2. Particle sources and Guns

- Electrons
  - Thermionic emission
  - Field emission
  - Photo-emission
  - Beam quality
  - Space-charge
- Protons and ions

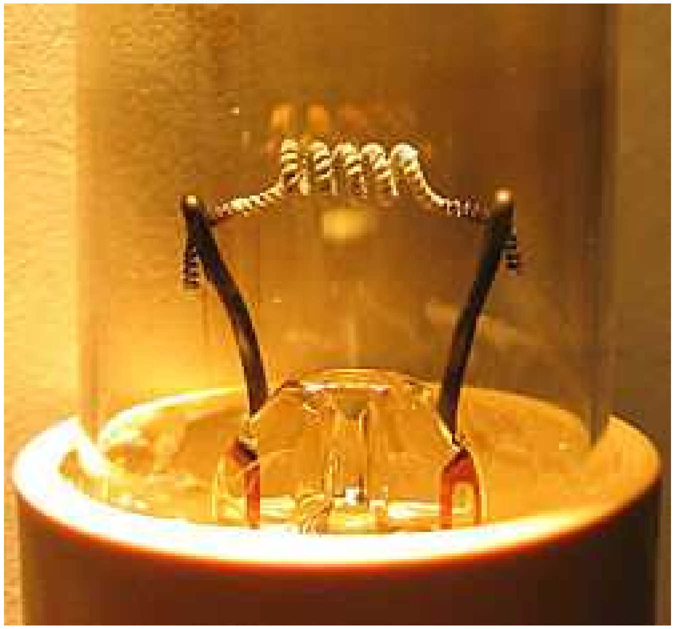
Particle sources

- How particles are first produced?
- How to extract particles with the right properties?
- What are the limitations of the sources?
- *The quality of the source is very important. If the particles emitted by the source do not have the right properties, it will be very difficult and/or expensive to rectify it later.*

Emission of electron: Thermionic effect

- Remember the Maxwell-Boltzmann energy distribution: $f = e^{\frac{-E}{k_B T}}$
- Electrons (fermions) obey a different but similar law.
- When a metal is heated more electrons can populate high energy levels.
- Above a certain threshold they electrons can break their bound and be emitted:

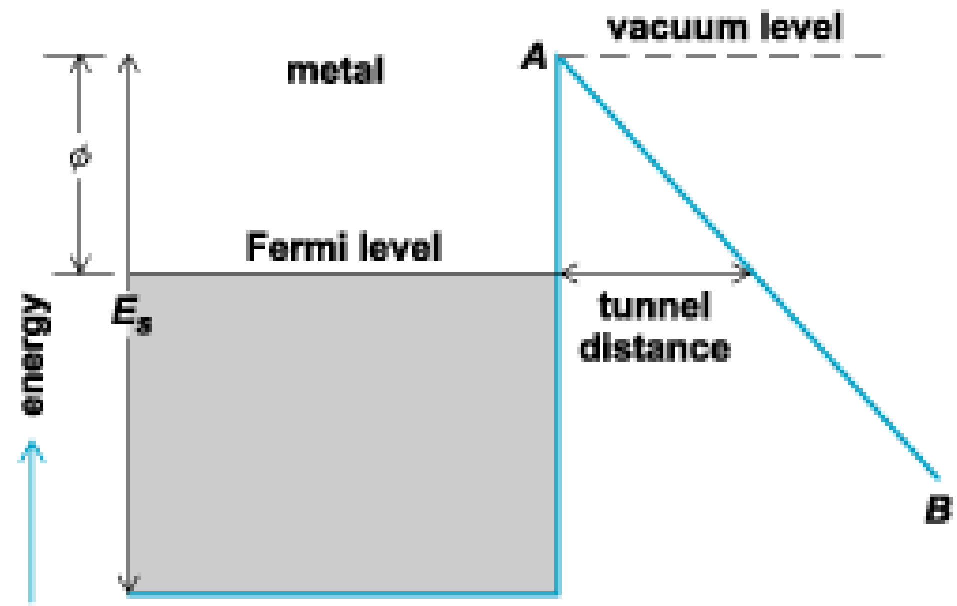
  This is thermionic emission.



(image source: wikipedia)

Emission of electron: Field effect

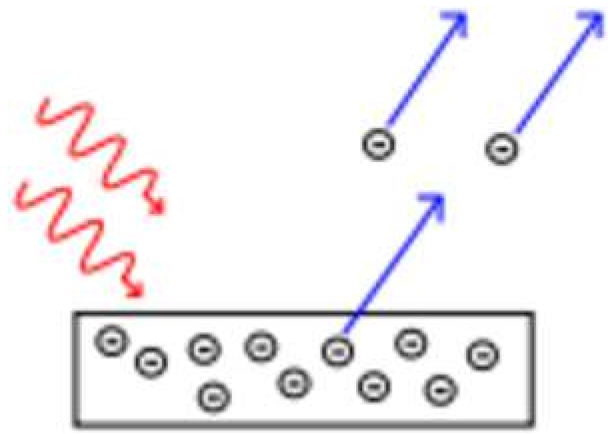
- Under a very intense electric field some electrons will be able to tunnel across the potential barrier and become free.
- This is known as field effect emission.



(image source: answers.com)

Emission of electron: Photo-electric effect

- A photon incident on a piece of metal can transfer its energy to an electron
- If the photon transfers enough energy the electron can be emitted.
- By using powerful lasers the photoelectric effect can be used to produce electron beams.
- This is known as the photo-electric emission.



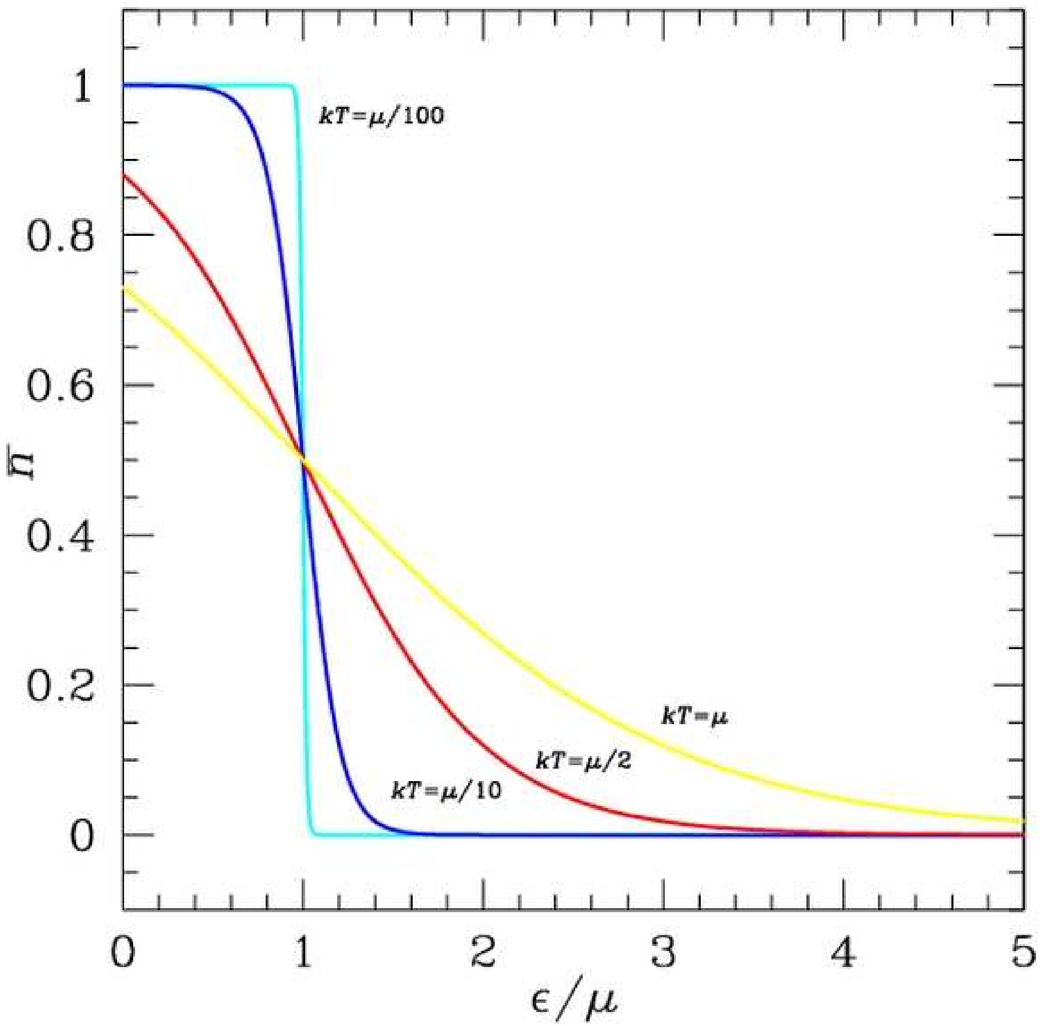
(image source: wikipedia)

Fermi-Dirac statistics

- Free electrons in metals will obey Fermi-Dirac statistics.

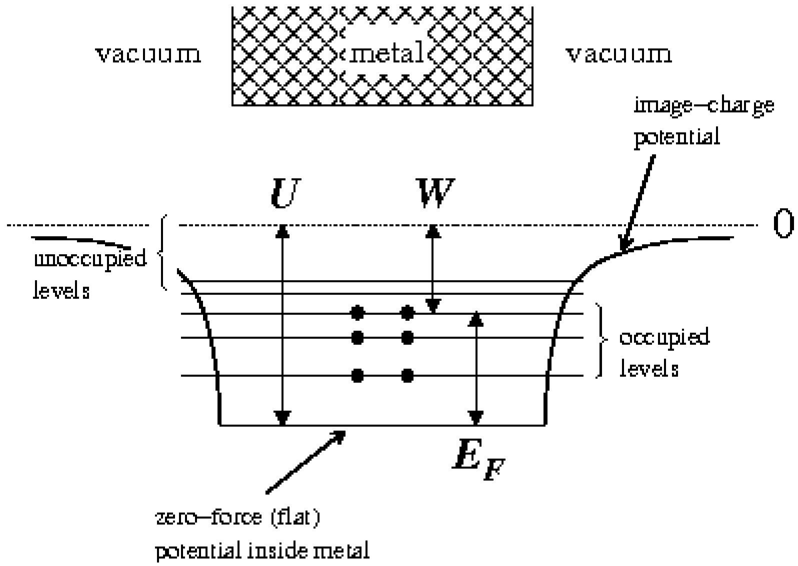
$$\overline{n_i} = \frac{1}{e^{\frac{\varepsilon_i - \mu}{k_B T}} + 1}$$

- $\overline{n_i}$ is the density of state i with energy ε_i
- μ is the chemical potential
- At low T all electron populates bound states.
- At high temperature they will populate higher energy states.



Work function

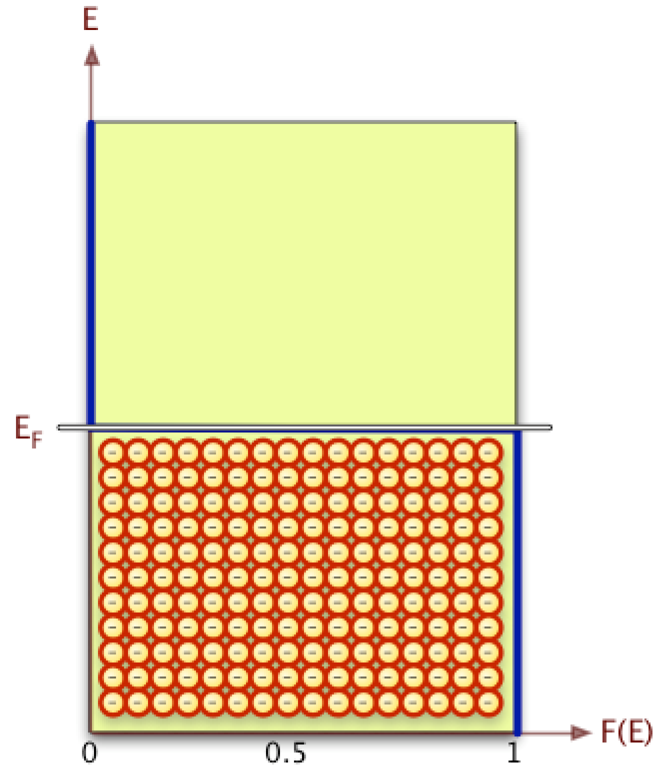
- To escape from the metal the electrons must reach an energy greater than the edge of the potential well.
- The energy that must be gained above the Fermi energy is called the “work function” of the metal.
- The work function is a property specific to a given metal. It can be affected by many parameters (eg: doping, crystaline state, surface roughness,...)

