Lecture on Sources of Particles

Part II

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Ion Sources

T. Thuillier

Laboratoire de Physique Subatomique et de Cosmologie, CNRS-IN2P3-UJF-INPG, 53 rue des martyrs, 38026 GRENOBLE cedex, France

A selection of ion sources is presented. Many other exists...

- Filament Ion Source
- Surface Ionization Ion Source
- Negative Ion Sources
- Electron Beam Ion Source
- Laser Ion Source
- Electron Cyclotron Ion Sources

Annex: Beam Extraction and beam selection
Filament Ion Source

- Filament ion sources use a primary themionic GUN to generate electrons with energy $E \approx 100$ eV
- Atom ionization is done by direct electron impact
- Very simple and robust design, used in industrial implanters
- 1+ beams are generated, with few % of 2+ & 3+ charge states
- Example here is the Niels-Bernas Ion Source
- Drawback: aging of filament by Sputtering
- 20 mA beam $\Rightarrow$ some 10 hours / 2 mA beam $\Rightarrow$ some 100 hours

![Diagram of Niels-Bernas Ion Source]

- Heated filament
- ~100 V
- Cathode Current
- 19.9 kV
- High Voltage
- 20 kV
- Discharge Voltage
- Negative electrode to repel cold electrons (discussed later in beam extraction study)
- Externally applied magnetic field (~300 gauss) to increase electron lifetime and improve ion density
Filament Ion Source

View of the plasma Chamber equipped with an electron repeller (see next slide)

View of the source and its mechanics, ready to be plugged in ionic implanter

View of the beam extraction slit
Indirectly Heated Cathod (IHC) Ion Source

- Modified Niel-Bernas Source
- Enhanced filament lifetime at high current thanks to the bulk cathode #2
- At 20 mA => lifetime is 200-800 h, depending on ions to produce
- Electron repeller added to improve electron confinement
- Dipole Magnetic field confinement
A metal with High Work Function can steal an electron to an adsorbed atom through Tunnel Effect.

**SAHA formula:**

\[
\frac{N^+}{N_0} = Ce^{((\Phi-I)/kT)}
\]

- First Ionisation Potential \( I \) of adsorbed atom
- Work function \( \Phi \) of metal
- \( kT \) Temperature of metal
- Provided \( \Phi > I \)

Works with High \( \Phi \) metals and low \( I \) atoms

- Metals used: W-Ox, Ir, Pt, C, Re, W
- Atoms ionized: Alkalines, Alkaline earths

High Temperature helps to desorb atoms

Very efficient method, very selective technique
Surface Ionization Source

- An alkaline metal is heated in an oven
- Atoms evaporates toward a heated ionizer tube made up with a high work function metal
- Atoms are adsorbed to the wall
- Atom desorbed by high kT with one e\textsuperscript{-} stolen by the metal $\Rightarrow$ ionization

![Diagram of Surface Ionization Source]

- Oven
- Ionizer
- Heated C tube IONIZER
- Alkaline metal
- Heated Oven Wolfram
- 20 kV
- 19 kV
- 0 kV
- $1^+$ beam
### What is a Negative Ion?
- Atoms with unclosed shells can accept an extra electron and form a **stable ion** with a net charge of \(-e\).
- The stability is quantified by the **Electron Affinity**, the minimum energy required to remove the extra electron.
- The electron affinities are substantially **smaller than the ionization energies**, covering the range between 0.08 eV for Ti\(^-\) and 3.6 eV for Cl\(^-\).

### Negative ions are very fragile!
- (M)any Collision can break the binding (see next slides).

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**Periodic table of electronic affinity in kJ/mol, actinids not represented**

<table>
<thead>
<tr>
<th>Element</th>
<th>Affinity (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.75</td>
</tr>
<tr>
<td>Li</td>
<td>0.08</td>
</tr>
<tr>
<td>Na</td>
<td>0.75</td>
</tr>
<tr>
<td>K</td>
<td>1.0</td>
</tr>
<tr>
<td>Rb</td>
<td>1.1</td>
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<tr>
<td>Cs</td>
<td>1.2</td>
</tr>
<tr>
<td>B</td>
<td>0.4</td>
</tr>
<tr>
<td>Al</td>
<td>0.4</td>
</tr>
<tr>
<td>Si</td>
<td>0.4</td>
</tr>
<tr>
<td>P</td>
<td>0.4</td>
</tr>
<tr>
<td>S</td>
<td>0.4</td>
</tr>
<tr>
<td>Cl</td>
<td>3.6</td>
</tr>
<tr>
<td>Ar</td>
<td>0</td>
</tr>
<tr>
<td>Br</td>
<td>0</td>
</tr>
<tr>
<td>Kr</td>
<td>0</td>
</tr>
<tr>
<td>Xe</td>
<td>0</td>
</tr>
</tbody>
</table>

