Manash Kumar Paul

Supervisor
Prof. Dhiraj Bora
D.D.G, ITER

Acknowledgement
Dr. S.K.P.Tripathi
UCLA

Institute for Plasma Research
Gandhinagar, Gujarat (India)
• To explore toroidal counterparts of conventional Helicon modes

• Advanced applications of Helicon waves in toroidal plasma experiments

  - In terms of an RF source to ionize neutrals, sustain plasma and drive toroidal plasma current
Helicon waves are derived from Maxwell’s equations (with EMHD assumptions)

\[ \nabla \times E = \frac{-\partial B}{\partial t}, \quad \nabla \times B = \mu_0 j, \quad E = \frac{j \times B_0}{en_0}, \quad j = -en_0 \frac{E \times B_0}{B_0^2} \]

For a perturbation \( \exp(i(m\omega + k_z z - \omega t)) \), \( i\omega B = \nabla \times E = \frac{\nabla \times (j \times B_0)}{en_0} = \frac{ikB_0 j}{en_0} \)

**Cylindrical Helicon plasma**

\[
B = \left( \frac{\nabla \times B}{\psi} \right)
\]

Here, \( \psi = \alpha = \frac{\omega \mu_0 en_0}{kB_0} \)

\[ \Rightarrow \nabla \times B = \alpha B \]

Where \( n_0 \) and \( B_0 \) are equilibrium density and external magnetic field

**Toroidal Helicon plasma**

\[
(i\omega e_n)B = \{B_0 \cdot \nabla\}l - (J \cdot \nabla)B_0
\]

where \( B_0 = \frac{B_T}{1 + \frac{r \cos \theta}{R}} \)

So, \( B = \left( \frac{\nabla \times B}{\psi} \right) \)

where \( \psi = \alpha \left(1 + \frac{r \cos \theta}{R}\right)^2 \)

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
\frac{2i \cos \theta}{l} & -\frac{2i \cos \theta}{l} & 1
\end{bmatrix}
\]

and \( l = k_\parallel (R + r \cos \theta) \)

DIFFERENCE - LINEAR AND TOROIDAL

- B-Profiles of $m = +1$
- Infinitely conducting wall
  $\Rightarrow B_r = 0$ (at boundary)

Wave magnetic field components in Cylinder

Wave magnetic field components in Torus

Mode Coupling Possible !!
**Experimental Set-Up**

**System Layout**

<table>
<thead>
<tr>
<th><strong>Gas</strong></th>
<th>Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Pressure</strong></td>
<td>$10^{-5}$ mbar</td>
</tr>
<tr>
<td><strong>Fill Pressure</strong></td>
<td>$(2-5) \times 10^{-3}$ mbar</td>
</tr>
<tr>
<td><strong>Major radius</strong></td>
<td>30cm</td>
</tr>
<tr>
<td><strong>Minor radius</strong></td>
<td>10.5cm</td>
</tr>
<tr>
<td><strong>Magnetic field</strong></td>
<td>1 kG (max.)</td>
</tr>
<tr>
<td><strong>Pulse duration</strong></td>
<td>50ms</td>
</tr>
<tr>
<td><strong>Launcher</strong></td>
<td>Right Helical</td>
</tr>
<tr>
<td><strong>Input Power</strong></td>
<td>2 kW (max.)</td>
</tr>
<tr>
<td><strong>Impedance Matching Networks</strong></td>
<td>L-type and Pi-type</td>
</tr>
<tr>
<td><strong>Op. Frequency</strong></td>
<td>(7-9), (30-33) MHz</td>
</tr>
<tr>
<td><strong>Plasma density</strong></td>
<td>$10^{18}$ m$^{-3}$</td>
</tr>
<tr>
<td><strong>Electron Temp.</strong></td>
<td>10eV</td>
</tr>
</tbody>
</table>

**Diagnostics**

<table>
<thead>
<tr>
<th><strong>Plasma Parameters</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>RF compensated Langmuir probe</td>
</tr>
<tr>
<td>Centre-tapped B-dot probes (with bifilar windings)</td>
</tr>
<tr>
<td>Dual Rogowski coil</td>
</tr>
</tbody>
</table>
- Helicon wave excited at (7-9)MHz*
- Same source initiate breakdown and sustain the plasma
- Drive $I_p = 1 \text{kA}$ with $P_{RF} = 1 \text{kW}$*

- Dominated by resonant Wave-Particle interactions (~750A with 1kW)

- Helicity supported - nonresonant processes also indicated (~230A with 1kW)

- Quality of current drive**, for LHCD, in present conditions, 200A with 1kW.

