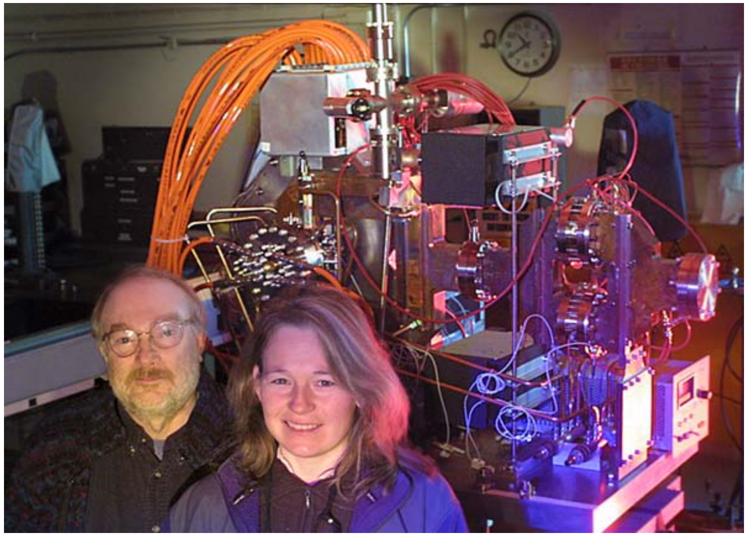
Electron and Ion Sources

Layout



- **Electron Sources**
  - Thermionic
  - Photo-Cathodes
  - Child-Langmuir Current Limitation
- **Ion Sources**
  - Particle motion in plasmas
  - Penning Ion Source
  - ECR Ion Source
  - Negative Ions

Richard Scrivens, BE Dept, CERN.

CAS, Varna, September 2010

Electron and Ion Sources

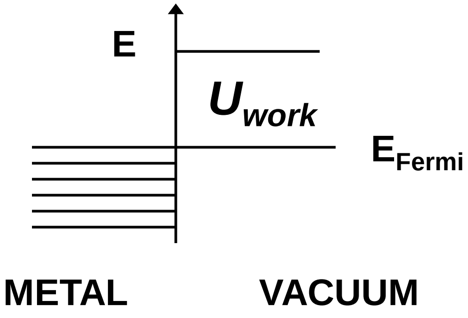
Electrons – Thermionic Emission

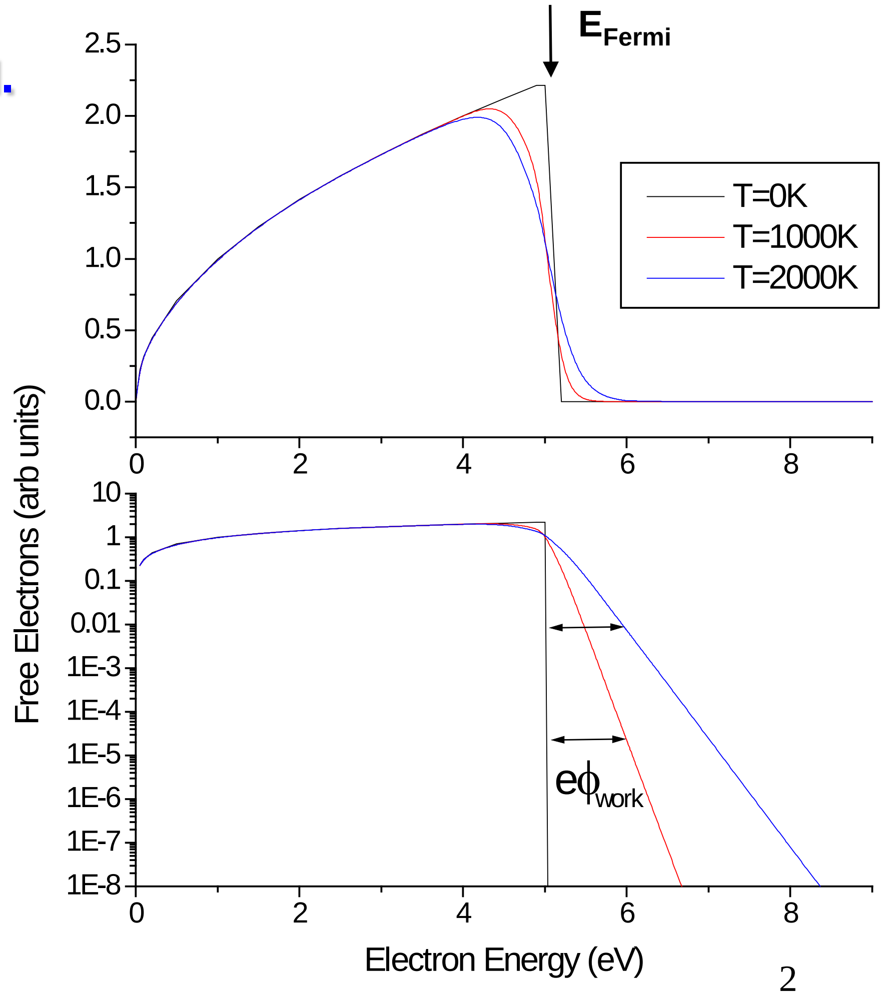
Conducting materials contain free electrons, who follow the Fermi-Dirac energy distribution inside the material.

When a material is heated, the electrons energy distribution shifts from the zero temperature Fermi distribution.

$$n(E)dE = \left[\frac{4\pi(2m_e)^{3/2}}{h^3}\right]\left[\frac{\sqrt{E}}{1+\exp\left(\frac{E-E_{Fermi}}{kT}\right)}\right]dE$$

Electrons above the work function energy, can be removed from the material.





Electron and Ion Sources

Electrons – Thermionic Emission

- Therefore at high temperatures there is an ELECTRON CLOUD around the material. The current density can then be found by integrating the available electrons and their energy.

$$J = nve$$

$$J = A \cdot T^2 \exp\left(\frac{-eU_{work}}{kT}\right)$$

$$A = \frac{4\pi e m_e k^2}{h^3} \approx 1.2 \times 10^6 \,\mathrm{Am}^{-2} K^{-2}$$

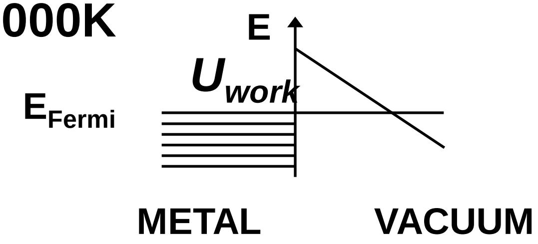
This electron current is available to be pulled off the surface… Richardson-Dushmann equation *Rev. Mod. Phys. 2, p382 (1930)*

This factor *A* is not achieved In practice.

- The current density is further increased by the Schottky effect – the electric field on the surface, used to extract the electrons, allows electron tunneling

$$J = J_{R-D} \times \exp\left(\frac{139 E_S}{T}\right)$$

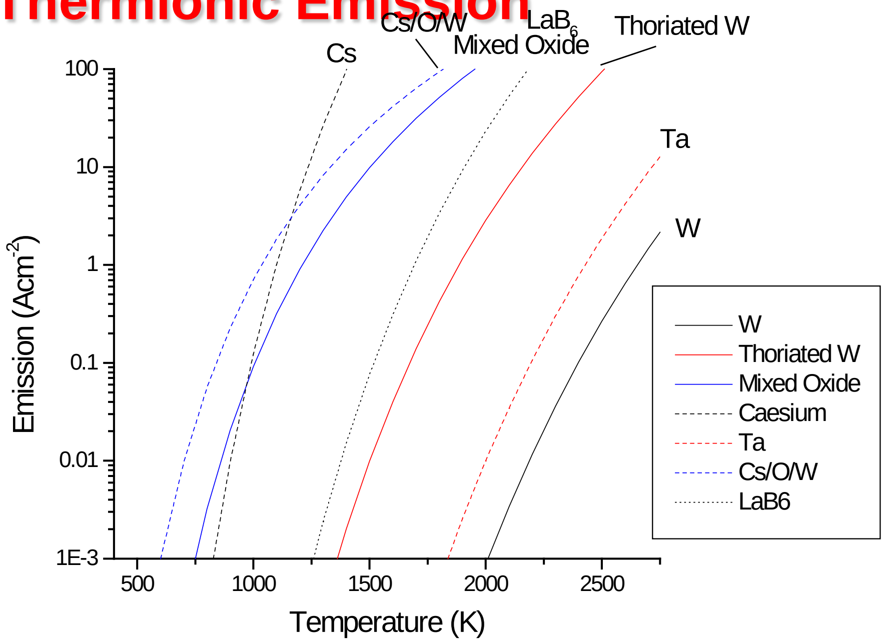
Where E_s is in kV/cm => 15% for 1kV/cm @1000K

