PARTICLE GENERATION

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  - Electron guns
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FERMI AND BOSE DISTRIBUTIONS

- Recall from Quantum Mechanics that Fermions (half-integer spin) and Bosons (integer spin) behave differently:

No fermions can occupy the same state
(Pauli Exclusion Principle)

Bosons don’t have this restriction!

FERMI AND BOSE DISTRIBUTIONS

- Recall from Quantum Mechanics that Fermions (half-integer spin) and Bosons (integer spin) behave differently
- These differences mean that they obey different equations of state and have different distributions:

$$f(E) = \frac{1}{e^{(E-\mu)/kT}+1}$$

Fermi-Dirac Distribution

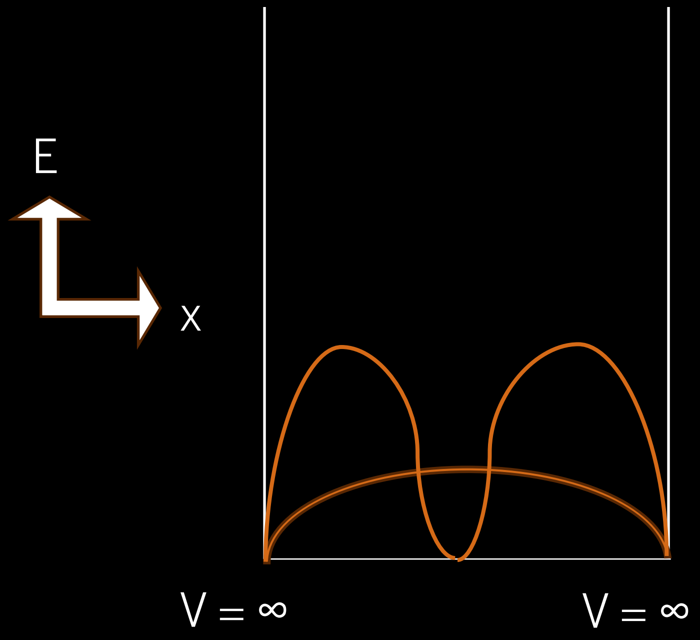
$$f(E) = \frac{1}{e^{E/kT}-1}$$

Bose-Einstein Distribution

Where:

E: Energy
T: Temperature
k: Boltzmann constant
μ: Chemical potential

FERMI PARTICLES IN A POTENTIAL WELL



- Recall that particles in a potential well make distinct energy states

  e.g., two examples shown at left

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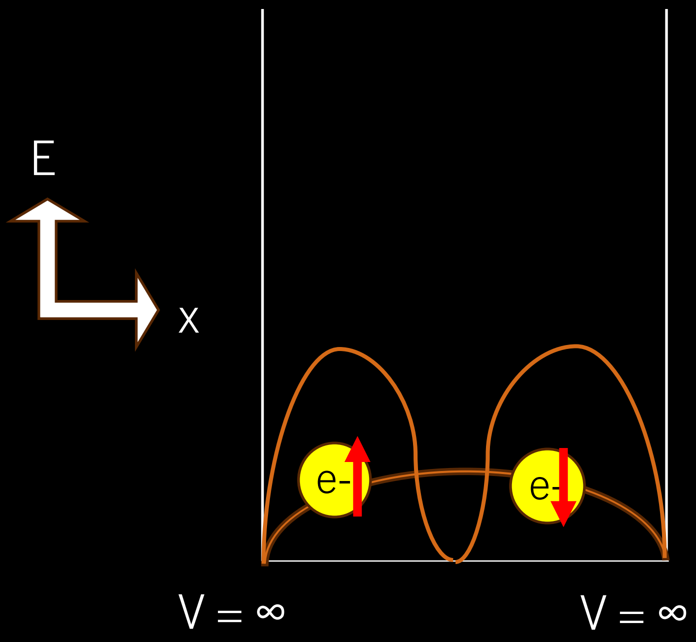

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  These are populated with a maximum of only two electrons each, up and down

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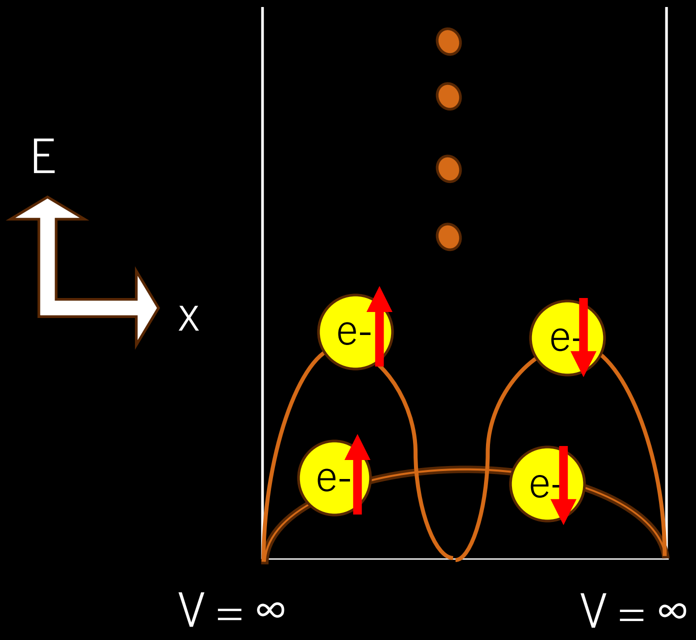


- Recall that particles in a potential well make distinct energy states

  e.g., two examples shown at left

  These are populated with a maximum of only two electrons each, up and down

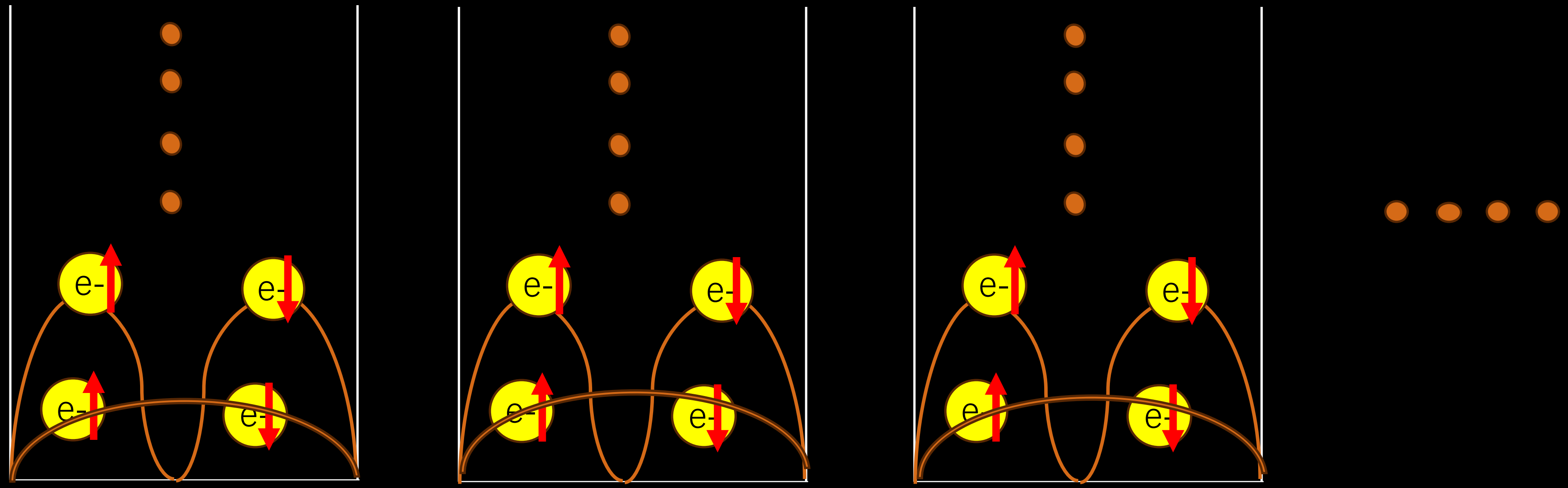
  → Even at T=0, higher energy states are filled

APPLICATION TO MATERIALS: BAND STRUCTURE

- Electrons in a solid preserve this behavior:

  consider solids as a lattice of electrons all put into near-identical potential wells

- Similar energy levels in each lattice well will form distinct energy bands



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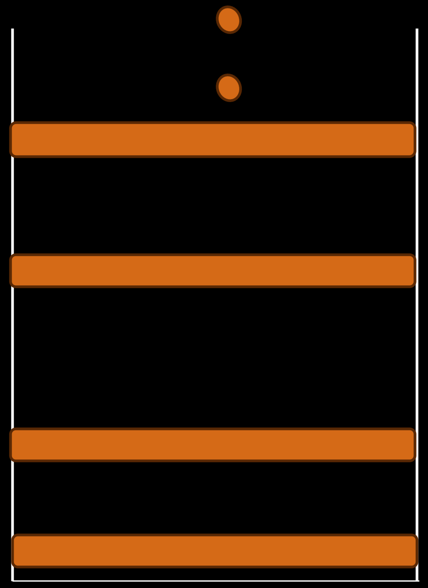

Electrons fill bands in the same way as they do energy levels.

The maximum level occupied by electrons at T=0 is known as the Fermi Level.

APPLICATION TO MATERIALS: BAND STRUCTURE

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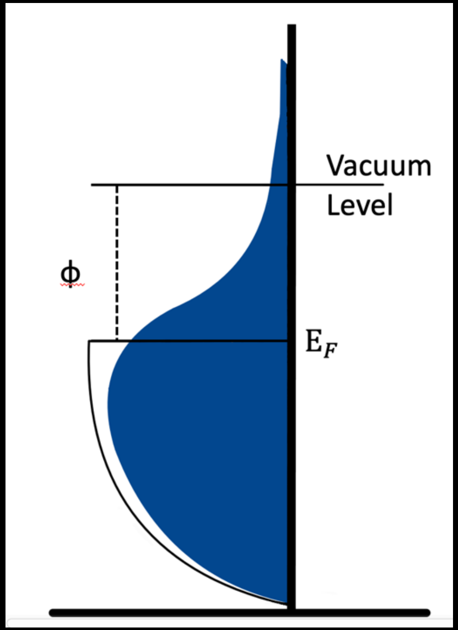


Electrons fill bands in the same way as they do energy levels.

The maximum level occupied by electrons at T=0 is known as the Fermi Level.

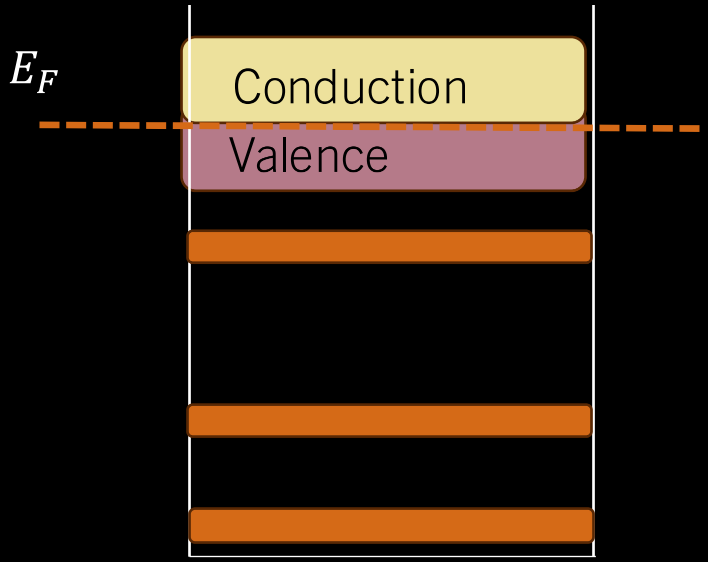
At T ≠ 0, they obey the Fermi-Dirac distribution shown on slide 4.

APPLICATION TO MATERIALS: BAND STRUCTURE

The band structure of a material determines its characteristics as a conductor, semiconductor, or insulator:

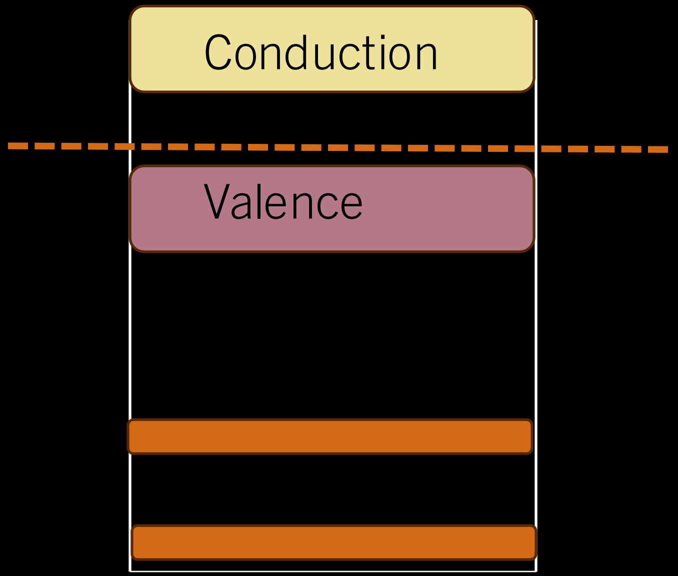
Metal (conductor):

E_F is inside a band
conduction and valence bands overlap
This band is only partially filled



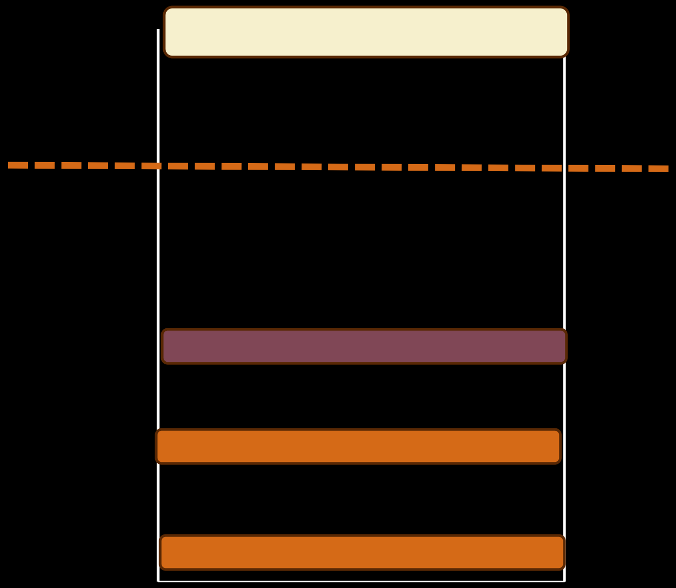
Semiconductor:

E_F is between bands, but relatively close to one.
Valence band is filled.



