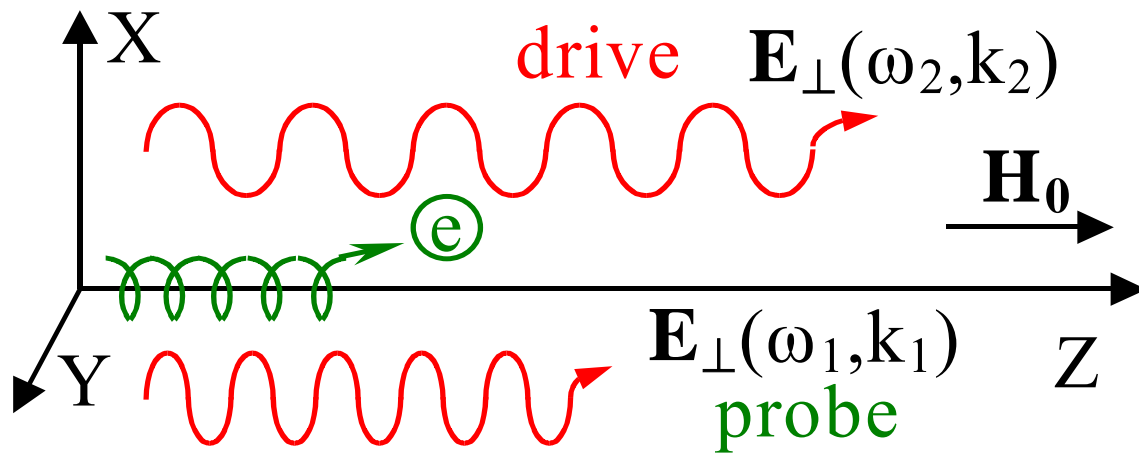


EFFECT OF ELECTROMAGNETICALLY INDUCED TRANSPARENCY FOR THE PROBE WAVE AT UPPER-HYBRID RESONANCE

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Previous Research: EIT in magnetoactive plasma for longitudinal propagation of the waves



$$\mathbf{E}_\perp(z, t) = \mathbf{E}_1 \exp(-i\omega_1 t + ik_1 z) + \mathbf{E}_2 \exp(-i\omega_2 t + ik_2 z)$$

$$\omega_1 \rightarrow \omega_H, \omega_1 - \omega_2 \rightarrow \omega_p$$

$$\vec{e}_+ = \sqrt{2}(\vec{x}_0 + i\vec{y}_0) \quad (\text{X-wave})$$

Litvak A.G., Tokman M.D.
Phys.Rev.Lett. 2002

- Cold plasma
- Hydrodynamic theory
- The first classical analog of EIT found

A.Yu.Kryachko, A.G.Litvak, M.D.Tokman.
JETP 2003, Nucl. Fusion 2004

- High-temperature plasma
- Hydrodynamic and kinetic theory
- Thermal motion drastically changes the formation of EIT effect

Motivation

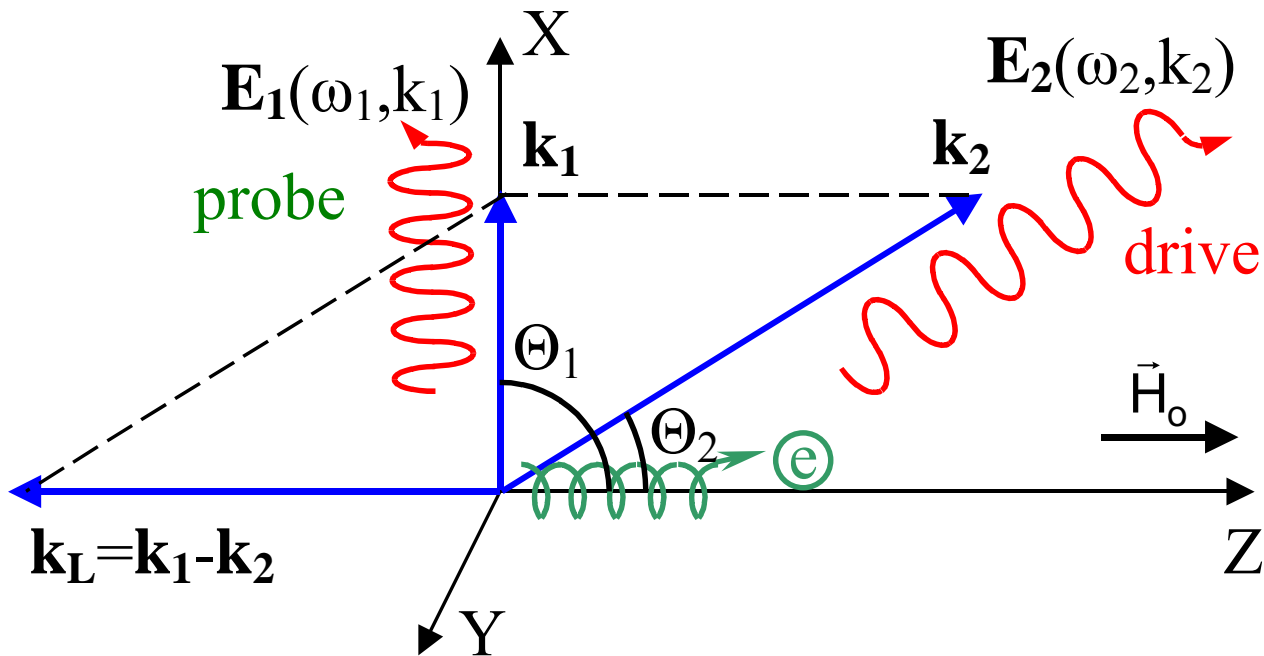
Upper-hybrid resonance (UHR):