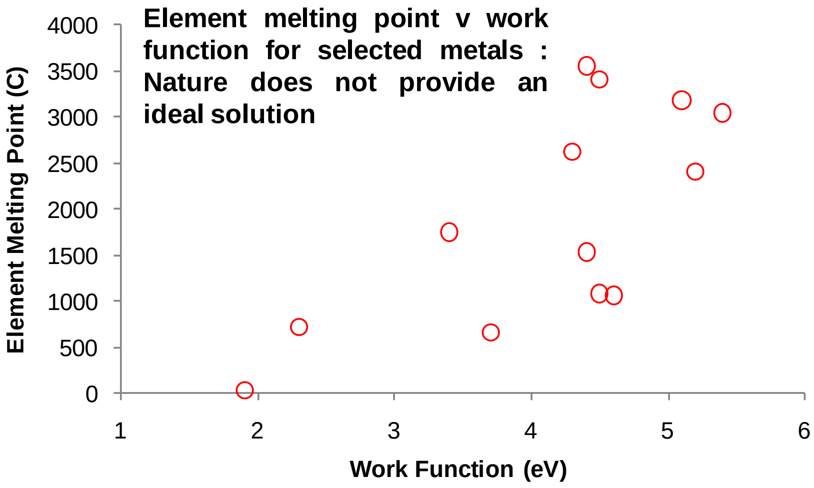


Electron and Ion Sources

Electrons – Thermionic Emission

	A $Acm^{-2}K^{-2}$	U_{work} eV
W	60	4.54
W Thoriated	3	2.63
Mixed Oxide	0.01	1
Cesium	162	1.81
Ta	60	4.12
Cs/O/W	0.003*	0.72*
LaB_6	29	2.66





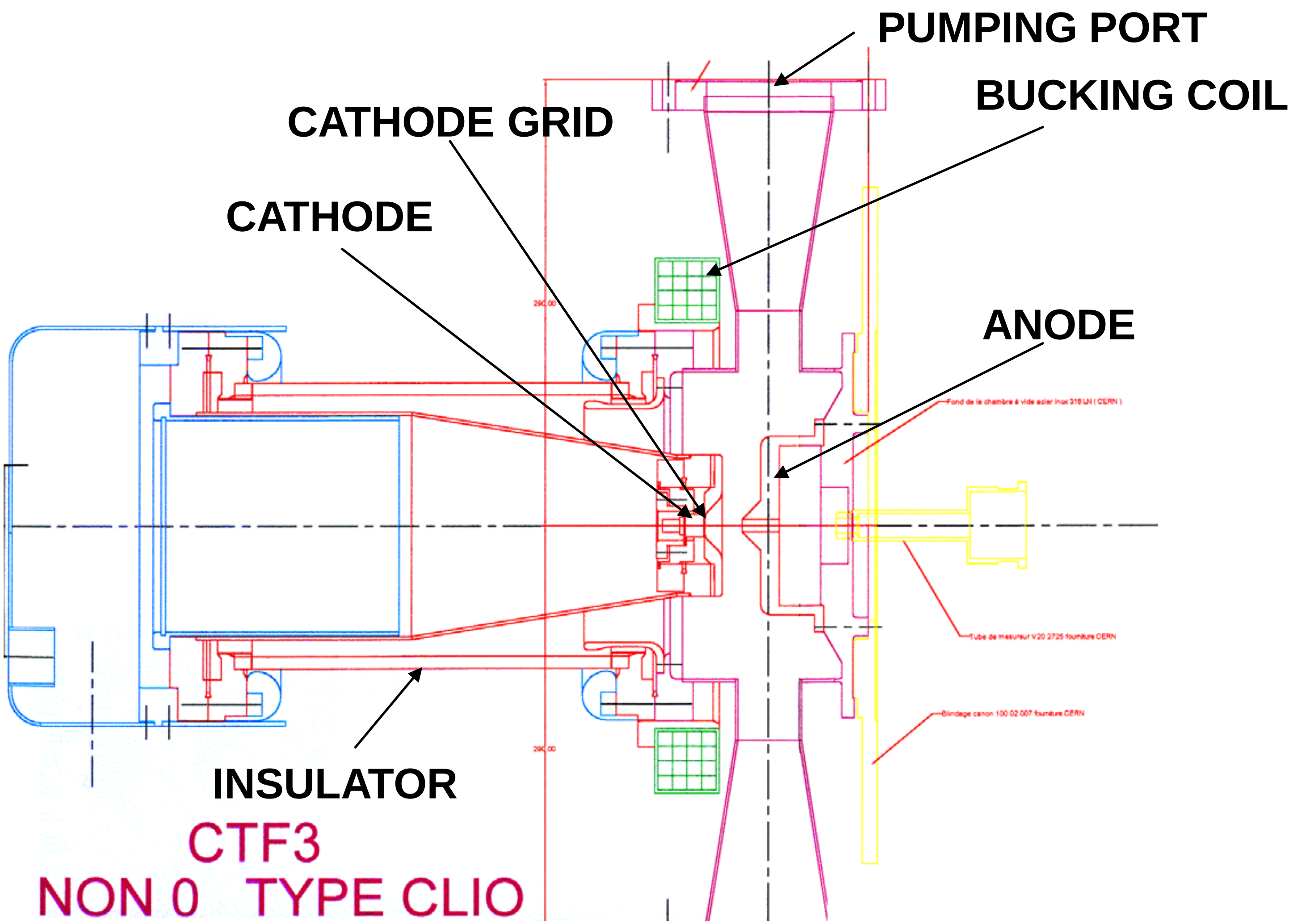
Element melting point v work function for selected metals : Nature does not provide an ideal solution

***- A and work function depend on the Cs/O layer**

Thickness and purity

Electron and Ion Sources

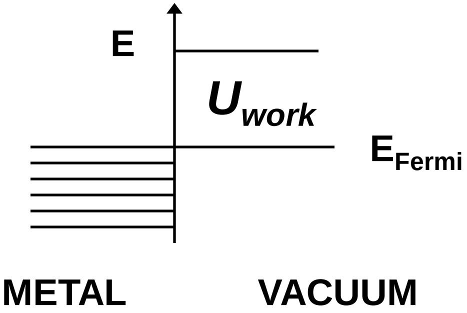
Electrons – A Gun

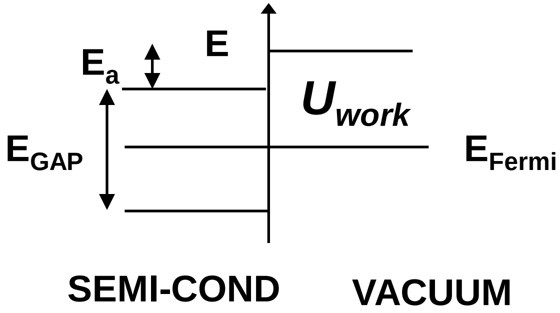


Electron and Ion Sources

Electrons – Photo Emission

- **The energy of an electron in a material can be increased above the vacuum energy by absorbing photons - photoelectric effect.**





$$\lambda_c = \frac{hc}{eU_{work}} = \frac{1239.8}{U_{work}}$$

$$\lambda_c = \frac{hc}{E_{GAP} + E_a} = \frac{1239.8}{E_{GAP} + E_a}$$

	U_{work} (eV)	λ_c (nm)
W	4.5	275
Mg	3.67	340
Cu	4.65	267

	E_g+E_a (eV)	λ_c (nm)
GaAs	5.5	225
Cs:GaAs	*	*
Cs_2Te	~3.5	350
K_2CsSb	2.1	590

Cs:GaAs – Surface Caesiated GaAs

can be used with 532nm radiation. Requires

Recaesiation after a few hundred C extraction.

