RF Ion Sources

W. Kraus

Max-Planck-Institut für Plasmaphysik
EURATOM Association
Boltzmannstr. 2, D-85748 Garching
Outline

• Introduction
• Simple theory
  - Power absorption
  - Skin effect
  - Electron temperature
• Capacitive discharges
• Inductive discharges
  - High power
  - Low pressure
• Design of RF sources for different applications
• Helicon wave sources
RF discharges

**Principle:**

- Acceleration of electrons in an oscillating electric field with amplitudes < source dimensions
- Electrons gain energy, if there is “friction” (i.e. collisions)
- Ionizing collisions
- Equilibrium between ionisation and loss rates

**Frequency range:** 0.1 – 30 MHz

**Power range:** 50 W – 800 kW
Three different ways of RF coupling

Capacitive coupling

$$f = 1 - 30 \text{ MHz}$$
$$P = 0.05 - 0.1 \text{ kW}$$

Inductive coupling

$$f = 0.1 - 13.5 \text{ MHz}$$
$$P = 0.1 - 100 \text{ kW}$$

Wave Coupling (Helicon)

$$f = 2 - 13.5 \text{ MHz}$$
$$P = 0.1 - 1 \text{ kW}$$
Outline

• Introduction

• **Simple theory**
  - Power absorption
  - Skin effect
  - Electron temperature

• Capacitive discharges

• Inductive discharges
  - High power
  - Low pressure

• Design of RF sources for different applications

• Helicon wave sources
Power absorption

Equation of motion of the electrons

\[ m_e \cdot \ddot{x} + \nu_{\text{coll}} \cdot (m_e \cdot \dot{x}) = -e \cdot E_0 \cdot e^{i\nu t} \]

Friction = Collision frequency x momentum

Solution

Current

\[ j_0 = n_e \cdot \frac{e^2 \cdot E_0}{m_e} \cdot \left\{ \frac{\nu}{\nu^2 + \omega^2} + i \cdot \frac{-\omega}{\nu^2 + \omega^2} \right\} \]

Conductivity

\[ \sigma_{\text{HF}} = n_e \cdot \frac{e^2}{m_e} \cdot \left\{ \frac{\nu}{\nu^2 + \omega^2} + i \cdot \frac{-\omega}{\nu^2 + \omega^2} \right\} \]

Absorbed power

\[ P_{\text{abs}} = n_e \cdot \frac{e^2 \cdot E_0^2}{2m_e} \cdot \left( \frac{\nu}{\nu^2 + \omega^2} \right) \]

Collisions necessary \( \nu > 0 \)

\( P_{\text{abs}} \) maximal at \( \nu \sim \omega \)

\( P_{\text{abs}} \) decreases at high frequency
Illustration of the RF absorption

Collisions

No collisions

Many collisions

Micro waves “GHz”

RF MHz-10MHz

“AC” kHz

$P_{\text{abs}} [\text{Watt/m}^3]$
Limitations of the model

- Local $E_{RF}$ field in has to be known
- $E_{RF}$ field constant (not dependent on the plasma parameters)
- Low power, because $B_{RF}$ field not considered (50 - 100 G at 100 kW)
- No Coulomb collisions
- $E_{RF}$ field homogenous (no skin effect)
Skin effect

The e.m wave vary as

\[ \alpha \, e^{i(kx-\omega t)} \]

If the RF frequency is much smaller than the plasma frequency the wave decays exponentially

\[ \omega \ll \omega_p \]

\[ \alpha \, e^{-x/\delta_s -i\omega t} \]

Decay length is the Skin depth

Collisionless

\[ \delta_s = \frac{c}{\omega_p} = \left( \frac{m_e}{e^2 \mu_0 n_e} \right)^{1/2} \]

Typically 0.5 – 2 cm, decreases at high frequency(!) and conductivity \( \sigma \)

Collisional

\[ \delta_s = \left( \frac{2}{\omega \mu_0 \sigma} \right)^{1/2} \]
Electron temperature

Particle balance in uniform low density discharges with Maxwellian electron temperature

\[ n_e \cdot n_0 \cdot \langle \sigma_{ion} \cdot v_e \rangle \approx \frac{n_e \cdot L}{c_s} \]

