Mode Conversion, Current Drive and Flow Drive with High Power ICRF Waves in Alcator C-Mod: Experimental Measurements and Modeling†

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Introduction and Highlights

- Mode converted waves in the vicinity of the ion-ion hybrid layer have been measured in Alcator C-Mod by means of Phase Contrast Imaging (PCI) diagnostic.
- Measured $k$-spectrum and spatial location of the waves is in agreement with theoretical and code predictions.
- For appropriate ion species (i.e., $\text{H}^-\text{He}$ in C-Mod, which is equivalent to $\text{D-T}$ in ITER), mode-conversion of the fast magnetosonic wave (FW) into the electromagnetic ion cyclotron waves (ICW) dominates over ion Bernstein waves (IBW).
- TORIC predicts mode conversion current drive of the order of 100 kA at 3 MW RF power at $n_e=10^{20}$ m$^{-3}$, $T_e=5$ keV ($\eta_{\text{CD}} = 0.1T_e[10\text{keV}]$ as for FW, but is reduced by MC efficiency $\approx 0.5$).
- Flow drive experiments with MCICW waves inconclusive, need better theoretical predictive capability.
- Measurement of MC waves on an absolute scale next step.
ICRF Mode Conversion

- In multi ion-species plasma (e.g. D-T) fast wave dispersion indicates possible mode conversion from fast wave (FW) to ion Bernstein (IBW) or ion cyclotron waves (ICW) in the sheared magnetic field of a tokamak.

- Narrow deposition may provide tool for modifying or controlling pressure and current profiles; efficiencies remain to be determined.

- Mode conversion power flow, current drive and flow drive need to be measured in present day experiments and full wave codes verified for predictive capability for future experiments (i.e, ITER).

Cold plasma, fast wave dispersion relation:

\[ n_{\perp}^2 = \frac{(n_{\parallel}^2 - R)(n_{\parallel}^2 - L)}{S - n_{\parallel}^2} \]

R, L and S are Stix notation

Dispersion relation in MC region
Simulation indicates waves with wavelengths ranging from 0.1 cm to 10 cm.

- IBW is typically $\sim$0.5 cm
- ICW is $\sim$1-2 cm, and
- FW is $\sim$10 cm.

Mode conversion to IBW or ICW depends strongly upon sheared magnetic field:
- Toroidal mode number, $N_\phi$, is conserved.
- $k_\theta$ and hence $k_\parallel$ rapidly upshift.

Mode converted ICW dominate the current or flow drive rather than IBW.
TORIC is a Finite Larmor Radius Full Wave Code

Solves Maxwell’s equations for a fixed frequency with a linear plasma response in a mixed spectral-finite element basis.

\[ \nabla \times \nabla \times \mathbf{E} = \frac{\omega^2}{c^2} \left\{ \mathbf{E} + \frac{4\pi i}{\omega} (\mathbf{J}^P + \mathbf{J}^A) \right\} \]

- \( \mathbf{J}^P \) is the plasma current response expressed using a FLR expansion up to second order in \( k_{\perp \rho_i} \);
- \( \mathbf{J}^A \) is the current sheet that models the antenna.
  - Defined to have the same poloidal extent and radial location as the real antenna.
  - Solve for single toroidal mode
  - To model experimental antenna, sum over antenna \( N_\phi \) spectrum.

\( \mathbf{J}^P = \sigma \cdot \mathbf{E} \) where \( \sigma \Rightarrow \sigma (k_{\perp \rho_i} < 1) \)

\[ E(x) = \sum_M E_M^N (\psi) \exp(i(M\theta + N_\phi \phi)) \]
TORIC Dielectric model includes IBW, ICW, FW

Electron Landau damping (ELD) of mode converted waves must be treated more precisely.

- ELD is underestimated using FLR expansion.
- Model damping by adding an imaginary part, $\delta \sigma$, to the FLR coefficient, $\sigma$, including all orders of $k_\perp \rho_i$.

Advantages of this approach include:

- Simulates ELD predicted by the local dispersion relation,
- Modifies only the mode converted wave,
- Mode conversion efficiency is unaffected,
- Computationally less intensive.

$$\sigma \Rightarrow \sigma + \delta \sigma$$

$$\delta \sigma = -i \sigma \frac{\text{Im}\{n_\perp^2\}}{n_\perp^2}$$

Benchmarked against AORSA (2-D all orders in $k_\perp \rho_i$) and METS (1-D all orders in $k_\perp \rho_i$) code and shown to have agreement.

