Electron and Ion Sources

- **Electron Sources**
  - Thermionic
  - Photo-Cathodes
- **Ion Sources**
  - Penning Ion Source
  - ECR Ion Source
  - Negative Ions

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**Electrons – Thermionic Emission**

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

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

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**Graphical Representation**

- Graph showing Free Electrons (arb units) vs. Electron Energy (eV) for different temperatures (T=0K, T=1000K, T=2000K).
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.

\[
J = A \cdot T^2 \exp\left(\frac{-e\Phi_{\text{work}}}{kT}\right)
\]

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

\[
A = \frac{4\pi em \cdot k^2}{h^3} \approx 1.2 \times 10^6 \text{Am}^{-2}K^{-2}
\]

This factor \(A\) is not achieved in practice.

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

Where \(E_s\) (field) is in kV/cm
=15% for 1kV/cm @1000K

- J is increased by the Schottky effect – the electric field on the surface, allows electron tunneling

<table>
<thead>
<tr>
<th>Material</th>
<th>(A)</th>
<th>(\Phi_{\text{work}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>60</td>
<td>4.54</td>
</tr>
<tr>
<td>Thoriated W</td>
<td>3</td>
<td>2.63</td>
</tr>
<tr>
<td>Mixed Oxide</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>Cesium</td>
<td>162</td>
<td>1.81</td>
</tr>
<tr>
<td>Ta</td>
<td>60</td>
<td>4.12</td>
</tr>
<tr>
<td>Cs/O/W</td>
<td>0.003*</td>
<td>0.72*</td>
</tr>
<tr>
<td>LaB(_6)</td>
<td>29</td>
<td>2.66</td>
</tr>
</tbody>
</table>

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

Electron and Ion Sources
Electrons – Thermionic Emission

Melting points
Cs: 301.6 K
Ta: 3290 K
W: 3695 K
LaB\(_6\): ~2800 K (decomp)
Electron and Ion Sources

Electrons – A Gun

- **CATHODE**
- **ANODE**
- **INSULATOR**
- **BUCKING COIL**
- **PUMPING PORT**

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

\[ \lambda_c = \frac{hc}{\phi_{\text{work}}} = \frac{1239.8}{\phi_{\text{work}}} \]

<table>
<thead>
<tr>
<th>( \phi_{\text{work}} ) (eV)</th>
<th>( \lambda_c ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>4.5</td>
</tr>
<tr>
<td>Mg</td>
<td>3.67</td>
</tr>
<tr>
<td>Cu</td>
<td>4.65</td>
</tr>
<tr>
<td>W</td>
<td>275</td>
</tr>
<tr>
<td>Mg</td>
<td>340</td>
</tr>
<tr>
<td>Cu</td>
<td>267</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( E_g + E_a ) (eV)</th>
<th>( \lambda_c ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>5.5</td>
</tr>
<tr>
<td>Cs₂Te</td>
<td>-3.5</td>
</tr>
<tr>
<td>K₂CsSb</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>590</td>
</tr>
</tbody>
</table>
Electron and Ion Sources
Electrons – Photo Injector

- Photo Injector Test Facility - Zeuthen

RF Injection – 1.5GHz

Cs₂Te Photo-Cathode
or Mo

262nm Laser
Pico-second pulses @ 1.5GHz
freq quadrupled

Δ=0.67ns

Electron and Ion Sources
Electrons – Photo Cathodes

- Quantum Efficiency = Electrons/photon [ Qₑ(λ) ]
  - GaAs:Cs=17%, CsTe=12.4%, K₂CsSb=29%, Cu~0.01%,

\[ P_{\text{laser}} = \frac{n \cdot W}{Q_e} = \frac{I}{e} \phi_{\text{norm}} \frac{1}{Q_e} \]

<table>
<thead>
<tr>
<th>P_{\text{laser}} (kW) – 1Amp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
</tr>
<tr>
<td>Cs₂Te</td>
</tr>
</tbody>
</table>

- METALS
  - 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=Cs₂Te (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.

