Mode conversion at the ion-ion-hybrid resonance in multidimensional tokamak plasmas

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Abstract:

Two-dimensional full-wave models have been used to simulate mode conversion near the ion-ion hybrid resonance in tokamak plasmas. Results show that, for high minority ion concentrations, mode conversion is dominated by a transition from the fast magnetosonic wave to the slow ion cyclotron wave (ICW) [1]. Unlike the ion Bernstein wave, the ICW is a cold plasma wave that propagates on the low field side of the mode conversion layer. It can be damped by ions as well as electrons, and the resulting ion interaction provides bulk ion heating as well as sheared poloidal flow at the mode conversion layer.

[1] F. W. Perkins, Nucl. Fusion 17, 1197 (1977)

Introduction

For time harmonic wave fields with frequency ω, Maxwell's equations combine to give the inhomogeneous wave equation

$$-\nabla \times \nabla \times \mathbf{E} + k_0^2 \left(\mathbf{E} + \frac{i}{\omega \epsilon_0} \mathbf{J}_p \right) = -i\omega\mu_0 \mathbf{J}_{ant} \qquad (1)$$

where k0 = ω/c. The relationship between the plasma current (Jp) and the wave electric field (E) is nonlocal and can be expressed to lowest order as an integral operator of the form

$$\mathbf{J}_p(\mathbf{r}) = \int d\mathbf{r}' \, \sigma(\mathbf{r}\,,\, \mathbf{r}' - \mathbf{r}\,) \cdot \mathbf{E}\,(\mathbf{r}'\,) \qquad (2)$$

where r ′ is the position vector and σ is the plasma conductivity

Numerical solutions of (1) and (2) have been carried out in 2-D using two different full-wave models

TORIC:

Uses a second order, finite Larmor radius (FLR) expansion to express the plasma current in Eq. (2) as a differential operator:

$$\rho_i \ll \lambda \implies \boxed{k_\perp \rho_i \ll 1}$$

Cyclotron interactions up to second harmonic are included ($l \leq 2$)

Spectral expansion in the poloidal angle reduces the parallel gradient operator to an algebraic expression

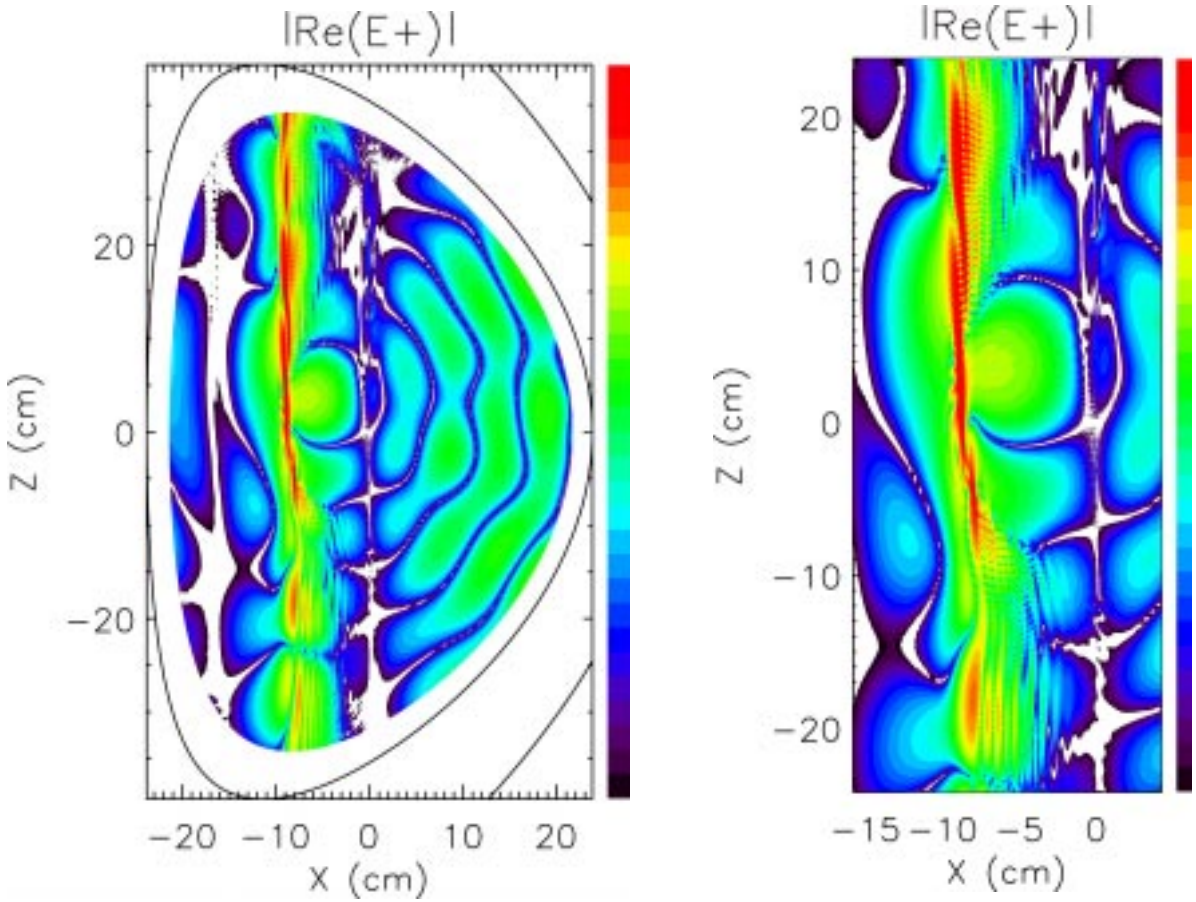
AORSA:

Includes the complete integral representation of the plasma current in Eq. (2) by using a full spectral representation for the wave field.

There is no limit on the number of cyclotron harmonics included

TORIC has been used to simulate mode conversion for a D-He3 plasma in Alcator C-mod

The plasma consists of deuterium ions with 24% He3 and 5% H, B_0 = 7.85 T.

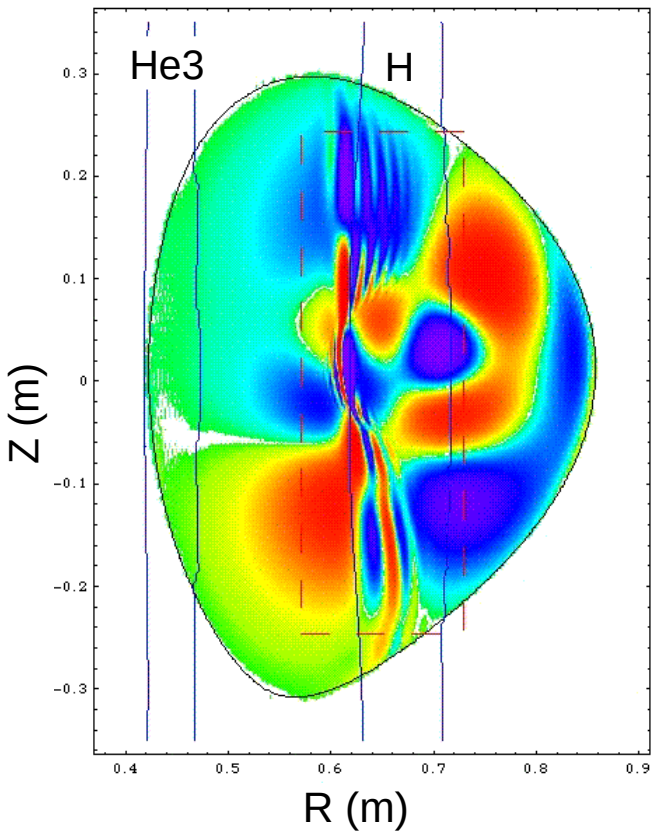


Over most of the plasma cross section, the mode-converted waves propagate on the low field side of the ion-ion hybrid resonance, with wavelength decreasing to the right. However, for the region immediately surrounding the magnetic axis, the opposite is true.

