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

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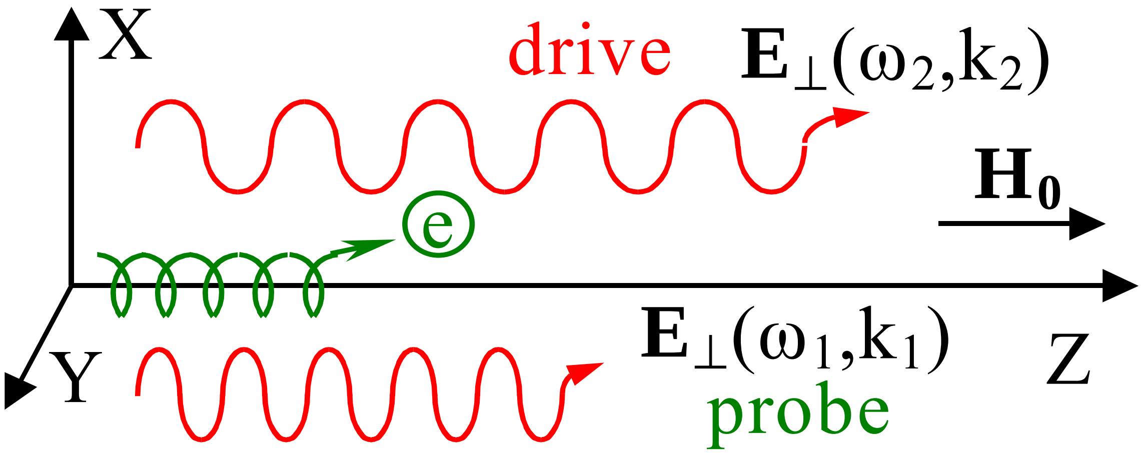
Previous Research: EIT in magnetoactive plasma for longitudinal propagation of the waves



$$\mathbf{E}_\perp(z,t) = \mathbf{E_1}\exp\left(-i\omega_1 t + ik_1 z\right) + \mathbf{E_2}\exp\left(-i\omega_2 t + ik_2 z\right)$$

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

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

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.

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

Motivation

Upper-hybrid resonance (UHR):

