



# Electron and Ion Sources

## Layout

### ◆ Electron Sources

- Thermionic
- Photo-Cathodes

### ◆ Ion Sources

- Penning Ion Source
- ECR Ion Source
- Negative Ions

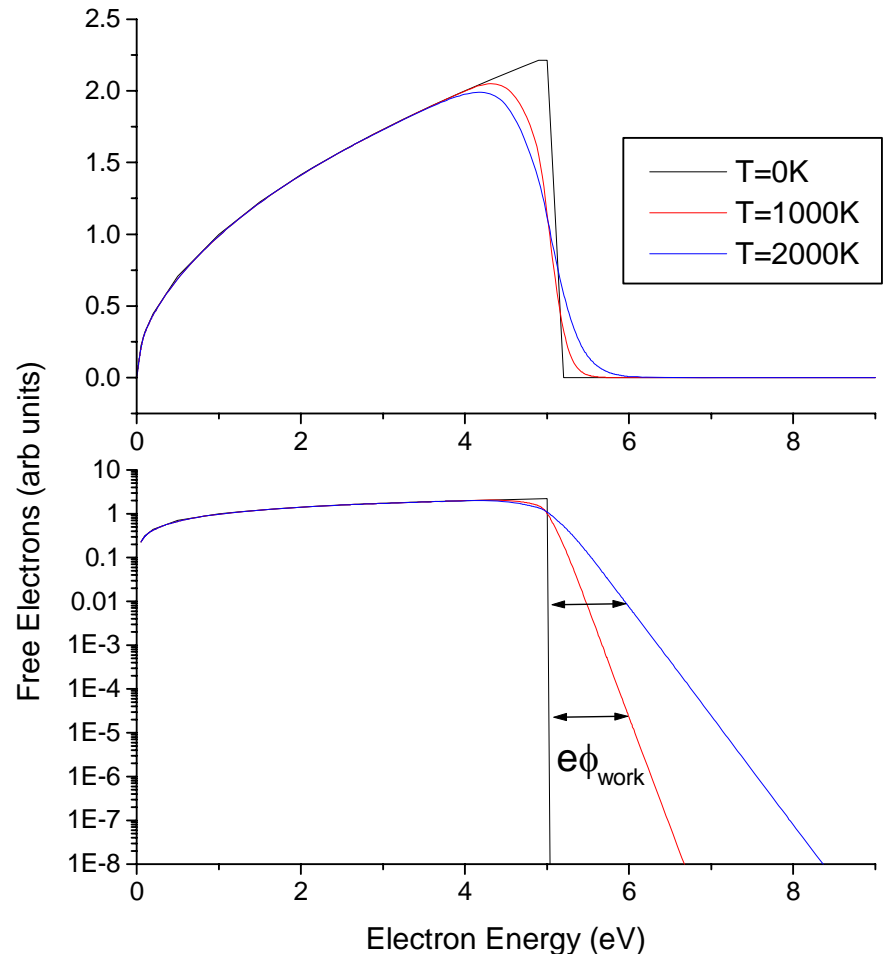


# Electron and Ion Sources

## Electrons – Thermionic Emission

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

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





# 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.

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

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

$$A = \frac{4\pi em_e k^2}{h^3} \approx 1.2 \times 10^6 \text{ Am}^{-2} \text{ K}^{-2}$$

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

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

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

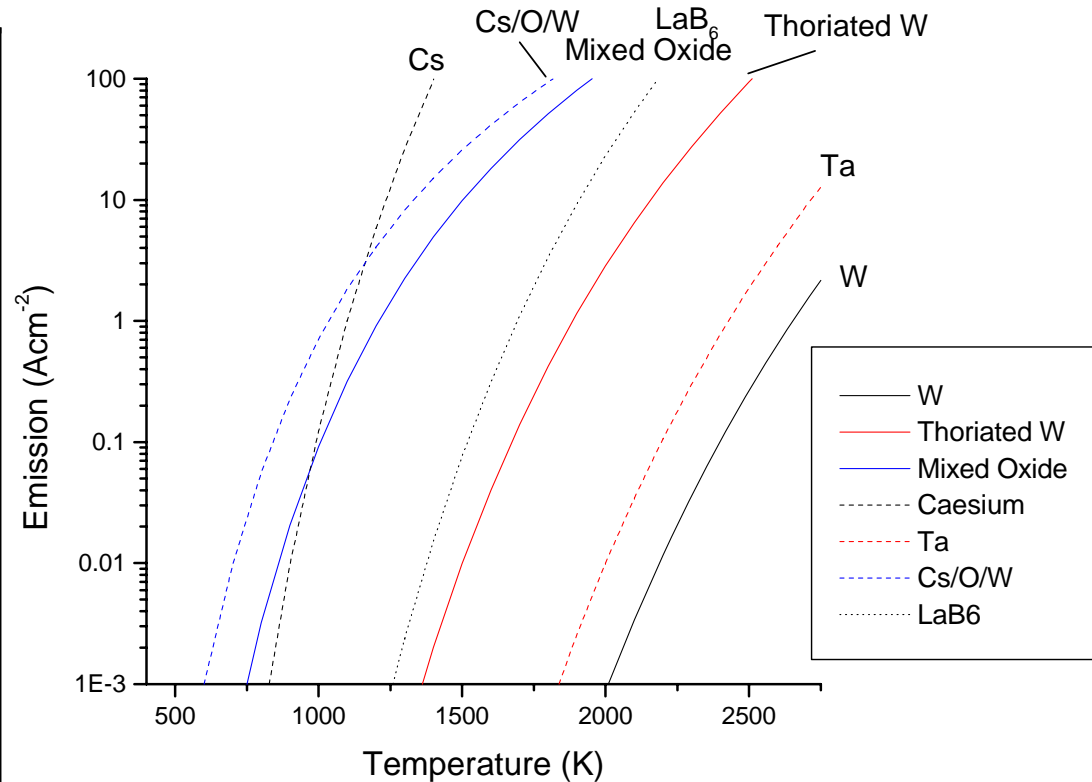


# Electron and Ion Sources

## Electrons – Thermionic Emission

	$A$ $\text{Acm}^{-2}\text{K}^{-2}$	$\phi_{\text{work}}$ 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 <sub>6</sub>	29	2.66