- Power partition between electrons and ions were shown to agree.
- E-field structure qualitatively agreed.
Computational Requirements are Scenario Dependent

Large number of poloidal modes are required to describe mode conversion scenario.

- Presence of IBW implies $k_\perp \rho_i \sim 1$ and if $k_\perp \sim m/r$, then $M_{\text{max}} \sim r/\rho_i < 255$, for C-Mod parameters.

TORIC has had numerous algorithm upgrades and been parallelized.

- Was extended to run with EFIT files for discharge analysis.
- Refined additional post processing for comparison with experimental data.

Run routinely on in house 48 processor, parallel cluster.

- 255 modes require 9.5 hours on a single 1.2 GHz Athlon processor with 2 GB RAM. (only 40 minutes on 24 nodes.)

Offers powerful tool to model ICRF experiments.
Three Antennas Couple ICRF Power from 4 transmitters

<table>
<thead>
<tr>
<th></th>
<th>D &amp; E Antennas</th>
<th>J Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>~ 80 MHz</td>
<td>40-80 MHz</td>
</tr>
<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>Phase</td>
<td>Fixed dipole</td>
<td>variable</td>
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Phase Contrast Imaging (PCI) Diagnostic Techniques

- Phase Contrast Imaging (PCI) measures the line integrated electron density fluctuations.
- PCI can simultaneously resolve a wide spectrum of wave-numbers over wide radial region.
- Poor spatial localization along beam chord.
- High frequency RF waves (80 MHz) can be detected by heterodyne or better, optical modulation techniques.
- 32 chords cover 60 cm < R < 79 cm, typically 62 cm to 74 cm.
  - $0.4 < |k_R| < 10 \text{ cm}^{-1}$
  - Frequency response is 2 KHz to 5.0 MHz.

\textbf{Sensitivity:}

- $10^{12} \text{ m}^{-2}/\text{Hz}^{1/2}$ (direct)
- $3 \times 10^{13} \text{ m}^{-2}/\text{Hz}^{1/2}$ (heterodyned)
In Phase Contrast Imaging, the Density Perturbations are Imaged on the Detector

- Before phase plate: \( E_0(1 + i\Delta \phi) \)
- After phase plate \( E_0(i + i\Delta \phi) \)
- \( I \propto |E|^2 = E_0^2(1 + 2\Delta \phi) \)

Phase Change represents plasma density

- Index of refraction for laser
  \[ N = (1 - \frac{\omega^2_{pe}}{\omega^2})^{\frac{1}{2}} \approx 1 - \frac{\omega^2_{pe}}{2\omega^2} \]

- Phase shift depends on density
  \[ \Delta \phi(R) \approx \int (N - 1)dz \propto \int \tilde{n}(R, z)dz \]

- Each detector channel \( i \) maps to a “radius” \( R_i \) (\( \perp \) to beam).
  Each signal is \( s_i = \int \tilde{n}(R_i, z)dz \)
High Frequency Beam Modulation Method

- acousto-optical frequency shifter
- beam modulation setup

- To measure RF waves, the laser is modulated near the RF frequency
- RF density fluctuation is measured at the beat frequency between the RF and the beam modulation
RF wave driven density fluctuations are proportional to the divergence of the perturbed velocity.

\[
\frac{\tilde{n}_e}{n_{e0}} = \frac{-i}{\omega} \nabla \cdot \tilde{\mathbf{v}}_e
\]

\[
\tilde{\mathbf{v}}_e \approx -i \frac{\Omega_e}{\omega} B_0 \frac{E_\zeta}{B_0} \hat{\zeta} + \frac{E_\eta}{B_0} \hat{\psi} - \frac{E_\psi}{B_0} \hat{\eta}
\]

\[
\frac{\Omega_e}{\omega} \gg 1 \text{ and } E_\eta \sim E_\psi
\]

- Where perturbed velocity and E-field is written in local Stix coordinates.
- Simple rule for predicting dominant contribution is difficult because it is a function of both wavelength and field strength.

Line integrate calculated 2-D fluctuations and use same analysis as used for experiment.
Electron Power Deposition Profile: Measured and Simulated

Measured power deposition profile and simulation are in good agreement. Measured deposition profile is determined from “break in slope” of electron kinetic stored energy.