$$\omega_1 \approx \omega_{uh} = (\omega_H{}^2 + \omega_p{}^2)^{1/2}$$

- 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

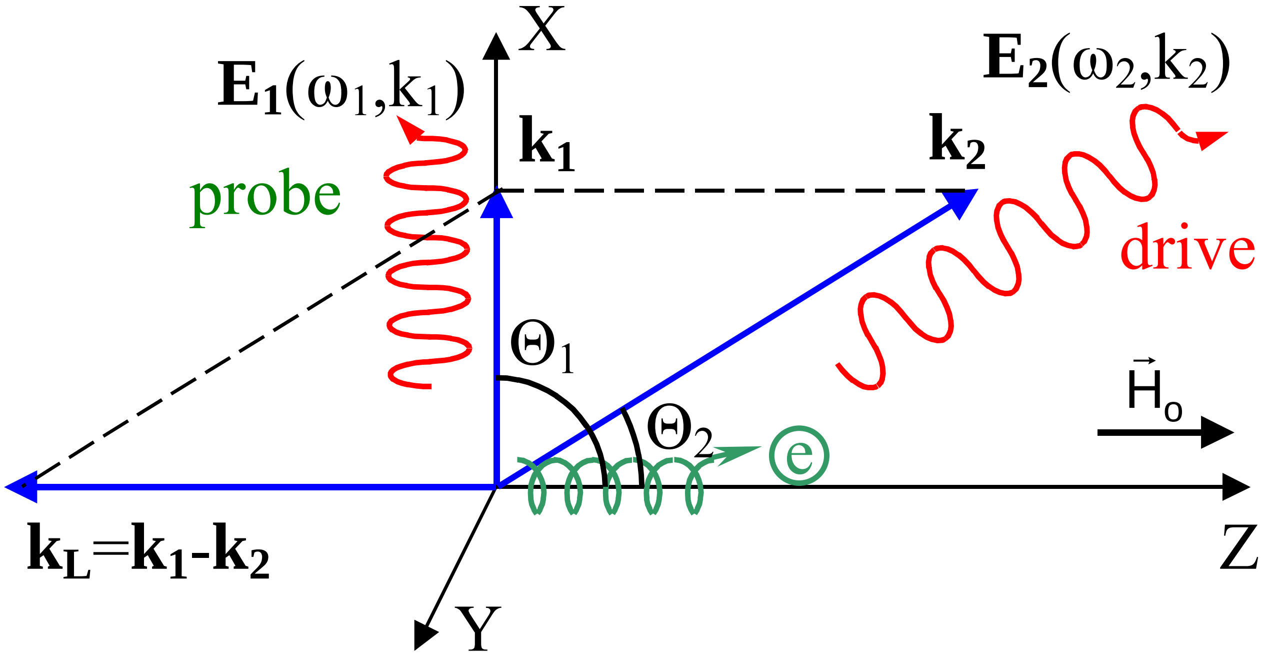
Formulation of the problem

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

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

1. $|\omega_1-\omega_{uh}|,\gamma << \omega_1,\omega_{uh}$
2. $|\omega_1-\omega_H|,\gamma << \omega_1,\omega_H$

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



$E_1\cdot E^*_2 \Rightarrow J_{L\ nonl} \Rightarrow E_L$