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

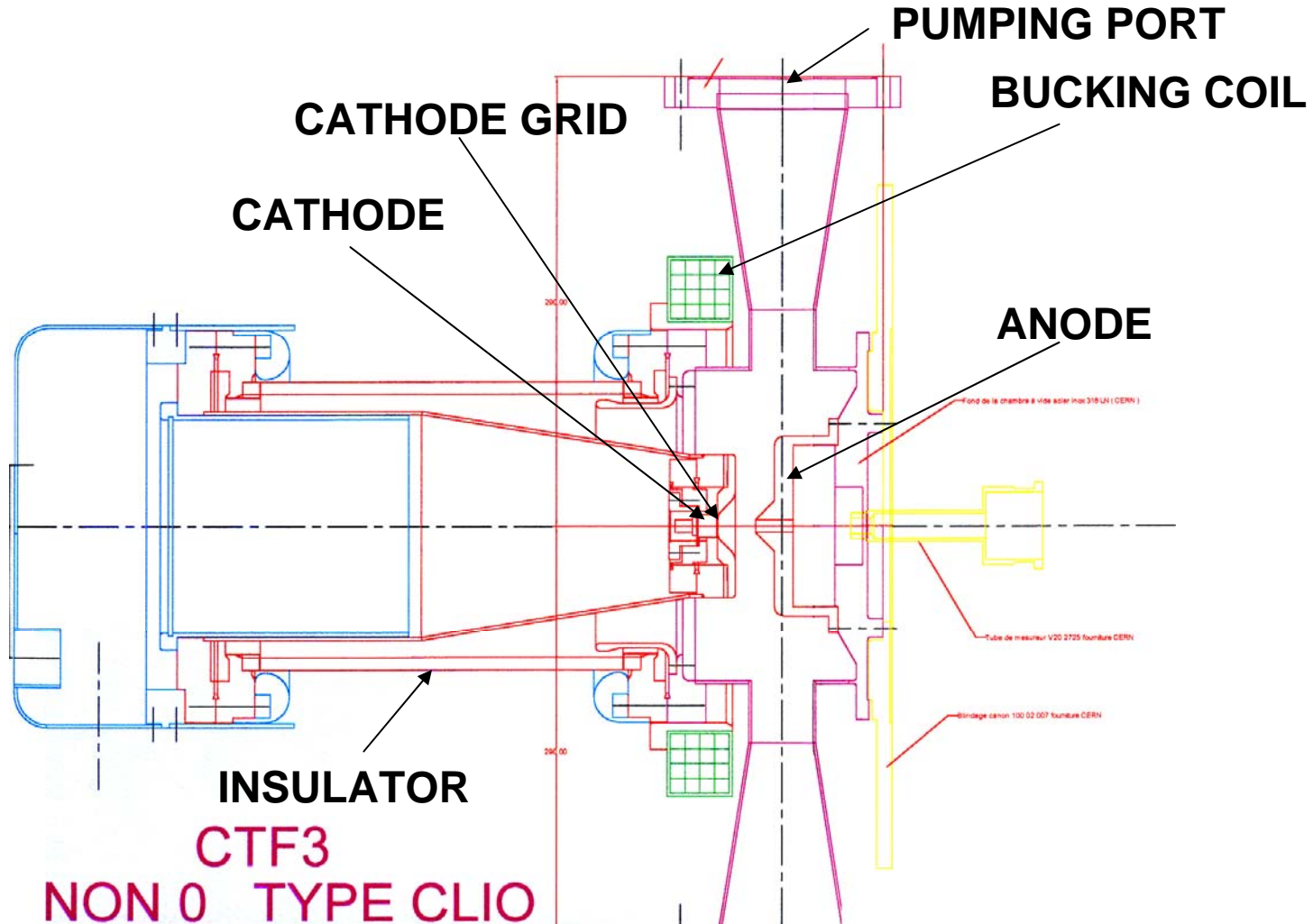


**Melting points**  
**Cs: 301.6 K**  
**Ta: 3290 K**  
**W: 3695 K**  
**LaB<sub>6</sub>: ~2800 K (decomp)**



# Electron and Ion Sources

## Electrons – A Gun

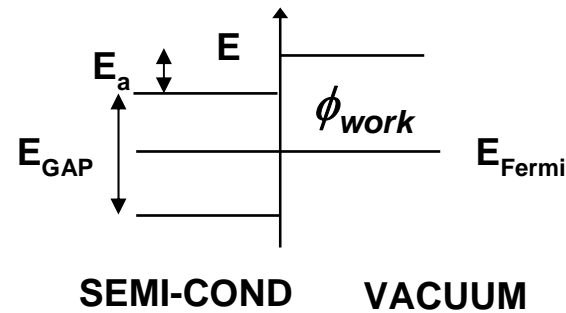
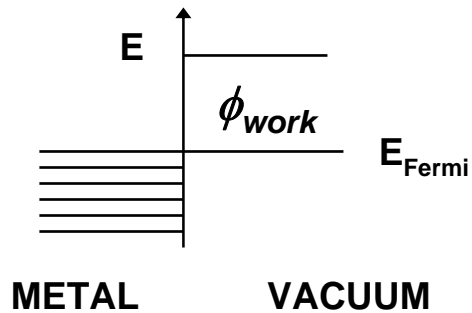




# Electron and Ion Sources

## Electrons – Photo Emission

- ◆ The energy of an electron in a material can be increased above the vacuum energy by absorbing photons - Photocathode