These electrons create an electric field
That repels these electrons

\[
\begin{align*}
\text{CATHODE} & \quad \text{ANODE} \\
E & \quad \text{That repels these electrons}
\end{align*}
\]

\[
\begin{align*}
\frac{d^2V}{dx^2} &= -\frac{\rho}{\varepsilon_0} \\
J &= \rho v \\
qV &= \frac{1}{2}mv^2 \\
V(x = 0) &= 0, V(x = d) = V' \\
dV(x = 0) &= 0
\end{align*}
\]

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.

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

\[
\begin{align*}
d & : \text{Cathode to Anode distance} \\
V' & : \text{Cathode to Anode voltage} \\
q & : \text{particle charge} \\
m & : \text{particle mass}
\end{align*}
\]

- If the cathode-anode voltage is varied, so is the electrode current.
- If the cathode-anode voltage is ZERO, no current is extracted \(\rightarrow\) Cathode Grid.
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.

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 + desorption, 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
Ion Source – Penning / PIG

- Penning or Philips Ionisation Gauge (PIG) source
  - Gas Pressure $10^{-3} \rightarrow 1 \text{ mbar}$
  - Arc Voltage $\sim 1 \text{kV}$
  - Arc Current $0.1 \rightarrow 50 \text{ A}$
  - Magnetic Field $>0.1 \text{T}$
- 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 ($>0.1 \text{T}$ 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 – 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.
  - The drive frequency must be above the plasma frequency.
  - If confined in a magnetic bottle, the electrons can be heated to the keV and even MeV range.
  - Ions also trapped in the bottle, can undergo multiple ionisations.
  - The solenoid magnetic field still allows losses on axis – these ions make the beam.

\[
\omega_{ecr} = \frac{eB}{m}
\]

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

\[
\omega_{ecr} > \omega_{\text{plasma}} = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}
\]

\[
n_e < 2.6 \times 10^{12} \text{ cm}^{-3} @ 14.5 \text{GHz}
\]
Electron and Ion Sources

Ion Source – ECR

CERN ECR4 – Built by GANIL

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\text{drift} to V\text{ecr}

\[ v_{\text{drift}} = \sqrt{\frac{2}{m} \left( K - \mu B \right)} \]

\[ \mu = \frac{mv^2}{2B} \]

\( \mu \) = magnetic moment

\( K \) = total kinetic energy
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. 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.

<table>
<thead>
<tr>
<th></th>
<th>Electron Affinity (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.7542</td>
</tr>
<tr>
<td>He</td>
<td>&lt;0</td>
</tr>
<tr>
<td>Li</td>
<td>0.6182</td>
</tr>
<tr>
<td>Be</td>
<td>&lt;0</td>
</tr>
<tr>
<td>B</td>
<td>0.277</td>
</tr>
<tr>
<td>C</td>
<td>1.2629</td>
</tr>
<tr>
<td>N</td>
<td>&lt;0</td>
</tr>
<tr>
<td>O</td>
<td>1.462</td>
</tr>
<tr>
<td>F</td>
<td>3.399</td>
</tr>
</tbody>
</table>

- 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.

\[
\begin{align*}
AB + e & \rightarrow A^- + B \\
A + B & \rightarrow A^- + B^+ \\
AB^+ + e & \rightarrow A^- + B \\
A^+ + B & \rightarrow A^- + B2^+
\end{align*}
\]
Electron and Ion Sources

Ion Sources – Negative Ions

- For H- Sources, the “Dissociative attachment to an vibrationally excited state” is believed to be the most important process (all others have small cross sections, by a factor >10^5).
- \( H_2^* + e \rightarrow H^- + H \) Cross section of attachment is maximum in the 0.5 – 1 eV range (10-30eV are needed to excite the \( H_2 \) molecules).
- Electrons are extracted along with negative ions! Electron current can be reduced with a dipole B field in extraction.

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

- CAS – 5th General School (CERN 94-01) and Cyclotrons, Linacs… (CERN-96-02)