Electron and Ion Sources

Layout

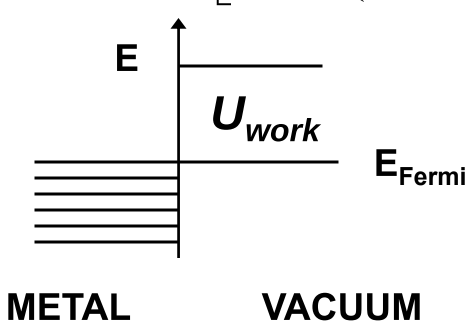
- **Electron Sources**
  - Thermionic
  - Photo-Cathodes
  - Child-Langmuir Current Limitation
- **Ion Sources**
  - Penning Ion Source
  - ECR Ion Source
  - Negative Ions

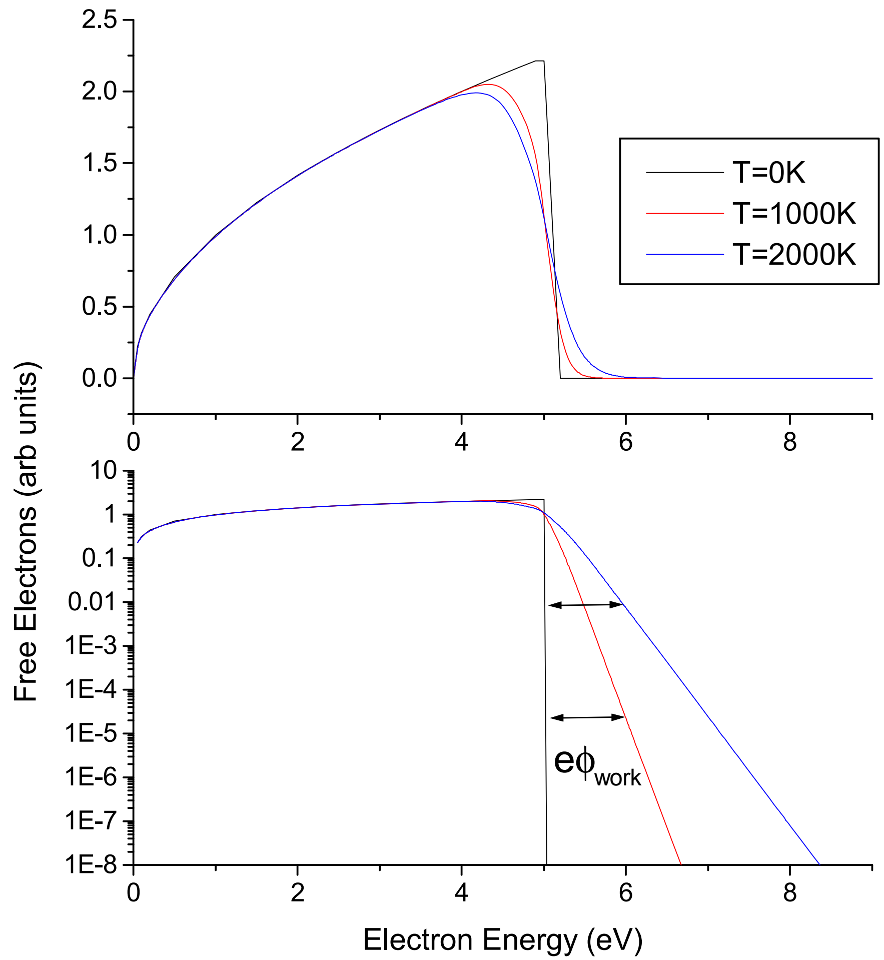
Electron and Ion Sources

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.

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

$$A = \frac{4\pi e m_e k^2}{h^3} \approx 1.2\times10^6\ \mathrm{Am}^{-2} K^{-2}$$

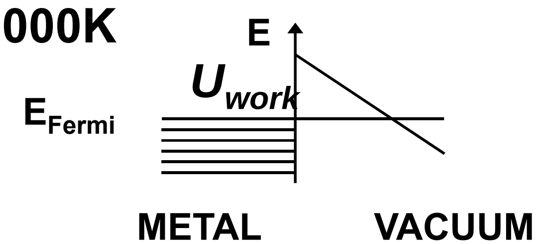
This electron current is available to be pulled off the surface… Richardson-Dushmann equation *Rev. Mod. Phys. 2, p382 (1930)*

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

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

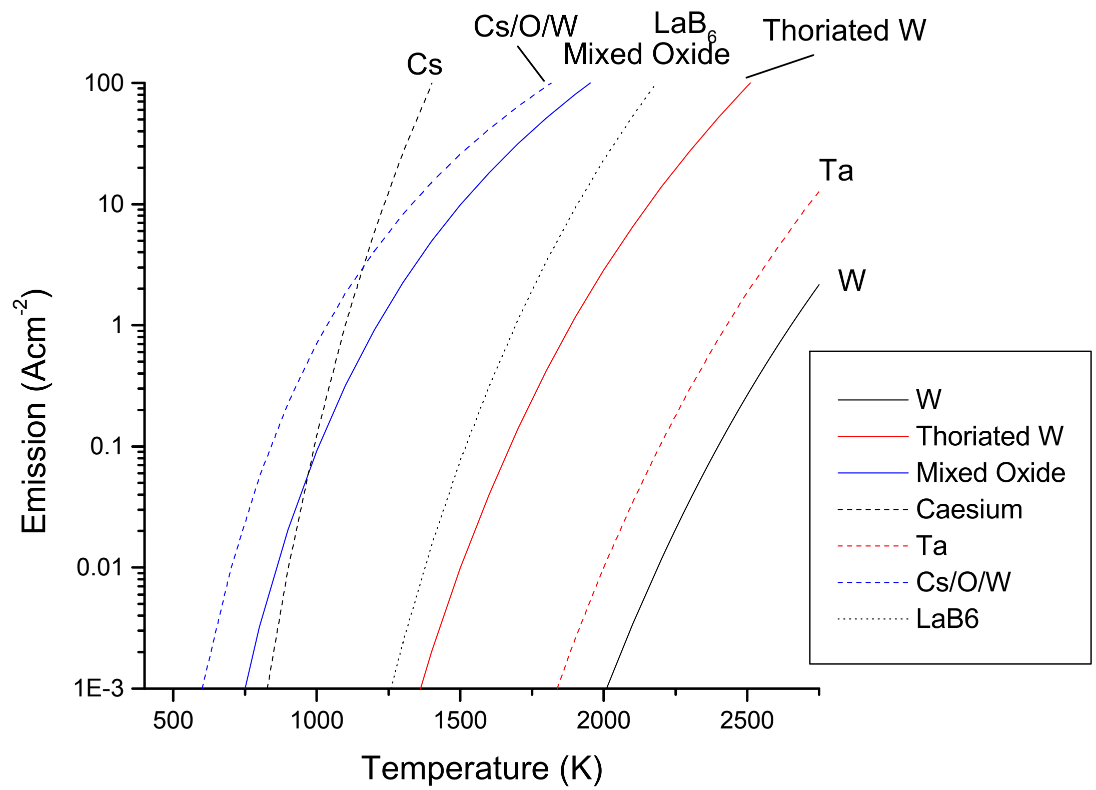
Where E_s is in kV/cm => 15% for 1kV/cm @1000K