$$\lambda_c = \frac{hc}{\phi_{work}} = \frac{1239.8}{\phi_{work}}$$

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

	$\phi_{work}$ (eV)	$\lambda_c$ (nm)
W	4.5	275
Mg	3.67	340
Cu	4.65	267

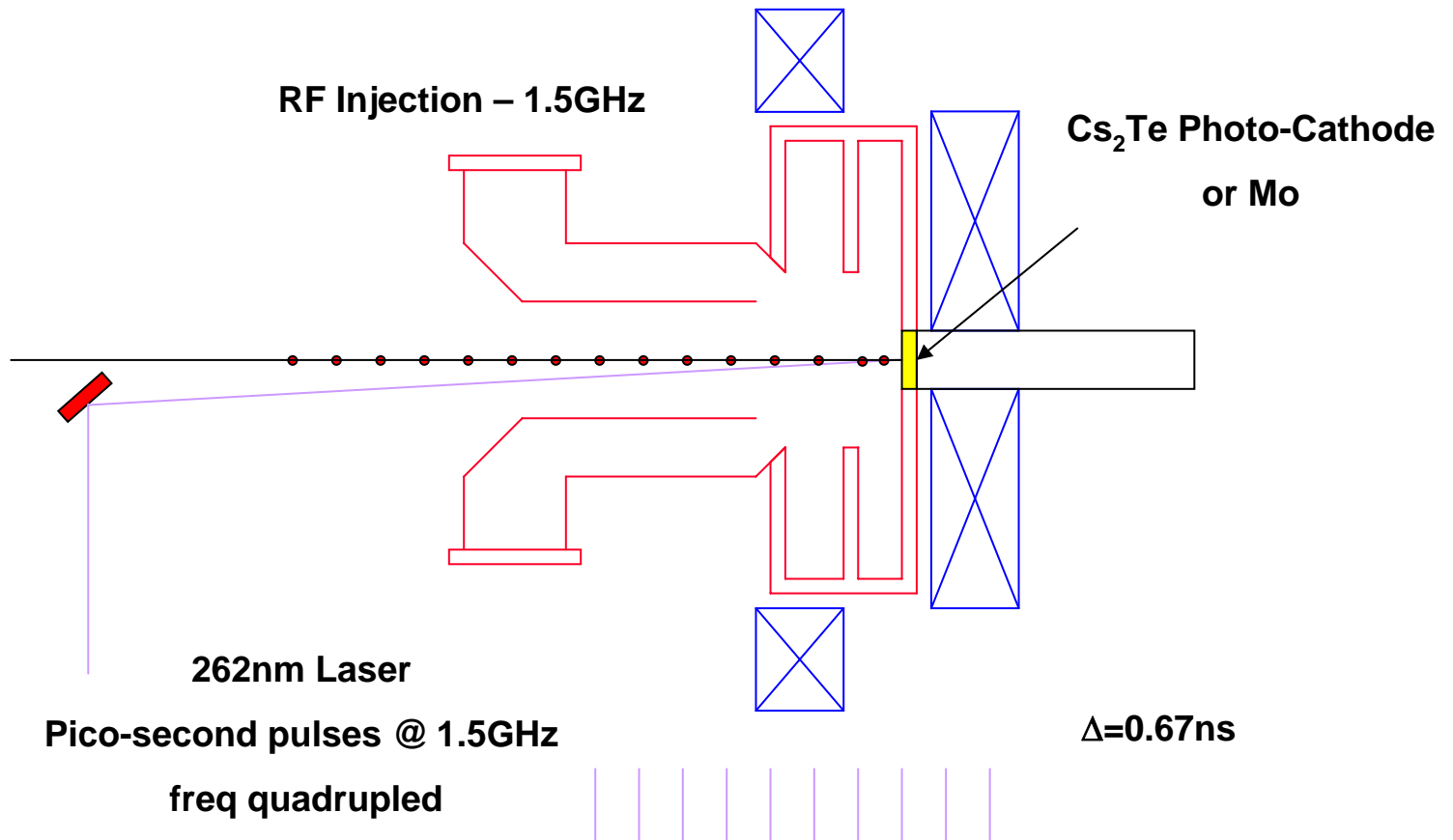
	$E_g + E_a$ (eV)	$\lambda_c$ (nm)
GaAs	5.5	225
Cs <sub>2</sub> Te	~3.5	350
K <sub>2</sub> CsSb	2.1	590



# Electron and Ion Sources

## Electrons – Photo Injector

### ◆ Photo Injector Test Facility - Zeuthen





# 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).
  - Common material= $\text{Cs}_2\text{Te}$  (Cesium Telluride)– High Quantum efficiency & stable.

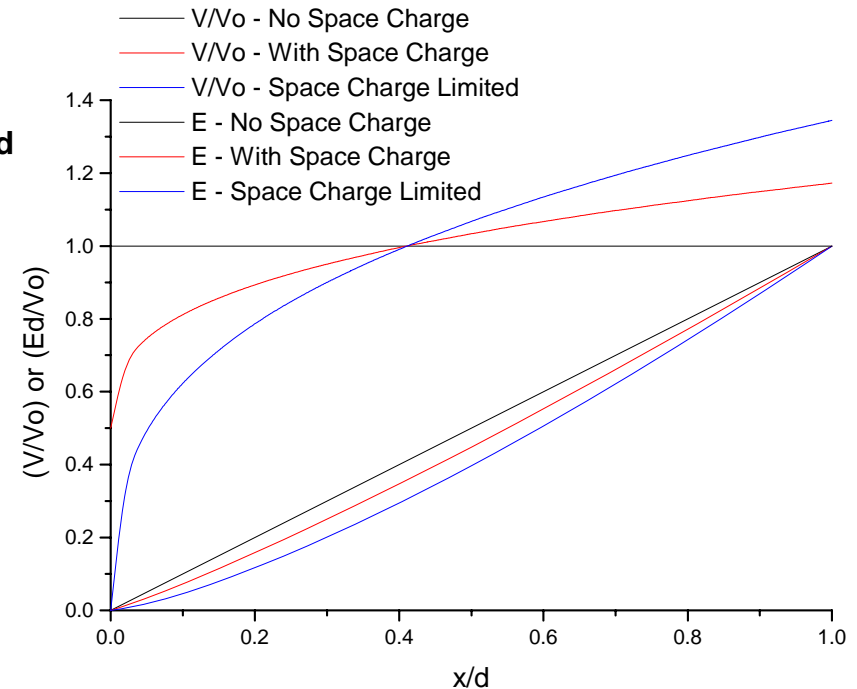
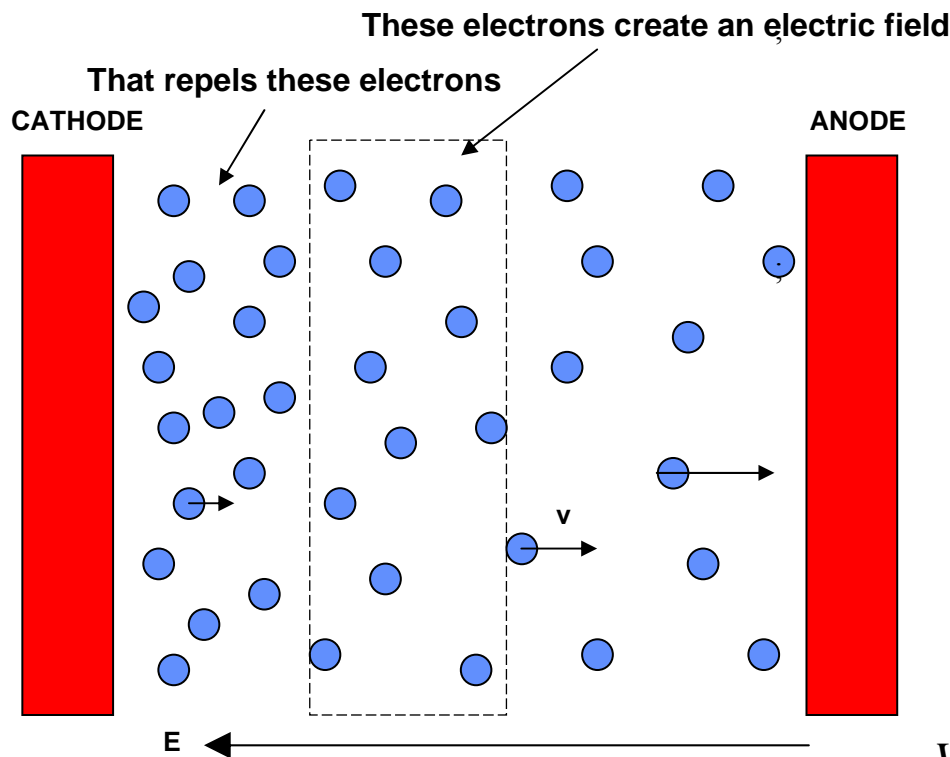




