Propagation and damping of electron Bernstein waves traveling from the high field side in tokamak plasmas

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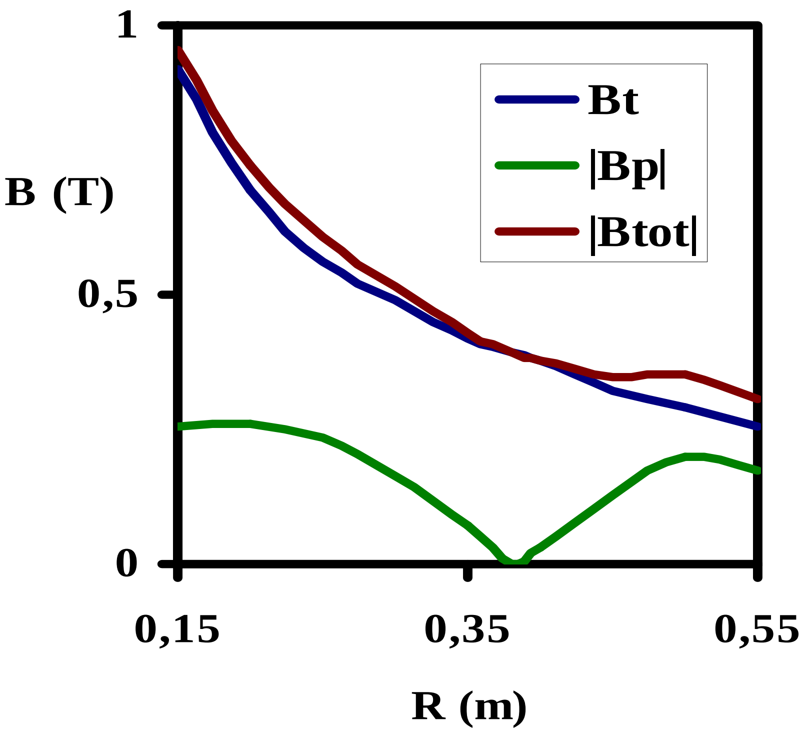
EBW Heating in a ST: possible schemes

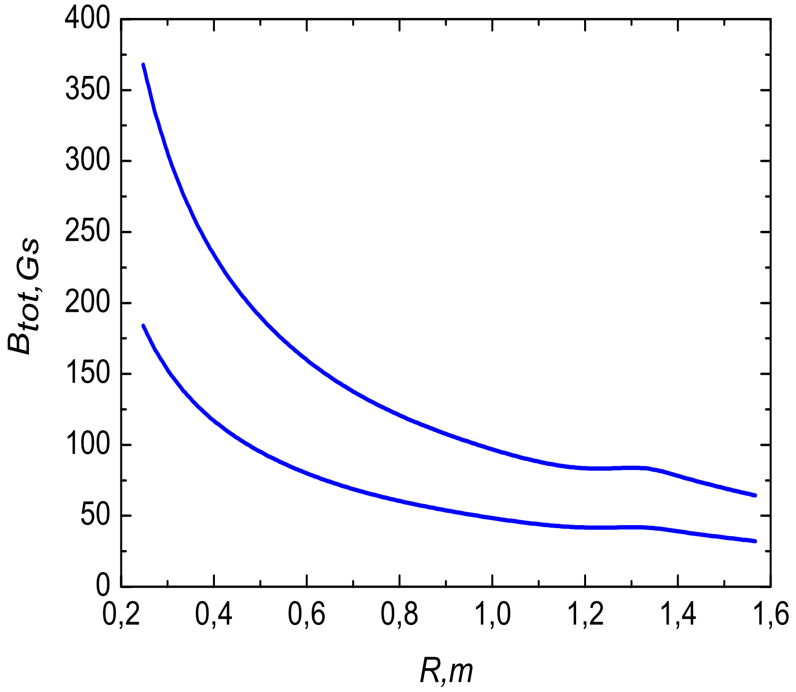
- As far as *ECR* heating is concerned, main feature of STs is high plasma density at comparatively low magnetic field. Relevant dimensionless parameter $\omega_{pe}^2/\omega_{ce}^2$ in the plasma center is of order unity for "conventional" tokamaks and equal to 50-100 in ST. As a result, plasma interior is not accessible for 1st and 2nd electro-magnetic wave harmonics. Only accessible to (but not optically thick for) higher harmonics.