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



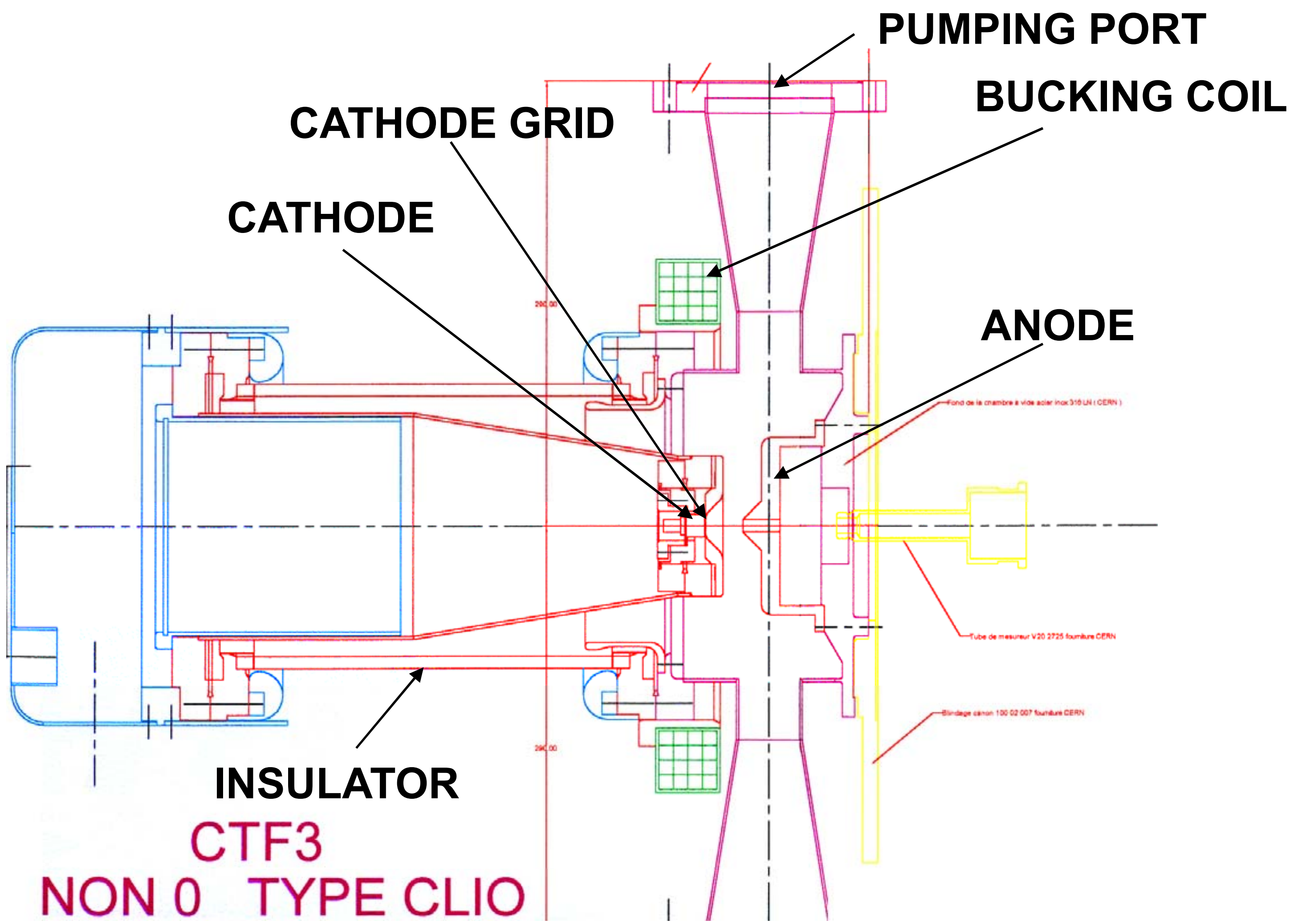
***- A and work function depend on the Cs/O layer**

Thickness and purity

Melting points
Cs: 301.6 K
Ta: 3290 K
W: 3695 K
LaB_6: ~2800 K (decomp)

