MODELLING OF SLOW WAVE PROPAGATION AND ABSORPTION AT THREE-ION ICRH IN W7-X

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Three-ion ICRH on Wendelstein 7-X

The ICRH system was designed[1)], installed and commissioned on W7-X plasmas[2)] in operational campaign OP2.1.

One of the main goals of the ICRH in W 7-X is to produce **high energy ions** for the investigations of the fast ions confinement in the "fully-optimized" stellarator.

Three-ion **D – (^{3}He) – H** **Fast Wave** heating is a promising method for the fast ions generation[3)].

1) J. Ongena et al. PHYSICS OF PLASMAS 21, 061514 (2014)
2) J. Ongena et al. IAEA-CN-316/EX-H/P8-1932 (London, 2023)
3) Ye. Kazakov et.al. Nature Physics (2017) doi:10.1038/nphys4167

Fast wave launching

In a 'cold' plasma limit, there are two waves in the plasma periphery:

1) a Fast Wave with $E_{//}=0$ and

2) a Slow Wave with $E_{//} \neq 0$.

ICRF antenna is designed so as to have $E_{//}=0$.

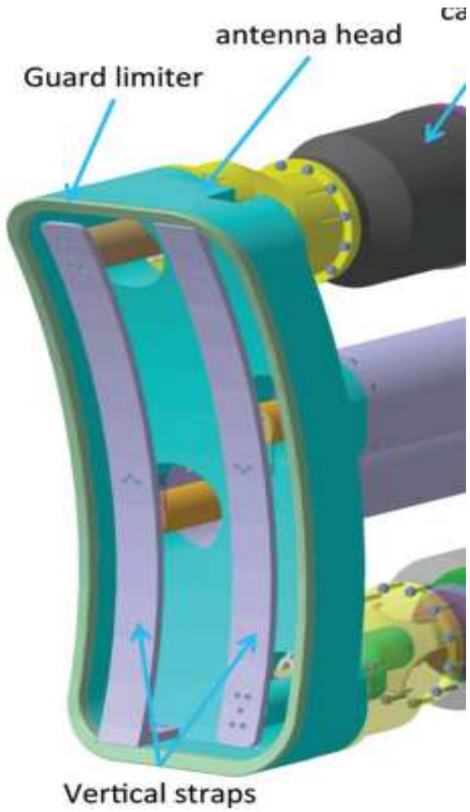
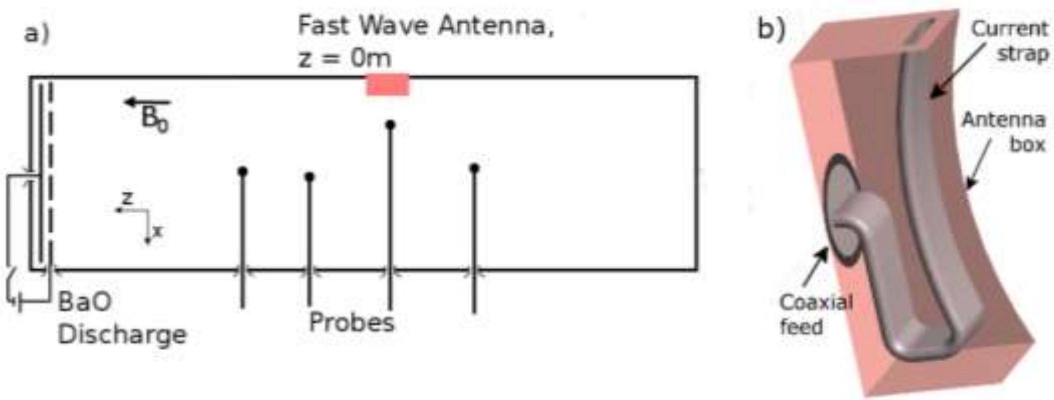
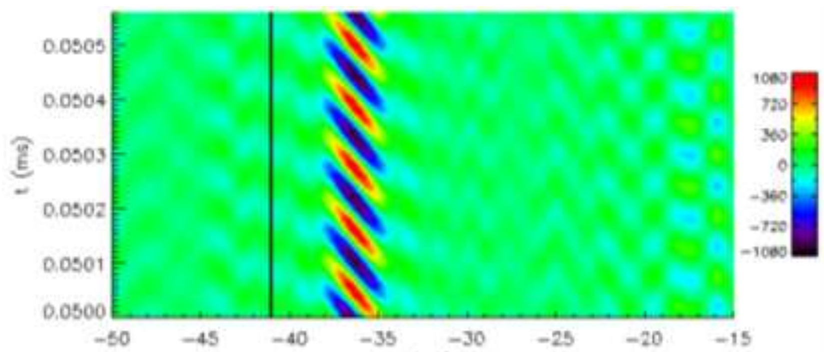


Figure from J. Ongena et al. PHYSICS OF PLASMAS 21, 061514 (2014)

Evidence that the ICRF antenna is emitting a slow wave (1)

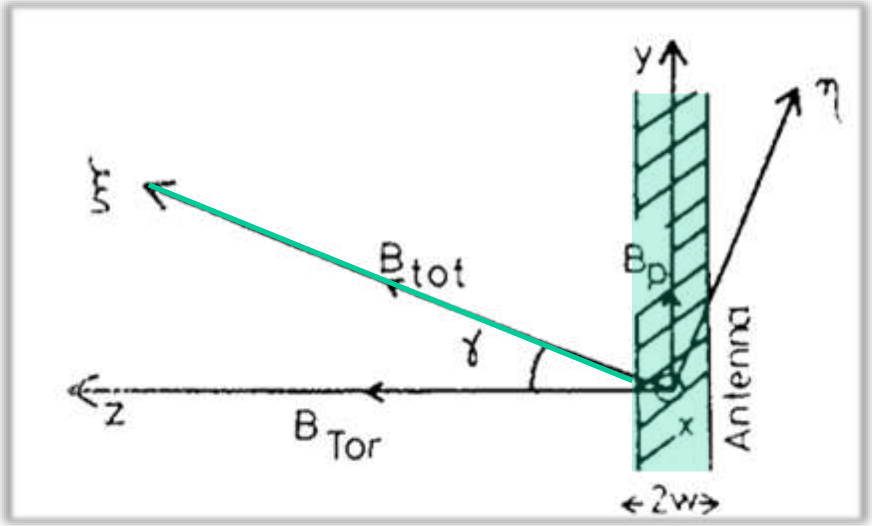
Results of ICRF experiments at the Large Plasma Device (LAPD) indicate parasitic coupling to the slow wave by the fast wave antenna.