Insulator:

Valence and conduction bands are far apart; E_F is far from any band.



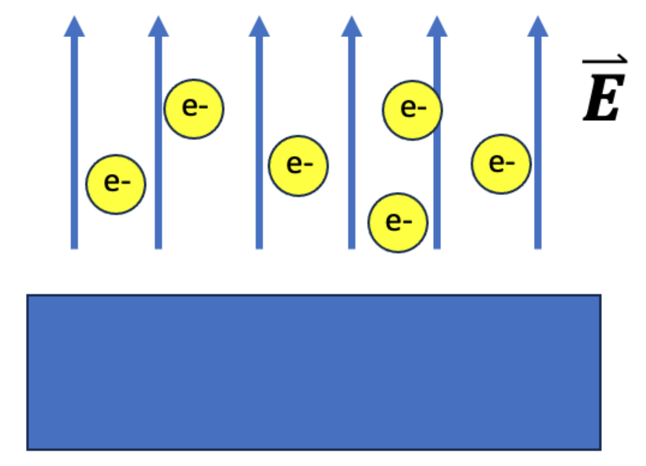
The energy gap between the conduction and valence bands is known as the *band gap.* This range has no allowable energy states, but in semiconductors electrons can be excited into the conduction band.

TYPES OF ELECTRON EMISSION

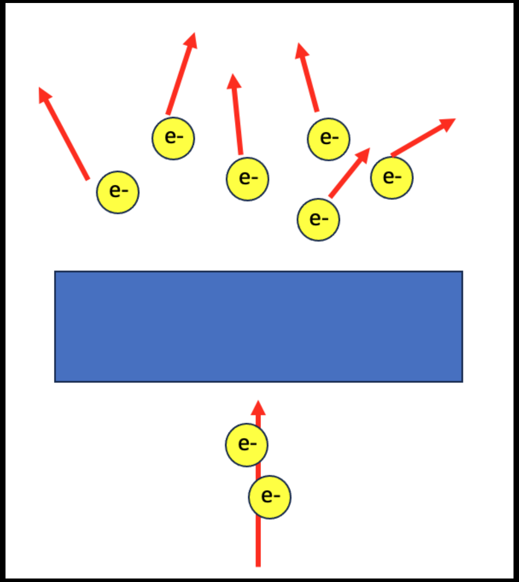
How do we excite electrons to overcome the band gap?

Thermionic

Photoelectric



Field

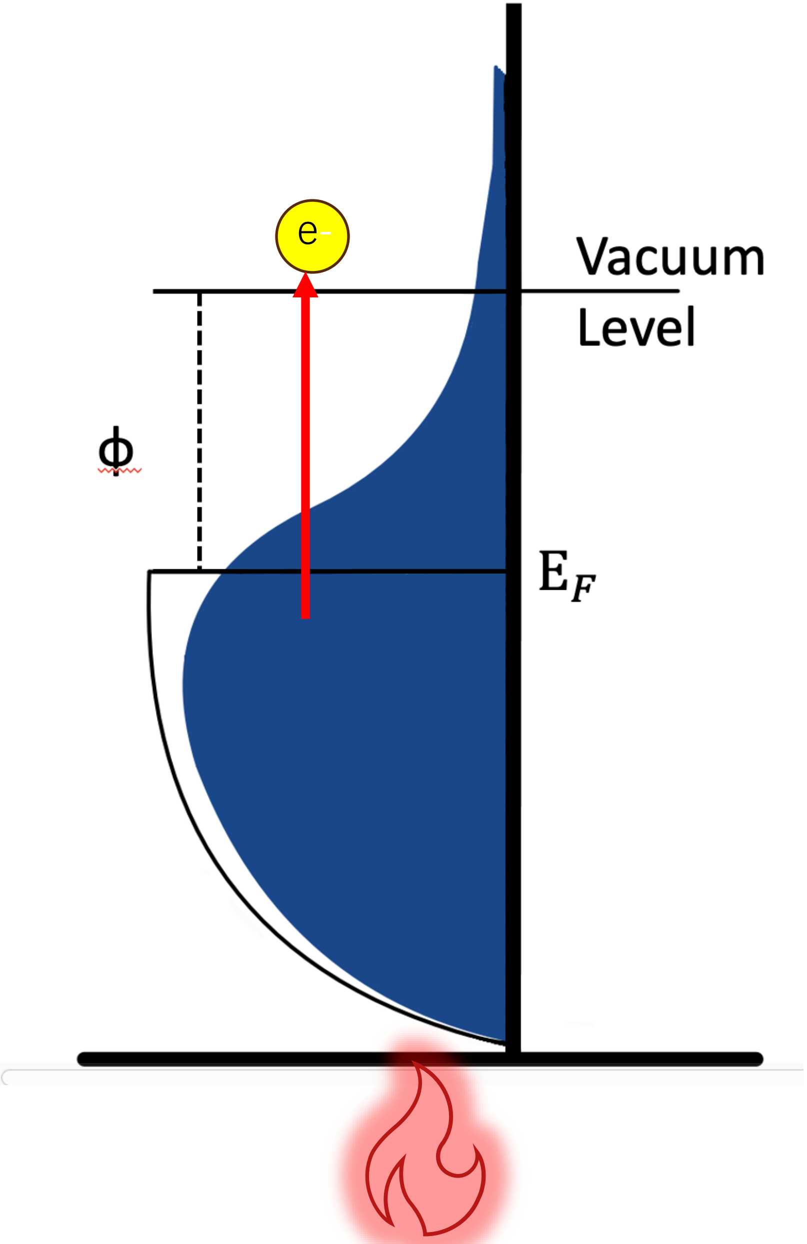


Secondary

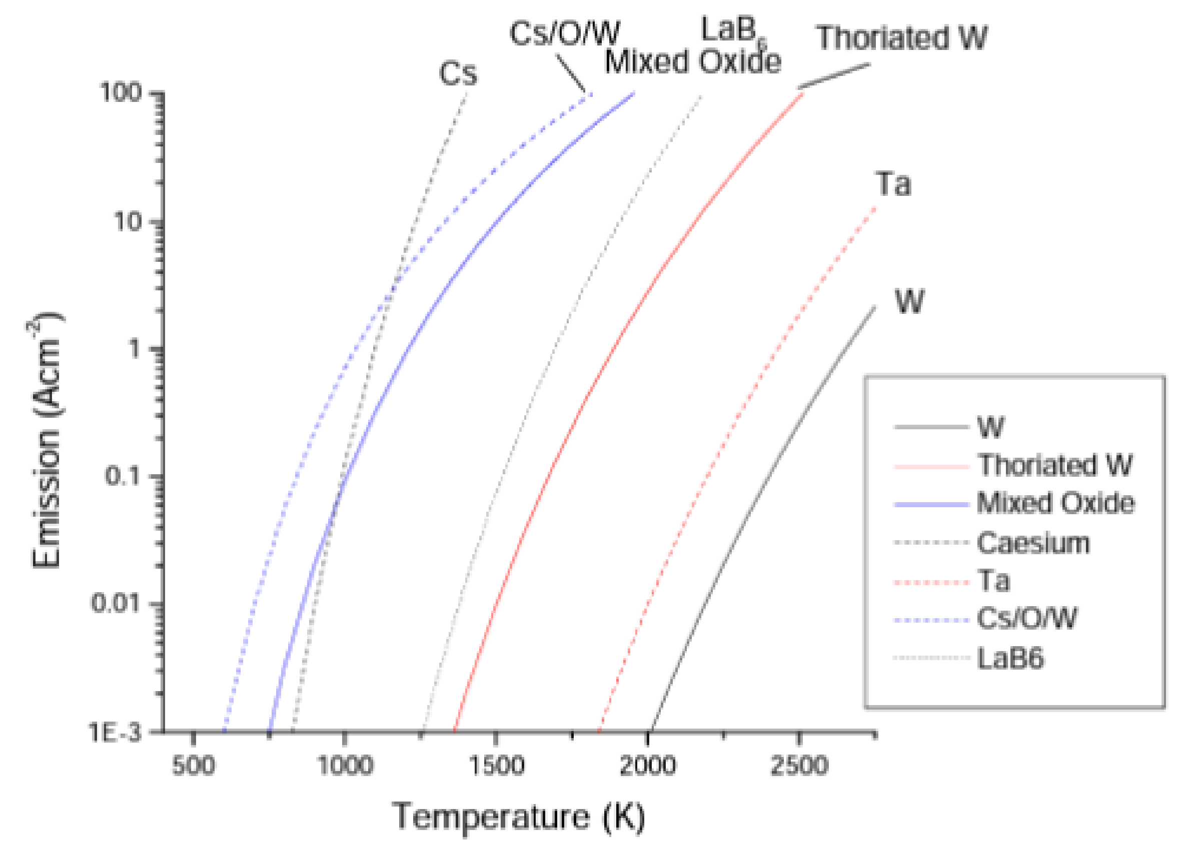
THERMIONIC EMISSION

- Increase the temperature to provide energy to electrons to overcome the band gap and escape into the vacuum
- The *Work function* ϕ is defined as the difference between the vacuum level and the Fermi level. That is, ϕ is the energy needed to remove an electron from the material into the vacuum.

Providing energy greater than the work function can stimulate emission of electrons



THERMIONIC EMISSION



Thermal emission as a function of temperature for several common cathode materials [1]

RICHARDSON-DUSHMANN EQUATION

- Emission of electrons from a material is characterized by the Richardson-Dushmann Equation:

$$J = AT^2 e^{-\frac{\phi}{kT}}$$

Where A is a thermionic emission constant given by

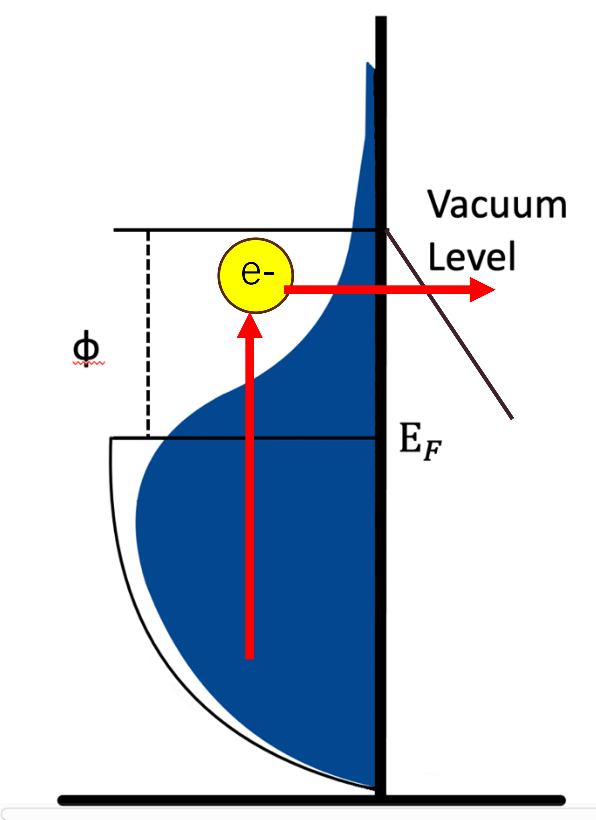
$$A = \frac{4\pi emk^2}{h^3}\ [\mathrm{A}\, m^{-2} K^{-2}]$$

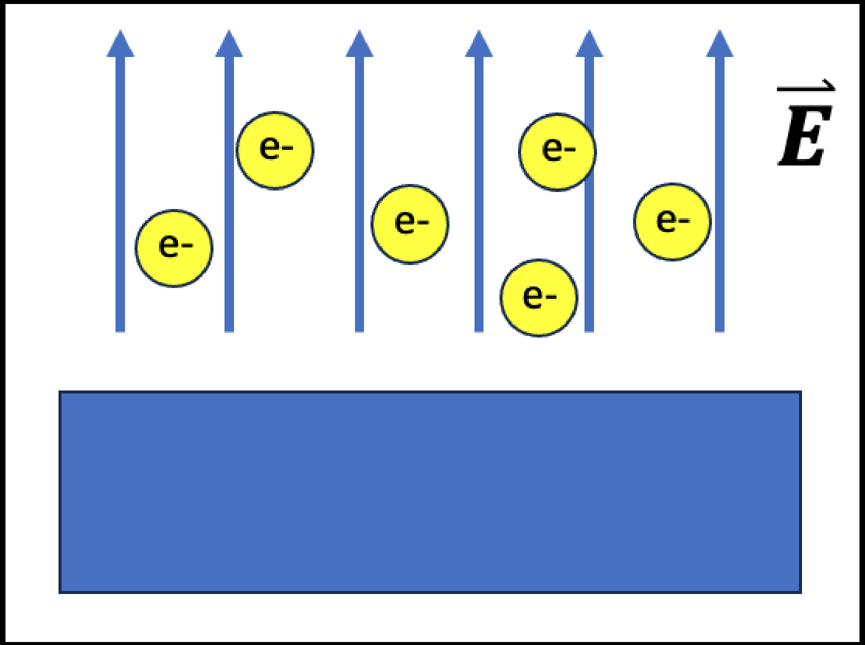
FIELD EMISSION

- We can also stimulate emission by applying a high electric field to the material.