- Plasma interior is accessible and optically thick for *EBW* produced via linear conversion of incident electromagnetic waves in the *UHR* region. Conversion process may include $O \to X \to B$ transformation, direct tunneling of combination of both.

Magnetic field configuration

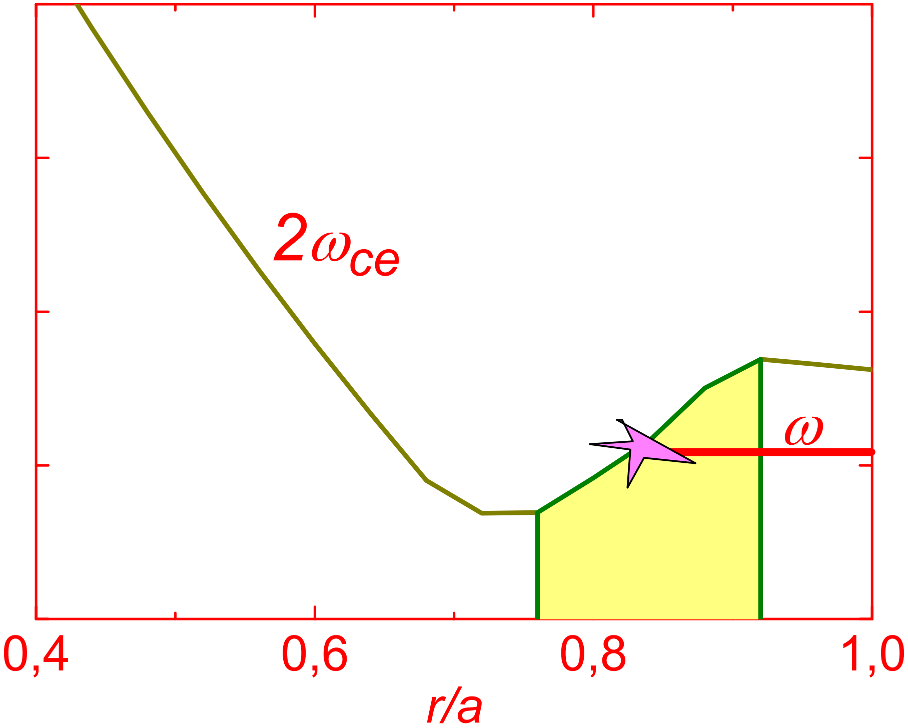


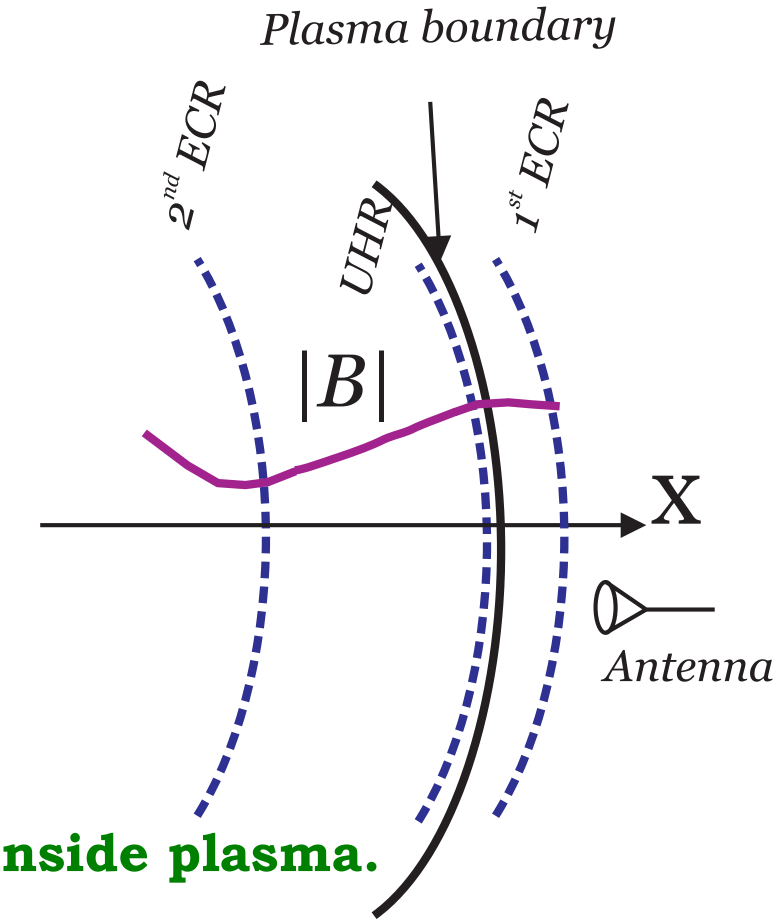
Globus-M, Ioffe Institute, V. Gusev, R.Levin et.al



MAST, V. Shevchenko

Configuration with “magnetic well”

