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

A Popov, E Gusakov, A Saveliev, E Sysoeva

Ioffe Institute, St. Petersburg, Russia

Ioffe Institute

The different scenarios of the low-threshold parametric decay instabilities (PDIs) leading to anomalous absorption in 2nd harmonic extraordinary wave and 1st harmonic ordinary wave ECRH experiments in the presence of non-monotonous density profile are considered. These instabilities can explain the anomalous phenomena being already observed and potentially important for the energy budget in the future ECRH experiments.

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

According to standard theory* **no anomalous reflection and absorption** in tokamak MW power level ECRH experiments utilizing gyrotrons **are expected**. This is due to huge energy loss of both the daughter waves from the decay region.

* Standard theory dealing with monotonic density profile :
[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 ECRH experiments at toroidal devices.

Observation of anomalous phenomena at 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 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 THESE NO 4479 (2009)]

TJ-II: The fast ion tails generation at the 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 physical mechanisms of which are:

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

b) features of plasma confinement in the magnetic islands.

c) the electron pump-out effect

Hypothesis:

1) The anomalous absorption is due to PDI of the pump EC wave
2) The power threshold of the PDI is somehow decreased by the presence of the *non-monotonic* density profile

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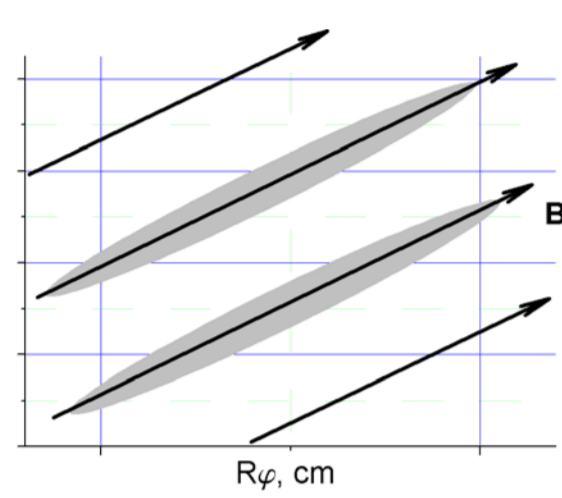
$$n_e = n_0 + \delta n$$
$$\delta n = \delta_n n_0 \exp\left(-\frac{(\rho - \rho_0)^2 + \rho^2\left(\vartheta - \varphi/q(\rho)\right)^2}{l^2}\right)$$

1) The perturbation relative amplitude used in the analysis (δ_n =0.05) is consistent with the values usually observed close to discharge separatrix or in the edge plasma, but is higher than the typical density fluctuation RMS in the central region (0.005 – 0.02). We justify this excess by the turbulence intermittency which manifests itself in bursts and non-Gaussian statistics making such high values probable.

2) l=0.3 cm (TEM)

Phase portrait of the EBW ray trajectory

3D trapping of the EBW

Power threshold of the absorptive PDI

$$\gamma_0\left(P_0^{th}\right)\frac{V_{PDI}}{V_{cavity}} = \nu_E$$

Non-linear pumping   EBW's loss

γ_0 - growth rate of the PDI under investigation in homogeneous plasma theory;
ν_E - characterizes the EBW's radiative energy loss;
V_{PDI}/V_{cavity} − a geometrical factor

Evolution of the EBW parameters in the course of the auxiliary ECRH

In the course of the X-mode ECRH T_e raises abruptly up to T_e =5keV at the approximately same or little less density

2 keV: 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 ions.
$$P^{th} = 7.4kW, \gamma_{1,0,0} = 0.6 \cdot 10^8 s^{-1} >> \omega_{blob}$$