# Electron and Ion Sources

## Electrons – Child-Langmuir Law

- ◆ Need electric field to remove electrons from surface.
- ◆ Electrons set up their own space charge field.



$$\frac{d^2V}{dx^2} = -\frac{\rho}{\epsilon_0} \quad J = \rho v \quad qV = \frac{1}{2}mv^2$$

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



# 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.

$$J_{C-L} = \frac{4}{9} \epsilon_0 \left( \frac{2q}{m} \right)^{1/2} \frac{V^{3/2}}{d^2}$$

***d*** : Cathode to Anode distance

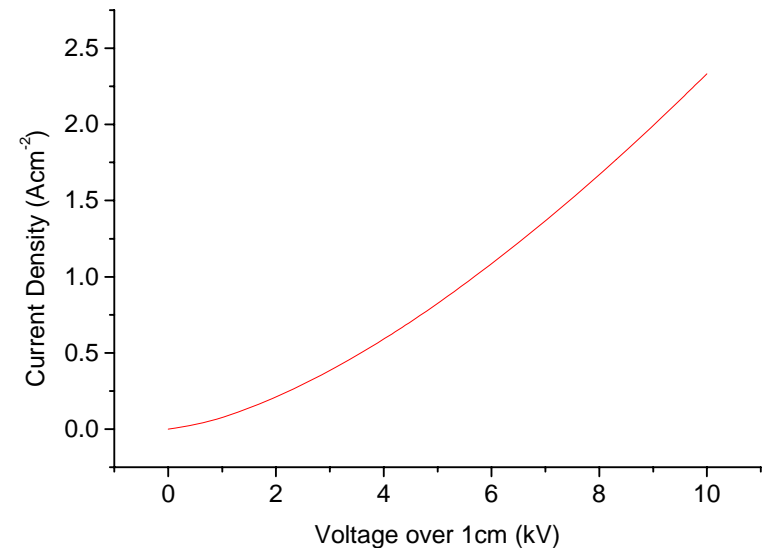
***V*** : Cathode to Anode voltage

***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.

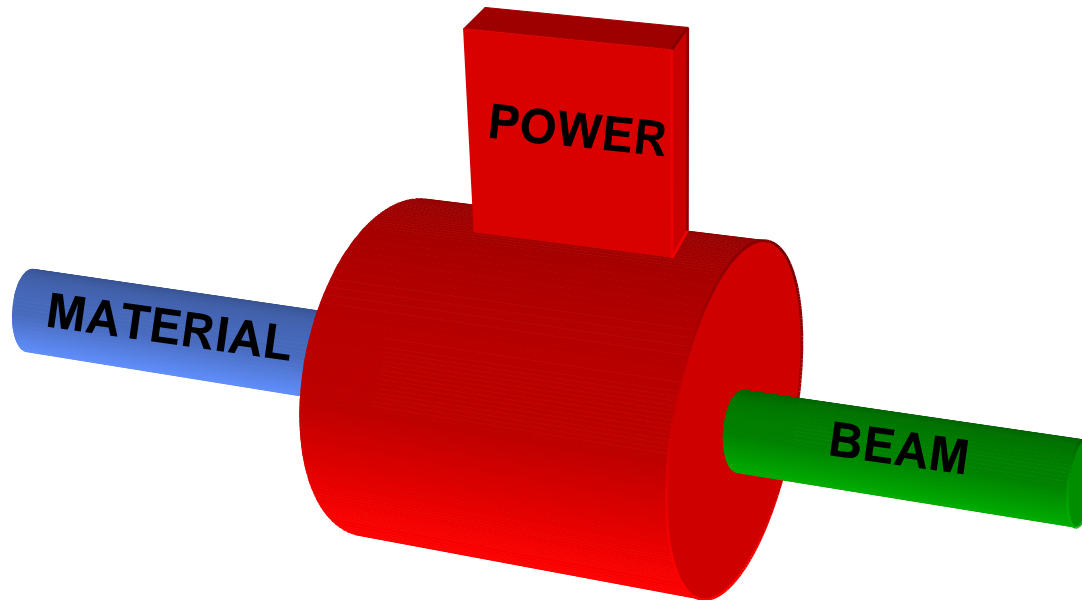




# Electron and Ion Sources

## 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

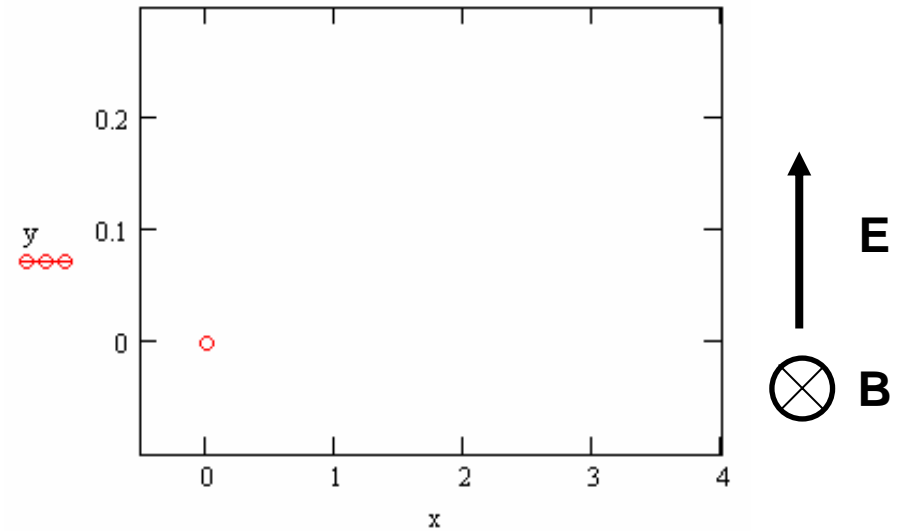
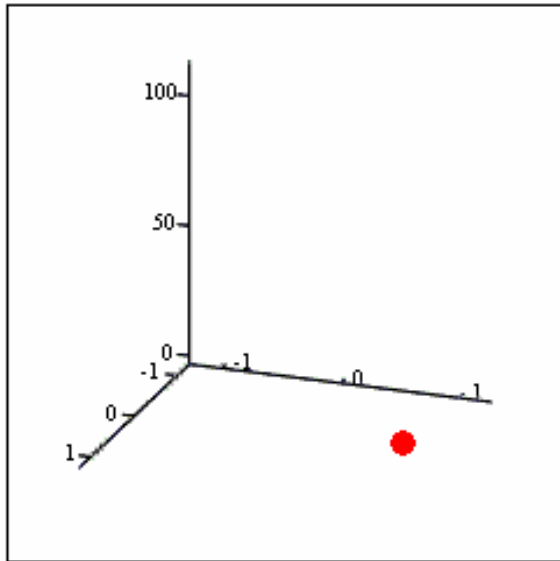
## Ion Sources - Basics