$$\omega_1 \approx \omega_{\text{uh}} = (\omega_{\text{H}}^2 + \omega_{\text{p}}^2)^{1/2}$$

- New step in the research of EIT in classical systems
- Why transverse propagation?
Possible applications of EIT: diagnostics in tokamaks but due to the technical reasons, it is difficult to provide the longitudinal propagation of the waves
- Why UHR?
For transverse propagation at UHR the probe wave has resonance absorption line and cut-off

Formulation of the problem

- ✓ Cold, homogeneous plasma
- ✓ Constant, homogeneous external magnetic field



$$\vec{E}_\perp(x, z, t) = \text{Re} \left(\vec{E}_1 \exp(-i\omega_1 t + ik_1 x) + \vec{E}_2 \exp(-i\omega_2 t + ik_{2x} x + ik_{2z} z) \right)$$

$$|k_{Lx}| = |k_1 - k_2 \sin(\Theta_2)| \ll |k_1|, |k_2|, |k_L|$$

$$1. |\omega_1 - \omega_{uh}|, \gamma \ll \omega_1, \omega_{uh}$$

$$2. |\omega_1 - \omega_H|, \gamma \ll \omega_1, \omega_H$$

$$(\omega_L = \omega_1 - \omega_2, k_L = k_1 - k_2)$$

$$E_1 \cdot E_2^* \Rightarrow J_{L \text{ nonl}} \Rightarrow E_L$$

$$E_L \cdot E_2 \Rightarrow J_{1 \text{ nonl}} \Rightarrow N_{\text{EIT}}^2$$

Basic equations and effective refractive index

$$\begin{cases} \partial^2 \vec{E} / \partial t^2 + c^2 \text{rotrot} \vec{E} + 4\pi \partial \vec{j} / \partial t = 0 \\ \partial \vec{V} / \partial t + \omega_H [\vec{V}, \vec{z}_0] + \gamma \vec{V} + (\vec{V}, \nabla) \vec{V} = -e/m \vec{E} - (e/mc) [\vec{V}, \vec{B}]; \\ c \cdot \text{rot} \vec{E} = -\partial \vec{B} / \partial t \\ \partial N_e / \partial t + \text{div}(N_e \vec{V}) = 0; \end{cases} \quad (\text{hydrodynamic theory})$$

$$N_{EIT}^2 = \frac{c^2 k_1^2}{\omega_1^2} = 1 - \frac{2(a - b + c)}{2a - b \pm \sqrt{b^2 - 4ac}}$$

$$a = \varepsilon_{xx} \sin^2 \Theta_1 + \varepsilon_{zz} \cos^2 \Theta_1 + (\varepsilon_{zx} + \varepsilon_{xz}) \sin \Theta_1 \cos \Theta_1,$$

$$b = \varepsilon_{xx} \varepsilon_{zz} + \varepsilon_{yy} \varepsilon_{zz} \cos^2 \Theta_1 + (\varepsilon_{xx} \varepsilon_{yy} - \varepsilon_{xy} \varepsilon_{yx}) \sin^2 \Theta_1 + (\varepsilon_{yy} \varepsilon_{zx} - \varepsilon_{yx} \varepsilon_{zy} + \varepsilon_{yy} \varepsilon_{xz} - \varepsilon_{xy} \varepsilon_{yz}) \sin \Theta_1 \cos \Theta_1,$$

$$c = \varepsilon_{zz} (\varepsilon_{xx} \varepsilon_{yy} - \varepsilon_{xy} \varepsilon_{yx}).$$

