Mode Conversion in Three Ion Species ICRF Heating Experiment

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ICRF antennas on Alcator C-Mod

Field-aligned 4-strap antenna at J port (78 MHz)

Two 2-strap antennas at D-port (80.5 MHz) and E-port (80 MHz)

Total RF source power: 4 x 2 MW transmitters.
- D and E antennas are each powered by one transmitter and provide up to 1.8 MW (combined up to ~ 3.6 MW) RF power to plasma.
- J antenna is powered by 2 transmitters and provides up to 3 MW power to plasma.

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Phase contrast imaging system (PCI)

- Plasma density fluctuations introduce phase variations to the laser beam.
- Laser phase variations are converted to intensity variations by a $\lambda/4$ phase plate.

- Acoustic-optical frequency shifter to modulate the laser beam to have a beat-frequency near the RF frequency (heterodyne scheme).
- RF waves can be measured in this setup at the beat frequency.


- The system has recently been upgraded to have higher sensitivity at high frequencies and better calibration.

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PCI is in front of E antenna but some toroidal angles away from D and J
RF signals shown in PCI data

RF wave appears as a coherent signal in the PCI spectra (contour image in frequency and time);

Signal amplitude is indicative of the wave E field amplitude;

Signal phases from different PCI channels $\leftrightarrow k_R$ of the RF waves.

80 MHz RF signal from E antenna, shown in PCI spectra at ~880 kHz after heterodyne modulation.

For this typical D(H) minority heating plasma, the PCI signal is mostly from the fast wave.
ICRF 3-ion heating scenario

- Majority D and H, e.g., ~50% each
- And small amount of $X[^3\text{He}] = n_{^3\text{He}}/n_e \sim \leq 1\%$
- $\Rightarrow ^3\text{He}$ cyclotron resonance in the vicinity of both the D-$^3\text{He}$ hybrid layer and $^3\text{He}$-H hybrid layer.
- Potentially strong absorption on $^3\text{He}$ ions due to favorable wave polarization at the $^3\text{He}$ cyclotron resonance.
- This scenario can be used for general plasma heating and also for fast ion generation, e.g., fast ion confinement study on W7-X.
- It is also possibly applicable for ITER D-T plasma heating.
ICRF waves in a 3-ion species plasma

- Two mode conversion (MC) layers exist: on the HFS and the LFS of the $^3\text{He}$ IC resonance.
- Mode conversion to the ICW (ion cyclotron wave) is a result of $k_\parallel$ up-shift caused by the magnetic shear at where $B_{\text{pol}} \neq 0$. MC IBW (ion Bernstein wave) is an electrostatic hot plasma wave.

Stix’s notations

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

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Energetic ions are generated in plasmas with low $^3$He and high RF power

- AE activities are indicative of the existence of a population of energetic $^3$He ions near the plasma center.
- $X[^3\text{He}] = n_{^3\text{He}}/n_e \sim 0.6\%$, $P_{\text{ICRF}} \sim 4$ MW

(More discussion in Kazakov’s and Wright’s talks)
Heating effectiveness strongly depends on the amount of $^3$He puffed.

- Best effective heating occurs at $X[^3\text{He}] = n_{^3\text{He}}/n_e \sim 0.5\%-1\%$.
- This study focuses on the two plasma shots, 1160901015 (75 ms $^3$He puff, 0.4 Torr-liter) and 1160901016 (200 ms $^3$He puff, 1.5 Torr-liter).
- In both shots, mode conversion was clearly observed by PCI.

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Shot 1160901015 (75 ms $^3$He puff) - double MC observed in PCI

- PCI has 32 channels, covering $0.64 \text{ m} < R < 0.74 \text{ m}$.
- Two peaks are observed at $R \sim 0.64 \text{ m}$ and $R \sim 0.71 \text{ m}$, corresponding to the HFS and LFS MC layer locations. Ion cyclotron resonance is at $R = 0.69 \text{ m}$.

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Determine $X[\text{^3He}]$ and $X[\text{H}]$ from the two observed MC locations

- The location of the two MC locations from PCI can be used to estimate $X[\text{H}]$ and $X[\text{^3He}]$
  - Larger $X[\text{H}]$ moves both layers to HFS;
  - Larger $X[\text{^3He}]$ increases the distance between the two layers.

- $X[\text{H}] \approx 65\%$ and $X[\text{^3He}] \approx 0.9\%$ have the best match.
MC locations vs. X\(^{3}\text{He}\) and X[H]

Increasing X\(^{3}\text{He}\) moves the two MC locations farther apart.