The field serves to lower the potential barrier between the material and vacuum, allowing electrons to tunnel more easily.

"High" is O(100 MV/m)





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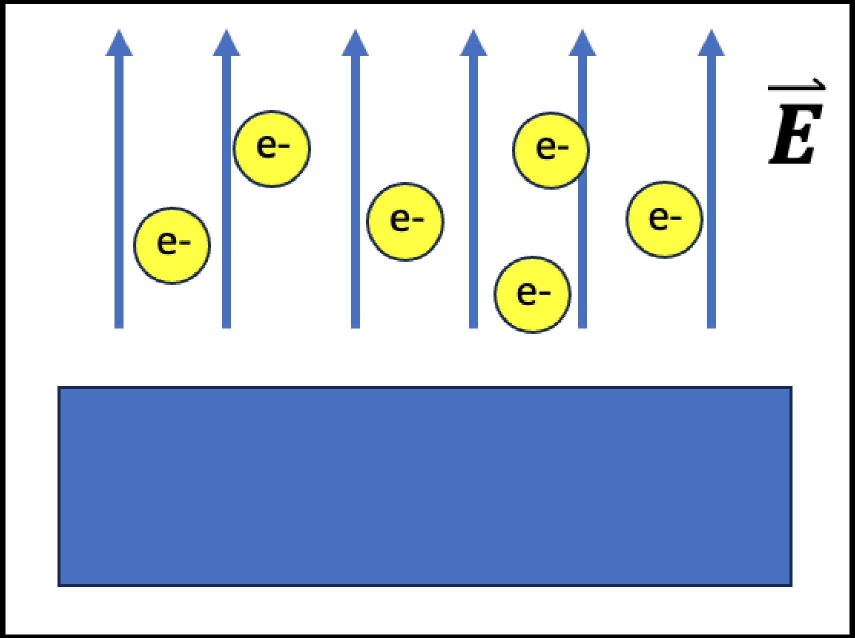


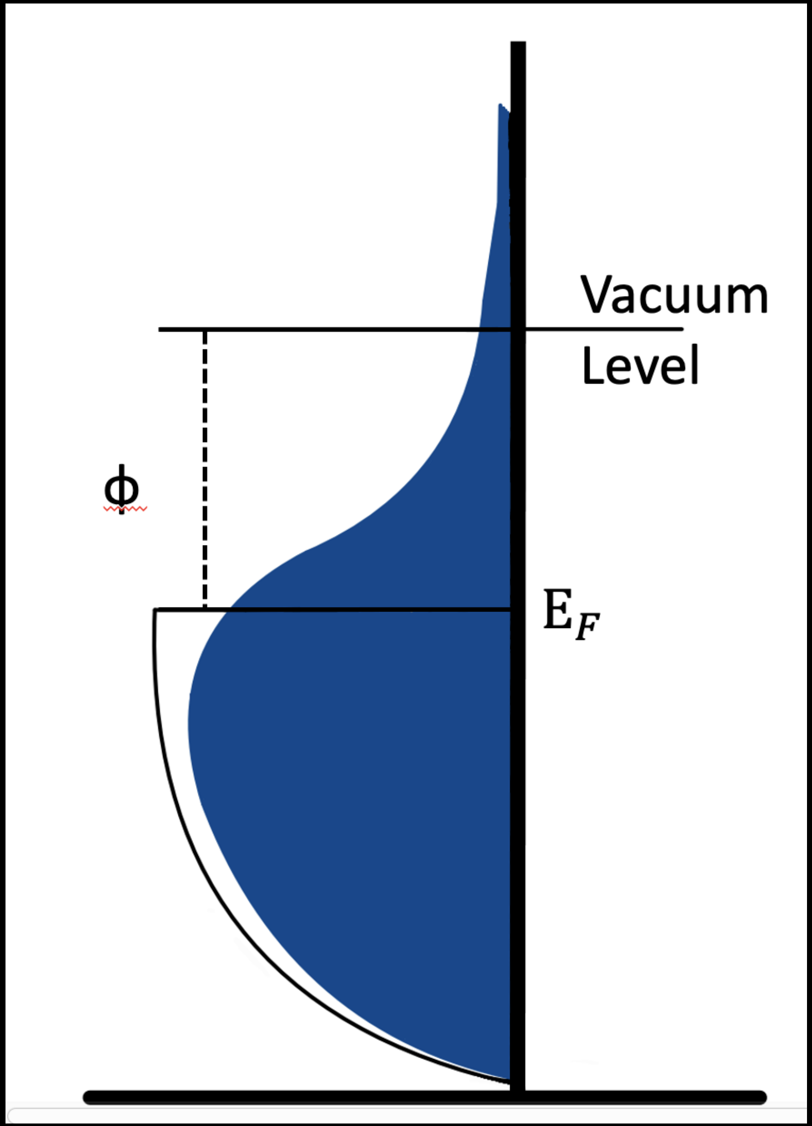
$$J = e\int_0^\infty \underbrace{\eta(\epsilon_z)}_{\text{Electron Density}}\underbrace{P(\epsilon_z)}_{\text{Tunneling Probability}}d\epsilon_z$$

Which we can write as: (Fowler-Nordheim Eq.)

$$J = \frac{e^3E^2}{8h\pi\phi}e^{-\frac{8\pi\sqrt{2m}}{3heE}\phi^{3/2}}$$

PHOTOELECTRIC EMISSION

- Use a source of photons to excite electrons to the conduction band and into vacuum.



PHOTOELECTRIC EMISSION

- Use a source of photons to excite electrons to the conduction band and into vacuum.
- Operates based on the Photoelectric effect – incoming photons must have an energy greater than the work function:

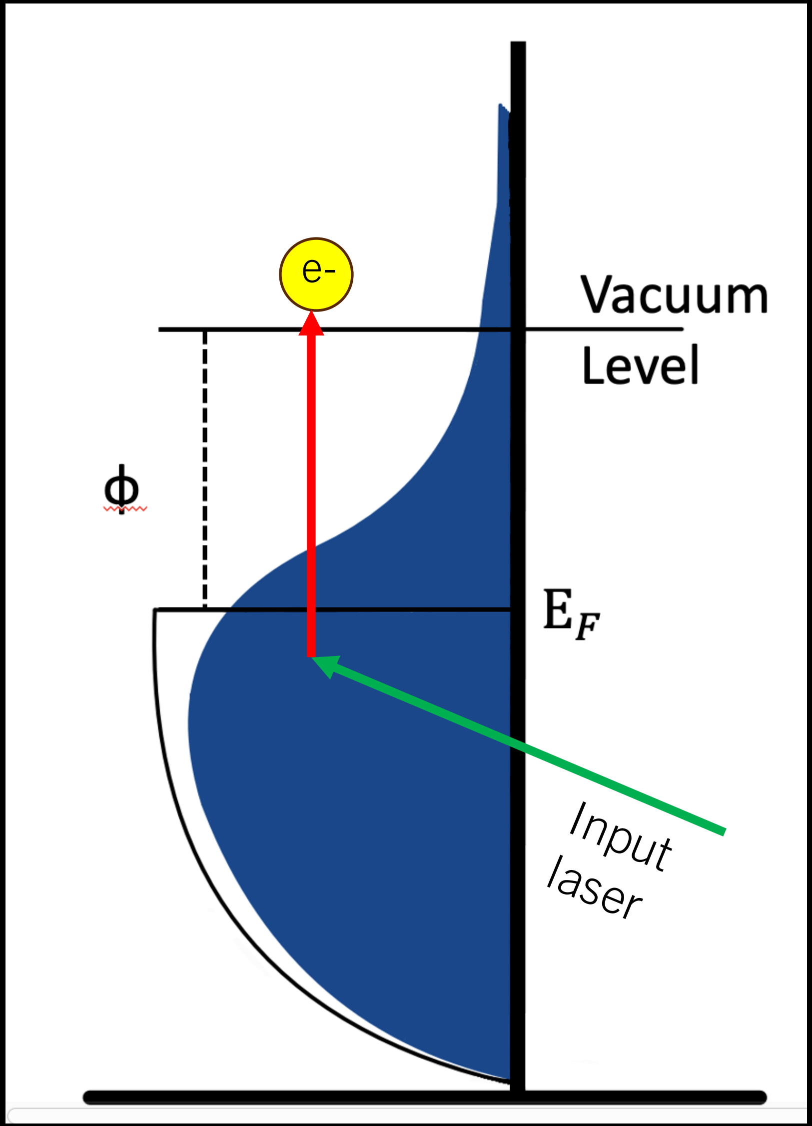
$$e > \ hv_0 = \ \phi$$

Or in terms of wavelength λ,

$$\lambda < \frac{c}{v_0} = \frac{hc}{\phi}$$

With a total current given by

$$J = \frac{4\pi emkT}{h^3} P \int_{E_0 - hv}^{\infty} ln[1 + \ e^{\frac{\mu - \epsilon_Z}{kT}}]\, d\epsilon_Z$$



QUANTUM EFFICIENCY

- We can quantify how well electrons are extracted from a photocathode by defining a *quantum efficiency* η.
- This parameter represents the number of electrons that are produced per incident photon:

$$\eta = \frac{N_e}{N_\gamma}$$

which can be expressed wrt the input laser power and wavelength as

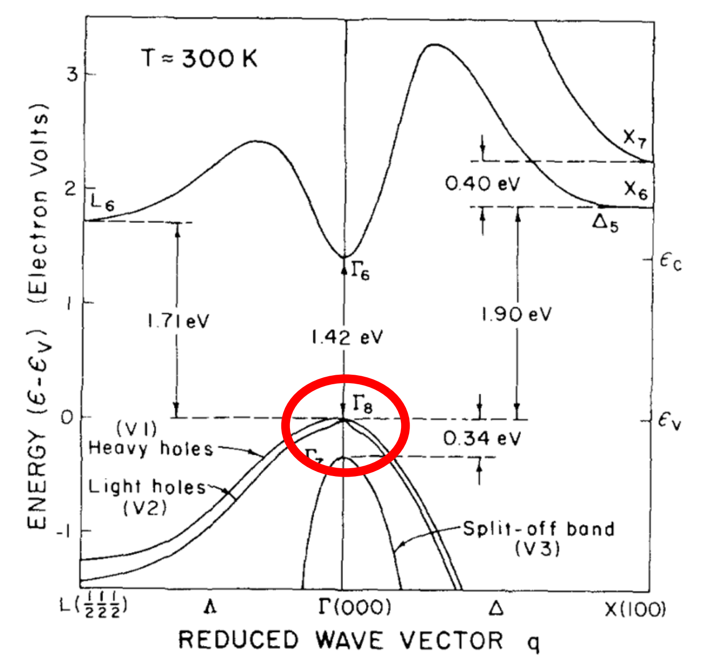
$$\eta\ [\%] = 124\ \frac{J\ [nA]}{P[\mu W]\lambda\ [nm]}$$

Where *J* is the measured output current.

POLARIZED SOURCES

- Using a circularly-polarized laser, we can induce emission of electrons selectively chosen for their magnetic spin state.
- This takes advantage of the structure of GaAs semiconductor band structure: 2 bands near the top of the valence band can produce selectively polarized electrons. By inducing a strain in the GaAs lattice structure, we can suppress one and pick the polarization state we want.

POLARIZED SOURCES



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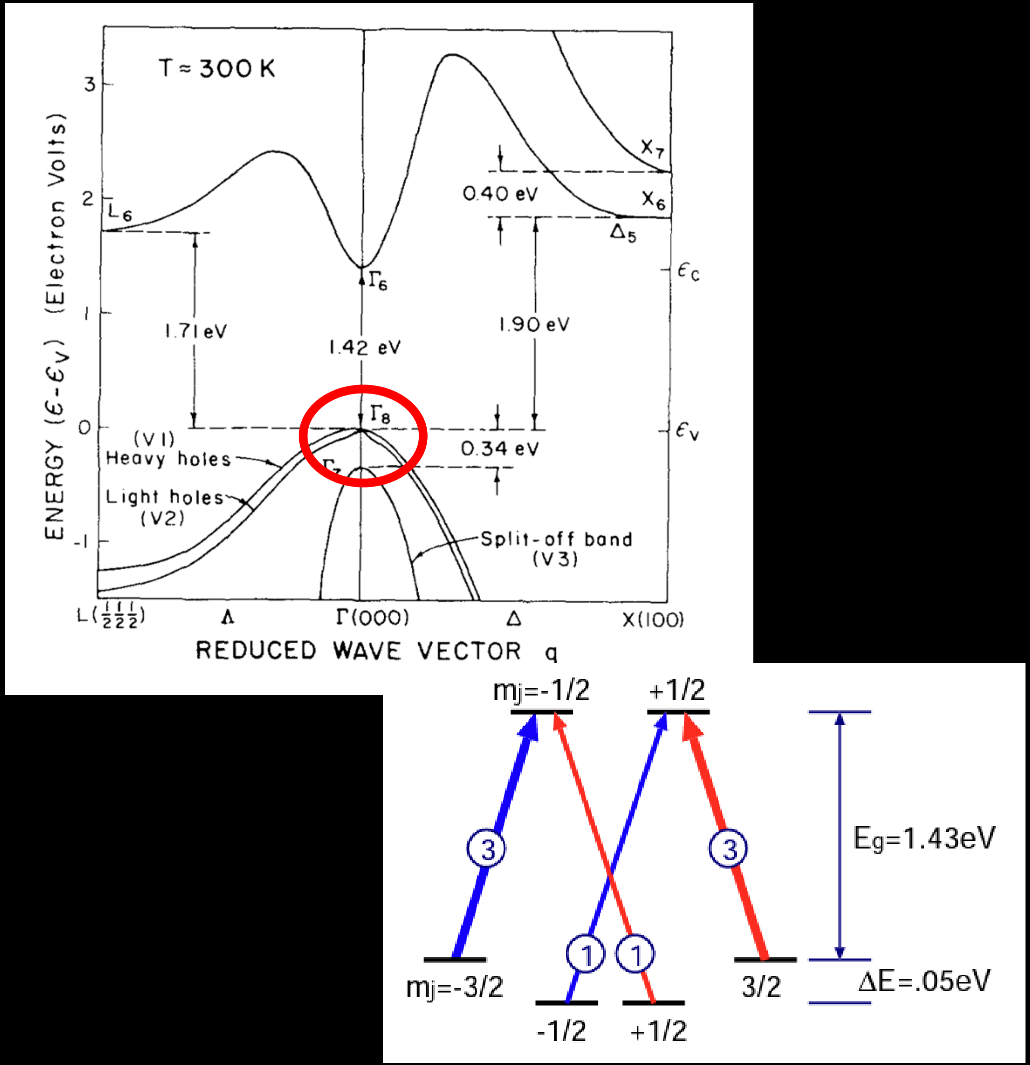