$E_L\cdot E_2 \Rightarrow J_{1\ nonl} \Rightarrow N^2_{EIT}$

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

Basic equations and effective refractive index

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

(hydrodynamic theory)

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

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

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

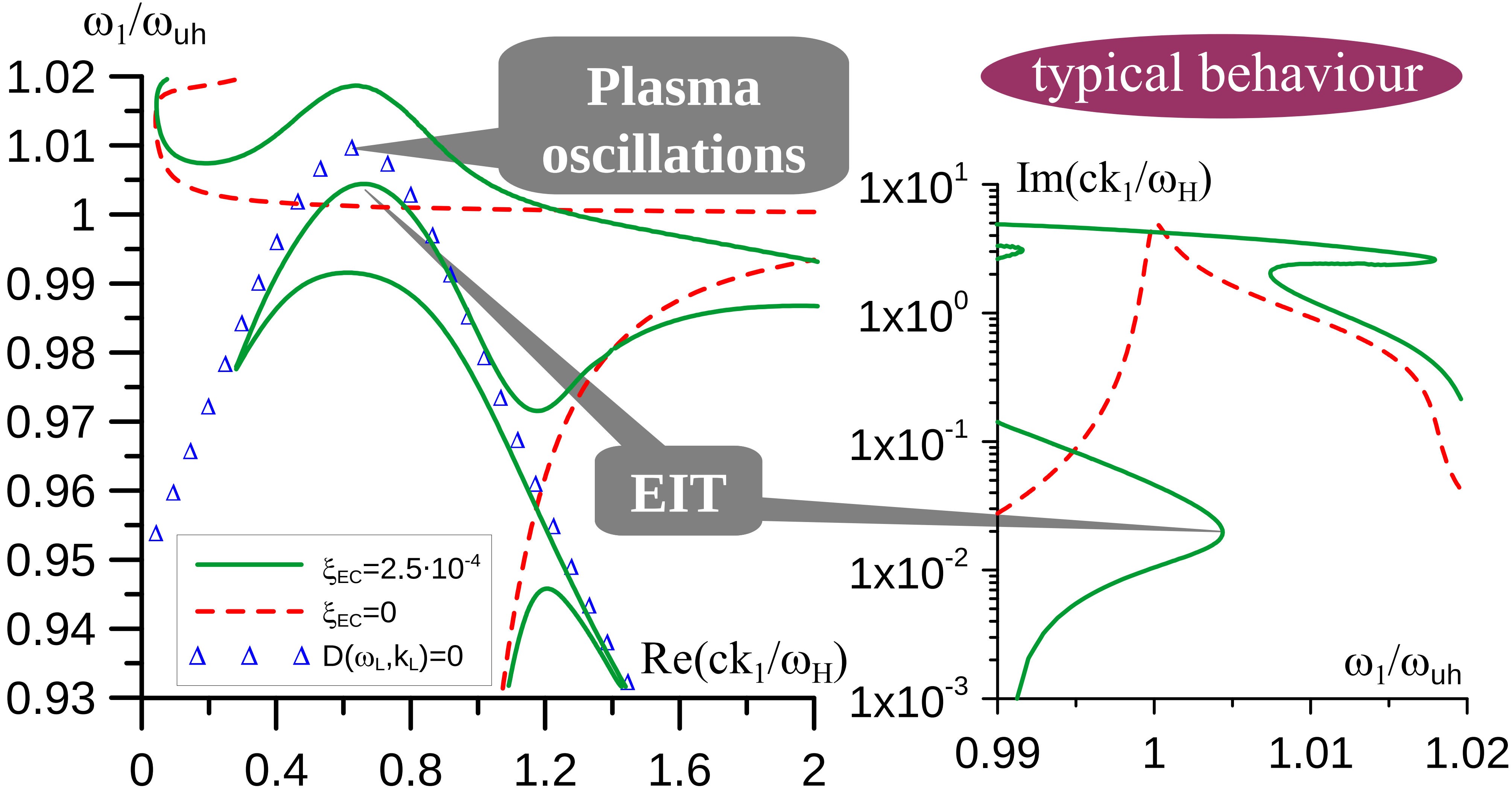
$$c = \varepsilon_{zz}\left(\varepsilon_{xx}\varepsilon_{yy} - \varepsilon_{xy}\varepsilon_{yx}\right).$$