**1 eV \sim 96.5 kJ/mol**
The creation of negative ions is exothermic. Excess energy should be dumped to a third particle.

- **Radiative Capture** = direct electron attachment
  
  \[ e^− + \text{H} → H^- + \gamma \]
  
  → Very low probability (e.g. \( \sigma \approx 5 \cdot 10^{-22} \text{ cm}^2 \) for H), rare event

- **Dissociative Attachment** = the excess energy in the collision can be transferred to a third particle when dissociating a molecule:
  
  \[ \text{AB} + e^- → \text{A} + \text{B} + e^- \]
  \[ \text{AB} + e^- → \text{A}^- + \text{B} \] (sometimes)
  
  → Higher probability to occur (e.g. \( \sigma \approx 10^{-20} \text{ cm}^2 \) for H\(_2\) and \( E_e > 10 \text{ eV} \))
  
  → Requires low energy electrons (~1-100 eV)
  
  → The dissociative attachment is enhanced if the molecule is first excited to a high vibrational state (near breakdown) by a fast electron
  
  \[ \text{e}^- + \text{H}_2 \text{ (fast)} = \text{H}_2^ν + \text{e}^- \]
  
  \( (\sigma \approx 5 \cdot 10^{-18} \text{ cm}^2 \) for \( 4 \leq ν \leq 9 \) and \( E_e > 15 \text{ eV} \))
  
  → Then \( \text{H}_2^ν + \text{e}^- \text{ (slow)} = \text{H} + \text{H}^- \)
  
  \( (\sigma \approx 3 \cdot 10^{-20} \text{ cm}^2 \) for \( 4 \leq ν \leq 9 \) \& \( E_e < 1 \text{ eV} \))

- **3 Body Collision:**
  
  \[ \text{A} + \text{B} + e^- → \text{A}^- + \text{B} \]
Negative ions are very easy to lose in a plasma

- **Electron impact ionization:**
  \[ A^- + e^- \rightarrow A + 2 e^- \]
  → For H\(^-\): \( \sigma \approx 30 \cdot 10^{-16} \text{ cm}^2 \)
  → So \( \sigma \) 30 times larger than for a typical neutral atom!!

- **Mutual neutralisation (Recombination)**
  \[ A^- + H^+ \rightarrow A + H \]
  → Dominant process for \( E_{p+} \approx eV \)
  → For H\(^-\), \( \sigma = 7 \cdot 10^{-14} \text{ cm}^2 \) for \( E_{p+} \approx 0.5eV \)

- **Collisional Detachment:**
  \[ A^- + B \rightarrow A + B^+ + e^- \]

- **Associative Detachment:**
  \[ A^- + B \rightarrow AB + e^- \]

Negative ions are totally destroyed a few cm away from their place of birth in a \( n \approx 10^{13} \text{ cm}^{-3} \) plasma

They must be extracted close to their place of birth
As seen in the Electron source part, Metals host an abundance of loosely bound electrons (conduction electrons) but it takes about 4.5 to 6 eV to remove an electron from the surface.

Alkali metals have lower work functions (2-3 eV). When adsorbed on a metal surface as a partial monolayer, alkali atoms can lower the surface work function ($\Phi$) to values even below their bulk work function, e.g. ~1.6 eV for Cs on Mo.

Electrons from metal can be captured by atoms stuck on surface (adatoms) through tunnel effect, provided $A > \Phi$.

Surface ionization works efficiently with Halogens and Chalcogens.