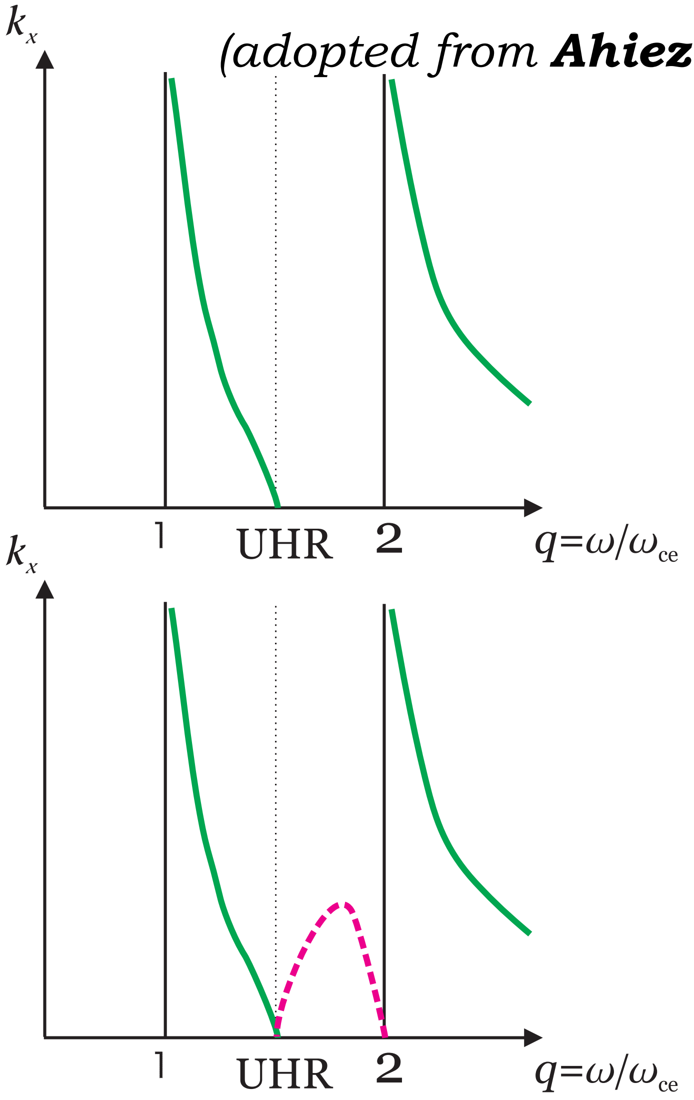


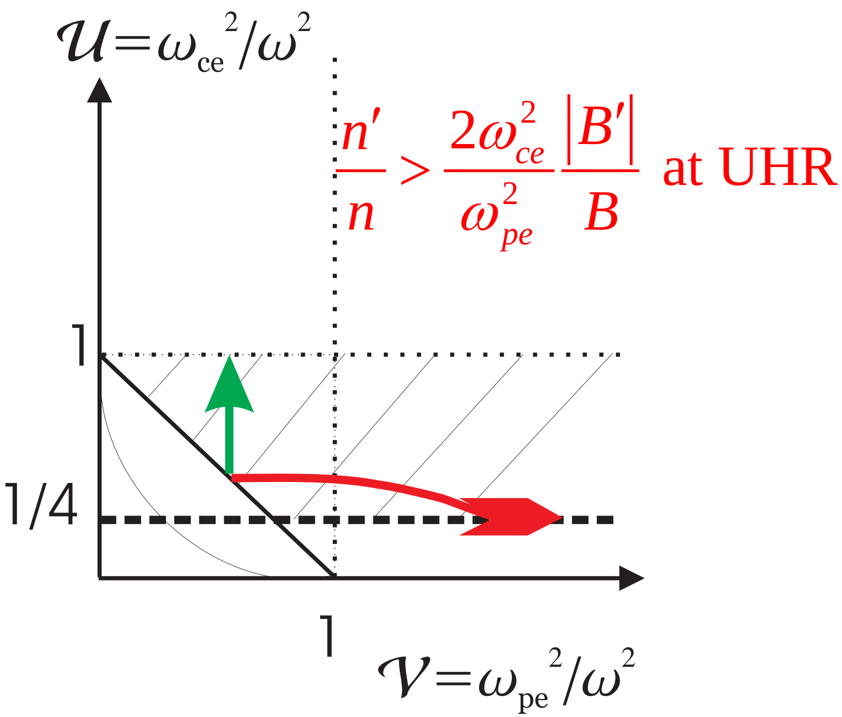


1) 1 ECR outside and 2 ECR inside plasma.
2) UHR close to plasma edge.
3) There is domain with q=2 accessible from high field side only.

Dispersion curves in homogeneous plasma and CMA diagram

(adopted from ***Ahiezer et.al)***





$$\frac{n'}{n} > \frac{2\omega_{ce}^2}{\omega_{pe}^2}\frac{|B'|}{B}$$ at UHR

1. ***In uniform plasma the wave moves to 1 ECR along green arrow***
2. ***In our case - along red one to 2 ECR***

Electrostatic approximation for EBW

Validity condition

$$n_\perp^2 \gg \upsilon, \qquad \upsilon = \frac{\omega_{pe}^2}{\omega^2} \gg 1$$

$$\Downarrow$$

Electrostatic approximation

$$\varepsilon\left(n_\perp, n_\parallel, x\right) = \frac{\vec{n}\cdot\overleftrightarrow{\varepsilon}\left(n_\perp, n_\parallel, x\right)\cdot\vec{n}}{n^2} = 0$$

