Plasma production by helicon and slow waves in HF/VHF bands of rf

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Abstract

Plasma production by helicon and slow waves in HF ($f = 13.56$ MHz) and VHF ($f = 50$ and $144$ MHz) bands of rf is studied. The experiments are conducted at rf power $P_{rf} < 4.5$ kW, Ar gas pressure $P = 3.5$ mTorr, and a static magnetic field of $B_0 = 1.0$ kG. The rf is applied to an antenna surrounding a Pyrex discharge tube (length = 90 cm, diameter = 5 cm) which is mounted on one end of a stainless steel vacuum chamber (length = 150 cm, diameter = 36 cm). A capacitive antenna, in which only rf voltage is applied, and an inductive antenna are used to excite the $m = 0$ mode of helicon wave and slow wave. By increasing $P_{rf}$ from $\approx 1$ W to $\approx 1$ kW, transition of discharge mode, slow-wave, capacitively-coupled (E), and helicon-wave discharges, are observed. Radial and axial profiles of oscillating magnetic field and potential are measured and compared with analytic and two-dimensional wave code calculations.
Experimental Setup

Magnetic coils: 150 cm

Antenna: VHF: f = 50, 144 MHz

Langmuir probe

Magnetic probe

Capacitive probe

Matching circuit

RF generator

HF: f = 13.56 MHz

End plate

Vacuum pump

Pyrex tube (Radius = 2.5 cm)

B₀ = 1.0 kG, Ar 3.5 mTorr

m = 0 mode
Two antenna configurations

Inductively-coupled antenna (Loop antenna)

RF current and voltage are applied

50mm

Capacitively-coupled antenna (Capacitive antenna)

Only RF voltage is applied

50mm

\[ V_{\text{rf}} \]
$n_p$ and $r_p$ at the Low-density mode are larger for higher $f$ both in HF and VHF bands
RF voltage plays an important role in plasma production at the LD mode both in HF and VHF bands.
$n_p$ peaks at $r = 0$ both at the LD and HD Modes for 144 MHz.
Radial position of $n_p$ peak at the LD Mode varies with $P_{rf}$ for 13.56 MHz

Loop Antenna, 13.56 MHz
Radial position of $n_p$ peak at the LD Mode varies with $P_{rf}$ for 50 MHz
Calculated dispersion relation of cold electromagnetic waves for 144 MHz

144 MHz, Ar, B₀ = 1 kG, Uniform nₚ

Slow-wave with λᵣ ≈ 20 - 50 cm, k⊥ = 1.53 cm⁻¹
Can be excited at nₚ ≈ 10¹⁰ - 10¹² cm⁻³
nₚ peaks at r = 0

Fast-wave with λᵣ ≈ 6 - 10 cm, k⊥ = 1.53 cm⁻¹
Can be excited at nₚ ≈ (0.5 - 1)×10¹³ cm⁻³
nₚ peaks at r = 0

k⊥ = 3.83 / a = 1.53 cm⁻¹ (1st radial mode)
Calculated dispersion relation of cold electromagnetic waves for 50 MHz

50 MHz, Ar, \( B_0 = 1 \) kG, Uniform \( n_p \)

- **Slow-wave** with \( \lambda_z < 100 \) cm, 1st or 2nd radial mode can be excited at \( n_p < 2 \times 10^{11} \) cm\(^{-3} \)
  - \( n_p \) peaks at \( r = 0 \)

- **Fast-wave** with \( \lambda_z \approx 20 \) cm, 1st radial mode can be excited at \( n_p \approx (5-10) \times 10^{12} \) cm\(^{-3} \)
  - \( n_p \) peaks at \( r = 0 \)

E-discharge: \( n_p \) peaks at \( r = 2.5 \) cm

\[
\begin{align*}
\lambda_z &= 200 \text{ cm} & 100 \text{ cm} & 20 \text{ cm} & 10 \text{ cm} \\
10^1 & 10^2 & 10^3 & 10^4 \\
N_\perp & 5 \times 10^9 \text{cm}^{-3} & 5 \times 10^{10} \text{cm}^{-3} & 5 \times 10^{11} \text{cm}^{-3} & 1 \times 10^{12} \text{cm}^{-3} \\
k_\perp &= 1.53 \text{ cm}^{-1} & 2.81 \text{ cm}^{-1} \\
n_p \text{ peaks at } r = 0 \\
\end{align*}
\]

\[
\begin{align*}
\lambda_z (\text{cm}) &
100 \\
10^0 & 10^1 & 10^2 & 10^3 \\
n_p (\text{cm}^{-3}) & 10^9 & 10^{10} & 10^{11} & 10^{12} & 10^{13} \\
1\text{st radial mode (}k_\perp = 1.53 \text{ cm}^{-1}) & & & & & \\
2\text{nd radial mode (}k_\perp = 2.81 \text{ cm}^{-1}) & & & & & \\
\end{align*}
\]
Electromagnetic wave is excited at the LD mode when peaked $n_p$ profile is observed for 50 MHz.

Capacitive Antenna, 50 MHz, $P_{rf} = 0.04$ W

$Z = 40$ cm

$B_z$ is measured using magnetic probe at $r = 0$

![Graph showing $n_p$ vs radial position and $B_z$ vs axial position.](image)
Measured $\lambda_z$ of electromagnetic wave agrees with the calculated dispersion relation of Slow-wave.