Electron and Ion Sources

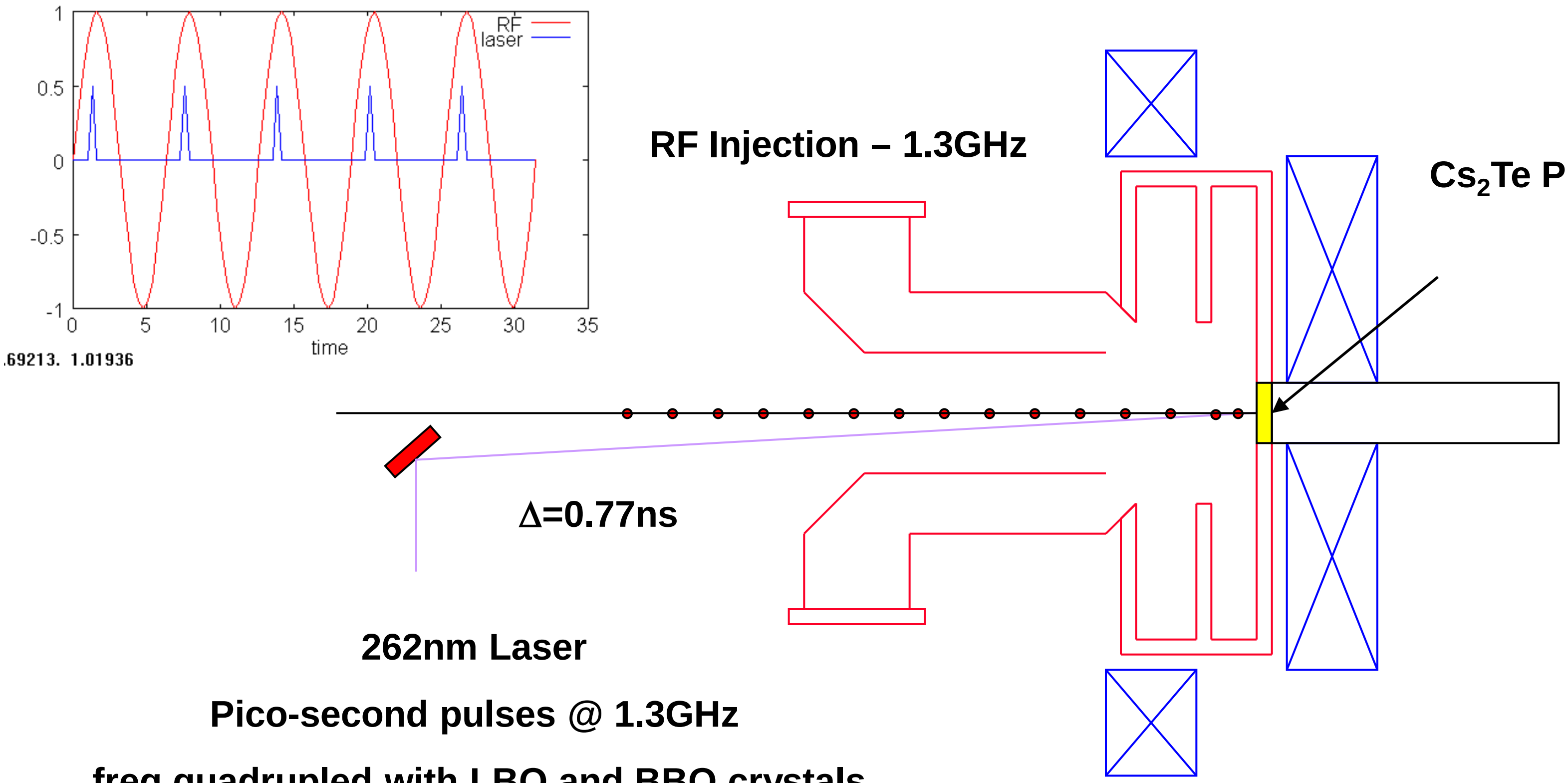
Electrons – Photo Cathodes

- **Quantum Efficiency = Electrons/photon [$Q_e(\lambda)$]**
  - **GaAs:Cs=17% , CsTe=12.4% , K2CsSb=29%, Cu~0.01%,**
- **METALS**
  - **If desired, can be almost-“blind” to optical or infra-red.**
  - **Using the thermal electrons above the Fermi Energy, can make a very low current source using optical wavelengths.**
  - **At high optical powers, a plasma is formed.**
- **SEMICONDUCTORS**
  - **Can find materials optical wavelengths with high quantum efficiency (cf Photo Cathode Tubes).**
  - **Difficult to use in a high radiation area of an electron-gun (x-rays and ions cause decomposition and surface damage).**
  - **GaAs:Cs has high QE at 532nm – High power lasers available. Cs surface not suited to RF guns.**
  - **Cs_2Te (Cesium Telluride)– High Quantum efficiency but needs UV lasers.**

Electron and Ion Sources

Electrons – Photo Injector

- **Photo cathodes can produce bunch structure of the same length as the light pulse.**
  Photo Injector Test Facility - Zeuthen



RF Injection – 1.3GHz

Cs_2Te Photo-Cathode

or Mo

Δ=0.77ns

262nm Laser

Pico-second pulses @ 1.3GHz

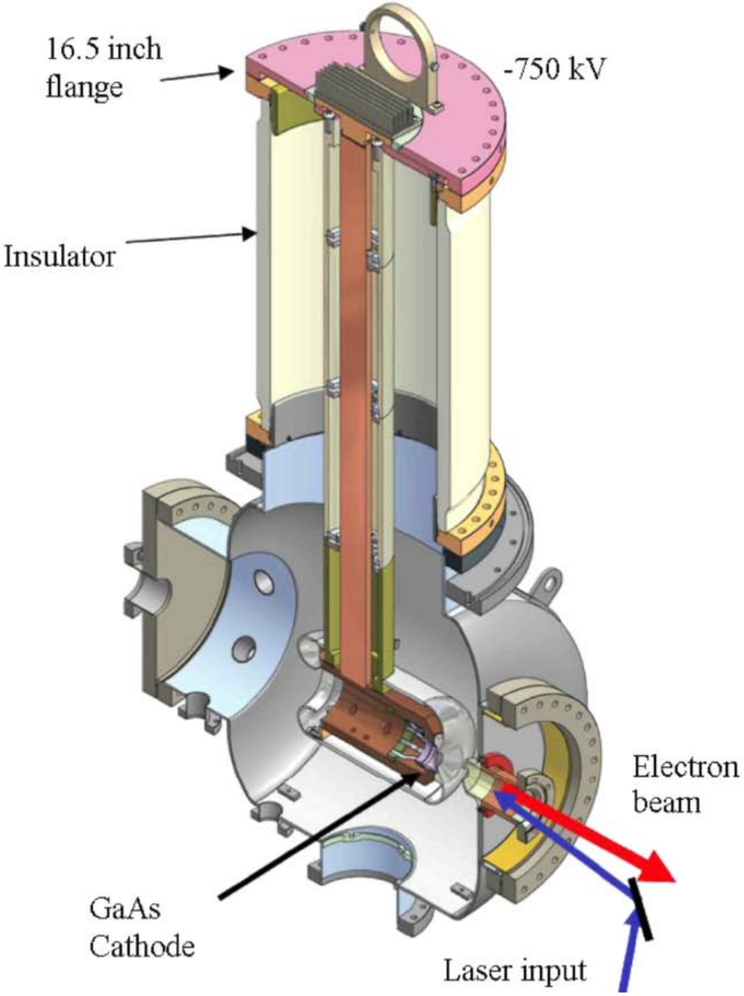
freq quadrupled with LBO and BBO crystals

Electron and Ion Sources

- **Cornell DC Photoemission gun.**

  laser = 520nm, 1.3GHz

  Cathode Cs:GaAs



Electron and Ion Sources

Limitations in Emittance

- **Thermal Emittance:**
  Electron and ion source have a minimum emittance that can be produced, due to the excess thermal energy of the particles before they are brought into vacuum.

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

$$\varepsilon_n = \frac{\gamma(\beta m_0 c\sigma_{x'})\sigma_x}{m_0 c}$$

- $\beta m_0 c\sigma_{x'}$ **Is the transverse momentum. Can be assess for particle sources.**

$$\varepsilon_{th} = \sigma_{laser}\sqrt{\frac{2E_{kin}}{3m_0c^2}}$$

Normalised emittance for photoelectrons

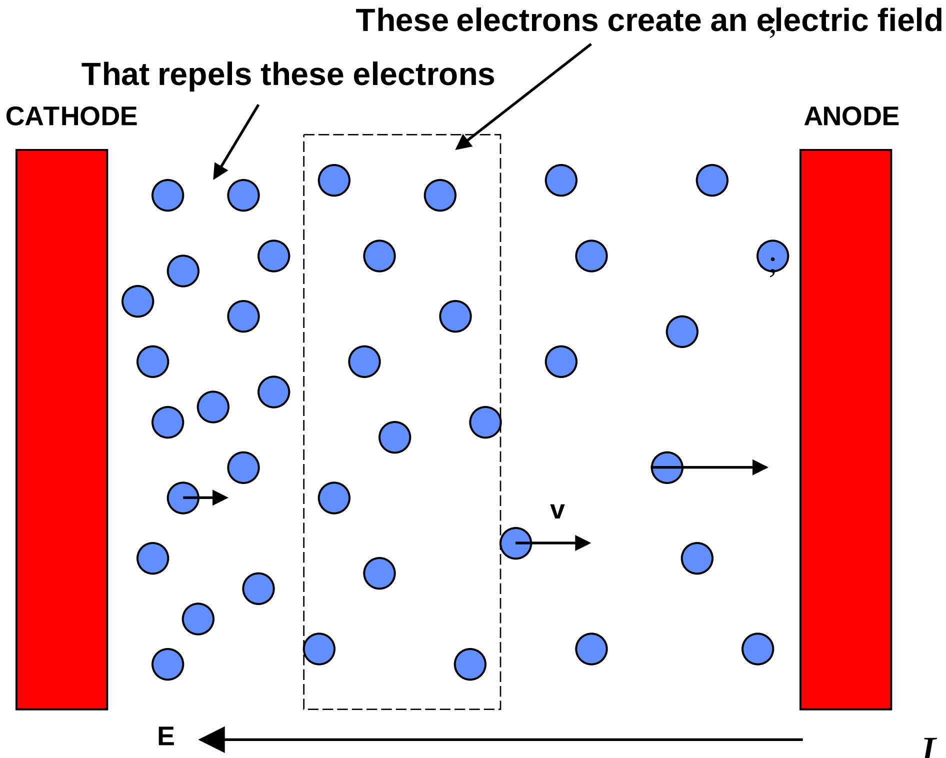
E_{kin}: **Electron excess kinetic energy**
σ_{laser} : **Laser beam spot**