Ion production by electron–neutral collisions
Wall losses
L = effective plasma size

\( v_e \) and \( c_s \) depend on \( T_e \)

\( \Rightarrow T_e \) is independent of the plasma density \( n_e \) and therefore independent of the input power
Electron temperature distribution

- Depends on the distance to the coil
- Determined by the gas density (pressure)

No Maxwell distribution

At high energy reduced by inelastic collisions
**Energy loss per electron-ion pair created**

Power balance

\[
P_{\text{loss}} = \frac{n_e}{\tau_p} \cdot (m \cdot E_{\text{ion}}) = P_{\text{abs}}
\]

- \(m\) represents energy losses by excitation of vibrational and rotational energy levels, molecular dissociation, energy loss at the wall.

- \(mE_{\text{ion}}\): energy needed for an electron-ion pair
  - Can be measured by the decay time of the plasma
  - Is for molecular gas one order of magnitude higher than the ionisation energy
Outline

• Introduction
• Simple theory
  - Power absorption
  - Skin effect
  - Electron temperature
• Capacitive discharges
• Inductive discharges
  - High power
  - Low pressure
• Design of RF sources for different applications
• Helicon wave sources
Capacitive discharges

“Electron cloud” oscillates between the electrodes
⇒ High RF voltage drop in the cathode sheath

RF frequency $\ll$ ion plasma frequency
⇒ Ions are accelerated in the sheath
⇒ most of the RF power goes for the ion acceleration
⇒ bombardement of the electrodes by energetic ions
   of some keV

⇒ Used for surface treatment in the plasma technology

RF frequency $\gg$ ion plasma frequency
⇒ Ions cannot follow the RF field
⇒ Low ion energy of some 10 eV
   Transition region 5 – 10 MHz

$$\omega_{pi} = \sqrt{\frac{Ze^2 \cdot n_e}{\varepsilon_0 \cdot m_i}}$$
Schematic of a CCNP Processing Chamber

F. F. Chen AVS, 2003
Outline

• Introduction
• Simple theory
  - Power absorption
  - Skin effect
  - Electron temperature
• Capacitive discharges
• **Inductive discharges**
  - High power
  - Low pressure
• Design of RF sources for different applications
• Helicon wave sources
Inductive discharges

1. RF current in the coil $I_{RF}$ produces an axial magnetic field

2. Magnetic field induces an electric field

3. Acceleration of the electrons and ionizing collisions with the neutrals

4. Plasma compression by Lorentz force
   => reduces skin effect
   => better coupling at high power
RF fields

- Mag. induction (short coil)
- E field (vacuum)
- E field (with plasma, skin effect)

At high power decrease enhanced by plasma compression
Limits of the classical theory in powerful inductive discharges

- Collisions needed for the power absorption
- Electron temperature not dependent on the plasma density or power
- Skin depth decreases at high conductivity
  i.e. increasing plasma density
  => saturation of the power coupling,
  reduced energy transfer to the center of the source
- Collisionless power absorption possible
  ⇒ Stochastic heating
- At high power induced E-field sufficient for ionisation
  \( T_e \) increases at high power
  due to neutral depletion
- No saturation observed
  due to plasma compression
Low pressure: Stochastic heating

Power absorption without collisions by
- Inhomogenous RF field (skin depth)
- Static magnetic fields

Reduction of the Gyration radius of the electrons in the stronger B field
⇒ Reflection
⇒ “anomalous collision frequency”

Enables operation with low gas density

Example
Neutral loop discharge
High Power: Neutral depletion

Most Ion Source modeling assumes:
- Neutral gas is at room temperature
- Neutral gas is uniformly distributed
- Degree of ionization is small

Theory: Neutral gas represents a constant background
Hold only when \(n_e, T_e\) are low and \(T_e \gg T_i\)

Reality: After the discharge ignites temperature and density change
=> RF coupling at high powers, i.e. low driver pressure difficult

Measured pressure drop during the discharge
The neutral pressure is depleted due to the pressure balance when the plasma pressure (electron pressure) becomes comparable to the neutral pressure.