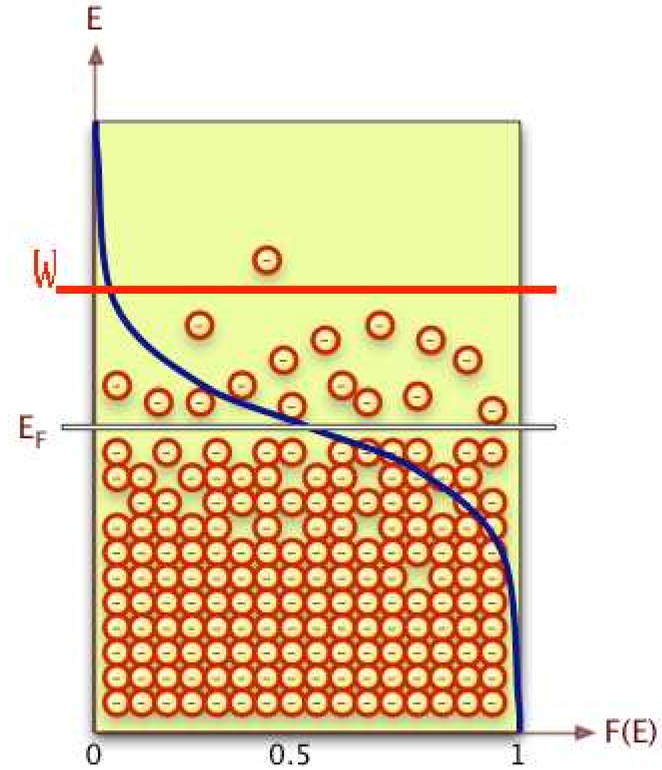


(image source: wikipedia)

- Example values:
Fe: 4.7 eV ; Cu: ~5eV; Al: ~4.1 eV; **Cs: ~2 eV**

Summary: electrons in solids





(image source: http://cnx.org/content/m13458/latest/

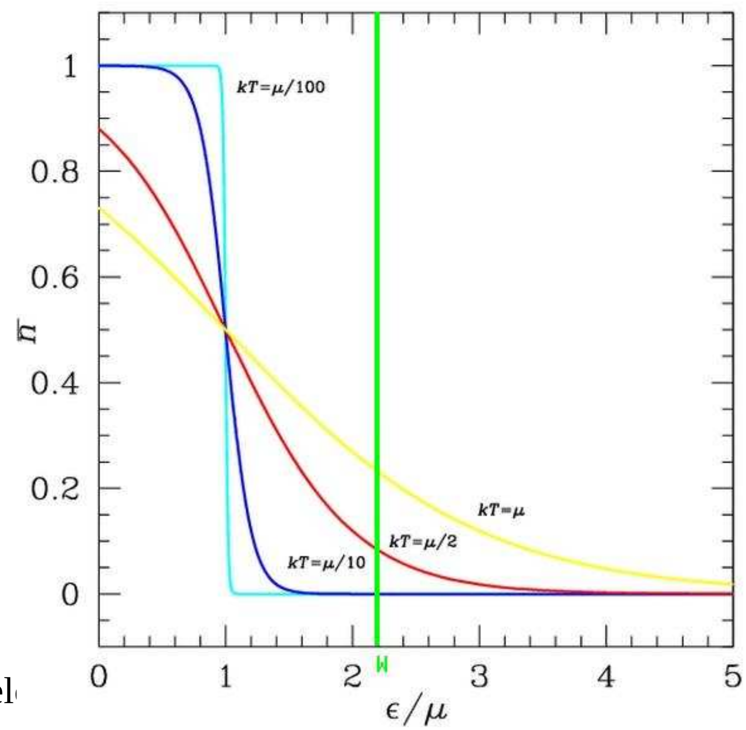
- At low temperature all electrons are in the lowest possible energy level, below the Fermi level.
- As the temperature increase some electrons will go above the Fermi level.
- But only those with an energy greater than the work function are "free".

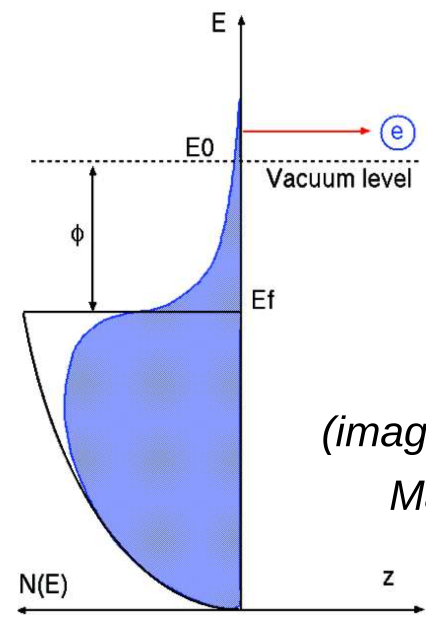
Thermionic emission

The Richardson-Dushman equation gives the electronic current density J (A/m^{-2}) emitted by a material as a function of the temperature:

$$J = AT^2 e^{\frac{-W}{k_B T}}$$

With A the Richardson constant: $A = \frac{4\pi m_e k_B^2 e}{h^3} = 1.2 \cdot 10^6 \frac{A}{m^2 K^2}$





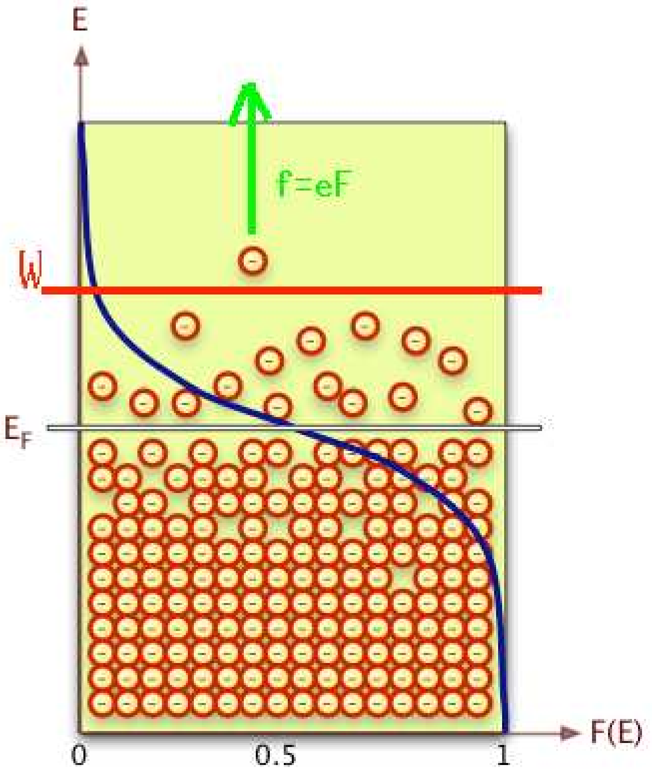
(image source: Masao Kuriki, ILC school)

Thermionic cathode material

- Two parameters are important when considering a thermionic cathode material:
  - W=Work function (as low as possible)
  - Te=Operation Temperature (preferably high)
- Cesium has a low work function (W~2eV) but a low operation temperature (Te=320K)
  => not good for high current
- Metals: Ta (4.1eV, 2680K), W(4.5eV, 2860K)
- BaO has good properties (1eV; 1000K) but can oxidize by exposure to air => sinter of BaO+W
  BaO provided slowly to the surface.

Electric field bias

- Once the electrons are free they may fall back on the cathode.
- To avoid this an electric field needs to be applied.
- If a negative potential is applied to the cathode the electrons will be attracted away from the cathode after being emitted.
- However this field affects the work function.



Schottky emission

- The application of an electric field F to a material modifies the work function, this is called the Schottky effect:

$$\Delta W = \sqrt{\frac{e3F}{4\pi \in_0}}$$

- This will lead to a reduction of the work function. The higher the field the lower the work function. The Richardson-Dushman equation becomes:

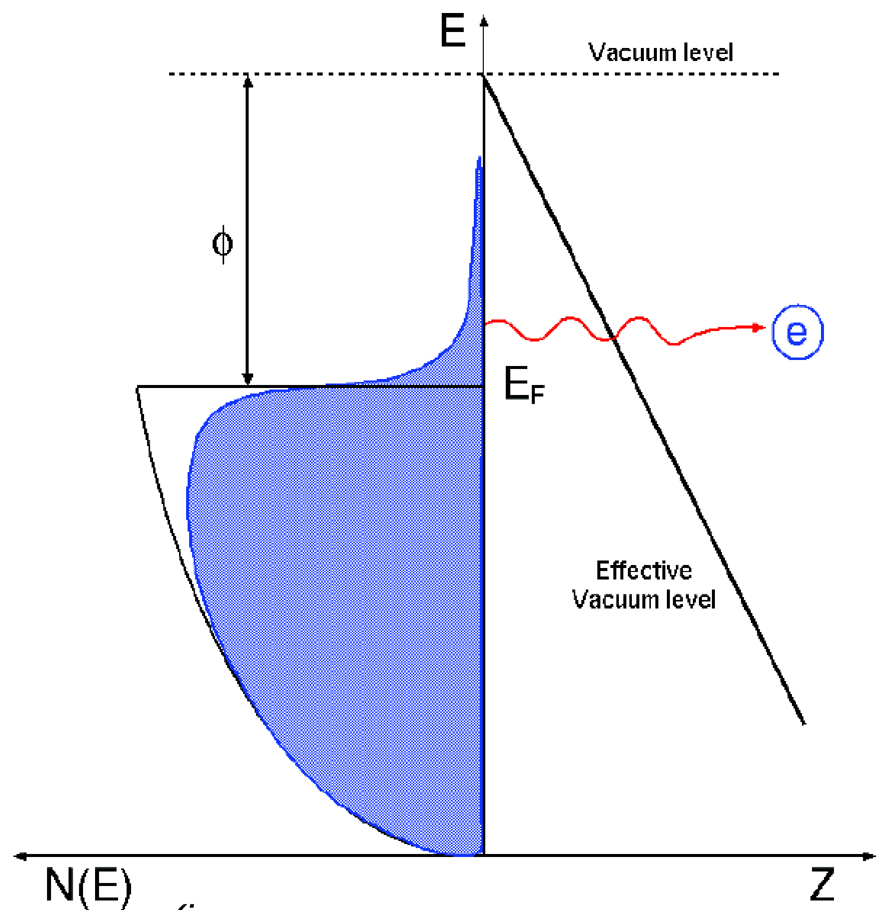
$$J = AT^2 e^{\frac{-W-\Delta W}{k_B T}}$$

- This formula is valid only up to 10^8V/m. For more intense fields additional phenomena happen.

Field emission

- With electric fields (F) more intense than 10^8V/m the potential barrier that prevents electrons from escaping becomes very thin.
- It becomes possible for electron to tunnel across the potential barrier.
- This may occur even at cold temperature. This is sometimes called “cold emission”.

