ICRF Mode Conversion Flow Drive on Alcator C-Mod and Projection to other Tokamaks


MIT Plasma Science and Fusion Center, USA
Mode Conversion (MC) Flow Drive on Alcator C-Mod

- Significant toroidal and poloidal flow (rotation) has been observed in ICRF mode conversion (MC) heated L-mode plasmas on Alcator C-Mod.

- MC ion cyclotron wave ion absorption is thought to be a key mechanism.

- Potentially applicable on other tokamaks, like JET and ITER.
Outline

1. Introduction
   - Rotation
   - Mode conversion
   - Experimental setup
2. Flow drive observation on C-Mod
3. MC wave detection
4. Exploration of flow drive mechanism
5. Projection to ITER and JET
6. Summary
Plasma Rotation is important, but its Magnitude is Uncertain on ITER

- Rotation is important for tokamaks
  - Modify MHD modes (e.g. RWM and NTM) stability
  - $E \times B$ shear $\rightarrow$ turbulence suppression $\rightarrow$ transport barrier

- But the benefits from rotation may be lost on ITER
  - Most existing medium and large tokamaks use neutral beams to generate toroidal rotation
    - 20-50 km/s per MW beam power.
  - Beam driven rotation is expected to be small on ITER and control of beam driven rotation profile will be difficult
    - $< 2$ km/s per MW beam power on ITER.
  - Intrinsic toroidal rotation exists without NB heating.
    - Mach number $\propto \beta_N$ \cite{Rice2007}
    - No simple external control technique (magnitude or profile).

Externally launched electromagnetic waves may provide a solution.
Flow Drive by ICRF Waves: Experiments and Theory/Modeling

- **Experiments:**
  - **JET:** fast wave on toroidal rotation, MC ion Bernstein wave on poloidal rotation.
  - **TFTR:** MC poloidal flow drive, direct-launch IBW poloidal flow drive.
  - **Other tokamaks:** Alfven wave toroidal flow drive on Phaedrus-T; direct launch IBW poloidal flow drive on PBX-M, FTU, Alcator C, etc.

- **Theory and modeling:**
  - MC flow drive theory by AORSA 2-D full wave simulation.
  - General RF wave flow drive theory and modeling.

- **We have demonstrated toroidal and poloidal flow drive using mode conversion on Alcator C-Mod.**
Alcator C-Mod Tokamak

Heating sources
**ICRF: 8 MW**
LH: 3 MW

R = 0.67 m
a = 0.22 m
B_t = 2 – 8 T
I_p = 0.2 – 2 MA
n_e0 = 0.2 – 15 \times 10^{20} \text{ m}^{-3}
T_e \sim T_i = 1 – 6 \text{ keV}
ICRF System for MC Flow Drive Experiments

<table>
<thead>
<tr>
<th>Two 2-strap Antennas</th>
<th>One 4-strap Antenna</th>
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<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td><strong>Source Power</strong></td>
</tr>
<tr>
<td>80 MHz for D(H) minority heating</td>
<td>2 x 2 MW</td>
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<tr>
<td>50 MHz for D(^3)He mode conversion</td>
<td>4 MW</td>
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Main Diagnostics and Simulation Tools

- **Rotation measurement:** High resolution x-ray crystal spectral tomography
  - Passive (no need for a neutral beam).
  - Rotation from Doppler shift of $\text{Ar}^{16+}$ (He-like) and $\text{Ar}^{17+}$ (H-like) lines.

- **Wave detection:** Phase contrast Imaging (PCI) [N. Tsujii, P-A41, this conference]
  - Measures line-integrated density fluctuations.
  - rf waves can be detected using a heterodyne scheme.

- **ICRF wave physics simulation:** TORIC
  - Solving Maxwell’s equation in 2-D.

- **Momentum transport modeling:**
  - Solving momentum transport equation in cylindrical coordinates
X-Ray Crystal Spectral Tomography for Rotation Measurement

- Flux-surface-averaged toroidal rotation $V_{I,\phi}(\psi)$, and poloidal rotation $V_{I,\theta}(\psi)$ can be obtained (after inversion) from the line-shift of multiple line-integrated spectra.

