ELECTRON BERNSTEIN WAVE HEATING AND EMISSION ON NSTX

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ELECTRON CYCLOTRON RESONANCE HEATING IN SPHERICAL TORI

- For the low magnetic fields in ST's sources in ECRF are readily available.
- ST plasmas are essentially overdense
  - In NSTX: $\dfrac{\omega_{pe}}{\omega_{ce}} \sim 6 - 10$
- In order for the X-mode and the O-mode to access the core of the plasma $\omega \gg \omega_{ce}$
  - waves are weakly damped.
- Electron Bernstein waves are a viable option
  - no density cutoffs
  - damp on electrons at fundamental or any harmonic of the Doppler-shifted electron cyclotron resonance
  - not vacuum modes!

    $\Longrightarrow$ indirect coupling via mode conversion of externally launched X or O modes.

OUTLINE OF THIS TALK

Provide a summary of our research results on

- Mode conversion excitation of electron Bernstein waves from externally launched X and O modes.
- Propagation and damping of electron Bernstein waves.
- Mode conversion to X and O modes from thermal emission of electron Bernstein waves inside the plasma.

MODE CONVERSION EXCITATION OF EBWs

- Necessary condition: $f \ > \ f_{\rm edge}^{\rm UHR} = \sqrt{f_{pe}^2 + f_{ce}^2}$

- Relevant parameter:

$$\eta \approx \frac{\omega_{ce} L_n}{c\alpha} \left[\sqrt{1+\alpha^2} - 1\right]^2$$

$\alpha = \omega_{pe}/\omega_{ce}$ at the upper hybrid resonance, $L_n^{-1} = \dfrac{1}{n}\dfrac{dn}{dx}$.

- For X-B mode conversion:
  - $|n_\parallel| \equiv |ck_\parallel/\omega| \ll 1$
  - $0.05 \lesssim \eta \lesssim 0.6 \implies$

$$1.3 \times 10^{-2}\ \text{T cm} \lesssim |BL_n| \lesssim 0.16\ \text{T cm}$$

- For O-B:
  - $n_\parallel \approx n_{\parallel,opt} = (1 + f_{pe}/f_{ce})^{-1/2}$
  - $\eta > 1$.

MODE CONVERSION EXCITATION OF EBWs

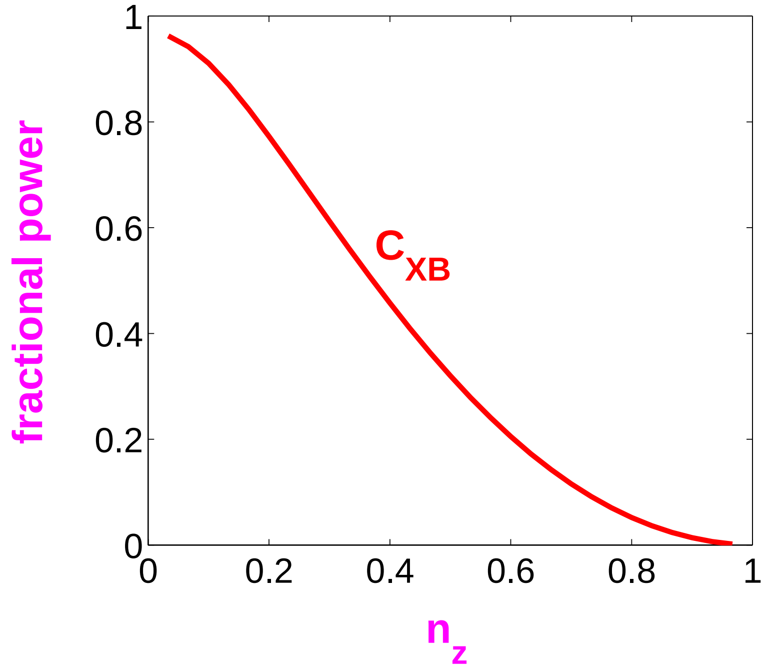
CONCLUSIONS

- X-B and O-B mode conversion processes are optimized in complementary regions of the phase space spanned by $(f, k_{\|})$.