\[ n_{n,w} k T_w = n_n k T_n + n_e k T_e + n_i k T_i \]
High power: Plasma compression by $E \times B$ forces

**Low power (0.1 kW)**
- Plasma fixed
- $I_{\text{coil}}$
- $j_{\theta} = \sigma_{HF} E_{\theta}$
- $\sigma_{HF} \propto \frac{n_r}{\nu + i\omega}$
- Small $j$ and $B$

**Medium power (some kW)**
- Ions fixed (< mm)
- $qE_r$
- $E_r > E_{\theta}$
- $\Phi(r)$
- Radial movement of the electrons
- $\sim jxB$
- some $\lambda_{\text{Debye}}$

**High Power (10 - 100 kW)**
- Radial movement of Ions and electrons
- $\sim jxB$
- High $j$ and $B$, low frequency
Outline

• Introduction
• Simple theory
  - Power absorption
  - Skin effect
  - Electron temperature
• Capacitive discharges
• Inductive discharges
  - High power
  - Low pressure
• Design of RF sources for different applications
• Helicon wave sources
Main ICP topologies in industrial applications

- **Cylindric Insulator**
  - 0.2 - 0.6 cm
  - Poor coupling

- **Plate Insulator**
  - 1-2 cm
  - Poor coupling

\[ B_{RF} \text{ field distribution} \]
ICP based plasma processing tool
ICP Enhanced with Ferrite Core

Ferrite cores for

- Concentration of the RF field => better coupling to the plasma
- RF shielding => support plate => thin insulator => better coupling to the plasma

V. Godyak, PSST 20, 025004, 2011
Internal antenna

- Better coupling to the plasma
- Lower wall losses due to larger area of magnetic cusps

Insulation

- Porcelain coating
- Quartz tubing

Problem: Lifetime of the insulation

- RF breakdowns,
- Sputtering
- Difficult to protect it by a Faraday shield
Design of high power ICPs

**Insulator**

- Quartz or Pyrex (low expansion coeff. but chemically active)
- $\text{Al}_2\text{O}_3$ (chemically stable, high temperature)
- AIN (high thermal conductivity)

**Magnetic cusp field**

- Improves the plasma confinement
- Reduces plasma losses

**Faraday shield**

- Shields capacitive coupling
- protects insulator from chemical and physical sputtering

**Ferrites**

- Shields RF fields
- Improves the coupling to the plasma
Internal Faraday shield for high power ICPs

B_{RF} field penetrates through the slits even when they are Z-shaped

- No power load on the insulator
- H_{a} radiation in the driver not changed

⇒ No additional power losses by eddy currents
Ignition of the plasma

Condition for the ignition

*Ionisation rate > rate of wall losses*

More difficult without capacitice coupling, i.e. with Faraday shield

**Additional electron source necessary**

- Electron gun
- Filament and/or pressure pulse
Matching circuit

RF coil and plasma are a transformer
Transformation of the plasma impedance depends on coil inductance

Matching to 50 Ω by a parallel and a (variable) series capacity or by frequency matching

Frequency mostly 13.56 MHz
Low frequency is advantageous
- larger skin depth $\propto \sqrt{\omega L}$
  => lower ohmic losses
- lower coil voltage
  => less capacitive coupling, less breakdowns

$Z_1 = j\omega(L_1 - \frac{(\omega M)^2 L_p}{R_p^2 + \omega^2 L_p^2}) + R_p \frac{(\omega M)^2}{R_p^2 + \omega^2 L_p^2}$

$M = k\sqrt{L_1 L_p}$
= mutual inductance, k = coupling
RF sources for accelerators

Up to 100 kW at 2 MHz in small volumes (L ~10 cm, Ø~ 5 cm)

Pulse duration 0.5 ms with a repetition rate of 4 - 60 Hz

40 - 80 mA H⁺ current produced by surface conversion on Caesium surfaces

First design by LBL (Berkeley, USA)

RF sources for accelerators: present design

Ion source of the spallations neutron source
(ORNL Oakridge National Laboratory)

100kW/2MHz RF source of the LINAC4 accelerator (CERN)
Ion thrusters for spacecraft propulsion