- Assume density is constant
- Typically $\Delta<1.5$ msec.

$$S_{abs} \approx \frac{3}{2} n_e \Delta \left\{ \frac{\partial T_e}{\partial t} \right\}$$

TORIC power deposition is calculated for each $N_\phi$. Total absorbed power is sum over vacuum spectrum, $G(N_\phi)$ weighted by the coupling efficiency for that $N_\phi$.

$$S_{abs}^{TORIC} = \sum_{N_\phi} G(N_\phi) \frac{R_L(N_\phi)}{\sum R_L(N_\phi)} P_{abs}^{TORIC}(N_\phi)$$

D plasmas with ~20% H $B_T=5.2$ T, $I_p = 0.8$ MA $n_{e0}=2.4 \times 10^{20}$ m$^{-3}$
ICRF (80.5 MHz, $n_\phi \sim 10$ cm$^{-1}$) mode conversion experiments in H-$^3$He(D) \{H:33\%, $^3$He: 23\%, D:21\%\} L-mode discharges at 5.8 T, $I_p \sim 0.8$ MA, $T_e=T_i=1.5$ keV, and $n_{e0} \sim 2.4 \times 10^{20}$ m$^{-3}$.

Measurements indicate:

- An intermediate wavenumber 7 cm$^{-1}$ (or $\lambda \sim 0.9$ cm)
- Propagating back towards the antenna
- On the low field side of the mode conversion surface.
The electromagnetic dispersion relation and TORIC simulation predict:

- Wavenumber agrees with experimentally measured value and
- Wave propagates on LFS of mode conversion layer.

Wave is identified as an electromagnetic ion cyclotron wave (ICW).

H-^3^He(D) {H:33%, 3He: 23%, D:21%}
L-mode discharges at 5.8 T, I_p~0.8 MA, 
T_e=T_i=1.5 keV, and n_e0~2.4x10^{20} m^{-3}. 

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First Identification of ICW in a Tokamak
$B_\theta$ Modifies Mode Conversion Physics

Presence of $B_\theta$ allows coupling of the FW to the ICW (Perkins, 1977).

- Mode converted waves are characterized by relatively large $m$ [$|m| > 100$]:

$$k_\parallel \approx \frac{m}{r} \frac{B_\theta}{B} + \frac{n_\phi}{R} \frac{B_\phi}{B}$$

Fields are up-down asymmetric for the mode converted waves.

- $k_\theta$ is negative above the midplane and positive below

For $N_\phi > 0$, $k_\parallel$ upshifts for waves propagating in lower half plane

- Waves damp rapidly

For $N_\phi > 0$, $k_\parallel$ reverses sign – in the upper half plane.

- Waves propagate further before damping
First Measurements of Mode Conversion Region

ICRF (50 MHz, $n_\phi \sim 7$ cm$^{-1}$) mode conversion experiments in $D(^3$He, H) L-mode discharges:
- $B_T = 5.1-5.6$ T, $I_p \sim 1$ MA,
- $T_e = T_i = 2.2$ keV, and $n_e_0 \sim 2 \times 10^{20}$ m$^{-3}$.

Expect mode conversion ICW and IBW within PCI view.

Measured forward and reflected FW.

Interference pattern from the two mode converted waves.
PCI Profile is Modified as Mode Conversion Shifts Near Axis

As expected, mode conversion shifts towards magnetic axis as $B_T$ is increased.
Profile also evolves as $B_T$ is increased.

- Density fluctuation is line integral of $k \cdot E$.
- Geometry effects on 1-D profile.

Analyze TORIC simulation with same analysis programs.
Remarkable Agreement Between Experiment and Simulation

Shape of the line integrated perturbed density profile is also in good agreement with experiment. Measured wave numbers and their evolution are also in agreement. Comparison of absolute experimental and simulation amplitudes is next step in this comparison.
Current on a flux surface is calculated by integrating the local driven current over the flux surface.

\[
J_{RF}(\psi) = \int_0^{2\pi} d\theta \sum_m G_{RF}^m(\psi, \theta_i) \sum_{m'} P_{abs}^{m,m'}(\psi, \theta_i)
\]

\[
G_{RF}^m(\psi, \theta_i) = G_{RF}(v_\parallel = \omega/k_\parallel, \varepsilon = r/R)
\]

- \(G_{RF}^m(\psi, \theta_i)\) is parametrization of the current drive efficiency computed from adjoint solution to Fokker Planck equation.
- \(P_{abs}^{m,m'}\) is the local absorbed power for a given \(N_\phi\).