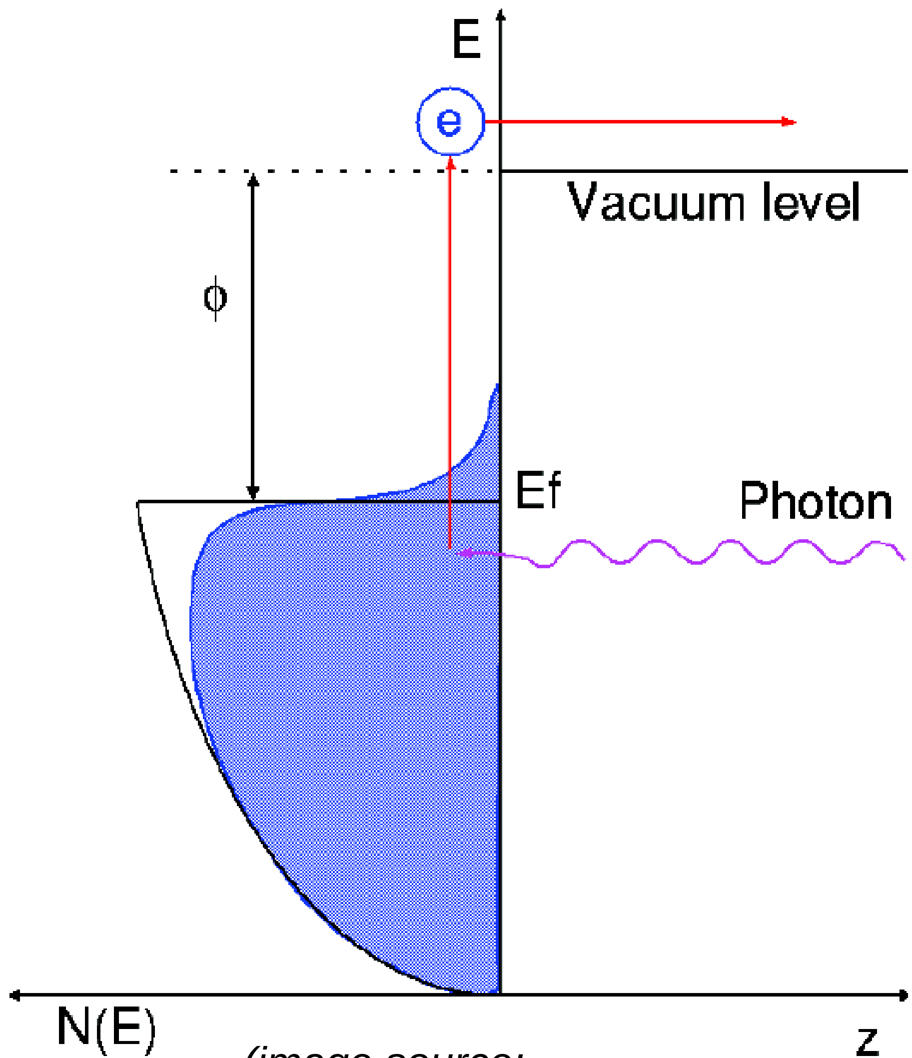
$$J = \frac{e^3 F^2}{8h\pi W} \exp^{\frac{-4\sqrt{2m_e}}{3heF} W^{3/2}}$$



(image source:
Masao Kuriki, ILC school)

Photo-electric emission

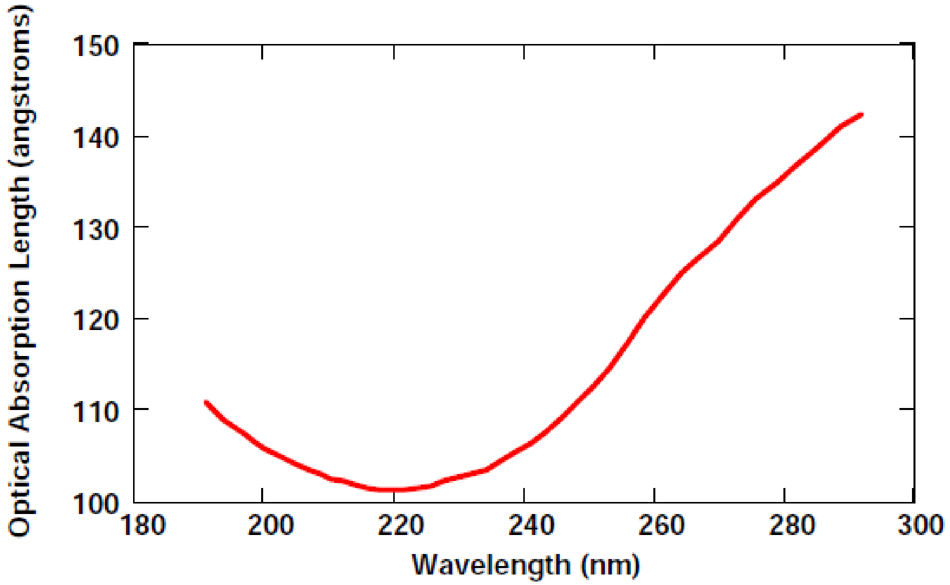
- A photon incident on a material will transfer its energy to an electron present in the metal.
- If the energy of this electron becomes bigger than the work function of the material, the electron can be emitted.
- This is called photo-electric emission.



(image source: Masao Kuriki, ILC school)

Photo-electric emission (2)

- A UV photon at 200nm carries an energy of about 6 eV, this is enough to “jump” over the work function of most metals.
- As seen in electromagnetism, electromagnetic waves (photons) can penetrate inside a metal.
- The photo-electric emission may thus take place away from the surface.



(image source: Dowell et al., Photoinjectors lectures)

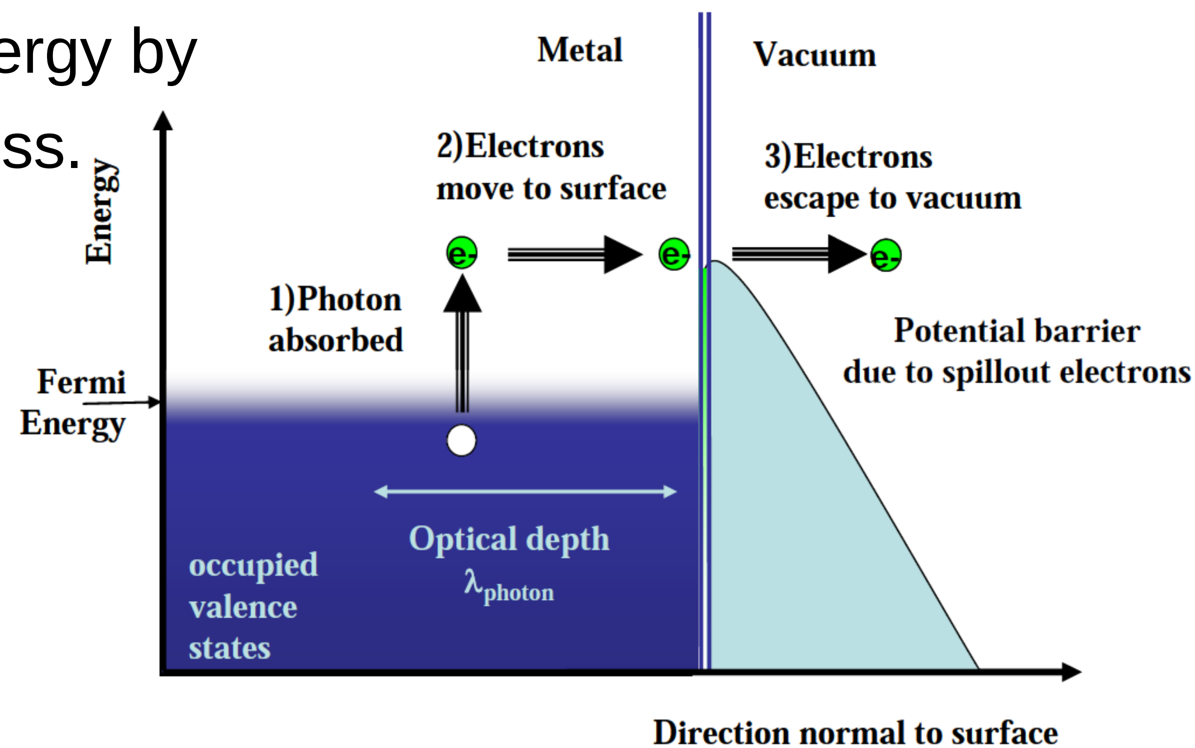
The 3 steps of photo-electric emission

Photo-electric emission takes place in 3 steps:

1) Absorption of a photon by an electron inside the metal. The energy transferred is proportional to the photon energy.

2) Transport of the photon to the physical surface of the metal. The electron may loose energy by scattering during this process.

3) Electron emission (if the remaining energy is above the work function; including Schottky effect)



Quantum efficiency (QE)

- For photo-electric emission, it is useful to define the “quantum efficiency”:

$$QE = \frac{Number\, of\ photo\, electrons}{Number\, of\ photons}$$

- Typical QE for a photo-cathode is only a few percent or less!
- The quantum efficiency will decrease during the life of the cathode: it may get damaged or contaminated.

Quizz

1) Which of these materials would give the highest thermionic emission current (at the same temperature)?

   (a) Iron (Fe); W=4.7 eV

   (b) Gadolinium (Gd); W=2.90 eV

   (c) Cobalt (Co); W=5 eV

2) Which laser would give the best Quantum efficiency on a Copper-based photo-cathode (W=5 eV)

   (a) A 5GW CO_2 laser (wavelength=10 micrometers)

   (b) A 10 kW frequency doubled Nd:YAG laser (wavelength=532nm)

   (c) A 3MW frequency quadrupled Ti-Sapphire laser (wavelength=200nm)

Answer 1: (b)

- The thermionic emission current is given by

$$J = AT^2 e^{\frac{-W}{k_B T}}$$

Gadolinium (b) has the lowest work function and thus it will give a higher current.

Answer 2: (c)

- Do not forget that QE is independent of the laser power.
- Remember that

$$E = h\nu = \frac{hc}{\lambda}$$

- The shortest the wavelength, the highest the energy. At 200nm a photon carries ~6 eV, so a 400nm photon carries ~3eV.
- Photon with a wavelength of 532nm (2.33eV) or 10 micrometer (~0.1eV) will have less energy than the work function of the photo-cathode.

Beam quality

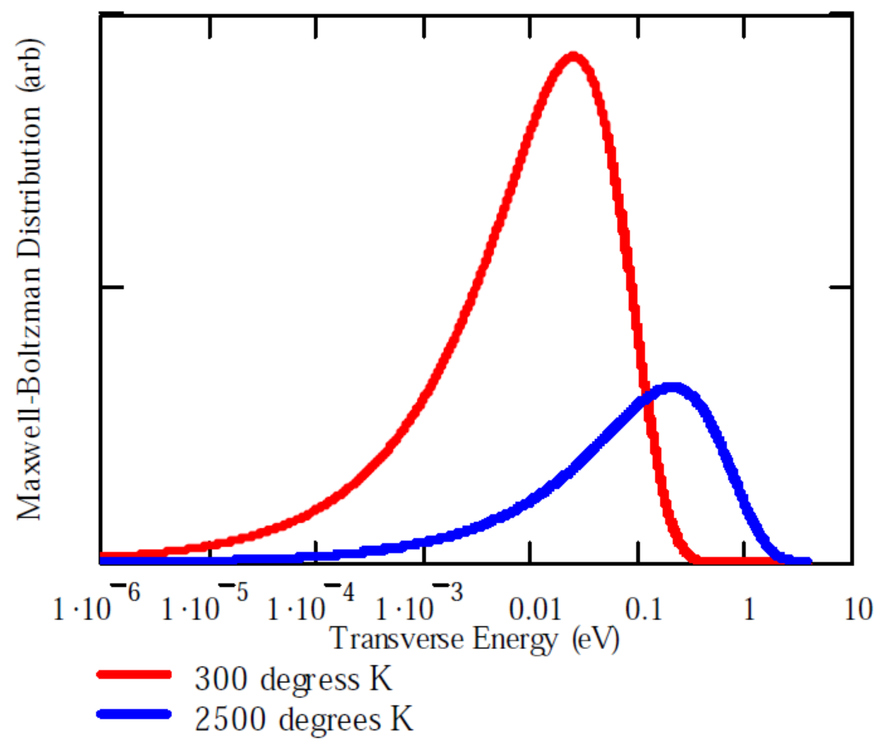
- The method used to produce the beam will impact its quality.
- A beam has a better quality if the particles have a low position and momentum spread.
- The *emittance* of a beam is the volume it occupied in a 6D position-momentum trace-space.
- We will discuss this more in details later but remember that a lower emittance (or a lower spread in position and momentum) means a better beam quality and a smaller beam size.