The Tsiolkovsky rocket equation:

\[ v_e = v_T \ln \frac{m_0}{m_e} \]

Maximum speed = exhaust velocity x ln(Initial mass/final mass)

<table>
<thead>
<tr>
<th>Chemical thrusters</th>
<th>small</th>
<th>large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical thrusters</td>
<td>up to 25 x larger</td>
<td>large</td>
</tr>
</tbody>
</table>

- Small thrust (0.1 - 1 N) but
- Very reliable
- High propellant capacity
- Propulsion energy provided by an electric source
- Exact control of the thrust
  => used for
  space missions, space probes
  orbit control of satellites
RF ion thrusters

RIT 10
Giessen university

Propellant: Xenon
(high mass => high momentum => high thrust)
10 cm diameter,
Thrust: 0.01 – 1 N

Acceleration voltage: ca 2 kV
Power supply: solar
4 MHz, few 100 W,
RF ion sources for the Neutral Beam Injection systems of Fusion Reactors

<table>
<thead>
<tr>
<th>Positive H/D ions</th>
<th>Negative H/D ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASDEX-Upgrade, 1997</td>
<td>ITER, 2015</td>
</tr>
<tr>
<td>100 kW / 1MHz,</td>
<td>800 kW / 1MHz,</td>
</tr>
<tr>
<td>32 x 59 cm²</td>
<td>8 “drivers”,</td>
</tr>
<tr>
<td></td>
<td>190 x 90 cm²</td>
</tr>
</tbody>
</table>
Outline

• Introduction
• Simple theory
  - Power absorption
  - Skin effect
  - Electron temperature
• Capacitive discharges
• Inductive discharges
  - High power
  - Low pressure
• Design of RF sources for different applications
• Helicon wave sources
RF antenna launches a wave, the **helicon wave**, that propagates along an static B-field with a phase velocity comparable of a 50 – 200 eV electron

- Very efficient ionisation
- Plasma density one order of magnitude higher than in ICPs

Helicon waves are **whistler waves** confined to a cylinder

RH polarized e. m. waves propagating along B₀, wave vector k at an angle Φ to B₀

Dispersion relation of whistler waves

\[
\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2} \frac{1}{1 - \frac{\omega_c}{\omega} \cos \phi} \quad \omega_c, \omega_p >> \omega
\]

\[
k^2 = k_z^2 + k_\perp^2
\]
Helicon dispersion relation

\[ k = \frac{\omega \Theta n_e \mu_0}{k_z B} \]

At fixed \( \omega \), radius of the source (\( \Rightarrow k_z \)), wavelength \( 2\pi/k \)

\( \Rightarrow \) Density \( n_e \) proportional to the magnetic field

Boundary conditions in a cylindrical discharge for the wave which varies like

\[ \vec{B} = B(r)e^{i(m\phi + k_z z - \omega t)} \]

fulfilled by **azimuthal wave numbers** \( m \)
Helicon modes in a cylindrical discharge

$m = 0$: changes from electrostatic (radial E) to electromagnetic (azimuthal E-lines)

$m = 1$: rotating E-field pattern, mostly right hand polarized observed ($m=+1$)
Helicon antennas and energy transfer

For $m = 0$: Ring antennas

For $m = 1$

- Half helical
- Nagoya Type III
- Double saddle (Boswell)

Energy transfer mechanism is not yet clear:

**Landau damping**: electrons with phase velocity below wave velocity gain energy (surfing boat)

Not consistent with EEDF measurements!

Alternative explanation: electron cyclotron waves **Trivelpiece-Gould modes**
Applications

\[ M = 0 \text{ or } 1, \quad B = 100 - 400 \text{G} \]

**Plasma etching**

MORI source

**Accelerator (VENETA)**

\[ m = 0 \text{ with spiral antenna} \]

(Windisch)

Multiple helicon source

(Chen) for uniform plasmas
Conclusion

Chen & Chang (“Principles of plasma processing”)

“In (source) plasma physics classical treatments like the above are doomed to failure, since plasmas are tricky and more often than not are found experimentally to disobey the simple laws of electromagnetics.”