- For NSTX:
  - X-B mode conversion: $f \approx 15$ GHz and $n_{\|} \approx 0$
  - O-B mode conversion: $f \approx 28$ GHz and $n_{\|} \approx 0.5$

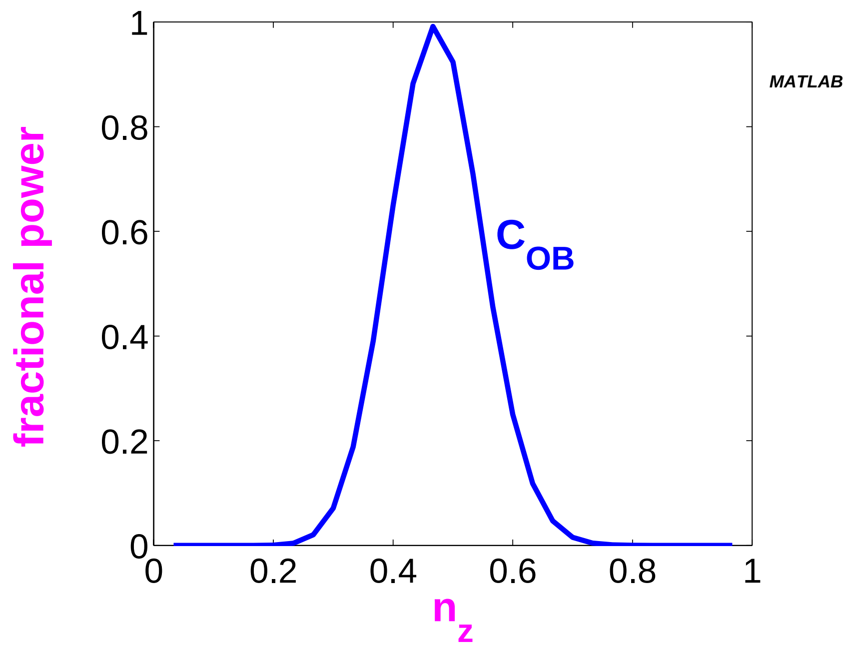
MODE CONVERSION OF X MODE TO EBW

(For NSTX parameters. $k_y = 0$ and $f = 15$ GHz)



MODE CONVERSION OF O MODE TO EBW

(For NSTX parameters. $k_y = 0$ and $f = 28$ GHz)



PROPAGATION AND DAMPING OF EBWs

From geometric optics analysis using a fully kinetic, non-relativistic dielectric tensor:

- EBWs are completely damped on electrons near the Doppler-shifted electron cyclotron resonance (or its harmonics)

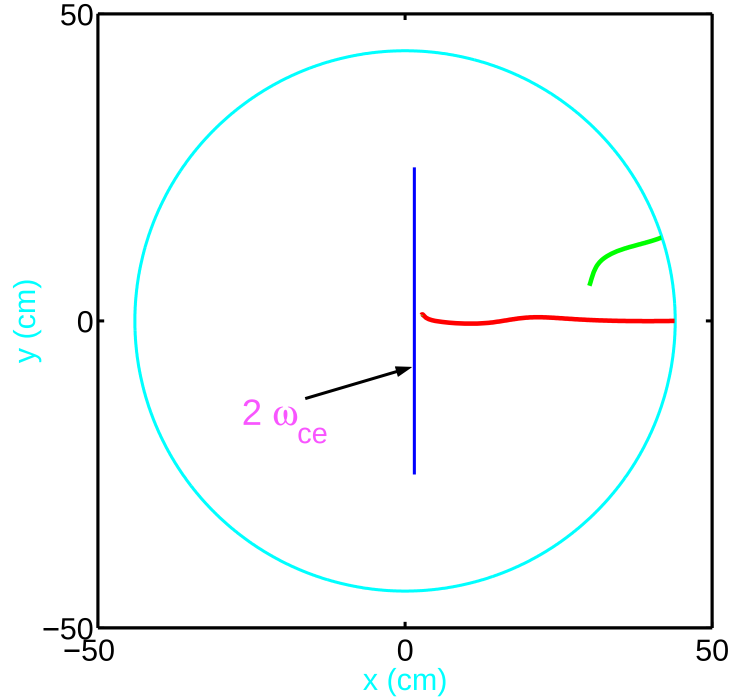
- For EBWs propagating above or below the equatorial plane there is a large shift in the parallel wavenumbers in NSTX-type equilibria