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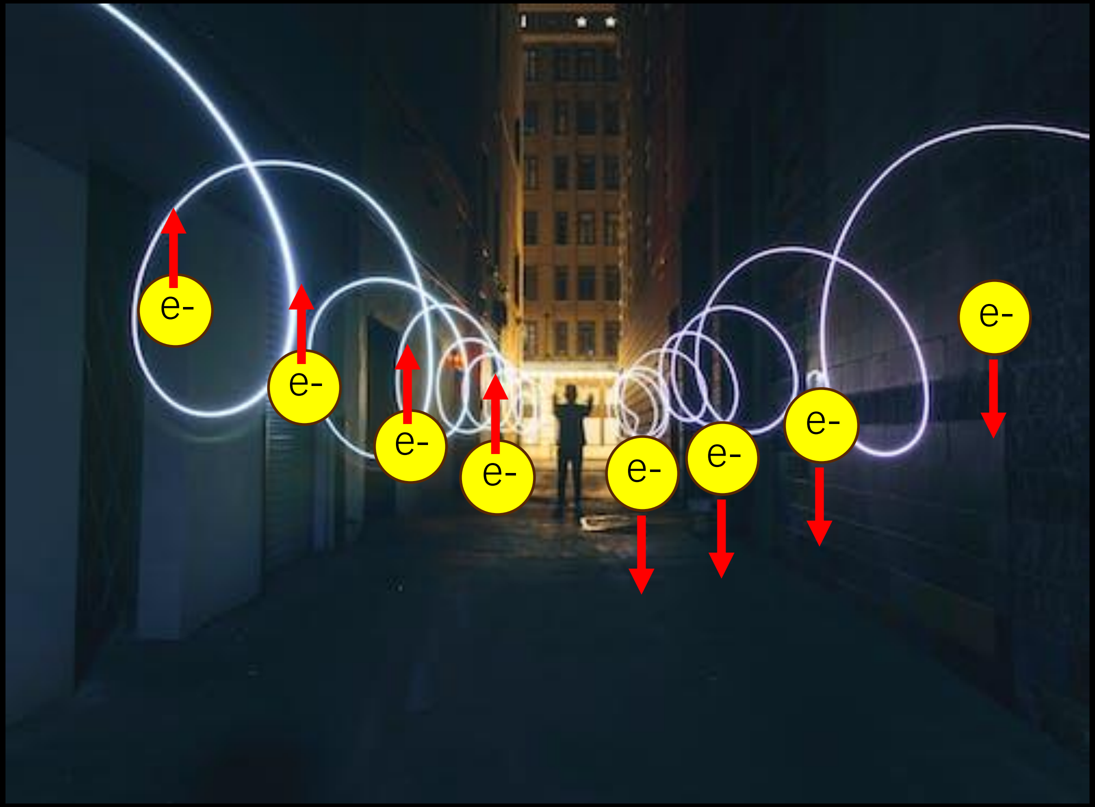


- Using a circularly-polarized laser, we can induce emission of electrons selectively chosen for their magnetic spin state.
- This takes advantage of the structure of GaAs semiconductor band structure: 2 bands near the top of the valence band can produce selectively polarized electrons. By inducing a strain in the GaAs lattice structure, we can suppress one and pick the polarization state we want.
- Changing the circular polarization direction changes the selected polarization state.

SPACE CHARGE LIMIT

- Space charge affects the E field between the anode and cathode

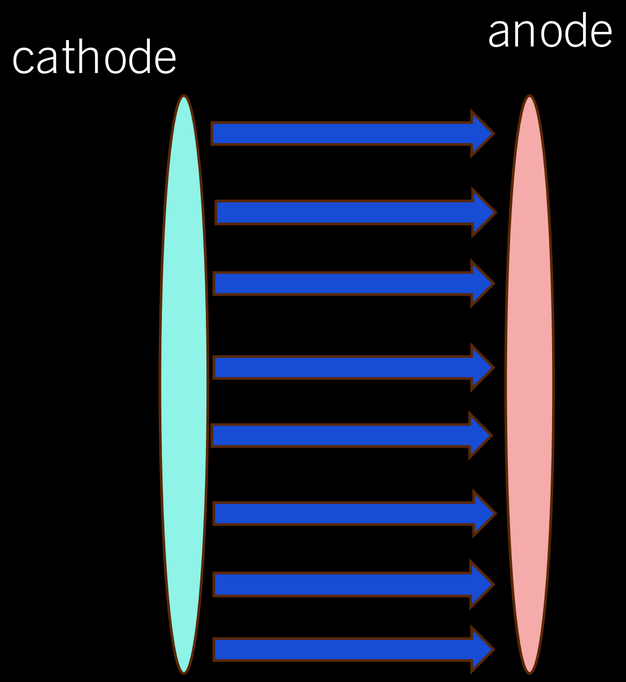
This in turn affects electron emission – weakened field → less emission

For a cathode and anode separated by distance *d*, we can calculate the current density *J* as the *Child-Langmuir Law* (three-halves law):

$$J = \frac{4}{9}\epsilon_0\left(\frac{2e}{m}\right)^{1/2}\frac{V_0^{3/2}}{d^2}$$

Which for electrons becomes

$$J = 2.33 \times 10^{-6}\frac{V_0^{3/2}}{d^2}\ [A\,m^{-2}]$$



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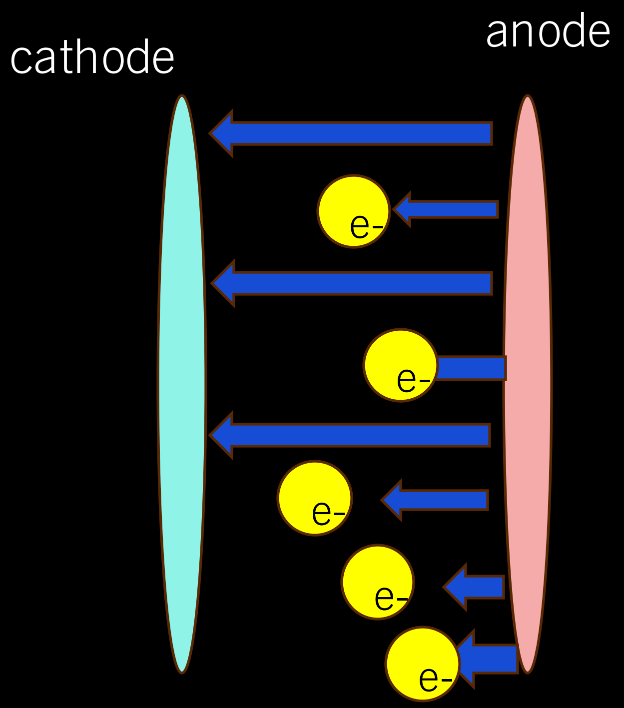

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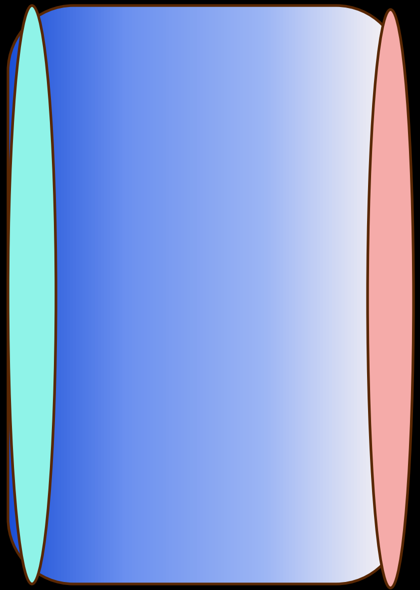


Representation of the electron cloud gradient

MAKING AN ELECTRON SOURCE

- To make an electron source for an accelerator, we need to choose one of the methods described above and use a method to extract the electrons to the beamline.

Thermionic Source

- High Current
- Continuous
- Poor emittance

Photocathode Source

DC Gun:

- Very Low Emittance
- Needs HV setup
- Bunch structure set by laser pulses

RF Gun:

- Low Emittance
- Requires Klystron
- High Energy
- Bunch set by RF field

THERMIONIC EMITTANCE

- Electrons taken from the cathode have an intrinsic thermal emittance due to the beam energy $\langle \epsilon_x \rangle = \frac{kT}{2}$.
- The transverse emittance due to this energy can be given by the Maxwell-Boltzmann distribution (usually expressed in units of mm mrad):

$$\epsilon_x = \sigma_x \sqrt{\frac{kT}{mc^2}}$$

Where σ_x represents the RMS beam size.

PHOTOELECTRIC EMITTANCE

- For photoemission, a further emittance term comes from the momentum given by the electron distribution function inside the cathode and in general requires solving some complicated integral.
- In terms of the photon energy and work function, we can represent it as

$$\epsilon_x = \sigma_x \sqrt{\frac{h\upsilon - \phi_{eff}}{3mc^2}}$$

DC PHOTOGUN

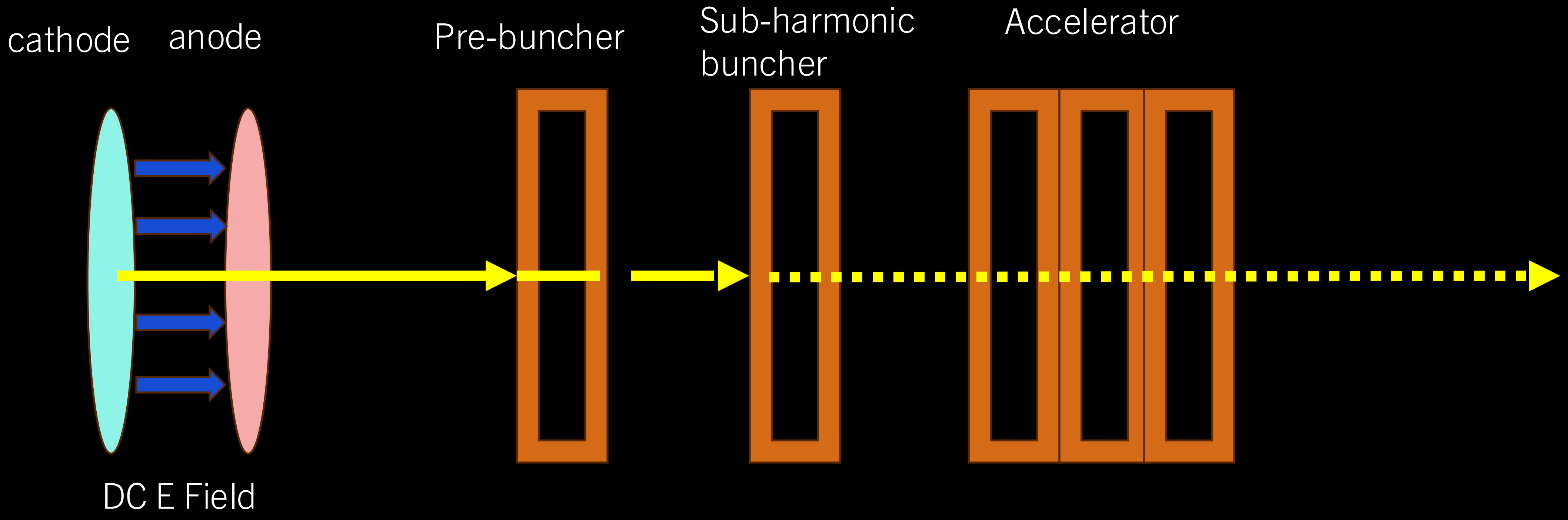
- Extract emitted electrons with a DC field
- Bunch energy at the exit is determined by the strength of the E field

  -Typically ~100s of keV range
- Bunch structure determined by laser pulses

  Laser can be time-locked to the RF field to match beam pulses with the downstream accelerator

THERMIONIC GUN SETUP

Because the thermionic gun is continuous, the beam needs to be processed by a buncher before it is sent to the accelerator.
The beam can then match the RF structure for acceleration without having out-of-phase electrons be negatively accelerated.