Assumptions

1) $k_\perp \rho_e \ll 1$

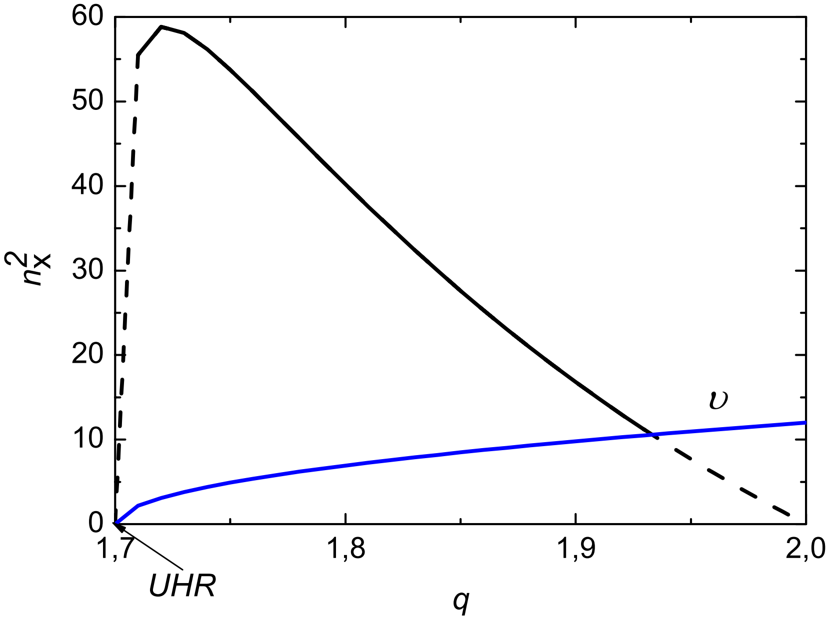
2) $k_\parallel \upsilon_{Te} / \omega = n_\parallel \beta \ll 1$

Omit $n_\parallel$ terms since EBW produced with $n_\parallel \leq 1$, while $n_\perp \gg 1$

Electrostatic approximation for EBW

$$n_\perp^2 = \frac{2}{3\beta^2 v}\varepsilon_{xx}^{(C)}\frac{(q^2-1)(4-q^2)}{q^4},\ \beta=\frac{\upsilon_{Te}}{c}, q=\frac{\omega}{\omega_{ce}}$$