Trapping is included by convolving the local absorbed power with the local current drive efficiency.

Variation in \(k_\parallel\) is directly accounted because the power absorption is reconstructed as a function of poloidal mode and convolved with local current drive efficiency.
Sawtooth Changes Suggest Local Driven Current

Performed on a series of L-mode, D(3He) discharges at 8 T to investigate MCCD.

- Power absorbed by electrons is ~0.3 MW, ~20% of total power.
- Simulation suggest RF driven current is ~10 kA.

With the deposition peaked near the sawtooth inversion radius, sawtooth period increases with Ctr-CD phasing and decreases with Co-CD phasing.

Ref.: Bhatnagar et al, Nucl. Fusion
Vol. 34, 1579 (1994)
For Ctr-CD phasing, the sawtooth period increases for deposition near the q=1 but unchanged with the deposition peaked away from q=1. Suggests a localized driven current.
Identified Scenario with High MCCD

Identified model scenario to maximize MCCD.
• 100 kA at 3 MW RF power
• $\eta_{CD} = 0.1T_e$ (where $T_e$ is in units of 10keV) as for FW, but is reduced by MC efficiency $\approx 0.5$.
• On-axis MCCD $j(r)$ exceeds local ohmic current density. Current is driven predominantly by the ICW.
  • IBW is bipolar and $j_{\text{max}}$ is $\sim$20 times less than ICW.
  • Current reversal results from up-down asymmetry.

Modeled target discharge:
• $B_T=5.4$ T,
• $I_p=0.8$ MA,
• $n_{e0} = 1.0 \times 10^{20}$ m$^{-3}$,
• $T_{e0} = 5$ keV, and
• 65% D, 15% $^3$He, 5% H
• J antenna@ 50 MHz (MCCD)
• D and E-antenna@ 80 MHz
Flow Drive using Mode Converted Waves

- A critical physics issue for AT and BPX is active control of pressure profile and ITB trigger and location.

- Theoretical calculations suggest sheared flow is possible if the ICW is damped at the ion cyclotron resonance (Jaeger, PRL 90 195001, (2003)).
  - RF force changes sign across the resonance.
  - Plasma response to RF force is larger for ion rather than electron absorption.

- Use mode converted ICW to damp on ions at the cyclotron resonance.
Initial Experimental Results on Flow-Drive

- Performed experiments on a series of L-mode, D($^3$He) discharges at 8 T to investigate flow drive via mode converted waves:
  - RF frequency is 78 MHz
  - $B_T \sim 8$ T, $I_p \sim 0.8$ MA, $n_{e0} \sim 2 \times 10^{20}$ m$^{-3}$, and $T_e = T_i = 3$ keV
- To date, measurements indicate no clear evidence of flow drive
- Simulations indicate that most of the power is damped by electrons before reaching the ion cyclotron layer:
  - Near the mode conversion surface, strong electron Landau absorption is predicted
  - Due to the large Doppler broadened resonance ($\sim 10$ cm) resulting from the $k_\parallel$ upshift, the ion absorption is quite broad, reducing the local Reynolds stress
Summary

- Mode converted waves in the vicinity of the ion-ion hybrid layer have been measured in Alcator C-Mod by means of a novel Phase Contrast Imaging (PCI) diagnostic technique.
- Measured $k$-spectrum and spatial location of the waves is in agreement with theoretical and code predictions.
- For appropriate ion species (i.e., H-3He in C-Mod, which is equivalent to D-T in ITER), mode-conversion of the fast magnetosonic wave (FW) into the electromagnetic ion cyclotron waves (ICW) dominates over ion Bernstein waves (IBW).
- TORIC predicts mode conversion current drive of the order of 100 kA at 3 MW RF power at $n_e=10^{20}\text{m}^{-3}$, $T_e=5\text{ keV}$; experiments are in progress to measure this current.
- To date, a few tens of kA may have been driven based on sawtooth behavior during non-optimized MCCD experiments.
- Flow drive demonstration has not been successful yet, and theoretical analysis to optimize success is in progress.
References