Electron and Ion Sources

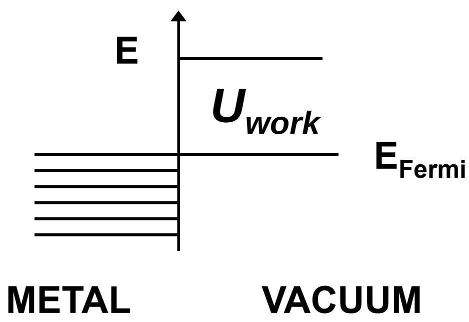
Electrons – A Gun

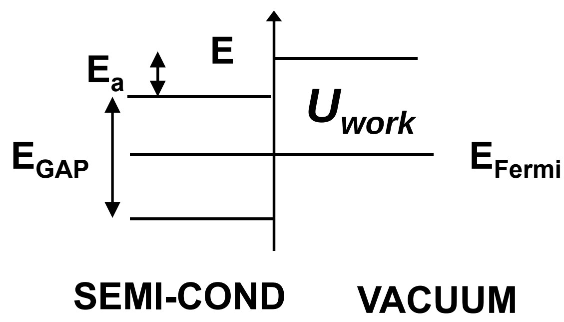


Electron and Ion Sources

Electrons – Photo Emission

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





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

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

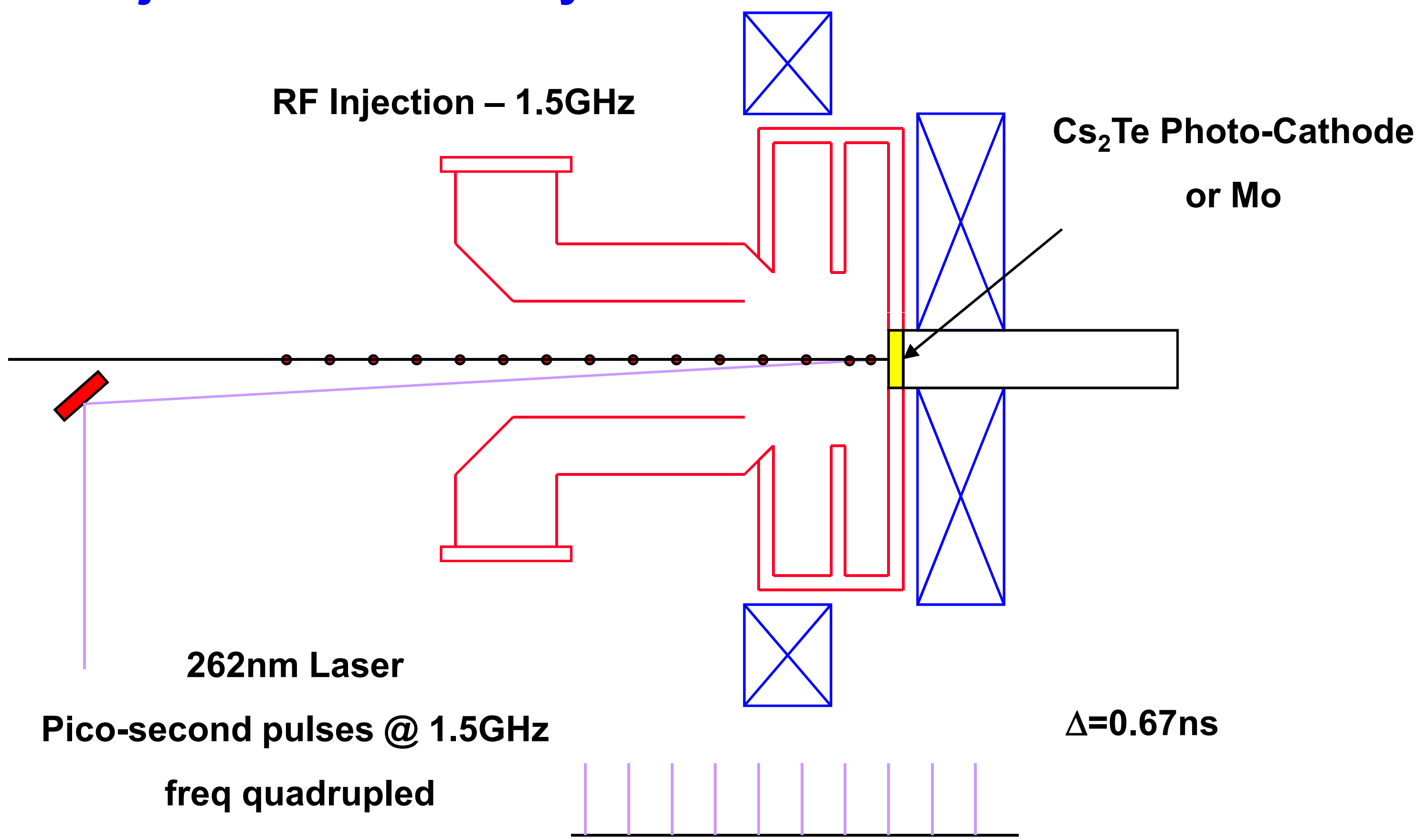
	U_{work} (eV)	λ_c (nm)
W	4.5	275
Mg	3.67	340
Cu	4.65	267