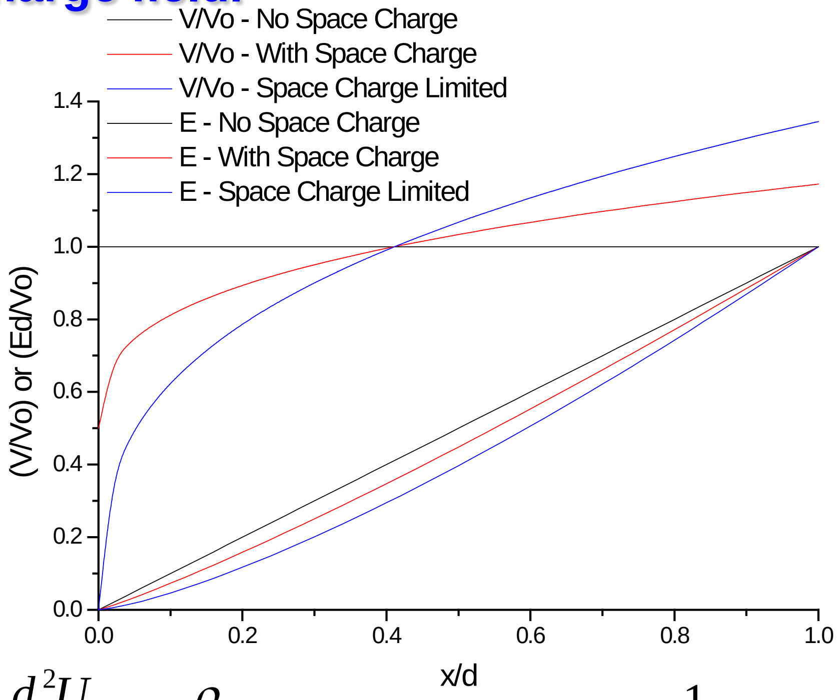
- **Typically values for the thermal emittance are 0.1 – 1 mm.mrad Can use λ_{laser} to change E_{kin}. But E_{kin} and high Q_e are not compatible.**

Electron and Ion Sources

Electrons – Child-Langmuir Law

- Child-Langmuir law (3/2 power law) gives the limit of current that can be removed from a surface.
- Need electric field to remove electrons from surface.
- Electrons set up their own space charge field.





$$\frac{d^2U}{dx^2} = -\frac{\rho}{\varepsilon_0} \qquad J = \rho v \qquad qU = \frac{1}{2}mv^2$$

$$U(x=0)=0; U(x=d)=V; \frac{dU(x=0)}{dx}=0$$

Electron and Ion Sources

Electrons – Child-Langmuir Law

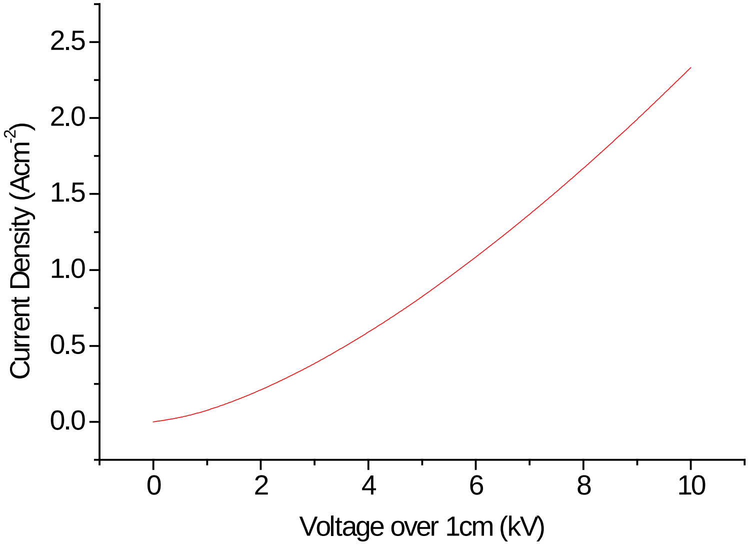
- Hence there is a MAXIMUM current density that can be extracted for a given voltage and gap.

$$J_{C-L} = \frac{4}{9}\varepsilon_0\left(\frac{2q}{m}\right)^{1/2}\frac{V^{3/2}}{d^2}$$

d : Cathode to Anode distance
V : Cathode to Anode voltage
q : particle charge
m : particle mass
This is not relativistic

- If the cathode-anode voltage is varied, so is the electrode current.

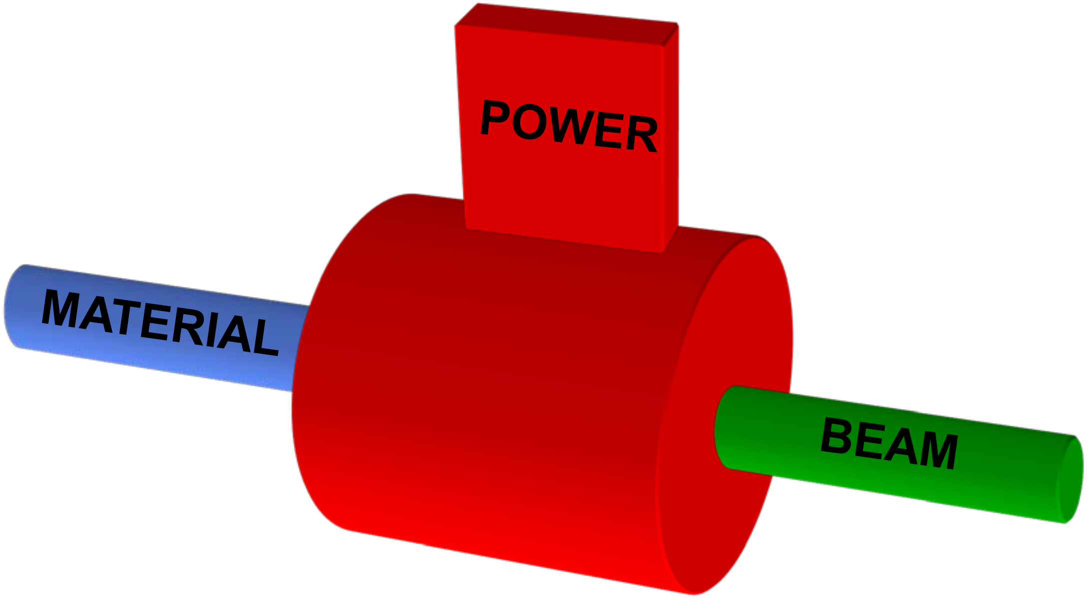
- If the cathode-anode voltage is ZERO, no current is extracted -> Cathode Grid.



Electron and Ion Sources

Ion Sources - Basics

- An Ion Source requires an “ion production” region and an “ion extraction” system.
- In most (but not all) cases, ion production occurs in a plasma.