$$\varepsilon_{jk} = \varepsilon_{0\,jk} + \frac{A_{jk}\left(\omega_1,k_1,\Theta_1\right)\xi_{EC}}{D\left(\omega_L,k_L\right) - B\left(\omega_1,k_1,\Theta_1\right)\xi_{EC}}$$

$D(\omega_L,k_L)$ – beatwave dispersion

$\xi_{EC}=|eE_2/2m\omega_2|^2\cdot(k_2/\omega_2)^2$ – nonlinear EIT parameter

Dispersion and dissipation



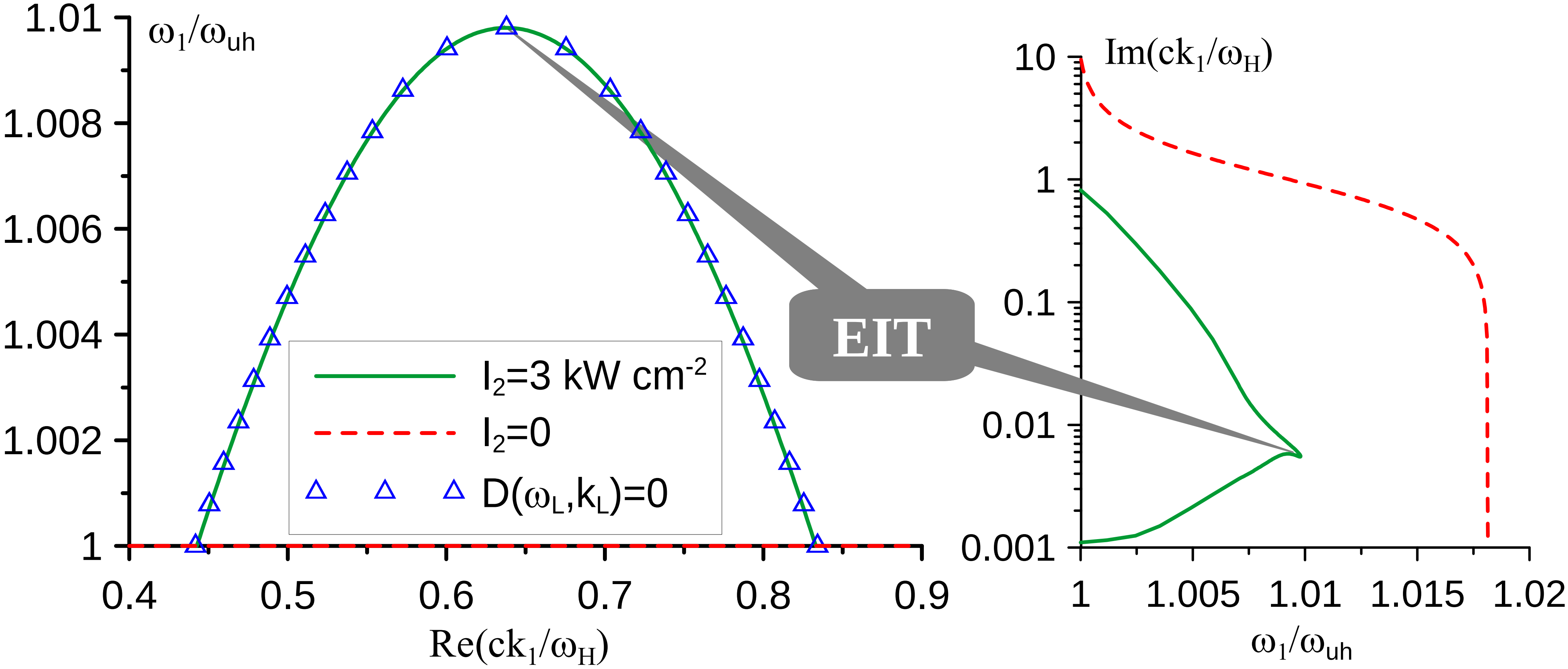
Plasma oscillations

EIT

typical behaviour

$N_0 = 5\cdot10^{12}$ cm^{-3}, H=35 kG ($\omega_H/2\pi$=94 GHz), $\gamma/\omega_H = 5\cdot10^{-4}$, $\omega_2/\omega_H = 0.83$, $\Theta_2 = 45°$

real parameters



H=35 kG ($\omega_{uh}/2\pi$=100 GHz), $N_0= 5\cdot10^{12}$ cm^{-3},
T=1 keV ($\gamma/\omega_H=1\cdot10^{-8}$), ω_2/ω_H=0.83, Θ_2=45°

Pump intensity I_2 , kW cm^{-2}	**10**	**3**	**1**	**0**
Transparency window $\Delta\omega/\omega_{uh}$ at level $\mathrm{Im}(k_1)/\mathrm{Re}(k_1)=0.1$	**$5\cdot10^{-3}$**	**$3\cdot10^{-3}$**	**$1.5\cdot10^{-3}$**	**—**
Dissipation length for signal wave $L=[2\mathrm{Im}(k_1)]^{-1}$, cm	**20**	**5**	**1.5**	**$2.5\cdot10^{-4}$**
Group velocity in EIT regime V_{gr}/c	**$6\cdot10^{-7}$**	**$2\cdot10^{-7}$**	**$6\cdot10^{-8}$**	**—**