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

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



Electron and Ion Sources

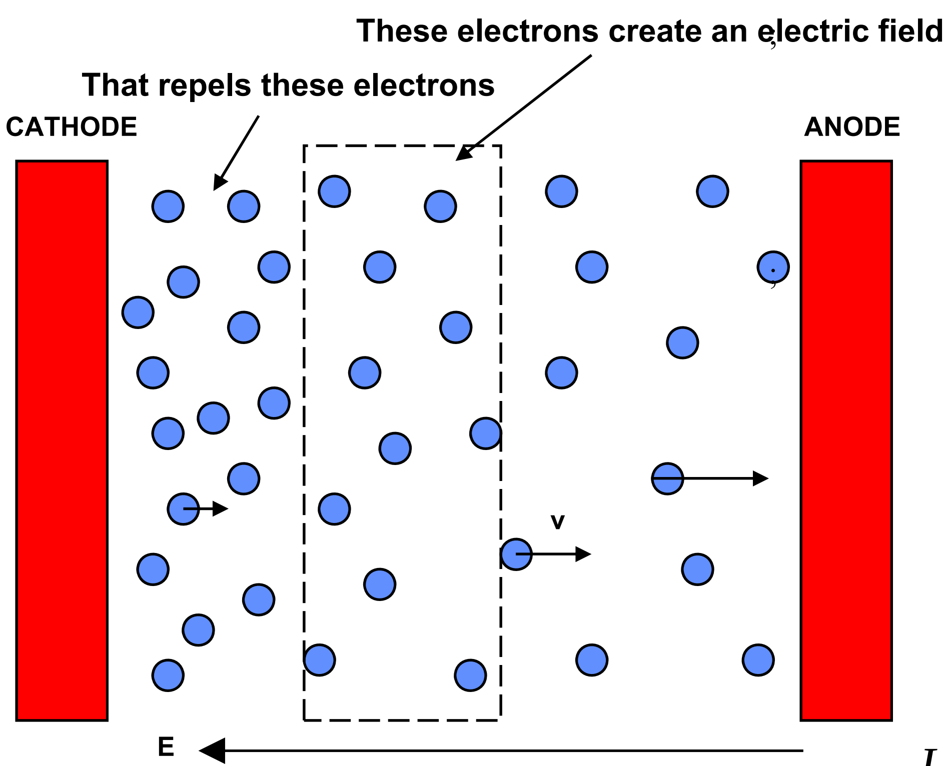
Electrons – Photo Cathodes

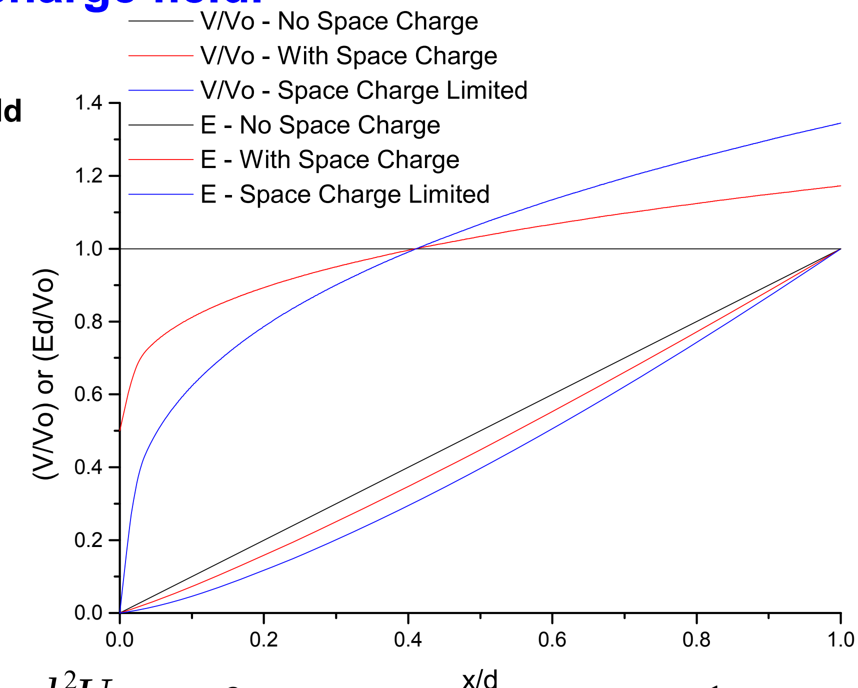
- **Quantum Efficiency = Electrons/photon [$Q_e(\lambda)$]**
  - GaAs:Cs=17% , CsTe=12.4% , K2CsSb=29%, Cu~0.01%,
- **METALS**
  - If desired, can be almost-“blind” to optical or infra-red.
  - Using the thermal electrons above the Fermi Energy, can make a very low current source using optical wavelengths.
  - 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=Cs_2Te (Cesium Telluride)– High Quantum efficiency & stable.

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

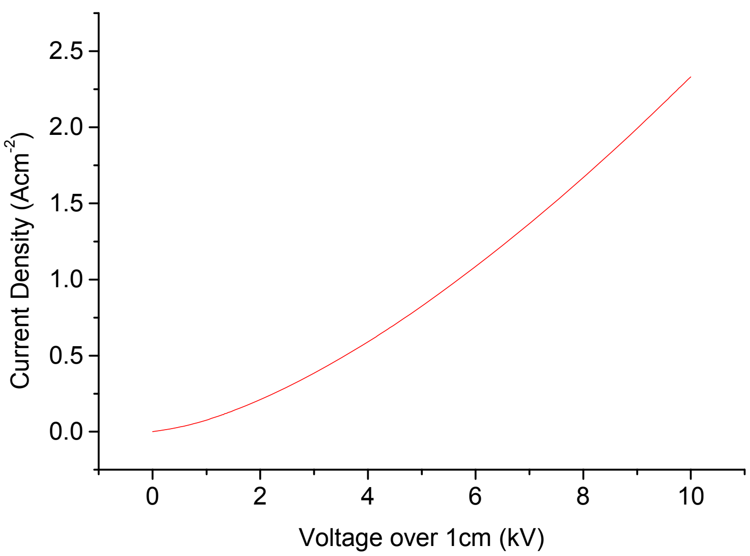
- **Hence there is a MAXIMUM current density that can be extracted for a given voltage and gap.**

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

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.**

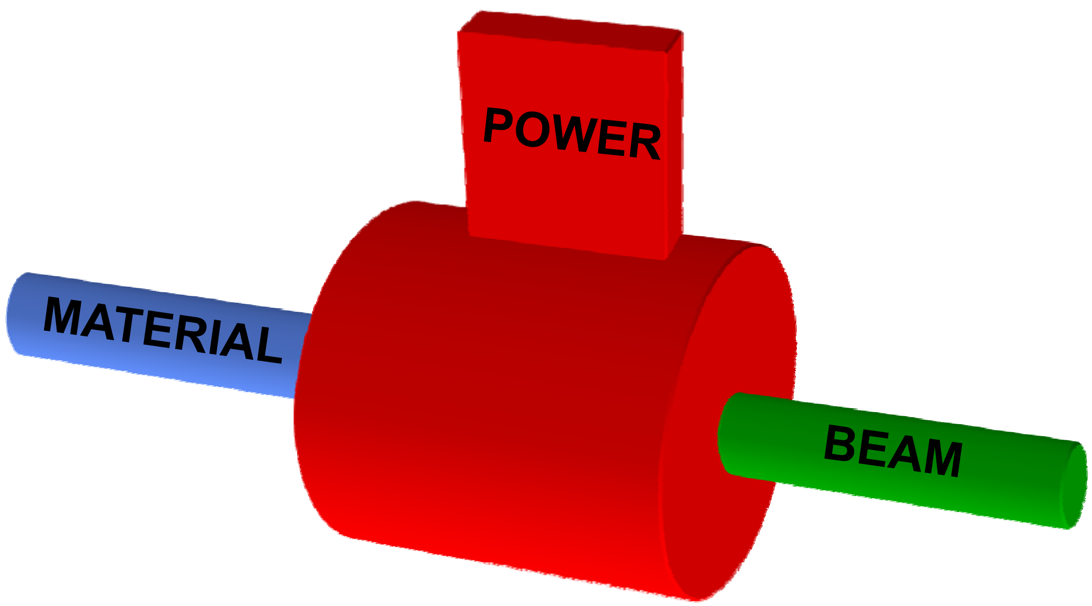
- **If the cathode-anode voltage is ZERO, no current is extracted -> Cathode Grid.**