Loop & Capacitive Antennas, 50 MHz, Ar, $B_0 = 1 \text{kG}$

$\lambda_z$ of electromagnetic wave is measured using magnetic probe at $r = 0$. 

### Graph

- **1st radial mode**
- **2nd radial mode**

**Axes:**
- **Axial wavelength $\lambda_z$ (cm)**
- **$n_p$ (cm$^{-3}$)**

**Legend:**
- **Measured**
- **Calculated**
Calculated dispersion relation of cold electrostatic (ES) and electromagnetic (EM) waves for 50 MHz

Dispersion relation of cold ES wave

\[ P N_z^2 + S N_\perp^2 = 0 \]

Dispersion relation of cold ES wave is nearly identical to that of slow wave.
Electrostatic wave is excited at the LD mode when peaked \( n_p \) profile is observed for 50 MHz.

Capacitive Antenna, 50 MHz, \( P_{rf} = 0.066 \) W

\[ z = 40 \text{ cm} \]

\[ V_{ES} \text{ is measured using capacitive probe at } r = 0 \]
Electrostatic wave with 1st radial mode is excited at the LD mode ($n_p = 7.4 \times 10^{10} \text{ cm}^{-3}$).

Capacitive Antenna

50 MHz, $P_{rf} = 2.0$ W

$n_p = 7.4 \times 10^{10} \text{ cm}^{-3}$

Measured using capacitive probe at $z = 123$ cm
Measured $\lambda_z$ of electrostatic wave agrees with the calculated dispersion relation of cold ES wave

Capacitive Antenna, 50 MHz, Ar, $B_0 = 1$ kG

$\lambda_z$ of electrostatic wave is measured using capacitive probe at $r = 0$.

Dispersion relation of cold ES wave

$\nabla \cdot \tilde{\varepsilon} \cdot \nabla \phi = 0$

for parabolic $n_p(r)$
2-D wave code calculation:
Electrostatic component of $E_z$ is larger than electromagnetic component at the LD mode.

\[ E_Z = E_Z^{ES} + E_Z^{EM} = -i k_Z \phi + i \omega A_Z \]

50 MHz, Ar, $B_0 = 1$ kG
Analytic model for ES and EM components of $E_z$

Oblique propagation of EM wave

\[
\begin{align*}
E_x &\propto (N^2 - S)(N^2 \sin^2 \theta - P) \\
E_y &\propto iD(N^2 \sin^2 \theta - P) \\
E_z &\propto (N^2 - S)(N^2 \sin \theta \cos \theta)
\end{align*}
\]

In x-z plane

\[
\frac{E_{ES}^E}{E_{EM}^E} = \frac{E_z \cos \theta + E_x \sin \theta}{-E_z \sin \theta + E_x \cos \theta}
\]

In z direction

\[
\frac{E_{z}^{ES}}{E_{z}^{EM}} = \frac{E_{z}^{ES} \cos \theta}{E_{z}^{EM} \sin \theta}
\]

\[
\tan \theta = \frac{N_{\perp}}{N_z}
\]
Analytic model (oblique propagation of EM wave) agrees well with 2-D wave code calculation for ES and EM components of $E_z$.

50 MHz, Ar, $B_0 = 1$ kG, $k_\perp = 3.83/a = 1.53$ cm$^{-1}$

$E_x$, $E_y$, $E_z$ (Arb. Units)

$E_y$ is electromagnetic

$N_\perp > N_z$: nearly perpendicular propagation
Conclusion

1. High-density ($n_p \sim 10^{13} \text{ cm}^{-3}$) Ar plasmas are produced using HF (13.56 MHz) and VHF (50, 144 MHz) bands of RF in helicon-wave discharges.

2. At the HD mode, $m = 0$ helicon wave (Fast-wave) is excited.

3. At the LD mode, RF voltage plays an important role in the plasma production.

4. For 144 MHz, $n_p$ peaks at
   \begin{align*}
   r &= 0 \text{ when } P_{rf} \sim 0.5 - 300 \text{ W } (n_p \sim 10^{10} - 10^{12} \text{ cm}^{-3}) \quad \text{Slow-wave} \\
   r &= 0 \text{ when } P_{rf} > 300 \text{ W } (n_p \sim 5 \times 10^{11} \text{ cm}^{-3}) \quad \text{Fast-wave (Helicon wave)}
   \end{align*}

5. For 50 MHz (and 13.56 MHz), $n_p$ peaks at
   \begin{align*}
   r &= 0 \text{ when } P_{rf} < 10 \text{ W } (n_p \sim 2 \times 10^{11} \text{ cm}^{-3}) \quad \text{Slow-wave, ES wave} \\
   r &= 2.5 \text{ cm when } P_{rf} = 60 - 800 \text{ W } (n_p \sim 5 \times 10^{11} - 10^{12} \text{ cm}^{-3}) \quad \text{E-discharge} \\
   r &= 0 \text{ when } P_{rf} > 1000 \text{ W } (n_p \sim 10^{13} \text{ cm}^{-3}) \quad \text{Fast-wave (Helicon wave)}
   \end{align*}

6. Large $E_z^{\text{ES}}/E_z^{\text{EM}}$ ratio obtained in 2D wave calculation is explained by nearly perpendicular propagation of EM wave.