Electron density and temperature in a helicon source by particle and energy balance

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A schematic of the plasma-source.
Density Increase with Magnetic Field Increase

- The reason: better confinement. This implies an anomalously high electron collisionality – 25 times the electron – neutral collision frequency.
- A more peaked radial profile for a higher magnetic field – support for this claim.
- Second possible reason: Higher magnetic field – better wave–plasma coupling. A larger fraction of the wave power is absorbed inside the helicon source, rather than in the vacuum vessel.
Maximal Measured Plasma Density Smaller than in Theory

• Part of the power is not absorbed inside the helicon source.

• Neutral depletion – the larger deviation for a higher power supports this claim.

• Note: taking nonlinear ion mobility due to ion-neutral collisions into account increases the deviation.
Prf=500W, B=42G

Ion current (mA)

Length (mm)

Radius (mm)

-0.2-0.3
-0.1-0.2
0-0.1

Ion current (mA)
Prf=500W, B=83G

Ion current (mA)

Length (mm)

Radius (mm)

0.1-0.2
0-0.1
Prf=500W, B=370G

Ion current (mA)

Length (mm)

Radius (mm)

-0.1-0.2
-0.2-0.3
-0.3-0.4
-0.4-0.5
Prf=500W, B=657G

Ion current (mA)

Length (mm)

Radius (mm)
Prf=300W, Ar=7.1 sccm, r=0. R

Ion density 1/cm^3 vs. Magnetic field (G)

Lines and markers for Z-340, Z-240, Z-120, Z-420, and Z-60 are shown.
Prf=500W, Ar=7.1 sccm, r=0. R

Ion density (1/cm^3) as a function of magnetic field (G) for different Z values:

- Z-340
- Z-240
- Z-120
- Z-420
- Z-60

Graph shows the trend of ion density with varying magnetic field strengths for each specified Z value.
Ar=7.1sccm, Po=2.5mTorr

Ion numbers vs Magnetic field (G)

- 500W
- 300W
- 200W
Prf=200W, Ar=7.1sccm, r=0R

Ion density \(1/\text{cm}^3\) for different values of Z (mm):

- 42G
- 83G
- 370G
- 657G
Prf=300W, Ar=7.1sccm, r=0R

Ion density \(1/\text{cm}^3\)

- 42G
- 83G
- 370G
- 657G

Z (mm)
Prf=500W, Ar=7.1 sccm, r=0 R

Ion density $1/\text{cm}^3$
Prf=500W, Ar=7.1 sccm, Z=-240mm

Ion density 1/cm³

r/R

42G
83G
370G
657G
Prf=500W, Ar=7.1sccm, B=657G, Z=-240mm

![Graph showing ion density variation with r/R for different power levels (500W, 300W, 200W).]
Radial Profiles, $B=0.13T$, $T_e=2.66\, \text{eV}$

- **density**
- $M_r$
- $M_\theta$
Dependence of the Axial Mobility on the Knudsen Number
The momentum equation:

\[
(M_z^2 - 1) \frac{\partial}{\partial \zeta} M_z = -\frac{1}{\varepsilon} \left[ \frac{1}{b} + \frac{1}{b \alpha} M_z^2 + M_z^3 \right],
\]

where

\[
M_z = \frac{v_z}{c_s}; \quad \zeta = \frac{z}{L/2};
\]

\[
\varepsilon = \frac{2 \lambda_i}{\pi L} = \frac{2}{\pi \sigma N L} \left( \lambda_i = \frac{1}{\sigma N} \right);
\]

\[
b = \frac{\pi \sigma c_s}{2 \beta}; \quad \alpha = \frac{1}{1 + \frac{v_T}{c_s} b} = \frac{1}{1 + \frac{\sigma v_T}{\beta}}.
\]

The continuity equation:

\[
\frac{\partial}{\partial \zeta} (n M_z) = \frac{1}{\varepsilon b} n
\]

Boundary conditions:

\[
M_z (\zeta = 0) = 0; \quad M_z (\zeta = 1) = 1
\]
The solution of the momentum equation is
\[ \sum_{j=1}^{3} d_j \left[ M_j M_z + \frac{1}{2} M_z^2 + (M_j^2 - 1) \ln \left( 1 - \frac{M_z}{M_j} \right) \right] = -\frac{\zeta}{\varepsilon}. \]

\( M_j \) are the solutions of
\[ \frac{1}{b} + \frac{1}{b\alpha} M_z^2 + M_z^3 = 0 \]

\[ d_1 \equiv \left( -M_1 M_2 + M_2 M_3 - M_1 M_3 + M_1^2 \right)^{-1}, \]
\[ d_2 \equiv \left( -M_1 M_2 + M_1 M_3 - M_2 M_3 + M_2^2 \right)^{-1}, \]
\[ d_3 \equiv \left( M_1 M_2 - M_1 M_3 - M_2 M_3 + M_3^2 \right)^{-1}, \]

Substituting \( \zeta = 1 = M_z \) yields a relation between \( \varepsilon, b, \) and \( \alpha \rightarrow T \)
\[ \eta_7 = \frac{n(M_z = 1)}{n_0}, \]
\[ \frac{n}{n_0} = \frac{\left( 1 - \frac{M_z}{M_1} \right)^{(M_1^2 - 1) M_2 M_3 d_1}}{\left( 1 - \frac{M_z}{M_2} \right)^{(M_2^2 - 1) M_1 M_3 d_2}} \frac{\left( 1 - \frac{M_z}{M_3} \right)^{(M_3^2 - 1) M_1 M_2 d_3}}{\left( 1 - \frac{M_z}{M_1} \right)^{(M_1^2 - 1) M_2 M_3 d_1}} \frac{\left( 1 - \frac{M_z}{M_2} \right)^{(M_2^2 - 1) M_1 M_3 d_2}}{\left( 1 - \frac{M_z}{M_3} \right)^{(M_3^2 - 1) M_1 M_2 d_3}} \]
Density Jumps?

- At certain locations the density increases sharply with the magnetic field.
- Inspection of the density profile shows that the sharp increase is a result of an increase of the volume occupied by the plasma.
- The total number of particles increases smoothly with the increase of the magnetic field.
Seven Cases

1. Linear diffusion–zero density at the boundary.
2. Linear diffusion–sonic velocity at the boundary.
3. Linear mobility–ion inertia is retained.
4. Nonlinear mobility–zero density at the boundary (Godyak).
5. Nonlinear mobility–sonic velocity at the boundary.
6. Nonlinear mobility-ion inertia is retained.
7. Full equation.