- ◆ **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



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

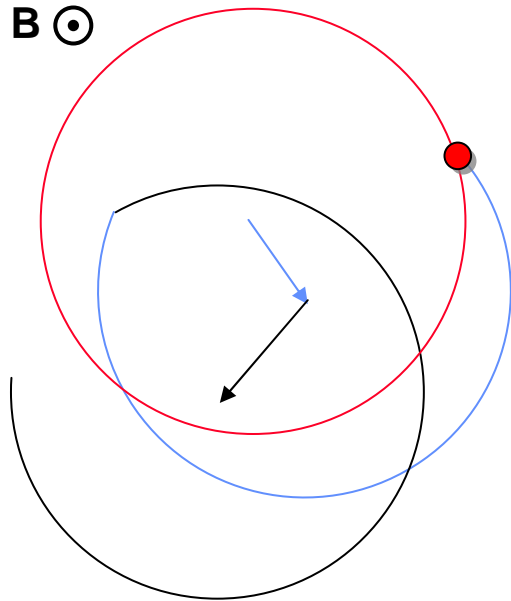
$$v_{drift} = \frac{\vec{E} \times \vec{B}}{B^2}$$



# Electron and Ion Sources

## Plasma Particle Motion – Classical Diffusion

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

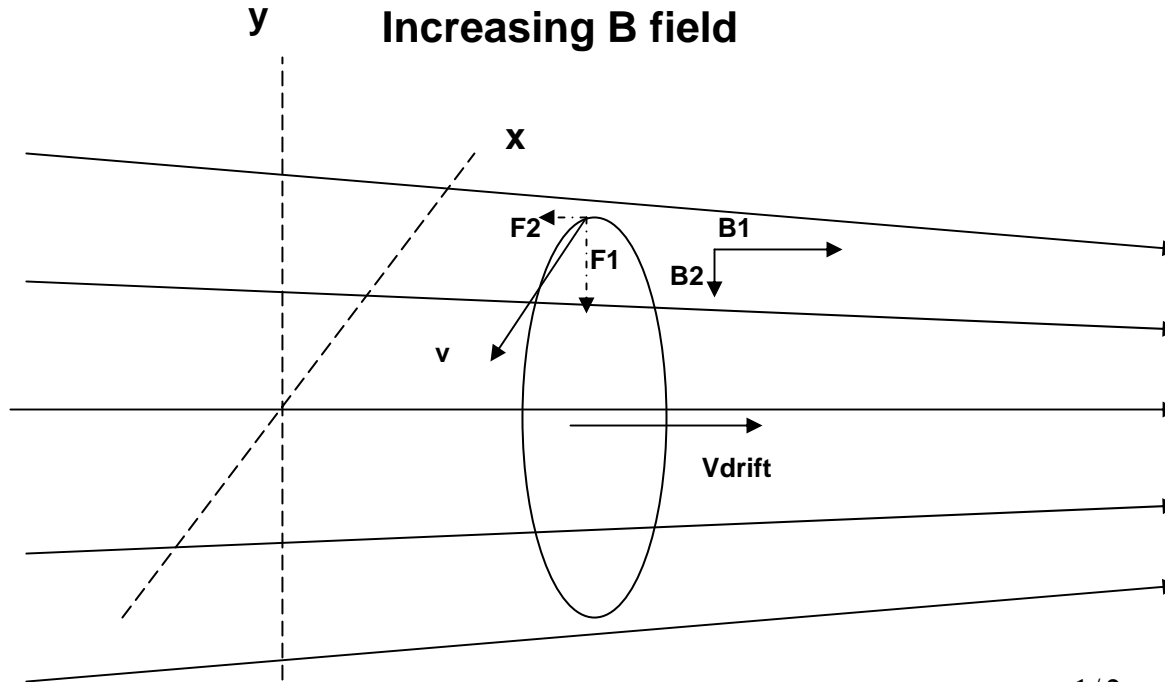




# Electron and Ion Sources

## ECR Source – Magnetic Mirror

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



Energy is transferred  
from  $v_{drift}$  to  $v_{ecr}$

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

$$\mu = \frac{mv_{\perp}^2}{2B}$$

$\mu$  = magnetic moment

$K$  = total kinetic energy



# Electron and Ion Sources

## Ion Source – Penning / PIG

$$r_c = \frac{v_{\perp}}{\omega_c} = \frac{\sqrt{2mK_{\perp}}}{eB}$$
$$r_c \approx 30\mu\text{m} @ 1\text{eV}$$