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.**



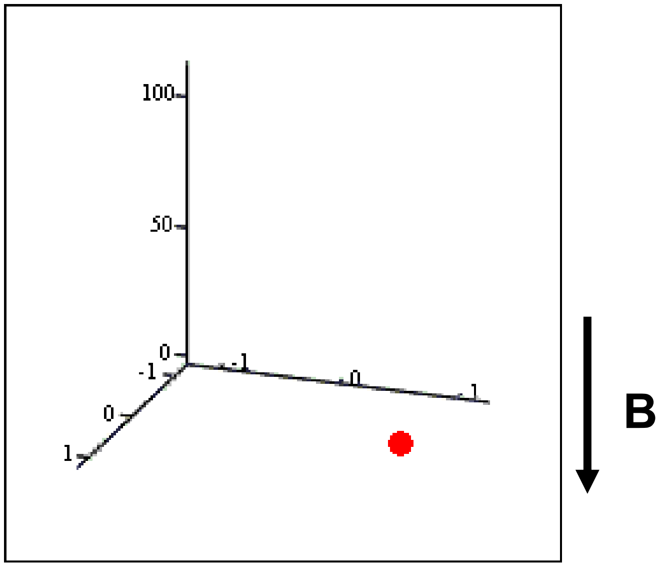
Electron and Ion Sources

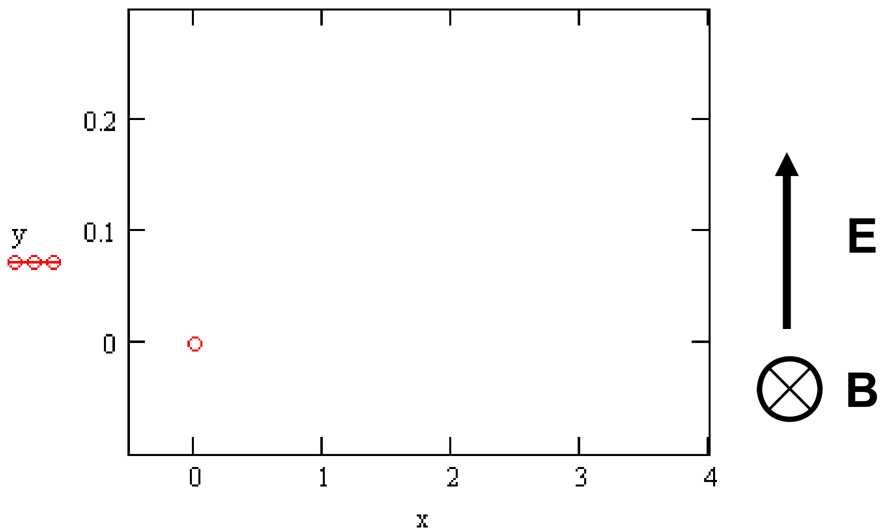
Ion Sources - Basics

- **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





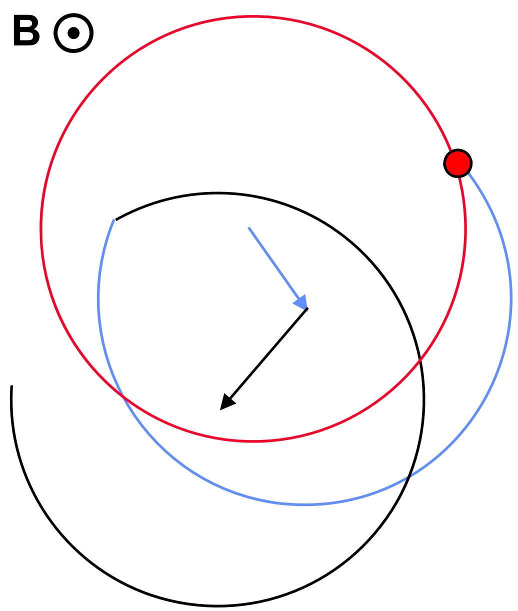
$$\rho_L = \frac{\sqrt{2mE_\perp}}{eB}, \omega_L = \frac{eB}{m}$$

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

Electron and Ion Sources

Plasma Particle Motion

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



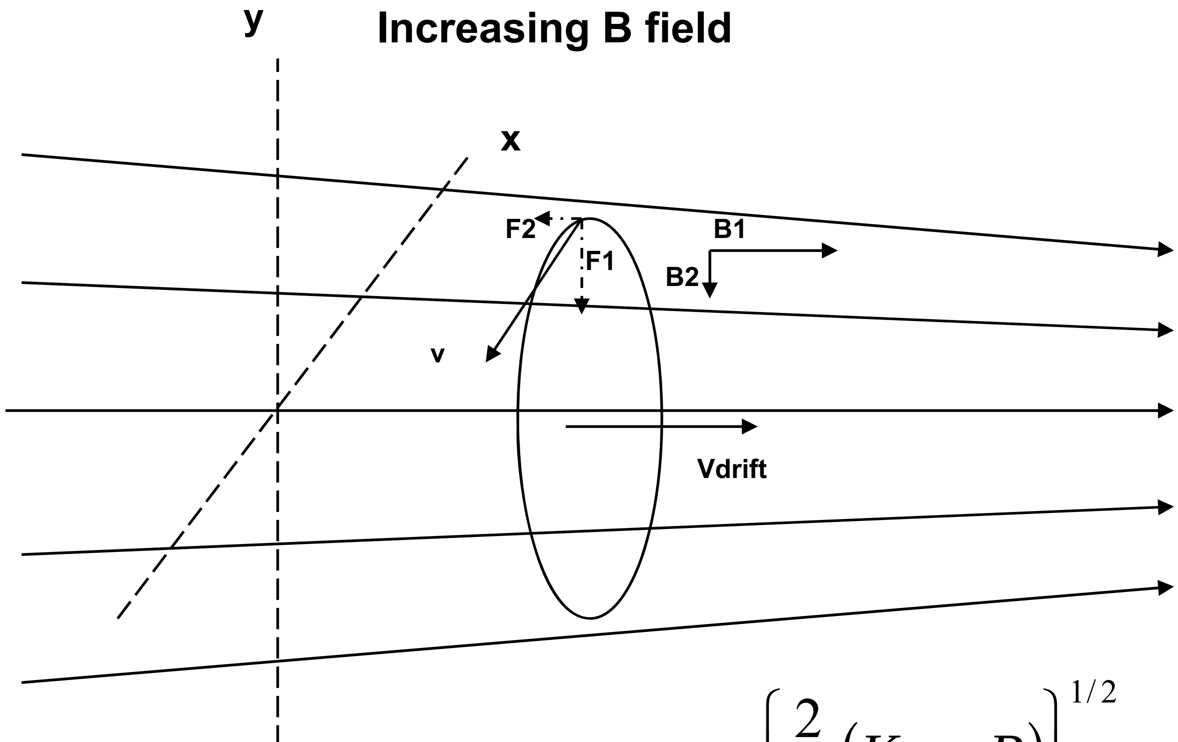
cf: opposite to classical energy – velocity equation !