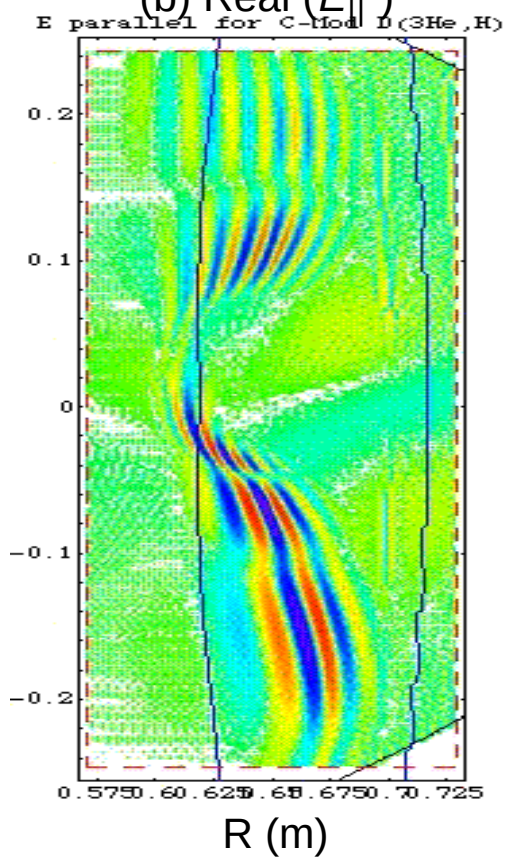
With AORSA, mode conversion has been simulated for a He3-H-D plasma in Alcator C-Mod.

The plasma consists of deuterium ions with 23% He3 and 33% H, B_0 = 5.85 T.

(a) Real ($E_\perp$)



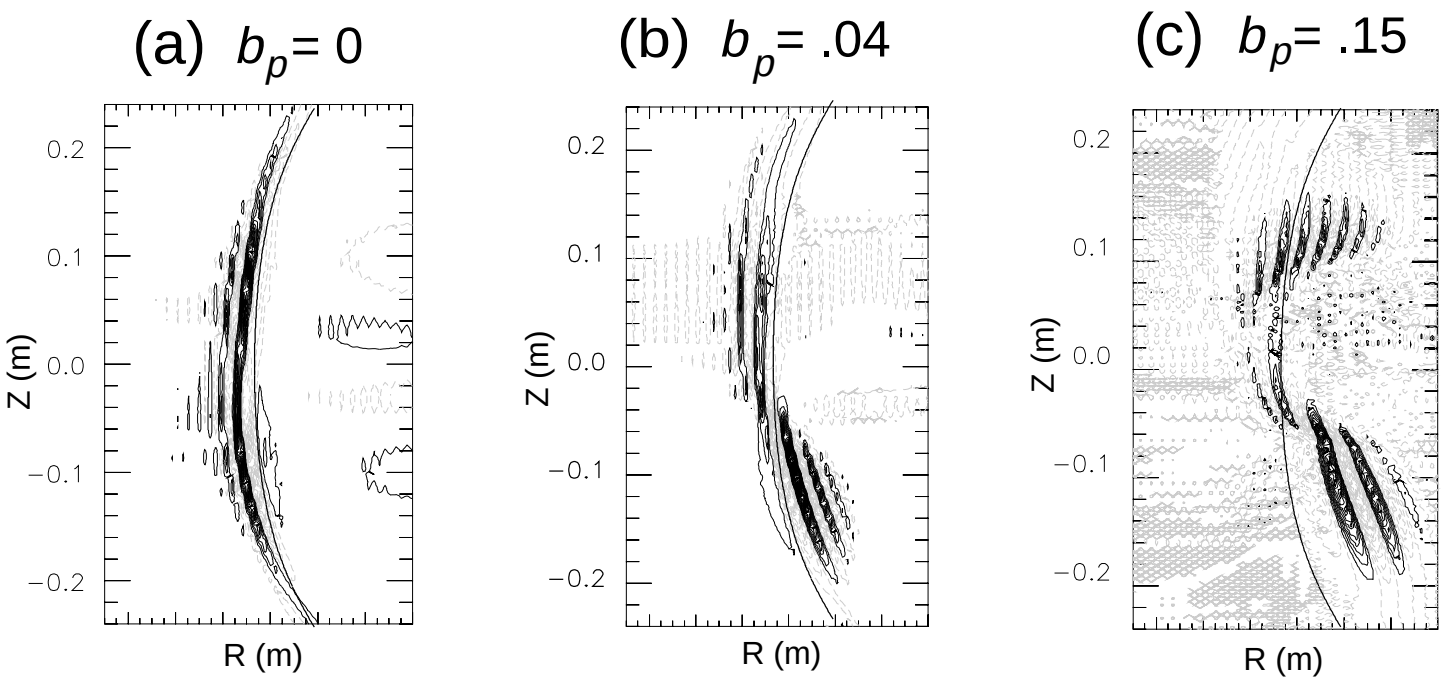
(b) Real ($E_\parallel$)



