5) The Electron Cyclotron Resonance Ion Source (ECRIS) – HF ion sources

5.1 The ECR:
Microwave ion sources (f > 1 GHz) have been developed for the production of multiple charged ions. The first sources which used the ECR-heating together with a magnetic-plasma-confinement were built at the end of the 1960's in the group of R. Geller. He took advantage from his experience with "mirror machines" for fusion-plasma-studies. For this purpose a "Min-B-configuration" was chosen. The better the magnetic confinement, the higher charge states of the ions can be produced.

One can distinguish between ECR-sources with f < 2.45 GHz for intense beams of low charged ions and f > 2.45 GHz for highly charged ions.

The principle setup of an ECR is shown on the right hand side. The magnetic plasma confinement in axial direction is provided by solenoids, the radial one by a multi-pole configuration of permanent magnets. A microwave is guided into the chamber and ensures the plasma-production. The plasma chamber is insulated and is biased with high voltage for extraction.

If a volume with sufficient high magnetic field, is irradiated with microwaves, it is possible to ignite a plasma by electron resonance at a given gas pressure level. With a special arrangement of axial and radial magnetic field components (min B configuration) the maximum plasma confinement is reached for the production of hot plasma electrons by microwave heating. The plasma chamber is a microwave cavity. For the microwave heating the condition applies:

$$\omega_c = \frac{e}{m_e} B \quad \Rightarrow \quad f = \frac{eB}{2\pi \cdot m_e} = 2.796 \times 10^{10} \cdot B[T]$$

For $B = 1 \text{T}$ this leads to $f = 28 \text{ GHz}$

or

$f = 10 \text{ GHz}$ requires $B = 0.36 \text{ T}$.

The mirror-relation $B_{\text{max}}/B_{\text{min}}$ is in general 2-4 and $B_{\text{max}}$ is of the order of two times the electron cyclotron (EC)-resonance field value. For frequencies above 20 GHz magnetic field above 1.5 T are needed, which can be reached with super-conducting magnets. The multi-pole geometry determines the shape of the loss lines and loss-areas. The higher the number of poles, the bigger are the total loss-areas on both ends of the confinement. The loss-areas are the result of a compensation of the axial field by the field of the permanent magnets forming the multi-pole at the positions of opposite polarity.
FIGURE 9.5
Axial loss lines of different multipoles.

FIGURE 9.6
Closed hexapole structure.

FIGURE 9.7
Open hexapole structure.
Modern ion sources are using an iron yoke to reduce the power consumption. Furthermore, an iron yoke also reduces the influence of stray field on the plasma and the extracted ion beam.

The first ion source, which was the basis of all ECR sources, was Geller's SuperMAFIOS (1975). The power consumption of 3MW was not acceptable for applications. Hence, Geller and coworkers developed the MiniMAFIOS with 100 kW power consumption and 10 Ghz microwave frequency.
In 1987, Geller and Sortais build the first ECR consisting out of permanent magnets. The so called NeoMAFIOS only needs the power for the microwave heating.

The ions inside the plasma are not heated by the microwave, but remain thermal. Hence, the interaction of the "slow" plasma ions with the magnetic field is week. The confinement of the plasma ions can thereby only be done by the electrostatic space-charge field of the magnetically confined plasma electrons.

The ECR plasma can be clearly distinguished from other plasma, by the significant difference between the ion and electron temperature. While the plasma-electron temperature can be up to some hundred keV, the temperature of the plasma-ions is of the order of eV, i.e. the mean kinetic energy is quite low. The magnetic moment of the plasma-ions is thereby quite low and there interaction with the external magnetic field is small. Hence, a magnetic confinement of the slow plasma-ions is not possible.
Characteristic of ECR plasma: Small potential dip of the central area with respect to the heated zone. This is the result of the two-component plasma with different electron temperatures. The electron distribution adjusts in a way that

\[ j_{e,\text{cold}} = j_{e,\text{hot}} \Rightarrow \rho_{e,\text{cold}} v_{\text{cold}} = \rho_{e,\text{hot}} v_{\text{hot}} \]

because \( v_{\text{hot}} > v_{\text{cold}} \Rightarrow \rho_{e,\text{cold}} > \rho_{e,\text{hot}} \)
The dependence of the electron density $n_e$ and temperature $T_e$ on the microwave heating power shows interesting behaviours.

