PERMANENT-MAGNET HELICON SOURCES FOR ETCHING, COATING, AND THRUST

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Low Temperature Plasma Teleseminar, June 14, 2013; originally prepared for (but not given at):
2013 Workshop on Radiofrequency Discharges, La Badine, La Presqu’ile de Giens, France, 29-31 May 2013
Helicons are RF plasmas in a magnetic field

Density increase over ICP

<table>
<thead>
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Helicon sources usually use heavy magnets

The MØRI source of Plasma Materials Technologies, Inc.
Size of the MØRI source
The source has been simplified to this

This uses a commercially available 2 x 4 x 0.5 inch NeFeB magnet

The discharge is 5 cm high and 5 cm in diameter
How did we get here?

First, the HELIC code of Arnush

Examples of HELIC results: $P_r, P_z$
Most important, RnB: power deposition

![Graph showing power deposition with B (G) and n (cm⁻³) on the axes. The graph is labeled with 27 MHz and H = 1.5 cm. Different lines represent varying B (G) values: 200, 150, 100, and 50.](image-url)
RnB results organized in matrices

Matrix A: B-field

Matrix C: pressure

Similar matrices for tube size determined the tube design.

After that, there are matrices for the experimental results.
Optimized discharge tube: 5 x 5 cm

1. Diameter: 2 inches
2. Height: 2 inches
3. Aluminum top
4. Material: quartz
5. “Skirt” to prevent eddy currents canceling the antenna current

The antenna is a simple loop, 3 turns for 13 MHz, 1 turn for 27 MHz. The antenna must be as close to the exit aperture as possible.

Antenna: 1/8” diam tube, water-cooled
Design of matching circuit (1)

N loads
R, L
R, L
R, L

Z2 - short cables
Z1 - long cable

Distributor

Matching ckt. (standard)
C2
C1

PS

Matching ckt. (alternate)
C2
C1

50Ω
Design of 50Ω matching circuit (2)

Let the load be \( R_L + jX_L \):

**Standard circuit:**

\[
C_1 = \left[ 1 - (1 - 2R)^2 \right]^{1/2} / 2R \\
C_2 = \left[ X - (1 - R)/C_1 \right]^{-1}
\]

**Alternate circuit:**

\[
C_1 = R/B, \quad C_2 = (X - B)/T^2 \\
T^2 \equiv R^2 + X^2 \\
B^2 \equiv R(T^2 - R)
\]

R and X have first to be transformed by cable length

\[
R = R_L / D, \quad D \equiv (\cos kz - X_L \sin kz)^2 + R_L^2 \sin^2 kz \\
X = \frac{\left[ 1 - \left( R_L^2 + X_L^2 \right) \right] \sin kz \cos kz + X_L (\cos^2 kz - \sin^2 kz)}{D}
\]

\[
k = \omega R_0 C, \quad R_0 = 50\Omega
\]
Forbidden regions of L, R, and Z (N = 8)
Instead, we can use annular PMs

PM \equiv \text{Permanent magnet}

NdFeB ring magnet
3” ID, 5” OD, 1” high

Stagnation point
The far-field is fairly uniform

Put plasma here

or here, to adjust B-field
Experimental chamber

The magnet height is set for optimum B-field

Langmuir probes at three ports
Optimization of the B-field

Peak density in Port 2 vs. B and Prf @ 27 MHz

30-60 G is best
Typical scan of “Low-field peak”
Density of ejected plasma

\[
\begin{array}{c|c|c|c|c|c|c|c|c}
\text{r (cm)} & -25 & -20 & -15 & -10 & -5 & 0 & 5 & 10 & 15 & 20 & 25 \\
\hline
n (10^{11}/\text{cm}^3) & & & & & 2.0 & 2.5 & 3.0 & 3.5 & 4.0 & 4.5 & \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c|c|c|c|c|c}
\text{r (cm)} & -20 & -10 & 0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 \\
\hline
n (10^{11} \text{cm}^{-3}) & 6.8 & 16.9 & 27.2 & 38 & 46 & 62 & 69 & 76 & 83 & 90 & 97 \\
\end{array}
\]