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

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

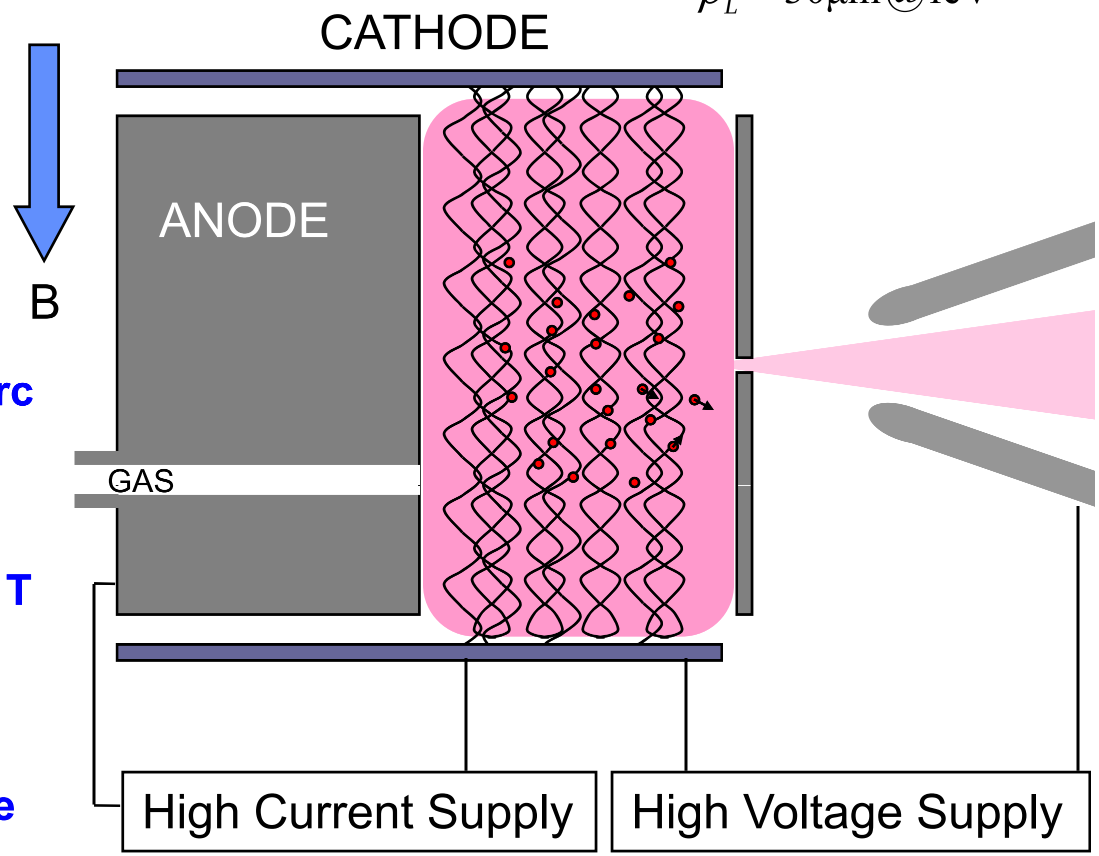
Ion Source – Penning / PIG

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

$$\rho_L \approx 30\mu m @ 1eV$$

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

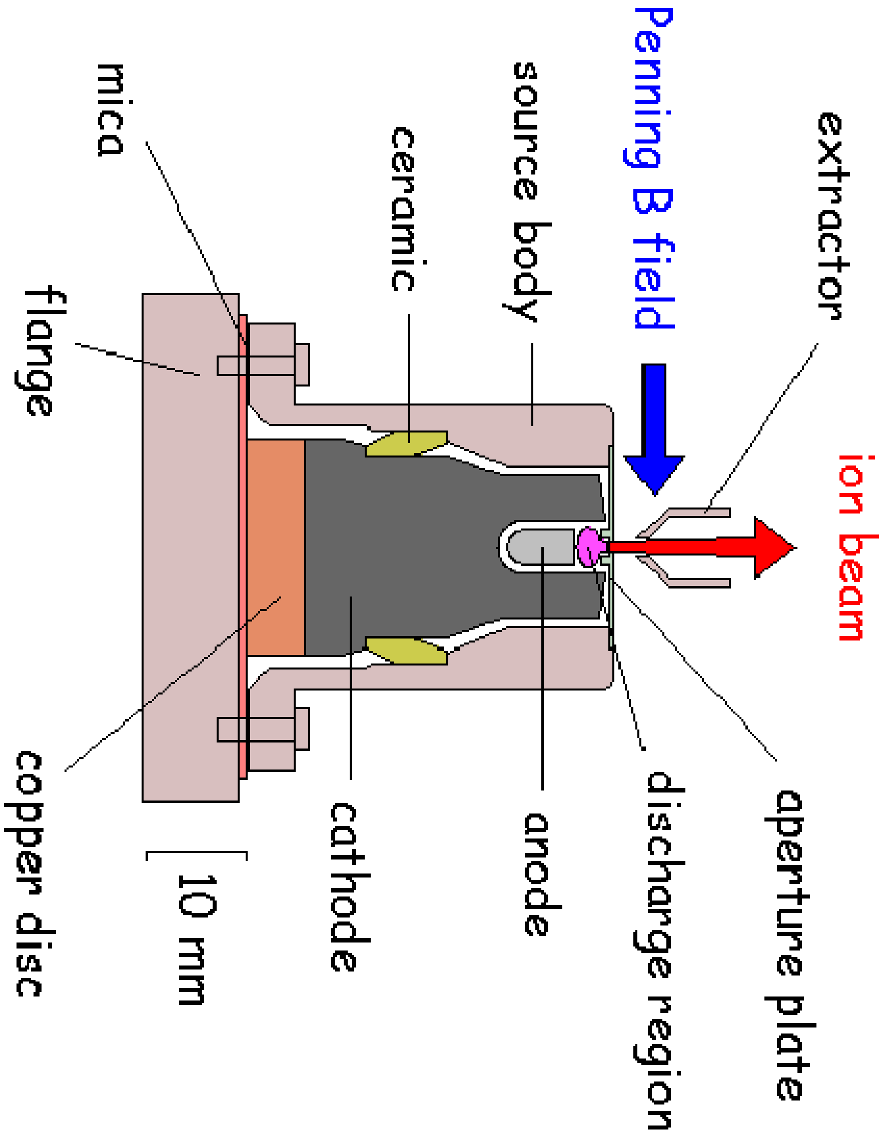
  Gas Pressure 10^{-3} -> 1 mbar
  Arc Voltage ~1kV
  Arc Current 0.1 -> 50 A
  Magnetic Field >0.1T



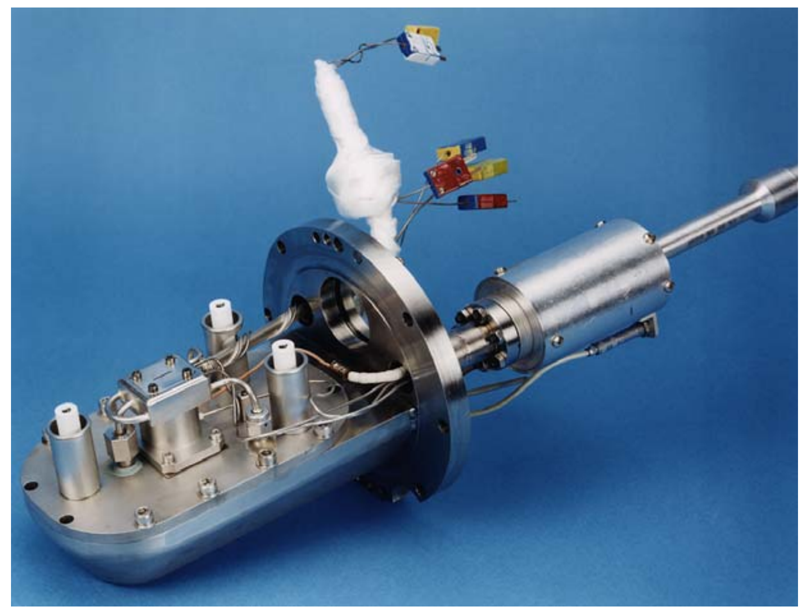
- **Cathode can be Hot or Cold**
- **Electrons are accelerated by the arc voltage across the cathode sheath layer.**
- **Magnetic field stops cathode electrons reaching the anode (>0.1T required).**
- **Some electrons strike the anti-cathode.**
- **Otherwise they may oscillate in the Penning Trap and 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 mutliple ionisation.**
- **The solenoid magnetic field still allows losses on axis – these ions make the beam.**