• Operating frequency increased to increase the phase velocity
• Nonresonant (ponderomotive forces*) contribution amplified
• Magnetic field ($B_T$) increased
• Appropriate diagnostics designed and developed

• Wave magnetic field components measured at
\[ n_e = 2 \times 10^{12} \text{ cm}^{-3}, \]
\[ P_{rf} = 1.3 \text{ kW}, \]
\[ B_T = 0.8 \text{ kGauss}, \]
\[ p = (2-3) \times 10^{-3} \text{ mbar} \]

• \( \textbf{m}=+1 \) mode excited at 32 MHz

CURRENT DRIVE

* Early decay of Ip*  

\[ B_T > 0.5 \text{kGauss} \]

support Helicon mode

Jump in density and plasma current after 0.75kW during low $B_T$ expts.

For $B_T = \begin{align*} 0.4 \text{ kGauss} \\
0.6 \text{ kGauss} \\
0.9 \text{ kGauss} \end{align*}$

Pressure = $2 \times 10^{-3} \text{ mbar}$

$P_{rf} = (0.6 - 1.5) \text{kW}$
ESTIMATION OF CURRENT DRIVE

\[ n_o j_o q \eta = q \langle n_e E \rangle - \langle J_e \times B \rangle + \langle \nabla \cdot P_e \rangle + \frac{m}{n_o q^2} \langle (J_e \cdot \nabla) J_e \rangle \]

\[ J_h = (0.325-1.740) \text{A cm}^{-2} \]
for \( n_e = (10^{10}-10^{12}) \text{cm}^{-3} \),

\[ \Rightarrow I_p = (25-140) \text{A} \]

Almost exact reversal of \( I_p \)!!

\[ J_C = 10^{-3} \text{ times } J_h \]
for \( n_e = 10^{12} \text{ cm}^{-3} \)

- Measured av. \( I_p = (30-150) \pm 10\% \text{ A} \)

- Estimated plasma resistivity \( ? = 8 \text{ Om}^* \)

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*John Dawson and Carl Oberman, Phys. Fluids, 5, 517 (1962)
CONCLUSION & FUTURE WORK

• Approximately 80% of the total plasma current is driven by the nonresonant interactions

• CD efficiency, estimated from the ratio of $P_{RF}$ and $n_e J_h$, is $6 \times 10^{16}$ A W$^{-1}$ m$^{-2}$

• These waves could be considered for starting up and then sustaining an efficient toroidal discharge.

• Our experimental studies have established the current driving and discharge sustaining capabilities of Helicon waves.

• Study of poloidal mode coupling

• Study of stability of toroidal helicon plasma in our device
THANK YOU
Electron energy distribution (EEDF) measured using RFCLP to verify the absence of energetic electrons in present parameter regime.

A valid application of the Druyvesteyn formula requires collisionless electron motion near the probe.

\[
\frac{d^2 I_e}{dV_b^2} = \frac{e^{3/2} A}{\sqrt{8m}} F(V_p - V_b)
\]

For the probe to be non-intrusive effectively,

\[d(0.1\text{mm}) < r(0.5\text{mm}) < mfp(10\text{mm})\]

Electron energy distribution measured at \((10^{16} - 10^{18})\text{m}^{-3}\), reveal absence of any super-thermal species for current drive by resonant process.

EEDF at higher power shows rise in temperature of bulk electrons.
PARAMETRIC STUDY OF CD

- Peak value of $I_p$ is chosen from a profile, for comparison.
- In the high pressure regime, low $I_p$ obtained, at constant $P_{rf}$ ($\sim 1kW$).
- Higher electron-neutral collisions may be responsible.

![Graph showing the relationship between $B_T$ (kGauss) and $I_p$ (Amp) with different pressures.](image-url)
Plasma Resistivity Estimation

Plasma resistivity $\eta$ is calculated for high frequency waves in the ion rest frame*, in the limits $(\frac{\Omega}{\Omega_p}) \ll 1$.

$$\text{Re} (\eta (\omega)) = (16\pi)^{\frac{1}{2}} \left[ \frac{Ze}{6m_v} \ln \left( \frac{m_e^2 v_{th}^6}{\omega_p Z^2 e^4} - 1 \right) \right]$$

Here $\Omega$, $Z$, $e$, $\Omega_p$, $m$, $v_{th}$ represent operational frequency, charge state, electronic charge, plasma frequency, electronic mass and electron thermal velocity respectively.

