ICRF Mode Conversion Flow Drive on the Alcator C-Mod Tokamak

Yijun Lin, J.E. Rice, S.J. Wukitch, M.L. Reinke, M. Greenwald, A. E. Hubbard, E.S. Marmar, Y. Podpaly, M. Porkolab, N. Tsujii and the Alcator C-Mod Team

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

Work supported by US DoE Cooperative agreement DE-FC02-99ER54512 at MIT.
Outline

• Background and experimental setup

• Parametric dependence of mode conversion flow drive
  – Minority concentration
  – Antenna phasing/plasma current/RF power
  – Plasma density/L-mode/H-mode
  – Magnetic field and RF frequency

• Empirical scaling law

• RF physics modeling using TORIC

• Summary
ICRF mode conversion flow drive may generate plasma rotation on ITER

• Plasma rotation is important for tokamaks
  – Stabilizing MHD modes and improve confinement

• But the benefits from rotation might be lost on ITER
  – Beam driven rotation is expected to be small on ITER
  – Intrinsic toroidal rotation exists, but no simple external control technique. (J. Rice et al, talk EX/3-3, this morning)

• Externally launched ICRF power may provide a solution
  – ICRF mode conversion flow drive was demonstrated on Alcator C-Mod, and rotation velocity significantly larger than the intrinsic rotation was achieved (Y. Lin et al, 22nd IAEA FEC, Geneva, 2008, talk PD/1-2);
  – Similar ICRF mode conversion scheme has been shown also to drive plasma rotation on JET (T. Tala et al, talk EX/C3-1, this morning).

• We report the result from a detailed experimental study of ICRF mode conversion flow drive on Alcator C-Mod.

Alcator C-Mod: R = 0.68 m, a = 0.22 m, 
B_t ≤ 8.1 T, I_p ≤ 2 MA, n_e0 ≤ 10^{21} m^{-3}
**Frequency and phasing variable high power ICRF systems on Alcator C-Mod**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>80 MHz</th>
<th>50/70/78 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2 x 2 MW</td>
<td>4 MW</td>
</tr>
<tr>
<td>Antenna</td>
<td>2 x 2 Strap</td>
<td>4 Strap</td>
</tr>
<tr>
<td>Phasing</td>
<td>Fixed (180°)</td>
<td>Variable (+90°, 180° and -90°) +90°: waves in the same direction as I_p (co-I_p).</td>
</tr>
</tbody>
</table>

**Images:**
1. [Image 1](#)
2. [Image 2](#)
ICRF minority heating vs. mode conversion heating shown in E⁻ field from TORIC

D(³He) plasmas, $X[³\text{He}] = n_{\text{He3}}/n_e$, $I_p = 0.8$ MA, $B_t = 5.1$ T, $f_{\text{RF}} = 50$ MHz
TORIC is a 2-dimensional full-wave RF physics code, $N_\phi = +6$ in this simulation
Previously reported result of mode conversion flow drive on Alcator C-Mod

- Significantly larger toroidal rotation with mode conversion than intrinsic rotation ($\propto \Delta W/I_p$)
- Rotation profile broadly peaked toward axis
- Localized poloidal rotation also observed
- Result from detailed study in this talk

Rotation is measured by spectroscopy and corroborated by changes in MHD frequencies

- Central rotation from spectroscopy measurement of the Doppler shift of Ar$^{16+}$ lines (positive $V \rightarrow co-I_p$)
  - RF power stepped up to 4.6 MW, and rotation velocities increases following $P_{RF}$.
- Rotation as seen in the change of MHD frequencies associated with sawteeth
  - Sawtooth precursors and post-cursors from magnetic coils and a bolometer AXUV diode array
    - $V \sim 2\pi\Delta fR$, 20 kHz corresponds to $\sim$90 km/s around $q = 1$ surface
Flow drive effect is sensitive to the $^3\text{He}$ level in D($^3\text{He}$) plasmas