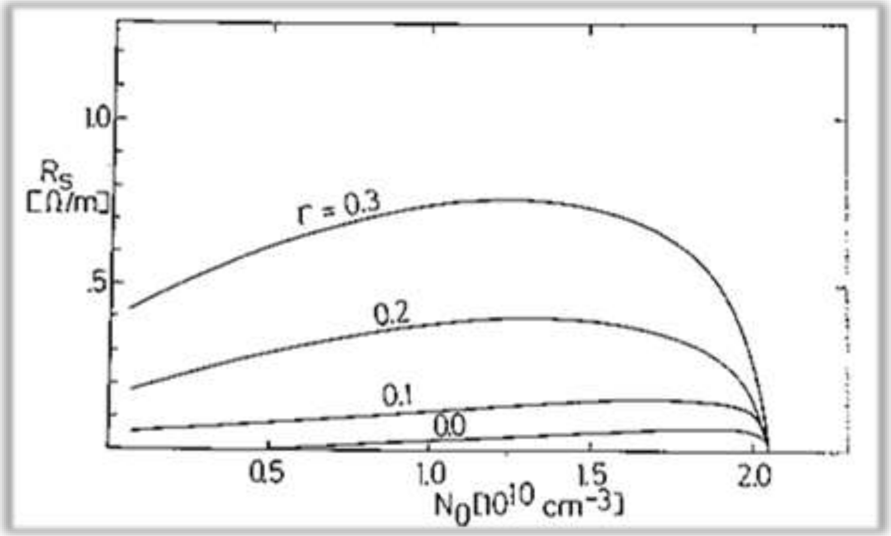




Figures from B. Van Compernolle *et al* 45th EPS Cof. on Plasma Phys., P5.1051

Evidence that the ICRF antenna is emitting a slow wave (2)





Due to a misalignment of the antenna strap and the magnetic field.

For the ICRF antenna with a Faraday shield

R_S/R_F ~ 3 – 30 %

Fig. from M.P. Evrard, R.R. Weynants
Heating in Toroidal Plasmas, 1982, v. 1, p. 339

Evidence that the ICRF antenna is emitting a slow wave (3)

For plasma production $E_{//} \neq 0$ (slow wave) is necessary.

Numerous successful experiments on plasma production by ICRF antenna (w/wo Faraday shield) in tokamaks and stellarators.

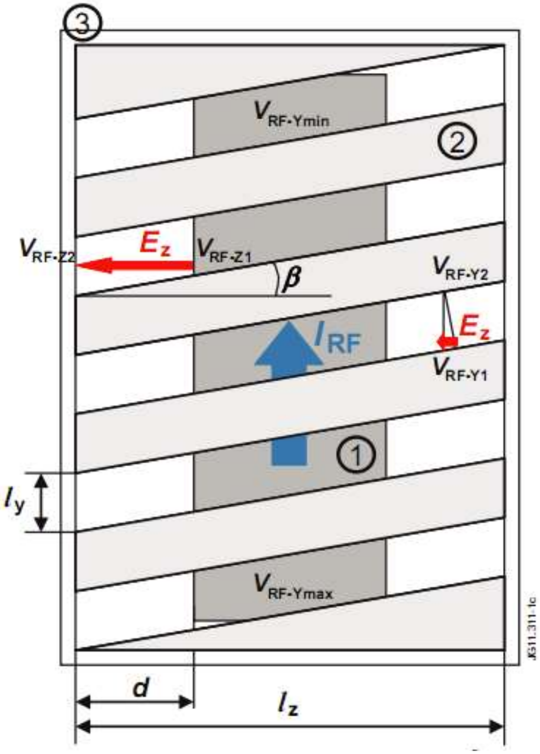
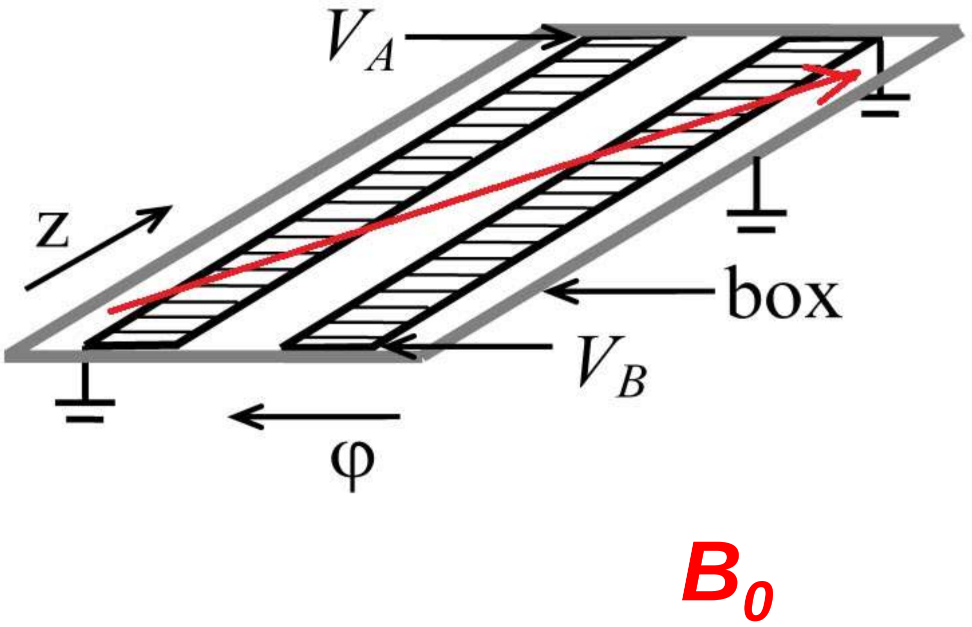


Figure from A. Lyssoivan *et al* Plasma Phys. Control. Fusion 54 (2012) 074014

Evidence that the ICRF antenna is emitting a slow wave (4)

W7-X ICRF antenna

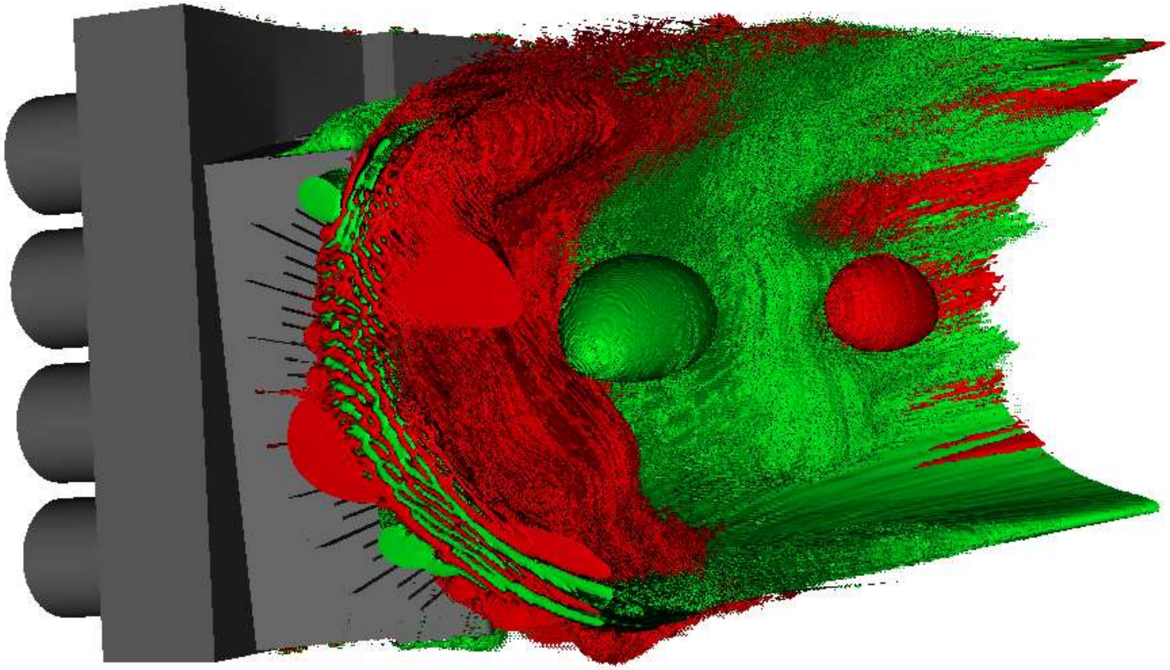
- misalignment;
- box – strap potential differences;
- strap – strap potential difference.