Propagating waves are confined between two cutoffs, one at the UHR ($\varepsilon_{xx}^{(C)}=0$) and the other at the $q=2$ resonance. Between the cut-offs the characteristic value $n_\perp$ is $\beta^{-1}\gg 1$



Dispersion relation close to 2 ECR. Full wave analysis.

Validity condition $n_\perp / \upsilon \ll 1$

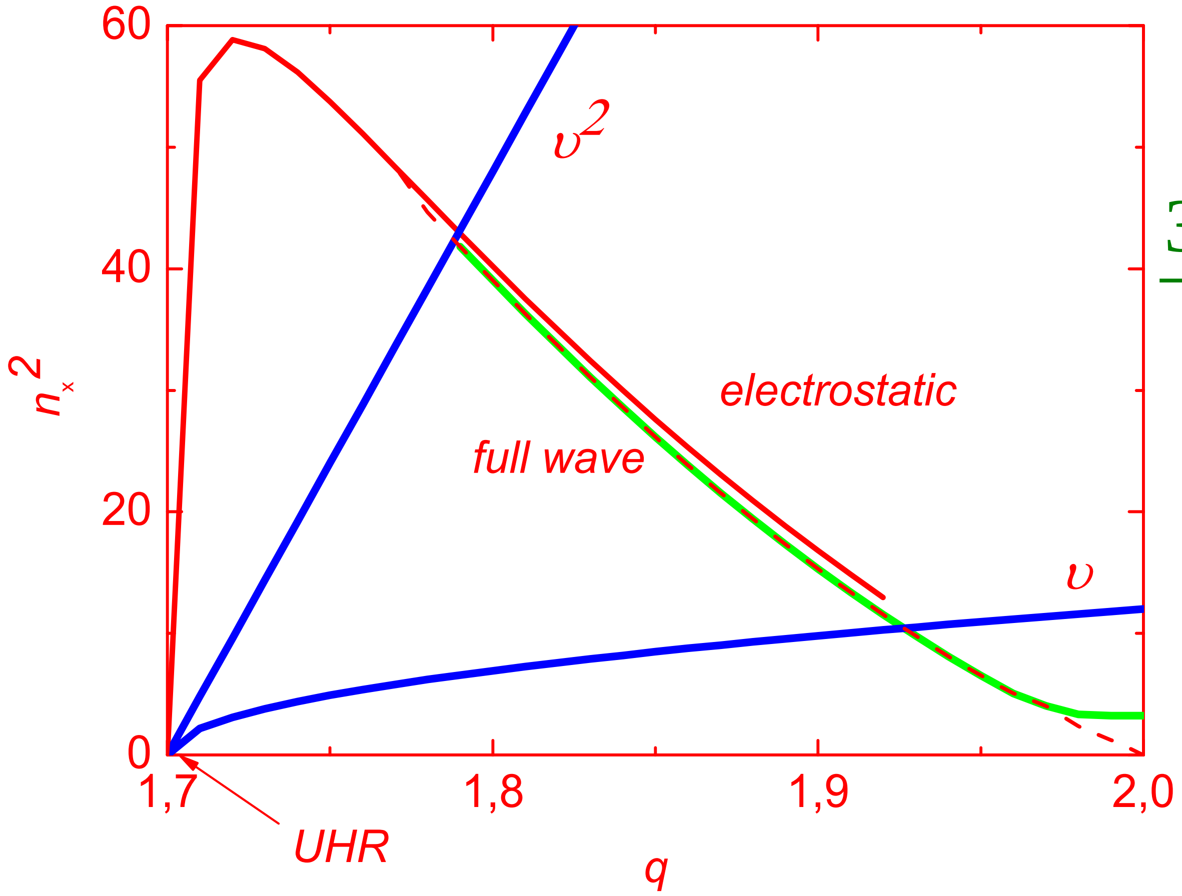
1. $k_\perp^2 \rho_e^2 \ll 1$ **approximation**