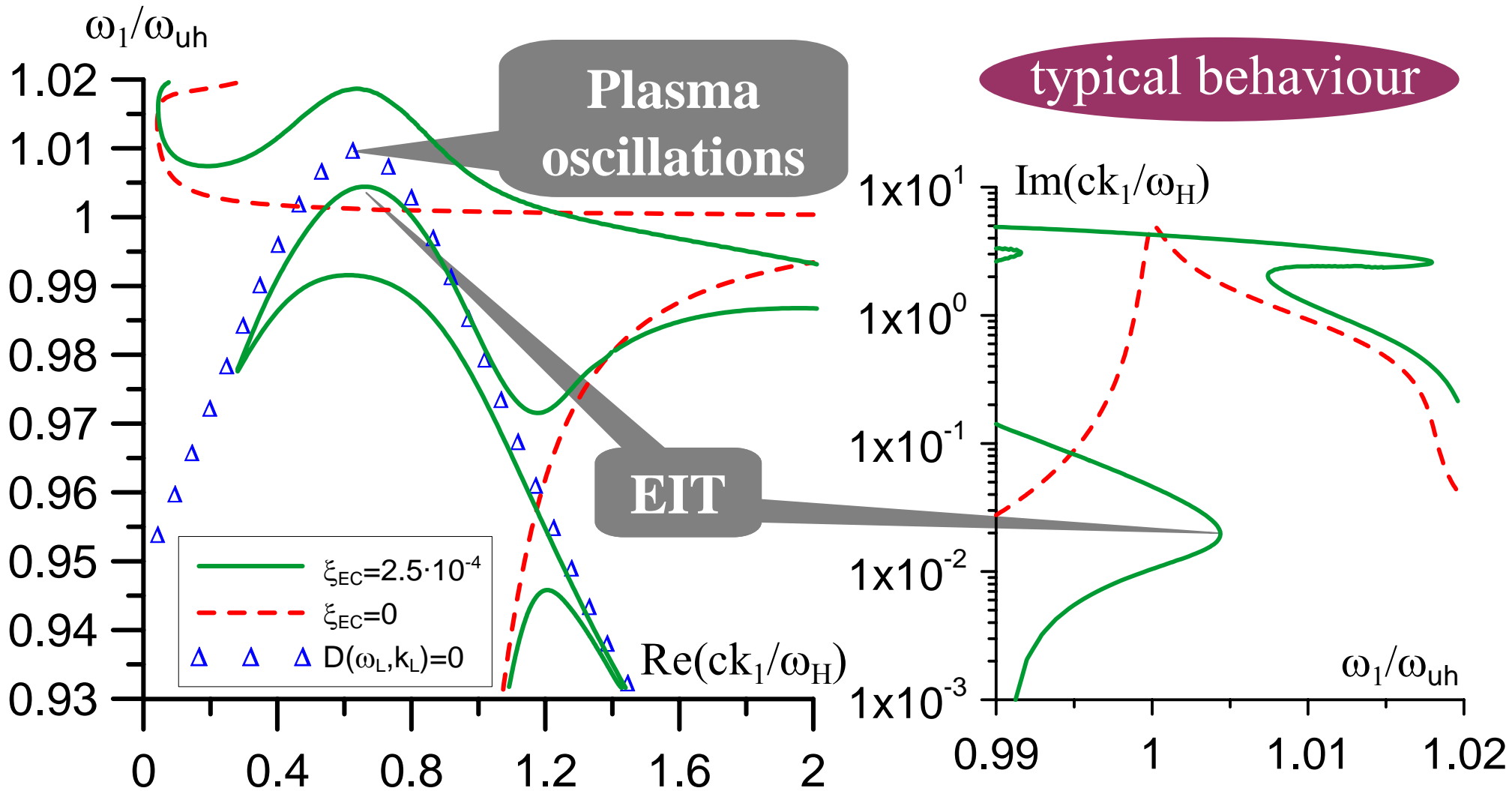
$$\varepsilon_{jk} = \varepsilon_{0jk} +$$

$$\frac{A_{jk}(\omega_1, k_1, \Theta_1) \xi_{EC}}{D(\omega_L, k_L) - B(\omega_1, k_1, \Theta_1) \xi_{EC}}$$