Thermionic emittance (1)

- Velocity distribution of thermionic electrons:

$$\frac{1}{n_e}\frac{dn(v_x)}{dv_x} = \frac{m}{k_B T} v_x e^{\frac{-m v_x^2}{2 k_B T}}$$

- The higher the temperature, the wider the transverse energy (momentum) spread.
- 300K => 0.049eV spread
- 2500K => 0.41eV spread
- The transverse momentum spread determines the beam divergence.



(image source: Dowell et al., Photoinjectors lectures)

Thermionic emittance (2)

- When measured near the cathode the thermionic emittance is the product of the beam width and the beam momentum spread.

$$\in_N = \beta\gamma\sigma_x\sigma_{x'}$$

- The transverse divergence can be rewritten as

$$\sigma_{x'} = \frac{1}{\beta\gamma}\frac{\sqrt{\langle v_x^2 \rangle}}{c} \qquad \langle v_x^2 \rangle = \frac{k_B T}{m_e}$$

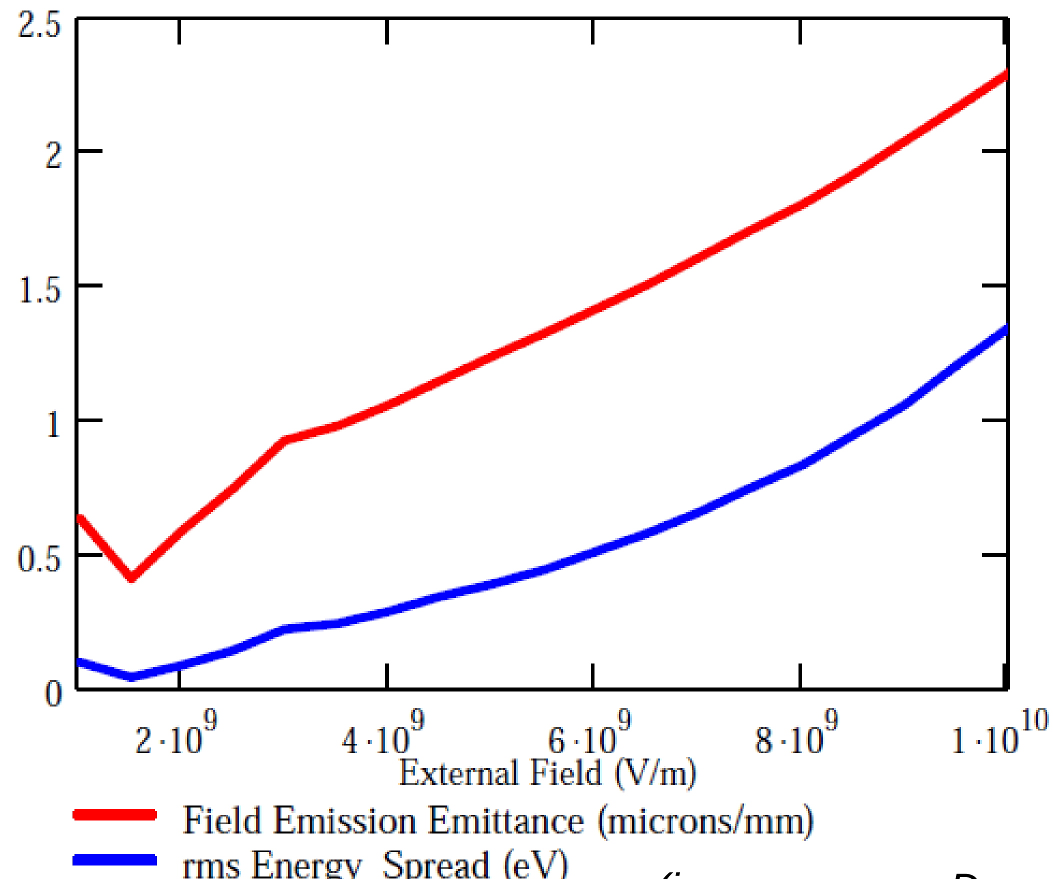
- Hence:

$$\in_N = \sigma_x \sqrt{\frac{k_B T}{m_e c^2}}$$

- The thermionic contribution to the emittance will be smaller at lower temperatures.

Field emission emittance

- Calculation difficult.
- Use numerical resolution



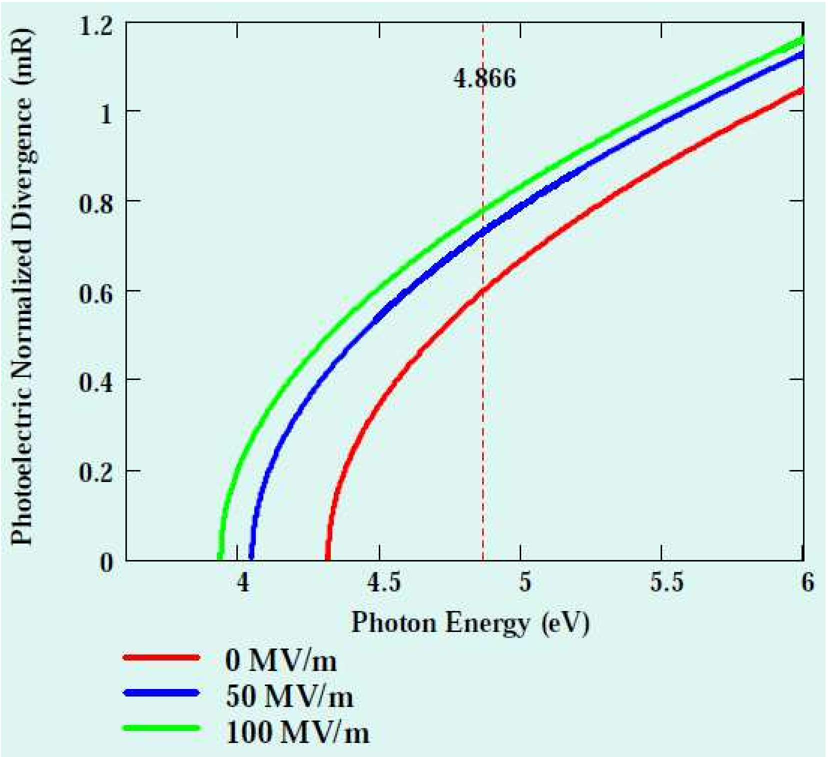
(image source: Dowell et al., Photoinjectors lectures)

Photo-electric emittance

- If the electron has a significant energy above the work function it is more likely to diverge.
- The photo-electric emittance is given by

$$\epsilon = \sigma_x \sqrt{\frac{\frac{hc}{\lambda} - (W - \Delta W)}{3 m_e c^2}}$$

- A high photon energy may lead to
a higher emittance.

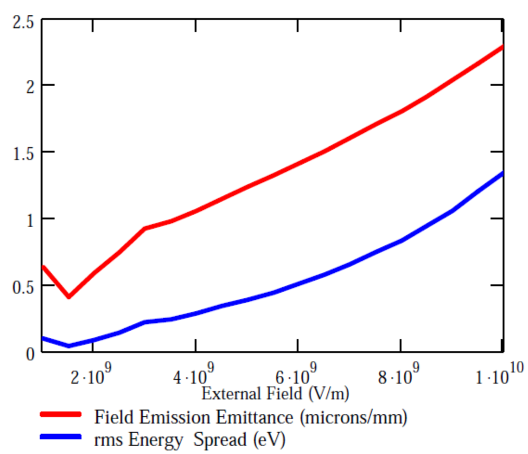


Particle source emittance trade-off

- We discussed in lecture 1 that to achieve high luminosity or high brilliance it is important to have a high current intensity with a small beam size.
- In the design of a gun (particle source) these two parameters will play against each other: high current will lead to a worse emittance!

$$J = AT^2 e^{\frac{-W}{k_B T}}$$

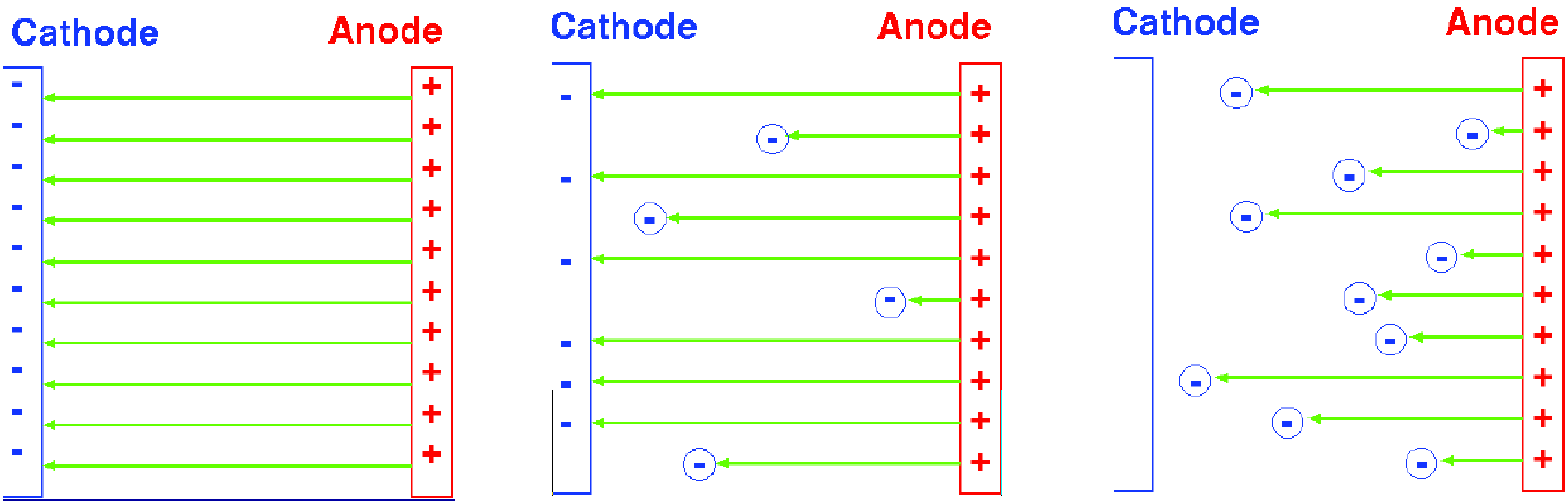
$$\epsilon_N = \sigma_x \sqrt{\frac{k_B T}{m_e c^2}}$$



$$J = \frac{e^3 F^2}{8h\pi W} e^{\frac{-4\sqrt{2m_e}}{3heF} W^{3/2}}$$

$$\epsilon = \sigma_x \sqrt{\frac{\frac{hc}{\lambda} - (W - \Delta W)}{3 m_e c^2}}$$

Space-charge limitation



(images source:Masao Kuriki, ILC school)

- Emitted electrons shield the cathode from the anode

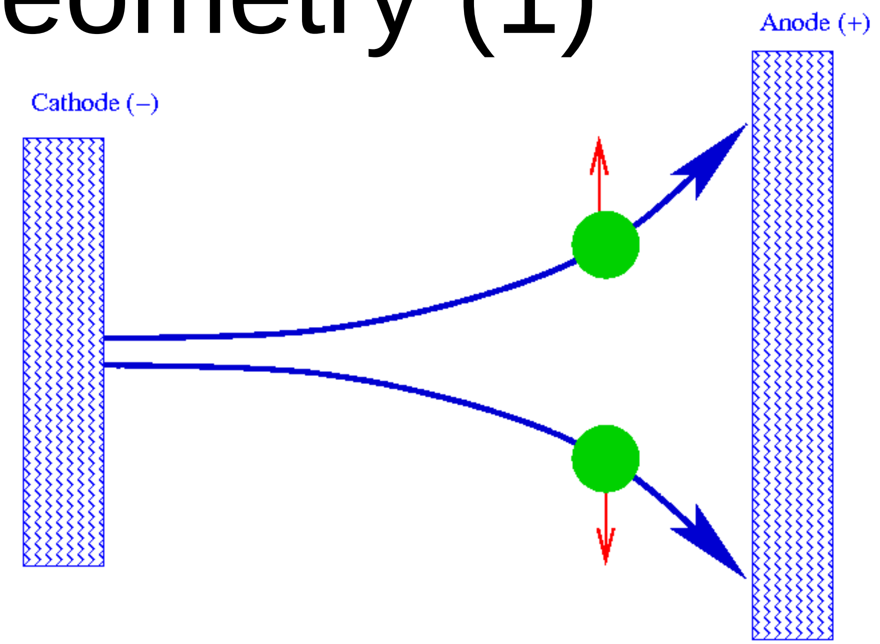
  => reduced field

- This limits the intensity of the emission.