5 keV: the LF daughter wave is heavily damped oscillation induced at frequency W =1.6 GHz due to the X-wave and EBW non-linear coupling and interacting with accelerated ions that leads to the pump energy transfer to latter.
$$P_0^{th} = 200kW, \gamma_{1,0,0} \approx 0.45 \cdot 10^8 s^{-1} \geq \omega_{blob}$$
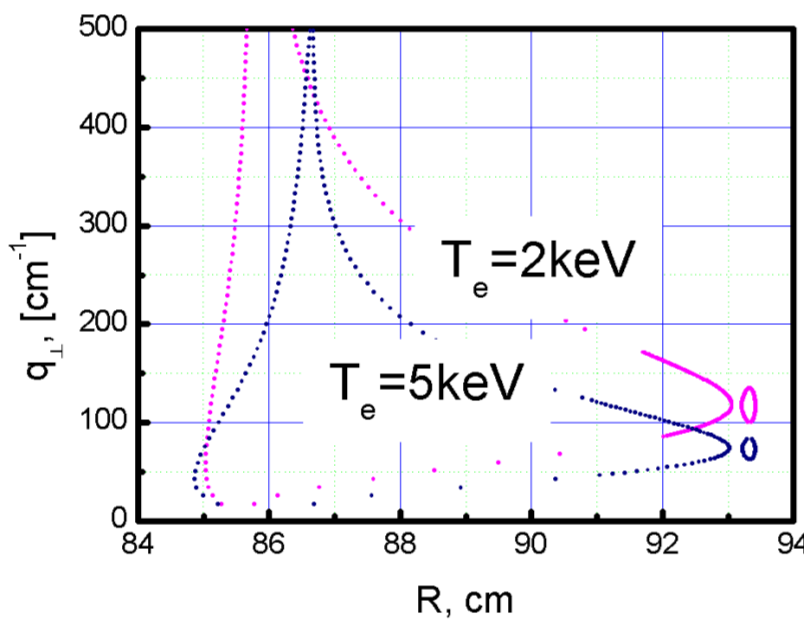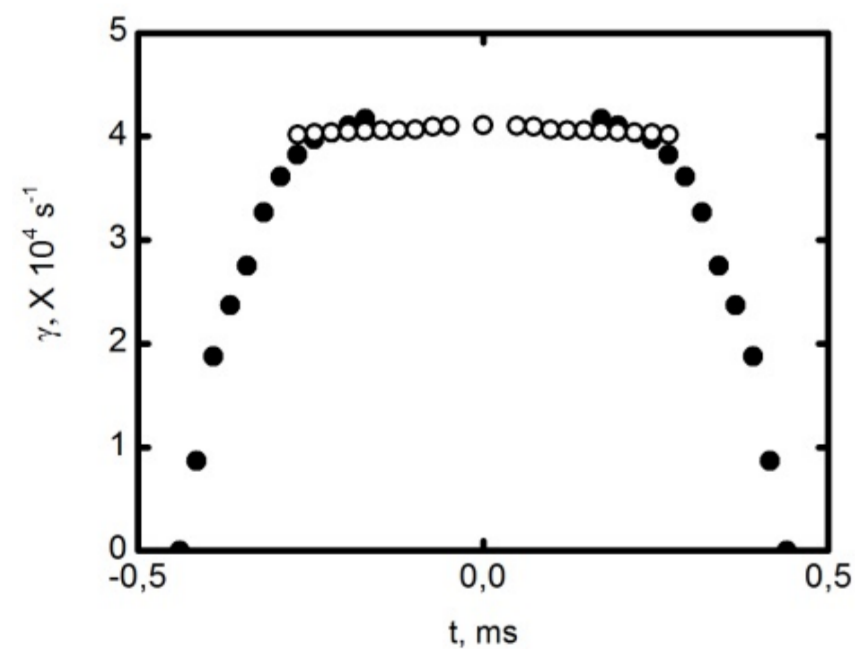
1st scenario summary
1) Acting in parallel with poloidal magnetic field inhomogeneity non monotonic profile of plasma density makes possible 3D localization of the electron Bernstein decay waves that leads to suppression of their energy loss from the decay region and, as result, the drastic decrease of the X wave absolute PDI power threshold .
2) The X wave PDI leading to excitation of the 2nd harmonic EBW and low frequency potential wave can explain anomalous ion acceleration and heating in the 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 growth rate and threshold under TEXTOR conditions

The poloidal rotation of the magnetic island leads to temporal evolution of the parameters of the effective wave-guide in which both the UH plasmons are radially trapped. Nevertheless, the additional trapping of both the UH plasmons on the magnetic surface persists, manifesting adiabatic modification of their Eigen-modes structure. But the absolute PDI growth rate value varies as well.

$$2\Gamma = 2\int \gamma(t)dt \approx 0.35 \times 10^8$$

The absolute PDI growth rate temporal evolution due to the magnetic island poloidal rotation, P_0=500 kW

PDI of X-wave leading to excitation of 2 UH plasmons in the presence of the magnetic island*

$\omega_0/2 = \sqrt{\omega_{ce}^2(x_m) + \omega_{pe}^2(x_m)}$

M. Yu. Kantor et al. 2009 PPCF 51 055002

(a, left and bottom axes) – 1D dispersion curves q_{44} (red curves) and q_{49}+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 convective losses in the radial direction are suppressed in full.

* The theoretical model being proposed to explain the anomalous X-wave backscattering in the ECRH experiments on Textor predicts anomalous damping as a consequence of the backscattering PDI saturation via cascading.