R_S/R_F - *unknown*

Tools for a slow wave investigation

Finite-difference time-domain simulations



Contours of the vertical electric field

Take 4-6 million processor core-hours per run, give 5-10 TB of output data

Figure from T.G. Jenkins, D.N. Smithe AIP Conf. Proc. **1689**, 030003, 2015

Ray tracing (1)

- The numerical problem of the simulation of the simultaneous launching of the fast and slow waves is very complicated due to its stiffness (particularly in the 3D geometry).

- The slow wave scale length in the W7-X plasma periphery λ ~ 2 mm << distance d between the LCMS and antenna and λ << the scale of variation of the plasma parameters.

- This justifies application of the ray tracing approximation for investigation of the slow wave propagation and absorption in the W7-X plasma periphery.

Ray tracing (2)

The ray tracing code **SLOWAR** (SLOw WAve Rays) was used for the calculations. The code solves the equations

$$\frac{d\vec{r}}{dt} = \frac{\partial D_R}{\partial \vec{k}} \Big/ \frac{\partial D_R}{\partial \omega}, \quad \frac{d\vec{k}}{dt} = -\frac{\partial D_R}{\partial \vec{r}} \Big/ \frac{\partial D_R}{\partial \omega}$$

where $\vec{r}$ is the spatial coordinates of the ray,

t is time, D_R is the real part of the dispersion equation

$\vec{k}$ is the wave vector,

ω is the wave frequency.

Ray tracing (3)

Define $k_{\|} = \vec{k} \cdot \vec{B} / B$ $N_{\|} = ck_{\|} / \omega$ $k_{\perp} = (k^2 - k_{\|}^2)^{1/2}$ $N_{\perp} = ck_{\perp} / \omega$

$$D = D_R + iD_I = \varepsilon_1 N_{\perp}^4 + \left[(\varepsilon_3 + \varepsilon_1)(N_{\|}^2 - \varepsilon_1) + \varepsilon_2^2 \right] N_{\perp}^2 + \varepsilon_3 \left[(N_{\|}^2 - \varepsilon_1)^2 - \varepsilon_2^2 \right] = 0$$

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_1 & i\varepsilon_2 & 0 \\ -i\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix}$$

The dielectric tensor is based on the warm plasma model and resolves only electron Landau damping and fundamental ion cyclotron resonances.

Transcendental equation, SW + FW.

Absorption

Power associated with certain ray is defined as $Q = Q_0 e^{-\Gamma}$

Here $\Gamma = \int_0^t \gamma \, dt$ $\gamma = -\frac{D_I}{\partial D_R / \partial \omega}$

Power dissipated along the ray $P_{tot} = Q_0 \left(1 - e^{-\Gamma}\right)$

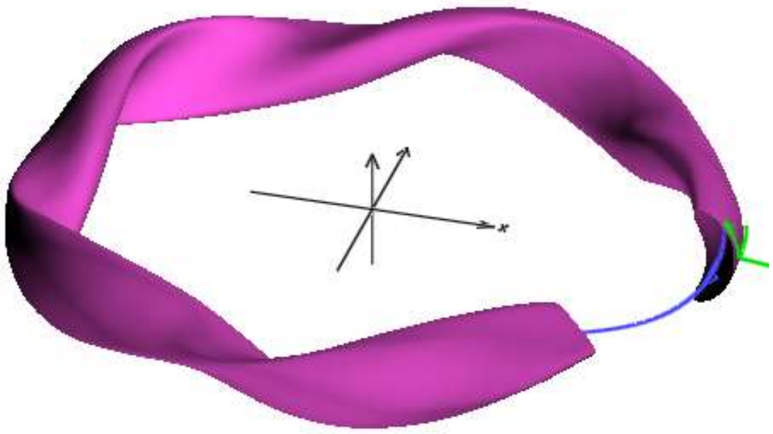
$$P_{tot} = \int_0^s \left(p_{col} + p_e + p_{i1} + p_{i2} + p_{i3}\right) ds \qquad s = \int_0^t \left|\vec{v}_g\right| dt$$

Electron Landau damping p_e, ion cyclotron damping $p_{i\alpha}$ (α = 1, 2, 3), and collisional damping p_{col} were taken into account.

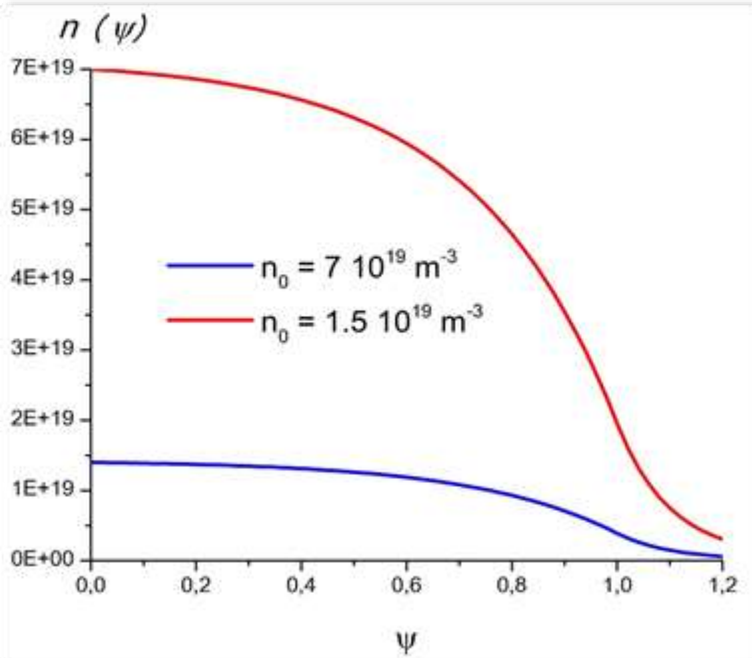
Equilibrium

The VMEC code was used in order to reconstruct a W 7-X equilibrium. VMEC data were extrapolated up to the flux surface label ψ = 1.2 behind the LCMS.

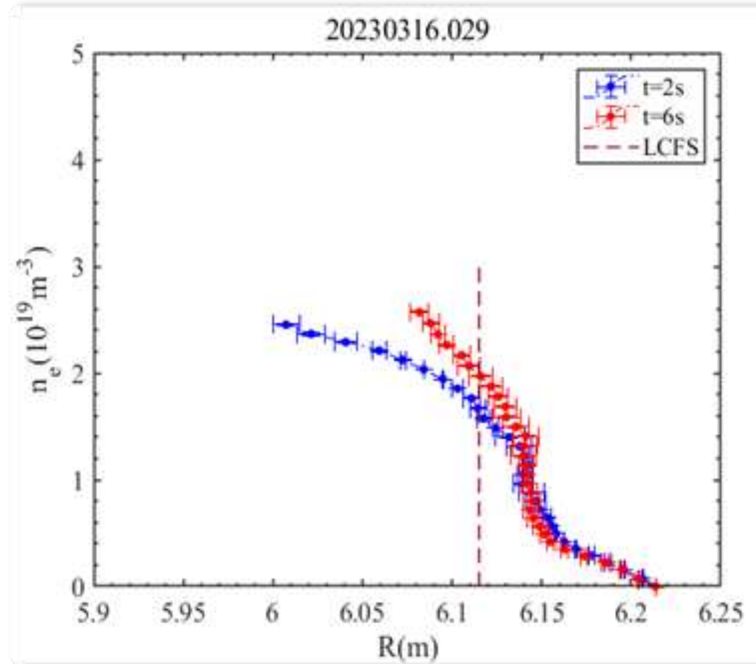
The “standard” magnetic configuration was used.