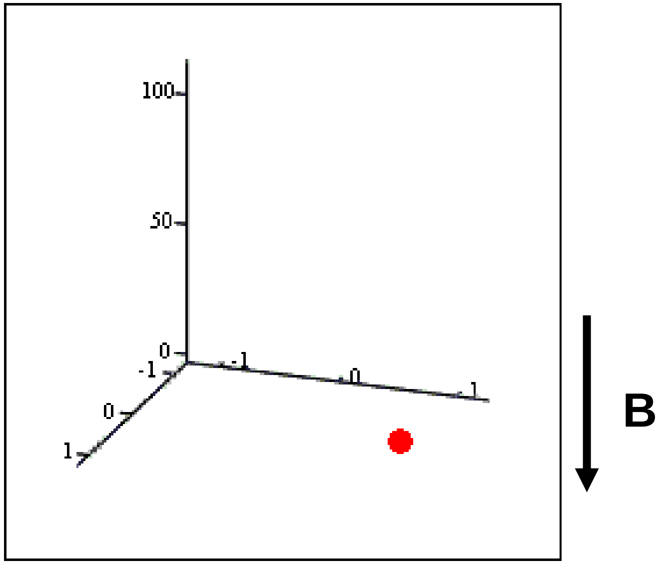
Electron and Ion Sources

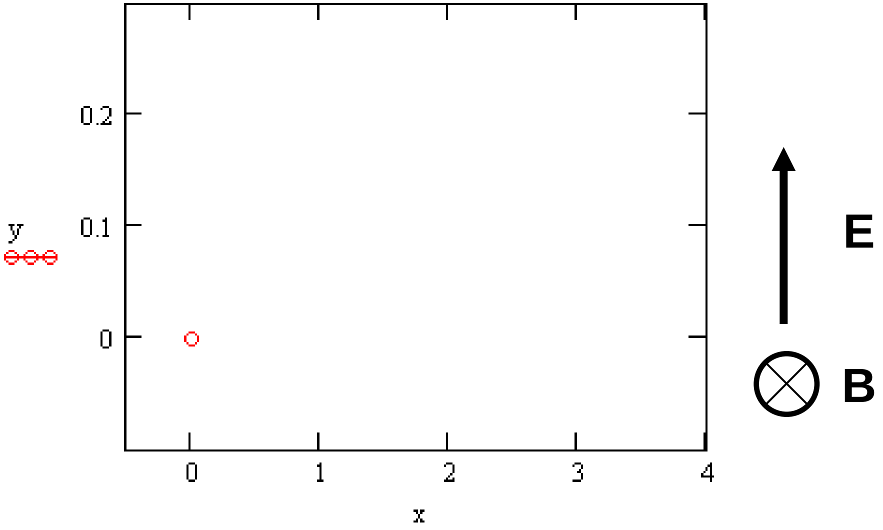
Ion Sources - Basics

- Plasma Processes
  - Electron heating
  - Plasma confinement (electric and magnetic)
  - Collisions (e-e, e-i, i-e, i-i + residual gas)
  - Atomic processes (ionisation, excitation, disassociation, recombination)
  - Surface physics (coatings + desorbtion, e-emission)
  - Mechanical processes (chamber heating+cooling, erosion)
- Ion Source Goal -> Optimise these processes to produce the required ion type and pulse parameters.
- AND maximize reliability, minimize emittance, power and material consumption.

Electron and Ion Sources

Plasma Particle Motion





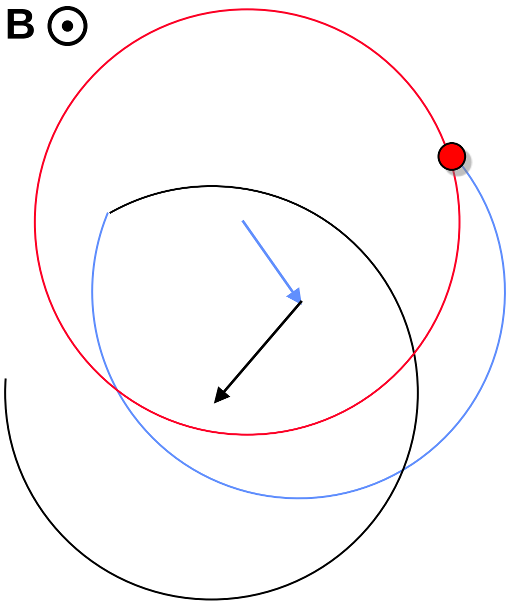
$$\rho_L = \frac{\sqrt{2mE_\perp}}{eB}, \omega_L = \frac{eB}{m}$$

$$v_{drift} = \frac{\vec{E} \times \vec{B}}{B^2}$$

Electron and Ion Sources

Plasma Particle Motion

$$D \sim \rho_L{}^2 \upsilon_c \sim \left(\frac{\sqrt{2m_p E_\perp}}{eB}\right)^2 \frac{1}{T^{3/2}} \left(\frac{m_e}{m_p}\right)^{1/2} \sim \frac{m_p^{1/2}}{T^{1/2}}$$



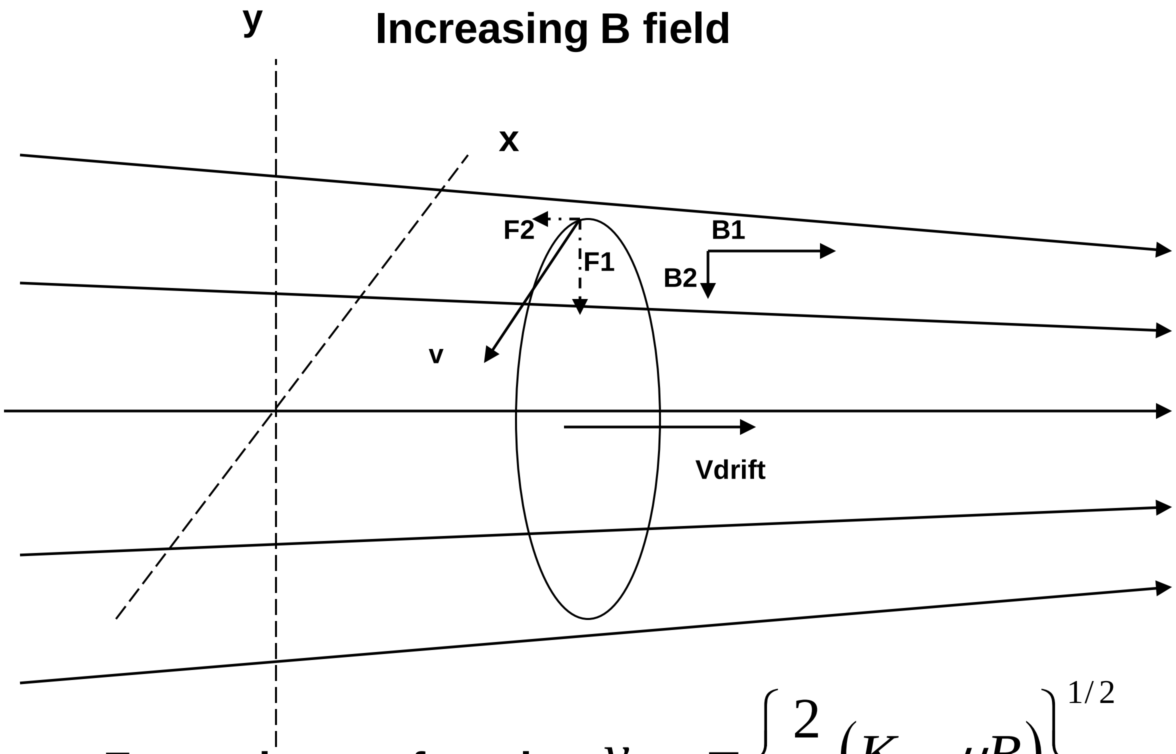
cf: opposite to classical
energy – velocity equation !