- Temporal resolution: 200 Hz

- Spatial resolution: $\sim 1$ cm
Phase Contrast Imaging (PCI) for MC Wave Detection

Basic setup:

- Plasma density fluctuations introduce phase variations to a laser beam passing through plasma vertically.

- Laser phase variations are converted to intensity variations by a $\lambda/4$ phase plate.

Heterodyne scheme for RF wave detection:

- Modulate the laser power at a frequency very close to the RF frequency.

- RF wave induced density fluctuation can be detected at the beat frequency.

- 32 line-integrated measurements. $k_R$ up to 15 cm$^{-1}$. 
Basics for ICRF Minority Heating (MH) in D(H) Plasmas

Minority Heating
80 MHz, 5.1 T, 4% H

Doppler broadened H cyclotron layer for fast wave overlaps D-H hybrid layer at a small $\Delta \leq 2$ cm for C-Mod, determined by the ratio of species concentration.

Doppler broadening:

$$\omega = \omega_c + k_{\parallel}v_{\parallel}$$

Fast wave (launched from the antenna) is mostly absorbed by the H ions through cyclotron resonance.
Basics for ICRF MC Heating in D\(^{(3\text{He})}\) Plasmas

Doppler broadened \(^{3}\text{He}\) cyclotron layer for fast wave does not overlap D\(^{-3}\text{He}\) hybrid layer at a larger \(\Delta \geq 2 \text{ cm for C-Mod}\).

Fast wave undergoes mode conversion at the hybrid layer → ion Bernstein wave (IBW) and ion cyclotron wave (ICW).

The MC waves then deposit energy directly to the electrons via Landau damping and to ions via cyclotron resonance.
MC Waves: IBW and ICW as Mentioned in an Early Review Paper


![Graph showing IBW and ICW](image)

**Fig. 5.**—Perpendicular wave number profiles in TFR, assuming a deuterium plasma containing 20% of hydrogen ($n_e = 1.10^{14}$ cm$^{-3}$; $B_z = 45$ kG; $f = 60$ MHz; $k_z = 10$ m$^{-1}$).

(a) In the equatorial plane for a cold plasma. (b) In the equatorial plane for $T_e = T_i = 1$ keV. (c) 10 cm above the equatorial plane for $T_e = T_i = 1$ keV.

Outside the equatorial plane and for a large enough value of the poloidal field, the slow wave will now transport the r.f. power towards the low field side of the plasma, with a gradual increase of $n_{||}$ as the wave approaches the minority ion cyclotron layer. The slow wave which can now be identified with the “ion cyclotron wave” originally suggested by Stix for ion heating in Stellarators [18] will thus transport part of the wave power incident from the high magnetic field side towards the cyclotron layer favouring ion heating outside the equatorial plane.
Compare Rotation in MC vs. MH @ Similar Plasma Condition

Compare MH (fast wave) heating and MC (slow wave) heating at the same B field, current, density, and also similar rf power deposition location in upper null L-mode plasmas.

→ Substantial difference in plasma rotation!

Minority Heating
80 MHz, 5.1 T, 4% H

Mode Conversion
50 MHz, 5.1 T, 10% \(^{3}\)He

Compare MH (fast wave) heating and MC (slow wave) heating at the same B field, current, density, and also similar rf power deposition location in upper null L-mode plasmas.