- $X[^3\text{He}]$ scanned shot by shot (antenna phasing +90°);
  - $X[^3\text{He}]$ estimated from the location of measured MC waves and also from direct RF power deposition to electrons
- Largest rotation observed for $X[^3\text{He}] \sim 8$-$15\%$.
- The dependence on $X[^3\text{He}]$ suggests that mode conversion plays an important role

L-mode,
- $I_p = 0.8$ MA,
- $B_{t0} = 5.1$ T,
- $n_{e0} = 2.0 \times 10^{20} \text{m}^{-3}$,
- $f_{RF} = 50$ MHz,
- $P_{RF}$ 2.6 MW,
- +90° phasing
D(\textsuperscript{3}He) mode conversion drives larger rotation than D(H) minority heating (intrinsic rotation)

L-mode, $I_p = 1.0$ MA, $n_{e0} = 1.5 \times 10^{20} m^{-3}$

L-mode, $I_p = 1.0$ MA, $n_{e0} = 1.6 \times 10^{20} m^{-3}$
At +90° antenna phasing, rotation scales with $P_{RF}$ and increases with $I_p$.

- Change of rotation velocity approximately scales with $P_{RF}$ at all $I_p$;
- Rotation is also generally larger at larger $I_p$.
  - Opposite to the intrinsic rotation scaling.

L-mode,
$B_{t0} = 5.1 \text{ T}$,
$f_{RF} = 50 \text{ MHz}$,
$n_{e0} = 1.9 \times 10^{20} \text{ m}^{-3}$,
+90° phasing.
At high power, rotation is smaller at\(-90^\circ\) phasing than at\(+90^\circ\) phasing

L-mode, \(B_{t0} = 7.9\) T, \(I_p = 1.2\) MA, \(f_{RF} = 78\) MHz, \(n_{e0} = 1.9\times10^{20}\) m\(^{-3}\)
Rotation at -90° phasing has complicated dependence on $P_{RF}$ and $I_p$.

- Flow drive effects diverges at high RF power;
- -90° phasing appears to introduce a counter-$I_p$ torque at high $P_{RF}$.
- → Momentum from the RF waves also plays a role at high RF power.
Larger rotation is obtained at lower plasma density

- Rotation velocity is much larger at low plasma density. At high density, the total gain of the angular momentum also decreases.
- This result may be a combined effect from \( n_e \) and \( T_e \) because lower \( n_e \) also have higher \( T_e \).

\[ \Delta V \text{ [km/s]} \]

\( n_e [10^{20} \text{ m}^{-3}] \)

\[ \Delta V \text{ [km/s]} n_e [10^{20} \text{ m}^{-3}] \]

\( n_e [10^{20} \text{ m}^{-3}] \)

L-mode, 
\( B_{t0} = 5.1 \text{ T}, \)
\( I_p = 1.0 \text{ MA}, \)
\( P_{RF} = 2.6 \text{ MW}, \)
\( f_{RF} = 50 \text{ MHz}, \)
\( +90^\circ \text{ phasing} \)
Flow drive effect in H-mode is small, consistent with density scaling

Use 2 MW at 80 MHz D(H) minority heating to obtain Enhanced $D_\alpha$ H-mode, then inject 2.6 MW power at 50 MHz for $D(^3\text{He})$ mode conversion flow drive;

$V_0$ in H-mode follows plasma stored energy (intrinsic rotation)

Additional rotation velocity from the MC power is $< 10$ km/s.
- In a comparable L-mode plasma, $\Delta V \sim 60$ km/s.
- Consistent with high density in H-mode

Plan to do experiment on I-mode, where density does not rise significantly while the energy confinement is improved. (D. Whyte et al, talk EXC1/3)

$B_{t0} = 5.1$ T, $I_p = 1.0$ MA
Rotation is largest when the ion cyclotron resonance and MC layer are both near axis