$$v = \left(\frac{2E}{m}\right)^{1/2}$$

Electron and Ion Sources

ECR Source – Magnetic Mirror

A force acts in the opposite direction to the Increasing B field



Energy is transferred from Vdrift to Vecr

$$v_{drift} = \left\{ \frac{2}{m}\left(K - \mu B\right) \right\}^{1/2}$$

$$\mu = \frac{m v_{\perp}^{2}}{2B}$$

μ = magnetic moment

K = total kinetic energy

Electron and Ion Sources

Ion Source – Penning / PIG

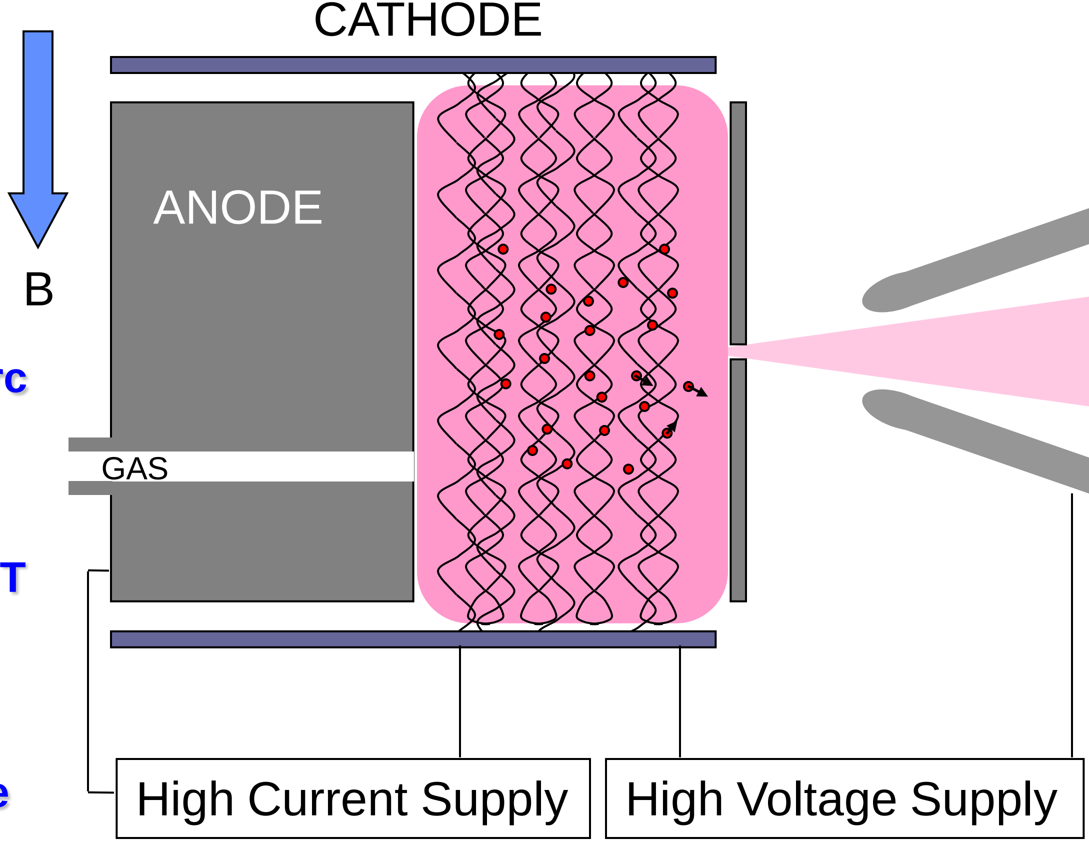
$$\rho_L = \frac{v_\perp}{\omega_c} = \frac{\sqrt{2mK_\perp}}{eB}$$

$$\rho_L \approx 30\mu\text{m}@1\text{eV}$$

- **Penning or Philips Ionisation Gauge (PIG) source**

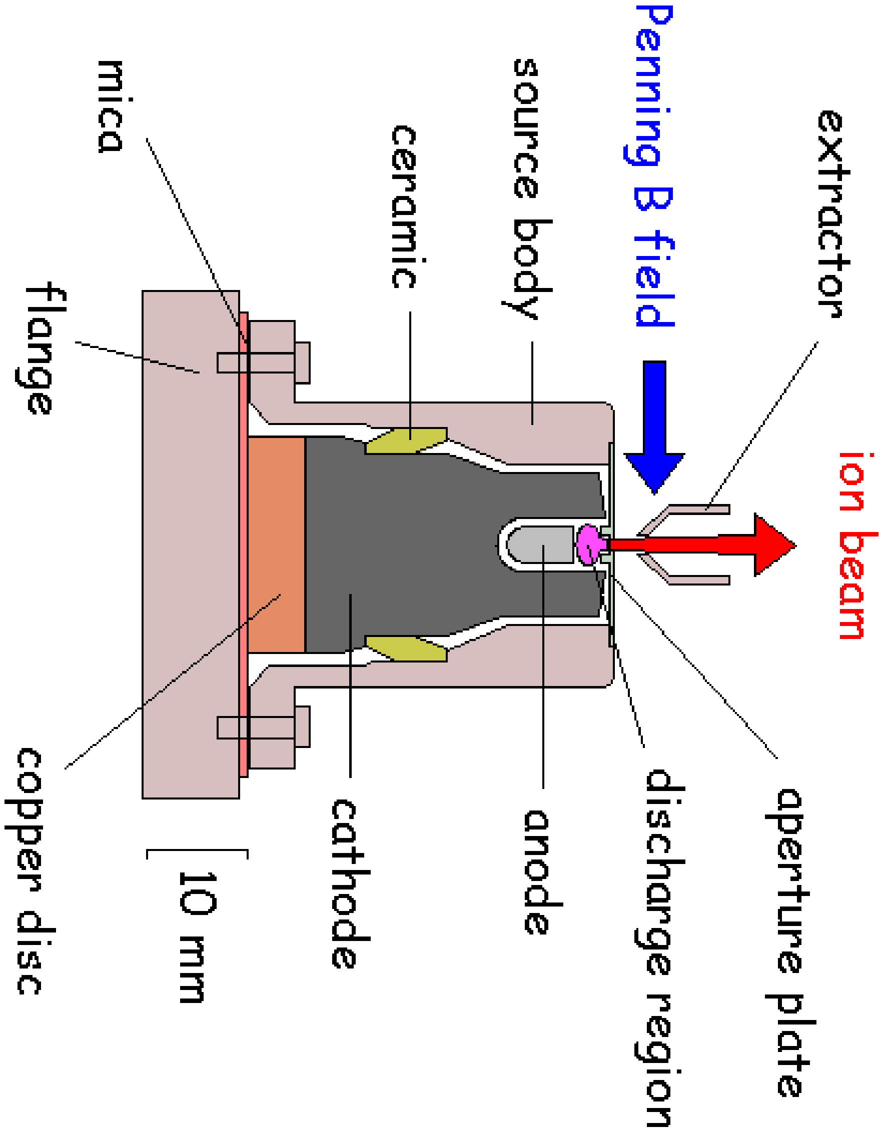
Gas Pressure 10^{-3} -> 1 mbar
Arc Voltage ~1kV
Arc Current 0.1 -> 50 A
Magnetic Field >0.1T

- **Cathode can be Hot or Cold**
- **Electrons are accelerated by the arc voltage across the cathode sheath layer.**
- **Magnetic field stops cathode electrons reaching the anode (>0.1T required).**
- **Some electrons strike the anti-cathode.**
- **Otherwise they may oscillate in the Penning Trap and ionise the gas.**
- **Electrons go to the anode by diffusion processes, plasma oscillations and the plasma-anode potential.**

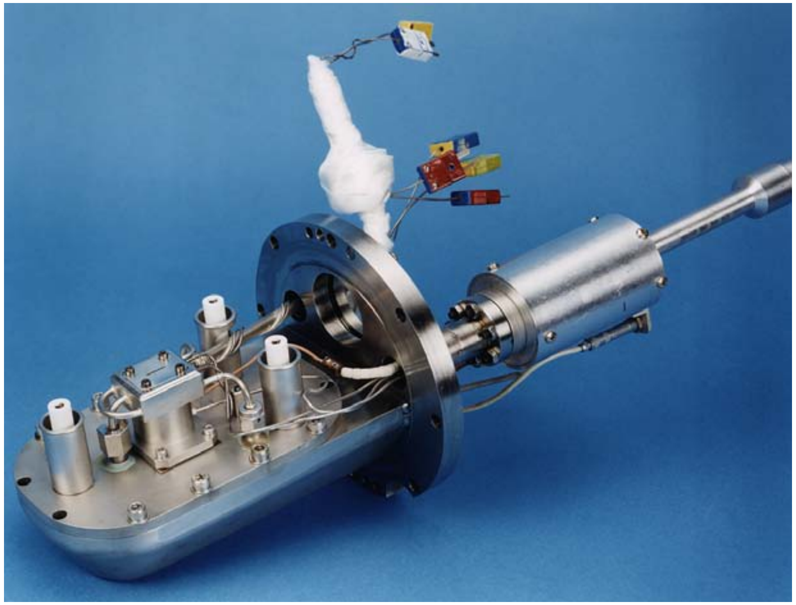


Electron and Ion Sources

Ion Source – Penning / PIG



- The Rutherford ISIS Penning source – John Thomason



Electron and Ion Sources

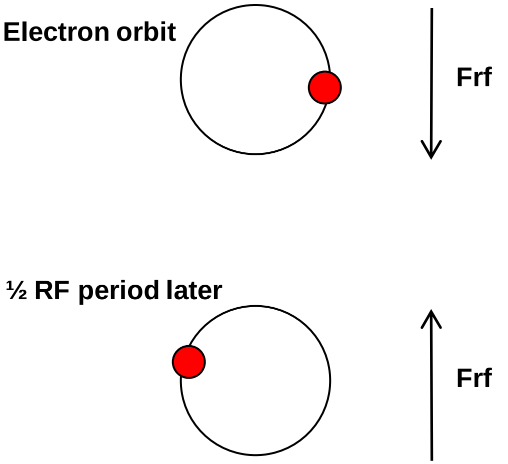
Ion Source – ECR

- **Electron Cyclotron Resonance Ion Source (ECR)**

- **For a given magnetic field, non-relativistic electrons have a fixed revolution frequency.**
- **The plasma electrons will absorb energy at this frequency (just as particles in a cyclotron).**
- **If confined in a magnetic bottle, the electrons can be heated to the keV and even MeV range.**
- **Ions also trapped by the charge of the electrons, but for milli-seconds allowing mutliple ionisation.**
- **The solenoid magnetic field still allows losses on axis – these ions make the beam.**