The value of plasma resistivity obtained in present parameter regime is $\sim 8 \ \Omega m$.

Plasma impedance plays an important role in deciding the magnitude of contribution of wave helicity in the plasma current driven at present operational regime.

*John Dawson and Carl Oberman, Phys. Fluids, 5, 517 (1962)
Helicity Current Drive

Contribution by the helicity of helicon waves in plasma current drive can be expressed as
the hall \((J \times B)\) term in the momentum equation

\[
\mu_0 \epsilon n J_h = \langle J_e \times B \rangle = -\langle (\vec{\nabla} \times \vec{B}) \phi \rangle \\
= \langle (B_r (\vec{\nabla} \times \vec{B})_\theta - B_\theta (\vec{\nabla} \times \vec{B})_r \rangle \\
= \frac{1}{(R+r \cos \Theta)} \left[ B_r \frac{\partial B_r}{\partial \phi} + B_\theta \frac{\partial B_\theta}{\partial \phi} \right] + \frac{B_\phi}{(R+r \cos \Theta)} \left[ B_\phi \sin \Theta - B_r \cos \Theta \right] \left[ B_r \frac{\partial B_\phi}{\partial r} + B_\theta \frac{\partial B_\phi}{r \partial \Theta} \right]
\]

- Wave magnetic field components, axial, radial and azimuthal variations of the same have been measured by B-dot probes on the plasma axis and these values are used for above estimation.
- Numerically estimated value of \(J_h\) vary betn. (0.325-1.740)A cm\(^{-2}\) for \(n_e = (10^{10}-10^{12})\)cm\(^{-3}\), which is (25-140)A (peak).
- Experimentally measured av. plasma current \(I_p\) vary betn. (30-150) ±10% Amp.
The convective term present in the momentum equation is derived from the formula given below. Current components, derived in toroidal coordinates are substituted in the equation given below.

\[
\left( \frac{n^2\phi e^3\eta}{m^e} \right) J_c = \langle \langle \vec{J}_e \bullet \vec{\nabla} \rangle \vec{J}_e \rangle = J_r \frac{\partial J_{\phi}}{\partial r} + J_\theta \frac{\partial J_{\phi}}{\partial \theta} + \frac{J_{\phi}}{R+r\cos \theta} \frac{\partial J_{\phi}}{\partial \phi}
\]

Wave magnetic field values being very small in comparison to the ambient magnetic field, nonlinear effects in present investigation are negligibly small.

Magnitude of \( J_C \) turns out to be \( 10^{-2} \) times helicity term at \( 10^{11}\text{cm}^{-3} \).

\( J_c \) further diminishes to \( 10^{-3} \) times \( J_h \) at \( 10^{12}\text{cm}^{-3} \) plasma density.
DIFFUSION/PRESSURE GRADIENT CURRENT

For steady state plasma, net contribution from pressure gradient term is

\[ J_{\text{dif}} \approx \left( \frac{r}{R} \right)^2 \frac{1}{2} \frac{\partial p}{\partial r} \frac{1}{B_\theta} \]

(approx. for bootstrap mech.*)

Almost exact reversal of Ip also shows negligible impact on plasma current due to pressure anisotropy

• Helicon waves form cavity modes in a bounded system

• Wavevectors no longer continuous but eigenvalues determined by boundary conditions ($B_r = 0$ ($r = a$))

• Length chosen according to toroidal mode number and phase velocity

• Radius optimized according to capacitive effects, dispersive parameter ($a$, for radial eigen modes) and gain factor ($a/ak_\parallel$)

Right Helical Antenna
Length = 11 cm, Radius = 6 cm
DISCHARGE MODE TRANSITIONS

- **Capacitive mode**
  - (0.2-0.3)kW & (0.1-0.25)kGauss
  - Potential diff. sustained discharge
  - Power transfer E (sheath) to plasma
  - Power distributed at antenna edges

- **Inductive mode**
  - (0.3-0.5)kW & (0.3-0.5)kGauss
  - E sustained discharge
  - Concentric to the antenna.