Density distribution



a)



b)

a) Density profiles – these calculations

b) Figure from H.M. Xiang et al 49 EPS Conf. (Bordeaux, France)

Parameters

The following set of parameters has been used for consideration: ***B_0=2.5 T, n_{e0}=7·10^{19} m^{-3}, n_{eb}=5·10^{17} m^{-3}, n_H/n_e = 0.68, n_D/n_e = 0.3, n_{He3}/n_e = 0.01, T_{e0}=1 keV, T_{eb}=5 eV, ω=f/2p=25 MHz***, a standard equilibrium.

$$\left(N_\perp^2 - N_{\perp S}^2\right)\left(N_\perp^2 - N_{\perp F}^2\right) = 0$$

SW simplified $|\varepsilon_3| >> |\varepsilon_1|, |\varepsilon_2|$

dispersion relation

$$N_{\perp S}^2 = \frac{-\varepsilon_3}{\varepsilon_1}\left(N_\parallel^2 - \varepsilon_1\right)$$

Initial conditions (1)

$$\vec{r}_0 = \left(R_0, \varphi_0, z_0\right)$$

The part of the surface ψ = 1.09 in front of the antenna was divided into 55 sections.

5 columns with coordinates in toroidal direction

φ_0 = [0.106, 0.1175, 0.129, 0.1405, 0.152]

and 11 rows with coordinates in vertical direction

z_0 = [0 m, ± 0.075 m, ± 0.15 m, ± 0.225 m, ± 0.3 m, ± 0.375 m]

Initial conditions (2)

SW electric field $E_{||}$ at the ICRH antenna was expanded into Fourier series of poloidal m_0 and toroidal l_0 angles

For the FW propagation in a stellarator or tokamak plasmas, it is usually supposed that $N_{||} = c(l + m\iota)/(R\omega) + N_R b_R, \quad b_R << 1$

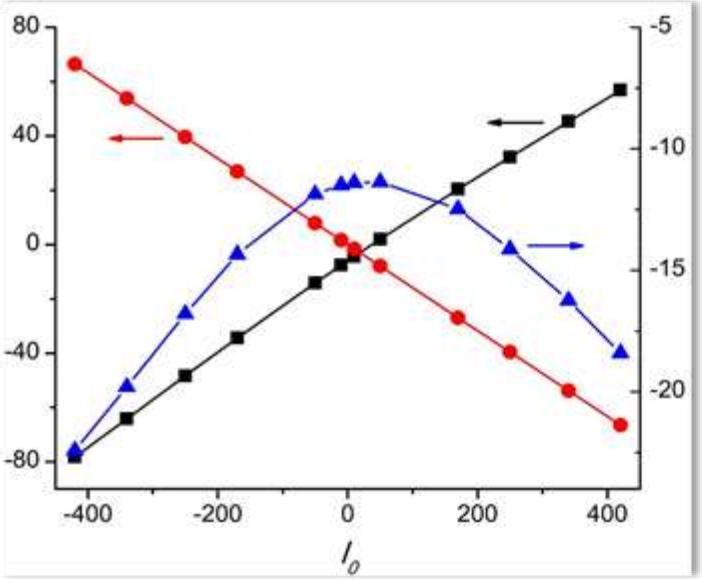
$$N_{R0} \qquad N_{\varphi 0} = (cl_0)/(\omega R_0) \qquad N_{z0} = \frac{cm_0}{\omega \bar{a}} \cos[arctg(z_0/R_0)]$$

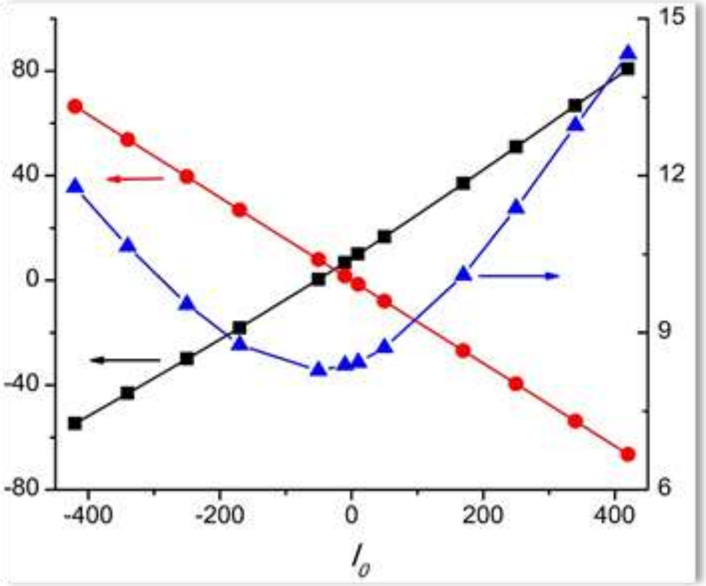
from the transcendental dispersion equation

As a result, $N_{||} = N_R b_R + N_\varphi b_\varphi + N_z b_z$

Initial conditions (3)

$$N_{\parallel} = N_R b_R + N_\varphi b_\varphi + N_z b_z$$

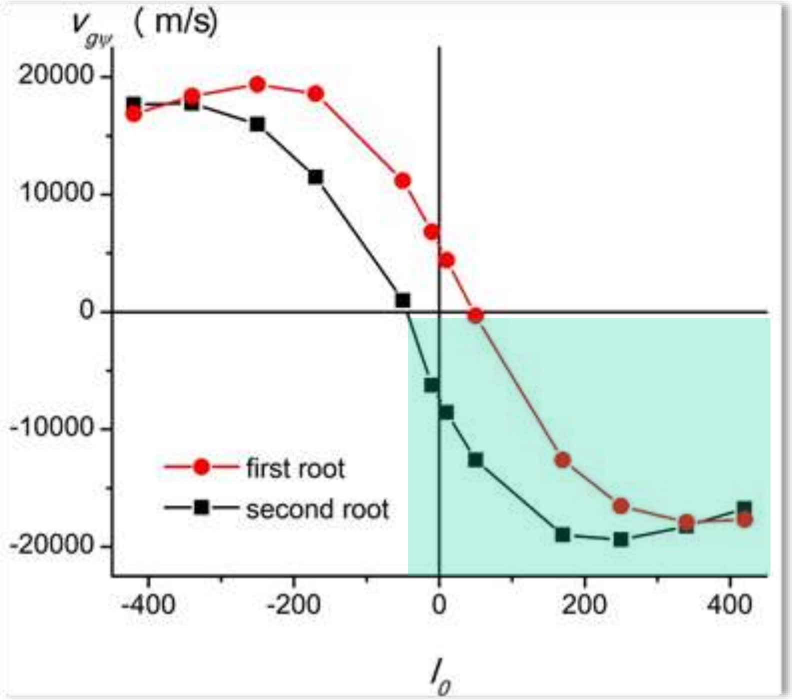




The initial $N_{\parallel 0}$ as a function of the toroidal wave number l_0.