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

$f_1 = 70.18GHz; f_2 = 69.82GHz$
$2\Gamma = 2\int \gamma(t)dt \approx 4.2 \times 10^3$

$$2\Gamma = 2\int \gamma(t)dt \approx 0.35 \times 10^5$$

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

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)

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

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

• 1D case: L.M. Gorbunov, Sov. Phys.- JETP 40, 689 (1975)
• 2D case: E Z Gusakov, A Yu Popov (2012) EPJ Web of Conference 32 0100072

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

1) The ray trajectory is finite that demonstrates the UH wave 2D trapping at the magnetic surface.
2) Both UH daughter waves are 3D trapped that leads to their temporal growing

2nd scenario summary:

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 on TEXTOR. Furthermore, saturating via cascading the two-plasmon PDI can lead to excitation of the secondary LH daughter waves, which are absorbed by ions.

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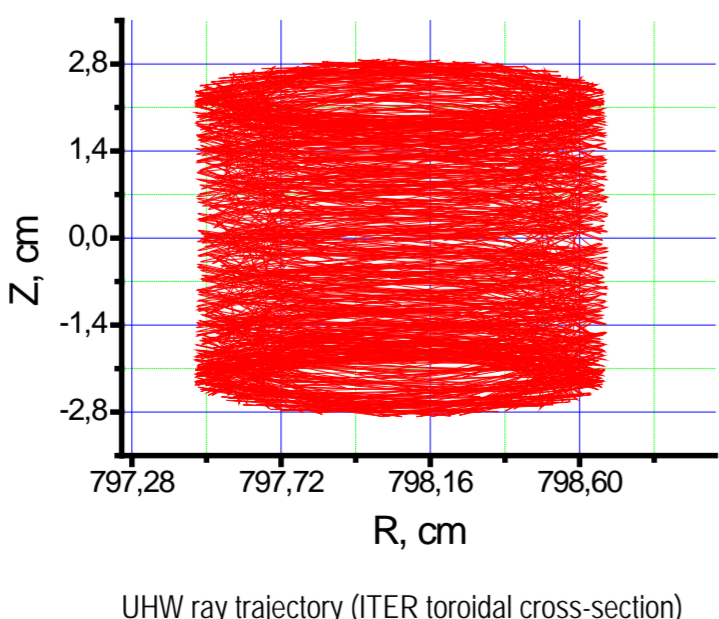A.Yu. Popov, E.Z. Gusakov (2014) JETP **146** 1

The possible role of PDI in the O wave ECRH experiments in ITER

1) Scenario of the O wave decay to the UH wave and the Ion Bernstein wave (IBW)
2) The UH behavior in the presence of Field-Aligned Structure (dift-wave eddy, filament, blob etc.):