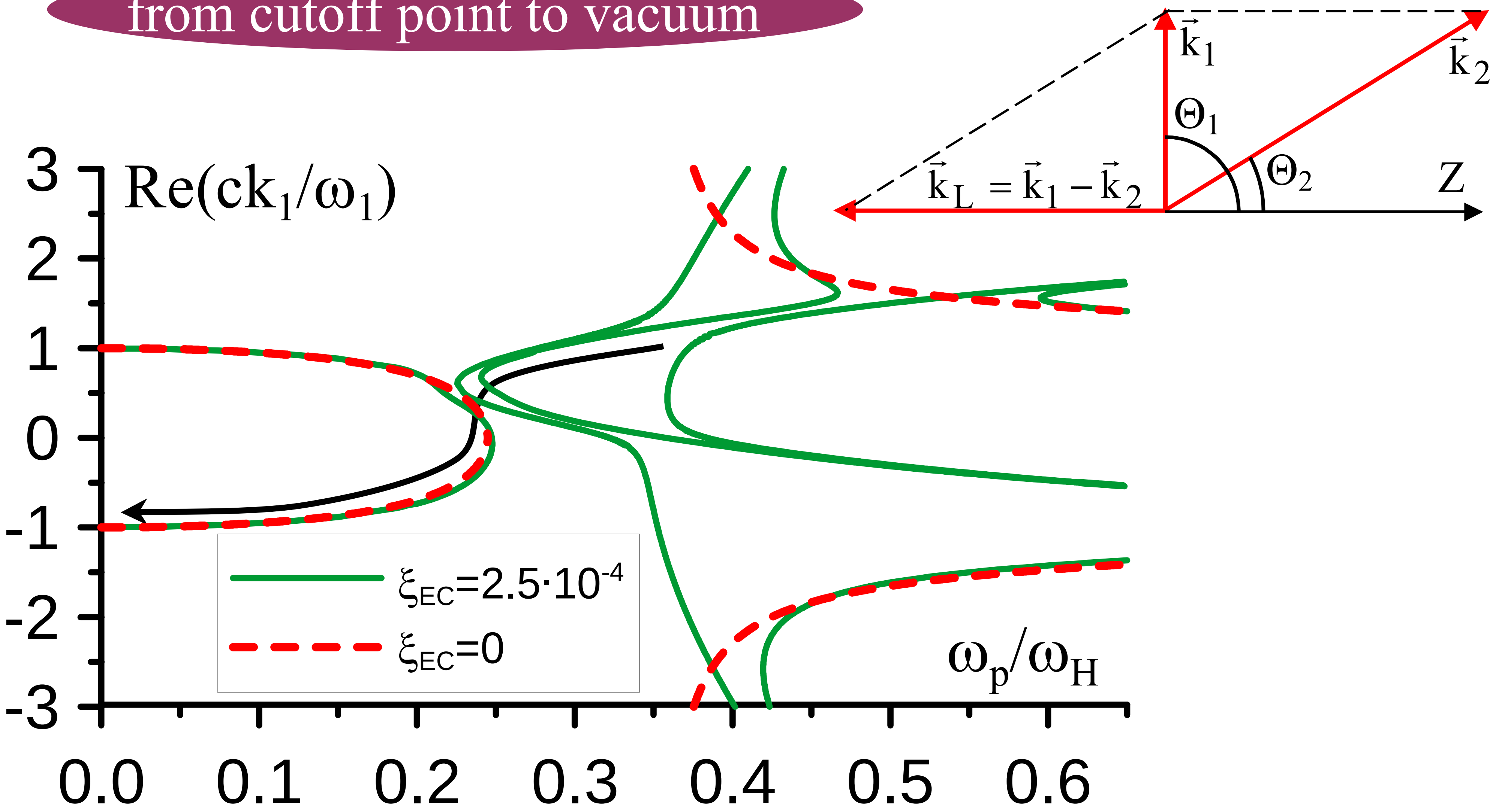
Main characteristics of propagation regime of probe wave

