Particle and power balance in a helicon operating with light gases [Experiment]


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Neutral fluid dynamics

Flow is measured by pitot tube located inside quartz tube. Before the plasma turns on, the flow is Knudsen flow into a vacuum giving a linear decrease of density to the end of quartz tube.

![Graph showing pressure vs. distance](image)

**Pressure [mtorr]**

**Distance [cm]**
Create plasma with RF power

- RF power up to 3 kW
- RF frequency ~ 25 MHz
- Gases used: H₂, D₂, He
- Degree of ionization is low, n_N > n_e.
Observations, pressure measurements with plasma

Observations: Pressure goes up

Presence of plasma is drag on neutral fluid

Cannot be explained by hot walls
**Ion dynamics**

- Electrons are heated by RF power. The electrons move along magnetic field, set up an ambipolar potential that accelerates ions with a maximum velocity of sound speed.

![Diagram showing pressure measurement, gas injection, and antenna with dimensions given in meters: 0.08m, 0.16m, 0.73m, and 1/4" OD S.S. 0.010" wall tube 12" long welded into a flange near the pressure measurement. quartz tube and Antenna are also labeled.]
Plasma flow from fluid model

\[ M^2 = \frac{2}{\gamma} \left[ \frac{P_{\text{upstream}}}{P_{\text{downstream}}} - 1 \right] \]
What can we conclude from pressure measurements?

- Collisions are important in explaining the pressure increase observed when plasma is turned on.
- Collisions with wall quickly develop an isotropic population.
- There is a plasma flow of order Mach 1 inside quartz tube.
Observations-thermocouples

Hotest region on quartz tube is downstream from antenna.
Heating is primarily from radiation-mostly resonance lines.

Conclusion: Region of highest density or temperature is downstream from helicon antenna, probably more than a half wavelength. Limited spatial resolution does not allow a more precise statement. Radiated power loss can be measured with same technique.
Particle flux

• Input particle flux is nearly same for all gases- about $10^{20}$ atoms/s
• Flow out as plasma ions is most efficient for helium

$$\varepsilon \equiv \frac{\text{Flux of plasma ions out}}{\text{atoms in}} \approx$$
Power flow-Diagnostics

• Electron density
  – Langmuir probe
    • Profile at one location
  – Interferometer

Estimate of electron density at other locations.
Power flow diagnostics

Electron temperature
- Langmuir probe
  - Limited value at high power
  - Gives profile information
- Spectroscopic diagnostics
Power flow diagnostics

- Plasma flow
  - Mach probe
  - Retarding potential analyzer [U of H]
  - Retarding potential analyzer [Rice]

- Generally observe a flow that is sound speed times a factor of order 1-2 depending on location of probe.

- Charge exchange collisions will limit ion flow even after leaving quartz tube.
Power flow diagnostics

• Radiation losses
  – Bolometer + visible
  – Thermocouples on quartz tube

• Circuit losses
Power balance-3 kW input power

Typical case

• No saturation of electron density with power has been observed.

• Losses
  – 700 W in Ohmic losses in antenna
  – Power into thermal and flow energy of plasma is about 200 W.
  – For H\textsubscript{2} and D\textsubscript{2}, and helium, radiated power is largest loss.
  – Little power flow to end plate where gas is injected.
  – Estimates of power loss from perpendicular transport to walls are small
Operating characteristics—Power scans in $D_2$ and He

Density and radiated power in deuterium. Flow rate: 100 sccm, $B = 0.058$ T.

Observed density increased with RF power. No saturation with power was noted.

Density and radiated power in Helium. Flow rate: 250 sccm, $B = 0.15$ T.
Operating characteristics - Neutral gas scan

Density and radiated power as a function of Neutral gas flow rate. Input power 3 kW and \( B = 0.58 \) T.
Operating characteristics—
magnetic field scan

Density and radiated power vs. magnetic field under the helicon antenna. Power = 3 kW and flow rate = 100 sccm.
We are varying only the field under magnet, not mirror field.
Operating conditions for highest density

<table>
<thead>
<tr>
<th>Gas</th>
<th>Flow rate</th>
<th>Helicon field</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>130</td>
<td>0.04</td>
</tr>
<tr>
<td>D₂</td>
<td>100</td>
<td>0.07</td>
</tr>
<tr>
<td>He</td>
<td>250</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Note that for “best” plasma conditions, the magnetic field scales with mass.
Summary

• Particles
  – Collisions are important in ion and neutral flow
  – Collisions with wall quickly make flow isotropic

• Power balance
  – Largest power loss is radiation

• Operating conditions
  – For best conditions, the magnetic field scales with mass.