$counter\ \vec{B}$ N_{R0} $co-\vec{B}$ N_{R0}

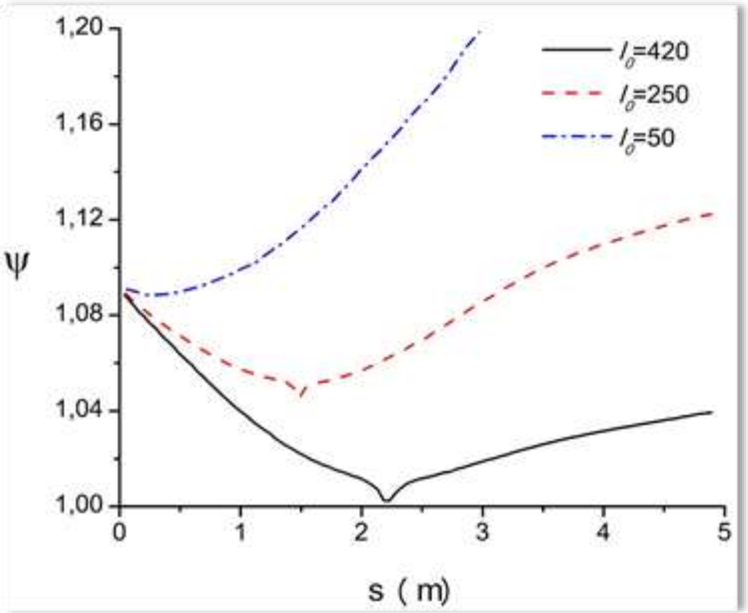
Initial conditions (4)

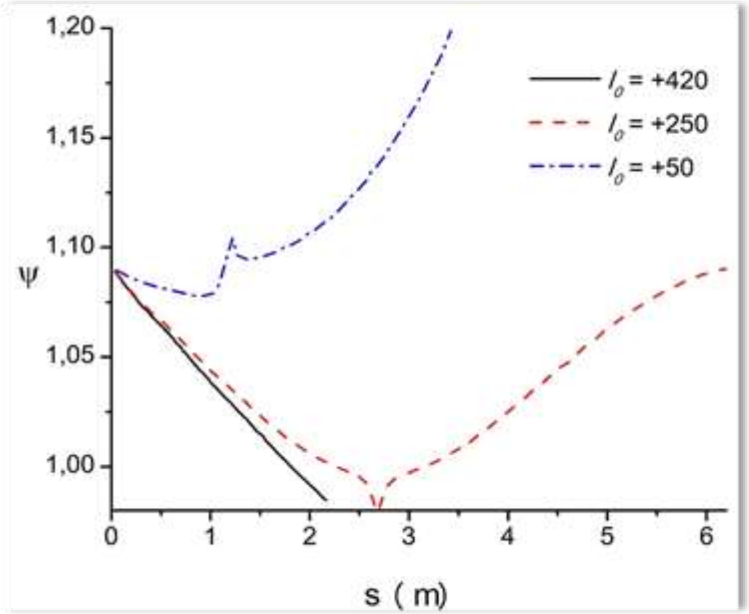


	$\delta\varphi < 0$, $co - \vec{B}$	$\delta\varphi > 0$, $counter\ \vec{B}$
$\delta\psi > 0$	2nd root, $l_0 < 0$	1st root, $l_0 < 0$
$\delta\psi < 0$	2nd root, $l_0 > 0$	1st root, $l_0 > 0$

The component of the group velocity in the direction of *grad(ψ)* at the start point

Typical SW ray characteristics (1)





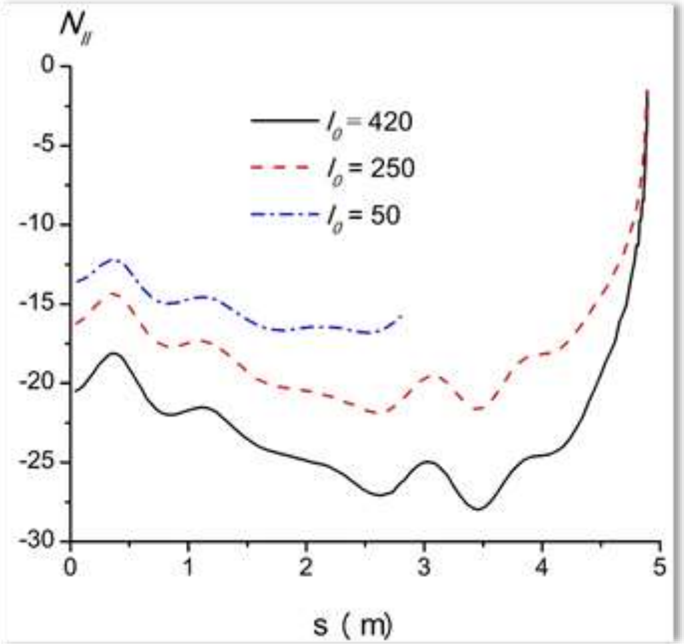
$counter\ \vec{B}$

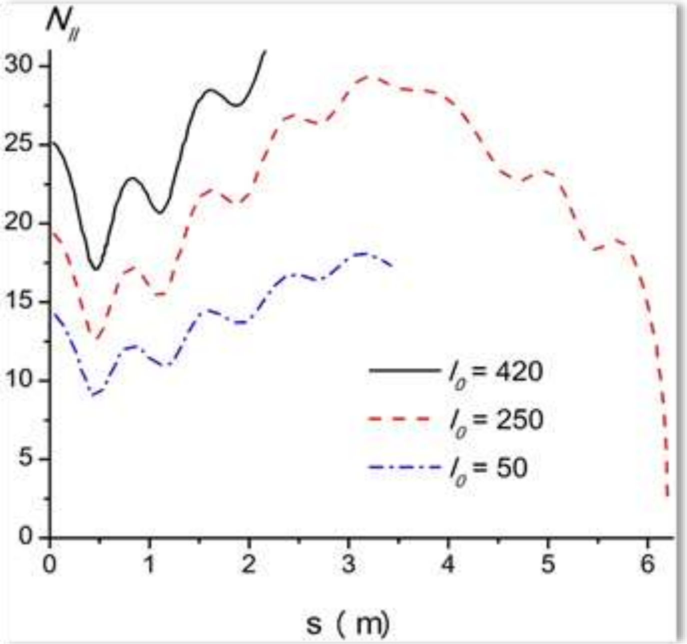
$co-\vec{B}$

$$z_e = \omega / \sqrt{2} k_{\parallel} v_{Te}$$

$\Delta\psi \approx 0.09$ → $\Delta\bar{a} \approx 0.05\, m$

Typical SW ray characteristics (2)