This result is strikingly similar to that from TORIC, even though the parameters are quite different.

The poloidal magnetic field has a profound effect on the mode conversion process

Effect of the poloidal magnetic field *bp* for He3-H-D mode conversion with nφ = 15 from AORSA:



For b_p = 0, the mode-converted wave (IBW) propagates on the high field side (left) of the mode conversion surface in agreement with previous 1-D results without a poloidal field. As the poloidal field is increased in (b), a new wave (ICW) appears on the low field side of the resonance. For poloidal field magnitudes typical of real tokamaks in (c), this new wave dominates the mode conversion process, except for the region immediately surrounding the magnetic axis.

A one dimensional dispersion model provides a simple basis for understanding these results

In the local approximation, the rf wave field is assumed to be dominated by a single mode number **k**, so that $\nabla \rightarrow i\mathbf{k}$, and Eq. (1) reduces to a simple, second-order dispersion relation,

$$\det\left[\mathbf{nn} - |\ \mathbf{n}\ |^2 + \epsilon^{(0)} + i\mathbf{k}_\perp \epsilon^{(1)} - \mathbf{k}_\perp^2 \epsilon^{(2)}\right] \ = \ 0, \qquad (3)$$

where $\mathbf{n} = \mathbf{k} / k_0$

Assuming $k_y = 0$ for the dispersion analysis, the parallel wave number can be written in terms of the perpendicular wave number as

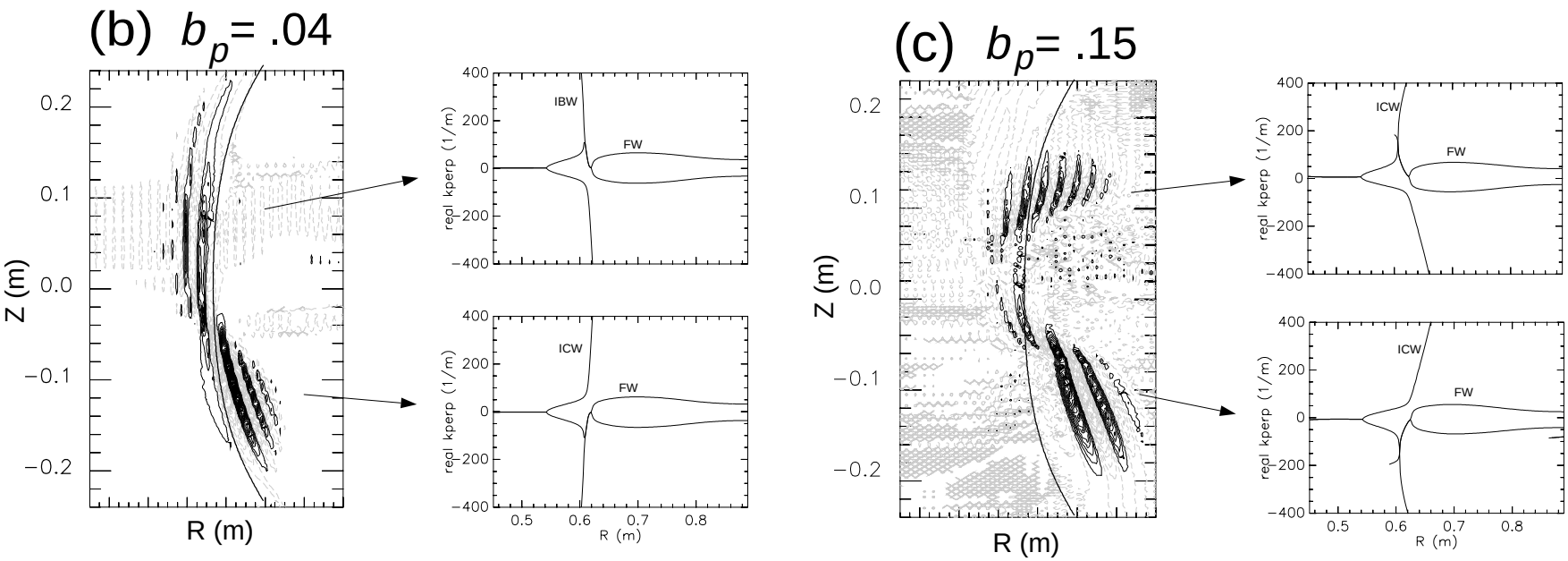
$$k_\parallel = \frac{1}{b_T}(b_p\, k_\perp + \ k_\varphi) \ \ . \qquad (4)$$