$D(\omega_L, \mathbf{k}_L)$ – beatwave dispersion

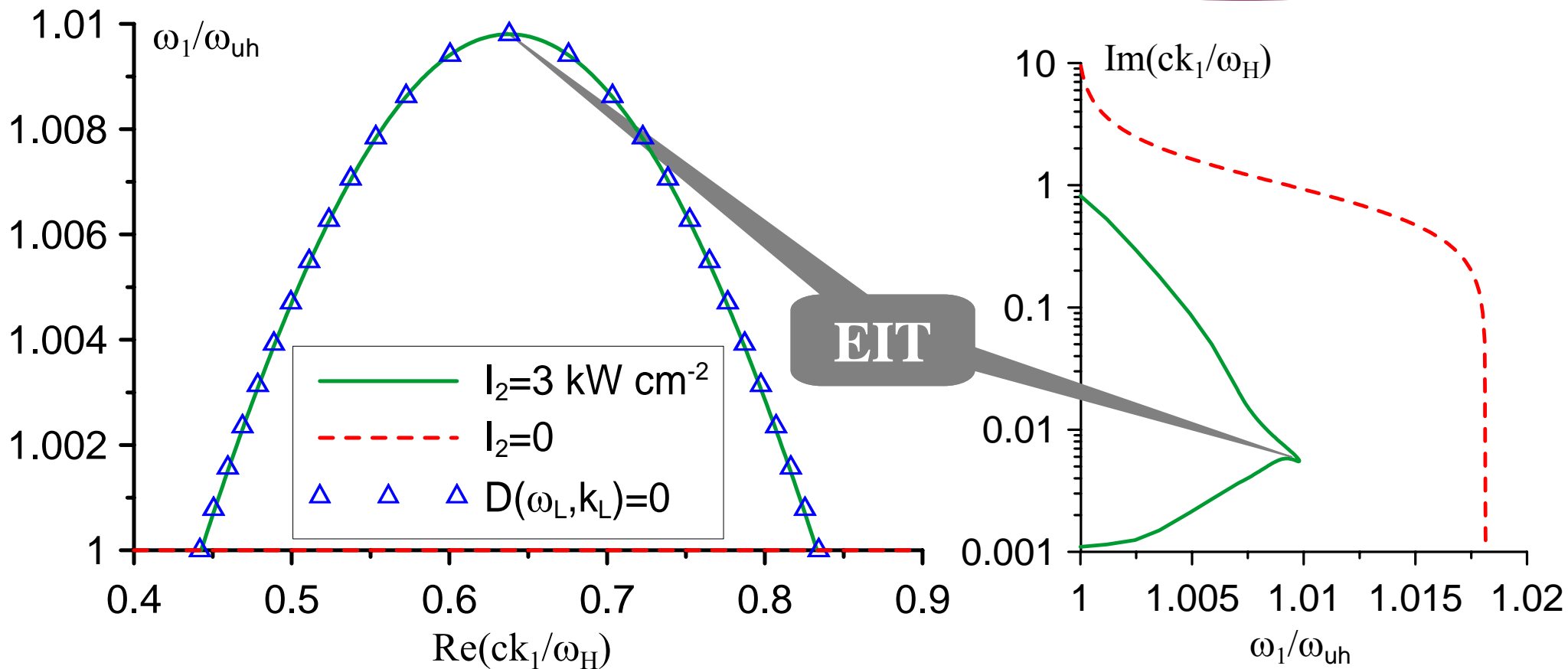
$\xi_{EC} = |\mathbf{eE}_2 / 2m\omega_2|^2 \cdot (\mathbf{k}_2 / \omega_2)^2$ – nonlinear EIT parameter

