ICRF Heating, Mode Conversion, and Flow Drive Experiments in $D(^3\text{He})$ Plasmas


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ICRF System in Alcator C-Mod

Top view of C-Mod

Two 2-strap antennas at D and E ports (~80 MHz)

A 4-strap phase and frequency variable antenna at J port (40-80 MHz)

Total RF source: 8 MW
Why Study D(He3) Plasmas

- Plasma pressure (absolute level) comparable to burning plasmas.
- At $B \sim 8$ T, D(He3) ICRF minority heating is the only heating method that can utilize all available ICRF power in Alcator C-Mod.
- We would like to find a good operation point and optimize the He3 minority heating in a compact tokamak.
- D(He3) mode conversion study. Easier to control species concentrations, although more difficult to measure.
Absorption:

\[ A = 1 - \exp(-2\eta) \]

\[ 2\eta = \frac{\pi}{2} \frac{\omega_{pm}}{c} \frac{n_m Z_m}{n_M Z_M} R \frac{|E_+|^2}{|E_y|^2} \]

Depolarization factor:

\[ \frac{|E_+|^2}{|E_y|^2} = \left( 1 - \frac{\omega}{\omega_{cM}} \right)^2 \frac{1}{1 + \sigma_1^2} = \begin{cases} 
1/(1 + \sigma_1^2) & \text{D(H)} \\
1/9(1 + \sigma_1^2) & \text{D(He3)}
\end{cases} \]

\[ \sigma_1^2 = \frac{\pi}{4} \left( \frac{n_m M Z_m^2}{n_M m Z_M^2} \right)^2 \left( 1 - \frac{\omega_{cM}^2}{\omega^2} \right)^2 \left( \frac{\omega}{k || v_{tm}} \right)^2 \]

D(He3) minority heating has a much smaller depolarization factor, which appears in the exponent and may severely reduce the single pass absorption.
D(H) and D(He3) Single-Pass

Power density assumed as 10 MW/m³ per 1 MW input power in the region of r/a < 0.2. Tail temperature estimated using Stix’ formula.
An Example of H-mode at D(He3)
At small He3 level, no H-mode was obtained. The performance is rather insensitive for He3 to D ratio >5%.

He3 level estimated by scaling the puffing time and PCI mode conversion waves measurement.
Efficiency from H-mode Threshold

Experimentally, we found the H-mode threshold

- D(H) plasma (5.4 T, 1040421001):
  - $P_{th} \sim 1.5$ MW Prf, 1 MW ohmic
- D(He3) plasma (8 T, 1040423017):
  - $P_{th} \sim 3.9$ MW Prf, 1.2 MW ohmic

Empirically, the H-mode threshold scales with B field.

\[
(1.5\eta_H + 1) \times 8 = (3.9\eta_{He3} + 1.2) \times 5.4 \\
12\eta_H + 1.5 = 21\eta_{He3} \\
\eta_{He3} \approx 0.6\eta_H
\]
The result we have is inconclusive, mainly limited by the amount of shots (and good break-in-slope events) available. Future study: J antenna at 50 MHz and D/E antenna at 80 MHz, so we can compare the efficiency in the same shot!
ICRF Mode Conversion

Mode conversion to the ICW is a result of $k_{\parallel}$ up-shift caused by the magnetic shear where $B_{\text{pol}} \neq 0$

$$R = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega + \Omega_j)}$$
$$L = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega - \Omega_j)}$$
$$S = (R + L)/2$$
Phase Contrast Imaging System

PCI measures line integrated electron density fluctuations along 32 vertical chords.

**Laser:** 25 W CO$_2$ CW, 10.6 µm
**Data:** Digitized at 10 MHz, 0.6 sec, 32 channels
**Localization:** 62 cm < R < 74 cm
**Wave number Range:** 0.5 cm$^{-1}$ < |k$_R$| < 8 cm$^{-1}$

**Heterodyne setup:**
- The laser beam is modulated at a frequency close to the RF frequency.
- RF waves show up as density fluctuations at the beat frequency.
MC Wave Seen in PCI

Coherent peak at 1740 kHz, anticipated frequency from J-port rf waves.
PCI RF Signal vs Time at 5.6 T

MC IBW
MC ICW
FW

R-space
k-space

Antenna frequency at 50 MHz

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Density fluctuations are estimated from fluid approximation.

Antenna spectrum and wave propagation from J-port to PCI location (E port) are also considered.

Line integrated to mimic PCI measurement.

The MC ICW usually has the largest contribution due to large $E_{||}$. 

PCI 32 channels
Comparing with TORIC at $B \sim 5.6$ T

The absolute level of PCI calibration is questionable (a factor of $\sim 100$ too small). It is part of future work.
PCI RF Signal vs Time at B ~ 8 T

IBW is too weak to be visible in PCI data.

Antenna frequency at 78 MHz
PCI and TORIC Comparison at B ~ 8 T

Note: the wave number of the MC ICW is similar to that in ~5 T plasmas.
B Field Scan 5 T

The MC waves structure moves towards the lower field side at higher B field.
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He3 Concentration Scan

The MC waves structure moves towards the higher field side at longer He3 puff time.
Flow Drive Experiment Setup

Two high resolution X-ray spectroscopy channels arranged to measure flows on the same flux surface.

Poloidal flow velocity can be obtained by subtracting the two measurements.
Experimental Result

- No RF modulated flow was observed in the study. An example plasma is shown here.

- The MC layer is close to the flux surface where flow was measured.
ICW is damped through both electron Landau damping and IC damping (by Doppler broadening at high $k_{\parallel}$), but ELD is dominant. (15%He3, 5%H, 65%D $N_{\phi}=8$, 255 poloidal modes).

Further study and interpretation of the result is under way.
Summary

- H-mode plasmas were obtained in 8 T using D(He3) ICRF minority heating method. The heating efficiency will be studied further by utilizing both D(H) and D(He3) heating in the same shot.
- Mode converted ICRF waves were observed using PCI. Experimental results were compared with a synthetic PCI using TORIC. Good agreement was found in wave structure.
- No ICRF mode conversion driven poloidal flow was detected. Interpretation and comparison with theoretical work is under way.