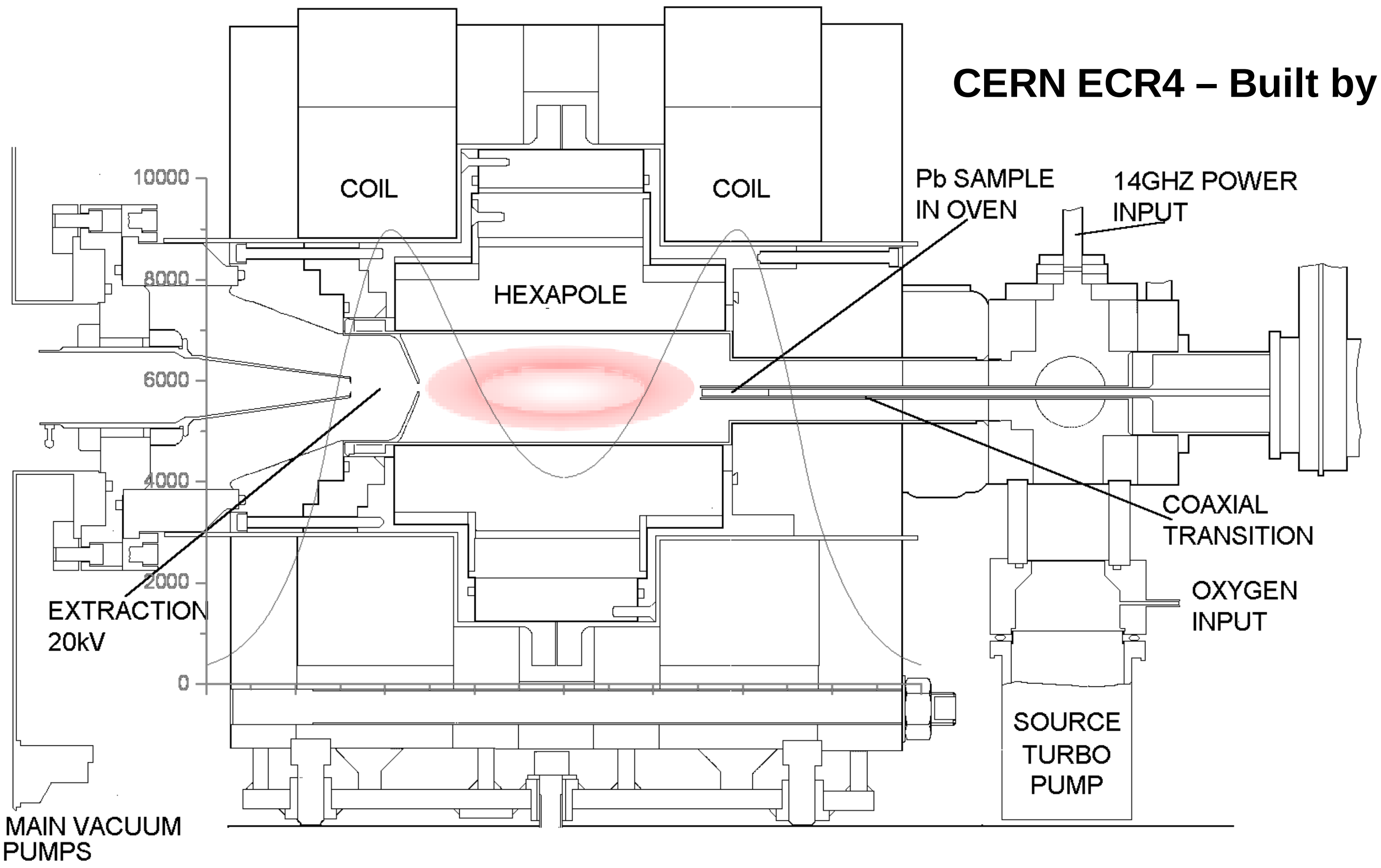
$$\omega_{ecr} = \frac{eB}{m}$$

$$f_{ce}[\mathrm{GHz}] = 2.8 \times B[\mathrm{kG}]$$



Electron and Ion Sources

Ion Source – ECR

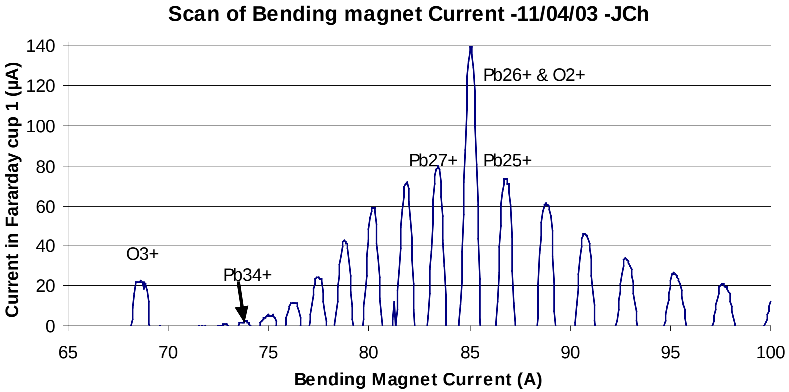


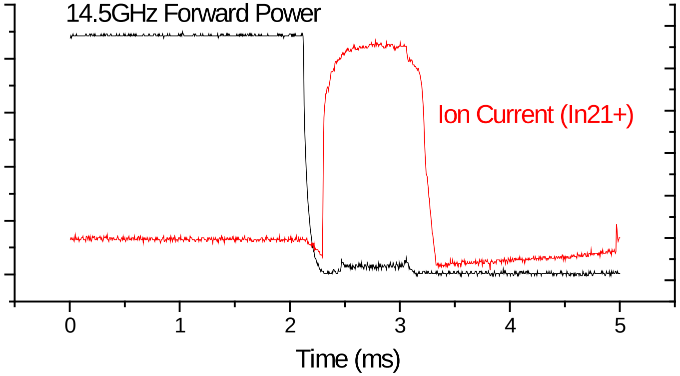
CERN ECR4 – Built by GANIL

Electron and Ion Sources

Ion Source – ECR – High charge states

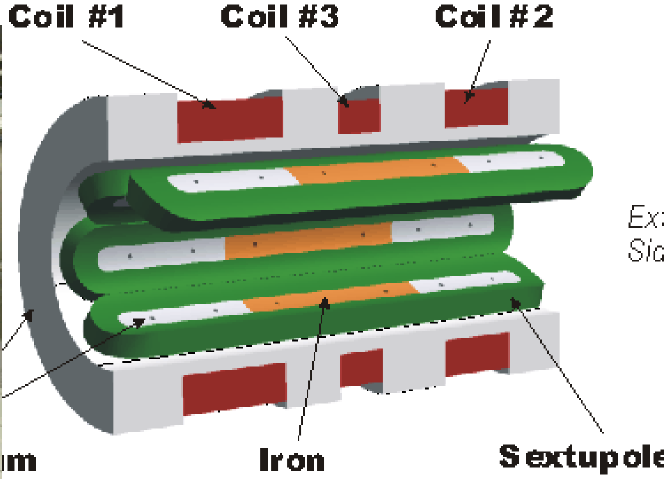
- No filament is needed, greatly increasing the source lifetime.
- Singly, multiply and highly charged ions can be produced by these sources (although the source construction will influence this).
  A → A+ → A2+ → A3+
  Stepwise ionisation.
- Gaseous ions are easily made. Metallic ions come from an OVEN or from a compound gas (e.g UF6 for uranium).
- In the afterglow mode, the ion intensity increases AFTER switching off the micro-waves.





Electron and Ion Sources

Ion Source – ECR – High charge states + industry solutions



- Plasma density increases with frequency and associated magnetic field.
- Example: VENUS source and Berkeley, Ca, uses superconducting solenoid and sextapole magnets.

- Industry can now provide turnkey solutions for ECR ions sources, usually using permanent magnets.

Electron and Ion Sources

Ion Sources – Negative Ions

- **Negative ion sources allow:**
  Charge exchange injection into synchrotrons.
  Charge exchange extraction from cyclotrons.
  Tandem accelerators.