$$\Delta n_{\parallel} \propto \sin(\theta)\frac{B_\theta}{|B|}$$

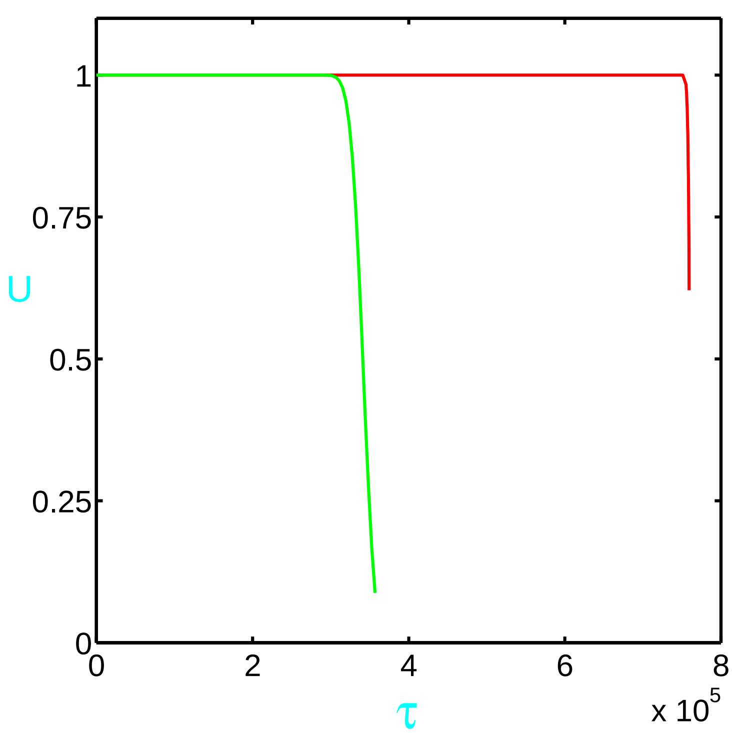
$\Longrightarrow$ the Doppler shifts can be large

$\Longrightarrow$ can be used to control the location of heating and/or current drive.