BUNCH COMPRESSION

BUNCH COMPRESSION

- Bunch compression can happen in two ways:

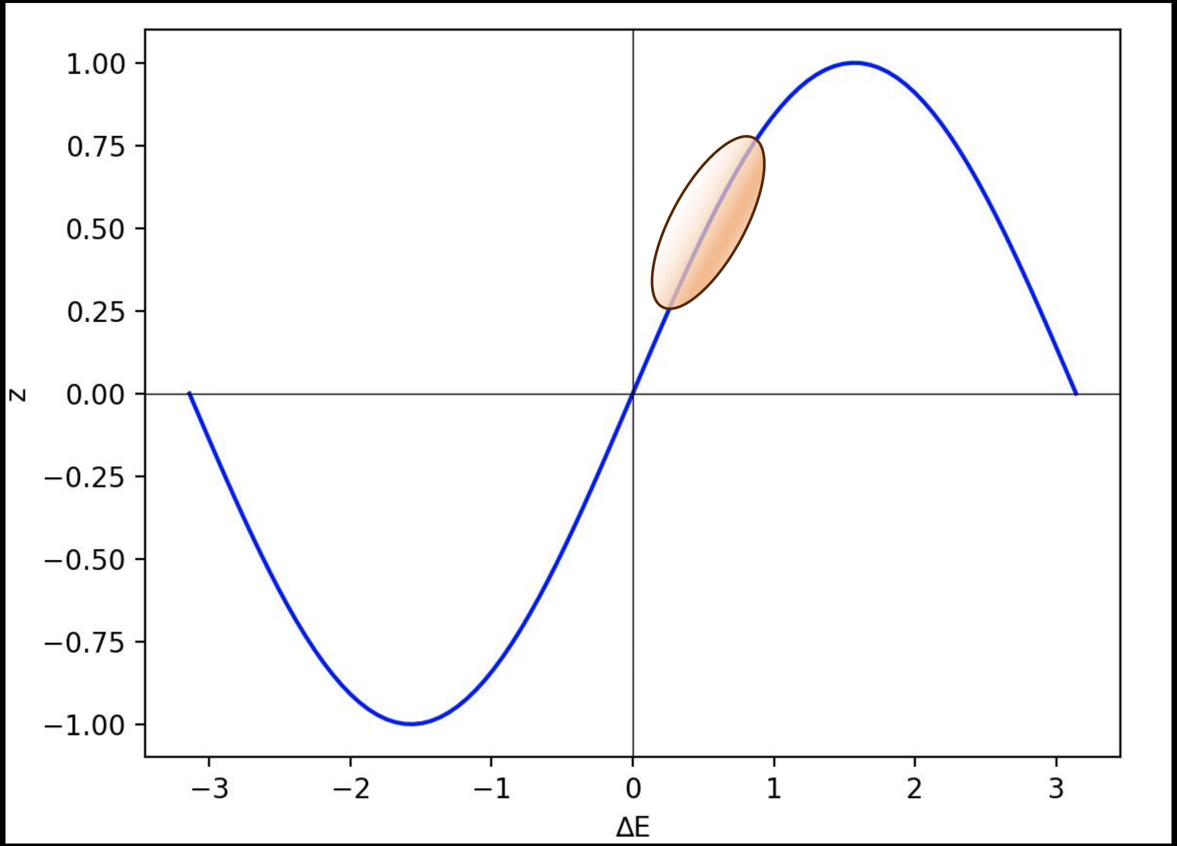
Velocity Bunching

- Only effective at low energies
- Useful for particle sources with continuous beams (e.g. thermionic gun) or long bunches

Magnetic Bunching

- Effective in all energy regions
- Capable of producing extremely short bunches

RF BUNCH MODULATION



- Energy gain/loss is an RF cavity is represented by

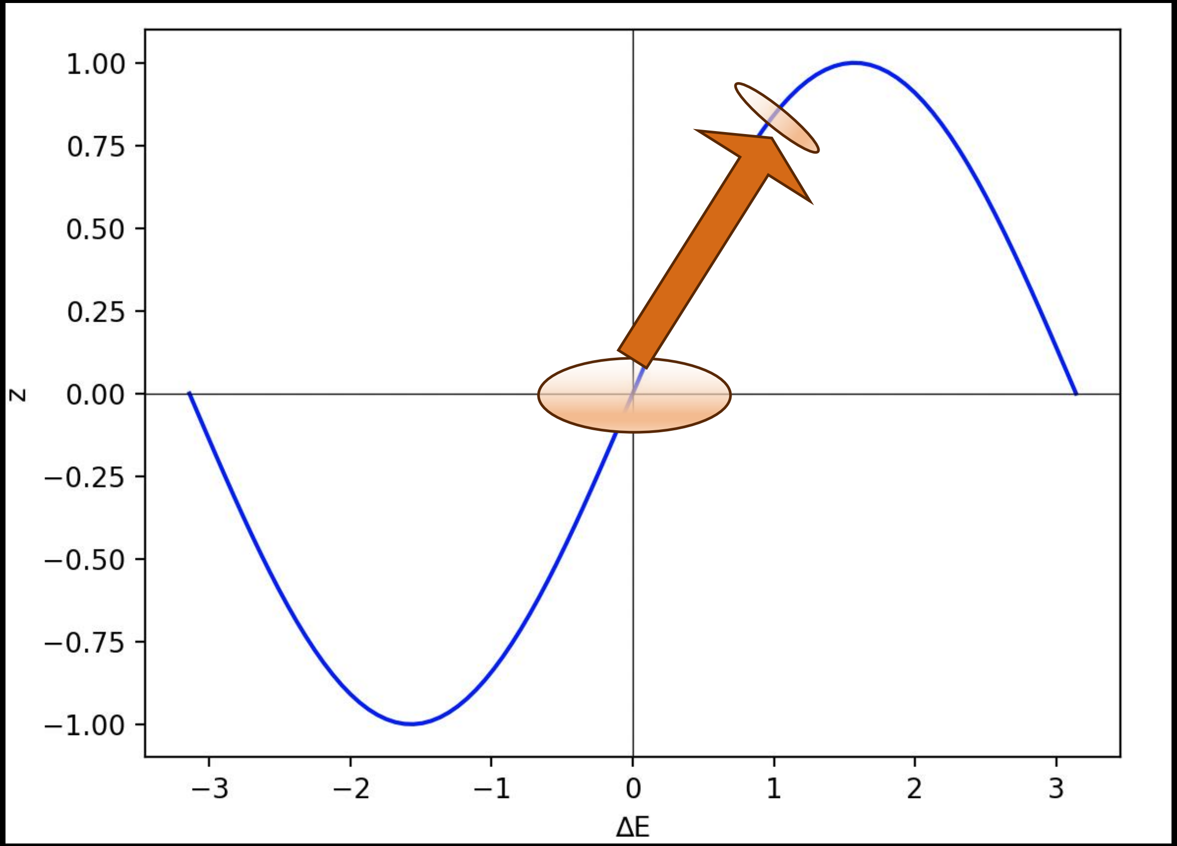
$$dE = eV_0 \frac{d\sin(\omega t)}{dt} dz$$

In the linear approximation,

$$\frac{dE}{E_0} \sim \frac{eV_0}{E_0} \omega\, dz$$

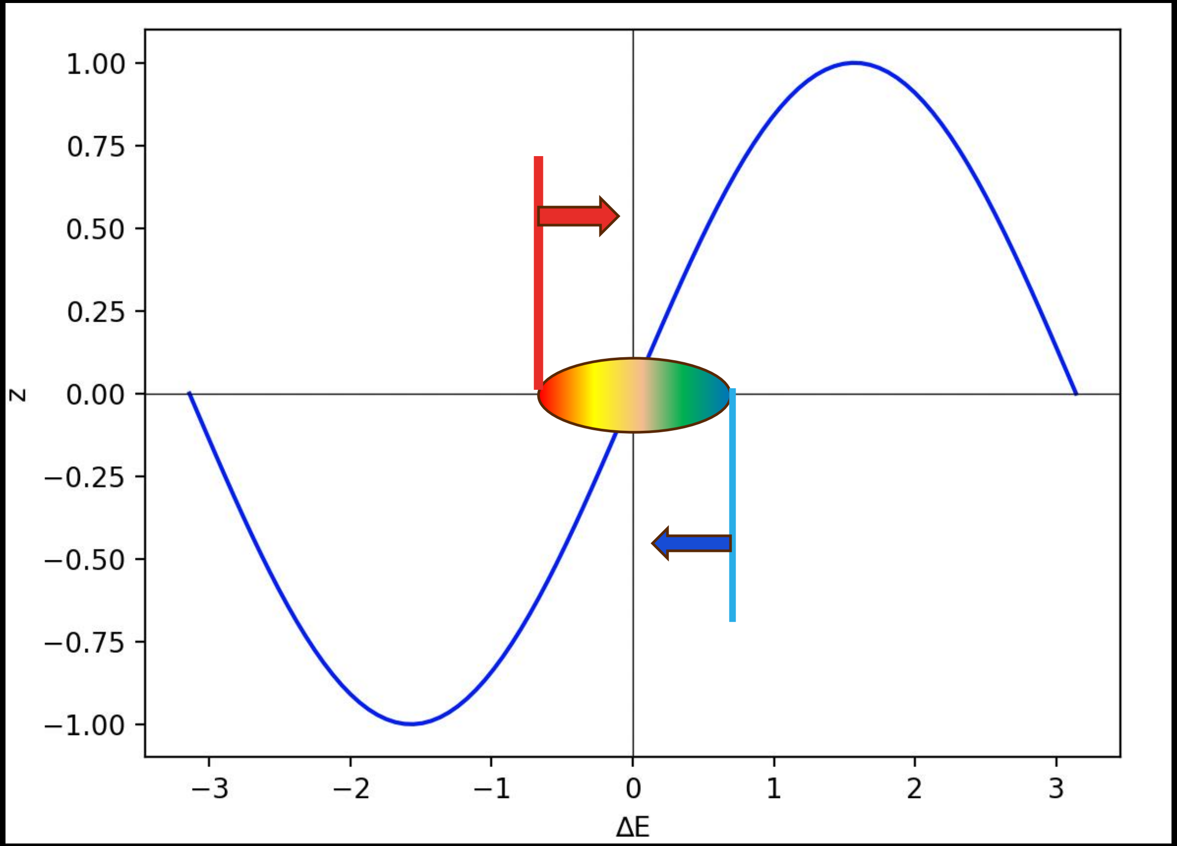
By accelerating on the slope of the RF, the head (tail) gain less (more) energy (known as *chirping*), and the longitudinal position can be made to correlate with the energy.

VELOCITY COMPRESSION



- Low-energy chirped bunches injected at zero crossing (non-accelerating phase) into a TW cavity will travel slower than the RF phase (β ~ 1) and will fall back to an accelerating phase while also being compressed.

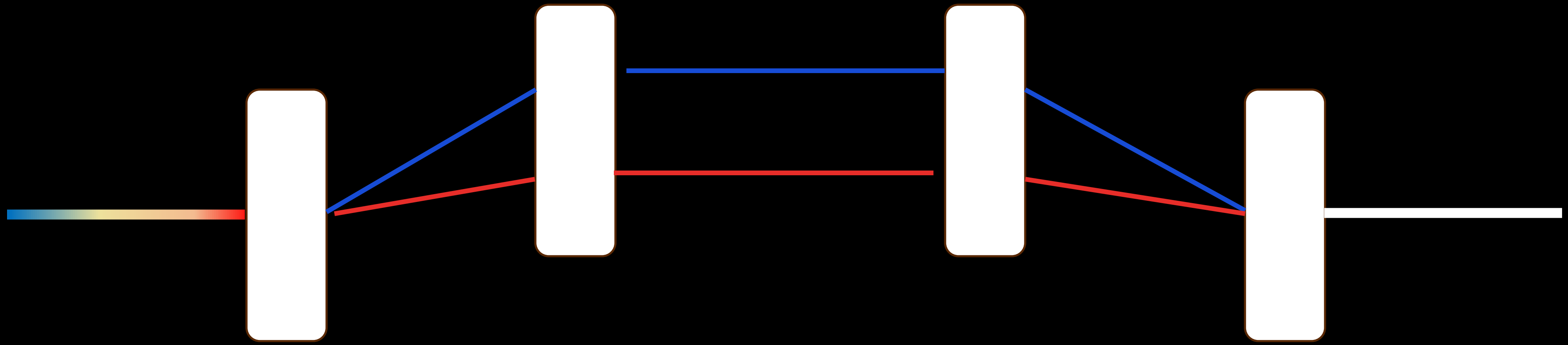
BALLISTIC COMPRESSION



- Low-energy chirped bunches injected at zero crossing (non-accelerating phase) into a TW cavity will travel slower than the RF phase ($\beta \sim 1$) and will fall back to an accelerating phase while also being compressed.
- Chirped bunches with the head (tail) at high (low) energy can also be allowed to drift, allowing higher-energy tail electrons to drift forward in the bunch and lower-energy head electrons to drift back, meeting in the center.