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

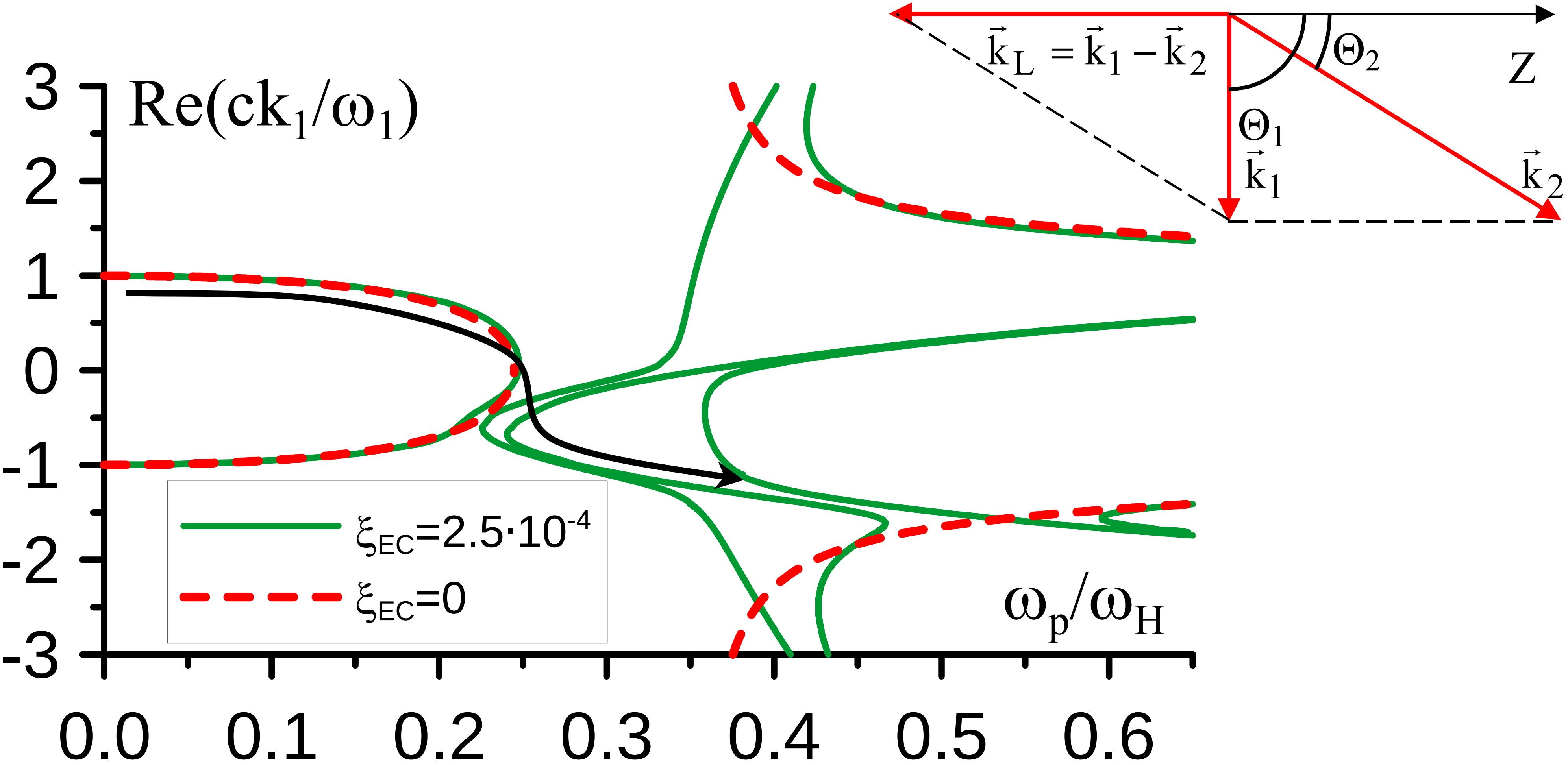
H=35 kG ($\omega_{uh}/2\pi$=100 GHz), $N_0= 5\cdot10^{12}$ cm^{-3}, T=1 keV ($\gamma/\omega_H=1\cdot10^{-8}$), $\omega_2/\omega_H=0.83$, $\Theta_2=45°$

Transportation in inhomogeneous plasma

from cutoff point to vacuum



from vacuum to cutoff point

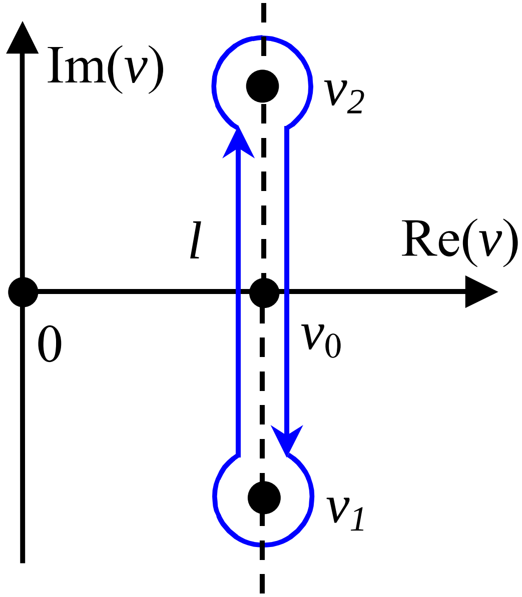


H=35 kG ($\omega_{uh}/2\pi$=100 GHz), T=1 keV ($\gamma/\omega_H=1\cdot10^{-8}$),
ω_2/ω_H=0.83, $|\Theta_2|$=45°