At 50 MHz, and about 10% X[^3]He], the rotation velocity is maximized at B_{t0} ~ 5.0 - 5.1 T

- IC resonance about 2 cm on the low-field-side of the magnetic axis, while the MC layer about 1 cm on the high-field-side.
Flow drive efficiency is higher at lower RF frequency and lower B field

- 50 MHz/5.1 T, 2.6 MW $\rightarrow$  
  $\Delta V \sim 75$ km/s
- 70 MHz/7.2 T, 2.6 MW $\rightarrow$  
  $\Delta V \sim 55$ km/s
- Approximately scales with $1/f$ (or $1/B$)

L-mode, $I_p = 1.0$ MA,
$n_{e0} = 1.4 \times 10^{20} \text{m}^{-3}$
Scaling law: \[ \Delta V \propto P_{RF}^{1.3} I_p^{0.5} n_e^{-0.9} f_{RF}^{-0.8} \]

Empirical scaling law obtained from multiple-parameter regression for all the +90° and 180° data.

- Intermediate X[³He]
- Optimized B field

Favorable scaling with \( P_{RF}, I_p \), unfavorable vs. \( n_e \) and \( f \) (or \( B \)).

Results from other machines needed for size scaling
Up-down asymmetry in the MC ICW may generate net torque

The MC ICW has a much larger $k_{\parallel}$ than the fast wave,
- slower wave carries larger momentum at the same power.

Up-down asymmetry in real space and also in $k$-space (because of poloidal B field)
- On different flux surfaces;
- Opposite signs of $k_{\parallel}$ and different magnitude;

This asymmetry may redistributes the RF momentum on different flux surfaces and might result in flow drive.

$X[^{3}\text{He}] = 20$
$N_{\phi} = +6$
$I_{p} = 0.8 \text{ MA}$
$n_{e0} = 2 \times 10^{20} \text{m}^{-3}$
$T_{e0} = 2.5 \text{ keV}$
RF power deposition to the $^3$He ions is sensitive to $X[^3\text{He}]$

- **Low $X[^3\text{He}]$:** All via fast wave (minority heating);
- **Intermediate $X[^3\text{He}]$:** mostly via the MC ICW, some via fast wave;
- **High $X[^3\text{He}]$:** mostly via ICW, but not much total power to $^3$He ions.

$N_\phi = +6$

$f_{\text{RF}} = 50 \text{ MHz}$

$B_{t0} = 5.1 \text{ T}$

$I_p = 0.8 \text{ MA}$

$n_{e0} = 2 \times 10^{20} \text{m}^{-3}$

$T_{e0} = 2.5 \text{ keV}$
Interaction between the MC ICW and $^3$He ions has a similar trend vs. X[$^3$He] as rotation

- Plasma rotation is determined by the momentum source and momentum transport.
- Further experimental study and theoretical analysis will be required to understand the flow drive mechanism.

TORIC simulation:
- $N_\phi = +6$, $f_{RF} = 50$ MHz
- $B_{t0} = 5.1$ T, $I_p = 0.8$ MA
- $n_{e0} = 2 \times 10^{20} m^{-3}$
- $T_{e0} = 2.5$ keV
Summary

• ICRF mode conversion flow drive (MCFD) can generate significantly larger rotation than ICRF minority heating (intrinsic rotation);

• At +90° and 180° phasings, MCFD scales favorably vs. $P_{RF}$ and $I_p$, but unfavorably vs. $n_e$ and RF frequency $f$ (or B field);

• RF momentum appears to contribute at high $P_{RF}$, as inferred from -90° antenna phasing.

• From TORIC simulation, the interaction between the MC ICW and $^3$He ions appears to follow a similar trend vs. $X[^3\text{He}]$ as the driven rotation.

• The up-down asymmetry and $k_{//}$ up-shift in the MC ICW can redistribute the RF momentum in space and might result in flow drive.