62 G, 400W

Port 1
Port 2
Port 3
To Turbo Pump
Gate Valve
WALL MAGNETS
PUMP BAFFLE AND GROUND PLANE

19 cm
Vertical probe for inside plasma

LANGMUIR PROBE

PERMANENT MAGNET

HEIGHT ADJUSTMENT

GAS FEED

UCLA PERMANENT MAGNET GAS FEED HEIGHT ADJUSTMENT LANGMUIR PROBE
Axial density profile inside the tube

Density inside the tube is low (<1013 cm$^{-3}$) because plasma is efficiently ejected.
Downstream density: \(6 \times 10^{11} \text{ cm}^{-3}\)

![Graph showing density increase over ICP](image)

- **Helicon**
- **ICP**

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Port 2 density is higher at 13 MHz

This was a surprise and is contrary to theory.
Cause and location of the “double layer”


\[ n_e = n_0 e^{-\eta}, \quad \text{where} \quad \eta = -eV/KT_e \]

\[ v_{is} = c_s = (KT_e / M)^{1/2} \quad \therefore W_{is} = \frac{1}{2} M v_{is}^2 = \frac{1}{2} K T_e \]

\[ \therefore \eta_s = \frac{1}{2}, \quad n_s / n_0 = e^{-1/2} \]

\[ B / B_0 = n / n_0 = (r_0 / r)^2 \]

\[ r / r_0 = e^{1/4} = 1.28 \]

Maxwellian electrons

Bohm sheath criterion

A sheath must form here

Single layer forms where \( r \) has increased 28%
Where a diffuse “double layer” would occur

Approx. location of "double layer"
Ion energy distribution by Impedans SEMion
IEDFs vs. $P_{rf}$ in Port 1
Conditions at Port 1 \((r = 0)\) at 400W

\[
\begin{array}{c|c|c|c}
T_e & eV_s & iV_s & n_{11} \\
\hline
2.14 & 15.9 & 27 & 4.21 \\
\end{array}
\]

Plasma potential
Mach probe (in Port 2)

Hutchinson:

\[
\frac{v_f}{c_s} = \frac{1}{K} \ln \left( \frac{I_{up}}{I_{down}} \right) = 0.75 \ln \left( \frac{I_{up}}{I_{down}} \right)
\]

\(K = 1.34\)

Result:

\[
\frac{v_f}{c_s} = 0.14
\]

This seems very low. It should be much higher in Port 1.
HELICON ARRAY SOURCES

MEDUSA

MEDUSA 1
The Medusa 2 large-area array
An array source for roll-to-roll processing

The source requires only 6” of vertical space above the process chamber. Two of 8 tubes are shown.
Top view of Medusa 2

Possible positions shown for 8 tubes.

Endplates: gas feed and probe port at each end.

Substrate motion

Tubes set in deeply (½ inch)

3/4” aluminum

1/2” aluminum
Two arrangements of the array

Staggered array
Covers large area uniformly for substrates moving in the y-direction

Compact array
Gives higher density, but uniformity suffers from end effects.
Operation with cables and wooden magnet tray

It’s best to have at least 3200W (400W per tube) to get all tubes lit equally.
Details of distributor and discharge tube

The top gas feed did not improve operation.
A rectangular 50Ω transmission line

50-Ω line with \(\frac{1}{4}\)" diam Cu pipe for cooled center conductor
Operation with rectangular transmission line
Radial profile at Z2 across rows

![Radial profile graph]

- $n \left(10^{11} \text{ cm}^{-3}\right)$
- $r \text{ (cm)}$

- $n$
- $KTe$
Density profiles with staggered array

Staggered configuration, 2kW

Bottom probe array

Staggered, 2kW, D=7", 20mTorr

Argon

$n \times 10^{11} \text{ cm}^{-3}$ vs. $x$ (in.)

$y$ (in.)

-3.5, 0, 3.5
Density profiles with compact array

Compact configuration, 3kW
Bottom probe array

Plans for an 8-tube array for round substrates

No center tube is necessary!