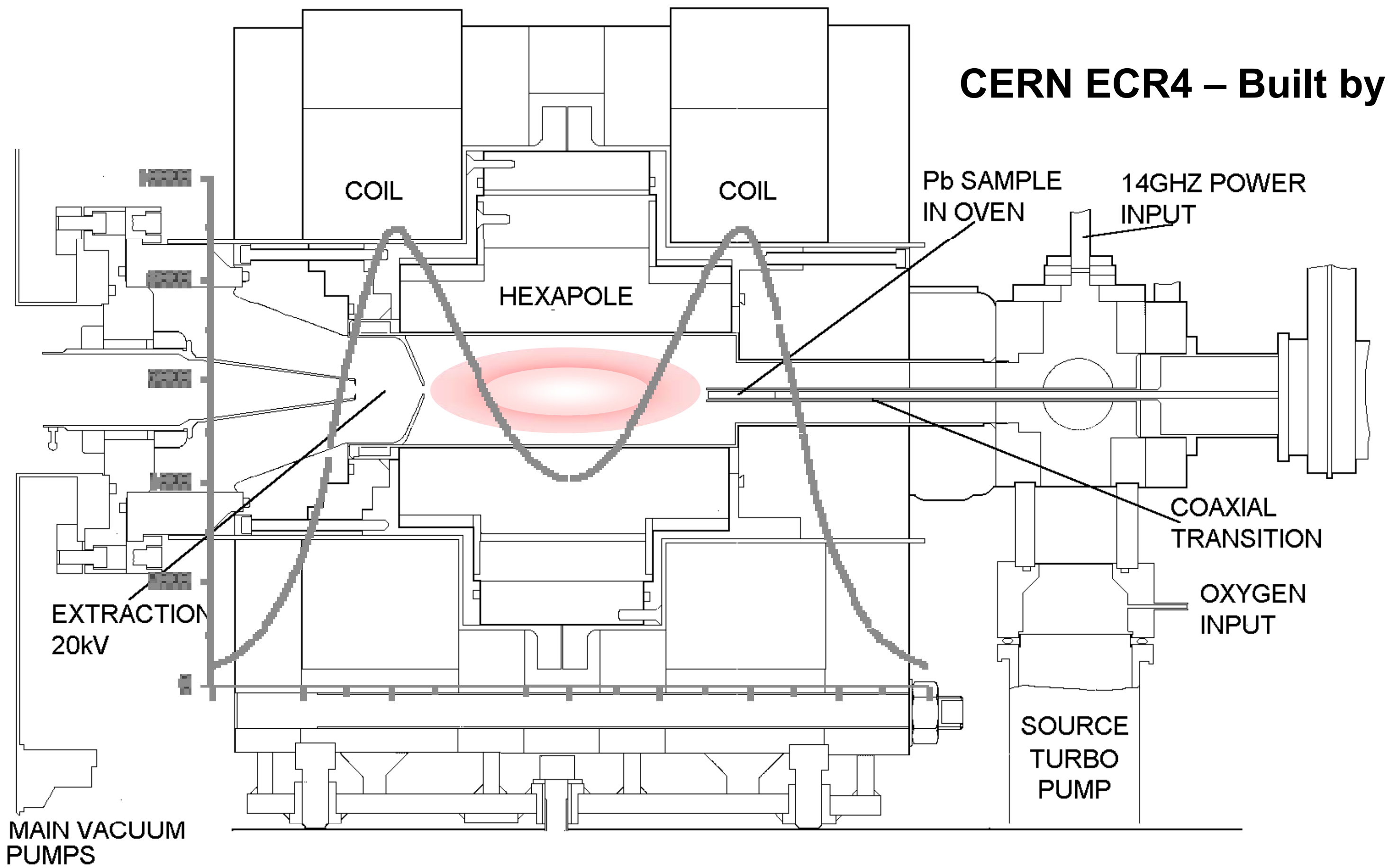
$$\omega_{ecr} = \frac{eB}{m}$$

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

Electron and Ion Sources

Ion Source – ECR

CERN ECR4 – Built by GANIL

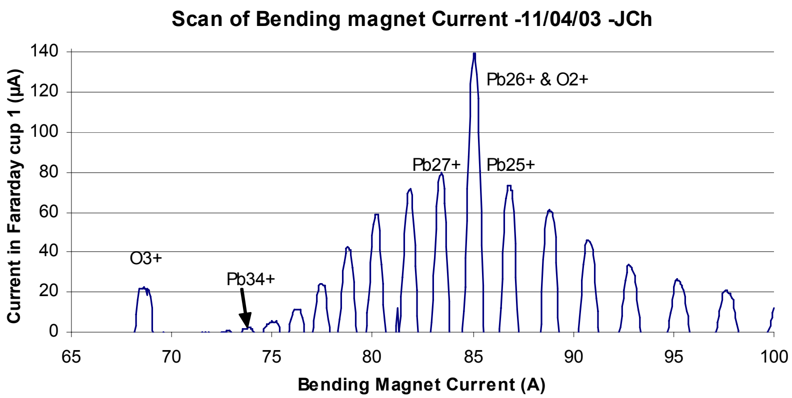


Electron and Ion Sources

Ion Source – ECR

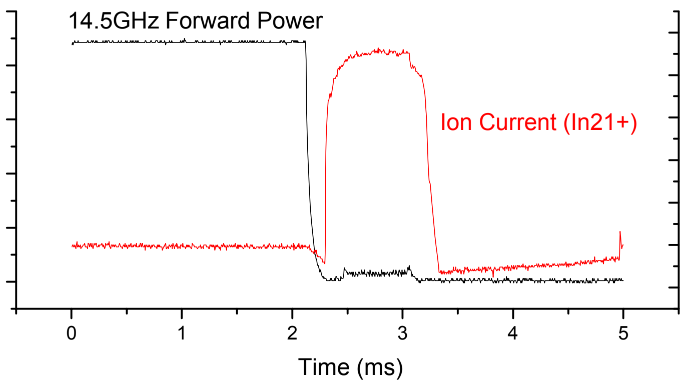
- No filament is needed, greatly increasing the source lifetime.

- 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 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.
- 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.

