The low threshold parametric decay instabilities leading to anomalous absorption at ECRH in toroidal devices

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OUTLINE

- Common theoretical understanding of the role of parametric decay instabilities (PDIs) and resent observations of anomalous phenomena in the ECRH experiments.

  Anomalous backscattering phenomena in the Textor and ASDEX-U tokamaks and fast ion generation in the TCV tokamak and the TJ-II stellarator which can not be explained by standard theory and appeal for further theoretical analysis.

- New theoretical approach – to study the decay instability under conditions when one (or both) daughter wave is 3D trapped.

- The possible role of low-threshold absolute PDIs in backscattering and ion acceleration:

  X-wave parametric decay leading to partial pump wave absorption by ions.

  Two-plasmon decay leading to partial pump wave backscattering.

  O-wave parametric decay for ITER conditions leading to anomalous absorption of the mm waves by ions.

- Conclusions.

Common understanding of the role of the PDI in the ECRH experiment

The PDIs, leading to anomalous effects are believed to be deeply suppressed in tokamak MW power level ECR 1st harmonic O-mode and 2nd harmonic X-mode heating experiments utilizing gyrotrons. According to standard theory* dealing with monotonic density profile, the typical RF power at which these nonlinear effects can be excited at tokamak plasma parameters is higher than 5 MW. This is due to huge energy loss of both the daughter waves from the decay region along plasma inhomogeneity direction and magnetic field (finite-size beam of the pump wave). Thus, no anomalous reflection, as well as absorption, is expected.

**** Standard theory:***

[1] M. Porkolab et al. Nucl. Fusion 28 (1988) 239;

[2] B. I. Cohen, R.H. Cohen, W.M. Nevins and T. D. Rognlien, Rev. Mod. Phys. 63, (1991) 949

[3] A. Litvak et al., Phys. Fluids B 5, (1993) 4347

However during the last decade a “critical mass” of observations has been obtained evidencing the presence of anomalous phenomena in the ECRH experiments at toroidal devices.

Observation of anomalous phenomena in X-mode ECRH experiments

1) Strong anomalous scattering of mm-waves (CTS technique)

- Textor: The anomalous backscattering at 2nd harmonic ECRH was firstly reported in [E. Westerhof et al. *Phys. Rev. Lett.* 103, 125001 (2009)]. It was demonstrated in [S.K. Nielsen et al., *PPCF* 55, 115003 (2013)] that the most intensive backscattering occurs at the plasma density in the magnetic island slightly exceeding the UHR value for half a pump frequency.
- ASDEX-UG: The anomalous scattering at 2nd harmonic ECRH was reported [V. Furtula et al. *The Review of scientific instruments* 83, 013507 (2012)], [S.K. Nielsen et al. *In Proc. of 9th Workshop "Strong Microwaves and Terahertz Waves: Sources and Applications"* July 24-30 2014 Nizhny Novgorod]

2) Ion heating and acceleration at ECRH (passive spectroscopy, CX diagnostic)

- TCV: The fast ion generation and the ion heating were observed in a course of the 2nd harmonic ECRH pulse when energy exchange between e and ions should be very low [A.N.Karpushov, S.Coda, B.P.Duval, in *Proceedings of the 30th EPS Conference on Plasma Physics* (2003), 27A, P–3.123]; [A. N. Karpushov, B. P. Duval, T. P. Goodman, et al., in *Proceedings of the 33rd EPS Conference on Plasma Physics* (2006), 30I, P–1.152]; [Christian Schlatter // Turbulent Ion Heating in TCV Tokamak Plasmas THÈSE NO 4479 (2009)]
- TJ-II: The fast ion tails generation at the 2nd harmonic ECRH is reported [D Rapisarda et al *PPCF* 49, 309 (2007)]

The anomalous phenomena (in particular the anomalous absorption of mm-waves) were observed in the presence of the *non-monotonic* density profile*.