MAGNETIC COMPRESSION

- At high energies, all electrons are essentially traveling with $\beta = c$, so velocity compression is no longer possible.
- Instead, we can use magnets to compress the bunch.
- Starting from a chirped bunch with higher-energy electrons at the back, we can change their path length with a chicane:



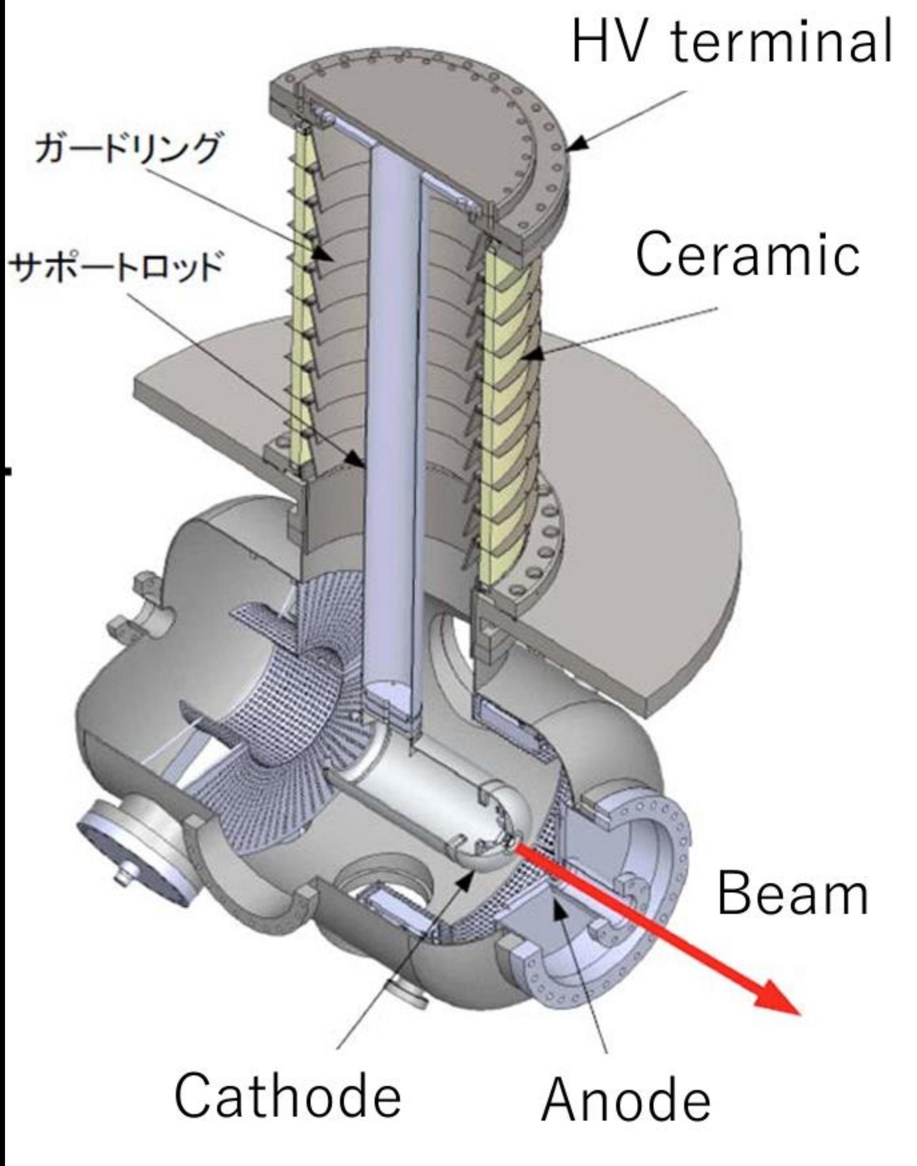
Higher-energy particles are bent less, meaning they travel a shorter path length, while lower-energy particles at the head travel farther. → Compression!

What we've effectively done is rotate the beam in (z, δ) phase space

R-MATRIX FORMALISM

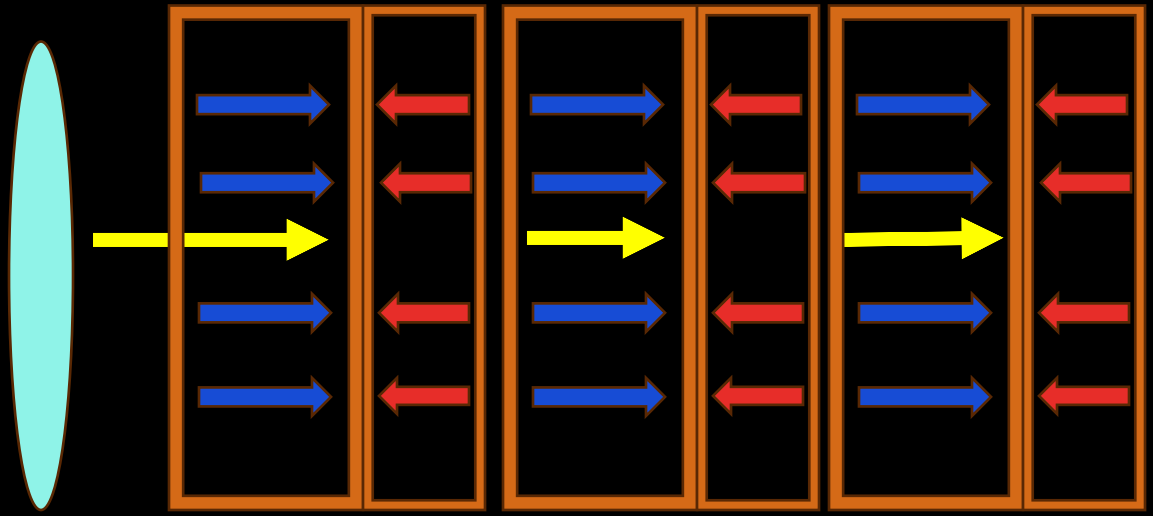
- Describing beam transport with a 6-D matrix
- $\vec{x} = \begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{pmatrix}, \quad \vec{x}_f = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{pmatrix} \vec{x}_0$
- In an ideal chicane, only the R_{56} term ($= \frac{\Delta z}{\delta}$) determines the longitudinal position:
- $z_f = (1 + R_{56}) z_i$
  (See Prof. Kim's talk on beam dynamics, slides 101-104, for an in-depth treatment of R_{56})
- And the final bunch length (ideal) is given by $\sigma_{z,f} = R_{56} \sigma_{\delta,i}$
  Non-linear effects limit how much we can compress the beam.

DC PHOTOGUN



RF GUNS

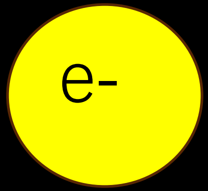
- Generate electrons directly inside of the RF cavity
- Higher power available then in DC guns – beam can leave with ~MeV energy
- Photocathode is a common choice for electron source



POSITRON SOURCES

- Positrons: the “anti-matter equivalent of electrons”
- Electrons are plentiful, but positrons are much less so.
- We can make them in two ways:

POSITRON SOURCES



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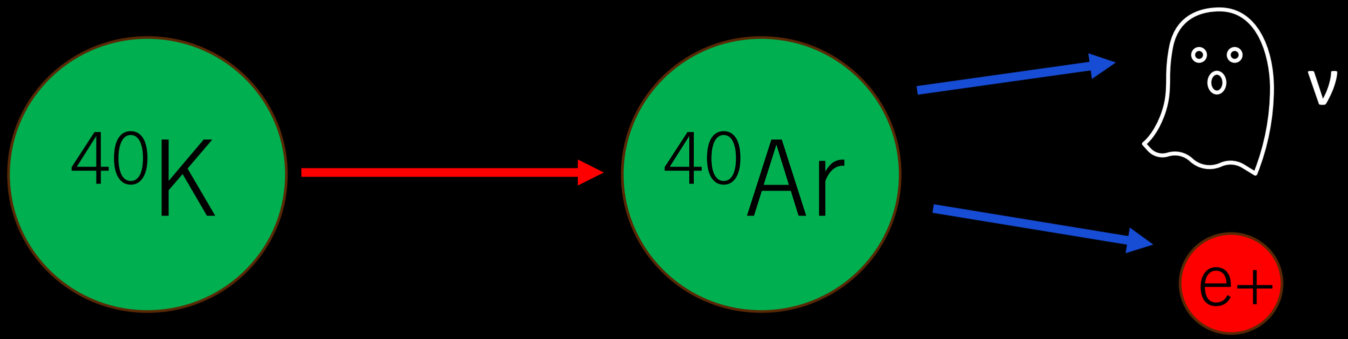


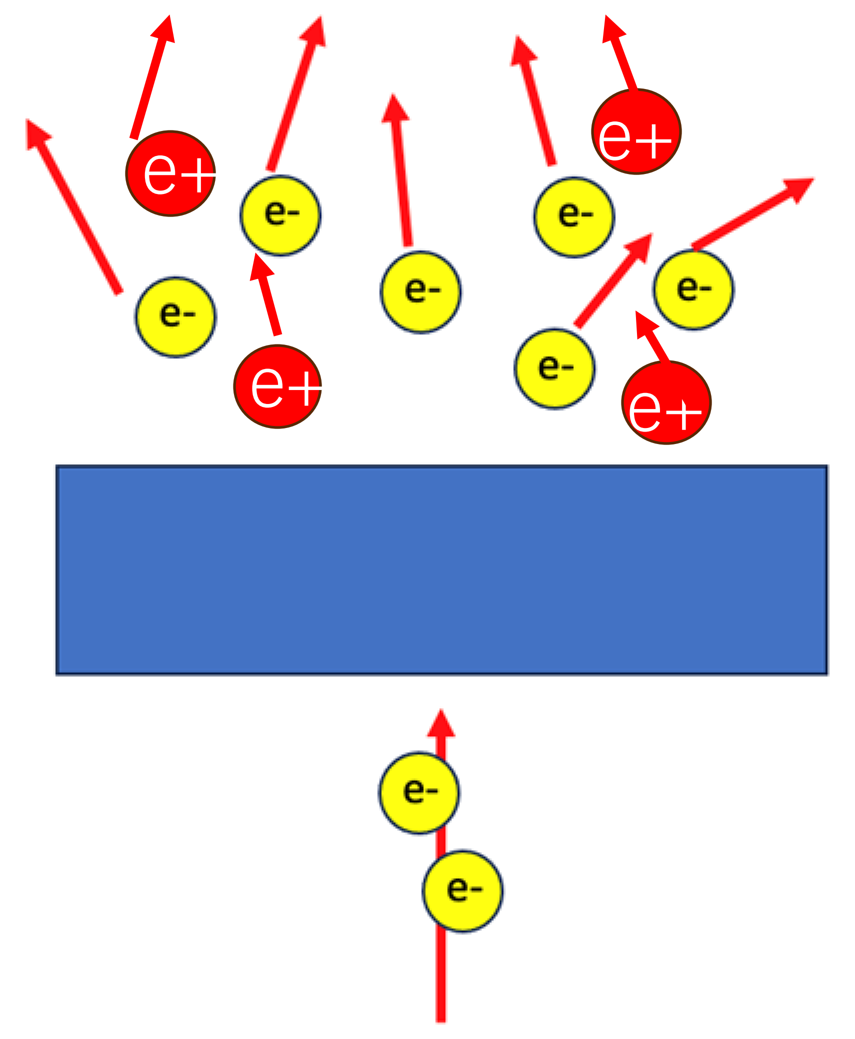
Difficult to produce a time structure with radioisotopes, because the process depends on nuclear decay that can’t be controlled.

POSITRON SOURCES

- Positrons: the “anti-matter equivalent of electrons”
- Electrons are plentiful, but positrons are much less so.
- We can make them in two ways:
  - Use radioisotopes that emit positrons
  - Pair production

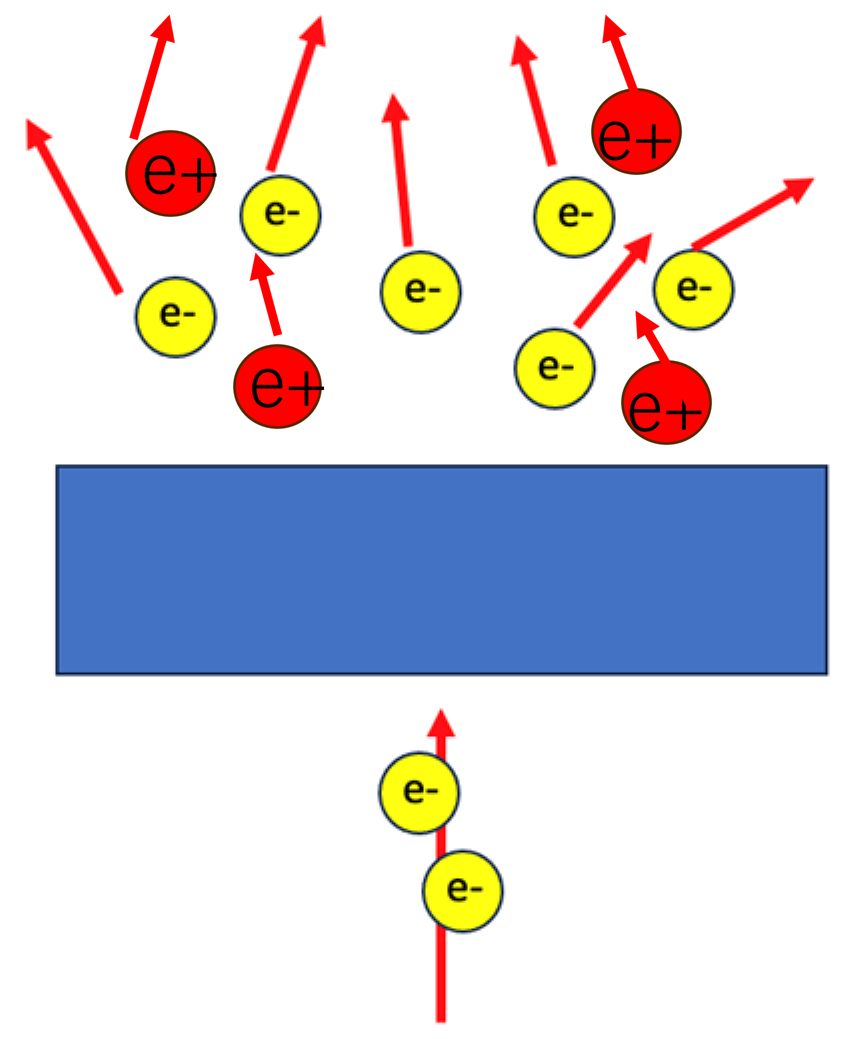
SECONDARY EMISSION

We can cause pair production to occur by creating a shower of secondaries via Bremsstrahlung from electrons incident on a target.