- **Helicon mode**
  - (0.6-0.9)kW & (0.5-0.6)kGauss
  - Wave sustained discharge
  - Uniform distribution of power in antenna diameter give rise to higher density at centre during Helicon discharge
Effect of an oscillating $V_p$ on LP present a great difficulty in interpretation of probe data when the RF excursions bring the electron current out of the exponential region.

Passive technique chosen for simplicity and better performance at almost all frequency

Harmonics considered in the plasma potential are

$$V_p = V_p \sin \beta t + \beta V_p \sin 2 \beta t,$$

where $\beta$ is fraction of 1st harmonic present in $V_p$.

Only first harmonic is considered for low $\beta$ at higher harmonics

$$Z = \frac{1}{j \omega C} + \frac{j \omega L_1}{1 - \omega^2 C L_1} + \frac{j \omega L_2}{1 - \omega^2 C L_2}$$

Capacitance of the cylindrical guard ring -- $r = 1 \text{ cm}$, $l = 10 \text{ mm}$, $C = 300 \text{ pF}$ for 30MHz.

Also, $\frac{V_0}{V_p} = \frac{-\omega^2 CL}{1 - \omega^2 CL}$, where $V_0$ is potential between probe tip and LC-sections and $V_p$ is plasma potential. Usually, $\omega^2 CL >> 1$, so that $V_0 > V_p$.

In order to achieve compensation within 1% of $V_p$, we take $\omega^2 CL \sim 100$.

Since $j \omega L << 100$ to make the sheath drop equal to 1% of the probe potential, harmonic rejection (HR) components are calculated for 2nd term=3rd term=30.
A valid application of the Druyvesteyn formula requires collisionless electron motion near the probe.

Debye length ($d_e$) << electron mean free path ($e_e$),
and the probe radius << $e_e$ (non-intrusive).

In the present case, $d_e(0.1\text{mm}) < \text{probe radius (0.5mm)} << e_e(10\text{mm})$

Sheath radius = 0.1mm and probe radius = 0.5mm. So, the ratio is 0.2, which is small enough to neglect the sheath effect in our case.

The effect on the Langmuir probes due to $B_T$ is negligible since the probe dimensions are much smaller than the Larmour radius ($R_L = 0.1\text{mm}$) of the collected plasma species.

Electrons with Larmour radius smaller than the dimensions of the probe can either be collected through cross-field diffusion or from flux tubes intersecting the probe. The electron saturation current is reduced by a factor ($s$)

$$s = 16 \lambda_{ei} \left( \frac{D}{D_{\parallel}} \right)^{1/2} \left[ 1 + \frac{T_i}{T_e} \right] \frac{1}{2 \pi a}$$

For electrons, radial diffusion is strongly inhibited whereas for ions, the ion diffusion is not severely limited. So, the usual standard expressions for the electron and ion probe currents will be used with appropriate corrections for the effective probe area.
TEMPORAL VARIATION

- Higher Plasma density in the central region.
- The density jump at the beginning indicates the initial transient phase of RF breakdown.
- Higher electron temperature with minute variation is expected during steady state high power Helicon discharge.
- Spatial evolution of floating potential is essential to understand the discharge equilibrium of a pulsed RF breakdown.
- The closed contours obtained from the spatial profiles of floating potential provide information about the discharge equilibrium.
- Closed curves obtained, reveal that a steady state discharge is obtained between (15-35) ms. the steady state discharge obtained in our experiment.
Efficiency of Helicon wave current drive

Current drive efficiency* for the present case, is calculated from the plasma parameters and the value of plasma impedance, given by

\[
\eta_{CD} = \frac{P_{rf}}{n_e \eta J_h} = \left( \frac{38.4 \times 10^{18}}{\ln \Lambda} \right) \left( \frac{T_e}{n_e} \right) \eta = 6 \times 10^{16} \text{AmpW}^{-1} \text{m}^{-2}
\]

Here \( \ln \Lambda, n_e, T_e \) represent coulomb logarithm, local electron density in SI units and electron temperature in keV respectively.

Efficiency can also be estimated from the ratio of \( n_e J_h \) and \( P_{rf} \), written in terms of toroidal wave damping factor \( \eta \) as

\[
\eta_{CD} = \frac{\eta}{v_f e^?}
\]

=> higher wave damping for efficient current drive