The latter is due to different physical mechanisms:

a) Hollow profiles due to the density-pump-out effect

b) features of plasma confinement in the magnetic islands

c) the presence of the drift-wave eddies, blobs possessing density maximum and aligned with the magnetic field

* The standard theory deals with the monotonic density profile

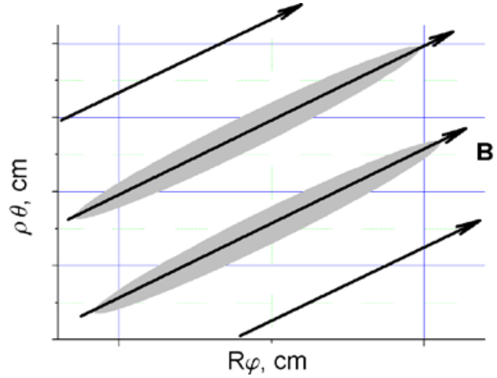
Hypothesis:

1) The anomalous absorption is due to the PDI of the pump mm-wave

2) The power threshold of the PDI is somehow decreased by mitigation (full suppression) of the energy loss of one (or both) daughter wave from the finite decay region in the presence of the *non-monotonic* density profile

X-wave parametric decay leading to excitation of the EBW and heavily damped low frequency oscillations in the presence of the drift-wave eddies (blobs, filaments) on TCV tokamak

$$t_{X\text{-}wave} \rightarrow l_{EBW} + l_{LF}$$

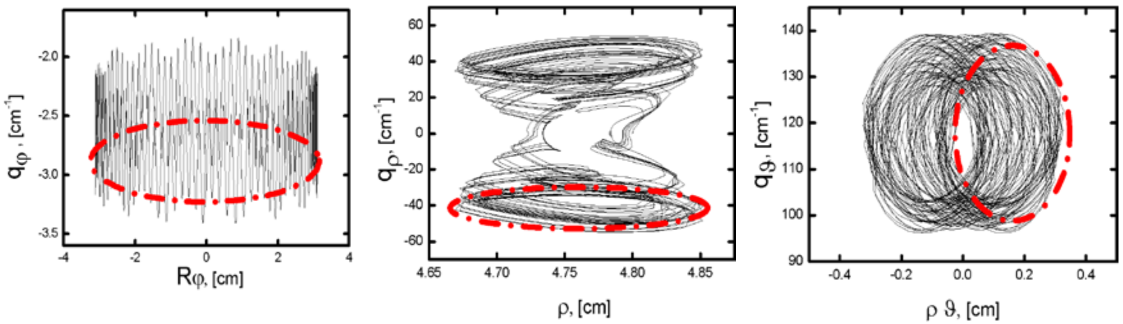


$$n_e = n_0 + \delta n$$

$$\delta n = \delta_n n_0 \exp\left(-\frac{(\rho-\rho_0)^2 + \rho^2 (\vartheta - \varphi / q(\rho))^2}{l^2} \right)$$

1) The perturbation relative amplitude used in the analysis (δ_n =0.05) is consistent with the values usually observed in the presence of turbulence intermittency manifesting itself in bursts and non-Gaussian statistics
2) l=0.3 cm (TEM)
3) Typical TCV tokamak parametrs

Phase portrait of the EBW ray trajectory



1) the EBW 3D trapping leads to full suppression of its energy loss from the decay region .

2) the LF daughter wave is a slow ion sound wave heavily damped due to the ion Landau damping. This wave directly transfers the pump power to the ion component.

$$P_0^{th} = 7.4kW, \gamma_{1,0,0} \simeq 0.6 \cdot 10^8 s^{-1} >> \omega_{blob}$$

Summary of the 1st scenario

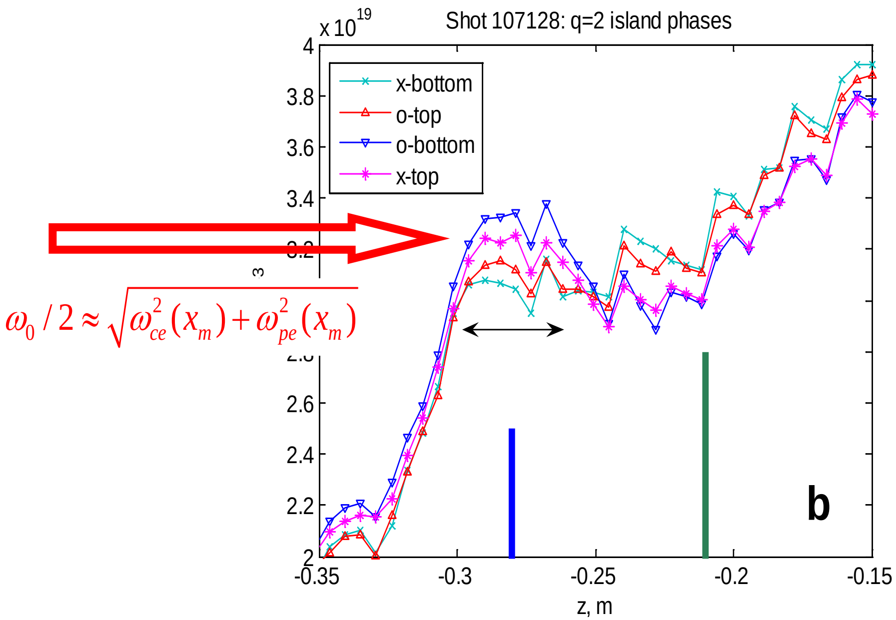
The presence of a coherent turbulence structure makes possible 3D localization of the electron Bernstein decay waves that leads to full suppression of their energy loss from the decay region and, as result, to the drastic decrease of the X wave absolute PDI power threshold.