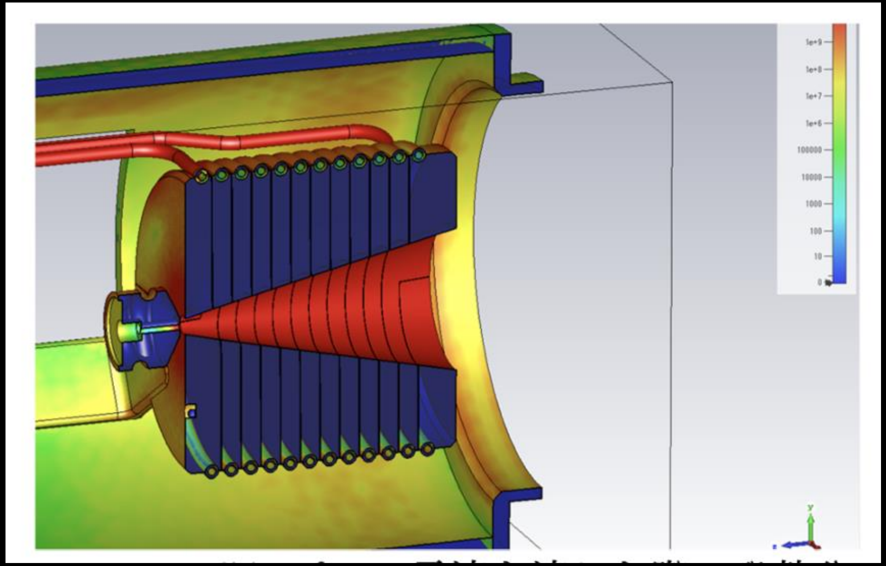
POSITRON PRODUCTION

- Positrons created this way have a large emittance and spread when leaving the target.
- They are also mixed in with electrons and need to be separated.
- Depending on the accelerator requirements, additional measures may be needed to reduce beam emittance, e.g., sending positrons to a circular damping ring



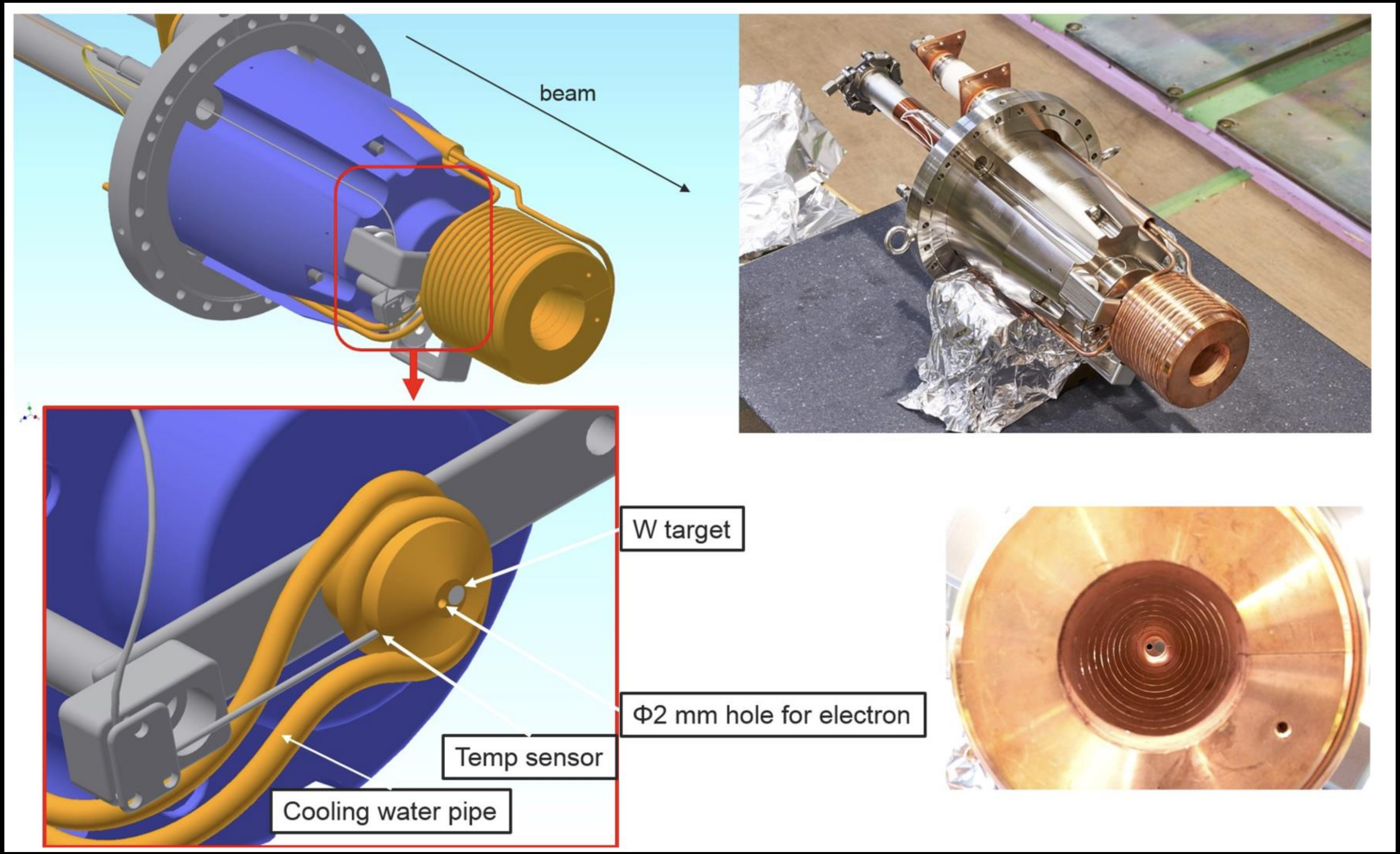
AMD/FLUX CONCENTRATOR

- Positrons can be captured and separated from electrons using an Adiabatic Matching Device (AMD), which uses a precise B field to capture the created positrons.
- The Flux Concentrator (FC) sits immediately after the target to insert captured particles into the beamline.



Y. Enomoto, OHO’19 Seminar Series

AMD/FLUX CONCENTRATOR



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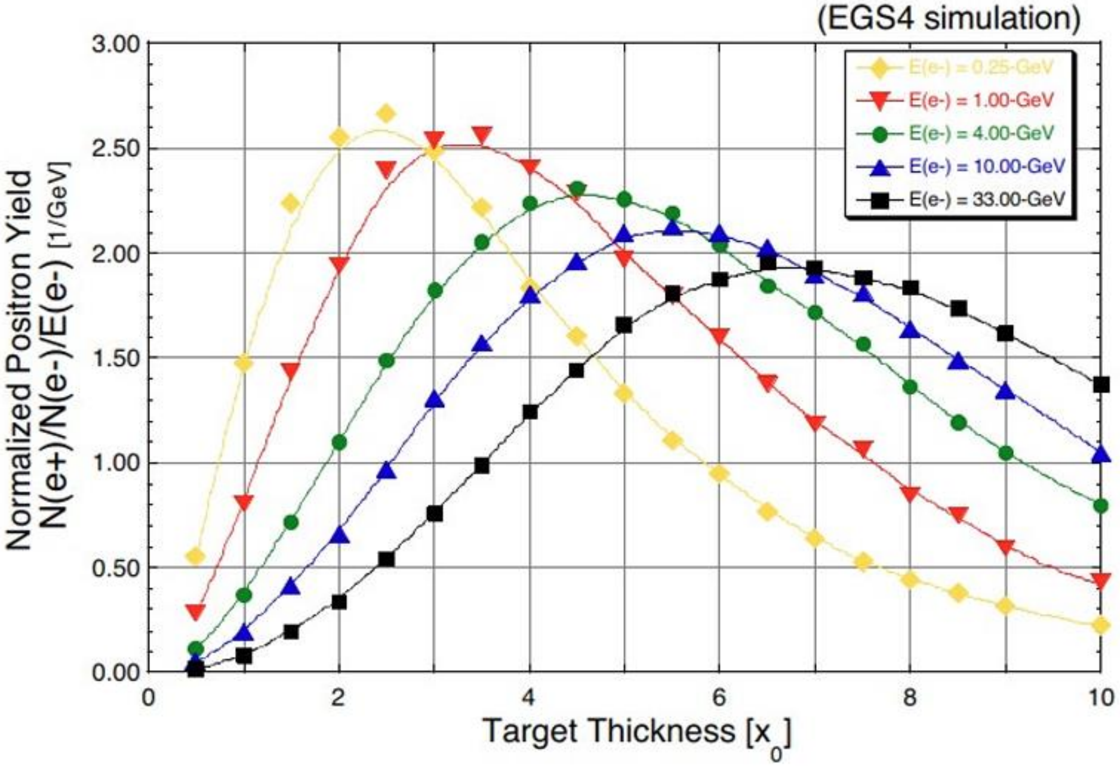
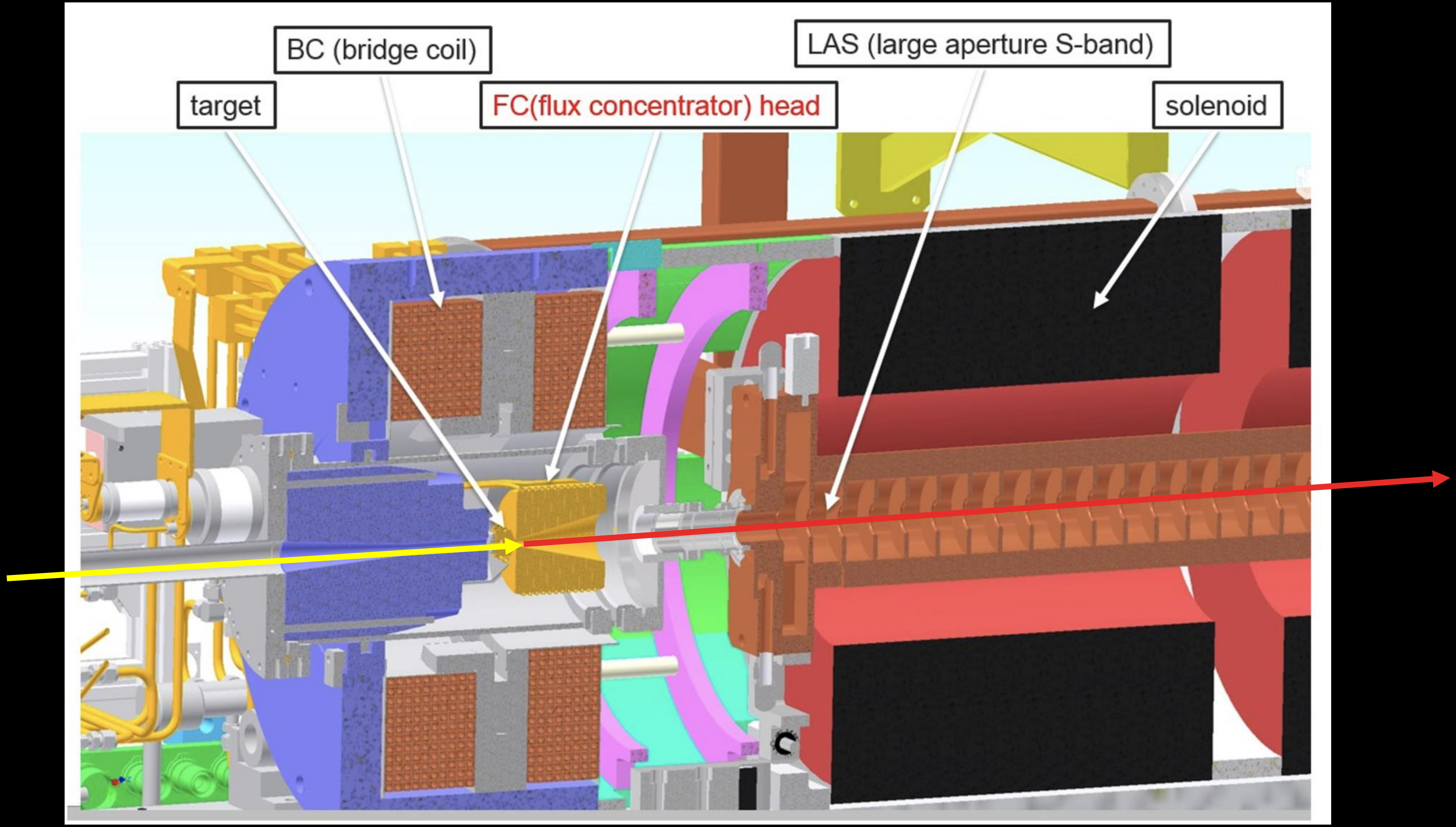
POSITRON PRODUCTION YIELD



Simulated positron yield by target thickness for different energy beams [2]

KEK POSITRON SOURCE



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DIRECT PRODUCTION FROM HIGH ENERGY PHOTONS

- We can also produce high-energy photons that can directly pair-produce.