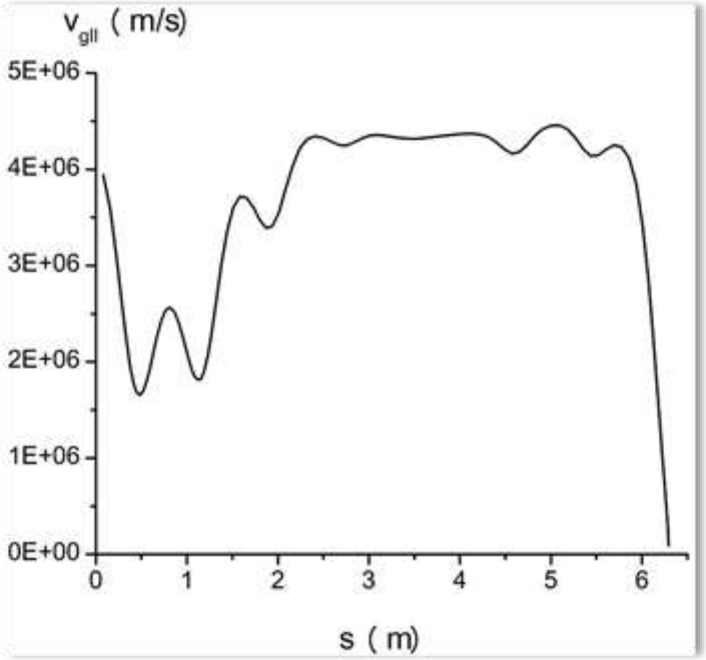


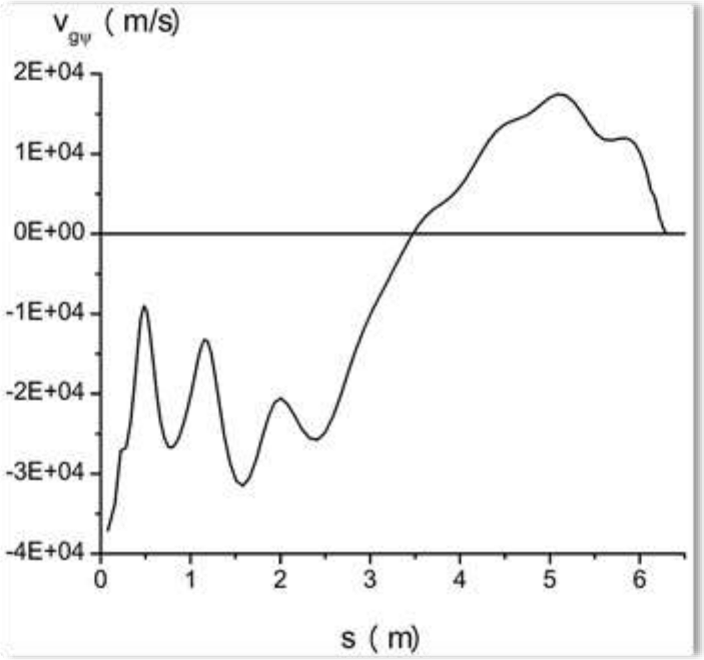


$counter\ \vec{B}$ $co-\vec{B}$

The parallel refractive index as a function of the ray length

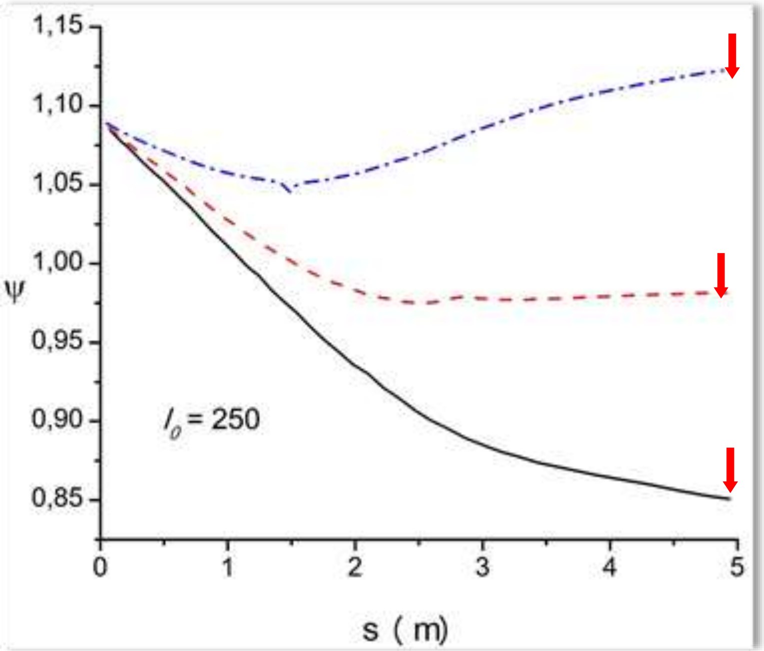
Typical SW ray characteristics (3)

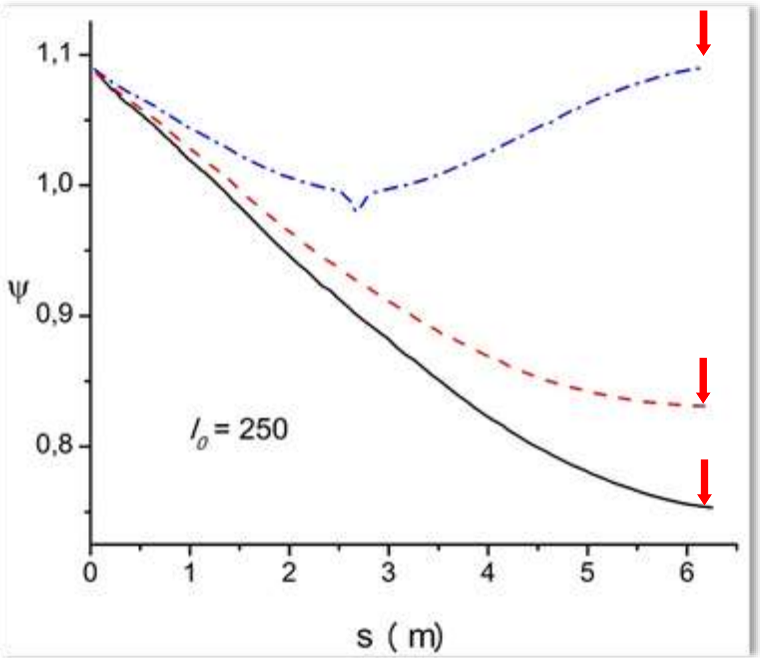




The components of group velocity $\frac{v_{g\parallel}}{v_{g\perp}} \sim \sqrt{\frac{m_\alpha}{m_e}}\kappa, \quad \kappa \geq 1$