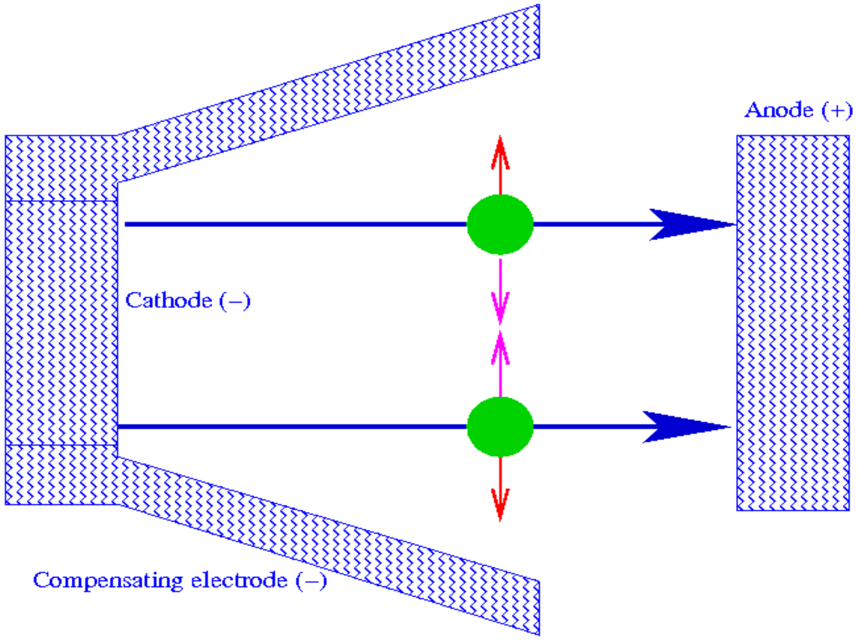
  Child-Landmuir law (potential V, area S, distance d)

$$J = 2.33 x 10^{-6} S \frac{V^{3/2}}{d^2}$$

Electrodes geometry (1)

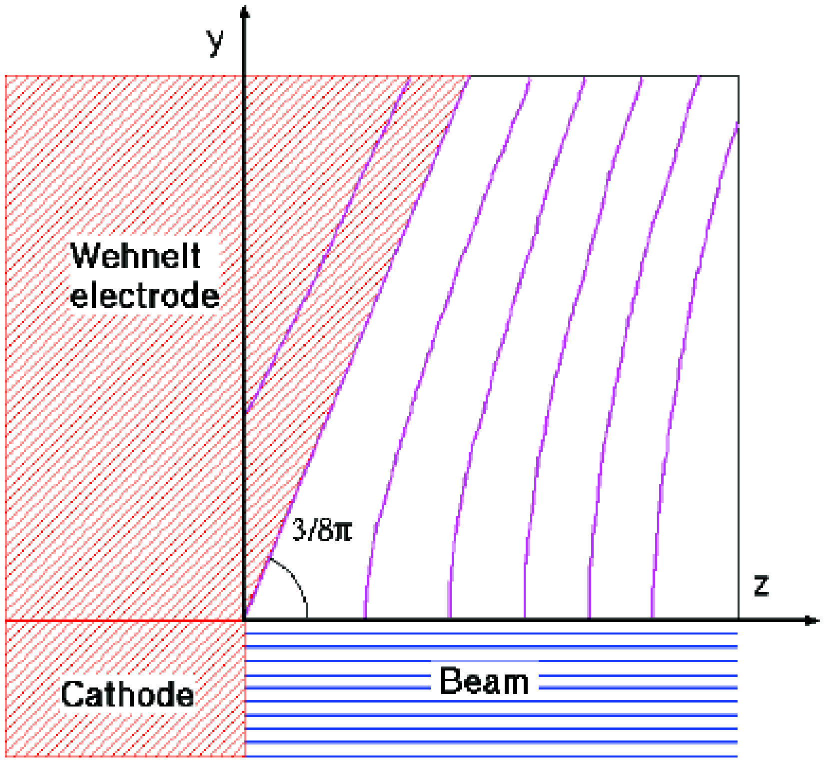


- Two emitted electrons repel each other.
- If the anode and the cathode are flat the beam will diverge due to the charges emitted.
- At low charge this effect will be small but with high current sources this will increase significantly the beam emittance.
- To avoid this the shape of the electrode must compensate the space charge forces.

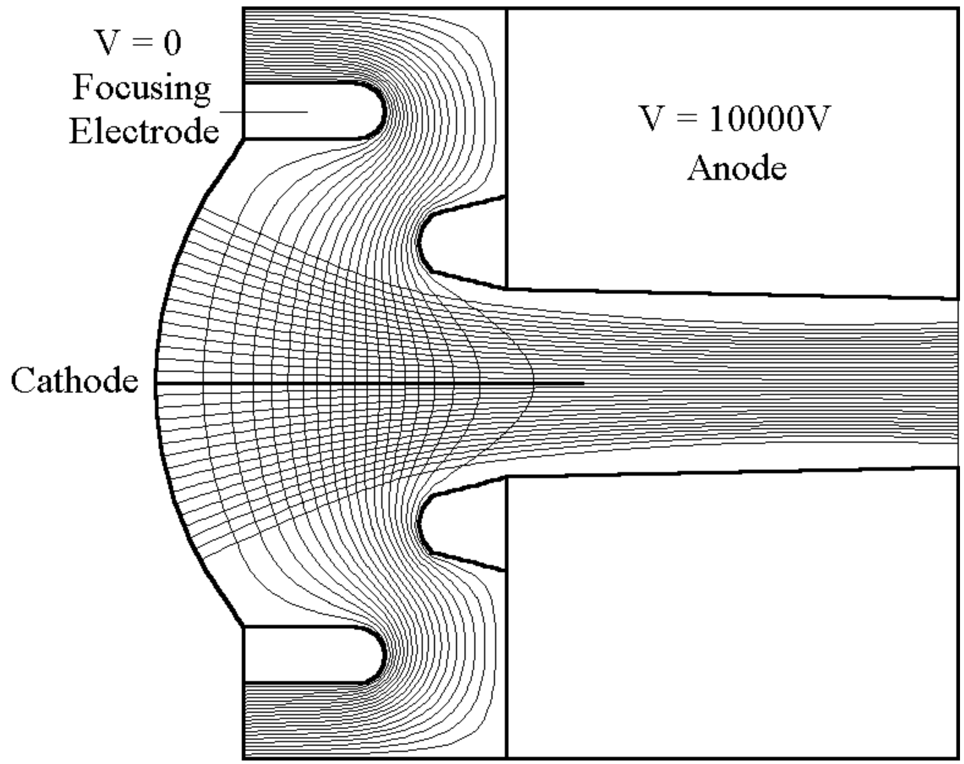


Electrodes geometry (2)

- The correct electrode shape will depend on the forces that must be compensated (ie beam current).
- By solving Laplace equation it is possible to find the best shape.



(images source:Masao Kuriki, ILC school)

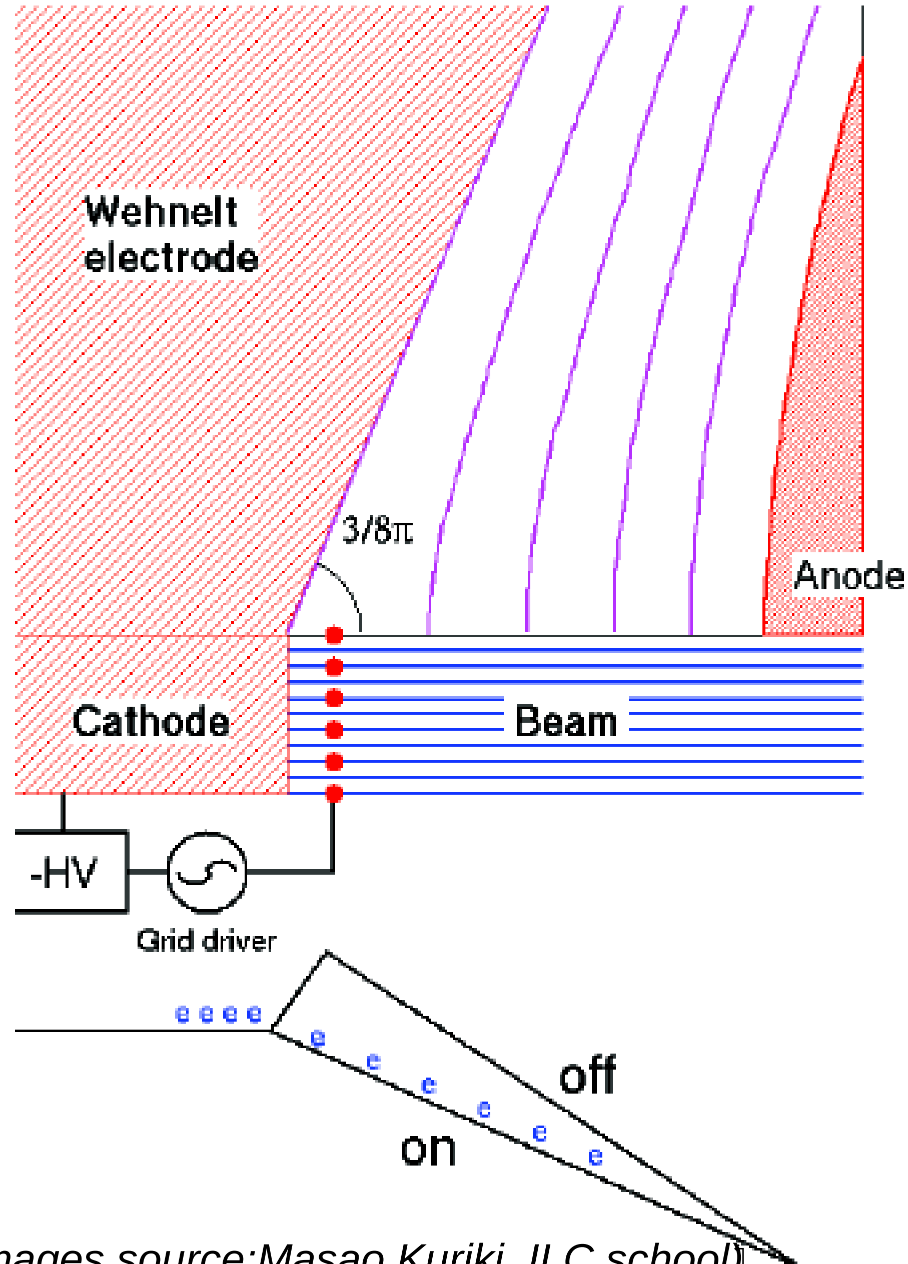


(images source: MEBS)

Pierce gun

Thermionic DC Gun

- Simplest gun design.
- Main features:
  - Thermionic cathode
  - Emission of the beam is controlled by a HV grid.
  - Compensating electrode
- Grid control limits pulse length. Typically >1ns.
- Operated in space charge limit.
- Such design is widely used.