The X wave PDI leading to excitation of the EBW and low frequency potential wave can explain anomalous ion acceleration and heating in the 2nd harmonic ECRH experiments on TCV tokamak and TJ-II stellarator.

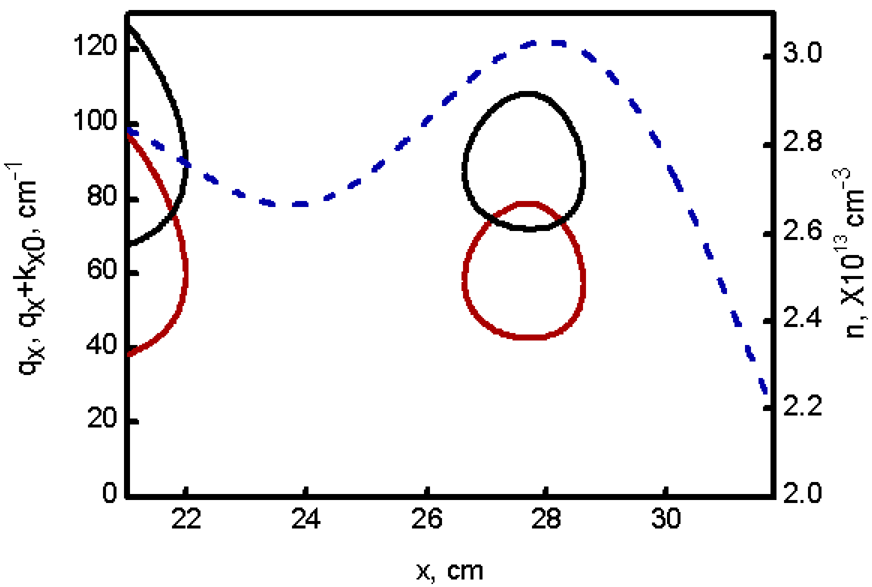
E Z Gusakov, A Yu Popov, A N Saveliev (2014) Plasma Phys. Control. Fusion 56 015010

PDI of X-wave leading to excitation of two upper hybrid (UH) plasmons in the presence of the magnetic island

$t_{X\text{-wave}} \rightarrow l_{UH} + l_{UH}$



M. Yu. Kantor et al. 2009 Plasma Phys. Control. Fusion 51 055002



(a, left and bottom axes) – 1D dispersion curves q_{x1} (red curves) and $q_{x2}+k_0$ (black curves);
(b, right and bottom axes) – actual density profile (blue)

$$T_e = 500eV,\ \omega_0 = 140GHz,\ \omega_0 / 2 = \sqrt{\omega_{ce}^2(x_m) + \omega_{pe}^2(x_m)},$$

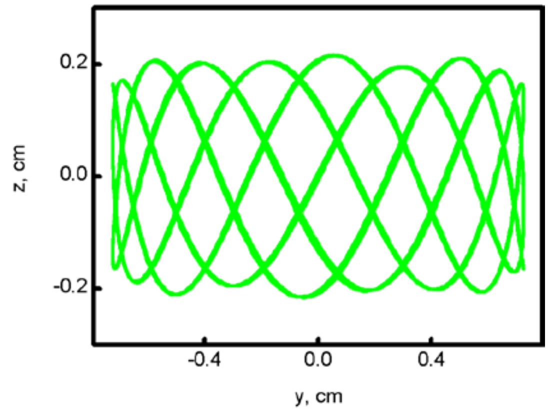
The UH waves are radially trapped in the vicinity of the density maximum and thus their energy loss in the radial direction is suppressed in full.