Saha Formula:

$$\frac{N^-}{N^0} = C \times e^{((A - \Phi)/kT)}$$

High $kT$ helps to desorb $A^-$.
Example of the ORNL $H^-$ Ion Source

- A multicusp magnetic structure increase plasma confinement
  → Permanent magnets

- $H_2$ gas is injected on the rear

- A RF antenna under vacuum generates the plasma (see next slide) and ionizes hydrogen to produce $H^+$, $H_2^+$, $e^-$

- Two filter magnets (SmCo 200 Gauss) repel hot electrons generated by the RF. (e.g. a 35 eV electron turns around on a 1 mm radius).
  → Cold electrons and cold ions undergo very many collisions with other particles, resulting in a diffusion process which favors the cold charged particles ($v_{\text{diff}} \sim T^{-\frac{1}{2}}$). Therefore the electron temperature decreases exponentially through the filter and extraction region.
  → Excited neutral molecules migrate freely to the extraction region.
  → The cold electron colliding with exited molecules near the outlet produce the extractable $H^-$ ions $\Rightarrow \sim 10$ mA achievable in the volume

- A Cs collar is present near to the source extraction to boost $H^-$ production

Source is pulsed with 6% Duty Cycle to produce 50 mA of $H^-$
The 3rd Maxwell Equation, $\nabla \times E = -\frac{\partial B}{\partial t}$ describes a curling $E$ field generated by a changing magnetic field in absence of any charge.

A changing magnetic field $B$ can be produced with an alternating current $i = i_o \cdot \cos(\omega t)$ in $N$ windings with radius $r_o$:

$$B = \frac{1}{2} \cdot \mu_o \cdot N \cdot i / r_o \quad \text{(Biot-Savart)}$$

Now integrate Maxwell's 3rd equation for Faraday's law:

$$\int E \cdot ds = -\frac{d}{dt} \int B \cdot dA$$

and solve for $E$:

$$E(r,t) = \frac{1}{4} \cdot \frac{r}{r_o} \cdot \mu_o \cdot \omega \cdot N \cdot i_o \cdot \sin(\omega t)$$

The electric field accelerate electrons and ions and favors electron impact ionization => PLASMA

- The $E$ field in the center is ~zero
- The $E$ field outside the winding is ~zero
- The $E$ field is most intense on the inside of the coils and parallel to the windings

The plasma is mostly generated near the inside of the windings.

The RF causes the plasma to drift in circular direction.

The multicups field guides the drifting plasma towards the center.
RF Negative Ion Source - Cesiation System and Beam Extraction

- **Cesium system:**
  - Cs flux controlled by an external oven temperature (ORNL/Fermilab design)

- **Gain of H⁻ current:**
  - 10 mA (no Cs) → 50 mA (Cs)
  - pulsed operation (6% Duty Factor)

- **H⁻ extraction**
  - Dumping magnet in the extraction area to deviate electrons extracted
  - Special Electrode to dump co-extracted electron beam

- Tilt of the source to have H⁻ extraction on axis
Hot Cathode Negative Ion Source

- **J-PARC, Japan**
  - Slow Electrons created by a heated cathod filament
  - Multicusp magnetic field (permanent magnets)
  - Cs Free
  - 0.5ms pulses, 25Hz, 50kW
  - Intensities → 30mA H⁻
  - Extraction in a dipolar magnetic field to dump electrons

*Many other types exist...*
Inversed Middleton Source

- A Surface Ionization Source produces Cs\(^+\) beam around the extraction aperture of the source
- Cs\(^+\) Ions are accelerated toward a metallic sample holder set to a negative voltage
- The Cs induces sputtering AND reduces the work function of the metal target

Positive Metal Ions are produced (helped with high kT)

Rotation of Sample to sputter to increase beam time
Electron Beam Ion Source (EBIS)

- **Electron beam issued from a gun**
  - Injected as a Brillouin flow on the axis of a solenoid, to get very high current densities. Close to the collector, it is generally slowed down to save power.

- **Stepwise ionization by e- impact.**
  - The charge exchange is avoided owing to a pulsed neutral injection.

- **Ion containment**
  - Due to the combination of the radial space charge e- potential well and a longitudinal voltage distribution applied on a series of tubes. The maximum charge number which may be trapped is $Q^+ \leq 10^{13} I V^{-1/2} L$.

- **The source is cyclic**
  - 3 phases: neutral injection, containment and expulsion,
  - Obtained by programming the tube potentials. The source output is then limited. The variation of the containment time allows to adjust the CSD.