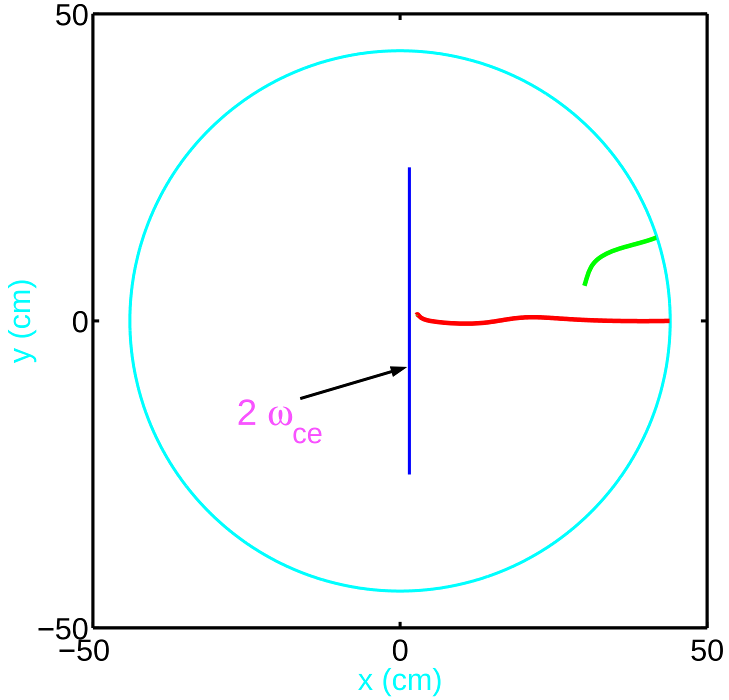
POLOIDAL PROJECTION OF EB RAYS



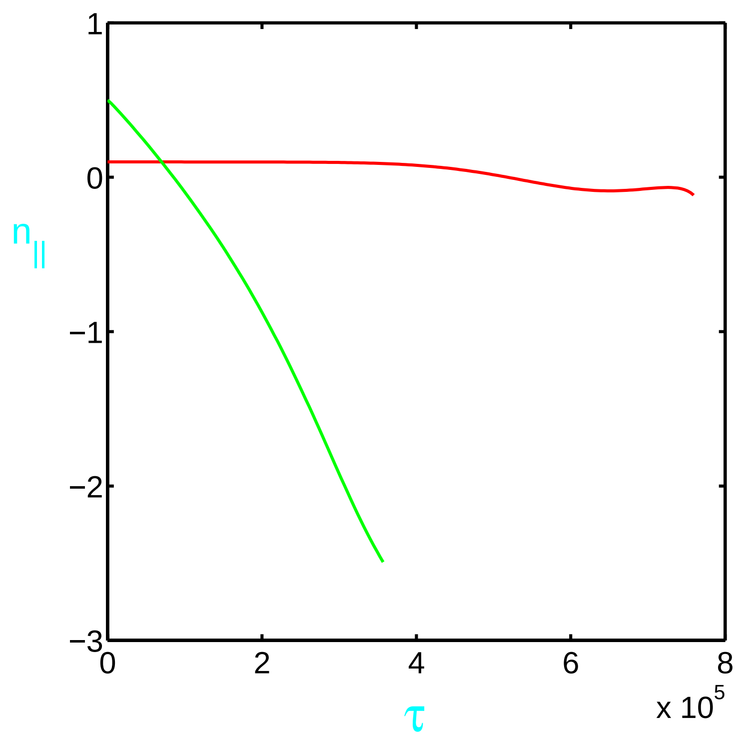
ENERGY DENSITY ALONG THE RAYS



POLOIDAL PROJECTION OF EB RAYS



PARALLEL WAVE INDEX ALONG THE RAYS



MODE CONVERSION EMISSION OF EBWs

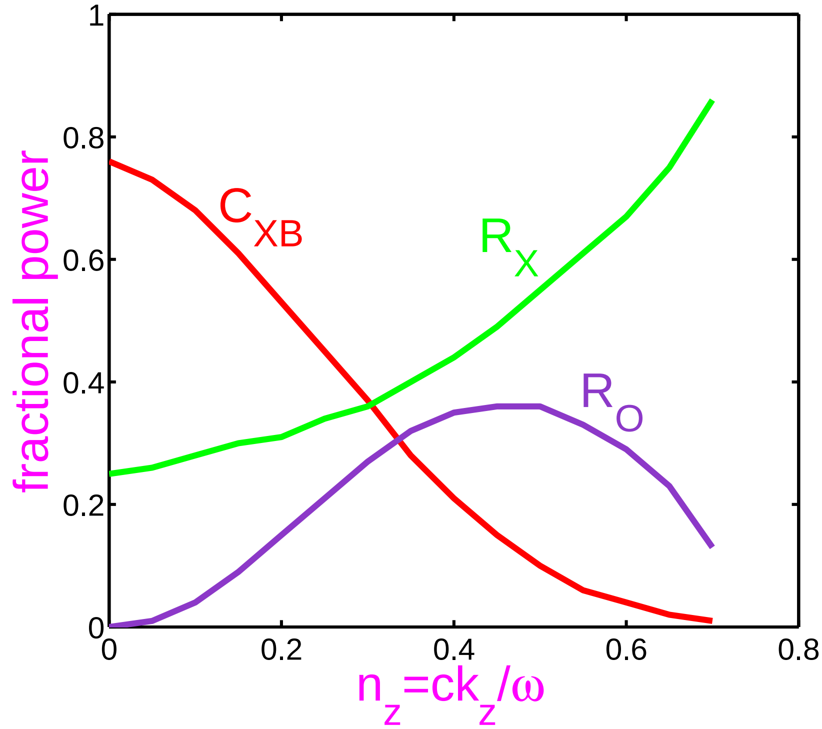
- The strong, and local, damping of EBWs on electrons implies that thermal emission of EBWs also occurs for frequencies corresponding to the local Doppler-shifted electron cyclotron resonance frequency (or its harmonics).