### ◆ Penning or Philips Ionisation Gauge (PIG) source

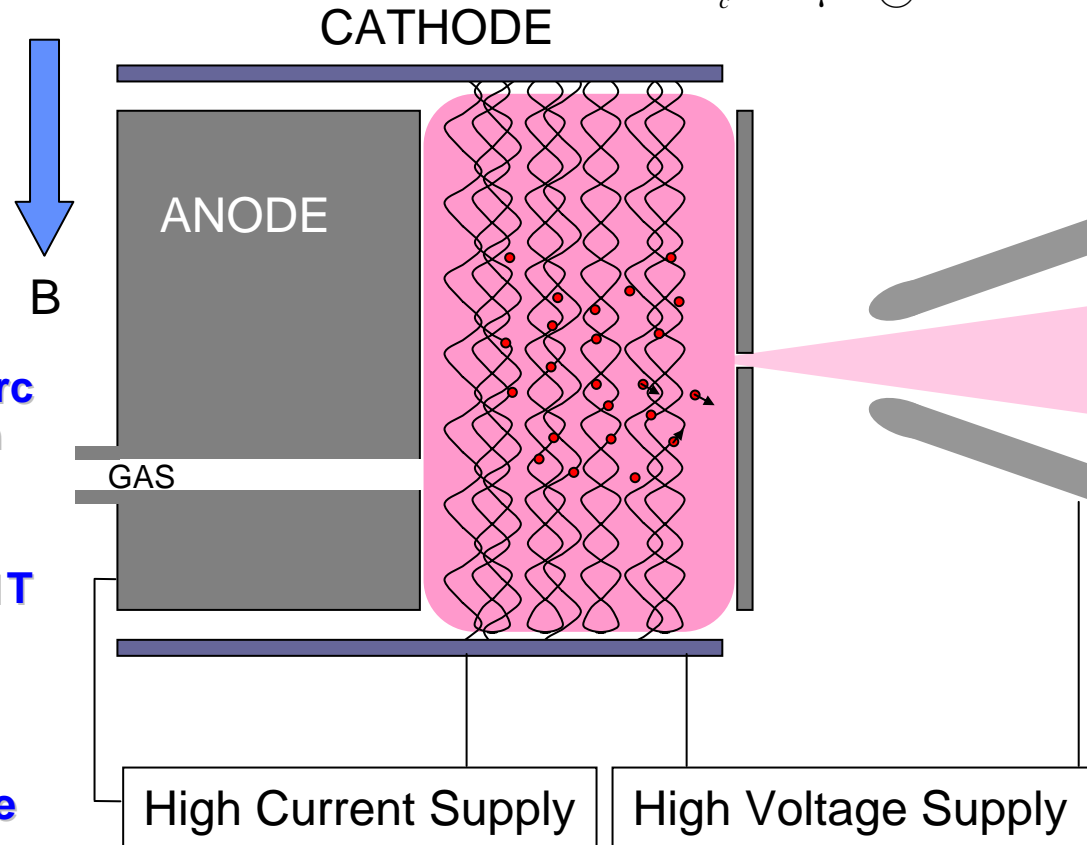
Gas Pressure  $10^{-3}$  -> 1 mbar

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.

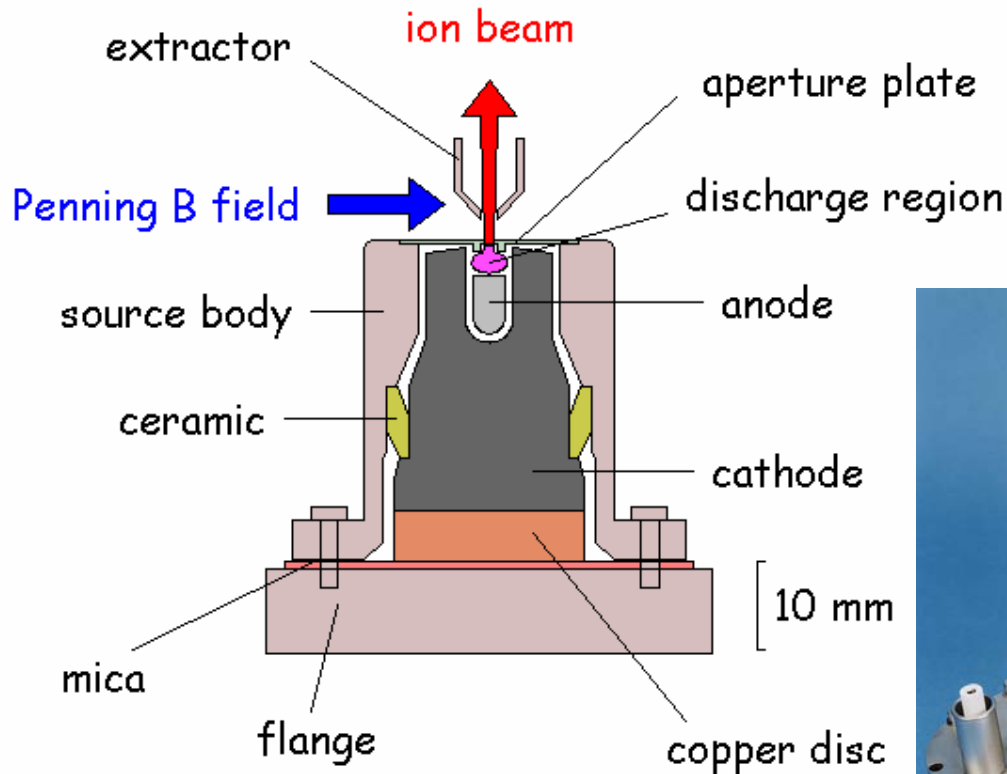




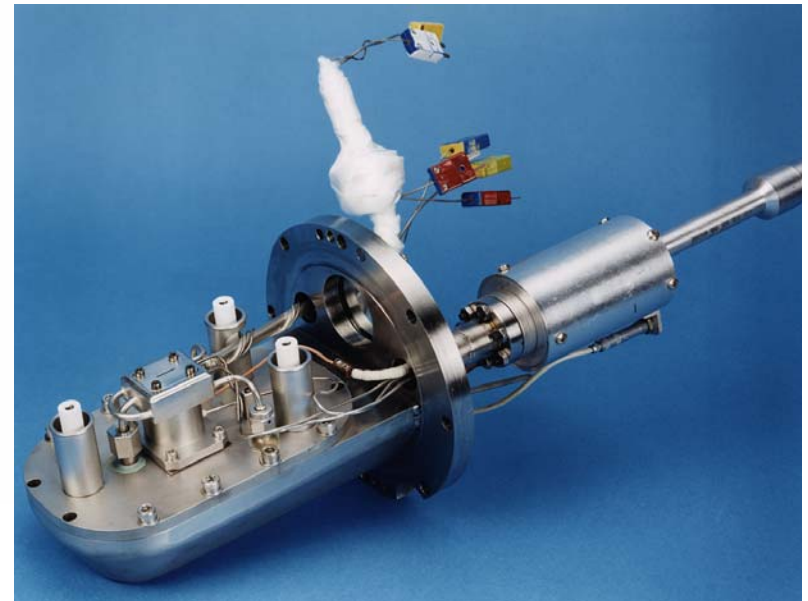


# Electron and Ion Sources

## 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.**
- ◆ **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 multiple ionisation.**
- ◆ **The solenoid magnetic field still allows losses on axis – these ions make the beam.**