SW propagation as a function of density on the axis

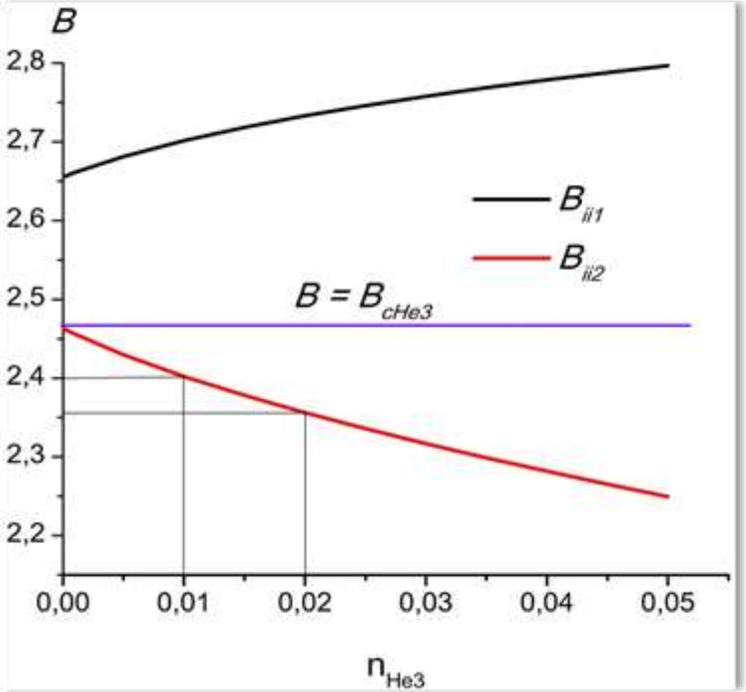




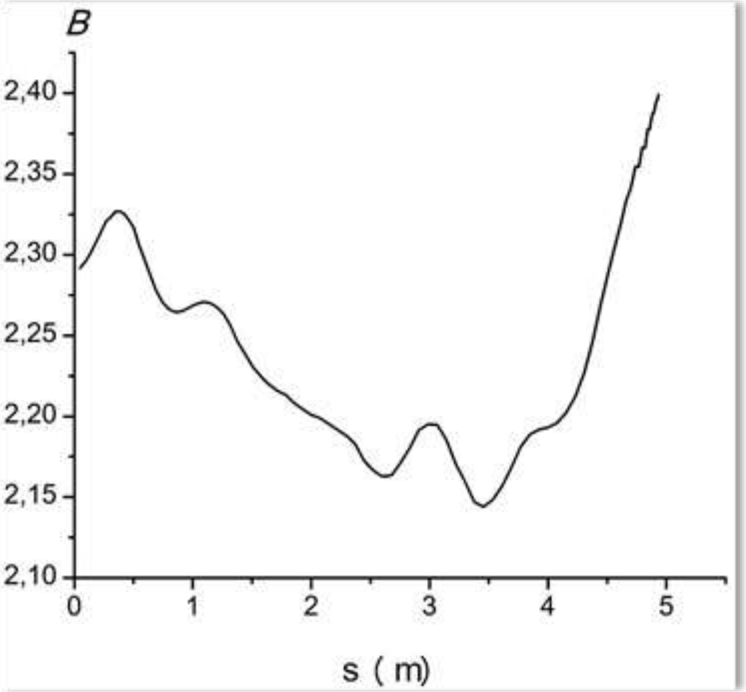
counter $\vec{B}$ ↓ - Ion – Ion Hybrid Resonance $co-\vec{B}$

$n_{e0}=3\cdot10^{18}\ m^{-3}$ – solid curve, $n_{e0}=1.5\cdot10^{19}\ m^{-3}$ – dashed curve, $n_{e0}=7\cdot10^{19}\ m^{-3}$ – dash-dotted curve.

Ion-ion hybrid resonance (1)



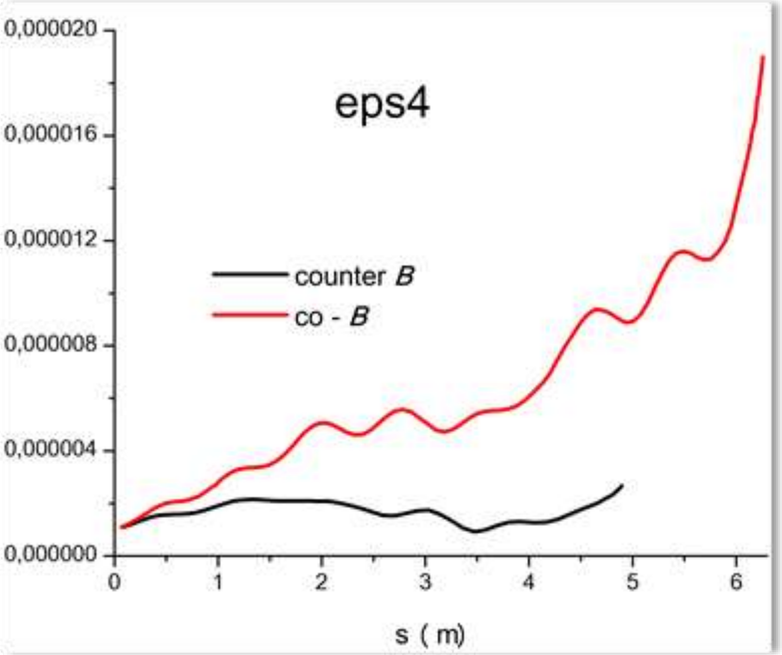
The values of the hybrid resonance magnetic fields and He^3 cyclotron resonance field *vs.* He^3 concentration



The typical distribution of magnetic field along the ray

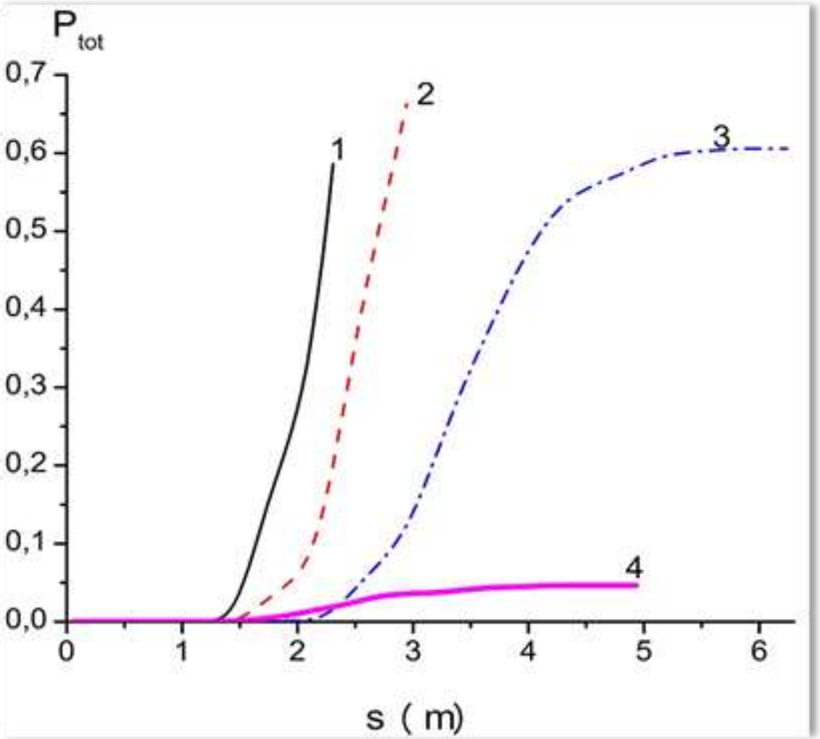
Ion-ion hybrid resonance (2)