Pro:

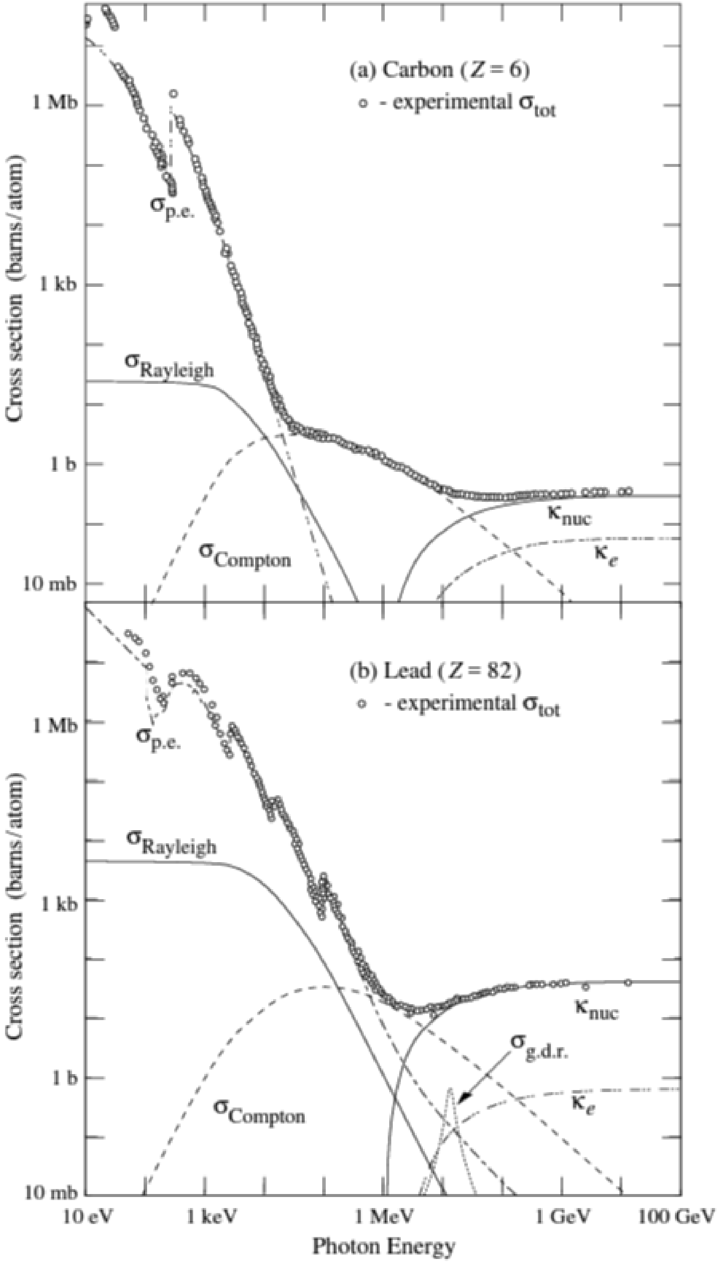
Polarized light will lead directly to polarized positrons

Cons:

Only one positron per photon – need many per bunch → need very intense source

Pair production doesn't occur beneath (2 x 0.511) MeV and is suppressed below ~10 MeV (see plot at right)

Need a very intense, very high energy source to produce such a beam!
e.g., FEL system



Photon cross-sections on C (top) and Pb (bottom).
Data from Particle Data Group (pdg.lbl.gov)

ION SOURCES

Up to now, we've only considered lepton (electron/positron) sources.

But how do we generate protons or heavy ions?

$e^{\pm}$
(0.511 MeV)

× ~2000

Proton (Helium nucleus)
(~1 GeV)

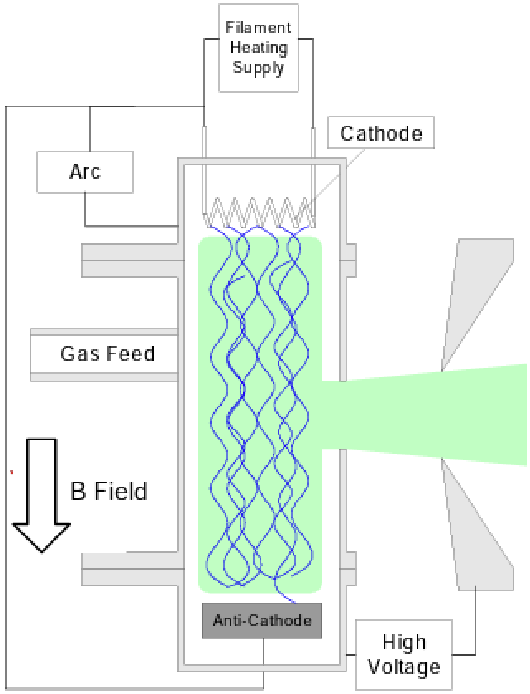
Heavy Ion
(~1 GeV × (p + n))

$H^{\pm}$ PRODUCTION

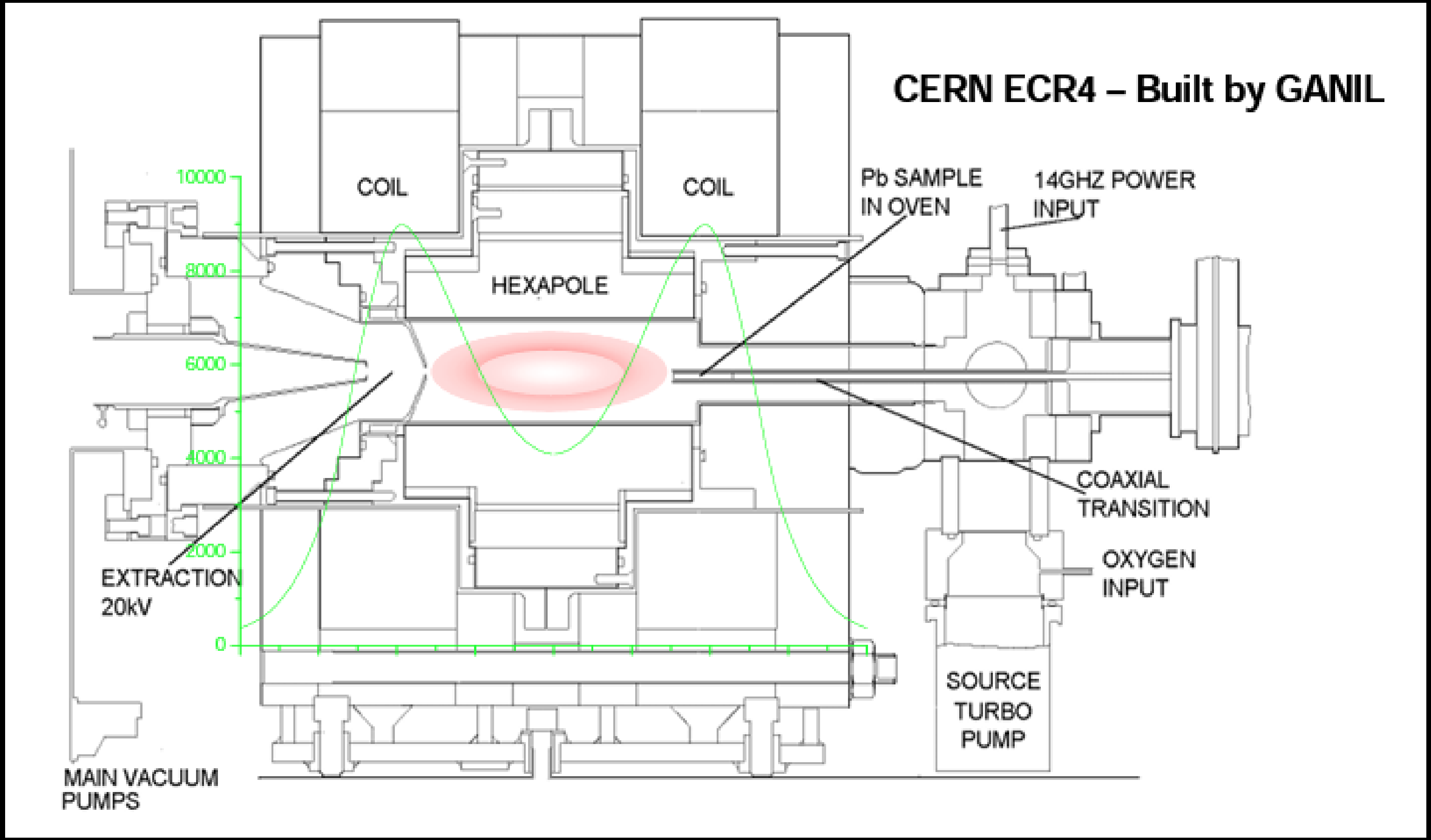
- Depending on the application, H^- or H^+ ions may be needed.
- Heavy ions (e.g., Pb, Au…) may also be used.
- Positively charged ions can be created by removing one or more electrons. This can be accomplished by bombarding atoms with energy above the ionization energy.
- Ions require an ion generating area (usually a plasma, but other processes exist – sputtering or desorption) and an extraction system.

PIG SOURCE

- Based on Penning Discharge and used in cyclotrons beginning in the 1940's
- Electrons from the cathode interact with the gas, forming a plasma. Most do not reach the anode and continue to strike gas molecules, ionizing the gas further.
- The cathode extracts the gas outward for use in the beam.



ELECTRON CYCLOTRON RESONANCE (ECR)



-Electrons are stored in a magnetic ‘bottle’ at the cyclotron frequency

$$\omega = 2\pi f = \frac{eB}{m}$$

- They interact with gas molecules similar to the PIG source, but can be confined longer and cause more collisions → more ionization
- Very highly charged ions can be produced: Au^{24+}, Pb^{27+}, U^{29+}

NEGATIVE ION PRODUCTION

- Negative ions are created by binding an extra electron (or possibly several) onto a neutral nucleus.
- The binding energy of this additional electron is known as the electron affinity.

  Not all elements can form negative ions: noble gases and some other stable elements have an electron affinity < 0 and so will not form stable negative ions
- Two main types:

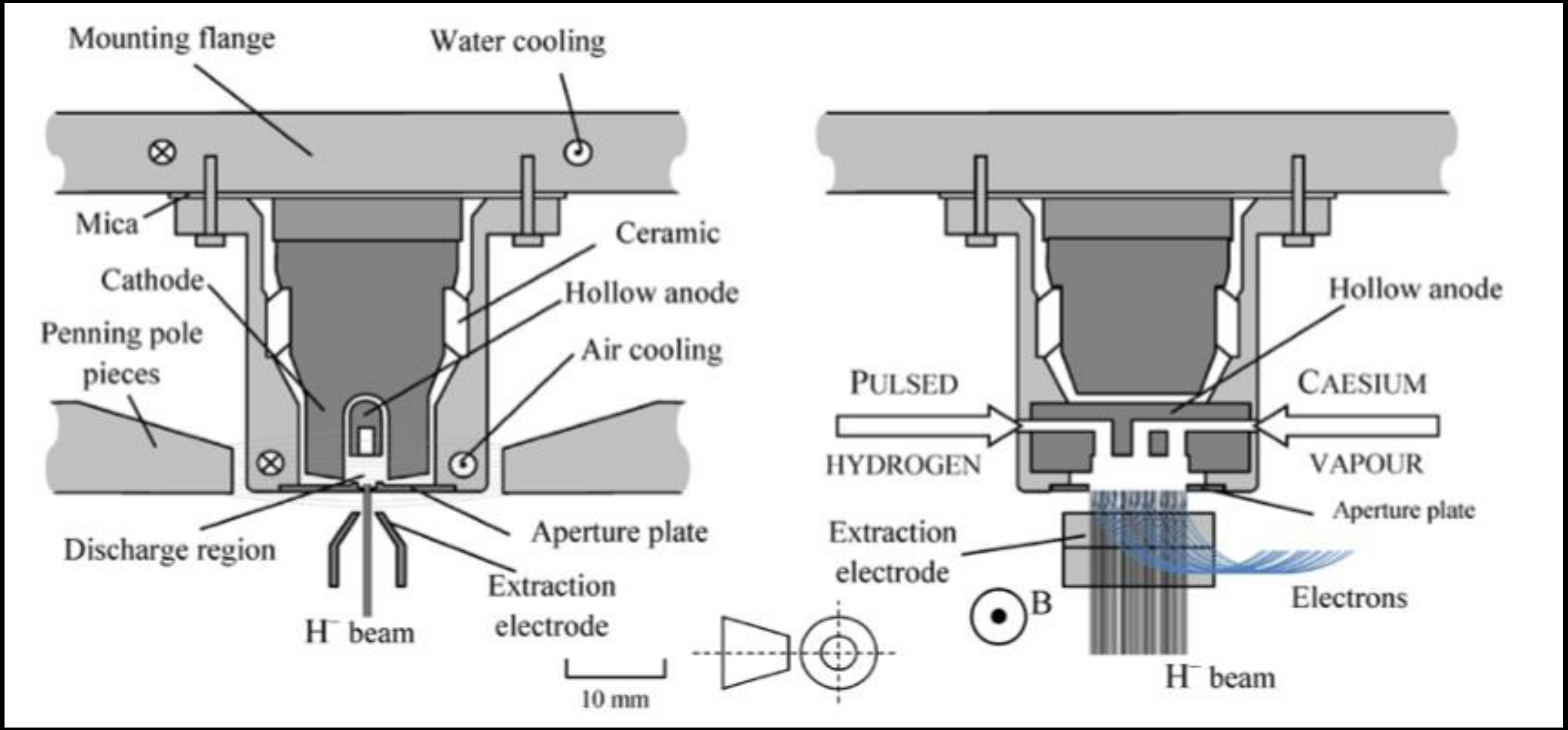
Surface Production

Material is absorbed onto a surface with small ϕ. When it leaves the surface, it often carries an extra charge (donor electron).

Volume Production

Ions are excited by an incident electron in a warm plasma, and have an electron attached in a cooler plasma.

MAGNETRON H⁻ ION SOURCE (VOLUME PRODUCTION)



Schematic of a magnetron source source for H⁻ ions [3].

SUMMARY

- Particle sources are needed to provide electrons, positrons and hadrons to be accelerated.
- Electron generation relies on themal, photonic, field or secondary emission to excite electrons (or positrons) and release them into the accelerating field.

  -Can make use of semiconducting nature of some cathodes to produce spin-polarized beams
- DC and RF photoguns can be used to extract the excited leptons.
- Hadron sources can produce either + or – ions by adding an electron (-) or stripping electrons away (+).

  - Very highly + charged ions can be created for use in hadron colliders.

REFERENCES

- [1] R. Scrivens. Electron and Ion Sources for Particle Accelerators. CERN document server (cds.cern.ch)
- [2] Y. Enomoto. OHO’23 Lecture
- [3] D.C. Faircloth. Negative Ion Sources: Magnetron and Penning (ArXiV 1404.0944)