The electron density saturates and even decreases above a certain power level. The temperature also saturates. This is due to the decrease of the confinement time and the increase of the plasma volume with higher heating power. Primarily, the stochastic-electron-heating becomes inefficient at to high heating power levels.

The plasma density is limited by $f_{\text{cutoff}} = f_p = f_{\mu-\text{wave}}$. 
\[ f_p = 8.98 \sqrt{n_e \text{[m}^{-3}\text{]}} \text{[Hz]} \implies n_e \leq \frac{f_p^2}{81} \text{[m}^{-3}\text{]} = 1.23 \times 10^{10} \cdot f^2 \text{[cm}^{-3}\text{]} \]

The electron confinement time is \( \tau_e = \frac{T_e^{3/2}}{n_e} \cdot \text{const} \) (Diffusion by collisions \( \rightarrow \) Spitzer formula)

For power balance follows \( \frac{P_{rf}}{V_p} \approx \frac{n_e kT_e}{\tau_e} \propto \frac{n_e^2 k}{T_e^{1/2}} \) and therewith \( n_e \propto \sqrt{\frac{P_{rf}}{V_p} \cdot T_e^{1/4}} \)

\( V_p \) is the plasma volume, which leads, guided by the field lines, to the extraction area. The extraction area increases faster than the HF power and the electron temperature. The ion current with charge state \( q \) follows

\[ I_q \approx \frac{n_q \cdot q \cdot e \cdot V_p}{\tau_q} \propto n_e \cdot V_p \propto B^2 \cdot V_p \propto \omega_{HF}^2 \]

Here \( \tau_q \) is the ion confinement time in the plasma. Typical values for the electron density are \( n_e \sim 10^{12} \) cm\(^{-3}\). For highly charged ions \( \tau_q \) must be \( \tau_q \geq 0.01s \).
The heating of the plasma electrons with microwaves at EC-resonance becomes optimal, if the electric-field-vector of the microwaves rotates perpendicular to the lines of the static magnetic field, i.e. the electromagnetic field has to be a circular polarized. Hence, during each half-wave the electron gains energy. An electron has to cross the heating zones several times to be heated to high energies. X-Ray spectroscopy shows that electrons can be accelerated up to 1 MeV. The field-strength of the microwaves is only about 100 V/cm, i.e. the electron have then crossed the heating zones many times.

The decoupling of the microwaves into the "multimode"-Plasma-Chamber can be done at several positions, as shown above.
The production of metal-ions is done by evaporation of the metal inside an oven or by sputter targets, which are moved close to the plasma.

The extraction of ions can be both continues or in the so-called "afterglow mode".

In the "afterglow mode" the HF is switched off and thereby the confinement of the ions. After an optimization of the magnetic field configuration it follows a high current of highly charged ions in one pulse.

For that purpose, the confinement has to be considerably good. One can see that the dc current decreases significantly for optimum afterglow mode settings.

The pulse length varies between 0.5 – 5 ms.

**FIGURE 9.13**
Possible sample position for the insertion technique (a) and oven (b).

**FIGURE 9.16**
Tuning of the afterglow: (a) dc, (b) pulsed, (c) afterglow optimized.
Concerning external injection the ions are transported to the plasma via the grounded electrode and decelerated to a few eV during the injection into the plasma, because the plasma chamber is put on high voltage. The ions are only captured if they are decelerated sufficiently due to collisions with plasma-ions.
Typical spectrum:

Metal ion production by evaporation of lead with an oven.

Spectrum for external injection of metal-ions like e.g. In$^{1+}$ or Pb$^{1+}$. 
Development of the ECR technology in 30 years. VENUS is an ECR source of the third generation (high performance device) were the magnetic fields are only produced by super conduction coils. The structure and the data of VENUS are given below. In addition, the scaling-laws, valid for modern ECR sources are given.
Here $M$ is the mass of the ion-species, which is extracted. Generally a gas is injected to produce highly charged ions of the desired isotope. For the production of exotic nuclei an external injection of single charged ions is necessary.