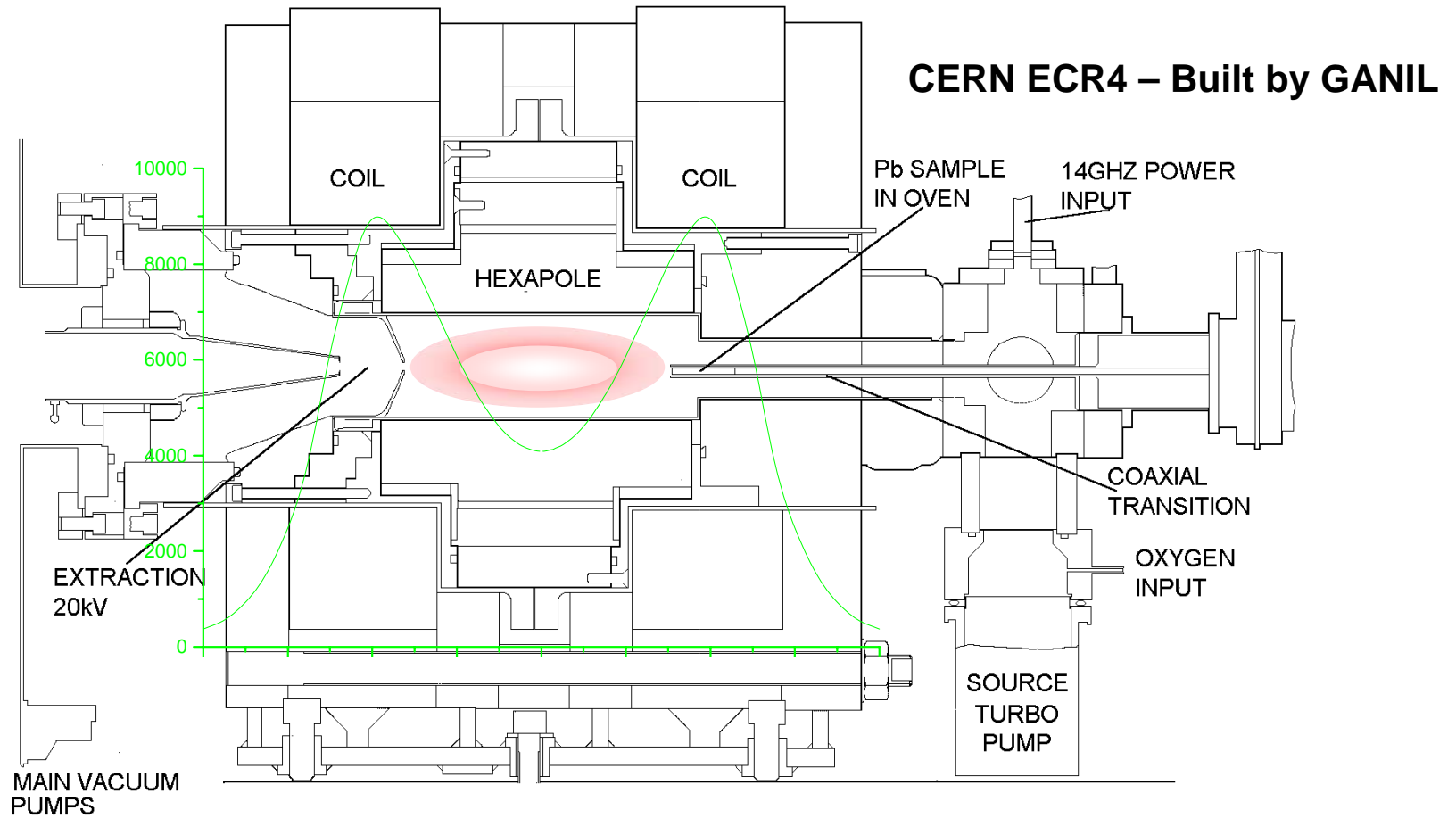
$$\omega_{ecr} = \frac{eB}{m}$$

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



# Electron and Ion Sources

## Ion Source – ECR

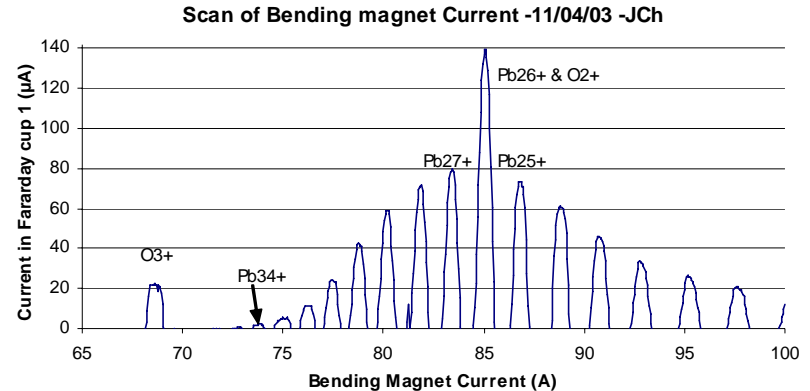
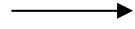




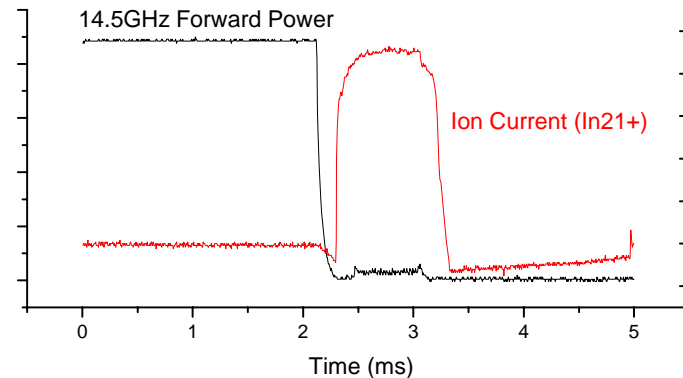
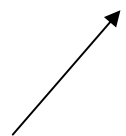
# Electron and Ion Sources

## Ion Source – ECR

- ◆ 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).  
 $A \rightarrow A^+ \rightarrow A^{2+} \rightarrow A^{3+}$   
Stepwise ionisation.



- ◆ Gaseous ions are easily made. Metallic ions come from an OVEN or from a compound gas (e.g UF<sub>6</sub> for uranium).
- ◆ In the afterglow mode, the ion intensity increases AFTER switching off the micro-waves.





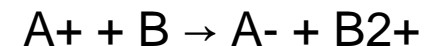
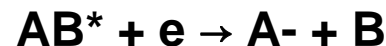
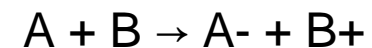
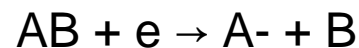
# Electron and Ion Sources

## Ion Sources – Negative Ions

- ◆ Negative ion sources allow charge exchange injection into synchrotrons.