Dispersion and dissipation



$N_0 = 5 \cdot 10^{12} \text{ cm}^{-3}$, $H = 35 \text{ kG}$ ($\omega_H/2\pi = 94 \text{ GHz}$), $\gamma/\omega_H = 5 \cdot 10^{-4}$, $\omega_2/\omega_H = 0.83$, $\Theta_2 = 45^\circ$

real parameters



$H = 35 \text{ kG}$ ($\omega_{uh}/2\pi = 100 \text{ GHz}$), $N_0 = 5 \cdot 10^{12} \text{ cm}^{-3}$,
 $T = 1 \text{ keV}$ ($\gamma/\omega_H = 1 \cdot 10^{-8}$), $\omega_2/\omega_H = 0.83$, $\Theta_2 = 45^\circ$

Pump intensity I_2 , kW cm ⁻²	10	3	1	0
Transparency window $\Delta\omega/\omega_{\text{uh}}$ at level $\text{Im}(k_1)/\text{Re}(k_1)=0.1$	$5 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	—
Dissipation length for signal wave $L=[2\text{Im}(k_1)]^{-1}$, cm	20	5	1.5	$2.5 \cdot 10^{-4}$
Group velocity in EIT regime V_{gr}/c	$6 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$6 \cdot 10^{-8}$	—

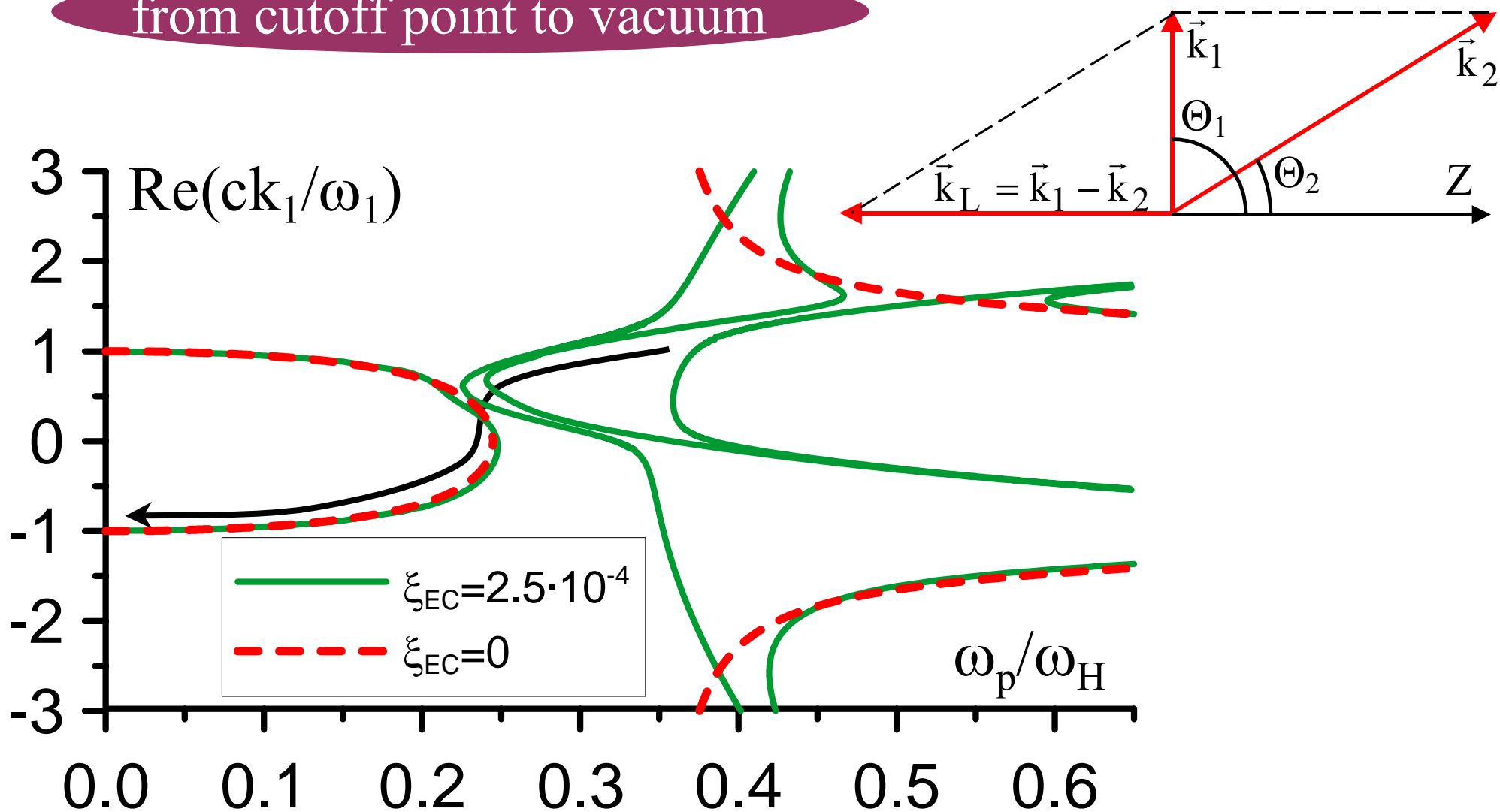
Main characteristics of propagation regime of probe wave