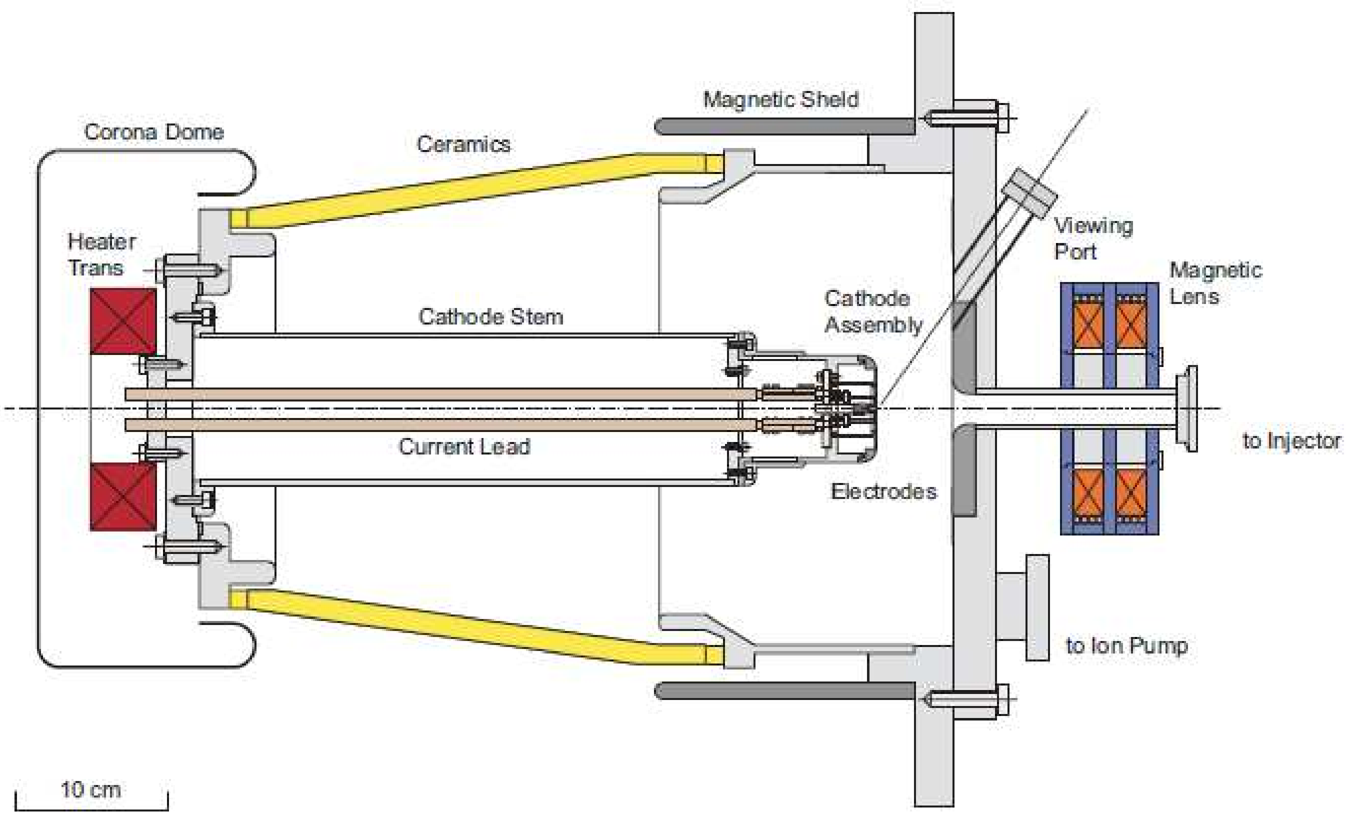


(images source:Masao Kuriki, ILC school)

Example of thermionic gun

SCSS

500kV Electron Gun

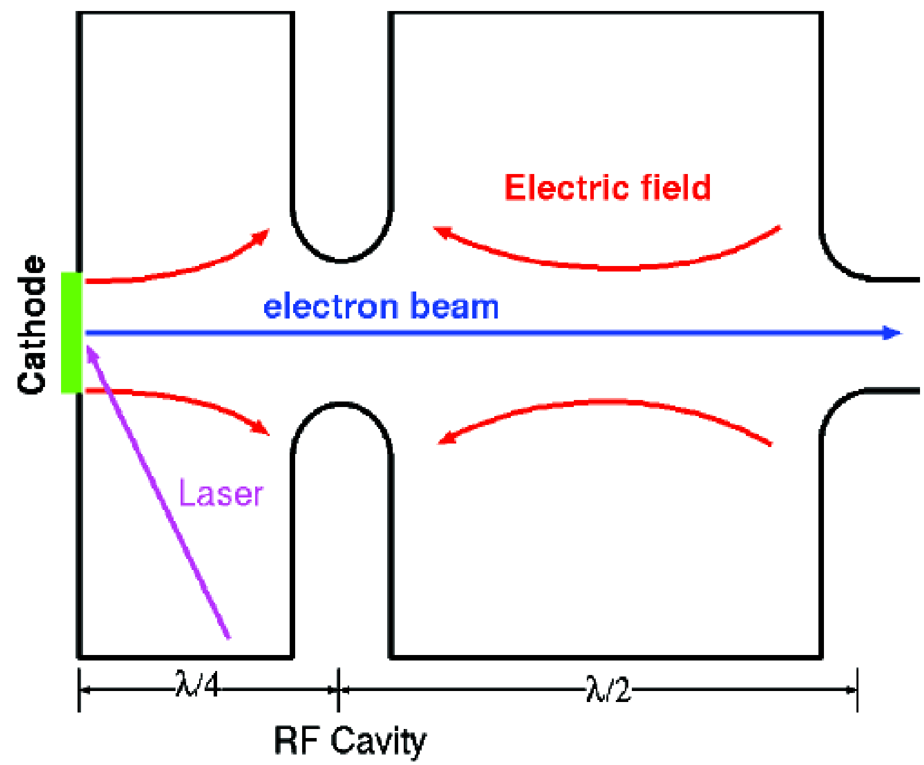


Spring 8 SCSS thermionic gun.

(images source: T. Shintake, Spring-8)

RF Gun

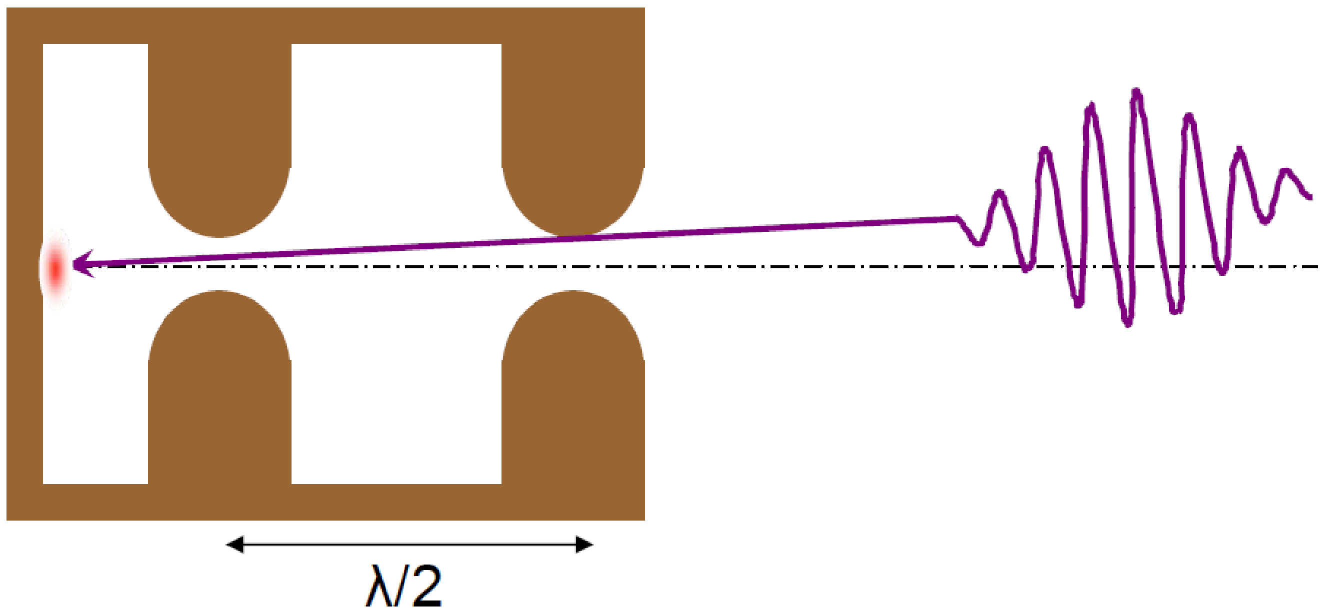
- The high voltage of a DC gun can be replaced by a RF cavity.
- This can provide much higher accelerating gradients and hence limit the space charge.
- RF guns are often coupled with a photo-cathode.
- RF gun can generate shorter bunches (using short laser pulses).



(images source:Masao Kuriki, ILC school)

Principle of a RF Photo-gun

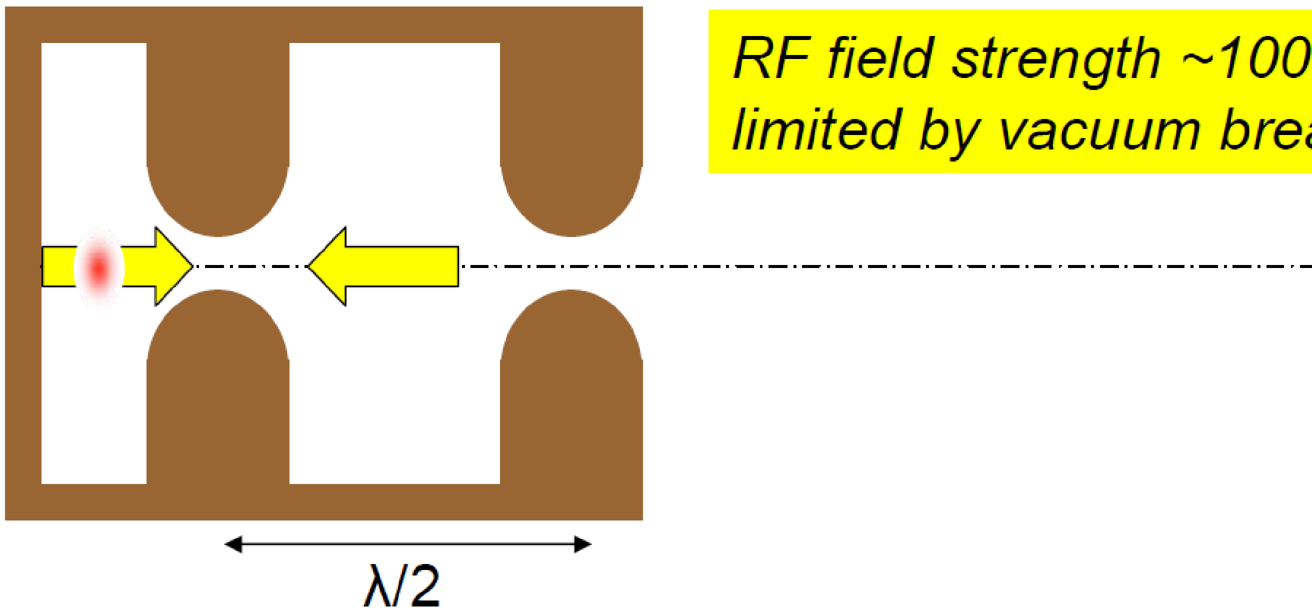
Pulsed laser photoemission...