$$\varepsilon_\perp = \varepsilon_\perp^{(C)} + \frac{q^2 n_\perp^2 \beta^2}{4} \frac{v}{n_\parallel \beta} Z\left(\frac{q-2}{q n_\parallel \beta}\right), \quad g = g^{(C)} + \frac{q^2 n_\perp^2 \beta^2}{4} \frac{v}{n_\parallel \beta} Z\left(\frac{q-2}{q n_\parallel \beta}\right)$$

2. $\upsilon \gg 1 \rightarrow$ **neglect** E_z

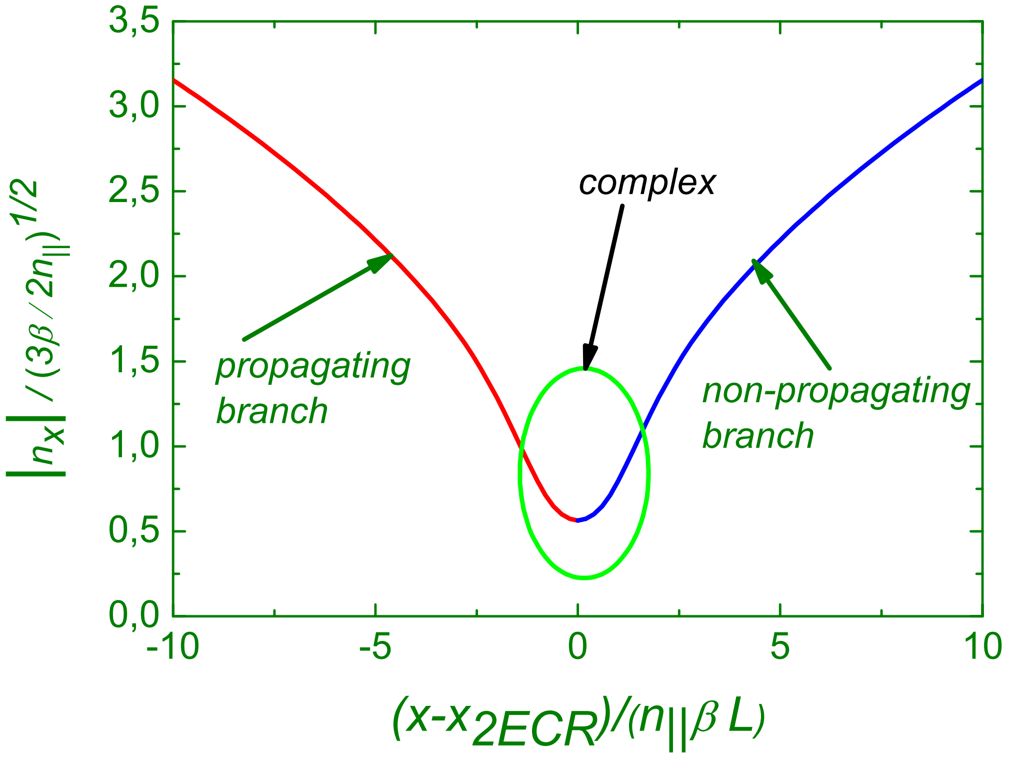
$$n_\perp^2 \varepsilon_\perp - \frac{\upsilon^2 q^4}{q^2 - 1}\left(1 - n_\perp^2 \frac{\beta(q+1)}{n_\parallel} Z\left(\frac{q-2}{q n_\parallel \beta}\right)\right) = 0$$