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$\Delta V_\phi (r=0)$ in MC Plasmas $> 2 \times$ that in MH Plasmas

**Mode Conversion:**
- $\Delta V_\phi \approx 90 \text{ km/s at 3 MW 50 MHz rf}$
- Co-current direction.
- Broad centrally-peaked profile

**Minority Heating:**
- $\Delta V_\phi \approx 35 \text{ km/s at 3 MW 80 MHz rf}$
- Co-current direction.
- Flat (slightly hollow) profile.
- Intrinsic plasma rotation
MC $\Delta V_\phi$ Exceeds Intrinsic Scaling (> a factor of 2)

- **Mode Conversion:**
  - More than a factor of 2 above the intrinsic rotation scaling

- **Minority Heating:**
  - $\Delta V_\phi \propto (\Delta W/Ip)$
  - Follows the empirical intrinsic rotation scaling
Localized Poloidal Rotation up to 2 km/s @ 3 MW Power

**Mode Conversion:**
- $\Delta V_\theta$ up to 2 km/s at 3 MW power.
- Ion diamagnetic drift direction.
- Localized.

**Minority Heating:**
- $\Delta V_\theta \sim 0$.
- No clear spatial structure.
MC ICW Detected by PCI, Consistent with Previous Studies

- MC ICW detected by PCI at about ~ 4 cm away from the $^3$He IC resonance and on the HFS of magnetic axis ($R_0 \sim 68$ cm).

- Wave number $k_R \sim 3$-7 cm$^{-1}$, consistent with observations in previous MC experiments and dispersion equation solution.
MC ICW is damped strongly onto $^3$He ions through a substantially broadened IC resonance.

$$\omega = \omega_{c, ^3He} + k_{||} v_{||}$$

Fast wave: $k_{||} \sim 10$ m$^{-1}$
MC ICW: $k_{||} \sim 40-50$ m$^{-1}$

More details: N. Tsujii, P-A41, this conference
MC ICW Ion Deposition has a Broad Profile

Hypothesis:
- MC ICW absorption on $^3$He ions $\rightarrow$ flow drive.
- $^3$He level:
  Minority heating $<$ MC ICW ion heating and flow drive $<$ MC electron heating.

Not clear how to calculate the drive force from the first principle.

But we can make an estimate from the experimental rotation data.
Estimate the Effective Force through $V_\phi$ Transport Modeling

\[ n_i m_i \frac{\partial V_\phi(r,t)}{\partial t} + \nabla \cdot \Gamma_P = n_i(r)m_i \alpha(r,t) \]

\[ \Gamma_P = -\chi_\phi m_i \frac{\partial}{\partial r} [n_i(r)V_\phi(r,t)] + n_i(r)m_i V_c(r) \]

**Assumptions:**

- $\chi_\phi = \text{constant in time and space, momentum diffusivity}$
- $V_c \propto r/a$, a phenomenological convective velocity
- **Effective total force:**
  \[ F(t) \approx 4\pi^2 R_0 m_i \int_0^a n_i(r)\alpha(r,t)rdr \]

**Procedure:**

- Calculate $V_\phi(r,t)$ for $\alpha(r,t)$ and $\chi_\phi$ and $V_c$, then scale the resulted $V_\phi(r,t)$ to match the modeling result and experimental data.
- Scan $\chi_\phi$ and $V_c$ to find the best match.
- Calculate effective total force.
Exp. + Model $\rightarrow$ Total Drive Force: 0.03-0.05 N per MW MC ICW

- If we assume $\alpha(r, t) \propto$ MC ICW power to ions profile
  $\rightarrow$ Best match: $\chi_\phi = 0.1$ m$^2$/s, $V_c = -2 \times r/a$ (m/s)

- Estimated total toroidal force $\sim$ 0.03-0.05 N per MW ICW power in order to match experimental data. ($\sim$ 0.02 N per MW total RF power)

- Simple estimate of toroidal force from the launched Fast wave (Power/Velocity) $\sim$ 0.03 N per MW.

- Implication: A momentum imbalance (either from source or dissipation) may be sufficient to provide the driving force.
Needs Support from Further Theoretical Work

• Possibility of MC ICW flow drive has been shown by AORSA (2-D full wave simulation) \[E.F. \text{Jaeger et al, PRL (2003)}\], but the magnitude is smaller than our observation.

• The magnitude of $V_\phi$ and $V_\theta$ are comparable to previous analytic estimates based on direct launch IBW (no MC considered) \[J.R. \text{Myra and D.A. D’Ippolito, Phys. Plasma (2002)}\].

