ions then diffuse out from an aperture on the plasma chamber and are accelerated by the voltage applied between anode the extraction electrode (puller).
Electron Cyclotron Resonance (ECR) sources exploit this mechanism. In such sources there is no cathode and the average lifetime and reliability are very good.

- Non-relativistic particles in a constant magnetic field move on a circular trajectory at a constant revolution frequency independently from their energy (cyclotron principle):
  - Let’s consider a plasma immersed in a solenoidal field. Applying an electromagnetic field with frequency \( \omega_0 \), the electrons in the plasma will resonate at their cyclotron frequency gaining energy from the field.
  - The electrons will describe spiraling orbits with increasing radius and ionizing additional atoms along their path.
  - Electron Cyclotron Resonance (ECR) sources, exploit this mechanism. In such sources there is no cathode and the average lifetime and reliability are very good.
  - Multipolar magnets (quadrupoles, sextupoles octupoles) are used to improve the confinement for the electrons, increasing the rate of ionization.
Negative ion (NI) sources, generally use the same plasma-based schemes described for the generation of positive ions (penning, magnetrons, ...).

The physics of NI sources is not fully understood. Three types of sources are generally used: charge exchange, surface and volume.

Double charge exchange of positive (or neutral) ion beams with alkali metal vapor targets was once a favored method of NI production. It is not a very efficient scheme, but is still very useful for producing “exotic” species of negative ions.

In a surface source, ~ a mono-layer of Cesium on the plasma chamber walls strongly increase the production of H-. Collision of the plasma particles with the Cs surface generates desorption of ions including the desired H-.

In Volume Sources, scattering between the gas molecules can generate NI. For example, measurements of H- ions in large-volume, low-pressure hydrogen discharges showed densities much larger than those predicted by theory.

NI find very important applications in Tandems and in injecting into accumulator rings by stripping the charge: the process is non-hamiltonian and the the Liovilie theorem does not apply.
According to quantum field theory, a photon can “oscillate” between the phase of photon and the one of a pair of virtual particle and relative antiparticle. (electron-positron, proton-antiproton, …)

Virtual particles cannot be detected and the total energy of the pair ($\Delta E$) can be arbitrarily large as long as its lifetime ($\Delta t$) is short enough to respect the Heisenberg Uncertainty Principle.

Necessary condition for a virtual particle pair to became real is that the energy of the photon must be equal or larger than the equivalent in energy of the rest mass of both the particle and the antiparticle.

If during this “virtual particle phase”, a photon with the proper energy crosses a region with a strong field (in proximity of nucleus for example) the interaction between the field and the pair can allow for the virtual particles to separate from each other and become real particles.
In existing positron sources, the high energy photons required for the electron-positron pair production (~ 1.02 MeV) are generated by impinging a high current electron beam on a high Z metallic target.

The electrons penetrating the material are deflected by the nuclei and radiate high energy photons. These photons can then interact with the nuclei and if they have the right energy can finally generate the pairs.

The newborn positrons leaving the target can be separated from the electrons (by magnetic fields for example), captured and accelerated to higher energies in a dedicated section of the linac optimized for the task.

Schemes under study for linear colliders use high energy beam inside unduLators to generate the 1+ MeV photons
Antiproton Sources

- Existing sources of antiprotons (Fermilab and CERN) exploit the proton-antiproton pair production mechanism when high energy protons scatters on the nuclei of a metallic target generating 2+GeV photons, that then generate the proton-antiproton pair.

Production rate is very small:
- $\sim 10^{-5}$ antiproton/proton
- $\sim 10^{11}$ antiproton/hour
• The more efficient neutron sources are nuclear reactors. However, their development is very limited because international treaties prohibits civilian use of highly enriched uranium U$_{235}$.

• An alternative scheme for generating neutrons is given by the so-called spallation neutron source, where a high energy-high power accelerator produces pulsed neutron beams by bombarding a target with intense proton beams.
  • Spallation sources are pulsed neutron sources.

1 GeV Protons at target
1.4 MW Proton Power at the Target
24 kJ/pulse
$1.5 \times 10^{14}$ protons /pulse

$> 1.5 \text{ G\$}$
• In a laser pulse, $10^8$ photons are all in the same state with the same energy level. Can that statement be correct? Can a similar statement for electrons be correct? Explain your answers.

• Calculate the RF frequency for an ECR H$^+$ source with a solenoidal field of 0.5 T.

• Calculate the minimum energy in eV units that a photon should have to potentially generate a proton-antiproton pair.

• Also estimate the maximum lifetime that a virtual pair proton-antiproton with 2.2 GeV total energy can have.

• Estimate the number of hours required to store 100 mA of antiprotons in the Tevatron at the Fermilab. The ring circumference is ~ 6400 m, the beam energy is 980 GeV. Assume an injection rate of about $6.5 \times 10^{11}$ antiprotons/hour.
Backup Slides
The Berkeley normal-conducting scheme satisfies all the LBNL FEL requirements simultaneously.

- 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/cm²
- 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 $\lambda_{RF}$ 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.