The following magnetic-field relations are valid for high power ECRs (see also 5.2):

\[
\begin{align*}
B_{\text{inj}}/B_{\text{ecr}} & \sim 4, \\
B_{\text{ext}}/B_{\text{ecr}} & \sim 2, \\
B_{\text{min}}/B_{\text{ecr}} & \sim 0.8, \\
B_{\text{rad}}/B_{\text{ecr}} & \geq 2, \\
B_{\text{ext}}/B_{\text{rad}} & \leq 0.9
\end{align*}
\]

Here $B_{\text{inj}}$ ($B_{\text{ext}}$) is the maximum field strength on the injection side (extraction side), $B_{\text{rad}}$ the radial field of the sextupole at the plasma chamber wall and $B_{\text{min}}$ the minimum field strength between the magnetic mirrors.
Typical values:

- Microwave power of 100–500W:
- $^{16}\text{O}^{6+}$- and $^{40}\text{Ar}^{10+}$- ion currents of more than 2µA and up to 10µA for $^{197}\text{Au}^{25+}$
- $^{209}\text{Bi}^{25+}$ and $^{238}\text{U}^{28+}$- ions can be produced

Comparison of different ECR source types:
5.2 High frequency (HF) driven ion sources:

The use of rf-generated plasma dates back to the 1940s. The rf-driven volume sources can be operated with any working gas, because there is no filament that can be damaged. An example is Oxygen, which degenerates the tungsten filaments of the volume sources. The basic principle is shown with a Thonemann-source-type. Typical working pressures are $10^{-2} - 10^{-3}$ mbar.

The rf-power to be applied varies from a few hundred Watt up to several kW. The applied radio-frequency is of the order of 1-100 MHz. There are two ways for the rf-coupling:

- **Capacitive** between two electrodes  
  Typically a setup like a cylindrical capacitor

- **Inductive** via an induction coil.  
  The coil can be put outside the vacuum chamber if the chamber is made out of glass or quartz. Or inside the chamber as spiral shaped antenna.

The advantages of the source:  
Almost no wear parts, better discharge stability, independent of the cathode characteristics. Hence, they can be used as ion thruster in spacecrafts.
FIGURE 7.6
Capacitively coupled rf ion source. Ion source cross section: (1) mounting flange; (2) ion source case; (3) source base of Al₂O₃; (4) plasma chamber walls of stainless steel — rf anode; (5) mounting slabs; (6) ceramic grid holder; (7) screen grid; (8) acceleration grid; (9) electrostatic end confinement made of Al₂O₃; (10) water cooling for the rf cathode; (11) cathode cover made of Al₂O₃; (12) rf cathode; (13) grid polarization; (14) gas inlet.
Plasma generation via rf-incoupling:

\[ E = E_p \sin(\omega t) \]

\[ m_e \frac{dv}{dt} = eE_p \sin(\omega t + \phi) \]

\[ \Rightarrow \quad v = v_0 + \frac{eE_p}{m_e \omega} \left[ \cos \phi - \cos(\omega t + \phi) \right] \]

Without collisions, the electrons do not take energy out of the rf-field!

The phase of the electron movement can be changed by collisions. Therewith electrons can take energy from rf-field. New electrons are generated by ionization processes. If the production rate is bigger than the loss rate, a stable rf-discharge follows.
The circuit, which provides the coupling of the rf is operated in resonance mode.

\[ Z = i\omega L_1 + R_V + \frac{1}{i\omega C} + \frac{1}{i\omega L_2} + \frac{1}{R_L} \]

A change in the plasma parameters leads to a change in \( R_L \).
By inductive coupling, an azimuthal AC-electric field is produced, which generates oscillating electrons inside the gas and therewith transfers enough energy for the generation of a plasma.

With inductively HF-driven multicusp-volume-sources, current densities of about 1A/cm² can be reached.

The achievable current densities depend on the ion mass, especially for very light ions.

**FIGURE 7.5**
Extracted beam current and density as functions of rf power for various inert gas plasmas.
Typical spectra of a multicusp ion source:

\[ \text{H}^+ (\sim 94\%) \]

[Graph showing ion spectra with \( \text{H}^+ \), \( \text{H}_2^+ \), \( \text{H}_3^+ \), \( \text{O}^+ \), \( \text{O}_2^+ \) ions and their corresponding intensities]