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

...and RF acceleration.

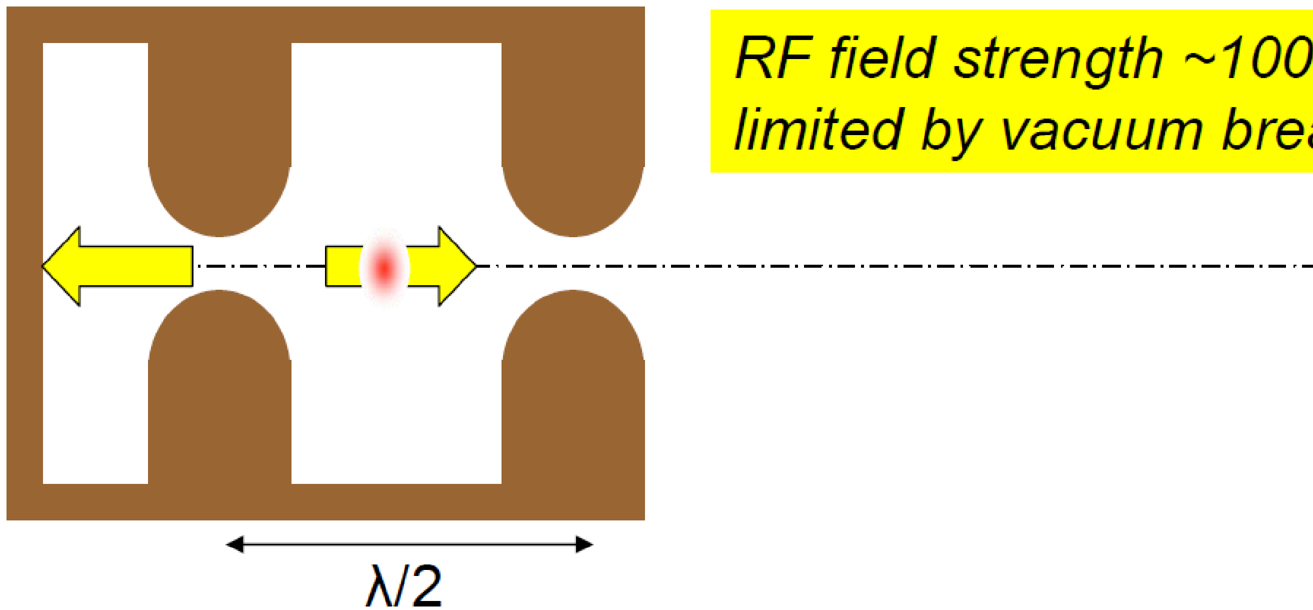


RF field strength ~100 MV/m, limited by vacuum breakdown

Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

...and RF acceleration.

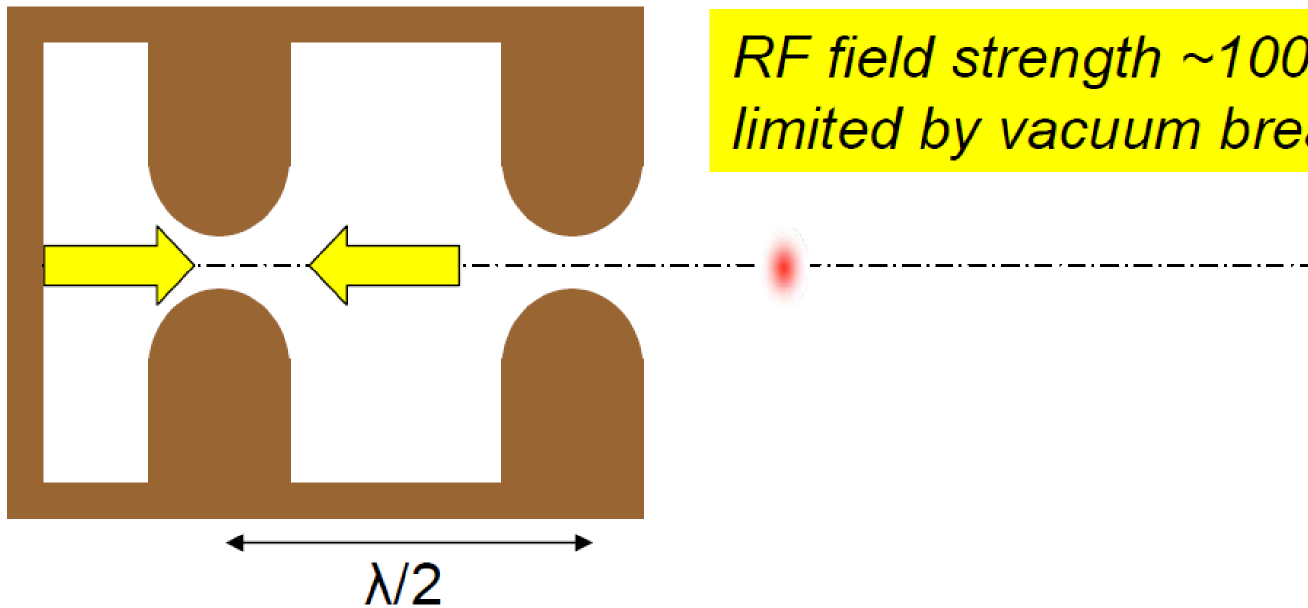


RF field strength ~100 MV/m, limited by vacuum breakdown

Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

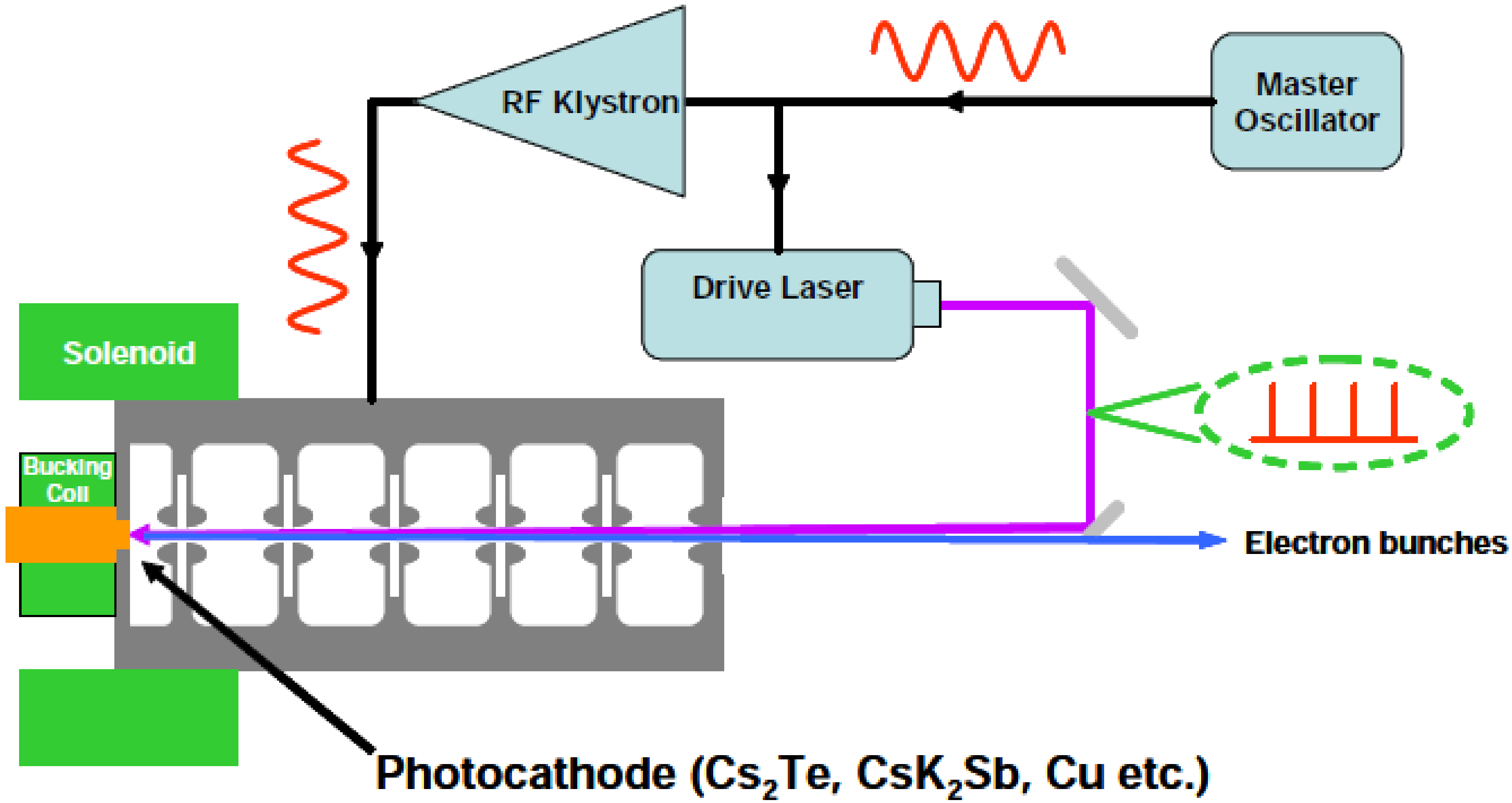
...and RF acceleration.