Additional 2D trapping of the UH plasmons by the pump beam in poloidal and toroidal directions

- UH waves propagate in opposite directions
- two-dimensionally finite-size beam of the pump wave

1D case: L.M. Gorbunov, Sov. Phys.- JETP 40, 689 (1975); A. Bers *in Basic Plasma Physics (Handbook of Plasma Physics)* by A.A. Galeev and R.N. Sudan, Elsevier Science Ltd (March 1985)

2D case: E Z Gusakov, A Yu Popov (2012) EPJ Web of Conferences 32 010072



The 1st UH wave ray trajectory on the magnetic surface in the presence of non-linear coupling with the 2nd UH wave due to 2D finite-size X-mode pump

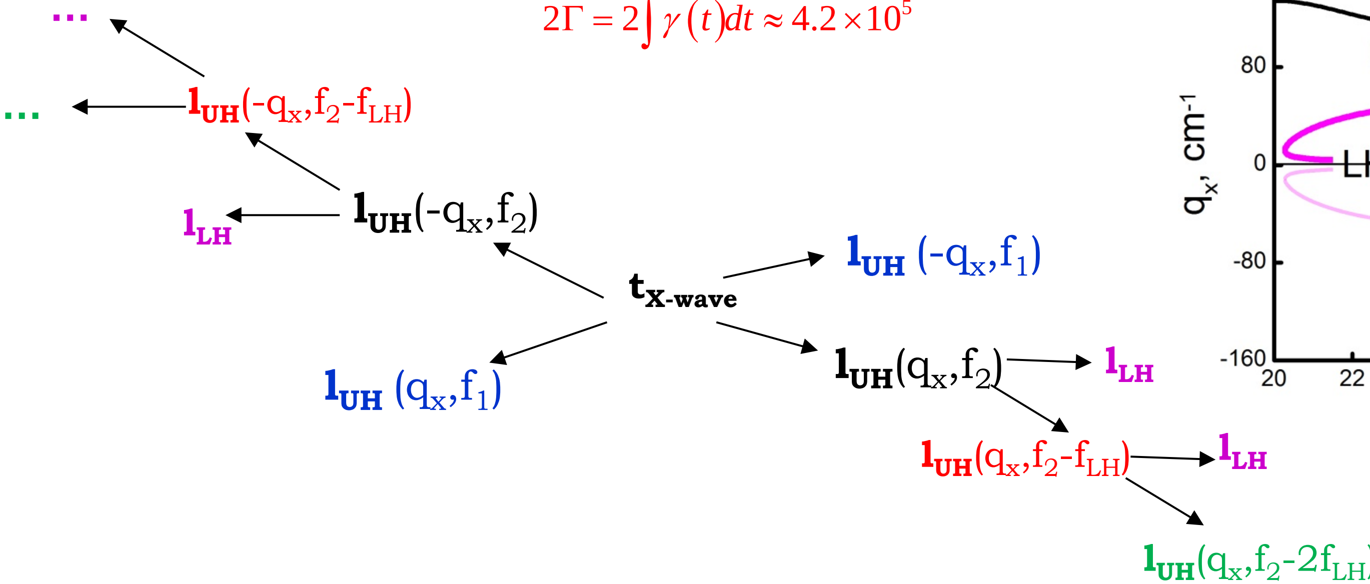
1) The ray trajectory is finite that demonstrates the UH wave 2D trapping on the magnetic surface.

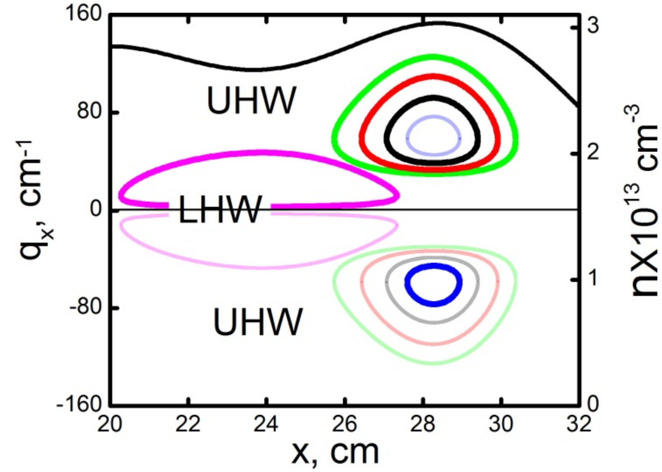
2) Both the UH daughter waves are 3D trapped that leads to their temporal growth (absolute PDI), $P_0^{th} = 24kW, \gamma\big|_{P_0=500kW} \approx 2\times10^7 s^{-1}$