- **EBIS can be used as a charge breeder**
  - 1+ injection, cooking, n+ bunch extraction

- **Low Pressure requirement**: $P < 10^{-9}$ mbar
Production of Very High Charge state

- The Ions charge state distribution increase with time
- Charge state distribution is narrow
- Ultra high charge state achievable
- Limited pulse repetition rate and beam intensity
  → space charge in the trap
  → Long Cooking time (10-100 ms)

Electron Beam Ion Source (EBIS)
High Intensity EBIS at RHIC

- 1.7 mA - 10 µs - 5 Hz

Narrow charge state distribution for Th beam

Magnetic field profile along the trap - Electron beam envelope

- Superconducting solenoid
- Electron gun
- Drift tubes
- Electron collector gate valve
- Electron collector
A very strong power laser pulse evaporates matter and generates a medium to high charge state hot plasma

- Very High density plasma
- Complicated plasma physics
- High charge state ions created
- High currents
- Very Hot ions (KeV to MeV)
- Complicated extraction and process
- Pulsed beams (~1 Hz)

Specifications:
CO\textsubscript{2}-N\textsubscript{2}-He laser  100J-10^{13} W.cm\textsuperscript{-2}
pulses of 50ns at 1Hz
1.4 \times 10^{10} \text{ Pb}^{25+} per pulse
The Magnetic Bottle or min-|B| structure

A multicharged ECR ion source contains a complicated magnetic field to confine ions.
Permanent magnet hexapole

HallBach Type structure:
- eg: 36 magnets
- 30° of magnetization angle between magnets
- FeNdB magnets
- SmCo magnets

Typical magnetic intensity available in the plasma:
- 1.2 to 1.6 Tesla
- 2 Tesla max at magnet surface possible
Superconducting hexapole

6 RaceTrack Coils to build The hexapole

Advantages:
- High radial magnetic field (>2 T)
- Tunable radial field
- Large plasma volume

Inconveniences:
- Strong forces induced in the coils => high risk @ building
- Expensive
The ECR Zone in an ECRIS: place where microwave frequency = electron cyclotron frequency

\[ \omega = \omega_c = \frac{qB_{ECR}}{m} \]

The ECR zone is usually a closed surface that do not touch walls.
Plasma Generation:

- Gas, or metallic vapor injection
- Secondary vacuum (=> charge exchange)
- Metallic cavity (multimode: $L \gg \lambda_{\text{wave}}$)
- Microwave injection

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

- Plasma Shape:

- A star with 3 wings

Lanzhou, China
**ECR Plasma characteristics:**

- Microwave frequency: \( f \sim 2.45 \rightarrow 28 \) GHz
- \( B_{ECR} \): \( B \sim 0.08 \rightarrow 1 \) Tesla
- Plasma density: \( n \sim 10^{11} \rightarrow 10^{13} \) cm\(^{-3}\)
- Ion Temperature: \( T_i \sim \text{eV} \) (cold plasma)
- Electron Temperature: \( T_e \sim \text{few keV} \) (non-maxwellian)

\( \Rightarrow \) Multi-charged ions Production

**Bremsstrahlung X-Rays Induced by electrons in VENUS Source (Berkely, USA)**
The frequency Scaling Laws

- Ions Current:
  \[ I \sim n_e \]

- Plasma Density:
  \[ n_e \sim f_{ECR}^2 \]

\[ B_{ECR} = \frac{f_{ECR}}{28 \text{ GHz}} \text{ Tesla} \]

Electron Cyclotron Resonance Ion Source

Current extracted

<table>
<thead>
<tr>
<th>( f_{ECR} ) [GHz]</th>
<th>( \Lambda ) [cm]</th>
<th>( n_e ) [cm(^{-3})]</th>
<th>( \Lambda_{0\rightarrow1+} ) [cm]</th>
<th>( T_{0\rightarrow1+} ) [( \mu \text{s} )]</th>
<th>( B_{ECR} ) [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>~12</td>
<td>( 7.4 \times 10^{10} )</td>
<td>~7</td>
<td>~10</td>
<td>0.09</td>
</tr>
<tr>
<td>14</td>
<td>~2</td>
<td>( 2.5 \times 10^{12} )</td>
<td>0.2</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>28</td>
<td>~1</td>
<td>( \sim 10^{13} )</td>
<td>0.05</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>~0.5</td>
<td>( 4.4 \times 10^{13} )</td>
<td>0.01</td>
<td>0.17</td>
<td>2</td>
</tr>
</tbody>
</table>
Electron Cyclotron Resonance Ion Source