RF field strength ~100 MV/m, limited by vacuum breakdown

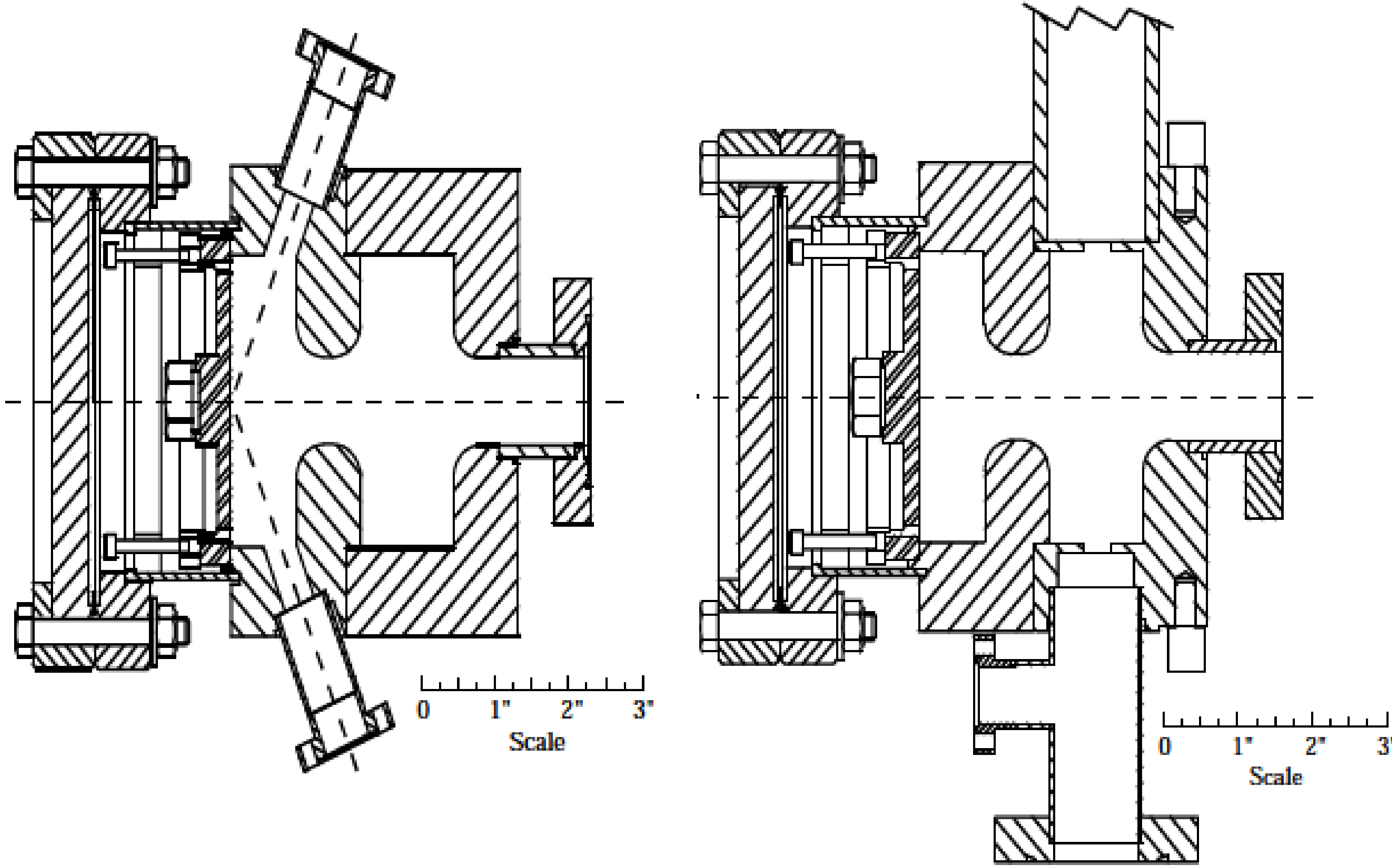
Courtesy Jom Luiten, TUV Eindhoven

RF photocathode gun



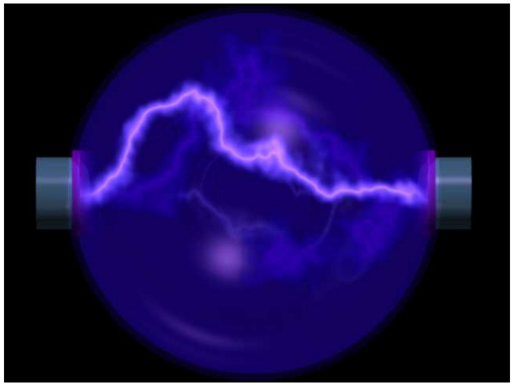
Slide compliments of P. O'Shea, UMd

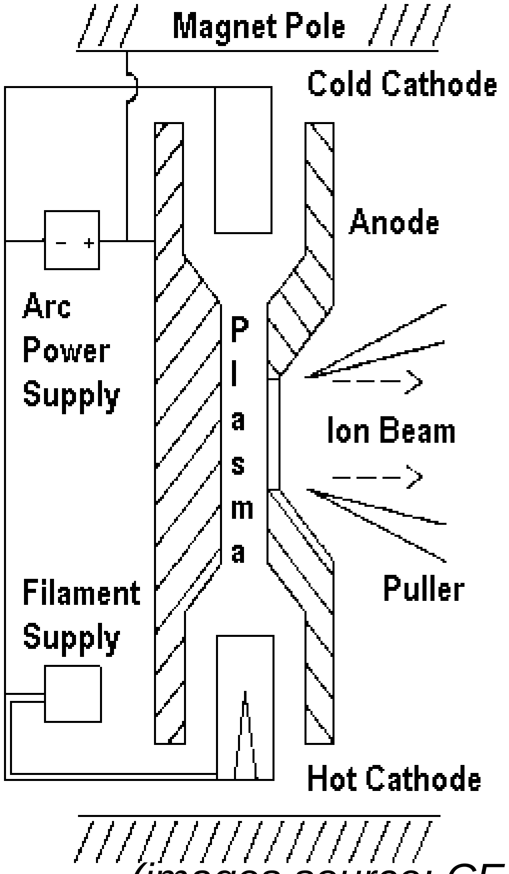
BNL/SLAC/UCLA RF photocathode gun



Ion (and proton) sources

- An electric discharge creates a plasma in which positively and negatively charged ions are present (as well as neutrals).
- If such plasma experiences an intense electric field ions will separate in opposite directions.
- This is a rather crude and inefficient (but very simple) way of producing any sort of ions.
- In a Penning ion source a magnetic field is used to increase the probability the free electron ionize extra neutrals.

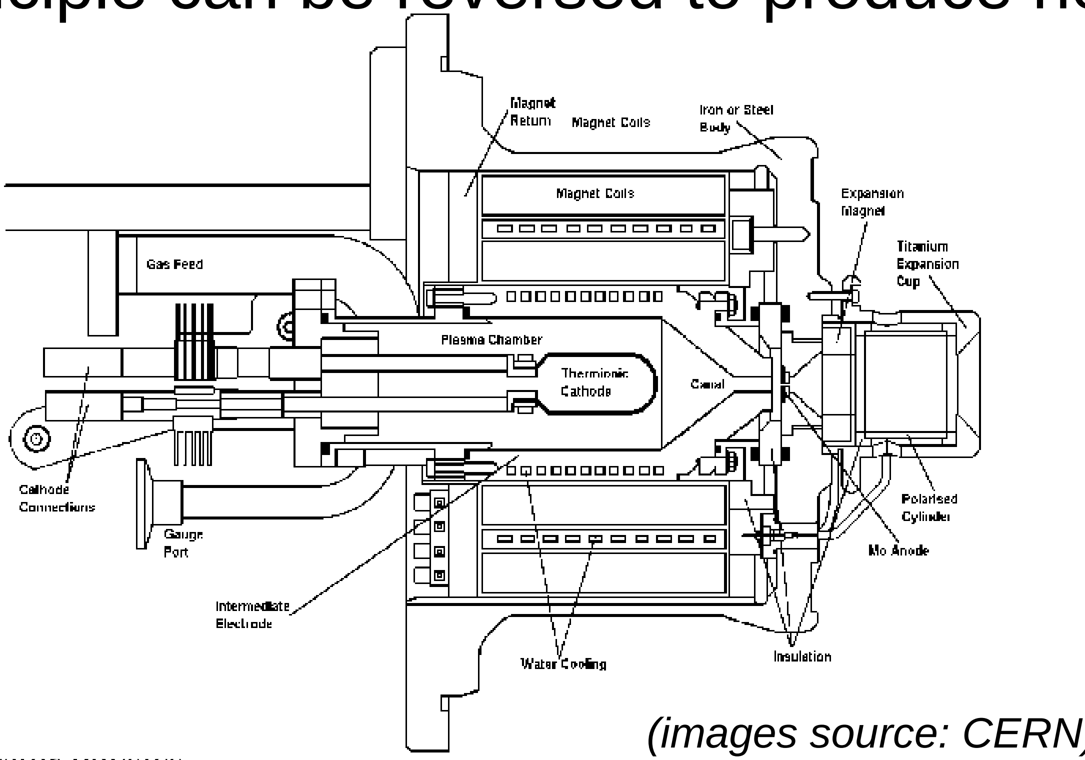




(images source: CERN)

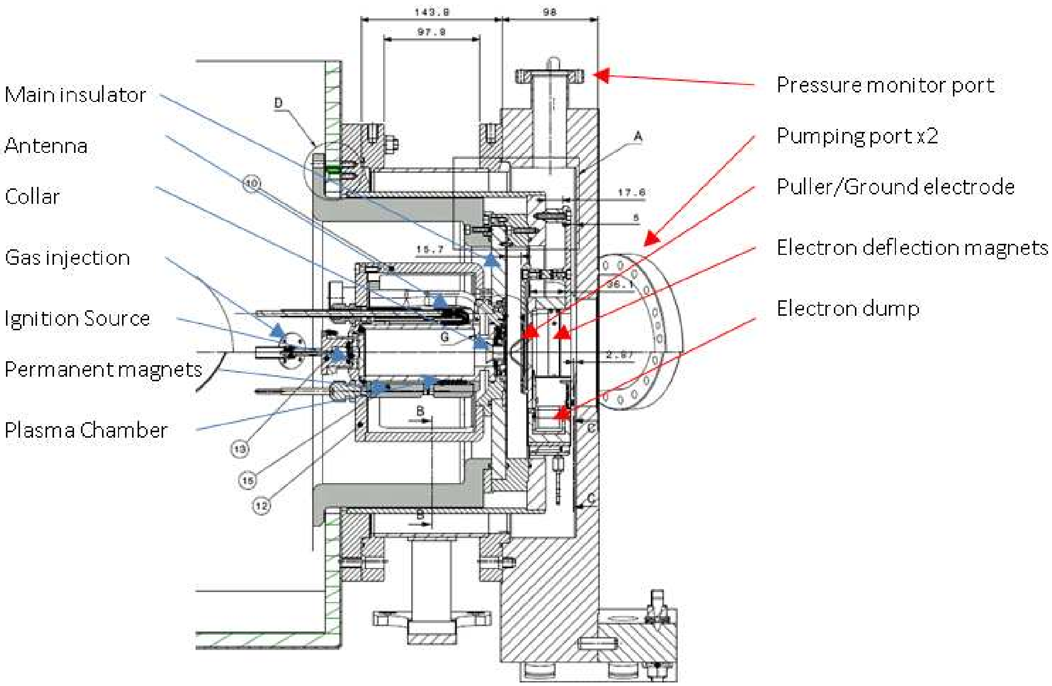
Plasmatrons

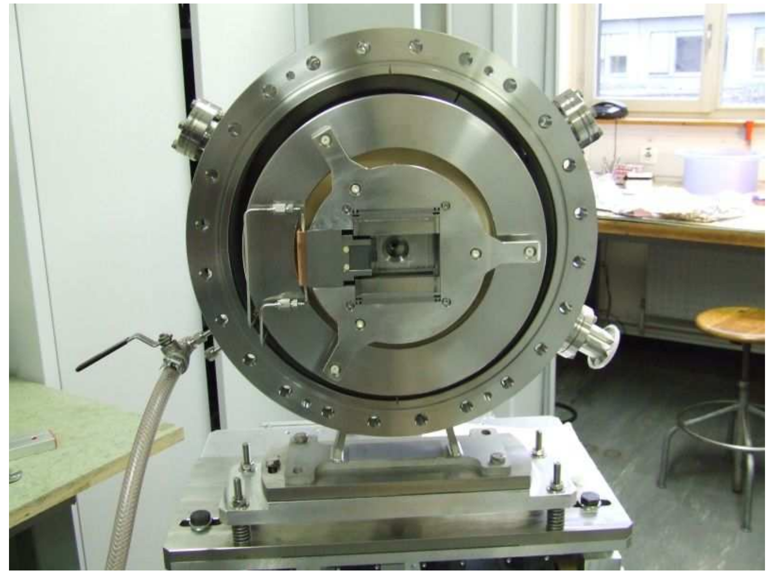
- The efficiency of the source can be increased by restricting the size of the anode.
- This will increase the plasma density near the exit and increase the potential (and thus the energy of the ions).
- This principle can be reversed to produce negative ions.



(images source: CERN)

CERN Linac 4 H- source





http://linac4ionsource.web.cern.ch/

Courtesy Richard Scrivens, CERN

... Particle sources

- We have discussed how to produce the particles used in accelerators.
- The requirement of the next generation of electron accelerators impose strong constraint on the quality of the beam produced by electron sources. Several recent development aim at improving this quality.
- Ion machine are limited by the beam intensity that can reliably be extracted form the source.
- For both electrons and ions the quality of the particle source has a strong impact on the overall accelerator performance.

Problem set 2

is available online at

http://www-pnp.physics.ox.ac.uk/~delerue/accelerator_option/