Saturation of the X wave two-UH-plasmon PDI via cascading

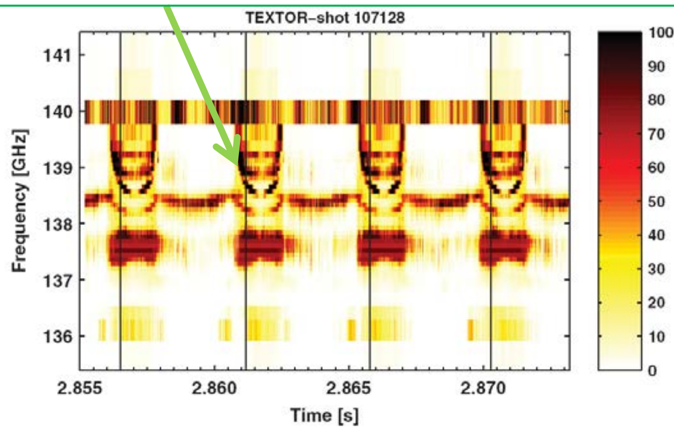
$f_1 = 70.18GHz;\ f_2 = 69.82GHz$

$2\Gamma = 2\int \gamma(t)dt \approx 4.2\times10^5$





$$l_{UH}(q_x,f_2-mf_{lh})+l_{UH}(-q_x,f_2) \rightarrow t_{back\ X\text{-wave}}(2f_2-m\ f_{lh})$$
$$l_{UH}(q_x,f_2-mf_{lh})+l_{UH}(-q_x,f_1) \rightarrow t_{back\ X\text{-wave}}(f_1+f_2-m\ f_{lh}),\ m=0,1\ldots$$



1) Coupling of the daughter UH waves can explain the fine structure of the backscattering spectrum measured

2) LHWs generated due to the UHW secondary decay to the UHW and the LHW can interact with ions and accelerate them

$$P_0^{loss} \leq 30\%$$

E. Westerhof et al. Phys. Rev. Lett. 103, 125001 (2009)

Summary of the 2nd scenario

The possibility of the 3D localization of both the UH daughter waves due to local maximum of the density in the O-point of the magnetic island in the radial direction and the 2D finite-size beam of the pump wave at the magnetic surface leads to excitation of the low threshold X-wave absolute two-UH-plasmon PDI.

It most likely plays a role in anomalous backscattering in the ECRH experiments in the TEXTOR tokamak. Furthermore, saturating via cascading the two-plasmon PDI can lead to excitation of the secondary LH daughter waves, which are absorbed by ions.

1. E Z Gusakov, A Yu Popov (2012) EPJ Web of Conferences 32 010072
2. A.Yu. Popov, E.Z. Gusakov (2014) JETP 146 1

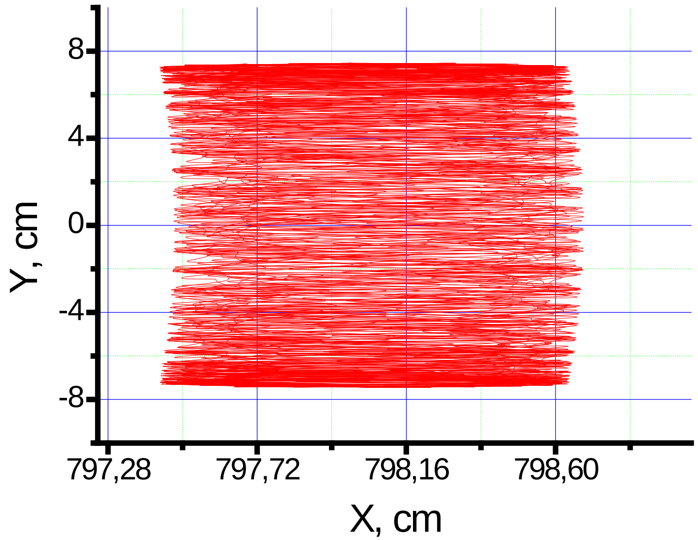
The O wave decay to the UH wave and the ion Bernstein wave for ITER conditions

