Investigation of ICRF Mode Conversion at the Ion-ion Hybrid Layer in Alcator C-Mod

Presented by Yijun Lin, MIT

In collaboration with

MIT, Plasma Science and Fusion Center, Cambridge, MA 02139, USA

C.K. Phillips, G. Schilling and J. R. Wilson
Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA

P. Phillips and A. Lynn
Fusion Research Center, University of Texas, Austin, TX 78712, USA

• Work supported at MIT by US DoE Cooperative Agreement No. DE-FC02-99ER54512
Motivation and Outline

Motivation:
• Localized mode conversion (MC) electron heating (EH).
• MC current drive.
• MC plasma flow drive.
→ Need better understanding of the ICRF MC physics.
→ Important for the Advanced Tokamak scenario.

Outline:
• First experimental observation of the MC ion cyclotron wave (ICW) in tokamak plasmas.
• Detailed study of MCEH, and examination of relative contributions from the MC ICW and MC ion Bernstein wave (IBW).
• Preliminary result of MC flow drive experiments.
Fast wave and Ion-ion Hybrid Layer

\[ n_{-}^2 = -\frac{(n_{||}^2 - L)(n_{||}^2 - R)}{n_{||}^2 - S}, \quad n = \frac{ck}{\omega} \]

Stix’ parameters:

\[ R = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega + \Omega_j)}, \quad L = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega - \Omega_j)} \]

\[ S = (R + L)/2, \quad 'j' \text{ denotes different species.} \]
The MC ICW has been experimentally observed for the first time in tokamak plasmas in Alcator C-Mod. The MC ICW was first studied analytically in Ref. [F.W. Perkins, Nucl. Fusion 17, 1197 (1977)]. ICW, which usually exists only at the plasma edge, can appear further inside the plasma with the help of $k_{||}$ up-shift caused by the magnetic shear.
ICRF Antennas in Alcator C-Mod

Total rf source: 8 MW.

- The exclusive auxiliary heating source at present.

Two 2-strap antennas at D (80.5 MHz) and E (80 MHz) ports:
  - Dominant toroidal modes $n_\phi = \pm 10$ at $[0, \pi]$ phasing.

A 4-strap antenna at J-port (40-80 MHz):
  - Dominant toroidal modes $n_\phi = \pm 13$ at $[0, \pi, 0, \pi]$ phasing.
Phase Contrast Imaging (PCI) System

- PCI measures line-integrated density fluctuations.
- A vertical CO$_2$ laser ($\lambda = 10.6$ µm) beam is expanded to a width up to 15 cm and imaged to a 12-channel detector.
- PCI is most sensitive to waves with vertically aligned wave fronts.
- Laser intensity is modulated so that waves at the rf frequency can be detected at the beat frequency (~350 kHz).
- Wave-number $k_R$ is obtained by spatial Fourier transformation on signals from all 12 channels.
Experimental Observation of the MC ICW

- Phase velocity is toward the low field side.
- Wavelength is shorter than FW, but generally longer than IBW.
- It is located on the low field side of the $^3$He-H hybrid layer.

\[ B_t = 5.8 \, \text{T}, \quad n_{e0} = 2 \times 10^{20} \, \text{m}^{-3}, \quad I_p = 800 \, \text{kA}, \quad T_{e0} = 1.3 \, \text{keV}, \quad 59\% \, \text{H}, \quad 33\% \, \text{D}, \quad 4\% \, ^3\text{He}. \]

Solving the Dispersion Equation

Dispersion Equation: $D = \begin{vmatrix} \varepsilon_{xx} - n_{||}^2 & \varepsilon_{xy} & \varepsilon_{xz} + n_\perp n_{||} \\ \varepsilon_{yx} & \varepsilon_{yy} - n_{||}^2 & \varepsilon_{yz} \\ \varepsilon_{zx} + n_\perp n_{||} & \varepsilon_{zy} & \varepsilon_{zz} - n_\perp^2 \end{vmatrix} = 0$

(Full EM, Maxwellian)

- $n_\phi$ is conserved while $k_\parallel$ and $k_\perp$ are under transformation

$$k_\parallel = k_r \frac{B_r}{B} + \frac{m_\theta}{r} \frac{B_{pol}}{B} + \frac{n_\phi}{R} \frac{B_\phi}{B}$$

$$k_\perp^2 = k_r^2 + \left( \frac{m_\theta}{r} \right)^2 + \left( \frac{n_\phi}{R} \right)^2 - k_\parallel^2$$

- Approximately, $k_\parallel \approx \frac{n_\phi}{R} \frac{B_\phi}{B} + k_\perp \frac{B_{pol}}{B}$, and $k_\perp \approx \frac{m_\theta}{r} >> k_r$

- $B_{pol}$ is estimated assuming a cylindrical plasma.
- Including $B_{pol}$ is crucial to find the MC ICW.
The dispersion equation has the roots of FW, IBW and ICW near the ion-ion hybrid layer.

- ICW is obtained on the magnetic surface tangential to the hybrid layer on the mid-plane. It appears with a significantly up-shifted $k_{||}$.
- FW and IBW are obtained on the mid-plane.

The MC ICW is absorbed through electron Landau damping, and also IC resonance if it reaches the IC layer ($R - R_0 \approx 8$ cm).
The MC ICW is a weakly damped mode on the low field side of the hybrid layer.

The same wave structure also appears clearly in the $E_z$ contour of TORIC simulation.