so that both $k_\parallel$ and $n_\parallel$ in (3) depend on $k_\perp$. This dependence reflects the "upshift" and "downshift" in $k_\parallel$ that occurs when waves propagate in a poloidal magnetic field.

In the large argument limit of the plasma dispersion function, the dielectric tensor elements are approximately independent of $k_\parallel$, and Eqs. (3) and (4) can be solved as a sixth order polynomial equation in $k_\perp$.

In all cases, the 1-D dispersion results agree qualitatively with the 2-D calculations

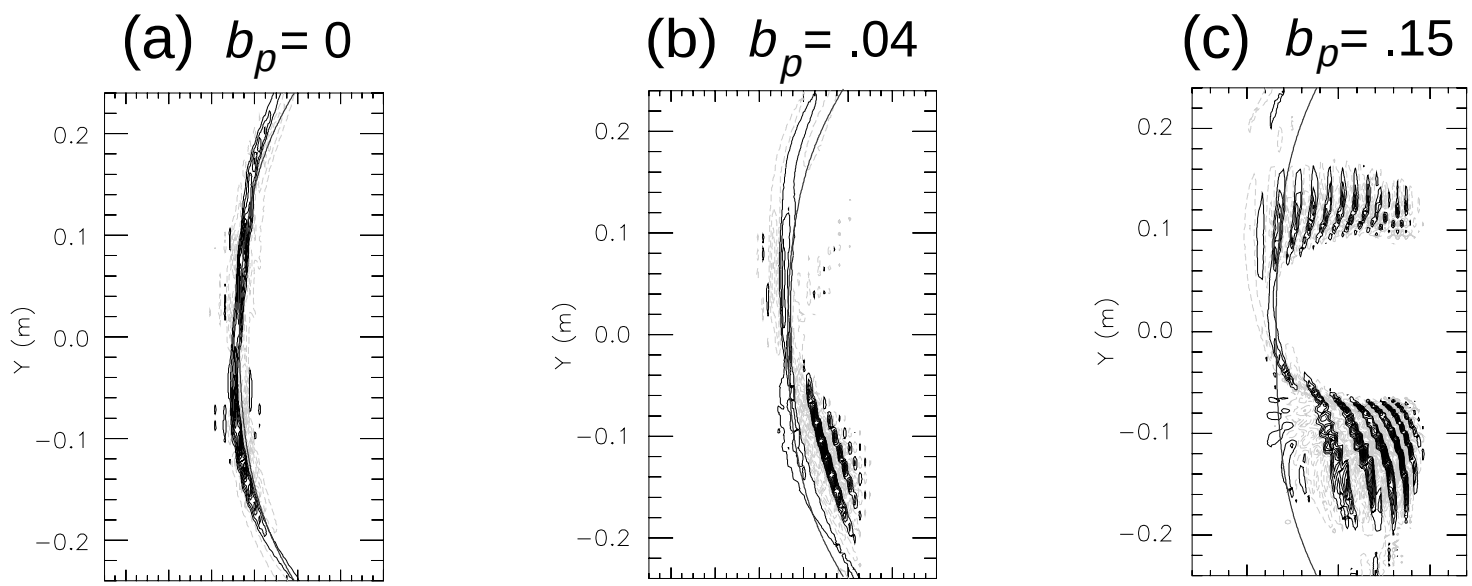
The phase velocity of the mode-converted waves is positive in x. Thus the relevant part of the dispersion plots is the upper half plane where $k_\perp > 0$.