Comparison of electrostatic and full wave approximations.



$$\frac{3\beta n_\perp}{2n_\parallel} \simeq \pm \frac{1}{\sqrt{Z\left(\frac{q-2}{q n_\parallel \beta}\right)}}$$

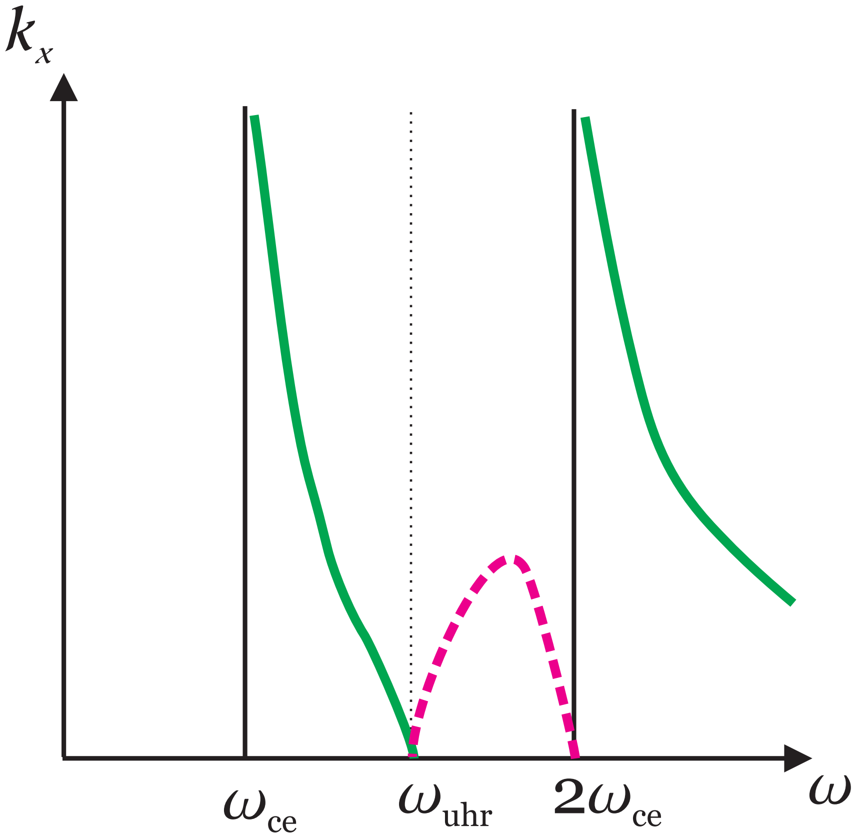
Wave behavior in the ECR layer.