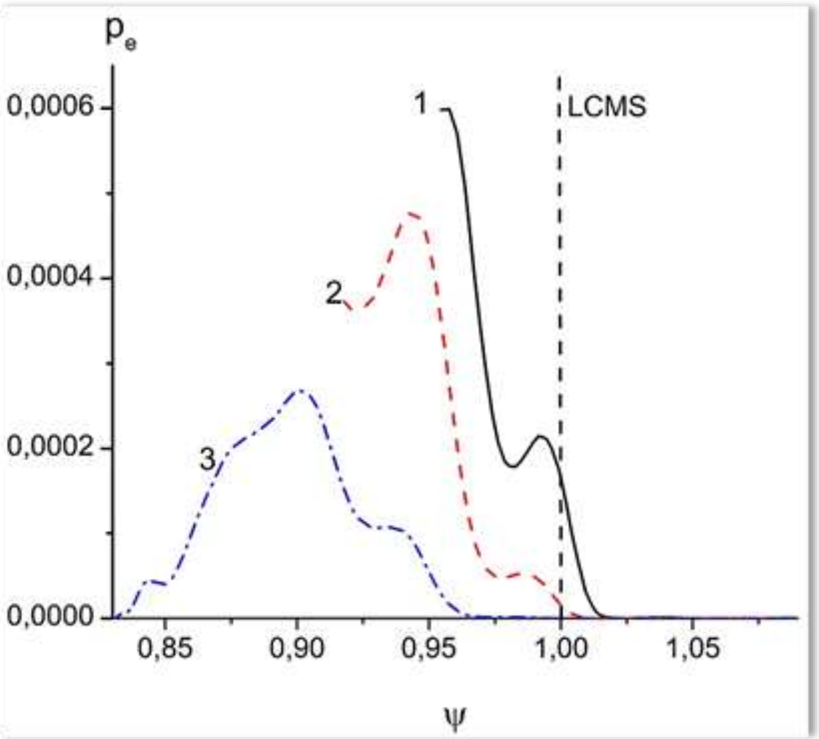
When $\varepsilon_1 \to 0$, the dispersion relation *D = 0* is inapplicable. To continue the study in this region, the contribution of the term proportional to the $k_\perp^2 \rho_{LHe3}^2$ has to be taken into account in the ε_1. Hence, ε_1 can be represented in the form $\varepsilon_1 = \varepsilon_{1cold} + \varepsilon_4 N_\perp^2$.



If $\varepsilon_4 > 0$, then the SWs are converted into small-scale ion-cyclotron waves, which propagate in the direction of the He3 cyclotron resonance.

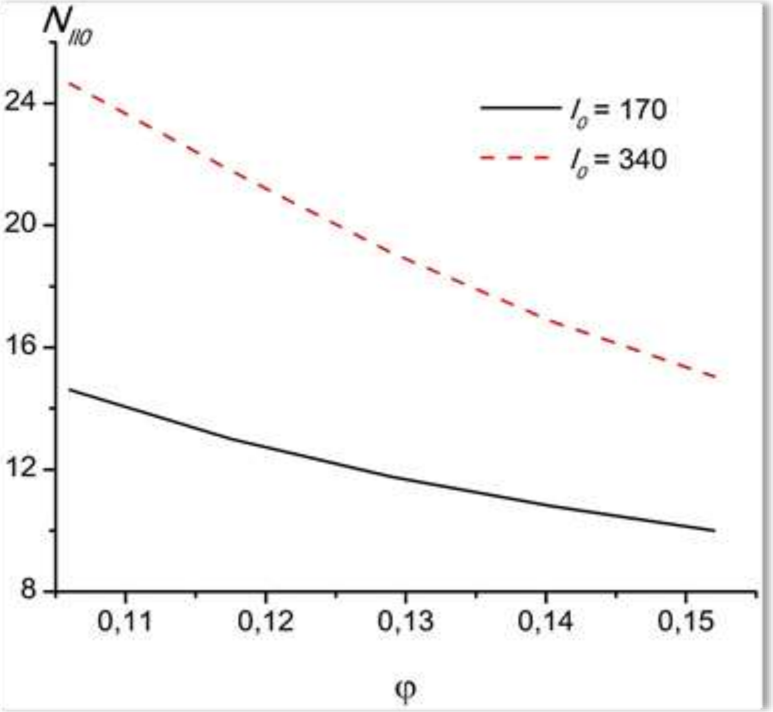
Landau damping

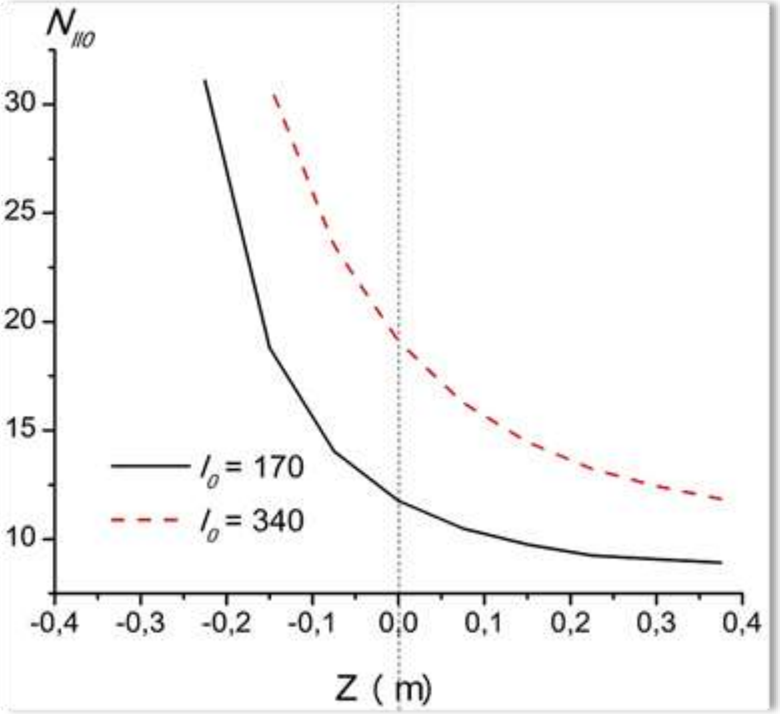




n_{e0}=$1.5 \cdot 10^{19}$ m^{-3}. Curve 1 l_0 = 420, curve 2 l_0 = 340, curve 3 l_0 = 250, *counter* $\vec{B}$ directed rays; curve 4 l_0 = 420, *co* – $\vec{B}$ directed ray.

Dependence on the initial azimuthal and vertical positions





The initial $N_{||0}$ as a function of the location of the ray start point in the toroidal and vertical directions, $co-\vec{B}$ directed rays .

Conclusion (1) – SW propagation

- The value of $N_{||}$ at the starting point determines both the ray propagation and absorption.
- Approximately half of the emitted slow waves propagate through the low-density plasma towards the vessel if symmetrical spectrum of toroidal wave numbers was assumed.
- The other half of the slow waves penetrate into the bulk plasma. The rays propagate mainly along the field lines for a distance of up to 6 m along and against the direction of the magnetic field. The penetration depth $\Delta\overline{a} \leq 0.15\, m$

Conclusion (2) – SW absorption

- Collisional absorption and cyclotron damping on H and D ions of these waves in the peripheral plasma is negligibly small.

- A smaller part of the slow wave spectrum is absorbed due to Landau damping. Although the rays that propagate in the direction of the magnetic field are absorbed stronger and deeper into the plasma than those in the opposite direction, this does not lead to the driving of the currents that could affect magnetic surfaces.

- The largest portion of the rays launched from the surface under the antenna falls into the region of ion-ion hybrid resonance. These waves are completely absorbed due to cyclotron resonance on He3 ions. Since absorption occurs in close proximity to the LCMS, this may cause increased losses of He3 ions from the confining volume. The presence of a source of hot He3 ions, which are poorly confined, at the periphery of the plasma can affect the experimental results.

THANK YOU FOR YOUR ATTENTION!