It is clear that some amount of upshift in $k_\parallel$ is necessary for mode conversion to ICW to occur. Near the magnetic axis, where the poloidal field is small, the upshift in $k_\parallel$ is not enough to support the ICW. However the IBW propagates readily in this region at small $k_\parallel$.

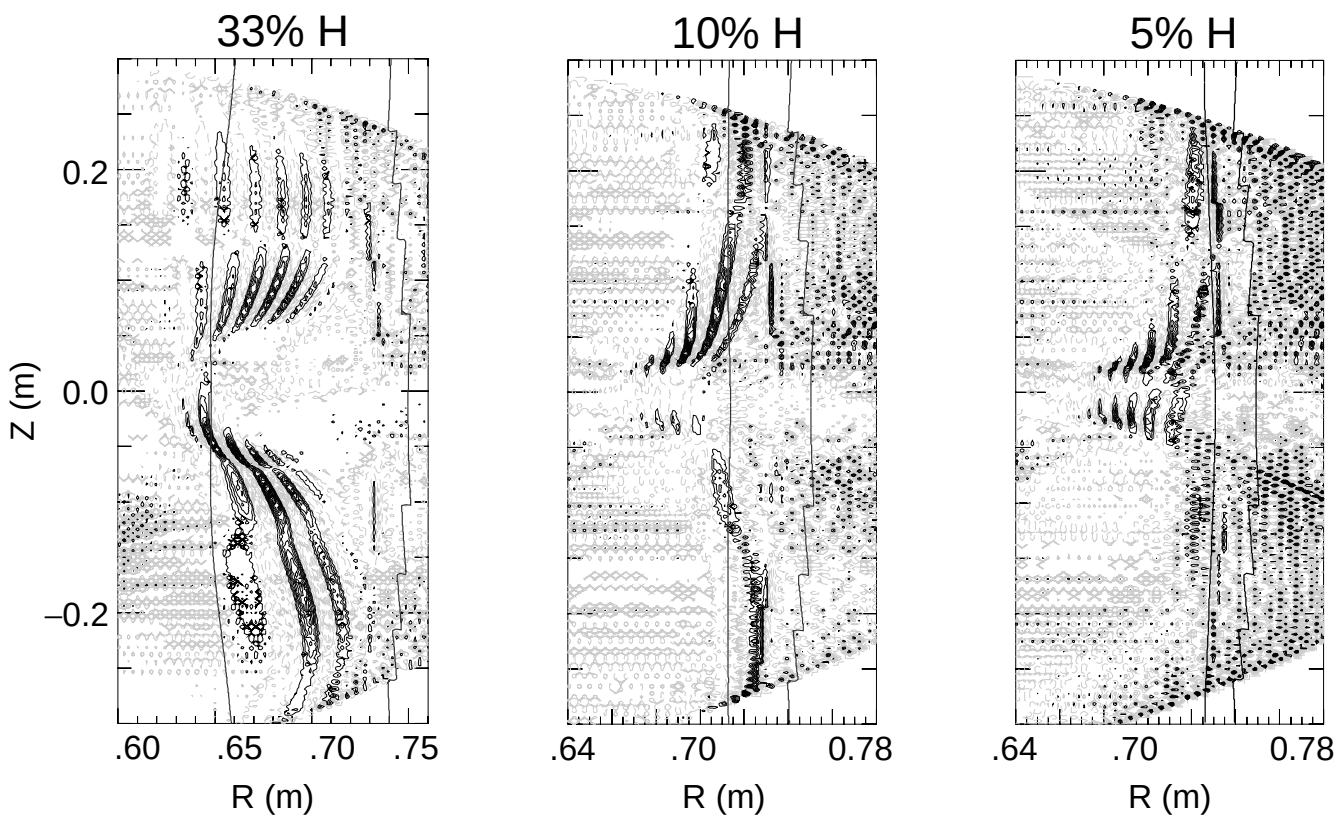
We can distinguish between the two waves by observing their temperature dependence

Repeating the calculations above for a very low ion temperature, we find that, on the low field side of the ion-ion hybrid resonance, the mode-converted waves are cold plasma, forward waves consistent with ICW. On the high field side, they are predominantly finite temperature, backward waves consistent with IBW.