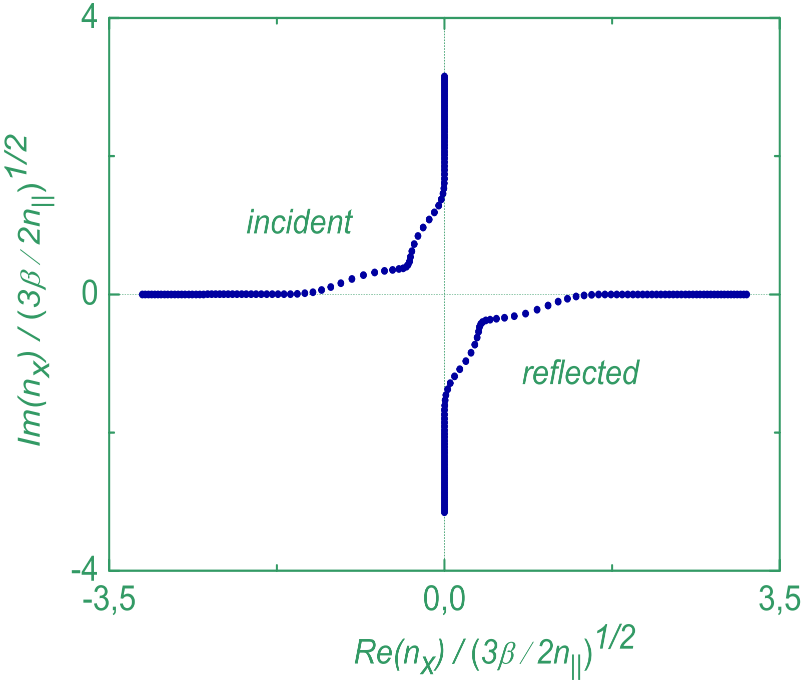


$$\mathrm{Re}(n_\perp) \sim \mathrm{Im}(n_\perp)$$

$$\omega/c \cdot \min |n_\perp| L = \omega/c \cdot l \beta^{1/2} n_{||}^{3/2} \gg 1$$

Transformation and reflection in ECR layer.





Reflection from the ECR layer can only be due to approximate nature of the WKB

Reflection

$$WKB \text{ is valid, } n_{\|}^{3/2} \geq \frac{1}{2l\beta^{1/2}}$$

Reflection is negligibly small $|R|^2 \sim \frac{1}{\Gamma_0^3}\exp\left(-\alpha\Gamma_0\right)$

$$WKB \text{ is inapplicable, } n_{\|}^{3/2} \ll \frac{1}{2l\beta^{1/2}}$$

Reflection coefficient close to unit

$$|R|^2 = 1-\gamma\left(2l\beta^{1/2}n_{\|}^{3/2}\right)^{4/3}, \quad \gamma = 2\pi^2 Ai^2\left(0\right)/12^{2/3}$$

Summary

1. Existence of *EBWs* in the region between the *UHR* and 2nd *ECR* requires inhomogeneous plasma density.

2. Waves in this region are adequately described by the approximate full-wave dispersion relation.

3. Incoming waves incident on the *ECR* layer from the high-field side are not converted in the resonance region into outgoing *EBWs* propagating on the low field side of the *ECR*._Instead, the incident waves become non-propagating beyond the resonance layer.

4. Decreasing of the wave amplitude within *ECR* layer is due to combine effect of the *ECR* damping and non-propagation.

5. In the *WKB* approximation, the waves are fully damped in the *ECR* layer. Reflection from the *ECR* layer is only due to approximate nature of the *WKB* theory.

6. Standard ray tracing method can be used for high-field side propagation only if the wave is damped in the periphery of the *ECR* layer. Otherwise the wave penetrates into the region of strong cyclotron damping where the ray tracing method is inapplicable.