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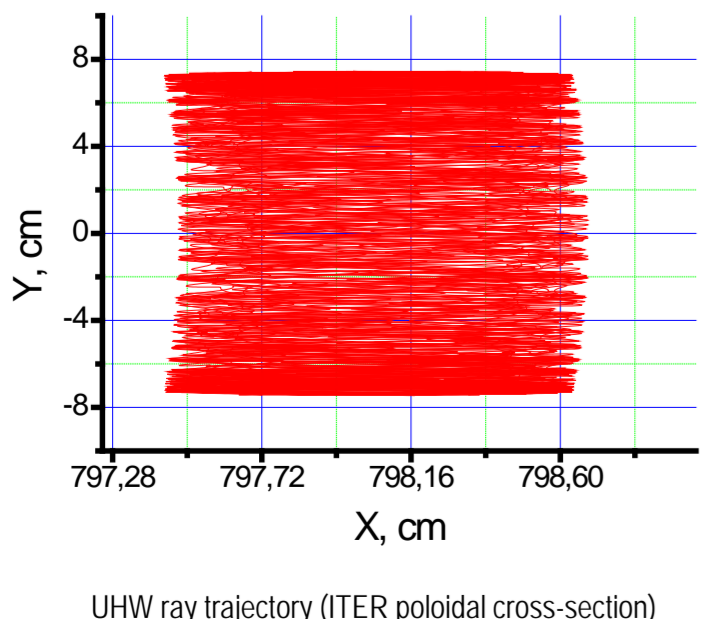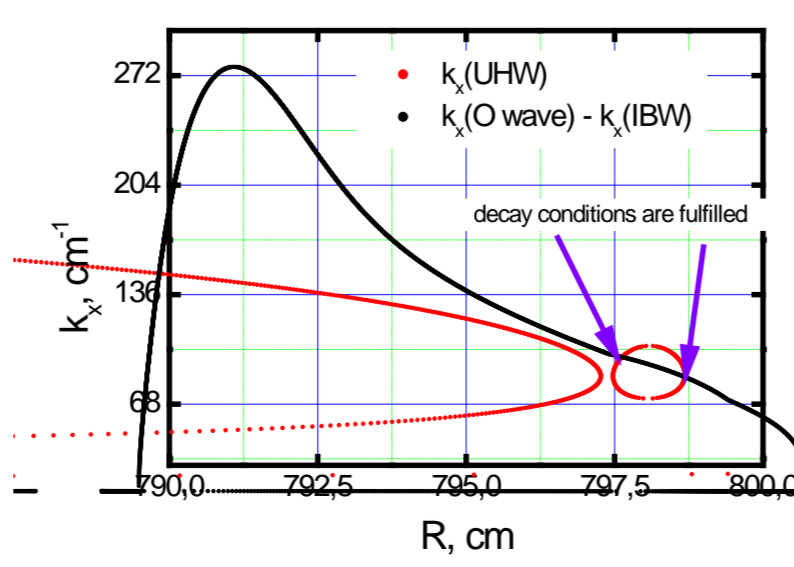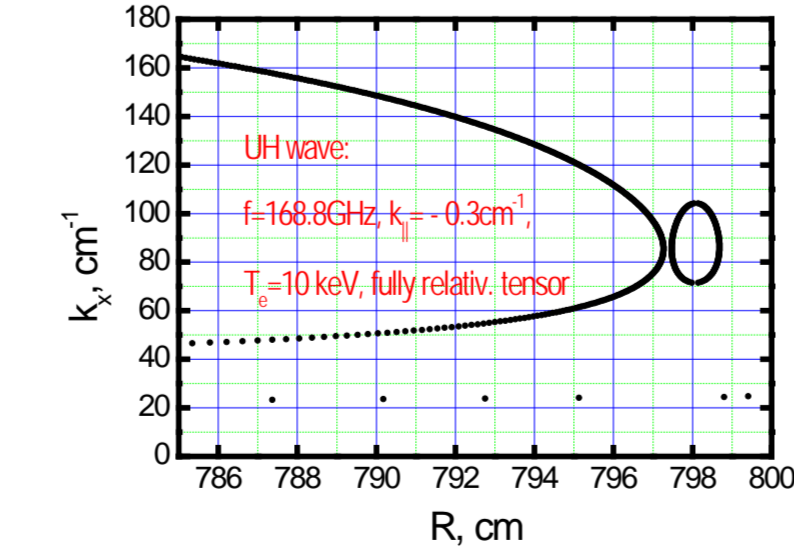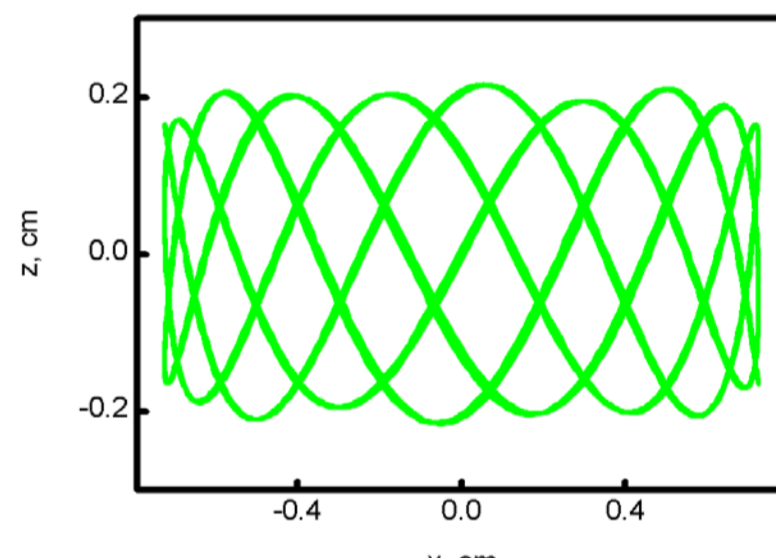

UHW ray trajectory (ITER poloidal cross-section)   UHW ray trajectory (ITER toroidal cross-section)

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

Possibility of the O wave absolute PDI for ITER conditions

1D UHW dispersion curves   1D IBW dispersion curves

1) The power threshold of the PDI is expected to be drastically lower than predicted by the standard model
2) Anomalous ion heating is possible

3d scenario summary:
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 often observed in the magnetic islands or in the magnetic field-aligned turbulent structures.

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

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. 41th EPS Conference on Plasma Physics P4.049

CONCLUSIONS

The absolute PDIs leading to the anomalous heating are able to change the power deposition profile 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 ion heating at the ECRH experiments observed in small-scale plasma experiments deserves more attentive study and testing in larger-scale ECRH experiments.