$$\Delta\omega \propto I_2^{1/2}, L \propto I_2, V_{gr} \propto I_2$$

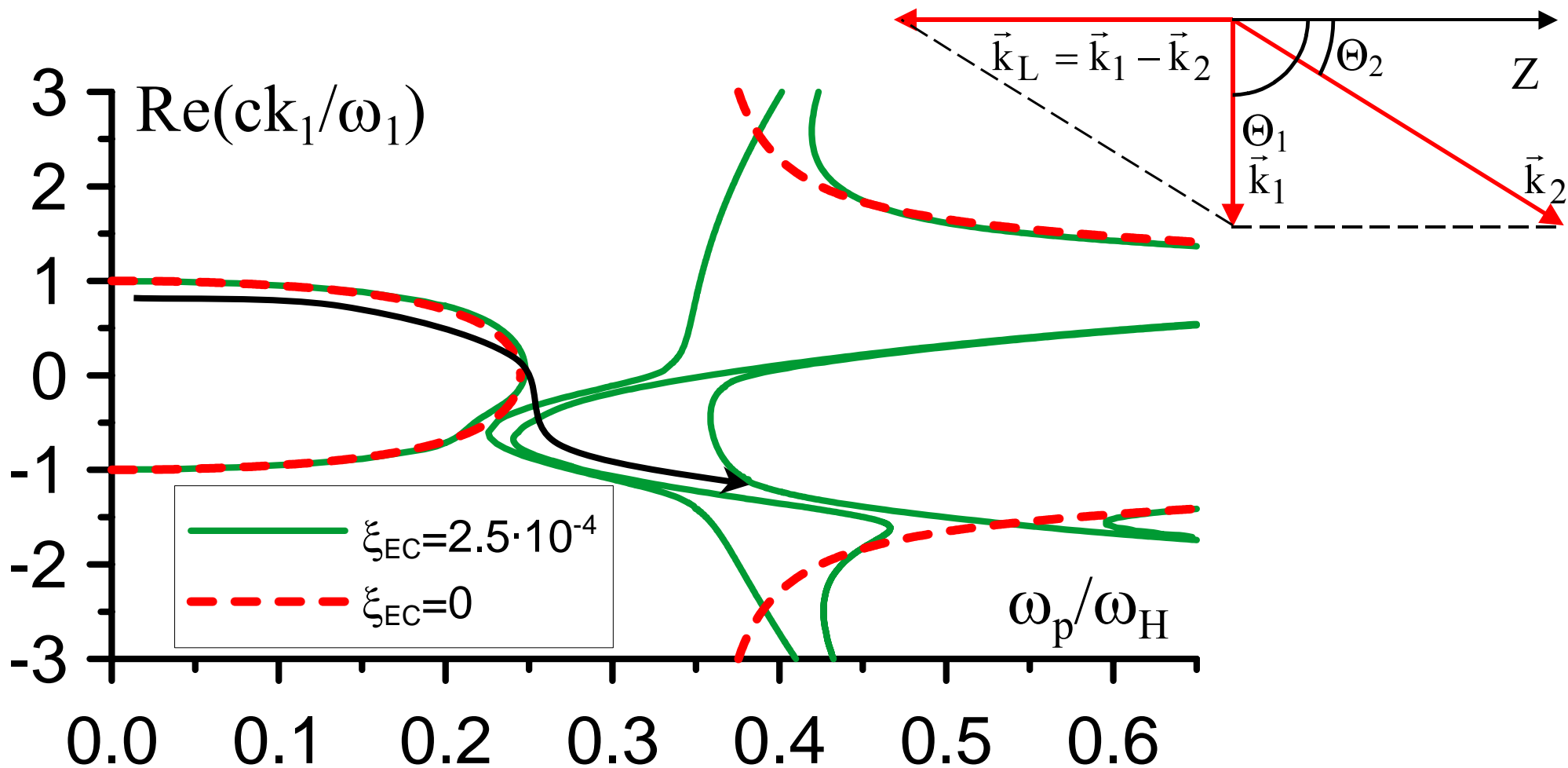
H=35 kG ($\omega_{\text{uh}}/2\pi=100$ GHz), $N_0=5 \cdot 10^{12}$ cm⁻³, T=1 keV ($\gamma/\omega_{\text{H}}=1 \cdot 10^{-8}$), $\omega_2/\omega_{\text{H}}=0.83$, $\Theta_2=45^\circ$