	Electron Affinity (eV)
H	0.7542
He	<0
Li	0.6182
Be	<0
B	0.277
C	1.2629
N	<0
O	1.462
F	3.399

- **The bonding energy for an electron onto an atom is the Electron Affinity.**
- **Ea < 0 for Noble Gasses**
- **Large Ea for Halogens**
- **Two categories of negative ion sources**
  - **Surface – an atom on a surface can be desorbed with an extra electron (whose wave-function overlapped the atom).**
  - **Volume – Through collisions, e-capture and molecular dissociation, negative ions can be formed.**

$AB + e \rightarrow A- + B$

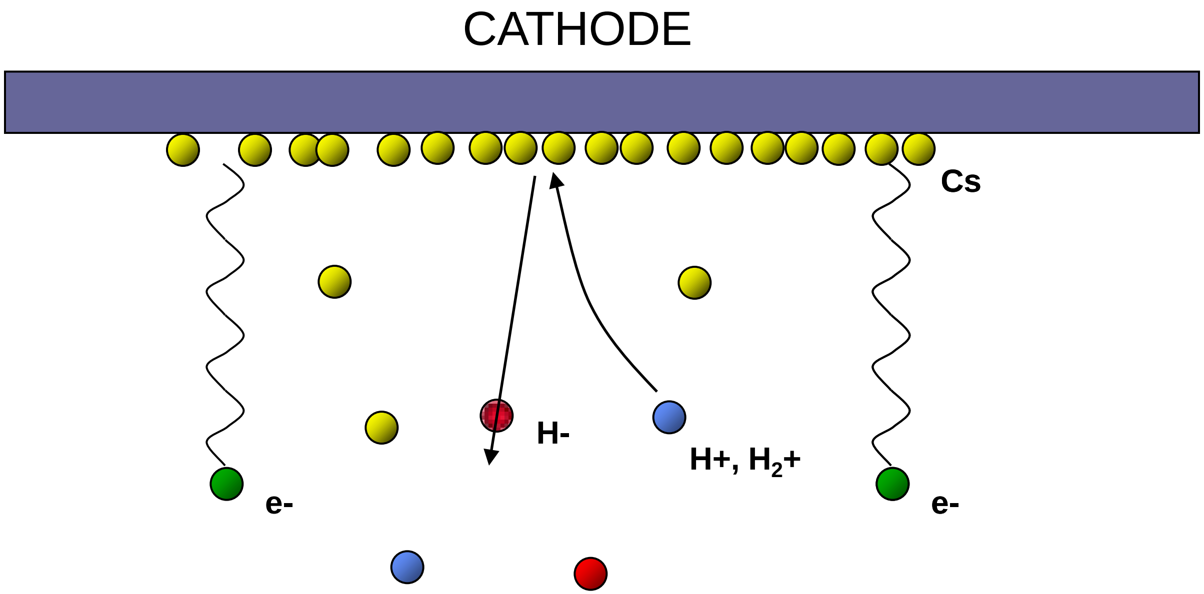
$\mathbf{AB^* + e \rightarrow A- + B}$

$A + B \rightarrow A- + B+$

$A+ + B \rightarrow A- + B2+$

Electron and Ion Sources

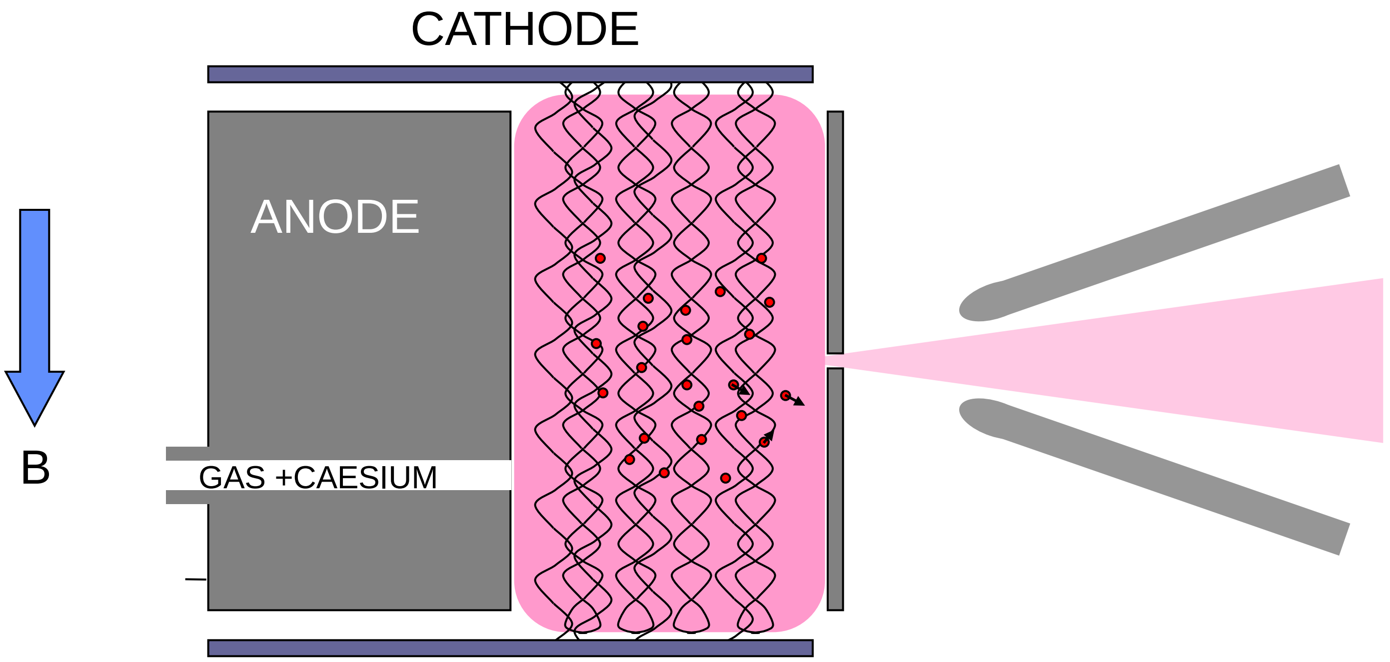
H- Surface Ion Production



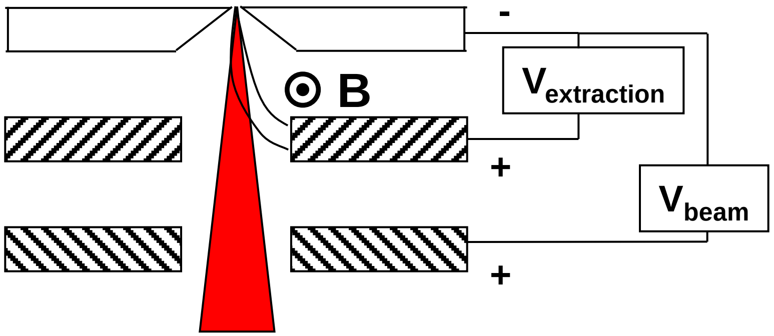
- Protons from the plasma are accelerated to the cathode, which has a coating of caesium.
- The protons desorbed from the low work function surface, with an additional electron.
- The plasma must not be too hot, to avoid ionising the H-.
- Penning, Magnetron, etc, sources produce H this way.

Electron and Ion Sources

Ion Sources – Negative Ions



- **Electrons are extracted along with negative ions! Electron current can be reduced with a dipole B field in extraction.**



Electron and Ion Sources

Summary

- Electron Source Summary
  - Thermionic Source. Some thermal electrons are above the Work-Function.
  - Use low work-function or high melting point materials to obtain the most electrons
  - Photo-cathodes – Use photons above the work-function or E_g+E_a.
  - Metals – Stable but have a low quantum efficiency
  - Semiconductors – high Q, but can be unstable and degrade in use.
  - Require an field to extract electrons $J \sim V^{3/2} / d^2$.
- Ion Source Summary
  - A vast array of ion source type. Using surfaces, sputtering, plasmas and different heating configurations.
  - PIG/Penning – Cathode-Anode discharge in a magnetic field, where electrons oscillate in a plasma, ionizing the rest gas.
  - ECR – Heating of electrons on the ECR resonance, producing a plasma. Electrons and ions are confined in a magnetic bottle. Confinement leads to multiple collisions and highly charged-ions.
  - Negative ions of elements with a high electron affinity can be produced. H- requires a warm plasma to excite H2. In a cooler plasma region, electron attachment and disassociation occurs.

Electron and Ion Sources

Further Reading

- Handbook of Ion Source, B. Wolf, Boca Raton, FL: CRC Press, 1995
- Ion Sources, Zhang Hua Shun, Berlin: Springer, 1999.
- The Physics and Technology of Ion Source, I. G. Brown, New York, NY: Wiley, 1989
- Large Ion Beams: Fundamentals of Generation and Propagation, T. A .Forrester, New York, NY: Wiley, 1988
- CAS – 5th General School (CERN 94-01) and Cyclotrons, Linacs… (CERN-96-02)

Electron and Ion Sources

◆ **Some Final Words**

- **Electron and ion sources still represent a challenging topic for particle accelerators.**
- **Demands continue to be for high intensities, lower emittances, shorter pulses (for electrons), high charge states (for high charge state ion sources), as well as improvements to the reliability and stability of these sources.**
- **Taking into account the varied nature of solutions for these devices (thermionic, photo cathode with different types, *Wolf* lists 14 species of ions sources) there is plenty of scope for scientists to make a impact in the field.**
- **This is an exciting field, that urgently needs new recruits!**

Electron and Ion Sources

E: Particle Energy
E: Electric field
J: Current density
n: particle density
T: Temperature
U,V: Voltage
v,: particle velocity