$t_{O\text{-}wave} \rightarrow 1_{UH} + 1_{IBW}$

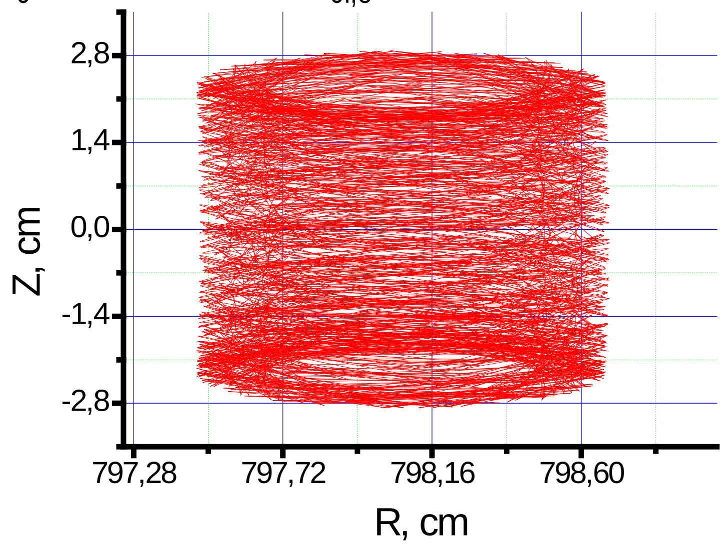
The UH behavior in the presence of
Field-Aligned Structure (dift-wave eddy, filament, blob etc.):

$$\delta n = \delta_n n_0 \exp\left(-\frac{(\rho-\rho_0)^2 + \rho^2(\vartheta - \varphi / q(\rho))^2}{l^2}\right), \delta_n = 0.03, l = 1cm$$

ITER conditions: D-T, 50%+50%, $n_0=1.1*10^{14}$ cm^{-3}, $T_{0i,e}$=10 keV



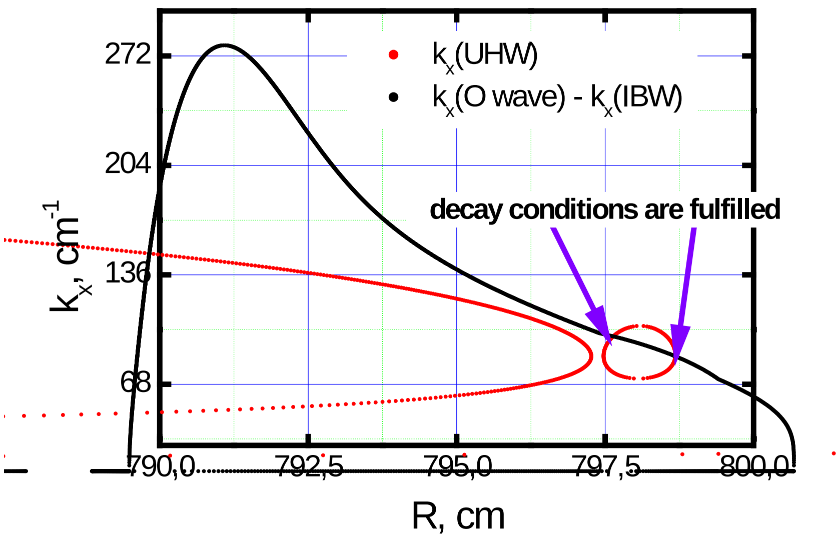
UHW ray trajectory (ITER poloidal cross-section)



UHW ray trajectory (ITER toroidal cross-section)

1) The UH daughter wave appears to be 3D trapped.
2) The power threshold of the O-wave PDI leading to excitation of the 3D trapped UH wave and the IBW is expected to be drastically lower than predicted by the standard theory.

Possibility of the O wave absolute PDI for ITER conditions



1D wave dispersion curves of the UH wave (red) and
the IBW down-shifted by the wavenumber of the O wave (black)

Anomalous absorption by electrons and ions is possible

Summary of the 3d scenario

Absolute PDI leading to excitation of the UHW and IBW can influence the neoclassical tearing mode control technique by ECRH in ITER experiments due to non-monotonous density profile in the magnetic field-aligned turbulent structures.

E.Z. Gusakov, A. Yu. Popov, E. V. Sysoeva, A. N. Saveliev // Low-threshold parametric excitation of UH wave trapped in a blob in the first harmonic O-mode ECRH experiment (2014) in Proc. 41st EPS Conference on Plasma Physics P4.049

CONCLUSIONS

The absolute PDIs leading to the anomalous absorption in the presence of non-monotonous density profile possess low threshold and therefore are potentially dangerous for the ECR neoclassical magnetic island control and heating methods planned for application at ITER.

To understand the role of different PDIs in the ECRH energy balance an assessment of the amplitude of the coherent structures as well as their spatial scales with the use of the numerical modelling of the ITER-like plasma turbulence is of great importance.

The phenomenon of the anomalous backscattering and ion acceleration at the ECRH observed in medium-scale plasma machines deserves more attentive experimental and theoretical study and testing in larger-scale experiments.