Transportation in inhomogeneous plasma

from cutoff point to vacuum



from vacuum to cutoff point



$H=35$ kG ($\omega_{uh}/2\pi=100$ GHz), $T=1$ keV ($\gamma/\omega_H=1 \cdot 10^{-8}$),
 $\omega_2/\omega_H=0.83$, $|\Theta_2|=45^\circ$

Conversion efficiency

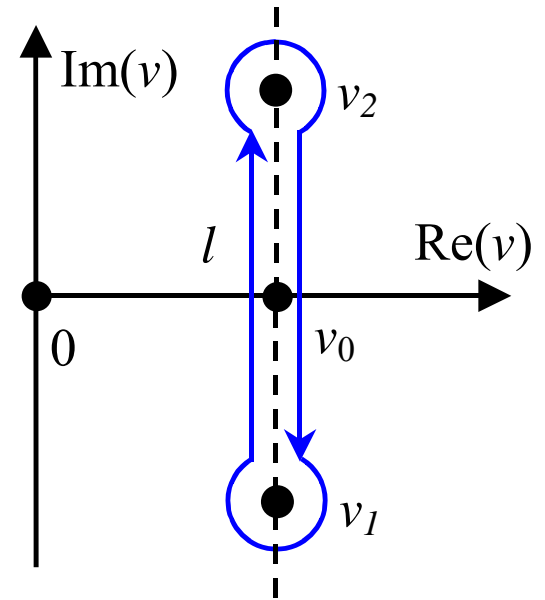
$$T \sim \exp(-\delta) \quad \delta = \left| \frac{\omega}{c} \int_l \frac{n_1 - n_2}{2} dv \right|$$

$$N_{EIT}^2 = \frac{c^2 k_1^2}{\omega_1^2} = 1 - \frac{2(a - b + c)}{2a - b \pm \sqrt{b^2 - 4ac}}$$

↓ approximation by 2 hyperbolas

$$[N - N_c - a_1(v - v_0)][N - N_c - a_2(v - v_0)] = \mu$$

$$\delta = \frac{\omega_1}{c} L_N \frac{2\pi\mu}{|a_1 - a_2|}$$



For pump intensity 10 kW cm^{-2} and inhomogeneity scale $\sim 10 \text{ m}$
transformation > 90%

Conclusions

- The effect of EIT exists for transverse propagation of the probe wave at upper-hybrid resonance: the strong group velocity slowing-down and significant reduction of dissipation are observed
- In EIT regime the probe wave can propagate in inhomogeneous plasma from vacuum to the cutoff point and vice versa

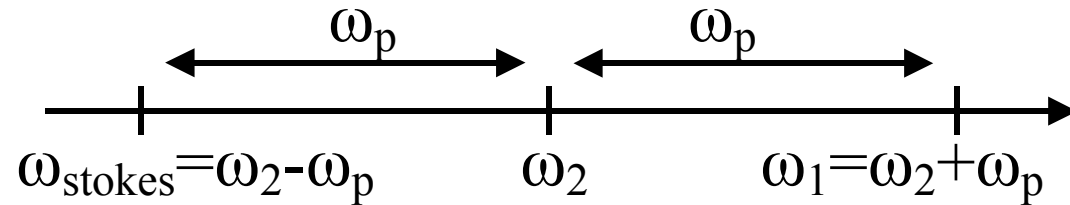
Possible applications

(general proposals only)

- **Plasma diagnostics ?**
the transportation of probe wave (e.g. spontaneous emission of the plasma) from cutoff region to the vacuum

Further investigations

- **“Stokes” component, influence of its instability**



- **Transportation of probe wave if $\omega_p > \omega_H$**