	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

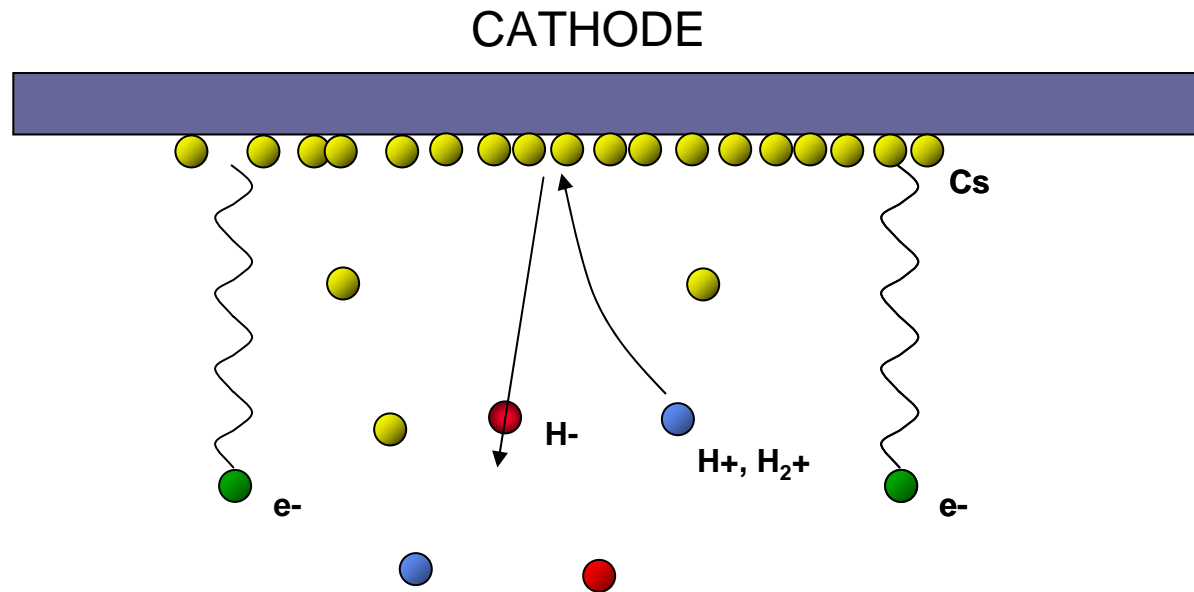
- ◆ The bonding energy for an electron onto an atom is the Electron Affinity.
- ◆  $E_a < 0$  for Noble Gasses
- ◆ Large  $E_a$  for Halogens
- ◆ Two categories of negative ion sources
  - Surface – an atom on a surface can be desorbed with an extra electron (whose wave-function overlapped the atom).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





# Electron and Ion Sources

## H- Surface Ion Production

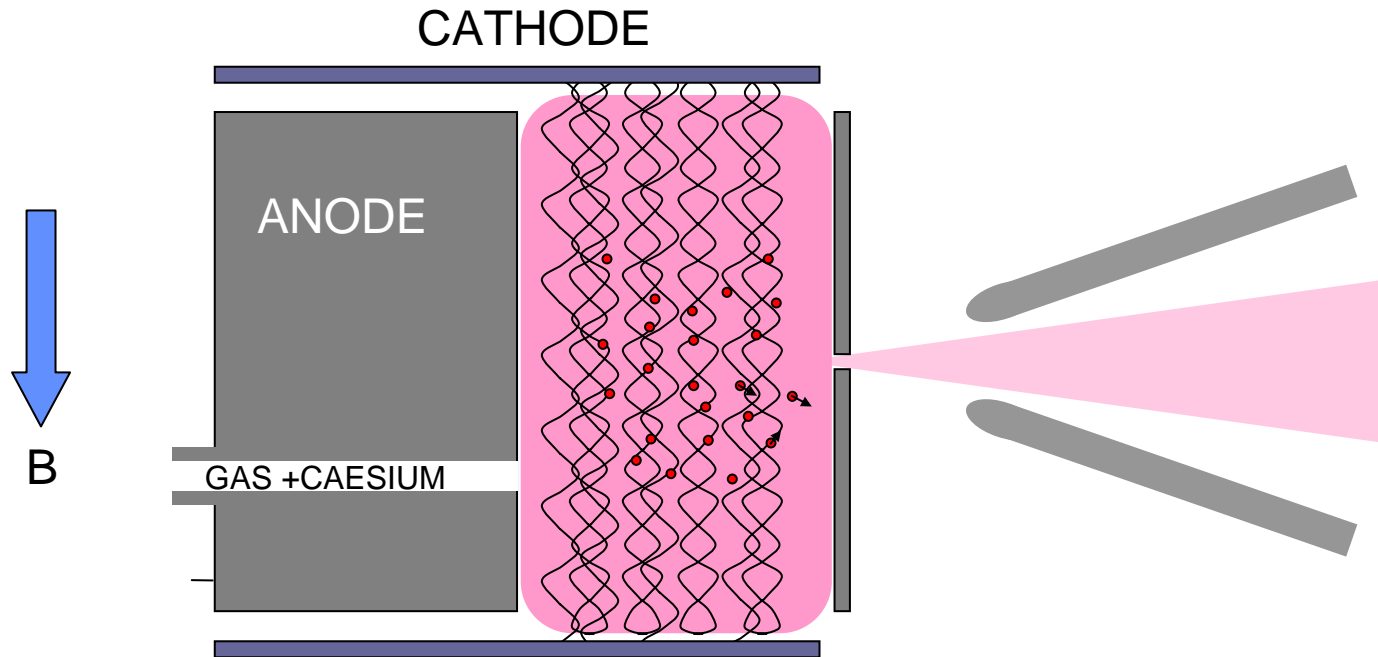


- ◆ Protons from the plasma are accelerated to the cathode, which has a coating of caesium.
- ◆ The protons desorb from the low work function surface, with an additional electron.
- ◆ The plasma must not be too hot, to avoid ionising the H-.
- ◆ Penning, Magnetron, etc, sources produce H this way.

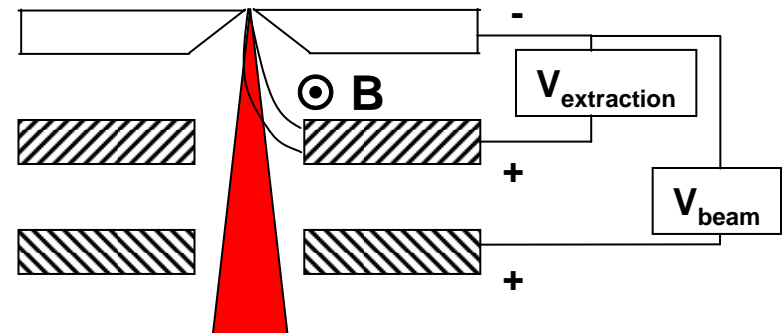


# Electron and Ion Sources

## 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 H<sub>2</sub>. 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 – 5<sup>th</sup> General School (CERN 94-01 ) and Cyclotrons, Linacs... (CERN-96-02 )**