- The emitted EBWs mode convert to X and O modes at the upper hybrid resonance (usually near the plasma edge in NSTX)

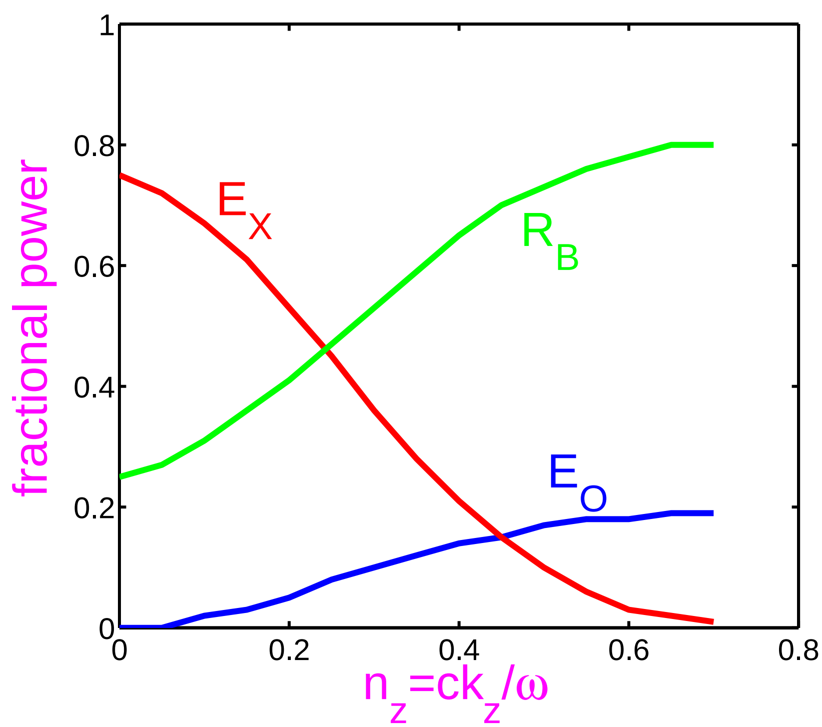
- Time-reversal invariance and conservation of energy lead to the following important relationships:

$$
\begin{aligned}
E_X &= C_{XB} \\
E_O &= C_{OB} \\
R_X &= R_O
\end{aligned}
$$

MODE CONVERSION OF X MODE TO EBW

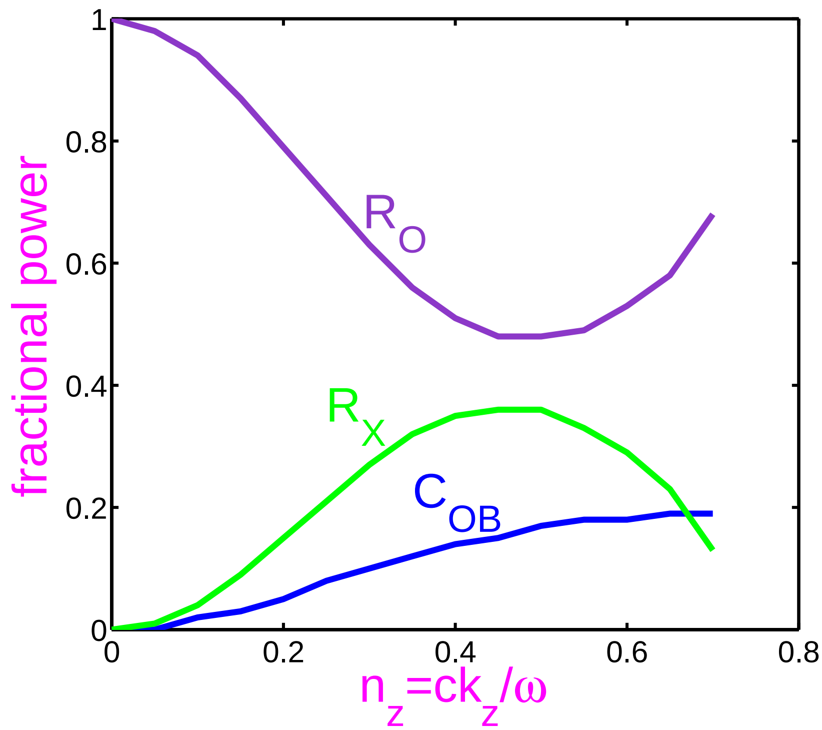


EMISSION OF X AND O MODES

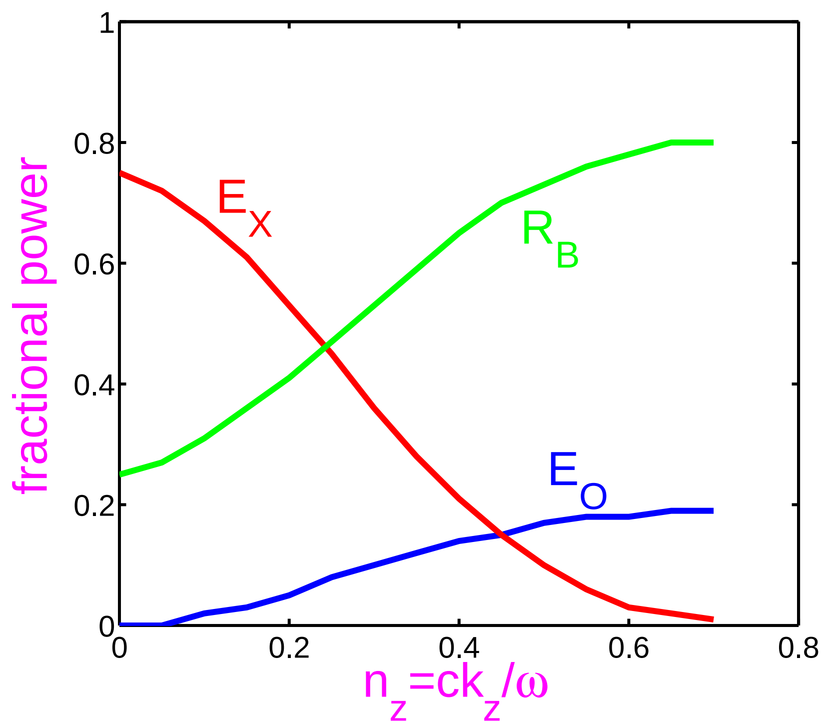


$$E_X = C_{XB}$$

MODE CONVERSION OF O MODE TO EBW



EMISSION OF X AND O MODES



$$E_O = C_{OB}$$

CONCLUSIONS

- In NSTX plasmas, electron cyclotron heating/current drive could be accomplished by EBWs
  - analytical and numerical models have been developed to study the coupling between X mode, O mode, and EBWs.
- X-B and O-B mode conversion processes are complementary to each other in $(f, k_{\|})$-space.
- EBWs damp strongly on electrons near the Doppler-shifted electron cyclotron resonance (or its harmonics)
  - thermal emission of EBWs occurs for frequencies corresponding to the local Doppler-shifted electron cyclotron resonance frequency.
- The EBW emission coefficients are the same as the EBW excitation coefficients
  - $\mathbf{E_X} = \mathbf{C_{XB}}$ and $\mathbf{E_O} = \mathbf{C_{OB}}$
  - $\mathbf{E_X} + \mathbf{E_O} \leq \mathbf{1}$
- Observations of EBW emission from NSTX plasmas can provide a useful guide for the design and optimization of EBW heating and current drive experiments.

THEORY ISSUES

ELECTRON BERNSTEIN WAVE EMISSION, HEATING, AND CURRENT DRIVE

- Edge plasma effects on coupling of high power to electron Bernstein waves
  - plasma density gradient
  - parametric processes

- Relativistic effects on the propagation and damping of electron Bernstein waves.

- Current drive by electron Bernstein waves
  - current profile control
  - efficiency of current drive
  - neoclassical effects (interaction with the bootstrap current)