$AB + e \rightarrow A- + B$

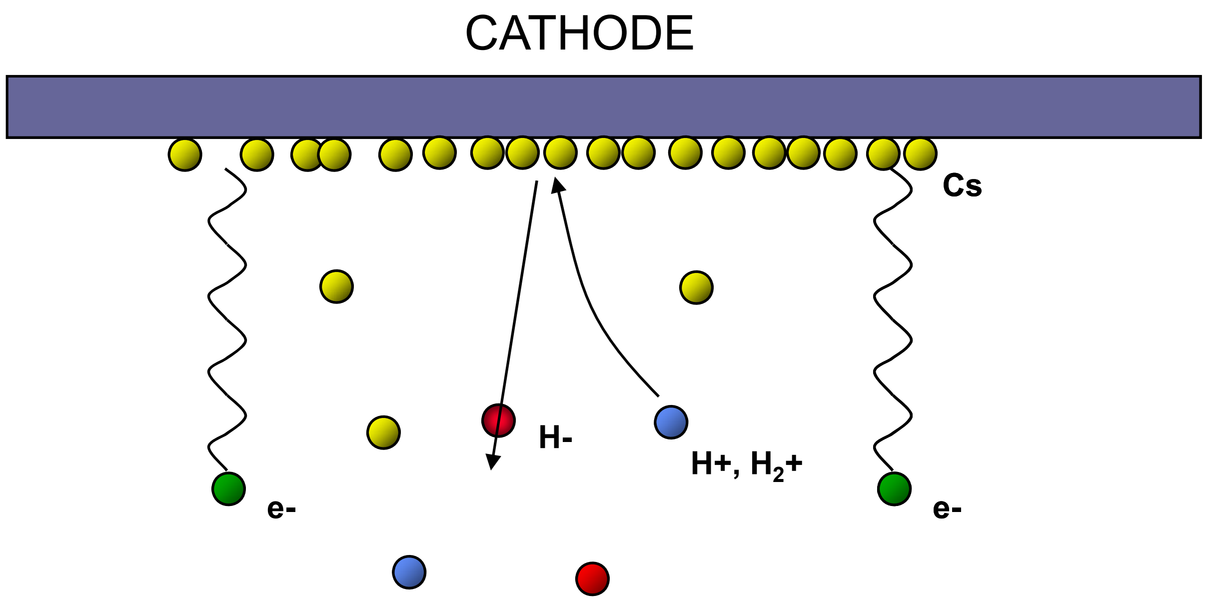
$A + B \rightarrow A- + B+$

$AB^* + e \rightarrow A- + B$

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

Electron and Ion Sources

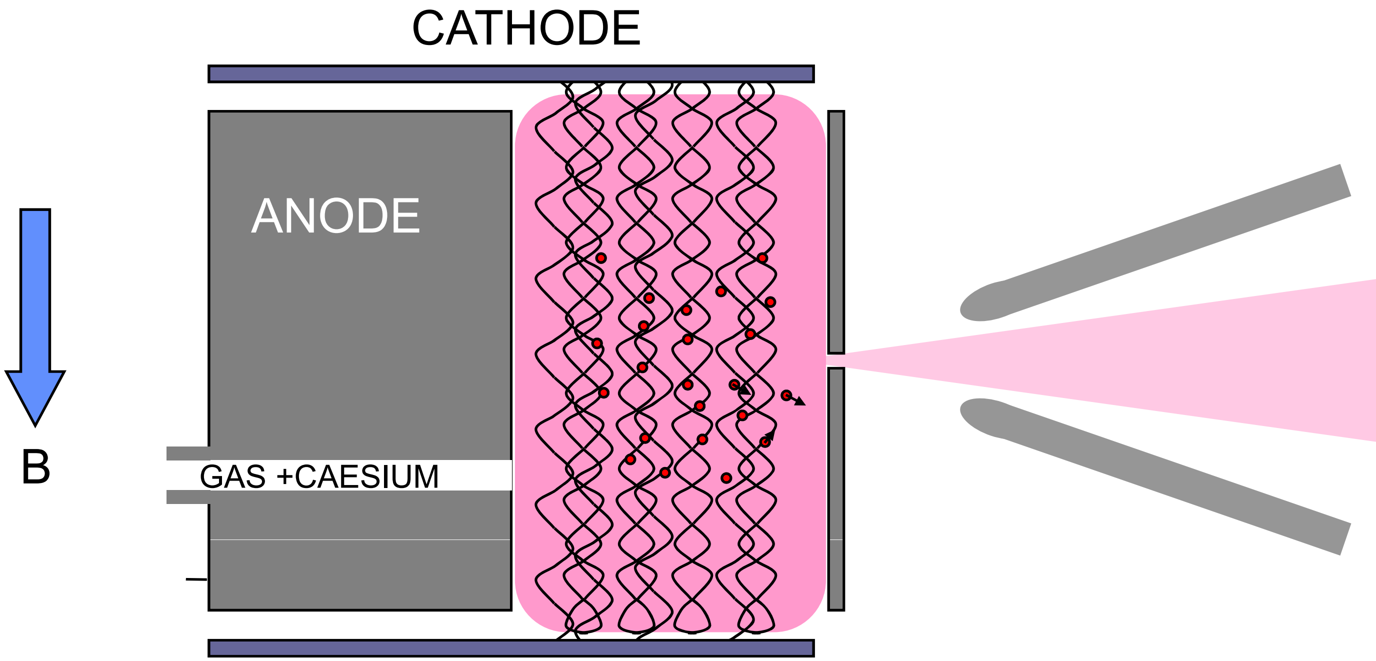
H- Surface Ion Production



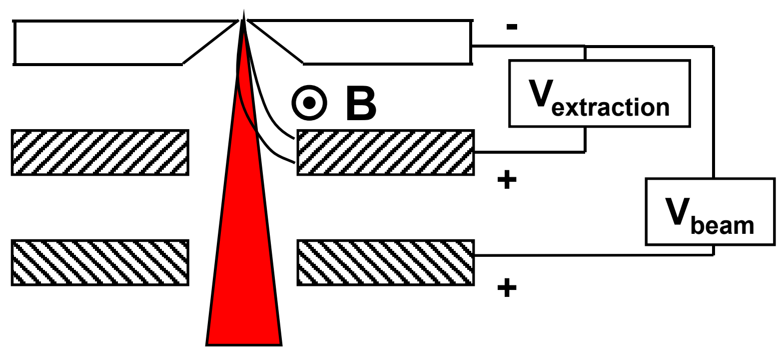
- Protons from the plasma are accelerated to the cathode, which has a coating of caesium.
- The protons desorbed from the low work function surface, with an additional electron.
- The plasma must not be too hot, to avoid ionising the H-.
- Penning, Magnetron, etc, sources produce H this way.

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)