Conversion efficiency

$T \sim \exp(-\delta)$

$$\delta = \left| \frac{\omega}{c\left(dv/dz\right)} \oint_l \frac{n_1 - n_2}{2}\, dv \right|$$



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

⇩ approximation by 2 hyperbolas

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

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

For pump intensity 10 kW cm^{-2} and inhomogeneity scale ~10 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

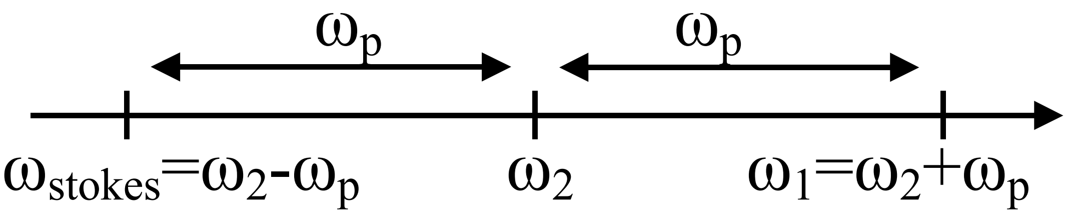
(general proposals only)

- **Plasma diagnostics ?**

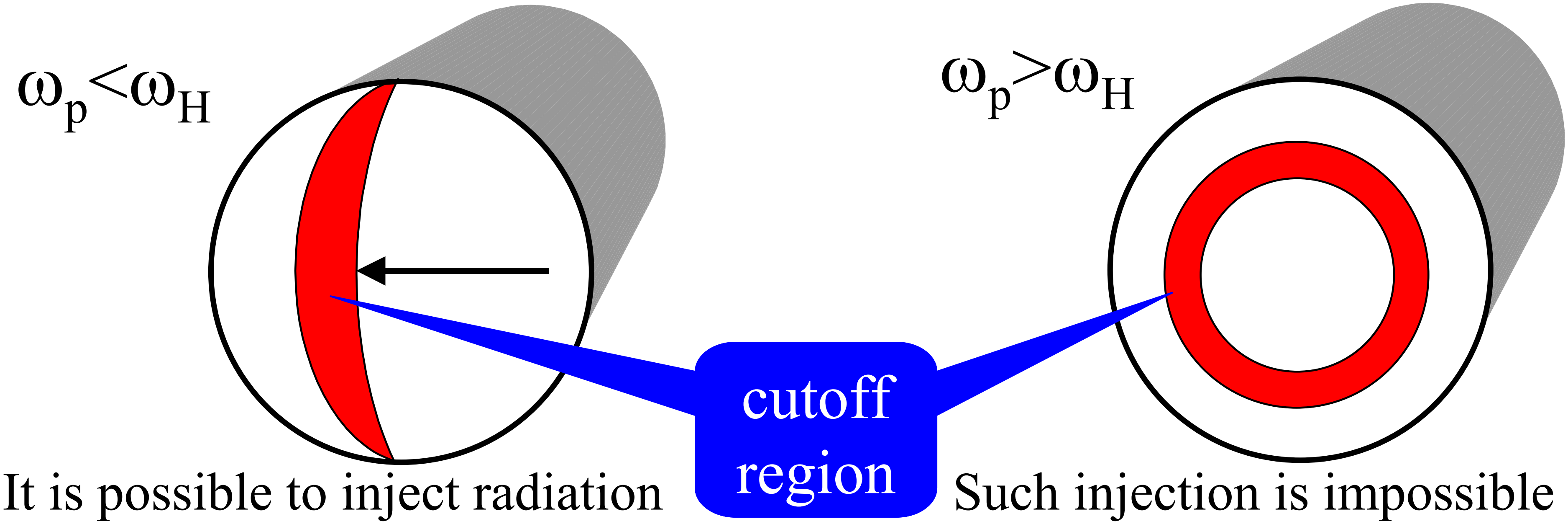
  the transportation of probe wave (e.g. spontaneous emission of the plasma) from cutoff region to the vacuum

Further investigations

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



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



It is possible to inject radiation from the inner part of the torus

Such injection is impossible and EIT might help