Magnetic Confinement Optimum for the High Charge State Ion Production:

Magnetic Confinement parameters

- $B_{inj}$
- $B_{ext}$
- $B_{med}$
- $B_{rad}$
- $B_{INJ}$
- $B_{rad}$
- $B_{med}$
- $B_{ext}$

$B_{ECR} = \frac{f_{ECR}}{28 \text{ GHz}} \text{ Tesla}$

<table>
<thead>
<tr>
<th>$f_{ECR} [\text{GHz}]$</th>
<th>$B_{ECR} [\text{Tesla}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1990</td>
<td>2003</td>
</tr>
</tbody>
</table>

$B_{INJ} \sim 3 - 4 B_{ECR}$

$B_{rad} \sim 2 B_{ECR}$

$B_{med} \sim 0.5 - 0.8 B_{ECR}$

$B_{ext} \leq B_{rad}$
Example of ECR4 GANIL (France) : 14 GHz
Electron Cyclotron Resonance Ion Source

- Example of the VENUS source Berkeley (USA): 28 GHz

Achieved magnetic fields:
Binj \leq 4 \, T, Bext \leq 3 \, T, Brad \leq 2.2 \, T
Annexe: Beam Extraction

Simple example of beam extraction from an ECR ion source

Extracted current $I=J \cdot A$

$J =$ current density
$A =$ area of the circular hole in the plasma electrode
Annexe: Beam extraction

- The Child Langmuir Law (1/2)
  - Beam extraction with space charge limitation
  - For electrons beam:
    \[ J \leq \frac{4\varepsilon_0}{9} \sqrt{\frac{2e}{m}} \frac{V^{3/2}}{d^2} \]
  - For ions beam:
    \[ J \leq \frac{4\varepsilon_0}{9} \sqrt{\frac{2Ze}{Am_A}} \frac{V^{3/2}}{d^2} \]

- $J$ = current density extracted from the source
- $V$ = acceleration voltage
- $d$ = gap between electrodes
- $Z, A$ = charge and atomic ion numbers
The Child Langmuir Law (2/2)

\[ \vec{E}(0) = \vec{E}_0 + \vec{E}_{\text{spacecharge}} \]

Limit case when \( E(0)=0 \) => Child Langmuir law

Without charges

Space charge of electrons

Without charges
Annexe: Beam Extraction

- **Extraction Geometry**: The Pierce angle (for electrons)

  - Angle calculated such that the static accelerating electric field compensates exactly the radial space charge component created by the presence of the beam.
  - \( \Rightarrow \) a parallel beam with reduced aberrations is created.

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*Electrode Machined at 67.5° from the beam axis*
The space charge compensation for ions beams

In the accelerating gap, the electric field accelerates the cold electrons toward the source => no space charge compensation here

Moreover, cold electrons scattering from the beam to the accelerating gap will be sucked toward the source => loss of space charge compensation in the beam line.
Annexe: Beam Extraction

-The Triode System (or « accel-decel »)

The cold electrons from the beam line are repelled by the negative voltage. The beam is space charge compensated.
Annexe: Low energy beam separation

Ions Beam composition

- Ions of interest
- Buffer gas (to optimize ion of interest and sustain plasma density)
- Gas contaminant (C, N, O, H, H2O, N2, O2...)
- Metallic contaminant (elements from the plasma chamber)
- And SEVERAL charge states mixed together for each element produced.

A selection to keep only the ion of interest is required
6. Low energy ions beam separation

- Selection Through a magnetic dipole

\[ \rho \text{ is the radius of curvature} \]
\[ B \text{ magnetic field in the dipole} \]
\[ U \text{ high voltage of the source} \]
\[ M \text{ mass of the ion} \]
\[ Z \text{ charge state of the ion} \]

\[ B\rho = \sqrt{\frac{2}{e}} \sqrt{\frac{M}{Z}} U \]

T. Thuillier, JUAS 2011/2012, Sources of Particles