These results depend on a relatively high minority ion concentration

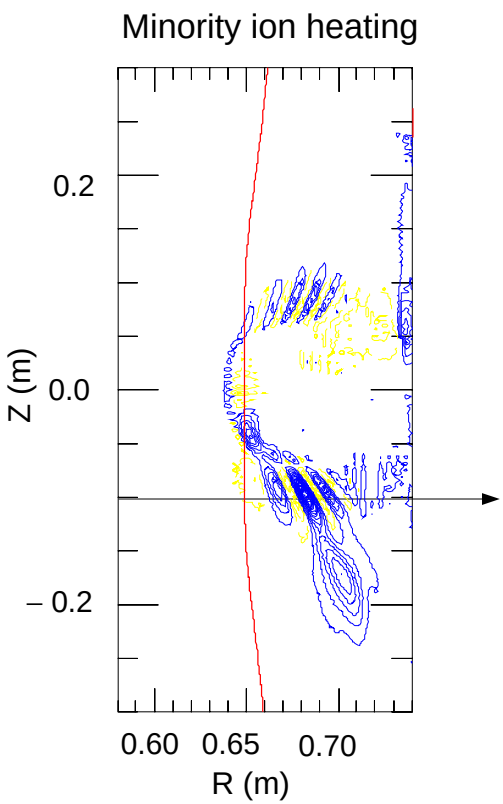
As the fraction of minority ions is reduced, FLR effects become more important in the mode conversion layer, and the IBW near the magnetic axis becomes more dominant.

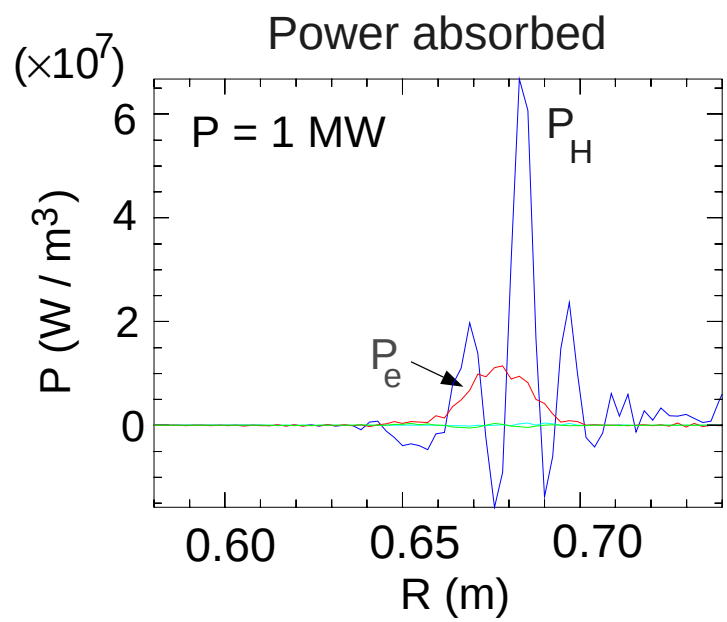


Effect of the minority ion concentration for He3-H-D mode conversion

The interaction between minority ions and the mode converted ICW leads to ion cyclotron damping

The poloidal magnetic field generates strong variations in the parallel wave number that broaden the cyclotron resonance and allow damping of the ICW by ions as well as by electrons