The distance in-between is approximately proportional to X\(^{3}\text{He}\).

Increasing X[H] moves both MC locations towards higher field side.

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TORIC simulation shows E-field pattern for strong ion absorption

E+ is the electric field that has left-hand polarization, i.e., ion cyclotron motion direction.

Note strong E+ on both sides of IC resonance.

• TORIC is a 2-D ICRF simulation code. Simulation using $X[H] \approx 65\%$ and $X[^3\text{He}] \approx 0.9\%$, RF frequency 78 MHz, and equilibrium of shot 1160901015.

• Shown are E fields for the case of toroidal mode $n_\phi = -13$. $R_{mgx} \approx 68$ cm, the magnetic axis.

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PCI also provides $k_R$ spectrum of the MC waves, in agreement with TORIC

- The observed MC waves have $k_R \sim 4 \text{ cm}^{-1}$, corresponding to $\lambda_R \sim 1.6 \text{ cm}$.
- In agreement with the field pattern of the short-wavelength waves shown in the TORIC simulation.

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Power deposition to ions and electrons in 2-D from simulation

\[ X[H] = 65\% , \quad X[^{3}\text{He}] = 0.9\% \]
\[ n_\phi = -13 \]
\[ f = 78 \text{ MHz} \]
\[ B_{t0} = 7.8 \text{ T} \]

- Power deposition to \(^3\text{He}\) ions is through the interaction of \(^3\text{He}\) ions with fast wave and the MC waves at the resonance;
- Power to electrons is mostly through MC waves and relatively much weaker.

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RF power mostly goes to the $^3$He ions

- For this plasma, most RF power is absorbed by the $^3$He ions.
- 69% to $^3$He ions, 30% to electrons, and the rest to D and H ions.
- See Wright - TO4.012 for simulation on how the fast ions are generated.
Shot 1160901016 (200 ms $^3$He) – only HFS MC layer shown in PCI (78 MHz)

- With increase of $^3$He, the distance between the HFS and LFS MC layers are increased.
- Only the HFS MC at $R \sim 0.64$ m is observed in the PCI window for J antenna power at 78 MHz and the LFS MC is out of the PCI window.

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The LFS MC is observed at 80.5 MHz

- The LFS MC at R ~ 0.74 m appears in 80.5 MHz D antenna signal, while the HFS MC at this frequency is out of the PCI window.

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Combined the observation of at 80.5 MHz and 78 MHz → $X[H]$ and $X[3He]$

- $X[H] \approx 58\%$ and $X[3He] \approx 2.8\%$ is the best match to the observed MC locations.
Electric field pattern is not conducive for ion absorption

- Clear short wavelength MC waves appear at both HFS and LFS MC layers.
- IC resonance is quite far away from the region with large E+ field. The Doppler broadening of the resonance (∼±1 cm for thermal ions) would be insufficient for strong ion absorption.

X[H] = 58%, X[³He] = 2.8%
nφ = −13
f = 78 MHz
Bₜ₀ = 7.8 T

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Power deposition to ions is weaker than to electrons

- Power deposition to $^3$He ions is much weaker than in shot 1160901015;
- Power to electrons is through MC waves and it is much broader and stronger than that in shot 1160901015.

$X[\text{H}] = 58\%$, $X[^3\text{He}] = 2.8\%$

$n\phi = -13$

$f = 78$ MHz

$B_{t0} = 7.8$ T
Most RF power goes to electrons via mode conversion electron heating.

- 15% power to $^3$He ions, 82% power electrons and the rest to D and H ions.
- Power to electrons is off-axis and broad.
- Heating effectiveness (increment in stored energy vs. $P_{RF}$) is low.
Summary

• RF waves have been measured by PCI in the 3-ion species ICRF heating experiment;

• Double mode-conversion has been confirmed, and the PCI measurement is used to infer the species concentrations;

• TORIC simulation shows that for the low $^3$He scenario ($X[^3\text{He}] < 1\%$), most RF power is deposited to ions and such power deposition can generate energetic ions at high RF power.

• At higher level of $X[^3\text{He}]$, most RF power is deposited to electrons via mode conversion, and heating effectiveness is significantly reduced.

More on 3-ion ICRF heating experiment on C-Mod and JET:
Yevgen Kazakov – Invited talk NI3.005, Wednesday morning
John Wright – ITER session TO4.012, Thursday morning