This wave agrees with the PCI observation with respect to both spatial location and wavelength.

The analysis identifies that the observed wave is an MC ICW.

→ First experimental observation in tokamak plasmas.

Historic context: the original goal of these experiments was to measure the MC IBW instead of the MC ICW. The MC IBW is to be investigated using an upgraded PCI system in the future. (L.Lin et al., FP1.005)
Polarization and Up-down Asymmetry

- The MC ICW has large $E_z$ due to its large $n_\perp$ and $n_\parallel$: $|E_z|/|E_p| \approx k_\perp v_{te}^2/2\omega_{ce}$
- The MC ICW is a left hand polarized slow wave $\rightarrow$ large $E^+$ component.
  - In contrast, FW is mostly right hand polarized $\rightarrow$ large $E^-$ component
- For $n_\phi > 0$, more ICW below the mid-plane. The asymmetry results from the fact that the MC ICW propagates towards the LFS and also requires $k_\parallel$ up-shift.
MC ICW also Seen in AORSA Simulations

TORIC:
- 2nd order FLR expansion
- Spectral expansion in poloidal modes

AORSA:
- Fully spectral approach
- No limit on the number of IC harmonics

Figure courtesy of E.F. Jaeger, ORNL.


Detailed comparison in the following talk by John C. Wright (GI2.006)
MCEH Study in D(H) Plasmas

Detailed MCEH study:
- To examine the relative contributions from the MC IBW and MC ICW.

Methods:
- High spatial resolution (< 7 mm) and temporal response ECE (5 µs) $T_e$ signals
- Break in slope technique
- Reliable spectroscopic H/D ratio diagnostic
- Comparison with TORIC Simulation

Break in slope is clearly seen in ECE signals near the axis at the rf shutoff.

- D-H hybrid layer on axis.
- H cyclotron resonance layer at \( r/a \sim 0.4 \) (LFS)

Deposition profile is calculated from the break in slope (\( \sim1 \) ms time window)

\[
S \approx \frac{3}{2} n_e \Delta \left( \frac{\partial T_e}{\partial t} \right)
\]
MC Efficiency (Expt. and Simulation)

On-axis MC

J antenna, \( t = 0.874 \) sec.
\( f_{\text{rf}} = 70 \text{ MHz}, \) 19\% H, 81\% D
MCEH region: \( 0 < r/a < 0.25 \)
Experiment: \( \eta^{\text{MCEH}} = 16\% \)
TORIC: \( \eta^{\text{MCEH}} = 14\% \)
IBW is the primary MC wave (\( B_{\text{pol}} \sim 0 \)).

Off-axis MC

E antenna, \( t = 1.502 \) sec
\( f_{\text{rf}} = 80 \text{ MHz}, \) 22.5\% H, 77.5\% D
MCEH peak at \( r/a = 0.35 \) (HFS)
Experiment: \( \eta^{\text{MCEH}} = 20\% \)
TORIC: \( \eta^{\text{MCEH}} = \eta^{\text{IBW}} + \eta^{\text{ICW}} = 18\% \)
- \( \eta^{\text{ICW}} = 8.7\% \) and \( \eta^{\text{IBW}} = 9.3\% \)
- Similar \( r/a \) location

Note: TORIC results are weighted summation of many toroidal modes in the antenna spectrum.
MC ICW and MC IBW Deposition Profiles

Off-axis MC, MC IBW and MC ICW depositions:

- On the different sides of the D-H hybrid layer.
- Similar magnitudes.
Power Partition vs. Plasma Current

- Larger $I_p \rightarrow$ Larger $B_{pol}$ → Stronger magnetic shear → Stronger MC ICW and longer propagation distance

- This $I_p$ dependence can be experimentally investigated by an upgraded PCI system. (L. Lin et al., FP1.005)
Preliminary Result of Flow Drive Expt.

- Flow velocity was measured only at one flux surface (due to a data system problem).
- RF correlated poloidal flow in the MC region was observed in a few discharges.
  - Preliminary evidence of MC flow drive
- Experiments with better and more comprehensive diagnostics are planned in the near future.

$B_t = 7.8 \, \text{T}, \ n_{e0} = 1.7 \times 10^{20} \, \text{m}^{-3}, \ I_p = 800 \, \text{kA}, \ T_{e0} = 3.5 \, \text{keV}$
$6\% \, \text{H}, \ 78\% \, \text{D}, \ 8\% \, ^3\text{He}.$
J-antenna counter-current drive phasing, $n_\phi = +7$, and $f_{rf} = 78 \, \text{MHz}.$ Total MC power about 300 kW at 2 MW input. (S. Wukitch et al., CO1.006)
Summary

1. **First experimental observation of the MC ICW in tokamak plasmas**
   - It is located on the low field side of the ion-ion hybrid layer.
   - Its wavelength is generally between the MC IBW and FW.
   - Experimental observation agrees with TORIC simulations and dispersion equation solution.

   ➔ *The MC physics is more complicated than previously thought.*

2. **Detailed MCEH study in Alcator C-Mod in D(H) plasmas**
   - Experimentally measured profiles agree with TORIC simulations.
   - The MC ICW can have comparable contribution as the MC IBW for off-axis mode conversion.

   ➔ *In D-T plasmas of future fusion reactors, the MC ICW may dominate IBW at certain plasma parameters.*

3. **Result on flow drive experiments**
   - Preliminary evidence of MC flow drive has been observed.
   - More experiments are planned in the near future.