• Observed rotation has a weak dependence on antenna phase (same rotation direction, similar magnitude)
  - Intrinsic asymmetry in the MC process to ICW?
  - Momentum transport? Asymmetric momentum dissipation?

Evidence from TFTR/JET, and scenarios on ITER.
TFTR: MC Flow Drive $\rightarrow$ MC ICW $^3$He Ion Absorption?

- D-$^4$He-$^3$He plasmas, 2 MW RF + 5 MW of NB.
- (Minority heating) $<^3$He fraction $<$ (Efficient MC electron heating).
- Temporal evolution correlates with the applied ICRF power.
- $\Delta V_\theta$ very localized, between MC and IC surfaces $\rightarrow$ MC ICW
- The reported result is not inconsistent with our hypothesis that MC ICW ion heating may drive plasma flow.

JET: D(³He) Plasmas @ 8-14% ³He → Significant MC ICW ³He Heating

- At 4% ³He, fast wave minority heating.
- At 20% ³He, MC electron heating.
- At 8-14% ³He, significant ³He ion heating via MC ICW.
- Now, dare to predict MC flow drive on JET? Any evidence from existing data?

B₀ = 3.45 T, Iₚ = 2.8 MA, f = 33 MHz

Y. Lin, Invited talk, 18th Topical Conference on RF Power in Plasmas, June 2009, Gent, Belgium
JET: Same Trend as MC ICW Ion Absorption, $\omega_\phi$ Peaked @ 12% $^3$He

- MC ICW ion heating from TORIC peaks @ ~10% $^3$He.
- (Previously unnoticed) rotation in JET ITB plasmas with $^3$He scan peaked ~ 100,000 rad/s @ 12% $^3$He.
  - Strong NB heating, but to explain the trend and the 70% increase in rotation, one has to rely on RF physics $\rightarrow$ ICRF MC flow drive.
- Dedicated JET experiment in near future (JET/C-Mod collaboration).
ITER: $^3$He Minority [T-D($^3$He)] $\rightarrow$ No MC Ion Heating

- $40\% T + 40\% D + 10\% ^3$He. $T_i = 20$ keV, $T_e = 24$ keV.
- $f = 53$ MHz, $B = 5.3$ T
- Fast wave electron heating and ion heating ($\Omega_{^3}$He and $2\Omega_T$)
- Nearly no mode conversion
- Same as $^4$He($^3$He) plasmas in non-radioactive phase.
ITER: Inverted Minority (T)-D \(\rightarrow\) Strong MC Ion Absorption

- \(8\% T + 92\% D, D\ IC\) out of plasma, \(T\ IC\) near axis. \(T_i = T_e = 10\) keV
- \(f = 27\) MHz, \(B = 5.3\) T
- Strong MC and T ion heating from MC waves.
- 70\% power to T ions via MC ICW and IBW \(\rightarrow\) for flow drive?
- Same as \(^{3}\)He)-H in non-radioactive phase but needs testing on existing machines.
ITER: D-T Plasma with $^7$Li → Some MC Ion Absorption

- 50% T, 42.5% D, 2.5% $^7$Li and $^7$Li IC near axis. $T_i = T_e = 10$ keV.

- $f = 34$ MHz, $B = 5.3$ T

- ~10% of total power to $^7$Li ions through ICW and IBW.

- A potential candidate for flow drive, but difficult to verify on existing machines.
Summary and Plan

Summary

• Direct RF driven toroidal and poloidal rotation has been observed in ICRF MC heated D($^3$He) plasmas on Alcator C-Mod.

• The interaction between the MC ICW and $^3$He ions is thought to be the mechanism.

• Momentum transport modeling gives an estimate of effective force of $\sim$0.02 N per MW total RF power.

• Scenarios for MC ICW ion absorption have been identified for ITER.

Plan

• Optimize flow drive on Alcator C-Mod.

• Verify flow drive on other tokamaks with ICRF capability (e.g., JET).

• Understand the mechanism with theory/modeling efforts.

• Study turbulence suppression through flow shear generation and develop flow drive as a useful knob.