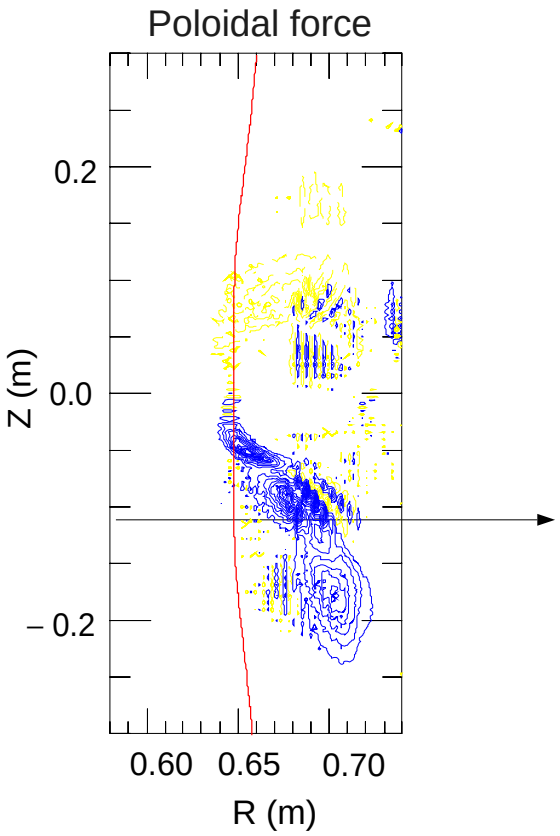


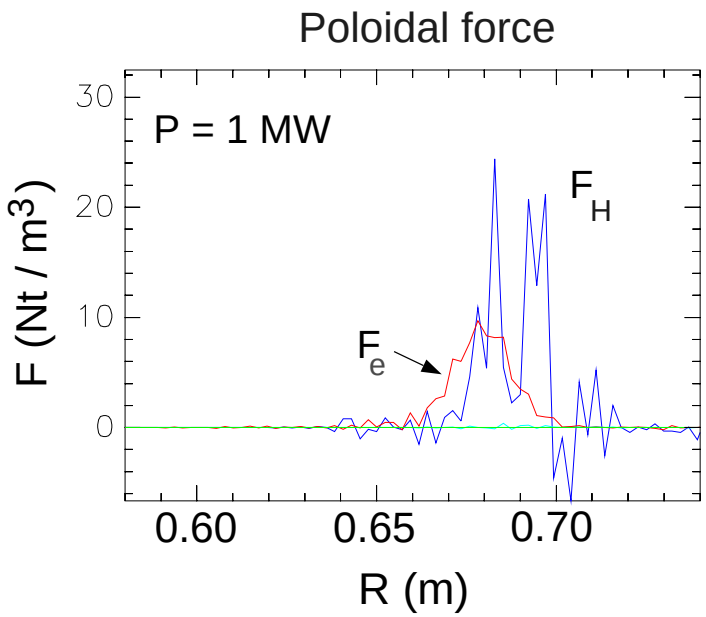
(a) 2-D contours of minority ion heating for the He3-H-D mode conversion example.

(b) Magnitude of the absorbed power for Z = – 0.1 m

There is sheared poloidal flow associated with ion and electron heating in the mode conversion region

With 1 MW of rf power, the magnitude of the peak force is greater than 10 Nt/m3. This is an order of magnitude larger than calculated for TFTR when 0.36 MW of high harmonic IBW is launched directly from the plasma edge and absorbed at the fifth harmonic cyclotron resonance.





This suggests that mode conversion to ICW could be used to drive sheared poloidal flow velocities in tokamak plasmas, thereby creating internal transport barriers and allowing access to enhanced confinement regimes.

Summary

Two complementary full-wave models have been used to simulate mode conversion near the ion-ion hybrid resonance in 2-D plasmas with a poloidal magnetic field

- TORIC: FLR expansion expresses the plasma current differentially
- AORSA: Includes full integral representation of the plasma current

Results from both models show that for high minority ion concentrations:

- Mode conversion is dominated by a transition from the fast magnetosonic wave to the slow ion cyclotron wave (ICW).
- Unlike the IBW, the ICW is a cold plasma wave that propagates on the low field side of the mode conversion layer.
- The poloidal magnetic field generates strong variations in the parallel wave number that broaden the cyclotron resonance and allow damping of the ICW by ions as well as by electrons.
- The resulting ion interaction can provide bulk ion heating as well as sheared poloidal flow at the mode conversion layer.

This suggests that mode conversion to ICW could be used to drive sheared poloidal flow velocities in tokamak plasmas, thereby creating internal transport barriers and allowing access to enhanced confinement regimes.